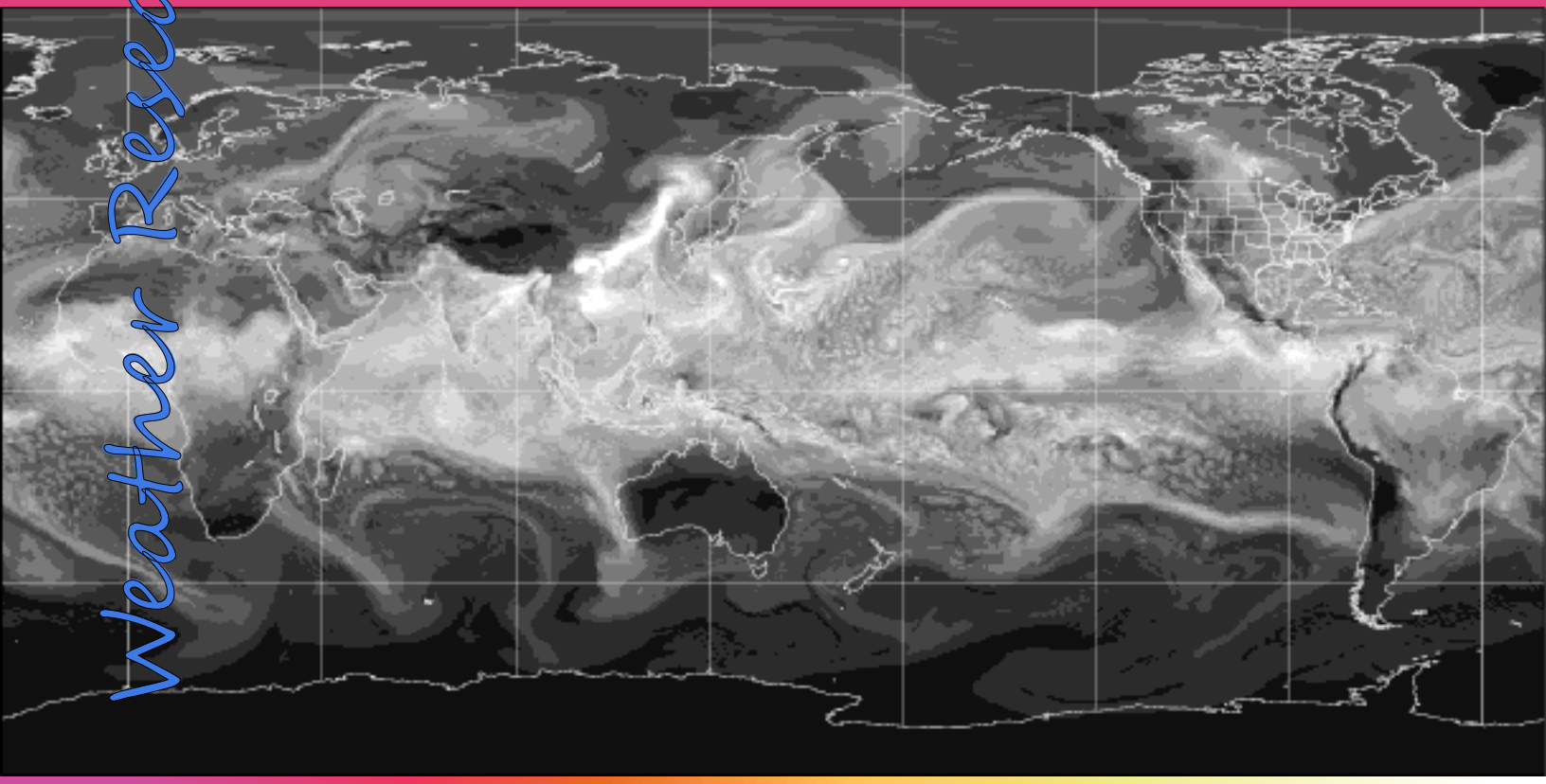
Weather Research & Forecasting

ARW

Version 3 Modeling System User's Guide

July 2017



Mesoscale & Microscale Meteorology Laboratory • National Center for Atmospheric Research

Foreword

This User's Guide describes the Advanced Research WRF (ARW) Version 3.9 modeling system, released in April 2017. As the ARW is developed further, this document will be continuously enhanced and updated. Please send feedback to wrfhelp@ucar.edu.

This document is complementary to the ARW Tech Note (http://www2.mmm.ucar.edu/wrf/users/docs/arw_v3.pdf), which describes the equations, numerics, boundary conditions, and nesting etc. in greater detail.

Highlights of updates to WRFV3.9 include:

- WRF model:
  Vertical coordinate:
  - Hybrid sigma-pressure vertical coordinate: terrain-following near the surface, and gradually transitions to constant pressure at higher levels.

  Physics:
  - P3 microphysics (contributed by Morrison and Milbrandt);
  - Three urban models are added to NoahMP (Salamanca of Arizona State, Yizhou Zhang of IUM/CMA, China, and Barlage of NCAR);
  - Physics suite specification via namelist;
  - Improvement to RAP/HRRR and other physics;
  - Stochastically perturbed parameter scheme and stochastically perturbed physics tendencies (Judith Berner of NCAR)
  - Introduction of physics suites.
- WPS*:*
  - Capability to drive WRF from MPAS native grid data;
  - 30-seconds BNU soil category dataset (Barlage of NCAR)
- WRF-DA updates:
  - New assimilation capability: 4DEnVar (Nils Gustafsson of Swedish Meteorological and Hydrological Institute and Feng Gao of NCAR)
  - Cloudy radiance assimilation capability for AMSR-2 (Chun Yang of Nanjing University of Information Science & Technology)
  - Radar "null-echo" assimilation (Ki-Hong Min and Yu-Shin Kim; Kyungpook National University, Daegu, South Korea)
- WRF-Chemistry
  - Tropospheric Ultraviolet and Visible (TUV) photolysis option (S. Walters, A. Hodzic, and S. Madronich of NCAR);
  - Coupled WSM6 microphysics with MOZART gas wet scavenging (Megan Bela of NOAA);
  - Modified GOGART dust scheme for SORGAM and MOSAIC chemistry;
  - A new trajectory option that monitors meteorological and chemical properties along air trajectories (ACOM/NCAR).

For the latest version of this document, please visit the ARW Users' Web site at http://www2.mmm.ucar.edu/wrf/users/.

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Chapter 1: Overview

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Introduction

The Advanced Research WRF (ARW) modeling system has been in development for the past few years. The current release is Version 3, available since April 2008. The ARW is designed to be a flexible, state-of-the-art atmospheric simulation system that is portable and efficient on available parallel computing platforms. The ARW is suitable for use in a broad range of applications across scales ranging from meters to thousands of kilometers, including:

- Idealized simulations (e.g. LES, convection, baroclinic waves)
- Parameterization research
- Data assimilation research
- Forecast research
- Real-time NWP
- Hurricane research
- Regional climate research
- Coupled-model applications
- Teaching

The Mesoscale and Microscale Meteorology Division of NCAR is currently maintaining and supporting a subset of the overall WRF code (Version 3) that includes:

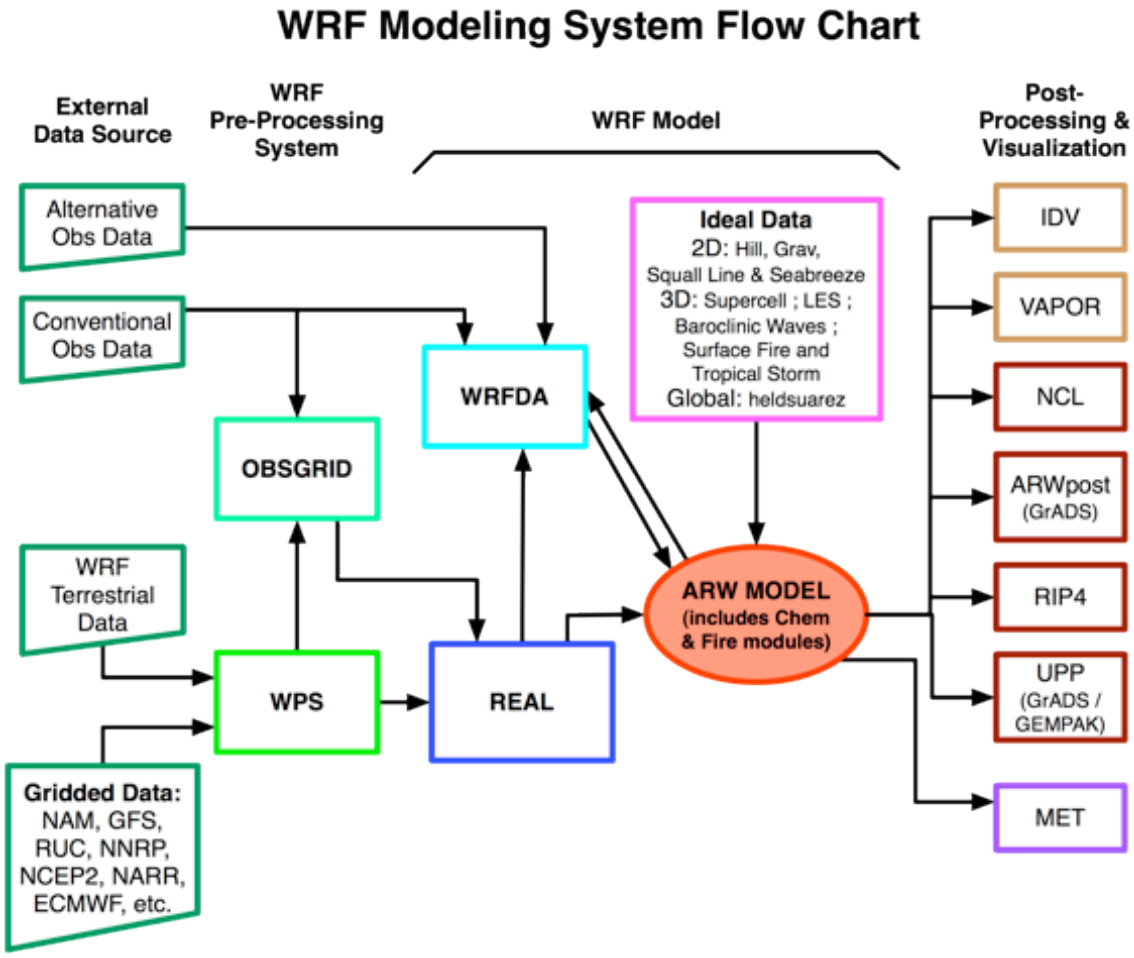
- WRF Software Framework (WSF)
- Advanced Research WRF (ARW) dynamic solver, including one-way, two-way nesting and moving nest.
- The WRF Preprocessing System (WPS)
- WRF Data Assimilation (WRF-DA) system which currently supports 3DVAR 4DVAR, and hybrid data assimilation capabilities
- Numerous physics packages contributed by WRF partners and the research community
- Several graphics programs and conversion programs for other graphics tools

And these are the subjects of this document.

The WRF modeling system software is in the public domain and is freely available for community use.

The WRF Modeling System Program Components

The following figure shows the flowchart for the WRF Modeling System Version 3.



As shown in the diagram, the WRF Modeling System consists of these major programs:

- The WRF Preprocessing System (WPS)
- WRF-DA
- ARW solver
- Post-processing & Visualization tools

WPS

This program is used primarily for real-data simulations. Its functions include 1) defining simulation domains; 2) interpolating terrestrial data (such as terrain, landuse, and soil types) to the simulation domain; and 3) degribbing and interpolating meteorological data from another model to this simulation domain. Its main features include:

- GRIB 1/2 meteorological data from various centers around the world
- USGS 24 category and MODIS 20 category land datasets; USGS GTOPO30 elevation dataset; Global 5-minutes United Nation FAO, and North-America STATSGO 30 sec soil category dataset; 10-min greenness fraction data based on AVHRR and 30-sec greenness fraction data based on 10 years MODIS; MODIS-based leaf-area index; 0.15 degree monthly albedo and snow albedo data; and 1-degree deep soil temperature data; plus a few specialized datasets
- Map projections for 1) polar stereographic, 2) Lambert-Conformal, 3) Mercator and 4) latitude-longitude
- Nesting
- User-interfaces to input other static data as well as met data

WRF-DA

This program is optional, but can be used to ingest observations into the interpolated analyses created by WPS. It can also be used to update WRF model's initial conditions when the WRF model is run in cycling mode. Its main features are as follows:

- It is based on an incremental variational data assimilation technique, and has both 3D-Var and 4D-Var capabilities
- It also includes the capability of hybrid data assimilation (Variational + Ensemble)
- The conjugate gradient method is utilized to minimize the cost function in the analysis control variable space
- Analysis is performed on an un-staggered Arakawa A-grid
- Analysis increments are interpolated to staggered Arakawa C-grid and it gets added to the background (first guess) to get the final analysis of the WRF-model grid
- Conventional observation data input may be supplied either in ASCII format via the “obsproc” utility or “PREPBUFR” format.
- Multiple satellite observation data input may be supplied in BUFR format
- Multiple radar data (reflectivity & radial velocity) input is supplied through ASCII format
- Multiple outer loop to address the nonlinearity
- Capability to compute adjoint sensitivity
- Horizontal component of the background (first guess) error is represented via a recursive filter (for regional) or power spectrum (for global). The vertical component is applied through projections on climatologically generated averaged eigenvectors and its corresponding Eigen values

- Horizontal and vertical background errors are non-separable. Each eigenvector has its own horizontal climatologically-determined length scale
- Preconditioning of the background part of the cost function is done via the control variable transform U defined as $B= UU^T$
- It includes the "gen_be" utility to generate the climatological background error covariance estimate via the NMC-method or ensemble perturbations
- A utility program to update WRF boundary condition file after WRF-DA

ARW Solver

This is the key component of the modeling system, which is composed of several initialization programs for idealized, and real-data simulations, and the numerical integration program. The key features of the WRF model include:

- Fully compressible nonhydrostatic equations with hydrostatic option
- Regional and global applications
- Complete Coriolis and curvature terms
- Two-way nesting with multiple nests and nest levels
- Concurrent one-way nesting with multiple nests and nest levels
- Offline one-way nesting with vertical nesting
- Moving nests (prescribed moves and vortex tracking)
- Mass-based terrain-following coordinate and optional hybrid sigma-pressure vertical coordinate
- Vertical grid-spacing can vary with height
- Map-scale factors for these projections:
    - polar stereographic (conformal)
    - Lambert-conformal
    - Mercator (conformal)
    - Latitude and longitude, which can be rotated
- Arakawa C-grid staggering
- Runge-Kutta 2nd and 3rd order time integration options
- Scalar-conserving flux form for prognostic variables
- 2nd to 6th order advection options (horizontal and vertical)
- Monotonic transport and positive-definite advection option for moisture, scalar, tracer, and TKE
- Weighted Essentially Non-Oscillatory (WENO) advection option
- Time-split small step for acoustic and gravity-wave modes:
    - small step horizontally explicit, vertically implicit
    - divergence damping option and vertical time off-centering
    - external-mode filtering option
- Upper boundary absorption and Rayleigh damping
- Lateral boundary conditions
    - idealized cases: periodic, symmetric, and open radiative
    - real cases: specified with relaxation zone

- Full physics options for land-surface, planetary boundary layer, atmospheric and surface radiation, microphysics and cumulus convection
- Ocean models
- Grid analysis nudging using separate upper-air and surface data, and observation nudging
- Spectral nudging
- Digital filter initialization
- Adaptive time stepping
- Orographic gravity wave drag
- Stochastic parameterization schemes
- A number of idealized examples

Graphics and Verification Tools

Several programs are supported, including RIP4 (based on NCAR Graphics), NCAR Graphics Command Language (NCL), and conversion programs for other readily available graphics packages like GrADS.

Program VAPOR, **V**isualization and **A**nalysis **P**latform for **O**cean, Atmosphere, and Solar **R**esearchers (http://www.vapor.ucar.edu/), is a 3-dimensional data visualization tool, and it is developed and supported by the VAPOR team at NCAR (vapor@ucar.edu).

Program MET, **M**odel **E**valuation **T**ools (http://www.dtcenter.org/met/users/), is developed and supported by the Developmental Testbed Center at NCAR (met_help@ucar.edu).

The details of these programs (with the exception of the MET program) are described more in the later chapters of this user's guide. See the above link for information about MET.

Chapter 2: Software Installation

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Introduction

The WRF modeling system software installation is fairly straightforward on the ported platforms listed below. The model-component portion of the package is mostly self-contained. The WRF model does contain the source code to a Fortran interface to ESMF and the source to FFTPACK . Contained within the WRF system is the WRFDA component, which has several external libraries that the user must install (for various observation types and linear algebra solvers). Similarly, the WPS package, separate from the WRF source code, has additional external libraries that must be built (in support of Grib2 processing). The one external package that all of the systems require is the netCDF library, which is one of the supported I/O API packages. The netCDF libraries and source code are available from the Unidata homepage at http://www.unidata.ucar.edu (select DOWNLOADS, registration required).

There are three tar files for the WRF code. The first is the WRF model (including the real and ideal pre-processors). The second is the WRFDA code. The third tar file is for WRF chemistry. In order to run the WRF chemistry code, both the WRF model and the chemistry tar file must be combined.

The WRF model has been successfully ported to a number of Unix-based machines. We do not have access to all of them and must rely on outside users and vendors to supply the required configuration information for the compiler and loader options. Below is a list of the supported combinations of hardware and software for WRF.

Vendor	Hardware	OS	Compiler
Cray	XC30 Intel	Linux	Intel
Cray	XE AMD	Linux	Intel
IBM	Power Series	AIX	vendor
IBM	Intel	Linux	Intel / PGI / gfortran
SGI	IA64 / Opteron	Linux	Intel
COTS*	IA32	Linux	Intel / PGI / gfortran / g95 / PathScale
COTS	IA64 / Opteron	Linux	Intel / PGI / gfortran / PathScale
Mac	Power Series	Darwin	xlf / g95 / PGI / Intel
Mac	Intel	Darwin	gfortran / PGI / Intel
NEC	NEC	Linux	vendor
Fujitsu	FX10 Intel	Linux	vendor

* Commercial Off-The-Shelf systems

The WRF model may be built to run on a single-processor machine, a shared-memory machine (that uses the OpenMP API), a distributed memory machine (with the appropriate MPI libraries), or on a distributed cluster (utilizing both OpenMP and MPI). The WRFDA and WPS packages run on the above-listed systems.

Required Compilers and Scripting Languages

The majority of the WRF model, WPS, and WRFDA codes are written in Fortran (what many refer to as Fortran 90). The software layer, RSL, which sits between WRF and WRFDA, and the MPI interface is written in C. WPS makes direct calls to the MPI libraries for distributed memory message passing. There are also ancillary programs that are written in C to perform file parsing and file construction, which are required for default building of the WRF modeling code. Additionally, the WRF build mechanism uses several scripting languages: including perl, Cshell and Bourne shell. The traditional UNIX text/file processing utilities are used: make, m4, sed, and awk. See Chapter 8: WRF Software (Required Software) for a more detailed listing of the necessary pieces for the WRF build.

Required/Optional Libraries to Download

The only library that is *always* required is the netCDF package from Unidata (login > Downloads > NetCDF). Most of the WRF post-processing packages assume that the data from the WRF model, the WPS package, or the WRFDA program are using the netCDF libraries. One may also need to add '/path-to-netcdf/netcdf/bin' to their path so that they may execute netCDF utility commands, such as **ncdump**. Use a netCDF version that is 3.6.1 or later. To utilize the compression capabilities, use netCDF 4.0 or later. Note that compression will require the use of HDF5.

Note 1: If one wants to compile WRF system components on a Linux or Darwin system that has access to multiple compilers, link the correct external libraries. For example, do not link the libraries built with PathScale when compiling the WRF components with gfortran. Even more, the same options when building the netCDF libraries must be used when building the WRF code (32 *vs* 64 bit, assumptions about underscores in the symbol names, etc.).

Note 2: If netCDF-4 is used, be sure that it is installed without activating parallel I/O based on HDF5. The WRF modeling system is able to use either the classic data model from netCDF-3 or the compression options supported in netCDF-4.

If you are going to be running distributed memory WRF jobs, you need a version of MPI. You can pick up a version of mpich, but you might want your system group to install the code. A working installation of MPI is required prior to a build of WRF using distributed memory. Either MPI-1 or MPI-2 are acceptable. Do you already have an MPI lying around? Try

```
which mpif90
which mpicc
which mpirun
```

If these are all defined executables in your path, you are probably OK. Make sure your paths are set up to point to the MPI **lib**, **include**, and **bin** directories. As with the netCDF libraries, you must build MPI consistently with the WRF source code.

Note that to output WRF model data in Grib1 format, Todd Hutchinson (WSI) has provided a complete source library that is included with the software release. However, when trying to link the WPS, the WRF model, and the WRFDA data streams together, always use the netCDF format.

Note 3: The entire step-by-step recipe for building the WRF and WPS packages is available at: http://www2.mmm.ucar.edu/wrf/OnLineTutorial/compilation_tutorial.php This page includes complete turn-key directions, from tests of your machines's utilities all the way up through where to download real-time data.

Post-Processing Utilities

The more widely used *(and therefore supported)* WRF post-processing utilities are:

- NCL (homepage and WRF download)
  - NCAR Command Language written by NCAR's Computer Information Systems Laboratory (formerly the Scientific Computing Division)
  - NCL scripts written and maintained by WRF support
  - many template scripts are provided that are tailored for specific real-data and ideal-data cases (http://www2.mmm.ucar.edu/wrf/OnLineTutorial/Graphics/NCL/NCL_examples.htm)
  - raw WRF output can be input with the NCL scripts
  - interactive or command-file driven

- GrADS (homepage and WRF download)
  - download GrADS executable, build format converter
  - programs (*ARWpost*) are available to convert the WRF output into an input format suitable for GrADS
  - simple to generate publication quality
  - interactive or command-file driven

- RIP4 (homepage and WRF download)
  - RIP4 written and maintained by Mark Stoelinga, UW
  - interpolation to various surfaces, trajectories, hundreds of diagnostic calculations
  - Fortran source provided
  - based on the NCAR Graphics package
  - pre-processor converts WRF, WPS, and WRFDA data to RIP input format
  - table driven

UNIX Environment Settings

There are only a few environmental settings that are WRF system related. Most of these are not required, but when things start acting badly, test some out. In Cshell syntax:

- **`setenv WRF_EM_CORE 1`**
  - explicitly defines which model core to build
- **`setenv WRF_NMM_CORE 0`**
  - explicitly defines which model core NOT to build
- **`setenv WRF_DA_CORE 0`**
  - explicitly defines no data assimilation
- **`setenv NETCDF /usr/local/netcdf`** (or wherever you have it stored)
  - all of the WRF components want both the lib and the include directories
- **`setenv OMP_NUM_THREADS n`** (where ***n*** is the number of procs to use)

  - if you have OpenMP on your system, this is how to specify the number of threads
- **`setenv MP_STACK_SIZE 64000000`**
  - OpenMP blows through the stack size, set it large
  - However, if the model still crashes, it may be a problem of over-specifying stack size. Set stack size sufficiently large, but not unlimited.
  - On some systems, the equivalent parameter could be KMP_STACKSIZE, or OMP_STACKSIZE
- **`unlimit`**
  - especially if you are on a small system

Building the WRF Code

The WRF code has a fairly complicated build mechanism. It tries to determine the architecture that you are on, and then presents you with options to allow you to select the preferred build method. For example, if you are on a Linux machine, it determines whether this is a 32 or 64 bit machine, and then prompts you for the desired usage of processors (such as serial, shared memory, or distributed memory). You select from among the available compiling options in the build mechanism. For example, do not choose a PGI build if you do not have PGI compilers installed on your system.

An instructional web site describes the sequence of steps required to build the WRF and WPS codes (though the instructions are specifically given for tcsh and GNU compilers).

http://www2.mmm.ucar.edu/wrf/OnLineTutorial/compilation_tutorial.php

- Get the WRF zipped tar file for WRFV3 from
  - **`http://www2.mmm.ucar.edu/wrf/users/download/get_source.html`**
  - Always get the latest version if you are not trying to continue a long project, or duplicate previous work
- unzip and untar the file
  - **`gzip -cd WRFV3.TAR.gz | tar -xf -`**
  - Alternatively **`tar -xzf WRFV3.TAR.gz`** on some systems
- **`cd WRFV3`**
- **`./configure`**
  - **serial** means single processor
  - **smpar** means Symmetric Multi-Processing/Shared Memory Parallel (OpenMP) – this does not reliably work on most non-IBM machines
  - **dmpar** means Distributed Memory Parallel (MPI)
  - **dm+sm** means Distributed Memory with Shared Memory (for example, MPI across nodes with OpenMP within a node) – usually better performance is through **dmpar** only
  - The second option is for nesting: 0 = no nesting, 1 = standard static

nesting, 2 = nesting with a prescribed set of moves, 3 = nesting that allows a domain to follow a vortex (typhoon tracking)
    - A typical option that may be included on the ./**configure** command is the flag "**-d**" (for debug). This option removes optimization, which is useful when running a debugger (such as gdb or dbx)
    - For bounds checking and some additional exception handling, the debugging flag "**-D**" may be selected. Only PGI, Intel, and gfortran have been set up to use this option.
- **./compile em_real** (or any of the directory names in **./WRFV3/test** directory)
- **ls -ls main/*.exe**
    - If you built a real-data case, you should see **ndown.exe**, **real.exe**, and **wrf.exe**
    - If you built an ideal-data case, you should see **ideal.exe** and **wrf.exe**

The WRF code supports a parallel *build* option, an option that compiles separate source code files in the WRF directories at the same time on separate processors (though those processors need to share memory) via a parallel make. The purpose of the parallel build option is to be able to speed-up the time required to construct executables. In practice, users typically see approximately a 2x speed-up, a limit imposed by the various dependencies in the code due to modules and USE association. To enable the parallel build option, the user sets an environment variable, J. In csh, to utilize two processors, before the ./compile command, issue the following:

```
setenv J "-j 2"
```

Users may wish to only use a single processor for the build. In which case:

```
setenv J "-j 1"
```

Users wishing to run the WRF chemistry code must first download the WRF model tar file, and untar it. Then the chemistry code is untar'ed in the WRFV3 directory (this is the **chem** directory structure). Once the source code from the tar files is combined, then users may proceed with the WRF chemistry build.

Building the WPS Code

Building WPS requires that WRFV3 be already built.

If you plan to use Grib2 data, additional libraries for zlib, png, and jasper are required. Please see details in Chapter 3.

- Get the WPS zipped tar file WPSV3.TAR.gz from
    - **http://www2.mmm.ucar.edu/wrf/users/download/get_source.html**
- Also download the geographical datasets from the same page. There are new data sets for land cover for North America (NLCD), and high-resolution urban data sets for select North American cities.

- Unzip and untar the source code file
  - **gzip -cd WPSV3.TAR.gz | tar -xf -**
- **cd WPS**
- **./configure**
  - Choose one of the options
  - Usually, serial builds are the best for an initial test. Most large domains work with a single processor for WPS
  - WPS requires that you build for the appropriate Grib decoding. Select an option that is suitable for the data you will use with the ungrib program (the Grib2 option will work for either Grib1 or Grib2 data)
  - If you select a Grib2 option, you must have those libraries prepared and built in advance (see the chapter on WPS for the location of these compression libraries). Add the paths to these libraries and include files using variables COMPRESSION_LIBS and COMPRESSION_INC in **configure.wps.** Also inside the **configure.wps** file is the location of the built WRFV3 directory, which needs to be modified. This is how the WPS picks up all of the required IO pieces to build the geogrid.exe and metgrid.exe files.
- **./compile**
- **ls -ls *.exe**
  - You should see **geogrid.exe**, **ungrib.exe**, and **metgrid.exe** (if you are missing both **geogrid.exe** and **metgrid.exe**, you probably need to fix where the path to WRF is pointing in the **configure.wps** file; if you are missing **ungrib.exe**, try a Grib1-only build to further isolate the problem)

- **ls -ls util/*.exe**
  - You should see a number of utility executables: **avg_tsfc.exe, calc_ecmwf_p.exe, g1print.exe, g2print.exe, height_ukmo.exe, mod_levs.exe, plotfmt.exe, plotgrids.exe**, and **rd_intermediate.exe** (files requiring NCAR Graphics are **plotfmt.exe** and **plotgrids.exe**)
- If **geogrid.exe** and **metgrid.exe** executables are missing, the path to the built WRFV3 directory structure is probably incorrect (found inside the **configure.wps** file)
- If the **ungrib.exe** is missing, the Grib2 libraries are probably not linked or built correctly
- If the **plotfmt.exe** or the **plotgrids.exe** programs is missing, the NCAR Graphics path is probably set incorrectly

Building the WRFDA Code (for 3DVAR)

WRFDA uses the same build mechanism as WRF; thus, this mechanism must be instructed to configure and build the code for WRFDA rather than WRF. Additionally, the paths to libraries needed by WRFDA code must be set, as described in the steps

below.

- Get the WRFDA zipped tar file, WRFDA_V3.7.TAR.gz, from **http://www2.mmm.ucar.edu/wrf/users/wrfda/download/get_source.html**
- Unzip and untar the WRFDA code
  - **tar -xf WRFDA_V3.7.TAR.gz**
  - This will create a directory, **WRFDA**
- **cd WRFDA**
  - In addition to netCDF, set up environmental variables pointing to additional libraries required by WRFDA, such as RTTOV
  - Please note: only the netCDF library is mandatory to compile the basic WRFDA system; all other libraries are optional
  - If you intend to use satellite radiance data, an RTM (Radiative Transfer Model) is required. The current RTM versions that WRFDA uses are **CRTM v2.1.3** and **RTTOV v11**. WRFDA can compile with CRTM only, or RTTOV only, or both CRTM and RTTOV together

    To compile WRFDA with CRTM: **setenv CRTM 1**

    (Note: the latest available CRTM, version 2.1.3, is included in this release version and it will be compiled automatically when the appropriate environmental variable is set. Users do not need to download and install CRTM).

    To compile WRFDA with RTTOV: RTTOV still must be downloaded (https://nwpsaf.eu/deliverables/rtm/rtm_rttov11.html) and installed using the same compiler that will be used to build WRFDA, since the library produced by one compiler may not be compatible with code compiled with another. Then, the necessary environment variable should be set with

    setenv RTTOV ${path_for_RTTOV}

- **./configure wrfda**
  - **serial** means single processor
  - **dmpar** means Distributed Memory Parallel (MPI)
  - **smpar and dm+sm are not recommended for use with WRFDA**
- WRFDA also supports parallel build.
- **./compile all_wrfvar**
- **ls -ls var/build/*.exe**
  - If the compilation was successful, **da_wrfvar.exe**, **da_update_bc.exe**, and other executables should be found in the var/build directory. Their links are in the var/da directory; **obsproc.exe** should be found in the var/obsproc/src directory

Building the WRFDA Code (for 4DVAR)

Building WRFDA 4DVAR requires that WRFPLUSV3.7 be already built.

- Get the WRFPLUSV3.7 zipped tar file WRFPLUS_V3.7.tar.gz from
  - **`http://www2.mmm.ucar.edu/wrf/users/wrfda/download/wrfplus.html`**
- unzip and untar the source code file
  - **`tar -xf WRFPLUS_V3.7.tar.gz`**
- **`cd WRFPLUSV3`**
- **`./configure wrfplus`**
  - **serial** means single processor
  - **dmpar** means Distributed Memory Parallel (MPI)
  - (Note: WRFPLUS does not support Shared Memory Parallel and WRFPLUS is compiled as realsize=8)
- WRFPLUS also supports parallel build.
- **`./compile em_real`**
- **`ls -ls main/*.exe`**
  - you should see **ndown.exe**, **real.exe**, and **wrf.exe**
- Set up the environmental variable pointing to WRFPLUS_DIR.
  - **setenv WRFPLUS_DIR ${path_of _wrfplusv3.7} (csh)**
  - **export WRFPLUS_DIR=${path_of _wrfplusv3.7} (bash)**
- Please refer to above section "Building WRFDA code (for 3DVAR)" to download code and set up necessary environmental variables.
- **`./configure 4dvar`**
  - **serial** means single processor
  - **dmpar** means Distributed Memory Parallel (MPI)
- **`./compile all_wrfvar`**
- **`ls -ls var/build/*.exe`**
  - If the compilation was successful, **`da_wrfvar.exe`**, **`da_update_bc.exe`**, and other executables should be found in the var/build directory. Their links are in the var/da directory; **`obsproc.exe`** should be found in the var/obsproc/src directory

Chapter 3: WRF Preprocessing System (WPS)

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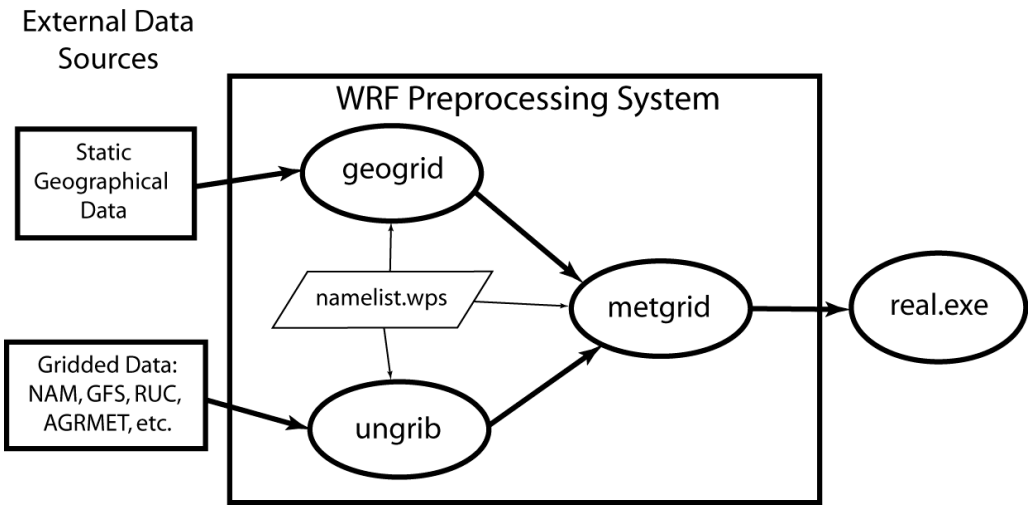
Introduction

The WRF Preprocessing System (WPS) is a set of three programs whose collective role is to prepare input to the *real* program for real-data simulations. Each of the programs performs one stage of the preparation: *geogrid* defines model domains and interpolates static geographical data to the grids; *ungrib* extracts meteorological fields from GRIB-formatted files; and *metgrid* horizontally interpolates the meteorological fields extracted

by ungrib to the model grids defined by geogrid. The work of vertically interpolating meteorological fields to WRF eta levels is performed within the *real* program.



The data flow between the programs of the WPS is shown in the figure above. Each of the WPS programs reads parameters from a common namelist file, as shown in the figure. This namelist file has separate namelist records for each of the programs and a shared namelist record, which defines parameters that are used by more than one WPS program. Not shown in the figure are additional table files that are used by individual programs. These tables provide additional control over the programs' operations, though they generally do not need to be changed by the user. The GEOGRID.TBL, METGRID.TBL, and Vtable files are explained later in this document, though for now, the user need not be concerned with them.

The build mechanism for the WPS, which is very similar to the build mechanism used by the WRF model, provides options for compiling the WPS on a variety of platforms. When MPI libraries and suitable compilers are available, the metgrid and geogrid programs may be compiled for distributed memory execution, which allows large model domains to be processed in less time. The work performed by the ungrib program is not amenable to parallelization, so ungrib may only be run on a single processor.

Function of Each WPS Program

The WPS consists of three independent programs: *geogrid*, *ungrib*, and *metgrid*. Also included in the WPS are several utility programs, which are described in the section on

utility programs. A brief description of each of the three main programs is given below, with further details presented in subsequent sections.

Program geogrid

The purpose of geogrid is to define the simulation domains, and interpolate various terrestrial data sets to the model grids. The simulation domains are defined using information specified by the user in the "geogrid" namelist record of the WPS namelist file, namelist.wps. In addition to computing the latitude, longitude, and map scale factors at every grid point, geogrid will interpolate soil categories, land use category, terrain height, annual mean deep soil temperature, monthly vegetation fraction, monthly albedo, maximum snow albedo, and slope category to the model grids by default. Global data sets for each of these fields are provided through the WRF download page, and, because these data are time-invariant, they only need to be downloaded once. Several of the data sets are available in only one resolution, but others are made available in resolutions of 30", 2', 5', and 10'; here, " denotes arc seconds and ' denotes arc minutes. The user need not download all available resolutions for a data set, although the interpolated fields will generally be more representative if a resolution of data near to that of the simulation domain is used. However, users who expect to work with domains having grid spacings that cover a large range may wish to eventually download all available resolutions of the static terrestrial data.

Besides interpolating the default terrestrial fields, the geogrid program is general enough to be able to interpolate most continuous and categorical fields to the simulation domains. New or additional data sets may be interpolated to the simulation domain through the use of the table file, GEOGRID.TBL. The GEOGRID.TBL file defines each of the fields that will be produced by geogrid; it describes the interpolation methods to be used for a field, as well as the location on the file system where the data set for that field is located.

Output from geogrid is written in the WRF I/O API format, and thus, by selecting the NetCDF I/O format, geogrid can be made to write its output in NetCDF for easy visualization using external software packages, including ncview, NCL, and RIP4.

Program ungrib

The ungrib program reads GRIB files, "degribs" the data, and writes the data in a simple format called the intermediate format (see the section on writing data to the intermediate format for details on the format). The GRIB files contain time-varying meteorological fields and are typically from another regional or global model, such as NCEP's NAM or GFS models. The ungrib program can read GRIB Edition 1 and, if compiled with a "GRIB2" option, GRIB Edition 2 files.

GRIB files typically contain more fields than are needed to initialize WRF. Both versions of the GRIB format use various codes to identify the variables and levels in the GRIB

file. Ungrib uses tables of these codes – called Vtables, for "variable tables" – to define which fields to extract from the GRIB file and write to the intermediate format. Details about the codes can be found in the WMO GRIB documentation and in documentation from the originating center. Vtables for common GRIB model output files are provided with the ungrib software.

Vtables are provided for NAM 104 and 212 grids, the NAM AWIP format, GFS, the NCEP/NCAR Reanalysis archived at NCAR, RUC (pressure level data and hybrid coordinate data), AFWA's AGRMET land surface model output, ECMWF, and other data sets. Users can create their own Vtable for other model output using any of the Vtables as a template; further details on the meaning of fields in a Vtable are provided in the section on creating and editing Vtables.

Ungrib can write intermediate data files in any one of three user-selectable formats: WPS – a new format containing additional information useful for the downstream programs; SI – the previous intermediate format of the WRF system; and MM5 format, which is included here so that ungrib can be used to provide GRIB2 input to the MM5 modeling system. Any of these formats may be used by WPS to initialize WRF, although the WPS format is recommended.

Program metgrid

The metgrid program horizontally interpolates the intermediate-format meteorological data that are extracted by the ungrib program onto the simulation domains defined by the geogrid program. The interpolated metgrid output can then be ingested by the WRF real program. The range of dates that will be interpolated by metgrid are defined in the “share” namelist record of the WPS namelist file, and date ranges must be specified individually in the namelist for each simulation domain. Since the work of the metgrid program, like that of the ungrib program, is time-dependent, metgrid is run every time a new simulation is initialized.

Control over how each meteorological field is interpolated is provided by the METGRID.TBL file. The METGRID.TBL file provides one section for each field, and within a section, it is possible to specify options such as the interpolation methods to be used for the field, the field that acts as the mask for masked interpolations, and the grid staggering (e.g., U, V in ARW; H, V in NMM) to which a field is interpolated.

Output from metgrid is written in the WRF I/O API format, and thus, by selecting the NetCDF I/O format, metgrid can be made to write its output in NetCDF for easy visualization using external software packages, including the new version of RIP4.

Installing the WPS

The WRF Preprocessing System uses a build mechanism similar to that used by the WRF model. External libraries for geogrid and metgrid are limited to those required by the WRF model, since the WPS uses the WRF model's implementations of the WRF I/O API; consequently, *WRF must be compiled prior to installation of the WPS* so that the I/O API libraries in the WRF external directory will be available to WPS programs. Additionally, the ungrib program requires three compression libraries for GRIB Edition 2 support; however, if support for GRIB2 data is not needed, ungrib can be compiled without these compression libraries.

Required Libraries

The only library that is required to build the WRF model is NetCDF. The user can find the source code, precompiled binaries, and documentation at the UNIDATA home page (http://www.unidata.ucar.edu/software/netcdf/). Most users will select the NetCDF I/O option for WPS due to the easy access to utility programs that support the NetCDF data format, and before configuring the WPS, users should ensure that the environment variable NETCDF is set to the path of the NetCDF installation.

Where WRF adds a software layer between the model and the communications package, the WPS programs geogrid and metgrid make MPI calls directly. Most multi-processor machines come preconfigured with a version of MPI, so it is unlikely that users will need to install this package by themselves.

Three libraries are required by the ungrib program for GRIB Edition 2 compression support. Users are encouraged to engage their system administrators for the installation of these packages so that traditional library paths and include paths are maintained. Paths to user-installed compression libraries are handled in the `configure.wps` file by the `COMPRESSION_LIBS` and `COMPRESSION_INC` variables. As an alternative to manually editing the `COMPRESSION_LIBS` and `COMPRESSION_INC` variables in the `configure.wps` file, users may set the environment variables `JASPERLIB` and `JASPERINC` to the directories holding the JasPer library and include files *before configuring the WPS*; for example, if the JasPer libraries were installed in `/usr/local/jasper-1.900.1`, one might use the following commands (in csh or tcsh):

```
> setenv JASPERLIB /usr/local/jasper-1.900.1/lib
> setenv JASPERINC /usr/local/jasper-1.900.1/include
```

If the zlib and PNG libraries are not in a standard path that will be checked automatically by the compiler, the paths to these libraries can be added on to the JasPer environment variables; for example, if the PNG libraries were installed in `/usr/local/libpng-1.2.29` and the zlib libraries were installed in `/usr/local/zlib-1.2.3`, one might use

```
> setenv JASPERLIB "${JASPERLIB} -L/usr/local/libpng-1.2.29/lib -
L/usr/local/zlib-1.2.3/lib"
> setenv JASPERINC "${JASPERINC} -I/usr/local/libpng-
1.2.29/include -I/usr/local/zlib-1.2.3/include"
```

after having previously set `JASPERLIB` and `JASPERINC`.

1) JasPer (an implementation of the JPEG2000 standard for "lossy" compression)
http://www.ece.uvic.ca/~mdadams/jasper/
Go down to “JasPer software”, one of the "click here" parts is the source.

```
> ./configure
> make
> make install
```

Note: The GRIB2 libraries expect to find include files in "jasper/jasper.h", so it may be necessary to manually create a "jasper" subdirectory in the "include" directory created by the JasPer installation, and manually link header files there.

2) PNG (compression library for "lossless" compression)
http://www.libpng.org/pub/png/libpng.html
Scroll down to "Source code" and choose a mirror site.

```
> ./configure
> make check
> make install
```

3) zlib (a compression library used by the PNG library)
http://www.zlib.net/
Go to "The current release is publicly available here" section and download.

```
> ./configure
> make
> make install
```

To get around portability issues, the NCEP GRIB libraries, w3 and g2, have been included in the WPS distribution. The original versions of these libraries are available for download from NCEP at http://www.nco.ncep.noaa.gov/pmb/codes/GRIB2/. The specific tar files to download are g2lib and w3lib. Because the ungrib program requires modules from these files, they are not suitable for usage with a traditional library option during the link stage of the build.

Required Compilers and Scripting Languages

The WPS requires the same Fortran and C compilers as were used to build the WRF model, since the WPS executables link to WRF's I/O API libraries. After executing the `./configure` command in the WPS directory, a list of supported compilers on the current system architecture are presented.

WPS Installation Steps

- Download the `WPSV3.TAR.gz` file and unpack it at the same directory level as WRFV3, as shown below.

```
> ls
-rw-r--r--  1  563863 WPS.TAR.gz
drwxr-xr-x 18    4096 WRFV3

> gzip -d WPSV3.TAR.gz

> tar xf WPSV3.TAR

> ls
drwxr-xr-x  7     4096 WPS
-rw-r--r--  1  3491840 WPSV3.TAR
drwxr-xr-x 18     4096 WRFV3
```

- At this point, a listing of the current working directory should at least include the directories WRFV3 and WPS. First, compile WRF (see the instructions for installing WRF in Chapter 2). Then, after the WRF executables are generated, change to the WPS directory and issue the configure command followed by the compile command as below.

```
> cd WPS

> ./configure
```

  - Choose one of the configure options

```
> ./compile >& compile.output
```

- After issuing the compile command, a listing of the current working directory should reveal symbolic links to executables for each of the three WPS programs: geogrid.exe, ungrib.exe, and metgrid.exe. If any of these links do not exist, check the compilation output in compile.output to see what went wrong.

```
> ls
drwxr-xr-x 2   4096 arch
-rwxr-xr-x 1   1672 clean
-rwxr-xr-x 1   3510 compile
-rw-r--r-- 1  85973 compile.output
-rwxr-xr-x 1   4257 configure
-rw-r--r-- 1   2486 configure.wps
drwxr-xr-x 4   4096 geogrid
lrwxrwxrwx 1     23 geogrid.exe -> geogrid/src/geogrid.exe
-rwxr-xr-x 1   1328 link_grib.csh
drwxr-xr-x 3   4096 metgrid
lrwxrwxrwx 1     23 metgrid.exe -> metgrid/src/metgrid.exe
-rw-r--r-- 1   1101 namelist.wps
-rw-r--r-- 1   1987 namelist.wps.all_options
-rw-r--r-- 1   1075 namelist.wps.global
-rw-r--r-- 1    652 namelist.wps.nmm
-rw-r--r-- 1   4786 README
drwxr-xr-x 4   4096 ungrib
lrwxrwxrwx 1     21 ungrib.exe -> ungrib/src/ungrib.exe
drwxr-xr-x 3   4096 util
```

Running the WPS

There are essentially three main steps to running the WRF Preprocessing System:

1. Define a model coarse domain and any nested domains with *geogrid*.
2. Extract meteorological fields from GRIB data sets for the simulation period with *ungrib*.
3. Horizontally interpolate meteorological fields to the model domains with *metgrid*.

When multiple simulations are to be run for the same model domains, it is only necessary to perform the first step once; thereafter, only time-varying data need to be processed for each simulation using steps two and three. Similarly, if several model domains are being run for the same time period using the same meteorological data source, it is not necessary to run ungrib separately for each simulation. Below, the details of each of the three steps are explained.

Step 1: Define model domains with geogrid

In the root of the WPS directory structure, symbolic links to the programs geogrid.exe, ungrib.exe, and metgrid.exe should exist if the WPS software was successfully installed. In addition to these three links, a namelist.wps file should exist. Thus, a listing in the WPS root directory should look something like:

```
> ls
drwxr-xr-x 2   4096 arch
-rwxr-xr-x 1   1672 clean
-rwxr-xr-x 1   3510 compile
-rw-r--r-- 1  85973 compile.output
-rwxr-xr-x 1   4257 configure
-rw-r--r-- 1   2486 configure.wps
drwxr-xr-x 4   4096 geogrid
lrwxrwxrwx 1     23 geogrid.exe -> geogrid/src/geogrid.exe
-rwxr-xr-x 1   1328 link_grib.csh
drwxr-xr-x 3   4096 metgrid
lrwxrwxrwx 1     23 metgrid.exe -> metgrid/src/metgrid.exe
-rw-r--r-- 1   1101 namelist.wps
-rw-r--r-- 1   1987 namelist.wps.all_options
-rw-r--r-- 1   1075 namelist.wps.global
-rw-r--r-- 1    652 namelist.wps.nmm
-rw-r--r-- 1   4786 README
drwxr-xr-x 4   4096 ungrib
lrwxrwxrwx 1     21 ungrib.exe -> ungrib/src/ungrib.exe
drwxr-xr-x 3   4096 util
```

The model coarse domain and any nested domains are defined in the "geogrid" namelist record of the namelist.wps file, and, additionally, parameters in the "share" namelist record need to be set. An example of these two namelist records is given below, and the user is referred to the description of namelist variables for more information on the purpose and possible values of each variable.

```
&share
 wrf_core = 'ARW',
 max_dom = 2,
 start_date = '2008-03-24_12:00:00','2008-03-24_12:00:00',
 end_date   = '2008-03-24_18:00:00','2008-03-24_12:00:00',
 interval_seconds = 21600,
 io_form_geogrid = 2
/

&geogrid
 parent_id         =   1,   1,
 parent_grid_ratio =   1,   3,
 i_parent_start    =   1,  31,
 j_parent_start    =   1,  17,
 e_we              =  74, 112,
 e_sn              =  61,  97,
 geog_data_res     = 'default','default',
 dx = 30000,
 dy = 30000,
 map_proj = 'lambert',
 ref_lat   = 34.83,
 ref_lon   = -81.03,
 truelat1  =  30.0,
 truelat2  =  60.0,
 stand_lon = -98.,
 geog_data_path = '/mmm/users/wrfhelp/WPS_GEOG/'
/
```

To summarize a set of typical changes to the "share" namelist record relevant to geogrid, the WRF dynamical core must first be selected with `wrf_core`. If WPS is being run for an ARW simulation, `wrf_core` should be set to `'ARW'`, and if running for an NMM simulation, it should be set to `'NMM'`. After selecting the dynamical core, the total number of domains (in the case of ARW) or nesting levels (in the case of NMM) must be chosen with `max_dom`. Since geogrid produces only time-independent data, the `start_date`, `end_date`, and `interval_seconds` variables are ignored by geogrid. Optionally, a location (if not the default, which is the current working directory) where domain files should be written to may be indicated with the `opt_output_from_geogrid_path` variable, and the format of these domain files may be changed with `io_form_geogrid`.

In the "geogrid" namelist record, the projection of the simulation domain is defined, as are the size and location of all model grids. The map projection to be used for the model domains is specified with the `map_proj` variable. Each of the four possible map projections in the ARW are shown graphically in the full-page figure below, and the namelist variables used to set the parameters of the projection are summarized in the following table.

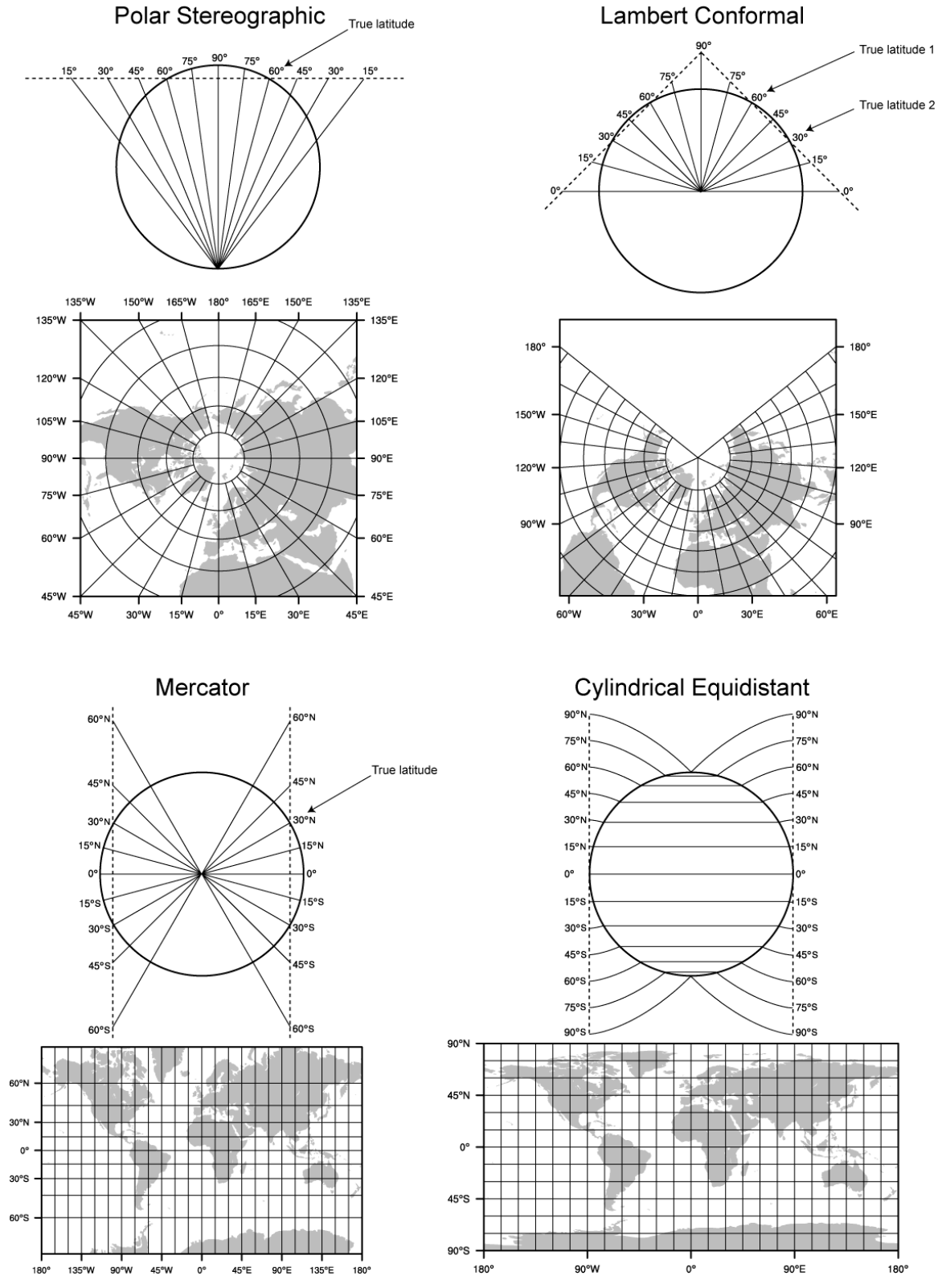
Map projection / value of `map_proj`	Projection parameters

`Lambert Conformal / 'lambert'`	`truelat1`
	`truelat2` (optional)
	`stand_lon`

Mercator / `'mercator'`	`truelat1`
Polar stereographic / `'polar'`	`truelat1` `stand_lon`

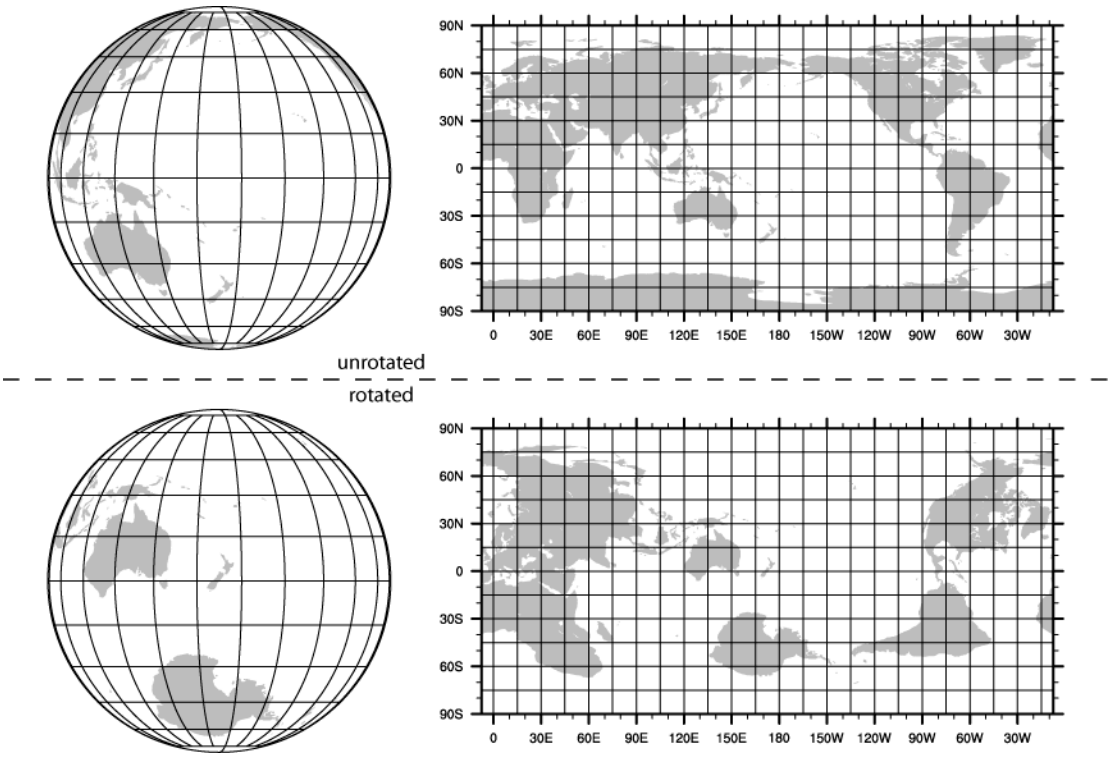
Regular latitude-longitude, or cylindrical equidistant / `'lat-lon'`	`pole_lat`
	`pole_lon`
	`stand_lon`

In the illustrations of the Lambert conformal, polar stereographic, and Mercator projections, it may be seen that the so-called true latitude (or true latitudes, in the case of the Lambert conformal), is the latitude at which the surface of projection intersects or is tangent to the surface of the earth. At this latitude, there is no distortion in the distances in the map projection, while at other latitudes, the distance on the surface of the earth is related to the distance on the surface of projection by a *map scale factor*. Ideally, the map projection and its accompanying parameters should be chosen to minimize the maximum distortion within the area covered by the model grids, since a high amount of distortion, evidenced by map scale factors significantly different from unity, can restrict the model time step more than necessary. As a general guideline, the polar stereographic projection is best suited for high-latitude WRF domains, the Lambert conformal projection is well-suited for mid-latitude domains, and the Mercator projection is good for low-latitude domains or domains with predominantly west-east extent. The cylindrical equidistant projection is required for global ARW simulations, although in its rotated aspect (i.e., when `pole_lat`, `pole_lon`, and `stand_lon` are changed from their default values) it can also be well-suited for regional domains anywhere on the earth's surface.


Polar Stereographic
True latitude
15° 30° 45° 60° 75° 90° 75° 60° 45° 30° 15°
135°W 150°W 165°W 180° 165°E 150°E 135°E
135°W 120°W 105°W 90°W 75°W 60°W 45°W
135°E 120°E 105°E 90°E 75°E 60°E 45°E
45°W 30°W 15°W 0° 15°E 30°E 45°E
Lambert Conformal
True latitude 1
True latitude 2
90° 75° 60° 45° 30° 15° 0°
180° 150°W 120°W 90°W
180° 150°E 120°E 90°E
60°W 30°W 0° 30°E 60°E
Mercator
True latitude
60°N 45°N 30°N 15°N 0° 15°S 30°S 45°S 60°S
60°N 30°N 0° 30°S 60°S
180° 135°W 90°W 45°W 0° 45°E 90°E 135°E 180°
Cylindrical Equidistant
90°N 75°N 60°N 45°N 30°N 15°N 0° 15°S 30°S 45°S 60°S 75°S 90°S
90°N 45°N 0° 45°S 90°S
180° 90°W 0° 90°E 180°

When configuring a rotated latitude-longitude grid, the namelist parameters `pole_lat`, `pole_lon`, and `stand_lon` are changed from their default values. The parameters `pole_lat` and `pole_lon` specify the latitude and longitude of the geographic north pole within the model's *computational grid*, and `stand_lon` gives the rotation about the earth's axis. In the context of the ARW, the computational grid refers to the regular latitude-longitude grid on which model computation is done, and on whose latitude circles Fourier filters are applied at high latitudes; users interested in the details of this filtering are referred to the WRF Version 3 Technical Note, and here, it suffices to note that the computational latitude-longitude grid is always represented with computational latitude lines running parallel to the x-axis of the model grid and computational longitude lines running parallel to the y-axis of the grid.

If the earth's geographic latitude-longitude grid coincides with the computational grid, a global ARW domain shows the earth's surface as it is normally visualized on a regular latitude-longitude grid. If instead the geographic grid does not coincide with the model computational grid, geographical meridians and parallels appear as complex curves. The difference is most easily illustrated by way of example. In top half of the figure below, the earth is shown with the geographical latitude-longitude grid coinciding with the computational latitude-longitude grid. In the bottom half, the geographic grid (not shown) has been rotated so that the geographic poles of the earth are no longer located at the poles of the computational grid.



When WRF is to be run for a regional domain configuration, the location of the coarse domain is determined using the `ref_lat` and `ref_lon` variables, which specify the latitude and longitude, respectively, of the center of the coarse domain. If nested domains are to be processed, their locations with respect to the parent domain are specified with the `i_parent_start` and `j_parent_start` variables; further details of setting up nested domains are provided in the section on nested domains. Next, the dimensions of the coarse domain are determined by the variables `dx` and `dy`, which specify the nominal grid distance in the x-direction and y-direction, and `e_we` and `e_sn`, which give the number of velocity points (i.e., *u*-staggered or *v*-staggered points) in the x- and y-directions; for the `'lambert'`, `'mercator'`, and `'polar'` projections, `dx` and `dy` are given in meters, and for the `'lat-lon'` projection, `dx` and `dy` are given in degrees. For nested domains, only the variables `e_we` and `e_sn` are used to determine the dimensions of the grid, and `dx` and `dy` should not be specified for nests, since their values are determined recursively based on the values of the `parent_grid_ratio` and `parent_id` variables, which specify the ratio of a nest's parent grid distance to the nest's grid distance and the grid number of the nest's parent, respectively.

If the regular latitude-longitude projection will be used for a regional domain, care must be taken to ensure that the map scale factors in the region covered by the domain do not deviate significantly from unity. This can be accomplished by rotating the projection such that the area covered by the domain is located near the equator of the projection, since, for the regular latitude-longitude projection, the map scale factors in the x-direction are given by the cosine of the computational latitude. For example, in the figure above showing the unrotated and rotated earth, it can be seen that, in the rotated aspect, New Zealand is located along the computational equator, and thus, the rotation used there would be suitable for a domain covering New Zealand. As a general guideline for rotating the latitude-longitude projection for regional domains, the namelist parameters `pole_lat`, `pole_lon`, and `stand_lon` may be chosen according to the formulas in the following table.

	(`ref_lat`, `ref_lon`) in N.H.	(`ref_lat`, `ref_lon`) in S.H.
`pole_lat`	90.0 – `ref_lat`	90.0 + `ref_lat`
`pole_lon`	180.0	0.0
`stand_lon`	`-ref_lon`	`180.0 - ref_lon`

For global WRF simulations, the coverage of the coarse domain is, of course, global, so `ref_lat` and `ref_lon` do not apply, and `dx` *and* `dy` *should not be specified*, since the nominal grid distance is computed automatically based on the number of grid points. Also, it should be noted that the latitude-longitude, or cylindrical equidistant, projection (`map_proj = 'lat-lon'`) is the only projection in WRF that can support a global domain. *Nested domains within a global domain must not cover any area north of computational latitude +45 or south of computational latitude -45, since polar filters are applied poleward of these latitudes (although the cutoff latitude can be changed in the WRF namelist).*

Besides setting variables related to the projection, location, and coverage of model domains, the path to the static geographical data sets must be correctly specified with the `geog_data_path` variable. Also, the user may select which resolution of static data geogrid will interpolate from using the `geog_data_res` variable, whose value should match one of the resolutions of data in the GEOGRID.TBL. If the complete set of static data are downloaded from the WRF download page, possible resolutions include `'30s'`, `'2m'`, `'5m'`, and `'10m'`, corresponding to 30-arc-second data, 2-, 5-, and 10-arc-minute data.

Depending on the value of the `wrf_core` namelist variable, the appropriate GEOGRID.TBL file must be used with geogrid, since the grid staggerings that WPS interpolates to differ between dynamical cores. For the ARW, the GEOGRID.TBL.ARW file should be used, and for the NMM, the GEOGRID.TBL.NMM file should be used. Selection of the appropriate GEOGRID.TBL is accomplished by linking the correct file to GEOGRID.TBL in the geogrid directory (or in the directory specified by `opt_geogrid_tbl_path`, if this variable is set in the namelist).

```
> ls geogrid/GEOGRID.TBL

lrwxrwxrwx 1      15 GEOGRID.TBL -> GEOGRID.TBL.ARW
```

For more details on the meaning and possible values for each variable, the user is referred to a description of the namelist variables.

Having suitably defined the simulation coarse domain and nested domains in the namelist.wps file, the geogrid.exe executable may be run to produce domain files. In the case of ARW domains, the domain files are named `geo_em.d0N.nc`, where `N` is the number of the nest defined in each file. When run for NMM domains, geogrid produces the file `geo_nmm.d01.nc` for the coarse domain, and `geo_nmm_nest.l0N.nc` files for each nesting level `N`. Also, note that the file suffix will vary depending on the `io_form_geogrid` that is selected. To run geogrid, issue the following command:

```
> ./geogrid.exe
```

When geogrid.exe has finished running, the message

```
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!  Successful completion of geogrid.        !
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
```

should be printed, and a listing of the WPS root directory (or the directory specified by `opt_output_from_geogrid_path`, if this variable was set) should show the domain files. If not, the geogrid.log file may be consulted in an attempt to determine the possible cause of failure. For more information on checking the output of geogrid, the user is referred to the section on checking WPS output.

```
> ls
drwxr-xr-x 2     4096 arch
```

```
-rwxr-xr-x 1     1672 clean
-rwxr-xr-x 1     3510 compile
-rw-r--r-- 1    85973 compile.output
-rwxr-xr-x 1     4257 configure
-rw-r--r-- 1     2486 configure.wps
-rw-r--r-- 1  1957004 geo_em.d01.nc
-rw-r--r-- 1  4745324 geo_em.d02.nc
drwxr-xr-x 4     4096 geogrid
lrwxrwxrwx 1       23 geogrid.exe -> geogrid/src/geogrid.exe
-rw-r--r-- 1    11169 geogrid.log
-rwxr-xr-x 1     1328 link_grib.csh
drwxr-xr-x 3     4096 metgrid
lrwxrwxrwx 1       23 metgrid.exe -> metgrid/src/metgrid.exe
-rw-r--r-- 1     1094 namelist.wps
-rw-r--r-- 1     1987 namelist.wps.all_options
-rw-r--r-- 1     1075 namelist.wps.global
-rw-r--r-- 1      652 namelist.wps.nmm
-rw-r--r-- 1     4786 README
drwxr-xr-x 4     4096 ungrib
lrwxrwxrwx 1       21 ungrib.exe -> ungrib/src/ungrib.exe
drwxr-xr-x 3     4096 util
```

Step 2: Extracting meteorological fields from GRIB files with ungrib

Having already downloaded meteorological data in GRIB format, the first step in extracting fields to the intermediate format involves editing the “share” and “ungrib” namelist records of the namelist.wps file – the same file that was edited to define the simulation domains. An example of the two namelist records is given below.

```
&share
 wrf_core = 'ARW',
 max_dom = 2,
 start_date = '2008-03-24_12:00:00','2008-03-24_12:00:00',
 end_date   = '2008-03-24_18:00:00','2008-03-24_12:00:00',
 interval_seconds = 21600,
 io_form_geogrid = 2
/

&ungrib
 out_format = 'WPS',
 prefix     = 'FILE'
/
```

In the “share” namelist record, the variables that are of relevance to ungrib are the starting and ending times of the coarse domain (`start_date` and `end_date`; alternatively, `start_year`, `start_month`, `start_day`, `start_hour`, `end_year`, `end_month`, `end_day`, and `end_hour`) and the interval between meteorological data files (`interval_seconds`). In the “ungrib” namelist record, the variable `out_format` is used to select the format of the intermediate data to be written by ungrib; the metgrid program can read any of the formats supported by ungrib, and thus, any of `'WPS'`, `'SI'`, and `'MM5'` may be specified for `out_format`, although `'WPS'` is recommended. Also in the "ungrib" namelist, the user

may specify a path and prefix for the intermediate files with the `prefix` variable. For example, if `prefix` were set to `'ARGRMET'`, then the intermediate files created by ungrib would be named according to AGRMET:*YYYY-MM-DD_HH*, where *YYYY-MM-DD_HH* is the valid time of the data in the file.

After suitably modifying the namelist.wps file, a Vtable must be supplied, and the GRIB files must be linked (or copied) to the filenames that are expected by ungrib. The WPS is supplied with Vtable files for many sources of meteorological data, and the appropriate Vtable may simply be symbolically linked to the file Vtable, which is the Vtable name expected by ungrib. For example, if the GRIB data are from the GFS model, this could be accomplished with

```
> ln -s ungrib/Variable_Tables/Vtable.GFS Vtable
```

The ungrib program will try to read GRIB files named GRIBFILE.AAA, GRIBFILE.AAB, …, GRIBFILE.ZZZ. In order to simplify the work of linking the GRIB files to these filenames, a shell script, link_grib.csh, is provided. The link_grib.csh script takes as a command-line argument a list of the GRIB files to be linked. For example, if the GRIB data were downloaded to the directory /data/gfs, the files could be linked with link_grib.csh as follows:

```
> ls /data/gfs
-rw-r--r-- 1  42728372 gfs_080324_12_00
-rw-r--r-- 1  48218303 gfs_080324_12_06

> ./link_grib.csh /data/gfs/gfs*
```

After linking the GRIB files and Vtable, a listing of the WPS directory should look something like the following:

```
> ls
drwxr-xr-x 2     4096 arch
-rwxr-xr-x 1     1672 clean
-rwxr-xr-x 1     3510 compile
-rw-r--r-- 1    85973 compile.output
-rwxr-xr-x 1     4257 configure
-rw-r--r-- 1     2486 configure.wps
-rw-r--r-- 1  1957004 geo_em.d01.nc
-rw-r--r-- 1  4745324 geo_em.d02.nc
drwxr-xr-x 4     4096 geogrid
lrwxrwxrwx 1       23 geogrid.exe -> geogrid/src/geogrid.exe
-rw-r--r-- 1    11169 geogrid.log
lrwxrwxrwx 1       38 GRIBFILE.AAA -> /data/gfs/gfs_080324_12_00
lrwxrwxrwx 1       38 GRIBFILE.AAB -> /data/gfs/gfs_080324_12_06
-rwxr-xr-x 1     1328 link_grib.csh
drwxr-xr-x 3     4096 metgrid
lrwxrwxrwx 1       23 metgrid.exe -> metgrid/src/metgrid.exe
-rw-r--r-- 1     1094 namelist.wps
-rw-r--r-- 1     1987 namelist.wps.all_options
-rw-r--r-- 1     1075 namelist.wps.global
-rw-r--r-- 1      652 namelist.wps.nmm
-rw-r--r-- 1     4786 README
```

```
drwxr-xr-x 4     4096 ungrib
lrwxrwxrwx 1       21 ungrib.exe -> ungrib/src/ungrib.exe
drwxr-xr-x 3     4096 util
lrwxrwxrwx 1       33 Vtable -> ungrib/Variable_Tables/Vtable.GFS
```

After editing the namelist.wps file and linking the appropriate Vtable and GRIB files, the ungrib.exe executable may be run to produce files of meteorological data in the intermediate format. Ungrib may be run by simply typing the following:

```
> ./ungrib.exe >& ungrib.output
```

Since the ungrib program may produce a significant volume of output, it is recommended that ungrib output be redirected to a file, as in the command above. If ungrib.exe runs successfully, the message

```
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!  Successful completion of ungrib.          !
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
```

will be written to the end of the ungrib.output file, and the intermediate files should appear in the current working directory. The intermediate files written by ungrib will have names of the form `FILE:`*`YYYY-MM-DD_HH`* (unless, of course, the `prefix` variable was set to a prefix other than `'FILE'`).

```
> ls
drwxr-xr-x 2       4096 arch
-rwxr-xr-x 1       1672 clean
-rwxr-xr-x 1       3510 compile
-rw-r--r-- 1      85973 compile.output
-rwxr-xr-x 1       4257 configure
-rw-r--r-- 1       2486 configure.wps
-rw-r--r-- 1  154946888 FILE:2008-03-24_12
-rw-r--r-- 1  154946888 FILE:2008-03-24_18
-rw-r--r-- 1    1957004 geo_em.d01.nc
-rw-r--r-- 1    4745324 geo_em.d02.nc
drwxr-xr-x 4       4096 geogrid
lrwxrwxrwx 1         23 geogrid.exe -> geogrid/src/geogrid.exe
-rw-r--r-- 1      11169 geogrid.log
lrwxrwxrwx 1         38 GRIBFILE.AAA ->
/data/gfs/gfs_080324_12_00
lrwxrwxrwx 1         38 GRIBFILE.AAB ->
/data/gfs/gfs_080324_12_06
-rwxr-xr-x 1       1328 link_grib.csh
drwxr-xr-x 3       4096 metgrid
lrwxrwxrwx 1         23 metgrid.exe -> metgrid/src/metgrid.exe
-rw-r--r-- 1       1094 namelist.wps
-rw-r--r-- 1       1987 namelist.wps.all_options
-rw-r--r-- 1       1075 namelist.wps.global
-rw-r--r-- 1        652 namelist.wps.nmm
-rw-r--r-- 1       4786 README
drwxr-xr-x 4       4096 ungrib
lrwxrwxrwx 1         21 ungrib.exe -> ungrib/src/ungrib.exe
-rw-r--r-- 1       1418 ungrib.log
```

```
      -rw-r--r-- 1      27787 ungrib.output
      drwxr-xr-x 3       4096 util
      lrwxrwxrwx 1         33 Vtable ->
ungrib/Variable_Tables/Vtable.GFS
```

Step 3: Horizontally interpolating meteorological data with metgrid

In the final step of running the WPS, meteorological data extracted by ungrib are horizontally interpolated to the simulation grids defined by geogrid. In order to run metgrid, the namelist.wps file must be edited. In particular, the “share” and “metgrid” namelist records are of relevance to the metgrid program. Examples of these records are shown below.

```
&share
 wrf_core = 'ARW',
 max_dom = 2,
 start_date = '2008-03-24_12:00:00','2008-03-24_12:00:00',
 end_date   = '2008-03-24_18:00:00','2008-03-24_12:00:00',
 interval_seconds = 21600,
 io_form_geogrid = 2
/

&metgrid
 fg_name                         = 'FILE',
 io_form_metgrid                 = 2,
/
```

By this point, there is generally no need to change any of the variables in the “share” namelist record, since those variables should have been suitably set in previous steps. If the "share" namelist was not edited while running geogrid and ungrib, however, the WRF dynamical core, number of domains, starting and ending times, interval between meteorological data, and path to the static domain files must be set in the “share” namelist record, as described in the steps to run geogrid and ungrib.

In the “metgrid” namelist record, the path and prefix of the intermediate meteorological data files must be given with `fg_name`, the full path and file names of any intermediate files containing constant fields may be specified with the `constants_name` variable, and the output format for the horizontally interpolated files may be specified with the `io_form_metgrid` variable. Other variables in the “metgrid” namelist record, namely, `opt_output_from_metgrid_path` and `opt_metgrid_tbl_path`, allow the user to specify where interpolated data files should be written by metgrid and where the METGRID.TBL file may be found.

As with geogrid and the GEOGRID.TBL file, a METGRID.TBL file appropriate for the WRF core must be linked in the metgrid directory (or in the directory specified by `opt_metgrid_tbl_path`, if this variable is set).

```
> ls metgrid/METGRID.TBL
```

```
lrwxrwxrwx 1      15 METGRID.TBL -> METGRID.TBL.ARW
```

After suitably editing the namelist.wps file and verifying that the correct METGRID.TBL will be used, metgrid may be run by issuing the command

```
> ./metgrid.exe
```

If metgrid successfully ran, the message

```
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!  Successful completion of metgrid.        !
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
```

will be printed. After successfully running, metgrid output files should appear in the WPS root directory (or in the directory specified by `opt_output_from_metgrid_path`, if this variable was set). These files will be named `met_em.d0N.YYYY-MM-DD_HH:mm:ss.nc` in the case of ARW domains, where `N` is the number of the nest whose data reside in the file, or `met_nmm.d01.YYYY-MM-DD_HH:mm:ss.nc` in the case of NMM domains. Here, `YYYY-MM-DD_HH:mm:ss` refers to the date of the interpolated data in each file. If these files do not exist for each of the times in the range given in the "share" namelist record, the metgrid.log file may be consulted to help in determining the problem in running metgrid.

```
> ls
drwxr-xr-x 2       4096 arch
-rwxr-xr-x 1       1672 clean
-rwxr-xr-x 1       3510 compile
-rw-r--r-- 1      85973 compile.output
-rwxr-xr-x 1       4257 configure
-rw-r--r-- 1       2486 configure.wps
-rw-r--r-- 1  154946888 FILE:2008-03-24_12
-rw-r--r-- 1  154946888 FILE:2008-03-24_18
-rw-r--r-- 1    1957004 geo_em.d01.nc
-rw-r--r-- 1    4745324 geo_em.d02.nc
drwxr-xr-x 4       4096 geogrid
lrwxrwxrwx 1         23 geogrid.exe -> geogrid/src/geogrid.exe
-rw-r--r-- 1      11169 geogrid.log
lrwxrwxrwx 1         38 GRIBFILE.AAA ->
/data/gfs/gfs_080324_12_00
lrwxrwxrwx 1         38 GRIBFILE.AAB ->
/data/gfs/gfs_080324_12_06
-rwxr-xr-x 1       1328 link_grib.csh
-rw-r--r-- 1    5217648 met_em.d01.2008-03-24_12:00:00.nc
-rw-r--r-- 1    5217648 met_em.d01.2008-03-24_18:00:00.nc
-rw-r--r-- 1   12658200 met_em.d02.2008-03-24_12:00:00.nc
drwxr-xr-x 3       4096 metgrid
lrwxrwxrwx 1         23 metgrid.exe -> metgrid/src/metgrid.exe
-rw-r--r-- 1      65970 metgrid.log
-rw-r--r-- 1       1094 namelist.wps
-rw-r--r-- 1       1987 namelist.wps.all_options
-rw-r--r-- 1       1075 namelist.wps.global
-rw-r--r-- 1        652 namelist.wps.nmm
```

```
      -rw-r--r-- 1       4786 README
      drwxr-xr-x 4       4096 ungrib
      lrwxrwxrwx 1         21 ungrib.exe -> ungrib/src/ungrib.exe
      -rw-r--r-- 1       1418 ungrib.log
      -rw-r--r-- 1      27787 ungrib.output
      drwxr-xr-x 3       4096 util
      lrwxrwxrwx 1         33 Vtable ->
ungrib/Variable_Tables/Vtable.GFS
```

Creating Nested Domains with the WPS

To run the WPS for nested-domain simulations is essentially no more difficult than running for a single-domain case; the difference with nested-domain simulations is that the geogrid and metgrid programs process more than one grid when they are run, rather than a single grid for the simulation. In order to specify the size and location of nests, a number of variables in the namelist.wps file must be given lists of values, one value per nest.

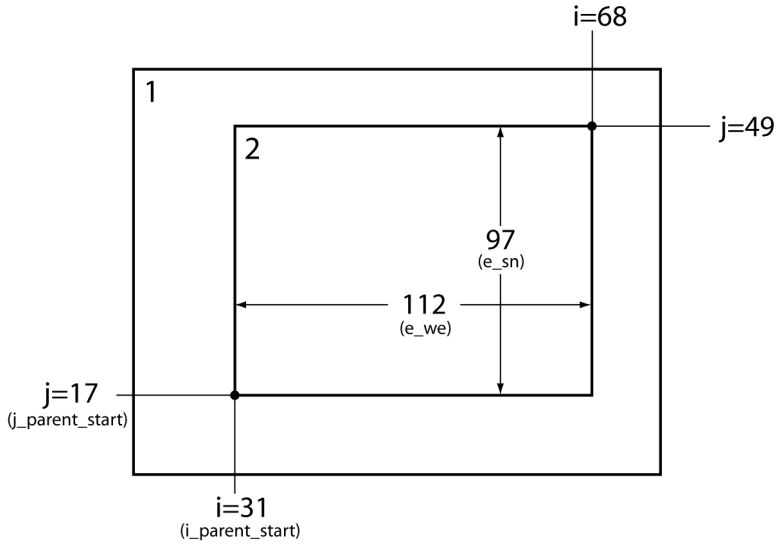
```
&share
 wrf_core = 'ARW',
 max_dom = 2,
 start_date = '2008-03-24_12:00:00','2008-03-24_12:00:00',
 end_date   = '2008-03-24_18:00:00','2008-03-24_12:00:00',
 interval_seconds = 21600,
 io_form_geogrid = 2
/

&geogrid
 parent_id         =   1,   1,
 parent_grid_ratio =   1,   3,
 i_parent_start    =   1,  31,
 j_parent_start    =   1,  17,
 e_we              =  74, 112,
 e_sn              =  61,  97,
 geog_data_res     = 'default','default',
 dx = 30000,
 dy = 30000,
 map_proj = 'lambert',
 ref_lat   = 34.83,
 ref_lon   = -81.03,
 truelat1  =  30.0,
 truelat2  =  60.0,
 stand_lon = -98.
 geog_data_path = '/mmm/users/wrfhelp/WPS_GEOG/'
/
```

The namelist variables that are affected by nests are shown in the (partial) namelist records above. The example shows namelist variables for a two-domain run (the coarse domain plus a single nest), and the effect on the namelist variables generalize to multiple

nests in the obvious way: rather than specifying lists of two values, lists of *N* values must be specified, where *N* is the total number of model grids.

In the above example, the first change to the "share" namelist record is to the `max_dom` variable, which must be set to the total number of nests in the simulation, including the coarse domain. Having determined the number of nests, all of the other affected namelist variables must be given a list of *N* values, one for each grid. The only other change to the "share" namelist record is to the starting and ending times. Here, a starting and ending time must be given for each nest, with the restriction that a nest cannot begin before its parent domain or end after its parent domain; also, it is suggested that nests be given starting and ending times that are identical to the desired starting times of the nest *when running WPS*. This is because the nests get their lateral boundary conditions from their parent domain, and thus, only the initial time for a nest needs to be processed by WPS, except when grid nudging, also called analysis nudging, is used in WRF. It is important to note that, *when running WRF*, the actual starting and ending times for all nests must be given in the WRF namelist.input file.

The remaining changes are to the "geogrid" namelist record. In this record, the parent of each nest must be specified with the `parent_id` variable. Every nest must be a child of exactly one other nest, with the coarse domain being its own parent. Related to the identity of a nest's parent is the nest refinement ratio with respect to its parent, which is given by the `parent_grid_ratio` variable; this ratio determines the nominal grid spacing for a nest in relation to the grid spacing of the its parent.



Next, the lower-left corner of a nest is specified as an (*i*, *j*) location in the nest's parent domain; this is done through the `i_parent_start` and `j_parent_start` variables, and the specified location is given with respect to the unstaggered grid. Finally, the dimensions of each nest, in grid points, are given for each nest using the `s_we`, `e_we`, `s_sn`, and `e_sn` variables. The nesting setup in our example namelist is illustrated in the figure above, where it may be seen how each of the above-mentioned variables is

determined. Currently, the starting grid point values in the south-north (`s_sn`) and west-east (`s_we`) directions must be specified as 1, and the ending grid point values (`e_sn` and `e_we`) determine, essentially, the full dimensions of the nest; to ensure that the upper-right corner of the nest's grid is coincident with an unstaggered grid point in the parent domain, both `e_we` and `e_sn` must be one greater than some integer multiple of the nesting ratio. Also, for each nest, the resolution (or list or resolutions; see the description of namelist variables) of source data to interpolate from is specified with the `geog_data_res` variable. For a complete description of these namelist variables, the user is referred to the description of namelist variables.

Selecting Between USGS and MODIS-based Land Use Classifications

By default, the geogrid program will interpolate land use categories from MODIS IGBP 21-category data. However, the user may select an alternative set of land use categories based on the USGS land-cover classification. Although the MODIS-based data contain 21 categories of land use, these categories are not a subset of the 24 USGS categories; users interested in the specific categories in either data set can find a listing of the land use classes in the section on land use and soil categories.

The 24-category USGS-based land use data may be selected instead of the MODIS data at run-time through the `geog_data_res` variable in the `&geogrid` namelist record. This is accomplished by prefixing each resolution of static data with the string "`usgs_30s+`". For example, in a two-domain configuration, where the `geog_data_res` variable would ordinarily be specified as

```
geog_data_res = 'default', 'default',
```

the user should instead specify

```
geog_data_res = 'usgs_30s+default', 'usgs_30s+default',
```

The effect of this change is to instruct the geogrid program to look, in each entry of the GEOGRID.TBL file, for a resolution of static data with a resolution denoted by 'usgs_30s', and if such a resolution is not available, to instead look for a resolution denoted by the string following the '+'. Thus, for the GEOGRID.TBL entry for the LANDUSEF field, the USGS-based land use data, which is identified with the string 'usgs_30s', would be used instead of the 'default', resolutions (or source) of land-use data in the example above; for all other fields, the 'default' resolutions would be used for the first and second. As an aside, when none of the resolutions specified for a domain in `geog_data_res` are found in a GEOGRID.TBL entry, the resolution denoted by 'default' will be used.

When changing from the default 21-class MODIS land-use data, the user must also ensure that the `num_land_cat` namelist variable is set correctly in `&physics` namelist

record in the WRF namelist.input file. For 24-class USGS data, `num_land_cat` should be set to 24.

Selecting Static Data for the Gravity Wave Drag Scheme

The gravity wave drag by orography (GWDO) scheme in the ARW requires ten static fields from the WPS. In fact, these fields will be interpolated by the geogrid program regardless of whether the GWDO scheme will be used in the model. When the GWDO scheme will not be used, the fields will simply be ignored in WRF, and the user need not be concerned with the resolution of data from which the fields are interpolated. However, it is recommended that these fields be interpolated from a resolution of source data that is slightly *lower* (i.e., coarser) in resolution than the model grid; consequently, if the GWDO scheme will be used, care should be taken to select an appropriate resolution of GWDO static data. Currently, five resolutions of GWDO static data are available: 2-degree, 1-degree, 30-minute, 20-minute, and 10-minute, denoted by the strings '2deg', '1deg', '30m', '20m', and '10m', respectively. To select the resolution to interpolate from, the user should prefix the resolution specified for the `geog_data_res` variable in the "geogrid" namelist record by the string "XXX+", where XXX is one of the five available resolutions of GWDO static data. For example, in a model configuration with a 48-km grid spacing, the `geog_data_res` variable might typically be specified as

```
geog_data_res = '10m',
```

However, if the GWDO scheme were employed, the finest resolution of GWDO static data that is still lower in resolution than the model grid would be the 30-minute data, in which case the user should specify

```
geog_data_res = '30m+10m',
```

If none of '2deg', '1deg', '30m', or '20m' are specified in combination with other resolutions of static data in the `geog_data_res` variable, the '10m' GWDO static data will be used, since it is also designated as the 'default' resolution in the GEOGRID.TBL file. It is worth noting that, if 10-minute resolution GWDO data are to be used, but a different resolution is desired for other static fields (e.g., topography height), the user should simply omit '10m' from the value given to the `geog_data_res` variable, since specifying

```
geog_data_res = '10m+30s',
```

for example, would cause geogrid to use the 10-mintute data in preference to the 30-second data for the non-GWDO fields, such as topography height and land use category, as well as for the GWDO fields.

Using Multiple Meteorological Data Sources

The metgrid program is capable of interpolating time-invariant fields, and it can also interpolate from multiple sources of meteorological data. The first of these capabilities uses the `constants_name` variable in the `&metgrid` namelist record. This variable may be set to a list of filenames – including path information where necessary – of intermediate-formatted files which contains time-invariant fields, and which should be used in the output for every time period processed by metgrid. For example, short simulations may use a constant SST field; this field need only be available at a single time, and may be used by setting the `constants_name` variable to the path and filename of the SST intermediate file. Typical uses of `constants_name` might look like

```
&metgrid
 constants_name = '/data/ungribbed/constants/SST_FILE:2006-08-16_12'
/
```

or

```
&metgrid
 constants_name = 'LANDSEA', 'SOILHGT'
/
```

The second metgrid capability – that of interpolating data from multiple sources – may be useful in situations where two or more complementary data sets need to be combined to produce the full input data needed by real.exe. To interpolate from multiple sources of time-varying, meteorological data, the `fg_name` variable in the `&metgrid` namelist record should be set to a list of prefixes of intermediate files, including path information when necessary. When multiple path-prefixes are given, and the same meteorological field is available from more than one of the sources, data from the last-specified source will take priority over all preceding sources. Thus, data sources may be prioritized by the order in which the sources are given.

As an example of this capability, if surface fields are given in one data source and upper-air data are given in another, the values assigned to the `fg_name` variable may look something like:

```
&metgrid
 fg_name = '/data/ungribbed/SFC', '/data/ungribbed/UPPER_AIR'
/
```

To simplify the process of extracting fields from GRIB files, the `prefix` namelist variable in the `&ungrib` record may be employed. This variable allows the user to control the names of (and paths to) the intermediate files that are created by ungrib. The utility of this namelist variable is most easily illustrated by way of an example. Suppose we wish to work with the North American Regional Reanalysis (NARR) data set, which is split into separate GRIB files for 3-dimensional atmospheric data, surface data, and fixed-field

data. We may begin by linking all of the "3D" GRIB files using the `link_grib.csh` script, and by linking the NARR Vtable to the filename `Vtable`. Then, we may suitably edit the `&ungrib` namelist record before running ungrib.exe so that the resulting intermediate files have an appropriate prefix:

```
&ungrib
 out_format = 'WPS',
 prefix = 'NARR_3D',
/
```

After running ungrib.exe, the following files should exist (with a suitable substitution for the appropriate dates):

```
NARR_3D:2008-08-16_12
NARR_3D:2008-08-16_15
NARR_3D:2008-08-16_18
...
```

Given intermediate files for the 3-dimensional fields, we may process the surface fields by linking the surface GRIB files and changing the `prefix` variable in the namelist:

```
&ungrib
 out_format = 'WPS',
 prefix = 'NARR_SFC',
/
```

Again running ungrib.exe, the following should exist in addition to the NARR_3D files:

```
NARR_SFC:2008-08-16_12
NARR_SFC:2008-08-16_15
NARR_SFC:2008-08-16_18
...
```

Finally, the fixed file is linked with the `link_grib.csh` script, and the `prefix` variable in the namelist is again set:

```
&ungrib
 out_format = 'WPS',
 prefix = 'NARR_FIXED',
/
```

Having run ungrib.exe for the third time, the fixed fields should be available in addition to the surface and "3D" fields:

```
NARR_FIXED:1979-11-08_00
```

For the sake of clarity, the fixed file may be renamed to remove any date information, for example, by renaming it to simply `NARR_FIXED`, since the fields in the file are static. In this example, we note that the NARR fixed data are only available at a specific time, 1979 November 08 at 0000 UTC, and thus, the user would need to set the correct starting

and ending time for the data in the `&share` namelist record before running ungrib on the NARR fixed file; of course, the times should be re-set before metgrid is run.

Given intermediate files for all three parts of the NARR data set, metgrid.exe may be run after the `constants_name` and `fg_name` variables in the `&metgrid` namelist record are set:

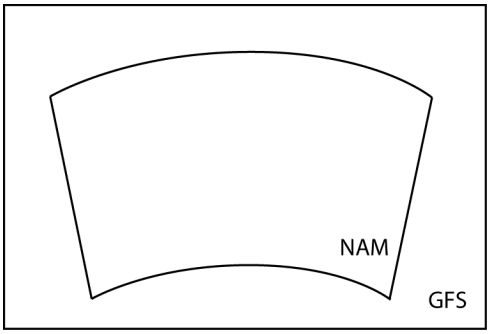
```
&metgrid
 constants_name = 'NARR_FIXED',
 fg_name = 'NARR_3D', 'NARR_SFC'
/
```

Although less common, another situation where multiple data sources would be required is when a source of meteorological data from a regional model is insufficient to cover the entire simulation domain, and data from a larger regional model, or a global model, must be used when interpolating to the remaining points of the simulation grid.

For example, to use NAM data wherever possible, and GFS data elsewhere, the following values might be assigned in the namelist:

```
&metgrid
 fg_name = '/data/ungribbed/GFS', '/data/ungribbed/NAM'
/
```

Then the resulting model domain would use data as shown in the figure below.



If no field is found in more than one source, then no prioritization need be applied by metgrid, and each field will simply be interpolated as usual; of course, each source should cover the entire simulation domain to avoid areas of missing data.

Using Non-isobaric Meteorological Datasets

When using non-isobaric meteorological datasets to initialize a WRF simulation, it is important that such datasets are supplied to the metgrid.exe program with 3-d pressure and geopotential height fields on the same levels as other 3-d atmospheric variables, such as temperature and humidity. These fields are used by the WRF real.exe pre-processor for vertical interpolation to WRF model levels, for surface pressure computation, and for other purposes.

For some data sources, namely ECMWF model-level data and UK Met Office model data, the 3-d pressure and/or geopotential height fields can be derived from the surface pressure and/or surface height fields using an array of coefficients, and the WPS provides utility programs for performing this derivation; see the section on WPS Utility Programs for more information on the calc_ecmwf_p.exe and height_ukmo.exe programs.

Other meteorological datasets explicitly provide 3-d pressure and geopotential height fields, and the user must only ensure that these fields exist in the set of intermediate files provided to the metgrid.exe program.

Alternative Initialization of Lake SSTs

The default treatment of sea-surface temperatures – both for oceans and lakes – in the metgrid program involves simply interpolating the SST field from the intermediate files to all water points in the WRF domain. However, if the lakes that are resolved in the WRF domain are not resolved in the GRIB data, and especially if those lakes are geographically distant from resolved water bodies, the SST field over lakes will most likely be extrapolated from the nearest resolved water bodies in the GRIB data; this situation can lead to lake SST values that are either unrealistically warm or unrealistically cold.

Without a higher-resolution SST field for metgrid to use, one alternative to extrapolating SST values for lakes is to manufacture a “best guess” at the SST for lakes. In the metgrid and real programs, this can be done using a combination of a special land use data set that distinguishes between lakes and oceans, and a field to be used as a proxy for SST over lakes. A special land use data set is necessary, since WRF’s real pre-processing program needs to know where the manufactured SST field should be used instead of the interpolated SST field from the GRIB data.

The alternative procedure for initializing lake SSTs is summarized in the following steps:

1. If they have not already been downloaded (either as a separate tar file or as part of the ‘full’ geographical data tar file), obtain the special land use data sets that distinguish between lakes and oceans. Two such data sets – based on USGS and MODIS land use categories – may be downloaded through the WRF download page.

For simplicity, it is recommended to place the two directories in the same directory as the other static geographical data sets (e.g., topo_30s, soiltype_top_30s, etc.) used by geogrid, since doing so will eliminate the need to modify the GEOGRID.TBL file. If the landuse_30s_with_lakes and modis_landuse_21class_30s directories are placed in a location different from the other static data sets, it will be necessary to change the paths to these directories from relative paths to absolute paths in the GEOGRID.TBL file.

2. Before running geogrid, change the specification of `geog_data_res` in the `&geogrid` namelist record to specify either the USGS-based or the MODIS-based land use data with inland water bodies. For example, in a two-domain configuration, setting

```
geog_data_res = 'usgs_lakes+10m', 'usgs_lakes+2m',
```

would tell geogrid to use the USGS-based land use data for both domains, and to use the 10-minute resolution data for other static fields in domain 1 and the 2-minute resolution data for other static fields in domain 2; for MODIS-based data, `usgs_lakes` should be replaced by `modis_lakes`.

Running geogrid should result in output files that use a separate category for inland water bodies instead of the general water category used for oceans and seas. The lake category is identified by the global attribute ISLAKE in the geogrid output files; this attribute should be set to either 28 (in the case of USGS-based data) or 21 (in the case of the MODIS-based data). See, e.g., the list of WPS output fields, where a value of -1 for ISLAKE indicates that there is no separate lake category.

3. After running the ungrib program, use the avg_tsfc.exe utility program to create an intermediate file containing a daily-average surface air temperature field, which will be substituted for the SST field only over lakes by the real program; for more information on the avg_tsfc.exe utility, see the section on WPS utility programs.

4. Before running the metgrid program, add the TAVGSFC file created in the previous step to the specification of `constants_name` in the `&metgrid` record of the namelist.wps file.

5. Run WRF's real.exe program as usual after setting the number of land categories (`num_land_cat`) in the `&physics` record of the namelist.input file so that it matches the value of the global attribute NUM_LAND_CAT in the metgrid files. If the global attribute ISLAKE in the metgrid files indicates that there is a special land use category for lakes, the real program will substitute the TAVGSFC field for the SST field only over those grid points whose category matches the lake category; additionally, the real program will change the land use category of lakes back to the general water category (the category used for oceans), since neither the LANDUSE.TBL nor the VEGPARM.TBL files contain an entry for a lake category.

Parallelism in the WPS

If the dimensions of the domains to be processed by the WPS become too large to fit in the memory of a single CPU, it is possible to run the geogrid and metgrid programs in a distributed memory configuration. In order to compile geogrid and metgrid for distributed memory execution, the user must have MPI libraries installed on the target machine, and must have compiled WPS using one of the "DM parallel" configuration options. Upon successful compilation, the geogrid and metgrid programs may be run with the *mpirun* or *mpiexec* commands, or through a batch queuing system, depending on the machine.

As mentioned earlier, the work of the ungrib program is not amenable to parallelization, and, further, the memory requirements for ungrib's processing are independent of the memory requirements of geogrid and metgrid; thus, ungrib is always compiled for a single processor and run on a single CPU, regardless of whether a "DM parallel" configuration option was selected during configuration.

Each of the standard WRF I/O API formats (NetCDF, GRIB1, binary) has a corresponding parallel format, whose number is given by adding 100 to the io_form value (i.e., the value of `io_form_geogrid` and `io_form_metgrid`) for the standard format. It is not necessary to use a parallel io_form, but when one is used, each CPU will read/write its input/output to a separate file, whose name is simply the name that would be used during serial execution, but with a four-digit processor ID appended to the name. For example, running geogrid on four processors with `io_form_geogrid=102` would create output files named geo_em.d01.nc.0000, geo_em.d01.nc.0001, geo_em.d01.nc.0002, and geo_em.d01.nc.0003 for the coarse domain.

During distributed-memory execution, model domains are decomposed into rectangular patches, with each processor working on a single patch. When reading/writing from/to the WRF I/O API format, each processor reads/writes only its patch. Consequently, if a parallel io_form is chosen for the output of geogrid, metgrid must be run using the same number of processors as were used to run geogrid. Similarly, if a parallel io_form is chosen for the metgrid output files, the real program must be run using the same number of processors. Of course, it is still possible to use a standard io_form when running on multiple processors, in which case all data for the model domain will be distributed/collected upon input/output. As a final note, when geogrid or metgrid are run on multiple processors, each processor will write its own log file, with the log file names being appended with the same four-digit processor ID numbers that are used for the I/O API files.

Checking WPS Output

When running the WPS, it may be helpful to examine the output produced by the programs. For example, when determining the location of nests, it may be helpful to see the interpolated static geographical data and latitude/longitude fields. As another

example, when importing a new source of data into WPS – either static data or meteorological data – it can often be helpful to check the resulting interpolated fields in order to make adjustments the interpolation methods used by geogrid or metgrid.

By using the NetCDF format for the geogrid and metgrid I/O forms, a variety of visualization tools that read NetCDF data may be used to check the domain files processed by geogrid or the horizontally interpolated meteorological fields produced by metgrid. In order to set the file format for geogrid and metgrid to NetCDF, the user should specify 2 as the `io_form_geogrid` and `io_form_metgrid` in the WPS namelist file (Note: 2 is the default setting for these options):

```
&share
 io_form_geogrid = 2,
/

&metgrid
 io_form_metgrid = 2,
/
```

Among the available tools, the ncdump, ncview, and new RIP4 programs may be of interest. The ncdump program is a compact utility distributed with the NetCDF libraries that lists the variables and attributes in a NetCDF file. This can be useful, in particular, for checking the domain parameters (e.g., west-east dimension, south-north dimension, or domain center point) in geogrid domain files, or for listing the fields in a file. The ncview program provides an interactive way to view fields in NetCDF files. Also, for users wishing to produce plots of fields suitable for use in publications, the new release of the RIP4 program may be of interest. The new RIP4 is capable of plotting horizontal contours, map backgrounds, and overlaying multiple fields within the same plot.

Output from the ungrib program is always written in a simple binary format (either 'WPS', 'SI', or 'MM5'), so software for viewing NetCDF files will almost certainly be of no use. However, an NCAR Graphics-based utility, *plotfmt*, is supplied with the WPS source code. This utility produces contour plots of the fields found in an intermediate-format file. If the NCAR Graphics libraries are properly installed, the plotfmt program is automatically compiled, along with other utility programs, when WPS is built.

WPS Utility Programs

Besides the three main WPS programs – geogrid, ungrib, and metgrid – there are a number of utility programs that come with the WPS, and which are compiled in the util directory. These utilities may be used to examine data files, visualize the location of nested domains, compute pressure fields, and compute average surface temperature fields.

A. avg_tsfc.exe

The avg_tsfc.exe program computes a daily mean surface temperature given input files in the intermediate format. Based on the range of dates specified in the "share" namelist section of the namelist.wps file, and also considering the interval between intermediate files, avg_tsfc.exe will use as many complete days' worth of data as possible in computing the average, beginning at the starting date specified in the namelist. If a complete day's worth of data is not available, no output file will be written, and the program will halt as soon as this can be determined. Similarly, any intermediate files for dates that cannot be used as part of a complete 24-hour period are ignored; for example, if there are five intermediate files available at a six-hour interval, the last file would be ignored. The computed average field is written to a new file named TAVGSFC using the same intermediate format version as the input files. This daily mean surface temperature field can then be ingested by metgrid by specifying 'TAVGSFC' for the `constants_name` variable in the "metgrid" namelist section.

B. mod_levs.exe

The mod_levs.exe program is used to remove levels of data from intermediate format files. The levels which are to be kept are specified in a new namelist record in the namelist.wps file:

```
&mod_levs
 press_pa = 201300 , 200100 , 100000 ,
             95000 ,  90000 ,
             85000 ,  80000 ,
             75000 ,  70000 ,
             65000 ,  60000 ,
             55000 ,  50000 ,
             45000 ,  40000 ,
             35000 ,  30000 ,
             25000 ,  20000 ,
             15000 ,  10000 ,
              5000 ,   1000
/
```

Within the `&mod_levs` namelist record, the variable `press_pa` is used to specify a list of levels to keep; the specified levels should match values of `xlvl` in the intermediate format files (see the discussion of the WPS intermediate format for more information on the fields of the intermediate files). The mod_levs program takes two command-line arguments as its input. The first argument is the name of the intermediate file to operate on, and the second argument is the name of the output file to be written.

Removing all but a specified subset of levels from meteorological data sets is particularly useful, for example, when one data set is to be used for the model initial conditions and a second data set is to be used for the lateral boundary conditions. This can be done by providing the initial conditions data set at the first time period to be interpolated by metgrid, and the boundary conditions data set for all other times. If the both data sets have the same number of vertical levels, then no work needs to be done; however, when these two data sets have a different number of levels, it will be necessary, at a minimum, to remove ($m - n$) levels, where $m > n$ and m and n are the number of levels in each of the

two data sets, from the data set with *m* levels. The necessity of having the same number of vertical levels in all files is due to a limitation in real.exe, which requires a constant number of vertical levels to interpolate from.

The mod_levs utility is something of a temporary solution to the problem of accommodating two or more data sets with differing numbers of vertical levels. Should a user choose to use mod_levs, it should be noted that, although the vertical locations of the levels need not match between data sets, all data sets should have a surface level of data, and, when running real.exe and wrf.exe, the value of `p_top` must be chosen to be below the lowest top among the data sets.

C. calc_ecmwf_p.exe

In the course of vertically interpolating meteorological fields, the real program requires 3-d pressure and geopotential height fields on the same levels as the other atmospheric fields. The calc_ecmwf_p.exe utility may be used to create these fields for use with ECMWF sigma-level data sets. Given a surface pressure field (or log of surface pressure field) and a list of coefficients A and B, calc_ecmwf_p.exe computes the pressure at an ECMWF sigma level *k* at grid point (*i*,*j*) as $P_{ijk} = A_k + B_k*Psfc_{ij}$. The list of coefficients used in the pressure computation can be copied from a table appropriate to the number of sigma levels in the data set from one of the following links:

http://www.ecmwf.int/en/forecasts/documentation-and-support/16-model-levels

http://www.ecmwf.int/en/forecasts/documentation-and-support/19-model-levels

http://www.ecmwf.int/en/forecasts/documentation-and-support/31-model-levels

http://www.ecmwf.int/en/forecasts/documentation-and-support/40-model-levels

http://www.ecmwf.int/en/forecasts/documentation-and-support/50-model-levels

http://www.ecmwf.int/en/forecasts/documentation-and-support/60-model-levels

http://www.ecmwf.int/en/forecasts/documentation-and-support/62-model-levels

http://www.ecmwf.int/en/forecasts/documentation-and-support/91-model-levels

http://www.ecmwf.int/en/forecasts/documentation-and-support/137-model-levels

This table should be written in plain text to a file, ecmwf_coeffs, in the current working directory; for example, with 16 sigma levels, the file emcwf_coeffs would contain something like:

```
0          0.000000       0.000000000
1       5000.000000       0.000000000
2       9890.519531       0.001720764
```

```
 3     14166.304688      0.013197623
 4     17346.066406      0.042217135
 5     19121.152344      0.093761623
 6     19371.250000      0.169571340
 7     18164.472656      0.268015683
 8     15742.183594      0.384274483
 9     12488.050781      0.510830879
10      8881.824219      0.638268471
11      5437.539063      0.756384850
12      2626.257813      0.855612755
13       783.296631      0.928746223
14         0.000000      0.972985268
15         0.000000      0.992281914
16         0.000000      1.000000000
```

Additionally, if soil height (or soil geopotential), 3-d temperature, and 3-d specific humidity fields are available, calc_ecmwf_p.exe computes a 3-d geopotential height field, which is required to obtain an accurate vertical interpolation in the real program.

Given a set of intermediate files produced by ungrib and the file ecmwf_coeffs, calc_ecmwf_p loops over all time periods in namelist.wps, and produces an additional intermediate file, PRES:*YYYY-MM-DD_HH*, for each time, which contains pressure and geopotential height data for each full sigma level, as well as a 3-d relative humidity field. This intermediate file should be specified to metgrid, along with the intermediate data produced by ungrib, by adding 'PRES' to the list of prefixes in the fg_name namelist variable.

D. height_ukmo.exe

The real program requires 3-d pressure and geopotential height fields to vertically interpolate the output of the metgrid program; however, data sets from the UKMO Unified Model contain a 3-d pressure field, but do not contain a geopotential height field. Accordingly, the height_ukmo.exe program may be used to compute a geopotential height field for data sets from the UKMO Unified Model. The height_ukmo.exe program requires no command-line arguments, but reads the `&metgrid` namelist record to get the prefix of the intermediate files created by ungrib.exe; the intermediate files indicated by the first prefix in the `fg_name` variable of the `&metgrid` namelist record are expected to contain a SOILHGT field, from which the height_ukmo.exe program computes, with the aid of an auxiliary table, the 3-d geopotential height field. The computed height field is written to a new intermediate file with the prefix HGT, and the prefix 'HGT' should then be added to the `fg_name` namelist variable in the `&metgrid` namelist record before running metgrid.exe. The name of the file containing the auxiliary table is currently hard-wired in the source code of the height_ukmo.exe program, and it is the responsibility of the user to change this file name in WPS/util/src/height_ukmo.F to the name of the table with the same number of levels as the GRIB data processed by ungrib.exe; tables for data with 38, 50, and 70 levels are provided in the WPS/util directory with file names vertical_grid_38_20m_G3.txt, vertical_grid_50_20m_63km.txt , and vertical_grid_70_20m_80km.txt, respectively.

E. plotgrids.ncl

The plotgrids.ncl program is an NCAR Graphics-based utility whose purpose is to plot the locations of all nests defined in the namelist.wps file. The program operates on the namelist.wps file, and thus, may be run without having run any of the three main WPS programs. Upon successful completion, plotgrids produces an Graphics file in the chosen format (see inside the plotgrids.ncl script for making changes to the output format), The coarse domain is drawn to fill the plot frame, a map outline with political boundaries is drawn over the coarse domain, and any nested domains are drawn as rectangles outlining the extent of each nest. This utility may be useful particularly during initial placement of domains, at which time the user can iteratively adjust the locations of nests by editing the namelist.wps file, running plotgrids.ncl, and determining a set of adjustments to the nest locations. To run this program, simply type 'ncl util/plotgrids.ncl' in the command line from inside the WPS/ directory. *Currently, this utility does not work for ARW domains that use the latitude-longitude projection* (i.e., when `map_proj = 'lat-lon'`).

F. g1print.exe

The g1print.exe program takes as its only command-line argument the name of a GRIB Edition 1 file. The program prints a listing of the fields, levels, and dates of the data in the file.

G. g2print.exe

Similar to g1print.exe, the g2print.exe program takes as its only command-line argument the name of a GRIB Edition 2 file. The program prints a listing of the fields, levels, and dates of the data in the file.

H. rd_intermediate.exe

Given the name of a singe intermediate format file on the command line, the rd_intermediate.exe program prints information about the fields contained in the file.

Writing Meteorological Data to the Intermediate Format

The role of the ungrib program is to decode GRIB data sets into a simple intermediate format that is understood by metgrid. If meteorological data are not available in GRIB Edition 1 or GRIB Edition 2 formats, the user is responsible for writing such data into the intermediate file format. Fortunately, the intermediate format is relatively simple, consisting of a sequence of unformatted Fortran writes. It is important to note that these *unformatted writes use big-endian byte order*, which can typically be specified with compiler flags. Below, we describe the WPS intermediate format; users interested in the SI or MM5 intermediate formats can first gain familiarity with the WPS format, which is very similar, and later examine the Fortran subroutines that read and write all three intermediate formats (metgrid/src/read_met_module.F and metgrid/src/write_met_module.F, respectively).

When writing data to the WPS intermediate format, 2-dimensional fields are written as a rectangular array of real values. 3-dimensional arrays must be split across the vertical dimension into 2-dimensional arrays, which are written independently. It should also be noted that, for global data sets, either a Gaussian or cylindrical equidistant projection must be used, and for regional data sets, either a Mercator, Lambert conformal, polar stereographic, or cylindrical equidistant may be used. The sequence of writes used to write a single 2-dimensional array in the WPS intermediate format is as follows (note that not all of the variables declared below are used for a given projection of the data).

```
integer :: version            ! Format version (must =5 for WPS format)
integer :: nx, ny             ! x- and y-dimensions of 2-d array
integer :: iproj              ! Code for projection of data in array:
                              !       0 = cylindrical equidistant
                              !       1 = Mercator
                              !       3 = Lambert conformal conic
                              !       4 = Gaussian (global only!)
                              !       5 = Polar stereographic
real :: nlats                 ! Number of latitudes north of equator
                              !       (for Gaussian grids)
real :: xfcst                 ! Forecast hour of data
real :: xlvl                  ! Vertical level of data in 2-d array
```

```
real :: startlat, startlon     ! Lat/lon of point in array indicated by
                               !      startloc string
real :: deltalat, deltalon     ! Grid spacing, degrees
real :: dx, dy                 ! Grid spacing, km
real :: xlonc                  ! Standard longitude of projection
real :: truelat1, truelat2     ! True latitudes of projection
real :: earth_radius           ! Earth radius, km
real, dimension(nx,ny) :: slab ! The 2-d array holding the data
logical :: is_wind_grid_rel    ! Flag indicating whether winds are
                               !      relative to source grid (TRUE) or
                               !      relative to earth (FALSE)
character (len=8)  :: startloc ! Which point in array is given by
                               !      startlat/startlon; set either
                               !      to 'SWCORNER' or 'CENTER  '
character (len=9)  :: field    ! Name of the field
character (len=24) :: hdate    ! Valid date for data YYYY:MM:DD_HH:00:00
character (len=25) :: units    ! Units of data
character (len=32) :: map_source  !  Source model / originating center
character (len=46) :: desc     ! Short description of data


!  1) WRITE FORMAT VERSION
write(unit=ounit) version

!  2) WRITE METADATA
! Cylindrical equidistant
if (iproj == 0) then
      write(unit=ounit) hdate, xfcst, map_source, field, &
                        units, desc, xlvl, nx, ny, iproj
      write(unit=ounit) startloc, startlat, startlon, &
                        deltalat, deltalon, earth_radius

! Mercator
else if (iproj == 1) then
      write(unit=ounit) hdate, xfcst, map_source, field, &
                        units, desc, xlvl, nx, ny, iproj
      write(unit=ounit) startloc, startlat, startlon, dx, dy, &
                        truelat1, earth_radius

! Lambert conformal
else if (iproj == 3) then
      write(unit=ounit) hdate, xfcst, map_source, field, &
                        units, desc, xlvl, nx, ny, iproj
      write(unit=ounit) startloc, startlat, startlon, dx, dy, &
                        xlonc, truelat1, truelat2, earth_radius

! Gaussian
else if (iproj == 4) then
      write(unit=ounit) hdate, xfcst, map_source, field, &
                        units, desc, xlvl, nx, ny, iproj
      write(unit=ounit) startloc, startlat, startlon, &
                               nlats, deltalon, earth_radius

! Polar stereographic
else if (iproj == 5) then
      write(unit=ounit) hdate, xfcst, map_source, field, &
                        units, desc, xlvl, nx, ny, iproj
      write(unit=ounit) startloc, startlat, startlon, dx, dy, &
```

```
                        xlonc, truelat1, earth_radius

end if

!  3) WRITE WIND ROTATION FLAG
write(unit=ounit) is_wind_grid_rel

!  4) WRITE 2-D ARRAY OF DATA
write(unit=ounit) slab
```

Required Meteorological Fields for Running WRF

In order to successfully initialize a WRF simulation, the real.exe pre-processor requires a minimum set of meteorological and land-surface fields to be present in the output from the metgrid.exe program. Accordingly, these required fields must be available in the intermediate files processed by metgrid.exe. The set of required fields is described in the table, below.

Field name in intermediate file	Units	Description	Notes
TT	K	3-d air temperature	
RH	%	3-d relative humidity	Not needed if SPECHUMD is available
SPECHUMD	kg kg^{-1}	3-d specific humidity	Not needed if RH is available
UU	m s^{-1}	3-d wind u-component	
VV	m s^{-1}	3-d wind v-component	
GHT	m	3-d geopotential height	
PRESSURE	Pa	3-d pressure	Only needed for non-isobaric datasets
PSFC	Pa	Surface pressure	
PMSL	Pa	Mean sea-level pressure	
SKINTEMP	K	Skin temperature	
SOILHGT	m	Soil height	
TT	K	2-meter air temperature	
RH	%	2-meter relative humidity	Not needed if SPECHUMD is available
SPECHUMD	kg kg^{-1}	2-meter specific humidity	Not needed if RH is available
UU	m s^{-1}	2-meter wind u-component	
VV	m s^{-1}	2-meter wind v-component	
LANDSEA	fraction	Land-sea mask (0=water, 1=land)	

SM*tttbbb*	m^3 m^{-3}	Soil moisture	'*ttt*' is the layer top depth in cm, and '*bbb*' is the layer bottom depth in cm
ST*tttbbb*	K	Soil temperature	
SOILM*mmm*	kg m^{-3}	Soil moisture	'*mmm*' is the level depth in cm, not needed if SMtttbbb available
SOILT*mmm*	K	Soil temperature	

Using MPAS Output for WRF Initial and Lateral Boundary Conditions

Beginning with the v3.9 release of the WPS, the metgrid.exe program is capable of reading native, unstructured mesh output in netCDF format from the Model for Prediction Across Scales (MPAS; https://mpas-dev.github.io/); the metgrid.exe program can then horizontally interpolate the MPAS fields directly to any domain defined by the geogrid.exe program to produce output files that are usable by the WRF real.exe program in exatly the same way as metgrid output interpolated from intermediate files. In this way, output from MPAS may be used to provide initial and lateral boundary conditions for WRF.

When running an MPAS simulation, an output stream must be set up to contain the minimum set of fields necessary to initialize a WRF simulation. The following output stream should be sufficient with the MPAS v5.x code.

```
<stream name="wrf_ic_bc"
        type="output"
        filename_template="MPAS.$Y-$M-$D_$h.nc"
        output_interval="3:00:00" >

 <var name="xtime"/>
 <var_array name="scalars"/>
 <var name="pressure"/>
 <var name="zgrid"/>
 <var name="theta"/>
 <var name="uReconstructZonal"/>
 <var name="uReconstructMeridional"/>
 <var name="u10"/>
 <var name="v10"/>
 <var name="q2"/>
 <var name="t2m"/>
 <var name="skintemp"/>
 <var name="surface_pressure"/>
 <var name="mslp"/>
 <var name="tslb"/>
 <var name="smois"/>

</stream>
```

After having run MPAS with a suitable output stream defined, a set of netCDF files containing fields on the native MPAS mesh will have been produced. Because these files do not contain fields describing the locations, geometry, and connectivity of the MPAS grid cells, this information must be provided to the metgrid program with a "static" file from the MPAS simulation. Therefore, it is necessary to specify MPAS netCDF files (prefixed with `'mpas:'`) in the `&metgrid` namelist record with both the `constants_name` and `fg_name` variables, e.g.,

```
&metgrid
 constants_name = 'mpas:static.nc'
 fg_name = 'mpas:MPAS'
/
```

In the above example, the metgrid.exe program would first read the MPAS 'static.nc' file to read mesh information and compute remapping weights from the MPAS mesh to the WRF domain defined by the geogrid.exe program, then all time periods of the MPAS files with a prefix of 'MPAS' (and a suffix of `YYYY-MM-DD_HH.nc`) would be processed. The real.exe program can then be run as usual.

Because the MPAS 'zgrid' field does not change in time, it can be omitted from the MPAS periodic output stream; in this case, however, the 'zgrid' field must be placed in its own netCDF file that must also define the dimension 'Time' as a netCDF unlimited dimension. Then, this file (say, 'zgrid.nc') can be supplied to the metgrid program using the `constants_name` namelist variable, e.g.,

```
&metgrid
 constants_name = 'mpas:static.nc', 'mpas:zgrid.nc'
 fg_name = 'mpas:MPAS'
/
```

Placing the 'zgrid' field in its own file can save considerable space when long MPAS simulations are run, or when the output stream to be used as WRF initial and boundary conditions is written out at high temporal frequency.

Creating and Editing Vtables

Although Vtables are provided for many common data sets, it would be impossible for ungrib to anticipate every possible source of meteorological data in GRIB format. When a new source of data is to be processed by ungrib.exe, the user may create a new Vtable either from scratch, or by using an existing Vtable as an example. In either case, a basic knowledge of the meaning and use of the various fields of the Vtable will be helpful.

Each Vtable contains either seven or eleven fields, depending on whether the Vtable is for a GRIB Edition 1 data source or a GRIB Edition 2 data source, respectively. The fields of a Vtable fall into one of three categories: fields that describe how the data are identified within the GRIB file, fields that describe how the data are identified by the

ungrib and metgrid programs, and fields specific to GRIB Edition 2. Each variable to be extracted by ungrib.exe will have one or more lines in the Vtable, with multiple lines for data that are split among different level types – for example, a surface level and upper-air levels. The fields that must be specified for a line, or entry, in the Vtable depends on the specifics of the field and level.

The first group of fields – those that describe how the data are identified within the GRIB file – are given under the column headings of the Vtable shown below.

```
GRIB1| Level| From |  To  |
Param| Type |Level1|Level2|
-----+------+------+------+
```

The "GRIB1 Param" field specifies the GRIB code for the meteorological field, which is a number unique to that field within the data set. However, different data sets may use different GRIB codes for the same field – for example, temperature at upper-air levels has GRIB code 11 in GFS data, but GRIB code 130 in ECMWF data. To find the GRIB code for a field, the g1print.exe and g2print.exe utility program may be used.

Given a GRIB code, the "Level Type", "From Level1", and "From Level2" fields are used to specify which levels a field may be found at. As with the "GRIB1 Param" field, the g1print.exe and g2print.exe programs may be used to find values for the level fields. The meanings of the level fields are dependent on the "Level Type" field, and are summarized in the following table.

Level	Level Type	From Level1	To Level2
Upper-air	100	*	(blank)
Surface	1	0	(blank)
Sea-level	102	0	(blank)
Levels at a specified height AGL	105	Height, in meters, of the level above ground	(blank)
Fields given as layers	112	Starting level for the layer	Ending level for the layer

When layer fields (Level Type 112) are specified, the starting and ending points for the layer have units that are dependent on the field itself; appropriate values may be found with the g1print.exe and g2print.exe utility programs.

The second group of fields in a Vtable, those that describe how the data are identified within the metgrid and real programs, fall under the column headings shown below.

```
| metgrid  | metgrid | metgrid                                  |
| Name     |  Units  | Description                              |
+----------+---------+------------------------------------------+
```

The most important of these three fields is the "metgrid Name" field, which determines the variable name that will be assigned to a meteorological field when it is written to the intermediate files by ungrib. This name should also match an entry in the METGRID.TBL file, so that the metgrid program can determine how the field is to be horizontally interpolated. The "metgrid Units" and "metgrid Description" fields specify the units and a short description for the field, respectively; here, it is important to note that if no description is given for a field, then *ungrib will not write that field out to the intermediate files*.

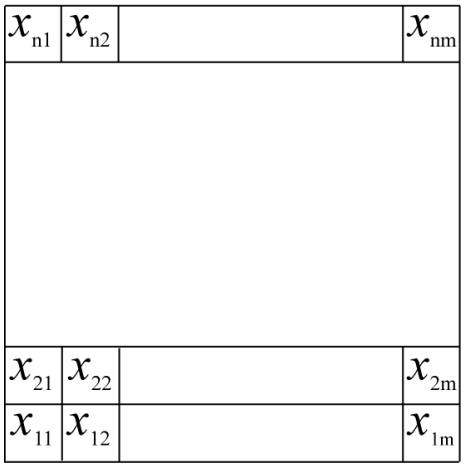
The final group of fields, which provide GRIB2-specific information, are found under the column headings below.

```
|GRIB2|GRIB2|GRIB2|GRIB2|
|Discp|Catgy|Param|Level|
+---------------------+
```

The GRIB2 fields are only needed in a Vtable that is to be used for GRIB Edition 2 data sets, although having these fields in a Vtable does not prevent that Vtable from also being used for GRIB Edition 1 data. For example, the Vtable.GFS file contains GRIB2 Vtable fields, but is used for both 1-degree (GRIB1) GFS and 0.5-degree (GRIB2) GFS data sets. Since Vtables are provided for most known GRIB Edition 2 data sets, the corresponding Vtable fields are not described here at present.

Writing Static Data to the Geogrid Binary Format

The static geographical data sets that are interpolated by the geogrid program are stored as regular 2-d and 3-d arrays written in a simple binary raster format. Users with a new source for a given static field can ingest their data with WPS by writing the data set into this binary format. The geogrid format is capable of supporting single-level and multi-level continuous fields, categorical fields represented as dominant categories, and categorical fields given as fractional fields for each category. The most simple of these field types in terms of representation in the binary format is a categorical field given as a dominant category at each source grid point, an example of which is the 30-second USGS land use data set.



For a categorical field given as dominant categories, the data must first be stored in a regular 2-d array of integers, with each integer giving the dominant category at the corresponding source grid point. Given this array, the data are written to a file, row-by-row, beginning at the bottom, or southern-most, row. For example, in the figure above, the elements of the $n \times m$ array would be written in the order x_{11}, x_{12}, ..., x_{1m}, x_{21}, ..., x_{2m}, ..., x_{n1}, ..., x_{nm}. When written to the file, every element is stored as a 1-, 2-, 3-, or 4-byte integer in big-endian byte order (i.e., for the 4-byte integer *ABCD*, byte *A* is stored at the lowest address and byte *D* at the highest), although little-endian files may be used by setting `endian=little` in the "index" file for the data set. Every element in a file must use the same number of bytes for its storage, and, of course, it is advantageous to use the fewest number of bytes needed to represent the complete range of values in the array.

When writing the binary data to a file, no header, record marker, or additional bytes should be written. For example, a 2-byte 1000×1000 array should result in a file whose size is exactly 2,000,000 bytes. Since Fortran unformatted writes add record markers, *it is not possible to write a geogrid binary-formatted file directly from Fortran*; instead, it is recommended that the C routines in read_geogrid.c and write_geogrid.c (in the geogrid/src directory) be called when writing data, either from C or Fortran code.

Similar in format to a field of dominant categories is the case of a field of continuous, or real, values. Like dominant-category fields, single-level continuous fields are first organized as a regular 2-d array, then written, row-by-row, to a binary file. However, because a continuous field may contain non-integral or negative values, the storage representation of each element within the file is slightly more complex. All elements in the array must first be converted to integral values. This is done by first scaling all elements by a constant, chosen to maintain the required precision, and then removing any remaining fractional part through rounding. For example, if three decimal places of precision are required, the value -2.71828 would need to be divided by 0.001 and rounded to -2718. Following conversion of all array elements to integral values, if any negative values are found in the array, a second conversion must be applied: if elements are stored using 1 byte each, then 2^8 is added to each negative element; for storage using 2 bytes, 2^{16} is added to each negative element; for storage using 3 bytes, 2^{24} is added to

each negative element; and for storage using 4 bytes, a value of 2^{32} is added to each negative element. It is important to note that no conversion is applied to positive elements. Finally, the resulting positive, integral array is written as in the case of a dominant-category field.

Multi-level continuous fields are handled much the same as single-level continuous fields. For an $n \times m \times r$ array, conversion to a positive, integral field is first performed as described above. Then, each $n \times m$ sub-array is written contiguously to the binary file as before, beginning with the smallest r-index. Categorical fields that are given as fractional fields for each possible category can be thought of as multi-level continuous fields, where each level k, $1 \leq k \leq r$, is the fractional field for category k.

When writing a field to a file in the geogrid binary format, the user should adhere to the naming convention used by the geogrid program, which expects data files to have names of the form *xstart-xend.ystart-yend*, where *xstart*, *xend*, *ystart*, and *yend* are five-digit positive integers specifying, respectively, the starting x-index of the array contained in the file, the ending x-index of the array, the starting y-index of the array, and the ending y-index of the array; here, indexing begins at 1, rather than 0. So, for example, an 800×1200 array (i.e., 800 rows and 1200 columns) might be named 00001-01200.00001-00800.

When a data set is given in several pieces, each of the pieces may be formed as a regular rectangular array, and each array may be written to a separate file. In this case, the relative locations of the arrays are determined by the range of x- and y-indices in the file names for each of the arrays. It is important to note, however, that *every tile in a data set must have the same* x- *and* y-*dimensions*, and that tiles of data within a data set must not overlap; furthermore, all tiles must start and end on multiples of the index ranges. For example, the global 30-second USGS topography data set is divided into arrays of dimension 1200×1200, with each array containing a 10-degree $\times$ 10-degree piece of the data set; the file whose south-west corner is located at (90S, 180W) is named 00001-01200.00001-01200, and the file whose north-east corner is located at (90N, 180E) is named 42001-43200.20401-21600.

If a data set is to be split into multiple tiles, and the number of grid points in, say, the x-direction is not evenly divided by the number of tiles in the x-direction, then the last column of tiles must be padded with a flag value (specified in the index file using the `missing_value` keyword) so that all tiles have the same dimensions. For example, if a data set has 2456 points in the x-direction, and three tiles in the x-direction will be used, the range of x-coordinates of the tiles might be 1 – 820, 821 – 1640, and 1641 – 2460, with columns 2457 through 2460 being filled with a flag value.

Clearly, since the starting and ending indices must have five digits, a field cannot have more than 99999 data points in either of the x- or y-directions. In case a field has more than 99999 data points in either dimension, the user can simply split the data set into several smaller data sets which will be identified separately to geogrid. For example, a

very large global data set may be split into data sets for the Eastern and Western hemispheres.

Besides the binary data files, geogrid requires one extra metadata file per data set. This metadata file is always named 'index', and thus, two data sets cannot reside in the same directory. Essentially, this metadata file is the first file that geogrid looks for when processing a data set, and the contents of the file provide geogrid with all of the information necessary for constructing names of possible data files. The contents of an example index file are given below.

```
type = continuous
signed = yes
projection = regular_ll
dx = 0.00833333
dy = 0.00833333
known_x = 1.0
known_y = 1.0
known_lat = -89.99583
known_lon = -179.99583
wordsize = 2
tile_x = 1200
tile_y = 1200
tile_z = 1
tile_bdr=3
units="meters MSL"
description="Topography height"
```

For a complete listing of keywords that may appear in an index file, along with the meaning of each keyword, the user is referred to the section on index file options.

Creating an Urban Fraction Field from NLCD Data

In order to create a more inhomogeneous and detailed urban fraction field for use with NUDAPT, users may obtain high-resolution land cover information from the National Land Cover Database (NLCD) through the Multi-Resolution Land Characteristics Consortium. Generation of the urban fraction field, called FRC_URB2D in WRF, involves first downloading the NLCD data over the region covered by the WRF domain, converting the data into the binary format used by geogrid, and finally extracting only the urban categories to a new urban fraction field. The following steps can serve as a guide through this process.

1. Download NLCD data from http://gisdata.usgs.net/website/MRLC/viewer.php. Either of the 1992, 2001, or 2006 datasets may be used. After selecting an area to download, make sure to select GeoTIFF format in the "Request Summary Page" by clicking on "Modify Data Request". If available, data may instead be

downloaded in BIL format, in which case the format conversion described in the next step can be skipped.

2. After downloading the data, unpacking the archive should yield a directory with a .tif file and a .tfw file, among others. In order for the information in the GeoTIFF file to be useful, the .tif image must be converted into the binary format used by the WPS. This conversion can be accomplished using the GDAL translation tool, gdal_translate, (http://gdal.org) by running the command

```
> gdal_translate -of ENVI foo.tif data.bil
```

   where foo.tif is the name of the GeoTIFF image that was downloaded in Step 1. The output format "ENVI" is a simple binary raster format that matches the format used by geogrid. After converting the GeoTIFF to a binary file, the resulting data.bil file must be renamed to 00001-ncols.00001-nrows, where ncols is the number of columns (in i5.5 format) and nrows is the number of rows (also in i5.5 format) in the image; *these values should have been printed to the screen when the gdal_translate program was run.*

3. Use the converter program available from http://www2.mmm.ucar.edu/people/duda/uf/ to extract the urban categories from the binary tile and write a new tile of data containing urban fraction. The output file of this converter should be copied over the original land use tile, i.e., the urban fraction file should be renamed to 00001-ncols.00001-nrows, where ncols is the number of columns (in i5.5 format) and nrows is the number of rows (also in i5.5 format) in the tile, as in Step 2.

4. Create an index metadata file for the urban fraction data. In the directory created by unpacking the land use data, a .tfw file should also exist. The last two lines in this file give the location of the north-west corner of the data tile, which is used in the index file for variables known_lat and known_lon. If this location is given as (x,y) coordinates, in meters, then the coordinate converter utility available from http://www2.mmm.ucar.edu/people/duda/uf/ may be used to convert to (latitude, longitude), which is required by the index file. The basic index file should contain the following elements:

```
type=continuous
projection=albers_nad83
dx=30.0
dy=30.0
known_x=1.0
known_y=2351.0             # <- edit
known_lat =   40.096571    # <- edit
known_lon = -105.405615    # <- edit
truelat1=29.5
truelat2=45.5
stdlon=-96.0
wordsize=1
scale_factor=0.01
```

```
row_order=top_bottom
tile_x=2407               # <- edit
tile_y=2351               # <- edit
tile_z=1
units="unitless"
description="urban fraction"
```

5. Add the following entry to the GEOGRID.TBL file before re-running the geogrid.exe program:

```
==============================
name=FRC_URB2D
        priority=1
        dest_type=continuous
        fill_missing = 0.
        interp_option=default: average_gcell(1.0)+four_pt
        abs_path=default:/path/to/dataset/
==============================
```

   The path to the dataset and index files created in Step 3 and Step 4, respectively, should be substituted for '/path/to/dataset/' in the entry above.

Description of the Namelist Variables

A. SHARE section

This section describes variables that are used by more than one WPS program. For example, the `wrf_core` variable specifies whether the WPS is to produce data for the ARW or the NMM core – information which is needed by both the geogrid and metgrid programs.

1. WRF_CORE : A character string set to either `'ARW'` or `'NMM'` that tells the WPS which dynamical core the input data are being prepared for. Default value is `'ARW'`.

2. MAX_DOM : An integer specifying the total number of domains/nests, including the parent domain, in the simulation. Default value is 1.

3. START_YEAR : A list of MAX_DOM 4-digit integers specifying the starting UTC year of the simulation for each nest. No default value.

4. START_MONTH : A list of MAX_DOM 2-digit integers specifying the starting UTC month of the simulation for each nest. No default value.

5. START_DAY : A list of MAX_DOM 2-digit integers specifying the starting UTC day of the simulation for each nest. No default value.

6. START_HOUR : A list of MAX_DOM 2-digit integers specifying the starting UTC hour of the simulation for each nest. No default value.

7. END_YEAR : A list of MAX_DOM 4-digit integers specifying the ending UTC year of the simulation for each nest. No default value.

8. END_MONTH : A list of MAX_DOM 2-digit integers specifying the ending UTC month of the simulation for each nest. No default value.

9. END_DAY : A list of MAX_DOM 2-digit integers specifying the ending UTC day of the simulation for each nest. No default value.

10. END_HOUR : A list of MAX_DOM 2-digit integers specifying the ending UTC hour of the simulation for each nest. No default value.

11. START_DATE : A list of MAX_DOM character strings of the form `'YYYY-MM-DD_HH:mm:ss'` specifying the starting UTC date of the simulation for each nest. The `start_date` variable is an alternate to specifying `start_year`, `start_month`, `start_day`, and `start_hour`, and if both methods are used for specifying the starting time, the `start_date` variable will take precedence. No default value.

12. END_DATE : A list of MAX_DOM character strings of the form `'YYYY-MM-DD_HH:mm:ss'` specifying the ending UTC date of the simulation for each nest. The `end_date` variable is an alternate to specifying `end_year`, `end_month`, `end_day`, and `end_hour`, and if both methods are used for specifying the ending time, the `end_date` variable will take precedence. No default value.

13. INTERVAL_SECONDS : The integer number of seconds between time-varying meteorological input files. No default value.

14. ACTIVE_GRID : A list of MAX_DOM logical values specifying, for each grid, whether that grid should be processed by geogrid and metgrid. Default value is `.TRUE.`.

15. IO_FORM_GEOGRID : The WRF I/O API format that the domain files created by the geogrid program will be written in. Possible options are: 1 for binary; 2 for NetCDF; 3 for GRIB1. When option 1 is given, domain files will have a suffix of .int; when option 2 is given, domain files will have a suffix of .nc; when option 3 is given, domain files will have a suffix of .gr1. Default value is 2 (NetCDF).

16. OPT_OUTPUT_FROM_GEOGRID_PATH : A character string giving the path, either relative or absolute, to the location where output files from geogrid should be written to and read from. Default value is `'./'`.

17. DEBUG_LEVEL : An integer value indicating the extent to which different types of messages should be sent to standard output. When `debug_level` is set to 0, only generally useful messages and warning messages will be written to standard output. When `debug_level` is greater than 100, informational messages that provide further runtime details are also written to standard output. Debugging messages and messages

specifically intended for log files are never written to standard output, but are always written to the log files. Default value is 0.

B. GEOGRID section

This section specifies variables that are specific to the geogrid program. Variables in the geogrid section primarily define the size and location of all model domains, and where the static geographical data are found.

1. PARENT_ID : A list of MAX_DOM integers specifying, for each nest, the domain number of the nest's parent; for the coarsest domain, this variable should be set to 1. Default value is 1.

2. PARENT_GRID_RATIO : A list of MAX_DOM integers specifying, for each nest, the nesting ratio relative to the domain's parent. No default value.

3. I_PARENT_START : A list of MAX_DOM integers specifying, for each nest, the x-coordinate of the lower-left corner of the nest in the parent *unstaggered* grid. For the coarsest domain, a value of 1 should be specified. No default value.

4. J_PARENT_START : A list of MAX_DOM integers specifying, for each nest, the y-coordinate of the lower-left corner of the nest in the parent *unstaggered* grid. For the coarsest domain, a value of 1 should be specified. No default value.

5. S_WE : A list of MAX_DOM integers which should all be set to 1. Default value is 1.

6. E_WE : A list of MAX_DOM integers specifying, for each nest, the nest's full west-east dimension. For nested domains, `e_we` must be one greater than an integer multiple of the nest's `parent_grid_ratio` (i.e., `e_we` = *n**`parent_grid_ratio`+1 for some positive integer *n*). No default value.

7. S_SN : A list of MAX_DOM integers which should all be set to 1. Default value is 1.

8. E_SN : A list of MAX_DOM integers specifying, for each nest, the nest's full south-north dimension. For nested domains, `e_sn` must be one greater than an integer multiple of the nest's `parent_grid_ratio` (i.e., `e_sn` = *n**`parent_grid_ratio`+1 for some positive integer *n*). No default value.

9. GEOG_DATA_RES : A list of MAX_DOM character strings specifying, for each nest, a corresponding resolution or list of resolutions separated by + symbols of source data to be used when interpolating static terrestrial data to the nest's grid. For each nest, this string should contain a resolution matching a string preceding a colon in a `rel_path` or `abs_path` specification (see the description of GEOGRID.TBL options) in the GEOGRID.TBL file for each field. If a resolution in the string does not match any such

string in a rel_path or abs_path specification for a field in GEOGRID.TBL, a default resolution of data for that field, if one is specified, will be used. If multiple resolutions match, the first resolution to match a string in a rel_path or abs_path specification in the GEOGRID.TBL file will be used. Default value is 'default'.

10. DX : A real value specifying the grid distance in the x-direction where the map scale factor is 1. For ARW, the grid distance is in meters for the 'polar', 'lambert', and 'mercator' projection, and in degrees longitude for the 'lat-lon' projection; for NMM, the grid distance is in degrees longitude. Grid distances for nests are determined recursively based on values specified for parent_grid_ratio and parent_id. No default value.

11. DY : A real value specifying the nominal grid distance in the y-direction where the map scale factor is 1. For ARW, the grid distance is in meters for the 'polar', 'lambert', and 'mercator' projection, and in degrees latitude for the 'lat-lon' projection; for NMM, the grid distance is in degrees latitude. Grid distances for nests are determined recursively based on values specified for parent_grid_ratio and parent_id. No default value.

12. MAP_PROJ : A character string specifying the projection of the simulation domain. For ARW, accepted projections are 'lambert', 'polar', 'mercator', and 'lat-lon'; for NMM, a projection of 'rotated_ll' must be specified. Default value is 'lambert'.

13. REF_LAT : A real value specifying the latitude part of a (latitude, longitude) location whose (i,j) location in the simulation domain is known. For ARW, ref_lat gives the latitude of the center-point of the coarse domain by default (i.e., when ref_x and ref_y are not specified). For NMM, ref_lat always gives the latitude to which the origin is rotated. No default value.

14. REF_LON : A real value specifying the longitude part of a (latitude, longitude) location whose (i, j) location in the simulation domain is known. For ARW, ref_lon gives the longitude of the center-point of the coarse domain by default (i.e., when ref_x and ref_y are not specified). For NMM, ref_lon always gives the longitude to which the origin is rotated. For both ARW and NMM, west longitudes are negative, and the value of ref_lon should be in the range [-180, 180]. No default value.

15. REF_X : A real value specifying the i part of an (i, j) location whose (latitude, longitude) location in the simulation domain is known. The (i, j) location is always given with respect to the mass-staggered grid, whose dimensions are one less than the dimensions of the unstaggered grid. Default value is (((E_WE-1.)+1.)/2.) = (E_WE/2.).

16. REF_Y : A real value specifying the j part of an (i, j) location whose (latitude, longitude) location in the simulation domain is known. The (i, j) location is always given with respect to the mass-staggered grid, whose dimensions are one less than the dimensions of the unstaggered grid. Default value is (((E_SN-1.)+1.)/2.) = (E_SN/2.).

17. TRUELAT1 : A real value specifying, for ARW, the first true latitude for the Lambert conformal projection, or the only true latitude for the Mercator and polar stereographic projections. For NMM, `truelat1` is ignored. No default value.

18. TRUELAT2 : A real value specifying, for ARW, the second true latitude for the Lambert conformal conic projection. For all other projections, `truelat2` is ignored. No default value.

19. STAND_LON : A real value specifying, for ARW, the longitude that is parallel with the y-axis in the Lambert conformal and polar stereographic projections. For the regular latitude-longitude projection, this value gives the rotation about the earth's geographic poles. For NMM, `stand_lon` is ignored. No default value.

20. POLE_LAT : For the latitude-longitude projection for ARW, the latitude of the North Pole with respect to the computational latitude-longitude grid in which -90.0° latitude is at the bottom of a global domain, 90.0° latitude is at the top, and 180.0° longitude is at the center. Default value is 90.0.

21. POLE_LON : For the latitude-longitude projection for ARW, the longitude of the North Pole with respect to the computational lat/lon grid in which -90.0° latitude is at the bottom of a global domain, 90.0° latitude is at the top, and 180.0° longitude is at the center. Default value is 0.0.

22. GEOG_DATA_PATH : A character string giving the path, either relative or absolute, to the directory where the geographical data directories may be found. This path is the one to which `rel_path` specifications in the GEOGRID.TBL file are given in relation to. No default value.

23. OPT_GEOGRID_TBL_PATH : A character string giving the path, either relative or absolute, to the GEOGRID.TBL file. The path should not contain the actual file name, as GEOGRID.TBL is assumed, but should only give the path where this file is located. Default value is `'./geogrid/'`.

C. UNGRIB section

Currently, this section contains only two variables, which determine the output format written by ungrib and the name of the output files.

1. OUT_FORMAT : A character string set either to `'WPS'`, `'SI'`, or `'MM5'`. If set to `'MM5'`, ungrib will write output in the format of the MM5 pregrid program; if set to `'SI'`, ungrib will write output in the format of grib_prep.exe; if set to `'WPS'`, ungrib will write data in the WPS intermediate format. Default value is `'WPS'`.

2. PREFIX : A character string that will be used as the prefix for intermediate-format files created by ungrib; here, prefix refers to the string *PREFIX* in the filename

PREFIX:*YYYY-MM-DD_HH* of an intermediate file. The prefix may contain path information, either relative or absolute, in which case the intermediate files will be written in the directory specified. This option may be useful to avoid renaming intermediate files if ungrib is to be run on multiple sources of GRIB data. Default value is `'FILE'`.

2. ADD_LVLS : A logical that determines whether ungrib will attemp to vertically interpolate to an additional set of vertical levels specified using the `NEW_PLVL` and `INTERP_TYPE` namelist options. Default value is `.FALSE.`.

2. INTERP_TYPE : An integer value specifying the method that ungrib will use when vertically interpolating to new levels. A value of `0` causes ungrib to interpolate linearly in pressure, and a value of `1` causes ungrib to interpolate linearly in log pressure. Default value is `0`.

2. NEW_PLVL : An array of real values that specify the additional vertical levels, given in Pa, to which the ungrib program will attempt to interpolate when `ADD_LVLS` is true. The set of new levels can be specified explicitly, or, if the levels are evenly spaced in pressure, exactly three values can be specified: the starting pressure, the ending pressure, and the pressure increment. When a starting pressure, ending pressure, and increment are specified, the pressure increment must be a negative number to signal to the ungrib program that this value is not a target pressure level, but rather, an increment to be used between the first and second values. No default value.

D. METGRID section

This section defines variables used only by the metgrid program. Typically, the user will be interested in the `fg_name` variable, and may need to modify other variables of this section less frequently.

1. FG_NAME : A list of character strings specifying the path and prefix of ungribbed data files. The path may be relative or absolute, and the prefix should contain all characters of the filenames up to, but not including, the colon preceding the date. When more than one `fg_name` is specified, and the same field is found in two or more input sources, the data in the last encountered source will take priority over all preceding sources for that field. Default value is an empty list (i.e., no meteorological fields).

2. CONSTANTS_NAME : A list of character strings specifying the path and full filename of ungribbed data files which are time-invariant. The path may be relative or absolute, and the filename should be the complete filename; since the data are assumed to be time-invariant, no date will be appended to the specified filename. Default value is an empty list (i.e., no constant fields).

3. IO_FORM_METGRID : The WRF I/O API format that the output created by the metgrid program will be written in. Possible options are: 1 for binary; 2 for NetCDF; 3

for GRIB1. When option 1 is given, output files will have a suffix of .int; when option 2 is given, output files will have a suffix of .nc; when option 3 is given, output files will have a suffix of .gr1. Default value is 2 (NetCDF).

4. OPT_OUTPUT_FROM_METGRID_PATH : A character string giving the path, either relative or absolute, to the location where output files from metgrid should be written to. The default value is the current working directory (i.e., the default value is `'./'`).

5. OPT_METGRID_TBL_PATH : A character string giving the path, either relative or absolute, to the METGRID.TBL file; the path should not contain the actual file name, as METGRID.TBL is assumed, but should only give the path where this file is located. Default value is `'./metgrid/'`.

5. PROCESS_ONLY_BDY: An integer specifying the number of boundary rows and columns to be processed by metgrid for time periods after the initial time; for the initial time, metgrid will always interpolate to every grid point. Setting this option to the intended value of spec_bdy_width in the WRF namelist.input will speed up processing in metgrid, but it should not be set if interpolated data are needed in the domain interior. If this option is set to zero, metgrid will horizontally interpolate meteorological data to every grid point in the model domains. *This option is only available for ARW.* Default value is 0.

Description of GEOGRID.TBL Options

The GEOGRID.TBL file is a text file that defines parameters of each of the data sets to be interpolated by geogrid. Each data set is defined in a separate section, with sections being delimited by a line of equality symbols (e.g., '==========='). Within each section, there are specifications, each of which has the form of *keyword=value*. Some keywords are required in each data set section, while others are optional; some keywords are mutually exclusive with other keywords. Below, the possible keywords and their expected range of values are described.

1. NAME : A character string specifying the name that will be assigned to the interpolated field upon output. No default value.

2. PRIORITY : An integer specifying the priority that the data source identified in the table section takes with respect to other sources of data for the same field. If a field has *n* sources of data, then there must be *n* separate table entries for the field, each of which must be given a unique value for `priority` in the range [1, *n*]. No default value.

3. DEST_TYPE : A character string, either `categorical` or `continuous`, that tells whether the interpolated field from the data source given in the table section is to be treated as a continuous or a categorical field. No default value.

4. INTERP_OPTION : A sequence of one or more character strings, which are the names of interpolation methods to be used when horizontally interpolating the field. Available

interpolation methods are: `average_4pt`, `average_16pt`, `wt_average_4pt`, `wt_average_16pt`, `nearest_neighbor`, `four_pt`, `sixteen_pt`, `search(`*r*`)`, and `average_gcell(`*r*`)`. For the search method (`search`), the optional argument *r* specifies the maximum search radius in units of grid points in the grid of the source data; the default search radius is 1200 points. For the grid cell average method (`average_gcell`), the optional argument *r* specifies the minimum ratio of source data resolution to simulation grid resolution at which the method will be applied; unless specified, *r* = 0.0, and the option is used for any ratio. When a sequence of two or more methods are given, the methods should be separated by a + sign. No default value.

5. SMOOTH_OPTION : A character string giving the name of a smoothing method to be applied to the field after interpolation. Available smoothing options are: `1-2-1`, `smth-desmth`, and `smth-desmth_special` (ARW only). Default value is null (i.e., no smoothing is applied).

6. SMOOTH_PASSES : If smoothing is to be performed on the interpolated field, `smooth_passes` specifies an integer number of passes of the smoothing method to apply to the field. Default value is 1.

7. REL_PATH : A character string specifying the path relative to the path given in the namelist variable `geog_data_path`. A specification is of the general form *RES_STRING*:*REL_PATH*, where *RES_STRING* is a character string identifying the source or resolution of the data in some unique way and may be specified in the namelist variable `geog_data_res`, and *REL_PATH* is a path relative to `geog_data_path` where the index and data tiles for the data source are found. More than one `rel_path` specification may be given in a table section if there are multiple sources or resolutions for the data source, just as multiple resolutions may be specified (in a sequence delimited by + symbols) for `geog_data_res`. See also `abs_path`. No default value.

8. ABS_PATH : A character string specifying the absolute path to the index and data tiles for the data source. A specification is of the general form *RES_STRING*:*ABS_PATH*, where *RES_STRING* is a character string identifying the source or resolution of the data in some unique way and may be specified in the namelist variable `geog_data_res`, and *ABS_PATH* is the absolute path to the data source's files. More than one `abs_path` specification may be given in a table section if there are multiple sources or resolutions for the data source, just as multiple resolutions may be specified (in a sequence delimited by + symbols) for `geog_data_res`. See also `rel_path`. No default value.

9. OUTPUT_STAGGER : A character string specifying the grid staggering to which the field is to be interpolated. For ARW domains, possible values are `U`, `V`, and `M`; for NMM domains, possible values are `HH` and VV. Default value for ARW is `M`; default value for NMM is `HH`.

10. LANDMASK_WATER : One or more comma-separated integer values giving the indices of the categories within the field that represents water. When `landmask_water` is specified in the table section of a field for which `dest_type=categorical`, the

LANDMASK field will be computed from the field using the specified categories as the water categories. The keywords `landmask_water` and `landmask_land` are mutually exclusive. Default value is null (i.e., a landmask will not be computed from the field).

11. LANDMASK_LAND : One or more comma-separated integer values giving the indices of the categories within the field that represents land. When `landmask_water` is specified in the table section of a field for which `dest_type=categorical`, the LANDMASK field will be computed from the field using the specified categories as the land categories. The keywords `landmask_water` and `landmask_land` are mutually exclusive. Default value is null (i.e., a landmask will not be computed from the field).

12. MASKED : Either `land` or `water`, indicating that the field is not valid at land or water points, respectively. If the `masked` keyword is used for a field, those grid points that are of the masked type (land or water) will be assigned the value specified by `fill_missing`. Default value is null (i.e., the field is not masked).

13. FILL_MISSING : A real value used to fill in any missing or masked grid points in the interpolated field. Default value is 1.E20.

14. HALT_ON_MISSING : Either `yes` or `no`, indicating whether geogrid should halt with a fatal message when a missing value is encountered in the interpolated field. Default value is `no`.

15. DOMINANT_CATEGORY : When specified as a character string, the effect is to cause geogrid to compute the dominant category from the fractional categorical field, and to output the dominant category field with the name specified by the value of `dominant_category`. This option can only be used for fields with `dest_type=categorical`. Default value is null (i.e., no dominant category will be computed from the fractional categorical field).

16. DOMINANT_ONLY : When specified as a character string, the effect is similar to that of the `dominant_category` keyword: geogrid will compute the dominant category from the fractional categorical field and output the dominant category field with the name specified by the value of `dominant_only`. Unlike with `dominant_category`, though, when `dominant_only` is used, the fractional categorical field will not appear in the geogrid output. This option can only be used for fields with `dest_type=categorical`. Default value is null (i.e., no dominant category will be computed from the fractional categorical field).

17. DF_DX : When `df_dx` is assigned a character string value, the effect is to cause geogrid to compute the directional derivative of the field in the x-direction using a central difference along the interior of the domain, or a one-sided difference at the boundary of the domain; the derivative field will be named according to the character string assigned to the keyword `df_dx`. Default value is null (i.e., no derivative field is computed).

18. DF_DY : When `df_dy` is assigned a character string value, the effect is to cause geogrid to compute the directional derivative of the field in the y-direction using a central difference along the interior of the domain, or a one-sided difference at the boundary of the domain; the derivative field will be named according to the character string assigned to the keyword `df_dy`. Default value is null (i.e., no derivative field is computed).

19. Z_DIM_NAME : For 3-dimensional output fields, a character string giving the name of the vertical dimension, or z-dimension. A continuous field may have multiple levels, and thus be a 3-dimensional field, and a categorical field may take the form of a 3-dimensional field if it is written out as fractional fields for each category. No default value.

20. FLAG_IN_OUTPUT : A character string giving the name of a global attribute which will be assigned a value of 1 and written to the geogrid output. Default value is null (i.e., no flag will be written for the field).

21. OPTIONAL : Either `yes` or `no`, indicating whether the dataset identified by the resolution specified in the `geog_data_res` namelist option is optional. If an entry in the GEOGRID.TBL file is optional and if the specified resolution of data cannot be read, geogrid will print an informational message indicating that the dataset was not interpolated and continue; otherwise, if the entry is not optional and the specified resolution of data cannot be read, geogrid will halt with an error. It is possible for different priority level entries for the same field to specify different values of the `optional` keyword, e.g., the `priority=2` entry for a field can be optional, while the `priority=1` entry can be non-optional (i.e., `optional=no`). Default value is `no`.

Description of index Options

Related to the GEOGRID.TBL are the index files that are associated with each static data set. An index file defines parameters specific to that data set, while the GEOGRID.TBL file describes how each of the data sets should be treated by geogrid. As with the GEOGRID.TBL file, specifications in an index file are of the form *keyword=value*. Below are possible keywords and their possible values.

1. PROJECTION : A character string specifying the projection of the data, which may be either `lambert`, `polar`, `mercator`, `regular_ll`, `albers_nad83`, or `polar_wgs84`. No default value.

2. TYPE : A character string, either `categorical` or `continuous`, that determines whether the data in the data files should be interpreted as a continuous field or as discrete indices. For categorical data represented by a fractional field for each possible category, `type` should be set to `continuous`. No default value.

3. SIGNED : Either `yes` or `no`, indicating whether the values in the data files (which are always represented as integers) are signed in two's complement form or not. Default value is `no`.

4. UNITS : A character string, enclosed in quotation marks ("), specifying the units of the interpolated field; the string will be written to the geogrid output files as a variable time-independent attribute. No default value.

5. DESCRIPTION : A character string, enclosed in quotation marks ("), giving a short description of the interpolated field; the string will be written to the geogrid output files as a variable time-independent attribute. No default value.

6. DX : A real value giving the grid spacing in the x-direction of the data set. If `projection` is one of `lambert`, `polar`, `mercator`, `albers_nad83`, or `polar_wgs84`, `dx` gives the grid spacing in meters; if `projection` is `regular_ll`, `dx` gives the grid spacing in degrees. No default value.

7. DY : A real value giving the grid spacing in the y-direction of the data set. If `projection` is one of `lambert`, `polar`, `mercator`, `albers_nad83`, or `polar_wgs84`, `dy` gives the grid spacing in meters; if `projection` is `regular_ll`, `dy` gives the grid spacing in degrees. No default value.

8. KNOWN_X : A real value specifying the i-coordinate of an (i,j) location corresponding to a (latitude, longitude) location that is known in the projection. Default value is 1.

9. KNOWN_Y : A real value specifying the j-coordinate of an (i,j) location corresponding to a (latitude, longitude) location that is known in the projection. Default value is 1.

10. KNOWN_LAT : A real value specifying the latitude of a (latitude, longitude) location that is known in the projection. No default value.

11. KNOWN_LON : A real value specifying the longitude of a (latitude, longitude) location that is known in the projection. No default value.

12. STDLON : A real value specifying the longitude that is parallel with the y-axis in conic and azimuthal projections. No default value.

13. TRUELAT1 : A real value specifying the first true latitude for conic projections or the only true latitude for azimuthal projections. No default value.

14. TRUELAT2 : A real value specifying the second true latitude for conic projections. No default value.

15. WORDSIZE : An integer giving the number of bytes used to represent the value of each grid point in the data files. No default value.

16. TILE_X : An integer specifying the number of grid points in the x-direction, *excluding any halo points*, for a single tile of source data. No default value.

17. TILE_Y : An integer specifying the number of grid points in the y-direction, *excluding any halo points*, for a single tile of source data. No default value.

18. TILE_Z : An integer specifying the number of grid points in the z-direction for a single tile of source data; this keyword serves as an alternative to the pair of keywords `tile_z_start` and `tile_z_end`, and when this keyword is used, the starting z-index is assumed to be 1. No default value.

19. TILE_Z_START : An integer specifying the starting index in the z-direction of the array in the data files. If this keyword is used, `tile_z_end` must also be specified. No default value.

20. TILE_Z_END : An integer specifying the ending index in the z-direction of the array in the data files. If this keyword is used, `tile_z_start` must also be specified. No default value

21. CATEGORY_MIN : For categorical data (`type=categorical`), an integer specifying the minimum category index that is found in the data set. If this keyword is used, `category_max` must also be specified. No default value.

22. CATEGORY_MAX : For categorical data (`type=categorical`), an integer specifying the maximum category index that is found in the data set. If this keyword is used, `category_min` must also be specified. No default value.

23. TILE_BDR : An integer specifying the halo width, in grid points, for each tile of data. Default value is 0.

24. MISSING_VALUE : A real value that, when encountered in the data set, should be interpreted as missing data. No default value.

25. SCALE_FACTOR : A real value that data should be scaled by (through multiplication) after being read in as integers from tiles of the data set. Default value is 1.

26. ROW_ORDER : A character string, either `bottom_top` or `top_bottom`, specifying whether the rows of the data set arrays were written proceeding from the lowest-index row to the highest (`bottom_top`) or from highest to lowest (`top_bottom`). This keyword may be useful when utilizing some USGS data sets, which are provided in `top_bottom` order. Default value is `bottom_top`.

27. ENDIAN : A character string, either `big` or `little`, specifying whether the values in the static data set arrays are in big-endian or little-endian byte order. Default value is `big`.

28. ISWATER : An integer specifying the land use category of water. Default value is 16.

29. ISLAKE : An integer specifying the land use category of inland water bodies. Default value is -1 (i.e., no separate inland water category).

30. ISICE : An integer specifying the land use category of ice. Default value is 24.

31. ISURBAN : An integer specifying the land use category of urban areas. Default value is 1.

32. ISOILWATER : An integer specifying the soil category of water. Default value is 14.

33. MMINLU : A character string, enclosed in quotation marks ("), indicating which section of WRF's LANDUSE.TBL and VEGPARM.TBL will be used when looking up parameters for land use categories. Default value is `"USGS"`.

34. FILENAME_DIGITS : An integer specifying the number of digits used in the names of data tiles. Possible values are 5 or 6. Default value is 5.

Description of METGRID.TBL Options

The METGRID.TBL file is a text file that defines parameters of each of the meteorological fields to be interpolated by metgrid. Parameters for each field are defined in a separate section, with sections being delimited by a line of equality symbols (e.g., '==========='). Within each section, there are specifications, each of which has the form of *keyword=value*. Some keywords are required in a section, while others are optional; some keywords are mutually exclusive with other keywords. Below, the possible keywords and their expected range of values are described.

1. NAME : A character string giving the name of the meteorological field to which the containing section of the table pertains. The name should exactly match that of the field as given in the intermediate files (and, thus, the name given in the Vtable used in generating the intermediate files). This field is required. No default value.

2. OUTPUT : Either `yes` or `no`, indicating whether the field is to be written to the metgrid output files or not. Default value is `yes`.

3. MANDATORY : Either `yes` or `no`, indicating whether the field is required for successful completion of metgrid. Default value is `no`.

4. OUTPUT_NAME : A character string giving the name that the interpolated field should be output as. When a value is specified for `output_name`, the interpolation options from the table section pertaining to the field with the specified name are used. Thus, the effects of specifying `output_name` are two-fold: The interpolated field is assigned the specified name before being written out, and the interpolation methods are taken from the section pertaining to the field whose name matches the value assigned to the `output_name` keyword. No default value.

5. FROM_INPUT : A character string used to compare against the values in the `fg_name` namelist variable; if `from_input` is specified, the containing table section will only be used when the time-varying input source has a filename that contains the value of `from_input` as a substring. Thus, `from_input` may be used to specify different interpolation options for the same field, depending on which source of the field is being processed. No default value.

6. OUTPUT_STAGGER : The model grid staggering to which the field should be interpolated. For ARW, this must be one of `U`, `V`, and `M`; for NMM, this must be one of `HH` and `VV`. Default value for ARW is `M`; default value for NMM is `HH`.

7. IS_U_FIELD : Either `yes` or `no`, indicating whether the field is to be used as the wind U-component field. For ARW, the wind U-component field must be interpolated to the U staggering (`output_stagger=U`); for NMM, the wind U-component field must be interpolated to the V staggering (`output_stagger=VV`). Default value is `no`.

8. IS_V_FIELD : Either `yes` or `no`, indicating whether the field is to be used as the wind V-component field. For ARW, the wind V-component field must be interpolated to the V staggering (`output_stagger=V`); for NMM, the wind V-component field must be interpolated to the V staggering (`output_stagger=VV`). Default value is `no`.

9. INTERP_OPTION : A sequence of one or more character strings, which are the names of interpolation methods to be used when horizontally interpolating the field. Available interpolation methods are: `average_4pt`, `average_16pt`, `wt_average_4pt`, `wt_average_16pt`, `nearest_neighbor`, `four_pt`, `sixteen_pt`, `search(`*r*`)`, and `average_gcell(`*r*`)`. For the search method (`search`), the optional argument *r* specifies the maximum search radius in units of grid points in the grid of the source data; the default search radius is 1200 points. For the grid cell average method (`average_gcell`), the optional argument *r* specifies the minimum ratio of source data resolution to simulation grid resolution at which the method will be applied; unless specified, $r = 0.0$, and the option is used for any ratio. When a sequence of two or more methods are given, the methods should be separated by a + sign. Default value is `nearest_neighbor`.

10. INTERP_MASK : The name of the field to be used as an interpolation mask, along with the value within that field which signals masked points and an optional relational symbol, < or >. A specification takes the form *field*(?*maskval*), where *field* is the name of the field, *?* is an optional relational symbol (< or >), and *maskval* is a real value. Source data points will not be used in interpolation if the corresponding point in the *field* field is

equal, greater than, or less than, the value of *maskval* for no relational symbol, a > symbol, or a < symbol, respectively. Default value is no mask.

11. INTERP_LAND_MASK : The name of the field to be used as an interpolation mask when interpolating to water points (determined by the static LANDMASK field), along with the value within that field which signals land points and an optional relational symbol, < or >. A specification takes the form *field*(?*maskval*), where *field* is the name of the field, *?* is an optional relational symbol (< or >), and *maskval* is a real value. Default value is no mask.

12. INTERP_WATER_MASK : The name of the field to be used as an interpolation mask when interpolating to land points (determined by the static LANDMASK field), along with the value within that field which signals water points and an optional relational symbol, < or >. A specification takes the form *field*(?*maskval*), where *field* is the name of the field, *?* is an optional relational symbol (< or >), and *maskval* is a real value. Default value is no mask.

13. FILL_MISSING : A real number specifying the value to be assigned to model grid points that received no interpolated value, for example, because of missing or incomplete meteorological data. Default value is 1.E20.

14. Z_DIM_NAME : For 3-dimensional meteorological fields, a character string giving the name of the vertical dimension to be used for the field on output. Default value is `num_metgrid_levels`.

15. DERIVED : Either `yes` or `no`, indicating whether the field is to be derived from other interpolated fields, rather than interpolated from an input field. Default value is `no`.

16. FILL_LEV : The `fill_lev` keyword, which may be specified multiple times within a table section, specifies how a level of the field should be filled if that level does not already exist. A generic value for the keyword takes the form *DLEVEL*:*FIELD*(*SLEVEL*), where *DLEVEL* specifies the level in the field to be filled, *FIELD* specifies the source field from which to copy levels, and *SLEVEL* specifies the level within the source field to use. *DLEVEL* may either be an integer or the string `all`. *FIELD* may either be the name of another field, the string `const`, or the string `vertical_index`. If *FIELD* is specified as `const`, then *SLEVEL* is a constant value that will be used to fill with; if *FIELD* is specified as `vertical_index`, then (*SLEVEL*) must not be specified, and the value of the vertical index of the source field is used; if *DLEVEL* is 'all', then all levels from the field specified by the `level_template` keyword are used to fill the corresponding levels in the field, one at a time. No default value.

17. LEVEL_TEMPLATE : A character string giving the name of a field from which a list of vertical levels should be obtained and used as a template. This keyword is used in conjunction with a `fill_lev` specification that uses `all` in the *DLEVEL* part of its specification. No default value.

18. MASKED : Either `land`, `water`, or `both`. Setting `MASKED` to `land` or `water` indicates that the field should not be interpolated to WRF land or water points, respectively; however, setting `MASKED` to `both` indicates that the field should be interpolated to WRF land points using only land points in the source data and to WRF water points using only water points in the source data. When a field is masked, or invalid, the static LANDMASK field will be used to determine which model grid points the field should be interpolated to; invalid points will be assigned the value given by the `FILL_MISSING` keyword. Whether a source data point is land or water is determined by the masks specified using the `INTERP_LAND_MASK` and `INTERP_WATER_MASK` options. Default value is null (i.e., the field is valid for both land and water points).

19. MISSING_VALUE : A real number giving the value in the input field that is assumed to represent missing data. No default value.

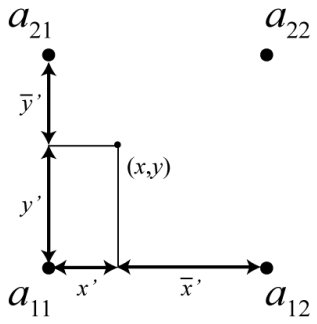
20. VERTICAL_INTERP_OPTION : A character string specifying the vertical interpolation method that should be used when vertically interpolating to missing points. Currently, this option is not implemented. No default value.

21. FLAG_IN_OUTPUT : A character string giving the name of a global attribute which will be assigned a value of 1 and written to the metgrid output if the interpolated field is to be output (output=yes). Default value is null (i.e., no flag will be written for the field).

Available Interpolation Options in Geogrid and Metgrid

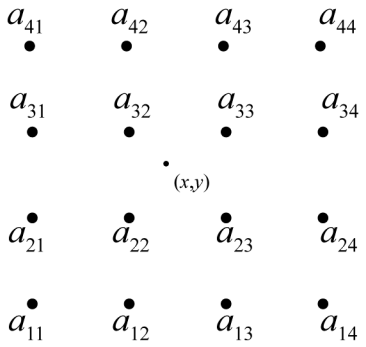
Through the GEOGRID.TBL and METGRID.TBL files, the user can control the method by which source data – either static fields in the case of geogrid or meteorological fields in the case of metgrid – are interpolated. In fact, a list of interpolation methods may be given, in which case, if it is not possible to employ the *i*-th method in the list, the (*i*+1)-st method will be employed, until either some method can be used or there are no methods left to try in the list. For example, to use a four-point bi-linear interpolation scheme for a field, we could specify `interp_option=four_pt`. However, if the field had areas of missing values, which could prevent the `four_pt` option from being used, we could request that a simple four-point average be tried if the `four_pt` method couldn't be used by specifying `interp_option=four_pt+average_4pt` instead. Below, each of the available interpolation options in the WPS are described conceptually; for the details of each method, the user is referred to the source code in the file WPS/geogrid/src/interp_options.F.

1. four_pt : Four-point bi-linear interpolation



The four-point bi-linear interpolation method requires four valid source points a_{ij}, $1 \le i, j \le 2$, surrounding the point (x,y), to which geogrid or metgrid must interpolate, as illustrated in the figure above. Intuitively, the method works by linearly interpolating to the x-coordinate of the point (x,y) between a_{11} and a_{12}, and between a_{21} and a_{22}, and then linearly interpolating to the y-coordinate using these two interpolated values.

2. sixteen_pt : Sixteen-point overlapping parabolic interpolation



The sixteen_pt overlapping parabolic interpolation method requires sixteen valid source points surrounding the point (x,y), as illustrated in the figure above. The method works by fitting one parabola to the points a_{i1}, a_{i2}, and a_{i3}, and another parabola to the points a_{i2}, a_{i3}, and a_{i4}, for row i, $1 \le i \le 4$; then, an intermediate interpolated value p_i within row i at the x-coordinate of the point is computed by taking an average of the values of the two parabolas evaluated at x, with the average being weighted linearly by the distance of x from a_{i2} and a_{i3}. Finally, the interpolated value at (x,y) is found by performing the same operations as for a row of points, but for the column of interpolated values p_i to the y-coordinate of (x,y).

3. average_4pt : Simple four-point average interpolation

The four-point average interpolation method requires at least one valid source data point from the four source points surrounding the point (x,y). The interpolated value is simply the average value of all valid values among these four points.

4. wt_average_4pt : Weighted four-point average interpolation

The weighted four-point average interpolation method can handle missing or masked source data points, and the interpolated value is given as the weighted average of all valid values, with the weight w_{ij} for the source point a_{ij}, $1 \le i, j \le 2$, given by

$$w_{ij} = \max\{0, 1 - \sqrt{(x - x_i)^2 + (y - y_j)^2}\}.$$

Here, x_i is the x-coordinate of a_{ij} and y_j is the y-coordinate of a_{ij}.

5. average_16pt : Simple sixteen-point average interpolation

The sixteen-point average interpolation method works in an identical way to the four-point average, but considers the sixteen points surrounding the point (x,y).

6. wt_average_16pt : Weighted sixteen-point average interpolation

The weighted sixteen-point average interpolation method works like the weighted four-point average, but considers the sixteen points surrounding (x,y); the weights in this method are given by

$$w_{ij} = \max\{0, 2 - \sqrt{(x - x_i)^2 + (y - y_j)^2}\},$$

where x_i and y_j are as defined for the weighted four-point method, and $1 \le i, j \le 4$.

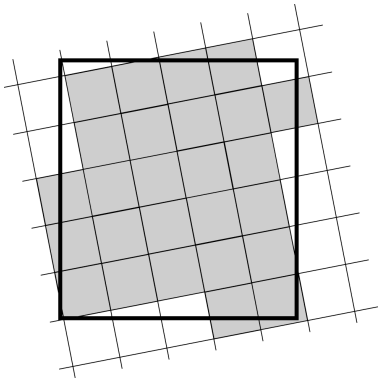
7. nearest_neighbor : Nearest neighbor interpolation

When used for continuous datasets (i.e., datasets that have `type=continuous` in their index files), the nearest neighbor interpolation method simply sets the interpolated value at (x,y) to the value of the nearest source data point, regardless of whether this nearest source point is valid, missing, or masked. For categorical datasets (i.e., datasets that have `type=categorical` in their index files), this option actually causes the geogrid program to consider all source pixels that lie within each WRF grid cell, and to find the fraction of the WRF grid cell that is comprised of each category in the source data.

8. search : Breadth-first search interpolation

The breadth-first search option works by treating the source data array as a 2-d grid graph, where each source data point, whether valid or not, is represented by a vertex. Then, the value assigned to the point (x,y) is found by beginning a breadth-first search at the vertex corresponding to the nearest neighbor of (x,y), and stopping once a vertex representing a valid (i.e., not masked or missing) source data point is found. In effect, this method can be thought of as "nearest *valid* neighbor".

9. average_gcell : Model grid-cell average



The grid-cell average interpolator may be used when the resolution of the source data is higher than the resolution of the model grid. For a model grid cell Γ, the method takes a simple average of the values of all source data points that are nearer to the center of Γ than to the center of any other grid cell. The operation of the grid-cell average method is illustrated in the figure above, where the interpolated value for the model grid cell – represented as the large rectangle – is given by the simple average of the values of all of the shaded source grid cells.

Land Use and Soil Categories in the Static Data

The default land use and soil category data sets that are provided as part of the WPS static data tar file contain categories that are matched with the USGS categories described in the VEGPARM.TBL and SOILPARM.TBL files in the WRF run directory. Descriptions of the 24 land use categories and 16 soil categories are provided in the tables below.

Table 1: USGS 24-category Land Use Categories

Land Use Category	Land Use Description
1	Urban and Built-up Land
2	Dryland Cropland and Pasture
3	Irrigated Cropland and Pasture
4	Mixed Dryland/Irrigated Cropland and Pasture
5	Cropland/Grassland Mosaic
6	Cropland/Woodland Mosaic
7	Grassland
8	Shrubland
9	Mixed Shrubland/Grassland
10	Savanna
11	Deciduous Broadleaf Forest
12	Deciduous Needleleaf Forest
13	Evergreen Broadleaf
14	Evergreen Needleleaf
15	Mixed Forest
16	Water Bodies
17	Herbaceous Wetland
18	Wooden Wetland
19	Barren or Sparsely Vegetated
20	Herbaceous Tundra
21	Wooded Tundra
22	Mixed Tundra
23	Bare Ground Tundra
24	Snow or Ice

Table 2: IGBP-Modified MODIS 20-category Land Use Categories

Land Use Category	Land Use Description
1	Evergreen Needleleaf Forest
2	Evergreen Broadleaf Forest
3	Deciduous Needleleaf Forest
4	Deciduous Broadleaf Forest
5	Mixed Forests
6	Closed Shrublands
7	Open Shrublands
8	Woody Savannas
9	Savannas
10	Grasslands

11	Permanent Wetlands
12	Croplands
13	Urban and Built-Up
14	Cropland/Natural Vegetation Mosaic
15	Snow and Ice
16	Barren or Sparsely Vegetated
17	Water
18	Wooded Tundra
19	Mixed Tundra
20	Barren Tundra

Table 3: 16-category Soil Categories

Soil Category	Soil Description
1	Sand
2	Loamy Sand
3	Sandy Loam
4	Silt Loam
5	Silt
6	Loam
7	Sandy Clay Loam
8	Silty Clay Loam
9	Clay Loam
10	Sandy Clay
11	Silty Clay
12	Clay
13	Organic Material
14	Water
15	Bedrock
16	Other (land-ice)

WPS Output Fields

Below, a listing of the global attributes and fields that are written to the geogrid program's output files is given. This listing is an abridged version of the output from the ncdump program when run on a typical geo_em.d01.nc file.

```
netcdf geo_em.d01 {
dimensions:
      Time = UNLIMITED ; // (1 currently)
      DateStrLen = 19 ;
      west_east = 73 ;
```

```
     south_north = 60 ;
     south_north_stag = 61 ;
     west_east_stag = 74 ;
     land_cat = 21 ;
     soil_cat = 16 ;
     month = 12 ;
     num_urb_params = 132 ;
variables:
     char Times(Time, DateStrLen) ;
     float XLAT_M(Time, south_north, west_east) ;
          XLAT_M:units = "degrees latitude" ;
          XLAT_M:description = "Latitude on mass grid" ;
     float XLONG_M(Time, south_north, west_east) ;
          XLONG_M:units = "degrees longitude" ;
          XLONG_M:description = "Longitude on mass grid" ;
     float XLAT_V(Time, south_north_stag, west_east) ;
          XLAT_V:units = "degrees latitude" ;
          XLAT_V:description = "Latitude on V grid" ;
     float XLONG_V(Time, south_north_stag, west_east) ;
          XLONG_V:units = "degrees longitude" ;
          XLONG_V:description = "Longitude on V grid" ;
     float XLAT_U(Time, south_north, west_east_stag) ;
          XLAT_U:units = "degrees latitude" ;
          XLAT_U:description = "Latitude on U grid" ;
     float XLONG_U(Time, south_north, west_east_stag) ;
          XLONG_U:units = "degrees longitude" ;
          XLONG_U:description = "Longitude on U grid" ;
     float CLAT(Time, south_north, west_east) ;
          CLAT:units = "degrees latitude" ;
          CLAT:description = "Computational latitude on mass grid" ;
     float CLONG(Time, south_north, west_east) ;
          CLONG:units = "degrees longitude" ;
          CLONG:description = "Computational longitude on mass grid" ;
     float MAPFAC_M(Time, south_north, west_east) ;
          MAPFAC_M:units = "none" ;
          MAPFAC_M:description = "Mapfactor on mass grid" ;
     float MAPFAC_V(Time, south_north_stag, west_east) ;
          MAPFAC_V:units = "none" ;
          MAPFAC_V:description = "Mapfactor on V grid" ;
     float MAPFAC_U(Time, south_north, west_east_stag) ;
          MAPFAC_U:units = "none" ;
          MAPFAC_U:description = "Mapfactor on U grid" ;
     float MAPFAC_MX(Time, south_north, west_east) ;
          MAPFAC_MX:units = "none" ;
          MAPFAC_MX:description = "Mapfactor (x-dir) on mass grid" ;
     float MAPFAC_VX(Time, south_north_stag, west_east) ;
          MAPFAC_VX:units = "none" ;
          MAPFAC_VX:description = "Mapfactor (x-dir) on V grid" ;
     float MAPFAC_UX(Time, south_north, west_east_stag) ;
          MAPFAC_UX:units = "none" ;
          MAPFAC_UX:description = "Mapfactor (x-dir) on U grid" ;
     float MAPFAC_MY(Time, south_north, west_east) ;
          MAPFAC_MY:units = "none" ;
          MAPFAC_MY:description = "Mapfactor (y-dir) on mass grid" ;
     float MAPFAC_VY(Time, south_north_stag, west_east) ;
          MAPFAC_VY:units = "none" ;
          MAPFAC_VY:description = "Mapfactor (y-dir) on V grid" ;
     float MAPFAC_UY(Time, south_north, west_east_stag) ;
          MAPFAC_UY:units = "none" ;
          MAPFAC_UY:description = "Mapfactor (y-dir) on U grid" ;
     float E(Time, south_north, west_east) ;
          E:units = "-" ;
          E:description = "Coriolis E parameter" ;
```

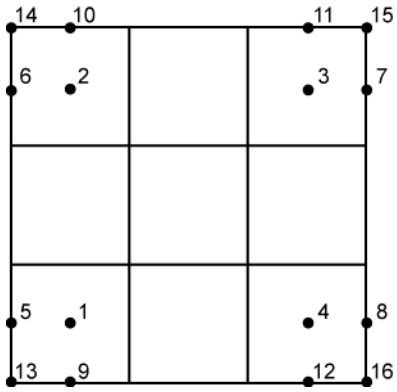
```
      float F(Time, south_north, west_east) ;
            F:units = "-" ;
            F:description = "Coriolis F parameter" ;
      float SINALPHA(Time, south_north, west_east) ;
            SINALPHA:units = "none" ;
            SINALPHA:description = "Sine of rotation angle" ;
      float COSALPHA(Time, south_north, west_east) ;
            COSALPHA:units = "none" ;
            COSALPHA:description = "Cosine of rotation angle" ;
      float LANDMASK(Time, south_north, west_east) ;
            LANDMASK:units = "none" ;
            LANDMASK:description = "Landmask : 1=land, 0=water" ;
      float XLAT_C(Time, south_north_stag, west_east_stag) ;
            XLAT_C:units = "degrees latitude" ;
            XLAT_C:description = "Latitude at grid cell corners" ;
      float XLONG_C(Time, south_north_stag, west_east_stag) ;
            XLONG_C:units = "degrees longitude" ;
            XLONG_C:description = "Longitude at grid cell corners" ;
      float LANDUSEF(Time, land_cat, south_north, west_east) ;
            LANDUSEF:units = "category" ;
            LANDUSEF:description = "Noah-modified 21-category IGBP-MODIS landuse"
;
      float LU_INDEX(Time, south_north, west_east) ;
            LU_INDEX:units = "category" ;
            LU_INDEX:description = "Dominant category" ;
      float HGT_M(Time, south_north, west_east) ;
            HGT_M:units = "meters MSL" ;
            HGT_M:description = "GMTED2010 30-arc-second topography height" ;
      float SOILTEMP(Time, south_north, west_east) ;
            SOILTEMP:units = "Kelvin" ;
            SOILTEMP:description = "Annual mean deep soil temperature" ;
      float SOILCTOP(Time, soil_cat, south_north, west_east) ;
            SOILCTOP:units = "category" ;
            SOILCTOP:description = "16-category top-layer soil type" ;
      float SCT_DOM(Time, south_north, west_east) ;
            SCT_DOM:units = "category" ;
            SCT_DOM:description = "Dominant category" ;
      float SOILCBOT(Time, soil_cat, south_north, west_east) ;
            SOILCBOT:units = "category" ;
            SOILCBOT:description = "16-category top-layer soil type" ;
      float SCB_DOM(Time, south_north, west_east) ;
            SCB_DOM:units = "category" ;
            SCB_DOM:description = "Dominant category" ;
      float ALBEDO12M(Time, month, south_north, west_east) ;
            ALBEDO12M:units = "percent" ;
            ALBEDO12M:description = "Monthly surface albedo" ;
      float GREENFRAC(Time, month, south_north, west_east) ;
            GREENFRAC:units = "fraction" ;
            GREENFRAC:description = "MODIS FPAR" ;
      float LAI12M(Time, month, south_north, west_east) ;
            LAI12M:units = "m^2/m^2" ;
            LAI12M:description = "MODIS LAI" ;
      float SNOALB(Time, south_north, west_east) ;
            SNOALB:units = "percent" ;
            SNOALB:description = "Maximum snow albedo" ;
      float SLOPECAT(Time, south_north, west_east) ;
            SLOPECAT:units = "category" ;
            SLOPECAT:description = "Dominant category" ;
      float CON(Time, south_north, west_east) ;
            CON:units = "" ;
            CON:description = "Subgrid-scale orographic convexity" ;
      float VAR(Time, south_north, west_east) ;
            VAR:units = "" ;
```

```
          VAR:description = "Subgrid-scale orographic variance" ;
     float OA1(Time, south_north, west_east) ;
          OA1:units = "" ;
          OA1:description = "Subgrid-scale orographic asymmetry" ;
     float OA2(Time, south_north, west_east) ;
          OA2:units = "" ;
          OA2:description = "Subgrid-scale orographic asymmetry" ;
     float OA3(Time, south_north, west_east) ;
          OA3:units = "" ;
          OA3:description = "Subgrid-scale orographic asymmetry" ;
     float OA4(Time, south_north, west_east) ;
          OA4:units = "" ;
          OA4:description = "Subgrid-scale orographic asymmetry" ;
     float OL1(Time, south_north, west_east) ;
          OL1:units = "" ;
          OL1:description = "Subgrid-scale effective orographic length scale" ;
     float OL2(Time, south_north, west_east) ;
          OL2:units = "" ;
          OL2:description = "Subgrid-scale effective orographic length scale" ;
     float OL3(Time, south_north, west_east) ;
          OL3:units = "" ;
          OL3:description = "Subgrid-scale effective orographic length scale" ;
     float OL4(Time, south_north, west_east) ;
          OL4:units = "" ;
          OL4:description = "Subgrid-scale effective orographic length scale" ;
     float VAR_SSO(Time, south_north, west_east) ;
          VAR_SSO:units = "meters2 MSL" ;
          VAR_SSO:description = "Variance of Subgrid Scale Orography" ;
     float LAKE_DEPTH(Time, south_north, west_east) ;
          LAKE_DEPTH:units = "meters MSL" ;
          LAKE_DEPTH:description = "Topography height" ;
     float URB_PARAM(Time, num_urb_params, south_north, west_east) ;
          URB_PARAM:units = "dimensionless" ;
          URB_PARAM:description = "Urban_Parameters" ;

// global attributes:
          :TITLE = "OUTPUT FROM GEOGRID V3.8" ;
          :SIMULATION_START_DATE = "0000-00-00_00:00:00" ;
          :WEST-EAST_GRID_DIMENSION = 74 ;
          :SOUTH-NORTH_GRID_DIMENSION = 61 ;
          :BOTTOM-TOP_GRID_DIMENSION = 0 ;
          :WEST-EAST_PATCH_START_UNSTAG = 1 ;
          :WEST-EAST_PATCH_END_UNSTAG = 73 ;
          :WEST-EAST_PATCH_START_STAG = 1 ;
          :WEST-EAST_PATCH_END_STAG = 74 ;
          :SOUTH-NORTH_PATCH_START_UNSTAG = 1 ;
          :SOUTH-NORTH_PATCH_END_UNSTAG = 60 ;
          :SOUTH-NORTH_PATCH_START_STAG = 1 ;
          :SOUTH-NORTH_PATCH_END_STAG = 61 ;
          :GRIDTYPE = "C" ;
          :DX = 30000.f ;
          :DY = 30000.f ;
          :DYN_OPT = 2 ;
          :CEN_LAT = 34.83001f ;
          :CEN_LON = -81.03f ;
          :TRUELAT1 = 30.f ;
          :TRUELAT2 = 60.f ;
          :MOAD_CEN_LAT = 34.83001f ;
          :STAND_LON = -98.f ;
          :POLE_LAT = 90.f ;
          :POLE_LON = 0.f ;
          :corner_lats = 28.17127f, 44.36657f, 39.63231f, 24.61906f, 28.17842f,
44.37617f, 39.57812f, 24.57806f, 28.03771f, 44.50592f, 39.76032f, 24.49431f,
```

```
28.04485f, 44.51553f, 39.70599f, 24.45341f ;
           :corner_lons = -93.64893f, -92.39661f, -66.00165f, -72.64047f, -
93.80048f, -92.59155f, -65.83557f, -72.5033f, -93.65717f, -92.3829f, -65.9313f,
-72.68539f, -93.80841f, -92.57831f, -65.76495f, -72.54843f ;
           :MAP_PROJ = 1 ;
           :MMINLU = "MODIFIED_IGBP_MODIS_NOAH" ;
           :NUM_LAND_CAT = 21 ;
           :ISWATER = 17 ;
           :ISLAKE = 21 ;
           :ISICE = 15 ;
           :ISURBAN = 13 ;
           :ISOILWATER = 14 ;
           :grid_id = 1 ;
           :parent_id = 1 ;
           :i_parent_start = 1 ;
           :j_parent_start = 1 ;
           :i_parent_end = 74 ;
           :j_parent_end = 61 ;
           :parent_grid_ratio = 1 ;
           :FLAG_MF_XY = 1 ;
           :FLAG_LAI12M = 1 ;
           :FLAG_LAKE_DEPTH = 1 ;
}
```

The global attributes `corner_lats` and `corner_lons` contain the lat-lon location of the corners of the domain with respect to different grid staggerings (mass, *u*, *v*, and unstaggered). The locations referred to by each element of the `corner_lats` and `corner_lons` arrays are summarized in the table and figure below.

Array index	**Staggering**	**Corner**
1	Mass	Lower-left
2		Upper-left
3		Upper-right
4		Lower-right
5	U	Lower-left
6		Upper-left
7		Upper-right
8		Lower-right
9	V	Lower-left
10		Upper-left
11		Upper-right
12		Lower-right
13	Unstaggered	Lower-left
14		Upper-left
15		Upper-right
16		Lower-right



In addition to the fields in a geogrid output file (e.g., geo_em.d01.nc), the following fields and global attributes will also be present in a typical output file from the metgrid program, run with the default METGRID.TBL file and meteorological data from NCEP's GFS model.

```
netcdf met_em.d01.2016-04-07_00\:00\:00 {
dimensions:
      Time = UNLIMITED ; // (1 currently)
      DateStrLen = 19 ;
      west_east = 73 ;
      south_north = 60 ;
      num_metgrid_levels = 27 ;
      num_st_layers = 4 ;
      num_sm_layers = 4 ;
      south_north_stag = 61 ;
      west_east_stag = 74 ;
      z-dimension0132 = 132 ;
      z-dimension0012 = 12 ;
      z-dimension0016 = 16 ;
      z-dimension0021 = 21 ;
variables:
      char Times(Time, DateStrLen) ;
      float PRES(Time, num_metgrid_levels, south_north, west_east) ;
            PRES:units = "" ;
            PRES:description = "" ;
      float SOIL_LAYERS(Time, num_st_layers, south_north, west_east) ;
            SOIL_LAYERS:units = "" ;
            SOIL_LAYERS:description = "" ;
      float SM(Time, num_sm_layers, south_north, west_east) ;
            SM:units = "" ;
            SM:description = "" ;
      float ST(Time, num_st_layers, south_north, west_east) ;
            ST:units = "" ;
            ST:description = "" ;
      float GHT(Time, num_metgrid_levels, south_north, west_east) ;
            GHT:units = "m" ;
            GHT:description = "Height" ;
      float HGTTROP(Time, south_north, west_east) ;
            HGTTROP:units = "m" ;
            HGTTROP:description = "Height of tropopause" ;
      float TTROP(Time, south_north, west_east) ;
            TTROP:units = "K" ;
            TTROP:description = "Temperature at tropopause" ;
```

```
float PTROPNN(Time, south_north, west_east) ;
     PTROPNN:units = "Pa" ;
     PTROPNN:description = "PTROP, used for nearest neighbor interp" ;
float PTROP(Time, south_north, west_east) ;
     PTROP:units = "Pa" ;
     PTROP:description = "Pressure of tropopause" ;
float VTROP(Time, south_north_stag, west_east) ;
     VTROP:units = "m s-1" ;
     VTROP:description = "V                 at tropopause" ;
float UTROP(Time, south_north, west_east_stag) ;
     UTROP:units = "m s-1" ;
     UTROP:description = "U                 at tropopause" ;
float HGTMAXW(Time, south_north, west_east) ;
     HGTMAXW:units = "m" ;
     HGTMAXW:description = "Height of max wind level" ;
float TMAXW(Time, south_north, west_east) ;
     TMAXW:units = "K" ;
     TMAXW:description = "Temperature at max wind level" ;
float PMAXWNN(Time, south_north, west_east) ;
     PMAXWNN:units = "Pa" ;
     PMAXWNN:description = "PMAXW, used for nearest neighbor interp" ;
float PMAXW(Time, south_north, west_east) ;
     PMAXW:units = "Pa" ;
     PMAXW:description = "Pressure of max wind level" ;
float VMAXW(Time, south_north_stag, west_east) ;
     VMAXW:units = "m s-1" ;
     VMAXW:description = "V                 at max wind" ;
float UMAXW(Time, south_north, west_east_stag) ;
     UMAXW:units = "m s-1" ;
     UMAXW:description = "U                 at max wind" ;
float SNOWH(Time, south_north, west_east) ;
     SNOWH:units = "m" ;
     SNOWH:description = "Physical Snow Depth" ;
float SNOW(Time, south_north, west_east) ;
     SNOW:units = "kg m-2" ;
     SNOW:description = "Water equivalent snow depth" ;
float SKINTEMP(Time, south_north, west_east) ;
     SKINTEMP:units = "K" ;
     SKINTEMP:description = "Skin temperature" ;
float SOILHGT(Time, south_north, west_east) ;
     SOILHGT:units = "m" ;
     SOILHGT:description = "Terrain field of source analysis" ;
float LANDSEA(Time, south_north, west_east) ;
     LANDSEA:units = "proprtn" ;
     LANDSEA:description = "Land/Sea flag (1=land, 0 or 2=sea)" ;
float SEAICE(Time, south_north, west_east) ;
     SEAICE:units = "proprtn" ;
     SEAICE:description = "Ice flag" ;
float ST100200(Time, south_north, west_east) ;
     ST100200:units = "K" ;
     ST100200:description = "T 100-200 cm below ground layer (Bottom)" ;
float ST040100(Time, south_north, west_east) ;
     ST040100:units = "K" ;
     ST040100:description = "T 40-100 cm below ground layer (Upper)" ;
float ST010040(Time, south_north, west_east) ;
     ST010040:units = "K" ;
     ST010040:description = "T 10-40 cm below ground layer (Upper)" ;
float ST000010(Time, south_north, west_east) ;
     ST000010:units = "K" ;
     ST000010:description = "T 0-10 cm below ground layer (Upper)" ;
float SM100200(Time, south_north, west_east) ;
     SM100200:units = "fraction" ;
     SM100200:description = "Soil Moist 100-200 cm below gr layer" ;
```

```
     float SM040100(Time, south_north, west_east) ;
          SM040100:units = "fraction" ;
          SM040100:description = "Soil Moist 40-100 cm below grn layer" ;
     float SM010040(Time, south_north, west_east) ;
          SM010040:units = "fraction" ;
          SM010040:description = "Soil Moist 10-40 cm below grn layer" ;
     float SM000010(Time, south_north, west_east) ;
          SM000010:units = "fraction" ;
          SM000010:description = "Soil Moist 0-10 cm below grn layer (Up)" ;
     float PSFC(Time, south_north, west_east) ;
          PSFC:units = "Pa" ;
          PSFC:description = "Surface Pressure" ;
     float RH(Time, num_metgrid_levels, south_north, west_east) ;
          RH:units = "%" ;
          RH:description = "Relative Humidity" ;
     float VV(Time, num_metgrid_levels, south_north_stag, west_east) ;
          VV:units = "m s-1" ;
          VV:description = "V" ;
     float UU(Time, num_metgrid_levels, south_north, west_east_stag) ;
          UU:units = "m s-1" ;
          UU:description = "U" ;
     float TT(Time, num_metgrid_levels, south_north, west_east) ;
          TT:units = "K" ;
          TT:description = "Temperature" ;
     float PMSL(Time, south_north, west_east) ;
          PMSL:units = "Pa" ;
          PMSL:description = "Sea-level Pressure" ;

// global attributes:
          :TITLE = "OUTPUT FROM METGRID V3.8" ;
          :SIMULATION_START_DATE = "2016-04-07_00:00:00" ;
          :WEST-EAST_GRID_DIMENSION = 74 ;
          :SOUTH-NORTH_GRID_DIMENSION = 61 ;
          :BOTTOM-TOP_GRID_DIMENSION = 27 ;
          :WEST-EAST_PATCH_START_UNSTAG = 1 ;
          :WEST-EAST_PATCH_END_UNSTAG = 73 ;
          :WEST-EAST_PATCH_START_STAG = 1 ;
          :WEST-EAST_PATCH_END_STAG = 74 ;
          :SOUTH-NORTH_PATCH_START_UNSTAG = 1 ;
          :SOUTH-NORTH_PATCH_END_UNSTAG = 60 ;
          :SOUTH-NORTH_PATCH_START_STAG = 1 ;
          :SOUTH-NORTH_PATCH_END_STAG = 61 ;
          :GRIDTYPE = "C" ;
          :DX = 30000.f ;
          :DY = 30000.f ;
          :DYN_OPT = 2 ;
          :CEN_LAT = 34.83001f ;
          :CEN_LON = -81.03f ;
          :TRUELAT1 = 30.f ;
          :TRUELAT2 = 60.f ;
          :MOAD_CEN_LAT = 34.83001f ;
          :STAND_LON = -98.f ;
          :POLE_LAT = 90.f ;
          :POLE_LON = 0.f ;
          :corner_lats = 28.17127f, 44.36657f, 39.63231f, 24.61906f, 28.17842f,
44.37617f, 39.57812f, 24.57806f, 28.03771f, 44.50592f, 39.76032f, 24.49431f,
28.04485f, 44.51553f, 39.70599f, 24.45341f ;
          :corner_lons = -93.64893f, -92.39661f, -66.00165f, -72.64047f, -
93.80048f, -92.59155f, -65.83557f, -72.5033f, -93.65717f, -92.3829f, -65.9313f,
-72.68539f, -93.80841f, -92.57831f, -65.76495f, -72.54843f ;
          :MAP_PROJ = 1 ;
          :MMINLU = "MODIFIED_IGBP_MODIS_NOAH" ;
          :NUM_LAND_CAT = 21 ;
```

```
            :ISWATER = 17 ;
            :ISLAKE = 21 ;
            :ISICE = 15 ;
            :ISURBAN = 13 ;
            :ISOILWATER = 14 ;
            :grid_id = 1 ;
            :parent_id = 1 ;
            :i_parent_start = 1 ;
            :j_parent_start = 1 ;
            :i_parent_end = 74 ;
            :j_parent_end = 61 ;
            :parent_grid_ratio = 1 ;
            :NUM_METGRID_SOIL_LEVELS = 4 ;
            :FLAG_METGRID = 1 ;
            :FLAG_EXCLUDED_MIDDLE = 0 ;
            :FLAG_SOIL_LAYERS = 1 ;
            :FLAG_SNOW = 1 ;
            :FLAG_PSFC = 1 ;
            :FLAG_SM000010 = 1 ;
            :FLAG_SM010040 = 1 ;
            :FLAG_SM040100 = 1 ;
            :FLAG_SM100200 = 1 ;
            :FLAG_ST000010 = 1 ;
            :FLAG_ST010040 = 1 ;
            :FLAG_ST040100 = 1 ;
            :FLAG_ST100200 = 1 ;
            :FLAG_SLP = 1 ;
            :FLAG_SNOWH = 1 ;
            :FLAG_SOILHGT = 1 ;
            :FLAG_UTROP = 1 ;
            :FLAG_VTROP = 1 ;
            :FLAG_TTROP = 1 ;
            :FLAG_PTROP = 1 ;
            :FLAG_PTROPNN = 1 ;
            :FLAG_HGTTROP = 1 ;
            :FLAG_UMAXW = 1 ;
            :FLAG_VMAXW = 1 ;
            :FLAG_TMAXW = 1 ;
            :FLAG_PMAXW = 1 ;
            :FLAG_PMAXWNN = 1 ;
            :FLAG_HGTMAXW = 1 ;
            :FLAG_MF_XY = 1 ;
            :FLAG_LAI12M = 1 ;
            :FLAG_LAKE_DEPTH = 1 ;
}
```

Chapter 4: WRF Initialization

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Introduction

The WRF model has two large classes of simulations that it is able to generate: those with an *ideal* initialization and those utilizing *real* data. The idealized simulations typically manufacture an initial condition file for the WRF model from an existing 1-D or 2-D sounding and assume a simplified analytic orography. The real-data cases usually require pre-processing from the WPS package, which provides each atmospheric and static field with fidelity appropriate to the chosen grid resolution for the model. The WRF model executable itself is not altered by choosing one initialization option over another (idealized *vs*. real), but the WRF model pre-processors (the real.exe and ideal.exe programs) are specifically built based upon a user's selection.

The real.exe and ideal.exe programs are never used together. Both the real.exe and ideal.exe are the programs that are processed just prior to the WRF model run.

The ideal *vs.* real cases are divided as follows:

- Ideal cases – initialization programs named “ideal.exe”
    - 3d
        - em_b_wave - baroclinic wave, 100 km
        - em_fire – surface fire, 50 m
        - em_heldsuarez – global case with polar filtering, 625 km
        - em_les – large eddy simulation, 100 m
        - em_quarter_ss - super cell, 2 km
        - em_tropical_cyclone – hurricane, 15 km
    - 2d
        - em_grav2d_x – gravity current, 100 m
        - em_hill2d_x – flow over a hill, 2 km
        - em_seabreeze2d_x – water and land, 2 km, full physics
        - em_squall2d_x – squall line, 250 m

        - em_squall2d_y – transpose of above problem

    - 1d
        - em_scm_xy – single column model, 4 km, full physics

- Real data cases – initialization program named "real.exe"
    - em_real – examples from 4 to 30 km, full physics

The selection of the type of forecast is made when issuing the **`./compile`** statement. When selecting a different case to study, the code must be re-compiled to choose the correct initialization for the model. For example, after configuring the setup for the architecture (with the **`./configure`** command), if the user issues the command **`./compile em_real`**, then the initialization program is built using **`module_initialize_real.F`** as the target module (one of the **`./WRFV3/dyn_em/module_initialize_*.F`** files). Similarly, if the user specifies **`./compile em_les`**, then the Fortran module for the large eddy simulation (**`module_initialize_les.F)`** is automatically inserted into the build for ideal.exe. Note that the WRF forecast model is identical for both of these initialization programs. In each of these initialization modules, the same sort of activities goes on:

- compute a base state / reference profile for geopotential and column pressure
- compute the perturbations from the base state for geopotential and column pressure
- initialize meteorological variables: u, v, potential temperature, vapor mixing ratio
- define a vertical coordinate
- interpolate data to the model's vertical coordinate
- initialize static fields for the map projection and the physical surface; for many of the idealized cases, these are simplified initializations, such as map factors set to one, and topography elevation set to zero

Both the real.exe program and ideal.exe programs share a large portion of source code, to handle the following duties:

- read data from the namelist
- allocate space for the requested domain, with model variables specified at run-time
- generate initial condition file

The real-data case does some additional processing:

- read meteorological and static input data from the WRF Preprocessing System (WPS)
- prepare soil fields for use in the model (usually, vertical interpolation to the required levels for the specified land surface scheme)

- check to verify that soil categories, land use, land mask, soil temperature, sea surface temperature are all consistent with each other
- multiple input time periods are processed to generate the lateral boundary conditions, which are required unless processing a global forecast
- 3d boundary data (u, v, potential temperature, vapor mixing ratio, total geopotential) are coupled with total column pressure

The "real.exe" program may be run as either a serial or a distributed memory job. Since the idealized cases only require that the initialization run for a single time period (no lateral boundary file is required) and are, therefore, quick to process, all of the "ideal.exe" programs should be run on a single processor. The Makefile for the 2-D cases will not allow the user to build the code with distributed memory parallelism. For large 2-D cases, if the user requires OpenMP, the variables **`nproc_x`** and **`nproc_y`** must be set in the **`domains`** portion of the namelist file **`namelist.input`** (**`nproc_y`** must be set to 1, and **`nproc_x`** then set to the number of processors).

Initialization for Ideal Cases

The program "ideal.exe" is the program in the WRF system that allows a user to run a controlled scenario. Typically this program requires no input except for the **`namelist.input`** and the **`input_sounding`** files (except for the b_wave case which uses a 2-D binary sounding file). The program outputs the **`wrfinput_d01`** file that is read by the WRF model executable ("wrf.exe"). Since no external data is required to run the idealized cases, even for researchers interested in real-data cases, the idealized simulations are an easy way to insure that the model is working correctly on a particular architecture and compiler.

Idealized runs can use any of the boundary conditions except "**`specified`**", and are not, by default, set up to run with sophisticated physics (other than from microphysics). Most have no radiation, surface fluxes or frictional effects (other than the sea breeze case, LES, and the global Held-Suarez). The idealized cases are mostly useful for dynamical studies, reproducing converged or otherwise known solutions, and idealized cloud modeling.

There are 1-D, 2-D and 3-D examples of idealized cases, with and without topography, and with and without an initial thermal perturbation. The namelist can control the size of the domain, number of vertical levels, model top height, grid size, time step, diffusion and damping properties, boundary conditions, and physics options. A large number of existing namelist settings are already found within each of the directories associated with a particular case.

The **`input_sounding`** file (already in appropriate case directories) can be any set of levels that goes at least up to the model top height (**`ztop`**) in the namelist. The first line

includes the surface pressure (hPa), potential temperature (K) and moisture mixing ratio (g/kg). Each subsequent line has five input values: height (meters above sea-level), potential temperature (K), vapor mixing ratio (g/kg), x-direction wind component (m/s), and y-direction wind component (m/s). The "ideal.exe" program interpolates the data from the **input_sounding** file, and will extrapolate if not enough data is provided.

The base state sounding for idealized cases is the initial sounding, minus the moisture, and therefore does not have to be defined separately. Note for the baroclinic wave case: a 1-D input sounding is not used because the initial 3-D arrays are read-in from the file **input_jet**. This means for the baroclinic wave case, the **namelist.input** file cannot be used to change the horizontal or vertical dimensions since they are specified in the **input_jet** file.

Making modifications, apart from namelist-controlled options or soundings, has to be done by editing the Fortran code. Such modifications would include changing the topography, the distribution of vertical levels, the properties of an initialization thermal bubble, or preparing a case to use more physics, such as a land-surface model. The Fortran code to edit is contained in **./WRFV3/dyn_em/module_initialize_[*case*].F**, where **[*case*]** is the case chosen in compilation, e.g. **module_initialize_squall2d_x.F**. The subroutine to modify is **init_domain_rk**. To change the vertical levels, only the 1-D array **znw** must be defined, containing the full levels, starting from 1 at k=1, and ending with 0 at k=kde. To change the topography, only the 2-D array **ht** must be defined, making sure it is periodic if those boundary conditions are used. To change the thermal perturbation bubble, search for the string "bubble" to locate the code to change.

Each of the ideal cases provides an excellent set of default examples to the user. The method to specify a thermal bubble is given in the super cell case. In the hill2d case, the topography is accounted for properly in setting up the initial 3-D arrays, so that example should be followed for any topography cases. A symmetry example in the squall line cases tests that your indexing modifications are correct. Full physics options are demonstrated in the seabreeze2d_x case.

Available Ideal Test Cases

The available test cases are

1. 2-D squall2d_x (test/em_squall2d_x)
    - 2D squall line (x,z) using Kessler microphysics and a fixed 300 m^2/s viscosity.
    - periodicity condition used in y so that 3D model produces 2D simulation.
    - v velocity should be zero and there should be no variation in y in the results.
2. 2-D squall2d_y (test/em_squall2d_y)
    - Same as squall2d_x, except with (x) rotated to (y).

- u velocity should be zero and there should be no variation in x in the results.

3. 3-D quarter-circle shear supercell simulation (test/em_quarter_ss).
   - Left and right moving supercells are produced.
   - See the README.quarter_ss file in the test directory for more information.
4. 2-D flow over a bell-shaped hill (x,z) (test/em_hill2d_x)
   - 10 km half-width, 2 km grid-length, 100 m high hill, 10 m/s flow, N=0.01/s, 30 km high domain, 80 levels, open radiative boundaries, absorbing upper boundary.
   - Case is in linear hydrostatic regime, so vertical tilted waves with ~6-km vertical wavelength.
5. 3-D baroclinic waves (test/em_b_wave)
   - Baroclinically unstable jet u(y,z) on an f-plane.
   - Symmetric north and south, periodic east and west boundaries.
   - 100-km grid size, 16-km top, with 4-km damping layer.
   - 41x81 points in (x,y), 64 layers.
6. 2-D gravity current (test/em_grav2d_x)
   - Test case is described in Straka et al, *INT J NUMER METH FL* **17** (1): 1-22 July 15 1993.
   - See the README.grav2d_x file in the test directory.
7. 2-D sea breeze (test/em_seabreeze_x)
   - 2-km grid size, 20-km top, land/water.
   - Can be run with full physics, radiation, surface, boundary layer, and land options.
8. 3-D large eddy simulation (test/em_les)
   - 100-m grid size, 2-km top.
   - Surface layer physics with fluxes.
   - Doubly periodic
9. 3-D Held-Suarez (test/em_heldsuarez)
   - global domain, 625 km in x-direction, 556 km in y-direction, 120-km top.
   - Radiation, polar filter above 45^{o}.
   - Period in x-direction, polar boundary conditions in y-direction
10. 1-D single column model (test/em_scm_xy)
    - 4-km grid size, 12-km top
    - Full physics
    - Doubly periodic
11. 3-D surface fire (test/em_fire)
    - Geoscientific Model Development Discussions (*GMDD*) **4**, 497-545, 2011, http://www.geosci-model-dev-discuss.net/4/497/2011/gmdd-4-497-2011.html
    - 50-m, 4.5-km top
    - 10:1 subgrid ratio, no physics
    - Open boundaries
12. 3-D tropical cyclone (test/em_tropical_cyclone)
    - Test case described in Jordan, *J METEOR* **15**, 91-97, 1958.

- 15-km, 25-km top
- f-plane (f=0.5e-5, about 20 N), SST=28 C
- Full physics with a simple radiative cooling, no cumulus
- Doubly periodic

13. 3-D convective-radiative equilibrium (test/em_convrad)
    - 1 km grid size, 30 km model top
    - tropical condition, small f, weak wind, constant SST
    - full physics
    - doubly periodic

Initialization for Real Data Cases

The real-data WRF cases are those that have the input data to the "real.exe" program provided by the WRF Preprocessing System (WPS). This data from the WPS was originally generated from a previously-run external analysis or forecast model. The original data was most-likely in GriB format and was most-likely ingested into the WPS by first ftp'ing the raw GriB data from one of the national weather agencies' anonymous ftp sites.

For example, suppose a single-domain WRF forecast is desired, with the following criteria:

- 2000 January 24 1200 UTC through January 25 1200 UTC
- the original GriB data is available at 6-h increments

The following coarse-grid files will be generated by the WPS (starting date through ending date, at 6-h increments):

- **met_em.d01.2000-01-24_12:00:00.nc**
- **met_em.d01.2000-01-24_18:00:00.nc**
- **met_em.d01.2000-01-25_00:00:00.nc**
- **met_em.d01.2000-01-25_06:00:00.nc**
- **met_em.d01.2000-01-25_12:00:00.nc**

The convention is to use "**met**" to signify data that is output from the WPS "metgrid.exe" program and input into the "real.exe" program. The "**d01**" portion of the name identifies to which domain this data refers, which permits nesting. The next set of characters is the validation date/time (UTC), where each WPS output file has only a single time-slice of processed data. The file extension suffix "**.nc**" refers to the output format from WPS which must be in netCDF for the "real.exe" program. For regional forecasts, multiple time periods must be processed by "real.exe" so that a lateral boundary file is available to the model. The global option for WRF requires only an initial condition.

The WPS package delivers data that is ready to be used in the WRF system by the "real.exe" program.

- The data adheres to the WRF IO API. Unless you are developing special tools, stick with the netCDF option to communicate between the WPS package and "real.exe".
- The data has already been horizontally interpolated to the correct grid-point staggering for each variable, and the winds are correctly rotated to the WRF model map projection.
- 3-D meteorological data required from the WPS: pressure, u, v, temperature, relative humidity, geopotential height
- Optional 3-D hydrometeor data may be provided to the real program at run-time, but these fields will not be used in the coarse-grid lateral boundary file. Fields named: QR, QC, QS, QI, QG, QH, QNI (mixing ratio for rain, cloud, snow, ice, graupel, hail, and number concentration) are eligible for input from the metgrid output files.
- 3D soil data from the WPS: soil temperature, soil moisture, soil liquid (optional, depending on physics choices in the WRF model)
- 2D meteorological data from the WPS: sea level pressure, surface pressure, surface u and v, surface temperature, surface relative humidity, input elevation
- 2-D meteorological optional data from WPS: sea surface temperature, physical snow depth, water equivalent snow depth
- 2D static data for the physical surface: terrain elevation, land use categories, soil texture categories, temporally-interpolated monthly data, land sea mask, elevation of the input model's topography
- 2D static data for the projection: map factors, Coriolis, projection rotation, computational latitude
- constants: domain size, grid distances, date
- The WPS data may either be isobaric or some more-generalized vertical coordinate, where each column is monotonic in pressure
- All 3-D meteorological data (wind, temperature, height, moisture, pressure) must have the same number of levels, and variables must have the exact same levels. For example, it is not acceptable to have more levels for temperature (for example) than height. Likewise, it is not acceptable to have an extra level for the horizontal wind components, but not for moisture.

Real Data Test Case: 2000 January 24/12 through 25/12

- A test data set is accessible from the WRF download page. Under the "WRF Model Test Data" list, select the January data. This is a 74x61, 30-km domain centered over the eastern US.
- Make sure you have successfully built the code (fine-grid nested initial data is available in the download, so the code may be built with the basic nest option),

./WRFV3/main/real.exe and **./WRFV3/main/wrf.exe** must both exist.

- In the **./WRFV3/test/em_real** directory, copy the namelist for the January case to the default name
    - **cp namelist.input.jan00 namelist.input**
- Link the WPS files (the "**met_em***" files from the download) into the **./WRFV3/test/em_real** directory.
- For a single processor, to execute the real program, type **real.exe** (this should take less than a minute for this small case with five time periods).
- After running the "real.exe" program, the files "**wrfinput_d01**" and "**wrfbdy_d01**" should be in this directory; these files will be directly used by the WRF model.
- The "wrf.exe" program is executed next (type **wrf.exe**), this should only take a few minutes (only a 12-h forecast is requested in the namelist file).
- The output file **wrfout_d01:2000-01-24_12:00:00** should contain a 12-h forecast at 3-h intervals.

Considerations for Recent Releases

- Since a new simple ocean model has been included in the WRF code, the old namelist option for activating an ocean mixed layer is no longer suitable. The variable OMLCALL has been switched to SF_OCEAN_PHYSICS.
- The default behavior of the base state has been modified. Starting with release version 3.5, the isothermal temperature is no longer zero. With this change, the base state temperature no longer gets colder than 200 K (default in the Registry, though a user can override this option with a namelist setting). This fixes the problem associated with layers being too thick near the model top. A side effect of thinning-out these model layers is that users may need to increase the number of vertical levels.
- The common availability of a valid seaice field in the input provided from the metgrid program has made obsolete the option to autoconvert "cold enough" water points to seaice. By default, the temperature at which water converts to seaice is now 100 K, a temperature cold enough that the option will never be triggered.

Chapter 5: WRF Model

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Introduction

The WRF model is a fully compressible and nonhydrostatic model (with a run-time hydrostatic option). Its vertical coordinate is selectable as either a terrain-following (TF)

or (beginning in Version 3.9) hybrid vertical coordinate (HVC) hydrostatic pressure coordinate. The grid staggering is the Arakawa C-grid. The model uses the Runge-Kutta 2nd and 3rd order time integration schemes, and 2nd to 6th order advection schemes in both the horizontal and vertical. It uses a time-split small step for acoustic and gravity-wave modes. The dynamics conserves scalar variables.

The WRF model code contains an initialization program (either for real-data, *real.exe*, or idealized data, *ideal.exe*; see Chapter 4), a numerical integration program (*wrf.exe*), a program to do one-way nesting (*ndown.exe*), and a program to do tropical storm bogussing (*tc.exe*). The WRF model, Version 3, supports a variety of capabilities. These include

- Real-data and idealized simulations
- Various lateral boundary condition options for real-data and idealized simulations
- Full physics options, and various filter options
- Positive-definite advection scheme
- Non-hydrostatic and hydrostatic (runtime option)
- One-way and two-way nesting, and a moving nest
- Three-dimensional analysis nudging
- Observation nudging
- Regional and global applications
- Digital filter initialization
- Vertical refinement in a child domain

Other References

- WRF tutorial presentation: http://www.mmm.ucar.edu/wrf/users/supports/tutorial.html
- WRF-ARW Tech Note: http://www.mmm.ucar.edu/wrf/users/pub-doc.html
- See chapter 2 of this document for software requirement.

Installing WRF

Before compiling the WRF code on a computer, check to see if the netCDF library is installed. This is because one of the supported WRF I/O options is netCDF, and it is the one commonly used and supported by the post-processing programs. If the netCDF is installed in a directory other than `/usr/local/`, then find the path, and use the environment variable NETCDF to define where the path is. To do so, type

```
setenv NETCDF path-to-netcdf-library
```

Often the netCDF library and its include/ directory are collocated. If this is not the case, create a directory, link both netCDF lib and include directories in this directory, and use the environment variable to set the path to this directory. For example,

```
netcdf_links/lib -> /netcdf-lib-dir/lib
netcdf_links/include -> /where-include-dir-is/include

setenv NETCDF /directory-where-netcdf_links-is/netcdf_links
```

If the netCDF library is not available on the computer, it needs to be installed first. NetCDF source code or pre-built binary may be downloaded from, and installation instruction can be found on, the Unidata Web page at http://www.unidata.ucar.edu/.

***Hint*:** for Linux users:

If PGI, Intel, gfortran or g95 compilers are are used on a Linux computer, make sure netCDF is installed using the same compiler. Use the NETCDF environment variable to point to the PGI/Intel/g95 compiled netCDF library.

Hint: If using netCDF-4, make sure that the new capabilities (such as parallel I/O based on HDF5) are not activated at the install time, unless you intend to use the compression capability from netCDF-4 (supported in V3.5. More info below).

The WRF source code tar file can be downloaded from http://www.mmm.ucar.edu/wrf/users/download/get_source.html. Once the tar file is unzipped (`gunzip WRFV3.TAR.gz`), and untared (`tar -xf WRFV3.TAR`), it will create a WRFV3/ directory. This contains:

`Makefile`	Top-level makefile
`README`	General information about the WRF/ARW core
`README_test_cases`	Explanation of the test cases
`README.NMM`	General information for the WRF/NMM core
`README.DA`	General information for WRFDA
`README.rsl_output`	Information for dealing with rsl files
`README.io_config`	Information for runtime IO
`README.windtrubine`	Information on using wind farm parameterization
`README.hydro`	Information on WRF-Hydro
`Registry/`	Directory for WRF Registry files
`arch/`	Directory where compile options are gathered
`clean`	script to clean created files and executables
`compile`	script for compiling the WRF code
`configure`	script to create the *configure.wrf* file for compiling
`chem/`	WRF chemistry, supported by NOAA/GSD

`dyn_em/`	Directory for ARW dynamics and numerics
`dyn_exp/`	Directory for a 'toy' dynamic core
`dyn_nmm/`	Directory for NMM dynamics and numerics, supported by DTC
`external/`	Directory that contains external packages, such as those for IO, time keeping and MPI
`frame/`	Directory that contains modules for the WRF framework
`inc/`	Directory that contains 'include' files
`main/`	Directory for main routines, such as wrf.F, and all executables after compilation
`phys/`	Directory for all physics modules
`run/`	Directory where one may run WRF
`share/`	Directory that contains mostly modules for the WRF mediation layer and WRF I/O
`test/`	Directory that contains test case directories, may be used to run WRF
`tools/`	Directory that contains tools for developers

The steps to compile and run the model are:

1. configure: generate a configuration file for compilation
2. compile: compile the code
3. run the model

Go to the WRFV3 (top) directory and type:

```
./configure
```

The build for the WRF model allows for a few options to be used with the configure command.

./configure –d *build the code with debugging turned on*

./configure –D *same as –d, plus bounds and range checking, uninitialized variables, floating traps*

./configure –r8 *build the code to use 64 bit reals for computation and output*

./configure –hyb *build the hybrid vertical coordinate option*

For any of the ./configure commands, a list of choices for your computer should appear. These choices range from compiling for a single processor job (serial), to using OpenMP

shared-memory (smpar), distributed-memory parallelization (dmpar) options for multiple processors, or a combination of shared-memory and distributed-memory options (dm+sm). When a selection is made, a second choice for compiling nesting will appear. For example, on a Linux computer, the above steps may look like:

```
> setenv NETCDF /usr/local/netcdf-pgi
> ./configure

checking for perl5... no
checking for perl... found /usr/bin/perl (perl)
Will use NETCDF in dir: /glade/apps/opt/netcdf/4.3.0/intel/12.1.5
HDF5 not set in environment. Will configure WRF for use without.
PHDF5 not set in environment. Will configure WRF for use without.
Will use 'time' to report timing information
$JASPERLIB or $JASPERINC not found in environment, configuring to build without grib2
I/O...
------------------------------------------------------------------------
Please select from among the following Linux x86_64 options:

  1. (serial)   2. (smpar)   3. (dmpar)   4. (dm+sm)   PGI (pgf90/gcc)
  5. (serial)   6. (smpar)   7. (dmpar)   8. (dm+sm)   PGI (pgf90/pgcc): SGI MPT
  9. (serial)  10. (smpar)  11. (dmpar)  12. (dm+sm)   PGI (pgf90/gcc): PGI accelerator
 13. (serial)  14. (smpar)  15. (dmpar)  16. (dm+sm)   INTEL (ifort/icc)
                                         17. (dm+sm)   INTEL (ifort/icc): Xeon Phi (MIC
architecture)
 18. (serial)  19. (smpar)  20. (dmpar)  21. (dm+sm)   INTEL (ifort/icc): Xeon (SNB with
AVX mods)
 22. (serial)  23. (smpar)  24. (dmpar)  25. (dm+sm)   INTEL (ifort/icc): SGI MPT
 26. (serial)  27. (smpar)  28. (dmpar)  29. (dm+sm)   INTEL (ifort/icc): IBM POE
 30. (serial)                31. (dmpar)               PATHSCALE (pathf90/pathcc)
 32. (serial)  33. (smpar)  34. (dmpar)  35. (dm+sm)   GNU (gfortran/gcc)
 36. (serial)  37. (smpar)  38. (dmpar)  39. (dm+sm)   IBM (xlf90_r/cc_r)
 40. (serial)  41. (smpar)  42. (dmpar)  43. (dm+sm)   PGI (ftn/gcc): Cray XC CLE
 44. (serial)  45. (smpar)  46. (dmpar)  47. (dm+sm)   CRAY CCE (ftn/cc): Cray XE and XC
 48. (serial)  49. (smpar)  50. (dmpar)  51. (dm+sm)   INTEL (ftn/icc): Cray XC
 52. (serial)  53. (smpar)  54. (dmpar)  55. (dm+sm)   PGI (pgf90/pgcc)
 56. (serial)  57. (smpar)  58. (dmpar)  59. (dm+sm)   PGI (pgf90/gcc): -f90=pgf90
 60. (serial)  61. (smpar)  62. (dmpar)  63. (dm+sm)   PGI (pgf90/pgcc): -f90=pgf90
 64. (serial)  65. (smpar)  66. (dmpar)  67. (dm+sm)   INTEL (ifort/icc): HSW/BDW
 68. (serial)  69. (smpar)  70. (dmpar)  71. (dm+sm)   INTEL (ifort/icc): KNL MIC
 72. (serial)  73. (smpar)  74. (dmpar)  75. (dm+sm)   FUJITSU (frtpx/fccpx): FX10/FX100
SPARC64 IXfx/Xlfx

Enter selection [1-75] : ------------------------------------------------------------------
-------
Compile for nesting? (0=no nesting, 1=basic, 2=preset moves, 3=vortex following) [default
0]:
```

Enter the appropriate options that are best for your computer and application.

When the return key is hit, a `configure.wrf` file will be created. Edit compile options/paths, if necessary.

Hint: It is helpful to start with something simple, such as the serial build. If it is successful, move on to build dmpar or smpar code. Remember to type '`./clean –a`' between each build when you either change one of the Registry files or when you change an option during the configure step.

Hint: If you would like to use parallel netCDF (p-netCDF) developed by Argonne National Lab (http://trac.mcs.anl.gov/projects/parallel-netcdf), you will need to install p-netCDF separately, and use the environment variable PNETCDF to set the path:

```
setenv PNETCDF path-to-pnetcdf-library
```

Hint: Since V3.5, compilation may take a bit longer due to the addition of the CLM4 module. If you do not intend to use the CLM4 land-surface model option, you can modify your `configure.wrf` file by removing `-DWRF_USE_CLM` from `ARCH_LOCAL`.

To compile the code, type

```
./compile
```

and the following choices will appear:

```
Usage:

compile wrf           compile wrf in run dir (Note, no real.exe,
ndown.exe or ideal.exe generated)

or choose a test case (see README_test_cases for details):

    compile em_b_wave
    compile em_convrad (new in V3.7)
    compile em_esmf_exp (example only)
    compile em_grav2d_x
    compile em_heldsuarez
    compile em_hill2d_x
    compile em_les
    compile em_quarter_ss
    compile em_real
    compile em_seabreeze2d_x
    compile em_squall2d_x
    compile em_squall2d_y
    compile em_tropical_cyclone
    compile exp_real (example of a toy solver)
    compile nmm_real (NMM solver)

compile -h              help message
```

where **em** stands for the Advanced Research WRF dynamic solver (which is the '**E**ulerian **m**ass-coordinate' solver). Type one of the above to compile. When you switch from one test case to another, you must type one of the above to recompile. The recompile is necessary to create a new initialization executable (i.e. `real.exe`, and `ideal.exe` - there is a different `ideal.exe` for each of the idealized test cases), while `wrf.exe` is the same for all test cases.

If you want to remove all object files (except those in the `external/` directory) and executables, type '`./clean`'.

Type `'./clean -a'` to remove built files in ALL directories, including `configure.wrf` (the original `configure.wrf` will be saved to `configure.wrf.backup`). The `'./clean -a'` command is required if you have edited the `configure.wrf` or any of the `Registry` files.

Beginning with V3.5, the compression function in netCDF4 is supported. This option will typically reduce the file size by more than 50%. It will require netCDF4 to be installed with the option `--enable-netcdf-4`. Before compiling WRF, you will need to set the environment variable NETCDF4. In a C-shell environment, type `setenv NETCDF4 1`, followed by '`configure`' and '`compile`'.

For more detailed information, visit:
http://www.mmm.ucar.edu/wrf/users/wrfv3.5/building-netcdf4.html

a. Idealized case

For any 2D test case (labeled in the case names), serial or OpenMP (smpar) compile options must be used. Additionally, you must only choose the '0=no nesting' option when you configure. For all other cases, you may use serial or parallel (dmpar) and nesting. Suppose you would like to compile and run the 2-dimensional squall case, type

```
./compile em_squall2d_x >& compile.log
```

After a successful compilation, you should have two executables created in the **`main`**/ directory: **`ideal.exe`** and **`wrf.exe`**. These two executables will be linked to the corresponding `test`/`case_name` and `run`/ directories. `cd` to either directory to run the model.

It is a good practice to save the entire compile output to a file. When the executables are not present, this output is useful to help diagnose the compile errors.

b. Real-data case

For a real-data case, type

```
./compile em_real >& compile.log &
```

When the compile is successful, it will create three executables in the **`main`**/directory: `ndown.exe`, `real.exe` and `wrf.exe`.

`real.exe`: for WRF initialization of real data cases
`ndown.exe` : for one-way nesting
`wrf.exe` : WRF model integration

Like in the idealized cases, these executables will be linked to the `test/em_real` and `run/` directories. `cd` to one of these two directories to run the model.

Running WRF

One may run the model executables in either the `run/` directory, or the `test/case_name` directory. In either case, one should see executables `ideal.exe` or `real.exe` (and `ndown.exe`), and `wrf.exe`, linked files (mostly for real-data cases), and one or more `namelist.input` files in the directory.

Hint: If you would like to run the model executables in a different directory, copy or link the files in the `test/em_*` directory to that directory, and run from there.

a. Idealized case

Suppose the test case `em_squall2d_x` is compiled. To run, type

```
cd test/em_squall2d_x
```

Edit the `namelist.input` file (see `README.namelist` in the `WRFV3/run/` directory or its Web version) to change length of integration, frequency of output, size of domain, timestep, physics options, and other parameters.

If you see a script in the test case directory, called `run_me_first.csh`, run this one first by typing:

```
./run_me_first.csh
```

This links some physics data files that might be needed to run the case.

*Note: when running *em_fire*, you must copy everything from the 'hill_simple' directory into your current working directory in order for it to run correctly.

```
cp hill_simple/* .
```

To run the initialization program, type

```
./ideal.exe
```

This program will typically read an input sounding file located in that directory, and generate an initial condition file `wrfinput_d01`. All idealized cases do not require a lateral boundary file because of the boundary condition choices they use, such as the

periodic option. If the job is run successfully, the last thing it prints should be: 'wrf: SUCCESS COMPLETE IDEAL INIT'.

To run the model and save the standard output to a file, type

```
./wrf.exe >& wrf.out &
```

or for a 3D test case compiled with MPI (dmpar) option,

```
mpirun -np 4 ./wrf.exe
```

If successful, the wrf output file will be written to a file named wrfout_d01_0001-01-01_00:00:00.

Pairs of rsl.out.* and rsl.error.* files will appear with any MPI runs. These are standard out and error files. Note that the execution command for MPI runs may be different on different machines and for different MPI installation. Check the user manual.

If the model run is successful, the last thing printed in the 'wrf.out' or rsl.*.0000 files should be: 'wrf: SUCCESS COMPLETE WRF'. Output files wrfout_d01_0001-01-01* and wrfrst* should be present in the run directory, depending on how namelist variables are specified for output. The time stamp on these files originates from the start times in the namelist file.

b. Real-data case

To make a real-data case run, cd to the working directory by typing

```
cd test/em_real (or cd run)
```

Start with the namelist.input template file in the directory and edit it to match your case.

Running a real-data case requires successfully running the **WRF Preprocessing System** programs (or WPS). Make sure met_em.* files from WPS are seen in the run directory (either link or copy the files):

```
cd test/em_real
ls -l ../../../WPS/met_em*
ln -s ../../..WPS/met_em* .
```

Make sure you edit the variables in the &time_control and &domains sections of the namelist.input file (the description of the namelists can be found in the later part of this chapter):

```
&time_control
 run_days                            = 0,
```

```
 run_hours                           = 24,
 run_minutes                         = 0,
 run_seconds                         = 0,
 start_year                          = 2000, 2000, 2000,
 start_month                         = 01,   01,   01,
 start_day                           = 24,   24,   24,
 start_hour                          = 12,   12,   12,
 end_year                            = 2000, 2000, 2000,
 end_month                           = 01,   01,   01,
 end_day                             = 25,   25,   25,
 end_hour                            = 12,   12,   12,
 interval_seconds                    = 21600
 input_from_file                     = .true.,.true.,.true.,
 history_interval                    = 180,  60,   60,
 frames_per_outfile                  = 1000, 1000, 1000,
/

&domains
 time_step                           = 180,
 max_dom                             = 1,
 e_we                                = 74,    112,   94,
 e_sn                                = 61,    97,    91,
 e_vert                              = 30,    30,    30,
 p_top_requested                     = 5000,
 num_metgrid_levels                  = 27,
 num_metgrid_soil_levels             = 4,
 dx                                  = 30000, 10000,  3333.33,
 dy                                  = 30000, 10000,  3333.33,
 grid_id                             = 1,     2,     3,
 parent_id                           = 0,     1,     2,
 i_parent_start                      = 1,     31,    30,
 j_parent_start                      = 1,     17,    30,
 parent_grid_ratio                   = 1,     3,     3,
 parent_time_step_ratio              = 1,     3,     3,
/
```

Make sure that the dates and dimensions of the domain match those set in WPS. If only one domain is used, entries in other columns will be ignored.

Other options for use to assist vertical interpolation in `&domains` are:

```
 interp_type                         = 2
 extrap_type                         = 2
 t_extrap_type                       = 2
 lowest_lev_from_sfc                 = .false.
 use_levels_below_ground             = .true.
 use_surface                         = .true.
 lagrange_order                      = 1
 force_sfc_in_vinterp                = 1
 zap_close_levels                    = 500
 sfcp_to_sfcp                        = .false.
 adjust_heights                      = .false.
 smooth_cg_topo                      = .false.
```

To run the real-data initialization program, compiled using serial or OpenMP (smpar) options, type

```
./real.exe >& real.out
```

Successful completion of the job should have 'real_em: SUCCESS EM_REAL INIT' printed at the end of the real.out file. It should also produce wrfinput_d01 and wrfbdy_d01 files. In the real data case, both files are required.

Run the WRF model by typing

```
./wrf.exe
```

A successful run should produce one or several output files with names like `wrfout_d<domain>_<date>` (where `<domain>` represents domain ID, and `<date>` represents a date string with the format `yyyy-mm-dd_hh:mm:ss`. For example, if you start the model at 1200 UTC, January 24 2000, then your first output file should have the name:

```
wrfout_d01_2000-01-24_12:00:00
```

The time stamp on the file name is always the first time the output file is written. It is always good to check the times written to the output file by typing:

```
ncdump -v Times wrfout_d01_2000-01-24_12:00:00
```

You may have other wrfout files, depending on the namelist options (how often you split the output files is determined by the namelist option `frames_per_outfile`). You may also create restart files if you have a restart frequency (`restart_interval` in the namelist.input file) set within your total integration time. The restart file(s) should have the following naming convention

```
wrfrst_d<domain>_<date>
```

The time stamp on a restart file is the time at which that restart file is valid.

For DM (distributed memory) parallel systems, some form of the **mpirun** command will be needed to run the executables. For example, on a Linux cluster, the command to run MPI code, using 4 processors, may look like:

```
mpirun -np 4 ./real.exe
mpirun -np 4 ./wrf.exe
```

or

`mpiexec_mpt ./wrf.exe` (on NCAR's *cheyenne*)

c. Restart Run

A restart run allows a user to extend a run to a longer simulation period. It is effectively a continuous run made of several shorter runs. Hence the results at the end of one or more restart runs should be identical to a single run without any restart.

In order to do a restart run, one must first create a restart file. This is done by setting the namelist variable `restart_interval` (default unit is in minutes) to be equal to or less than the simulation length in the first model run, as specified by `run_*` variables or `start_*` and `end_*` times. When the model reaches the time to write a restart file, a restart file named `wrfrst_d<domain>_<date>` will be written. The date string represents the time when the restart file is valid.

When one starts the restart run, edit the `namelist.input` file, so that your `start_*` time will be set to the restart time (which is the time the restart file is written). The other namelist variable one must set is `restart`, this variable should be set to .true. for a restart run.

In summary, these namelist entries should be modified:

`start_*, end_*:`	start and end times for restart model integration
`restart:`	logical to indicate whether the run is a restart or not

If the history and restart intervals are changed in a restart run, and the outcome isn't what is expected to be, use namelist '`override_restart_timers = .true.`'.

If history output is desired at the time of restart, use namelist
'`write_hist_at_0h_rst = .true.`'

***Hint*:** Typically the restart file is several times the size of the history file, hence one may find that it is even ok to write a single model history output time to a file in netCDF format (`frame_per_outfile=1`), but it may fail to write a restart file. This is because the basic netCDF file support is only 2Gb (with WRF v3.9, this restriction is removed by default). There are two solutions to the problem. The first is to simply set the namelist option `io_form_restart = 102` (instead of 2), and this will force the restart file to be written into multiple pieces, one per processor. As long as one restarts the model using the same number of processors, this option works well (and one should restart the model with the same number of processors in any case). The second solution is to recompile the code using the netCDF large file support option (for WRF versions before v3.9: see the section on "Installing WRF" in this chapter).

d. Two-way Nested Runs

A two-way nested run is a run in which multiple domains at different grid resolutions are run simultaneously and communicate with each other: The coarser domain provides

boundary values for the nest, and the nest feeds its calculation back to the coarser domain. The model can handle multiple domains at the same nest level (no overlapping nest), and multiple nest levels (telescoping).

When preparing for a nested run, make sure that the code is compiled with basic nest options (option 1).

Most of options to start a nest run are handled through the namelist. ***All variables in the*** `namelist.input` ***file that have multiple columns of entries need to be edited with caution***. Start with a namelist template. The following are the key namelist variables to modify:

`start_*, end_*`: start and end simulation times for the nest

`input_from_file`: whether a nest requires an input file (e.g. `wrfinput_d02`). This is typically used for a real data case, since the nest input file contains nest topography and land information.

`fine_input_stream`: which fields from the nest input file are used in nest initialization. The fields to be used are defined in the Registry.EM. Typically they include static fields (such as terrain and landuse), and masked surface fields (such as skin temperature, soil moisture and temperature). Useful for a nest starting at a later time than the coarse domain.

`max_dom`: the total number of domains to run. For example, if you want to have one coarse domain and one nest, set this variable to 2.

`grid_id`: domain identifier that is used in the wrfout naming convention. The most coarse grid must have grid_id of 1.

`parent_id`: used to indicate the parent domain of a nest. `grid_id` value is used.

`i_parent_start/j_parent_start`: lower-left corner starting indices of the nest domain in its parent domain. These parameters should be the same as in `namelist.wps`.

`parent_grid_ratio`: integer parent-to-nest domain grid size ratio. Typically an odd number ratio is used in real-data applications.

`parent_time_step_ratio`: integer time-step ratio for the nest domain. It may be different from the `parent_grid_ratio`, though they are typically set the same.

`feedback`: this is the key setup to define a two-way nested (or one-way nested) run. When feedback is on, the values of the coarse domain are overwritten by the values of the variables (average of cell values for mass points, and average of the cell-face values for horizontal momentum points) in the nest at the coincident points. For masked fields, only the single point value at the collocating points is fed back. If the `parent_grid_ratio` is even, an arbitrary choice of the southwest corner point value

is used for feedback. This is the reason it is better to use an odd `parent_grid_ratio` with this option. When feedback is off , it is equivalent to a one-way nested run, since nest results are not reflected in the parent domain.

`smooth_option`: this a smoothing option for the parent domain in the area of the nest if *feedback* is on. Three options are available: 0 = no smoothing; 1 = 1-2-1 smoothing; 2 = smoothing-desmoothing.

3-D Idealized Cases

For 3-D idealized cases, no nest input files are required. The key here is the specification of the `namelist.input` file. What the model does is to interpolate all variables required in the nest from the coarse domain fields. Set

```
input_from_file = T, F,
```

Real Data Cases

For real-data cases, three input options are supported. The first one is similar to running the idealized cases. That is to have all fields for the nest interpolated from the coarse domain (`input_from_file = T, F`). The disadvantage of this option is obvious: one will not benefit from the higher resolution static fields (such as terrain, landuse, and so on).

The second option is to set `input_from_file = T` for each domain, which means that the nest will have a nest wrfinput file to read in. The limitation of this option is that this only allows the nest to start at the same time as the coarse domain.

The third option is, in addition to setting `input_from_file = T` for each domain, also set `fine_input_stream = 2` for each domain. Why a value of 2? This is based on the Registry setting, which designates certain fields to be read in from the auxiliary input stream number 2. This option allows the nest initialization to use 3-D meteorological fields interpolated from the coarse domain, static fields and masked, and time-varying surface fields from the nest wrfinput; hence it allows a nest to start at a later time than hour 0. Setting `fine_input_stream = 0` is equivalent to the second option.

To run `real.exe` for a nested run, one must first run WPS and create data for all the nests. Suppose WPS is run for a 24 hour period, two-domain nested case starting at 1200 UTC Jan 24 2000. Then the following files should be generated in a WPS directory:

```
met_em.d01.2000-01-24_12:00:00
met_em.d01.2000-01-24_18:00:00
met_em.d01.2000-01-25_00:00:00
met_em.d01.2000-01-25_06:00:00
```

```
met_em.d01.2000-01-25_12:00:00
met_em.d02.2000-01-24_12:00:00
```

Typically only the first time period of the nest input file is needed to create a nest wrfinput file. Link or move all these files to the run directory.

Edit the `namelist.input` file and set the correct values for all relevant variables, described on the previous pages (in particular, set `max_dom = 2`, for the total number of domains to run), as well as physics options. Type the following to run:

```
./real.exe >& real.out
```
or
```
mpirun -np 4 ./real.exe
```

If successful, this will create all input files for coarse, as well as nested domains. For a two-domain example, these are created:

```
wrfinput_d01
wrfinput_d02
wrfbdy_d01
```

To run WRF, type

```
./wrf.exe
```
or
```
mpirun -np 4 ./wrf.exe
```

If successful, the model should create wrfout files for both domain 1 and 2:

```
wrfout_d01_2000-01-24_12:00:00
wrfout_d02_2000-01-24_12:00:00
```

e. One-way Nested Run Using ndown

WRF supports two separate one-way nested options. In this section, one-way nesting is defined as a finer-grid-resolution run, made as a subsequent run after the coarser-grid-resolution run, where the `ndown` program is run in-between the two simulations. The initial and lateral boundary conditions for this finer-grid run are obtained from the coarse grid run, with input from higher resolution terrestrial fields (e.g. terrain, landuse, etc.), and masked surface fields (such as soil temperature and moisture). The program that performs this task is `ndown.exe`.

***Note** that the use of this program requires the code to be compiled for nesting.

When one-way nesting is used, the coarse-to-fine grid ratio is only restricted to be an integer. An integer less than or equal to 5 is recommended. Frequent output (e.g. hourly) from the coarse grid run is also recommended to provide better boundary specifications.

Do not change physics options when running `ndown` (you can change some physics options when making wrf runs), and do not remove fields from Registry if you plan to use `ndown`.

Step 1: Make a coarse grid run.

This is no different than any of the single-domain WRF runs, as described above. Do output history files as often as you can, and this will provide better and more frequent boundary conditions for the next model run.

Step 2: Run geogrid.exe (gives geo_em.d01 and geo_em.d02 files) and metgrid.exe for two domains (as if you are making a 2-way nested run).

This will generate WPS output files for domain 1 (`met_em.d01.<date>`) and domain 2 (`met_em.d02.<date>`).

Step 3: Run real.exe for 2 domains.

The purpose of this step is to ingest higher resolution terrestrial fields and corresponding land-water masked soil fields.

- Copy the `met_em*` files into the directory in which you will be running real.exe.
- Edit the *`namelist.input`* file, changing 'max_dom = 2', and making sure columns 1 and 2 are set-up for a 2 domain run, editting the correct start time and grid dimensions.
- Run **`real.exe`**. This will produce a `wrfinput_d01` file, a `wrfinput_d02` file, and a `wrfbdy_d01` file.
- Rename the `wrfinput_d02` file to `wrfndi_d02`.

Step 4: Make the final fine-grid initial and boundary condition files, by running ndown.exe

- Since V3.2, one must add *`io_form_auxinput2`* = `2` in the `&time_control` section of *`namelist.input`* to run *ndown.exe* successfully. (If one desires to refine the vertical resolution when running *`ndown,`* set *`vert_refine_fact = integer`* (new in V3.2). There are no other changes required in the namelist or in the procedure. Another way to refine vertical resolution is to use the utility program *`v_interp`* (see the chapter for 'Utilities and Tools' for details)).

- Change namelist variable *`interval_seconds`* to reflect the history output interval from the coarse domain model run.

- Do not change physics options until after running the `ndown` program.

- Run **`ndown.exe`**, which uses input from the coarse grid `wrfout` file(s), and the `wrfndi_d02` file generated from Step 3 above. This will produce a `wrfinput_d02` and `wrfbdy_d02` file.

Note that the program `ndown` may be run serially or in MPI, depending on the selected compile option. The `ndown` program must be built to support nesting, however. To run the program, type

```
./ndown.exe
```
or
```
mpirun -np 4 ./ndown.exe
```

Step 5: Make the fine-grid WRF run

- Rename `wrfinput_d02` and `wrfbdy_d02` to `wrfinput_d01` and `wrfbdy_d01`, respectively.

- Rename (or move) the original `wrfout_d01*` files to something else (or another directory) so as to not overwrite them.

- Edit *`namelist.input`*, moving all of the fine-grid domain data from column 2 to column 1 so that this run will be for the fine-grid domain only. Make sure that the `time_step` is set to comply with the fine-grid domain (typically 6*DX). It may be beneficial to save `namelist.input` to something else prior to this step in case you need to repeat this process in the future. Save the newly-edited namelist as `namelist.input`.

- The WRF model's physics options may be modified between runs (the WRF model before ndown and the WRF model after ndown, but do use the same physics from the first run when running ndown), except generally for the land surface scheme option which has different number of soil depths depending on the scheme. Users may take advantage of a feature that allows both the initial and lateral boundaries to use the `moist` and `scalar` arrays (`have_bcs_moist` and `have_bcs_scalar`, respectively). This option is only to be used during the WRF model run which follows the ndown processing. With this option, a user must keep the microphysics options the same between forecasts. The advantage is that the previous WRF model provides realistic lateral boundary tendencies for all of the microphysical variables, instead of a simple "zero inflow" or "zero gradient outflow".

- Run WRF for this grid.

*Keep in mind that the output from this run will be in the form `wrfout_d01*` but it will actually be output for domain 2. It may help to rename these to avoid future confusion.

Running ndown.exe for Three or More Domains

It is possible to use the ndown program to run for more than one nest, but the procedure is a bit cumbersome. Because of the way the code it written, it expects particular file names (specifically for d01 and d02), and therefore it is important to follow these steps precisely:

Note: This example is for nesting down to a 3rd domain (3 domains total), and assumes that you already have wrfout_d01* files from a previous run.

Step A: Run the geogrid.exe and metgrid.exe programs for 3 domains. You should have files `met_em.d01.<date>`, `met_em.d02.<date>`, and `met_em.d03.<date>`.

Step B: Run real.exe for 3 domains.

- Copy the `met_em*` files into the directory in which you will be running real.exe.
- Edit the *`namelist.input`* file, changing 'max_dom = 3', and making sure columns 1, 2 and 3 are set-up for a 3 domain run, editting the correct start time and grid dimensions.
- Run **`real.exe`**. This will produce a `wrfinput_d01`, `wrfinput_d02`, a `wrfinput_d03` file, and a `wrfbdy_d01` file.
- Rename the `wrfinput_d02` file to `wrfndi_d02`.

Step C: Make the domain 02 grid initial and boundary condition files, by running ndown.exe (see the details in step 4 above)

Step D: Make the domain 2 WRF run (see the details in step 5 above). You will now have new files named `wrfout_d01*` which will correspond to domain 02.

Step E: Make the domain 03 grid initial and boundary condition files, by running ndown.exe

- Rename the `wrfinput_d03` file to `wrfndi_d02` (this is the name the program expects)

-Make sure the namelist still has *`io_form_auxinput2`* = 2 in the `&time_control` section.

- Change namelist variable *`interval_seconds`* to reflect the history output interval from the coarse domain model run.

- Do not change physics options until after running the `ndown` program.

- Run **`ndown.exe`**, which uses input from the (new) coarse grid `wrfout` file(s), and the `wrfndi_d02` file. This will produce a `wrfinput_d02` and `wrfbdy_d02` file (which will actually correspond to domain 03).

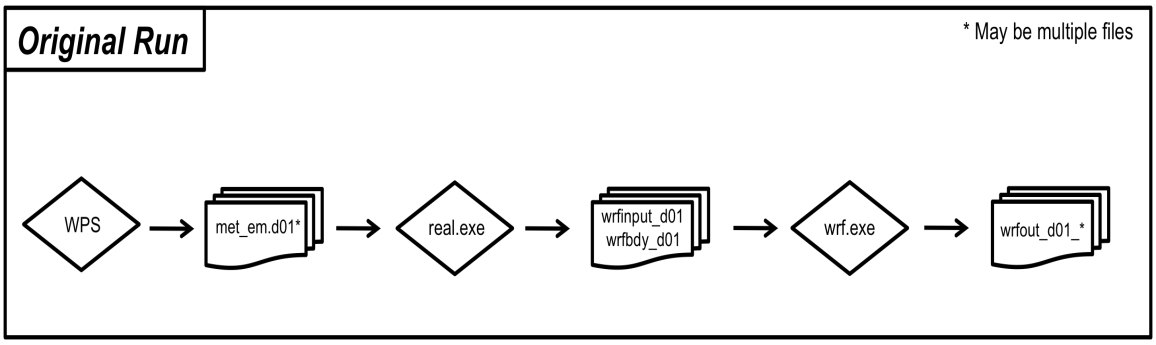
Step F: Make the fine-grid (d03) WRF run.

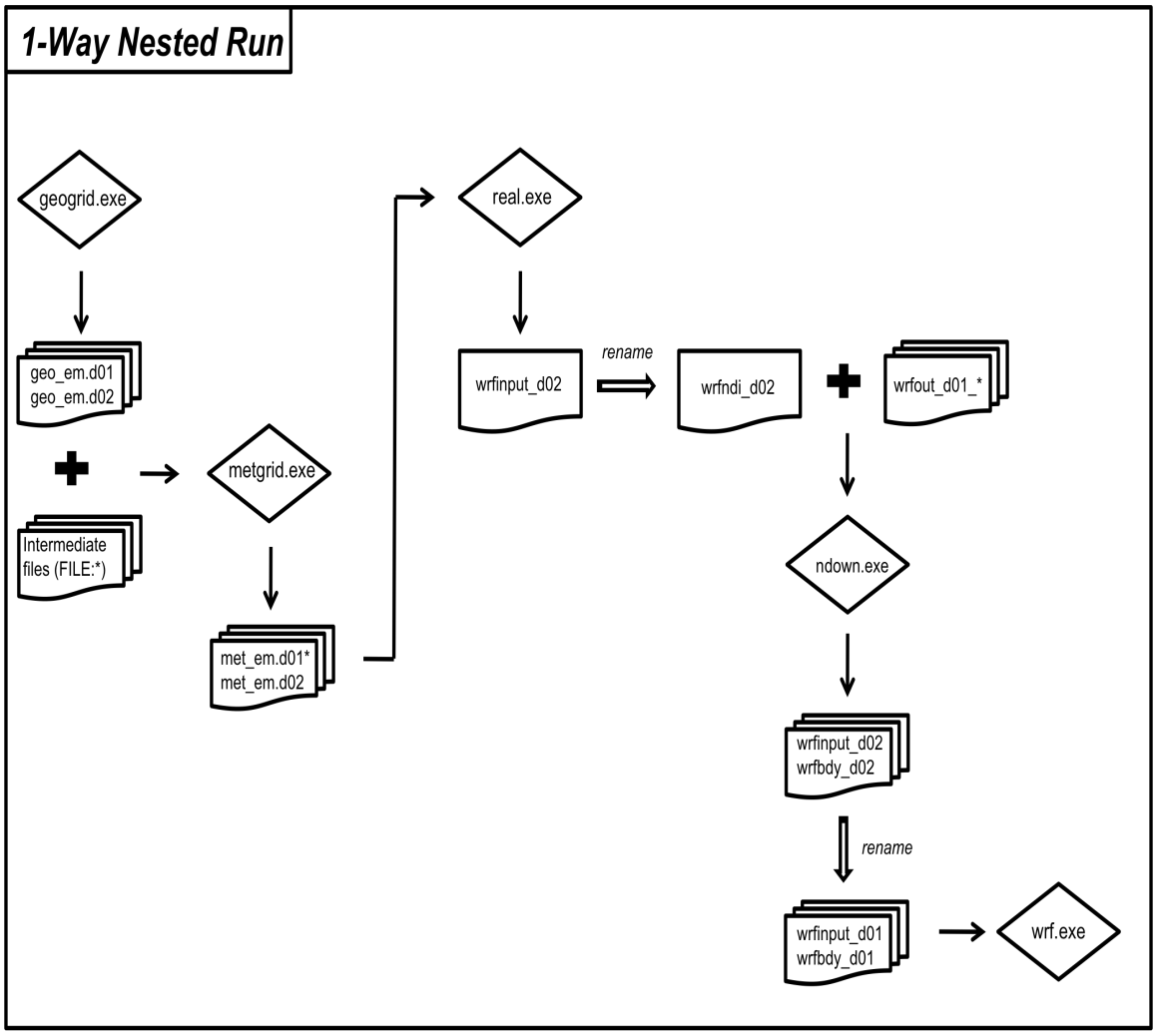
- Rename `wrfinput_d02` and `wrfbdy_d02` to `wrfinput_d01` and `wrfbdy_d01`, respectively.

- Rename (or move) the `wrfout_d01*` files to something else (or another directory) so as to not overwrite them (recall that these files correspond to d02).
- Edit *`namelist.input`*, moving all of the fine-grid domain data from column 3 to column 1 so that this run will be for the fine-grid domain only. Make sure that the `time_step` is set to comply with the fine-grid domain (typically 6*DX). It may be beneficial to save `namelist.input` to something else prior to this step in case you need to repeat this process in the future. Save the newly-edited namelist as `namelist.input`.

After running wrf.exe, you will have new `wrfout_d01*` files. These will correspond to domain 03. If you need to add any more nests, follow the same format, keeping the naming convention the same.

The figure on the next page summarizes the data flow for a one-way nested run using the program `ndown`.





f. Moving-Nested Run

Two types of moving tests are allowed in WRF. In the first option, a user specifies the nest movement in the namelist. The second option is to move the nest automatically, based on an automatic vortex-following algorithm. This option is designed to follow the movement of a well-defined tropical cyclone.

To make the specified moving nested run, select the right nesting compile option (option 'preset moves'). Note that code compiled with this option will not support static nested runs. To run the model, only the coarse grid input files are required. In this option, the

nest initialization is defined from the coarse grid data - no nest input is used. In addition to the namelist options applied to a nested run, the following needs to be added to the namelist section `&domains`:

`num_moves`: the total number of moves one can make in a model run. A move of any domain counts against this total. The maximum is currently set to 50, but it can be changed by changing MAX_MOVES in `frame/module_driver_constants.F`.

`move_id`: a list of nest IDs, one per move, indicating which domain is to move for a given move.

`move_interval`: the number of minutes from the beginning of the run until a move is supposed to occur. The nest will move on the next time step after the specified instant of model time has passed.

`move_cd_x,move_cd_y`: distance in the number of grid points and direction of the nest move (positive numbers indicate moving toward east and north, while negative numbers indicate moving toward west and south).

Parameter `max_moves` is set to be 50, but can be modified in the source code file *frame/module_driver_constants.F,* if needed.

To make the automatic moving nested runs, select the 'vortex-following' option when configuring. Again note that this compile would only support the auto-moving nest, and will not support the specified moving nested run or static nested run at the same time. Again, no nest input is needed. If one wants to use values other than the default ones, add and edit the following namelist variables in the `&domains` section:

`vortex_interval`: how often the vortex position is calculated in minutes (default is 15 minutes).

`max_vortex_speed`: used with *vortex_interval* to compute the search radius for the new vortex center position (default is 40 m/sec).

`corral_dist`: the distance in the number of coarse grid cells that the moving nest is allowed to get near the mother domain boundary (default is 8). This parameter can be used to center the telescoped nests so that all nests are moved together with the storm.

`track_level`: the pressure level (in Pa) where the vortex is tracked.

`time_to_move`: the time (in minutes) to move a nest. This option may help with the case when the storm is still too weak to be tracked by the algorithm.

When the automatic moving nest is employed, the model dumps the vortex center location, with minimum mean sea-level pressure and maximum 10-m winds in a standard-out file (e.g. `rsl.out.0000`). Typing '`grep ATCF rsl.out.0000`' will produce a list of storm information at a 15-minute interval:

```
ATCF    2007-08-20_12:00:00           20.37   -81.80     929.7      133.9
ATCF    2007-08-20_12:15:00           20.29   -81.76     929.3      133.2
```

In both types of moving-nest runs, the initial location of the nest is specified through `i_parent_start` and `j_parent_start` in the `namelist.input` file.

Since V3.6, a capability to incorporate high-resolution terrain and landuse input in a moving nest run (Chen, Shuyi S., Wei Zhao, Mark A. Donelan, James F. Price, Edward J. Walsh, 2007: The CBLAST-Hurricane Program and the Next-Generation Fully Coupled Atmosphere–Wave–Ocean Models for Hurricane Research and Prediction. *Bull. Amer. Meteor. Soc.*, **88**, 311–317.doi: http://dx.doi.org/10.1175/BAMS-88-3-311). To activate this option,

- At compile time, one needs to set environment variable, TERRAIN_AND_LANDUSE to 1. In cshell,

```
setenv TERRAIN_AND_LANDUSE 1
```

followed by doing 'configure' and 'compile'.

- At run time, add these namelists in &time_control:

```
input_from_hires       = .true., .true.,
rsmas_data_path        = "terrain_and_landuse_data_directory"
```

The automatic moving nest works best for a well-developed vortex.

g. Analysis Nudging Runs (Upper-Air and/or Surface)

Prepare input data to WRF as usual using WPS. If nudging is desired in the nest domains, make sure all time periods for all domains are processed in WPS. For surface-analysis nudging (new in Version 3.1), OBSGRID needs to be run after METGRID, and it will output a `wrfsfdda_d01` file that the WRF model reads for this option.

Set the following options before running `real.exe`, in addition to others described earlier (see the namelists in `examples.namelist` in the `test/em_real/` directory, for guidance):

```
grid_fdda = 1
grid_sfdda = 1
```

Run `real.exe` as before, and this will create, in addition to `wrfinput_d0*` and `wrfbdy_d01` files, a file named `'wrffdda_d0*'`. Other grid-nudging namelists are ignored at this stage, but it is good practice to fill them all in before one runs `real`. In particular, set

```
gfdda_inname    =  "wrffdda_d<domain>"
gfdda_interval  = time interval of input data in minutes
gfdda_end_h     = end time of grid-nudging in hours

sgfdda_inname    =  "wrfsfdda_d<domain>"
sgfdda_interval  = time interval of input data in minutes
sgfdda_end_h     = end time of surface grid-nudging in hours
```

See http://www2.mmm.ucar.edu/wrf/users/wrfv3.1/How_to_run_grid_fdda.html and `README.grid_fdda` in `WRFV3/test/em_real/` for more information.

A different surface data nudging option is added in V3.8, and activated by setting

```
grid_sfdda = 2
```

This option nudges surface air temperature and water vapor mixing ratio similar to that with option 1, but uses the tendencies generated from the direct nudging approach to constrain surface sensible and latent heat fluxes, thus ensuring thermodynamic consistency between the atmosphere and land surface. This works with YSU PBL and Noah LSM. (Alapaty et al. JAMC, 2008)

Spectral Nudging is a new upper-air nudging option since Version 3.1. This selectively nudges the coarser scales only, but is otherwise set up the same way as grid-nudging. This option also nudges geopotential height. The wave numbers defined here are the number of waves contained in the domain, and the number is the maximum one that is nudged.

```
grid_fdda = 2
xwavenum = 3
ywavenum = 3
```

h. Observation Nudging Run

In addition to the usual input data preparation using WPS, station observation files are required. See the Observation Nudging User's Guide and http://www2.mmm.ucar.edu/wrf/users/wrfv3.1/How_to_run_obs_fdda.html for details. The observation file names expected by WRF are `OBS_DOMAIN101` for domain 1, and `OBS_DOMAIN201` for domain 2, etc.

Observation nudging is activated in the model by the following namelists in `&fdda`:

```
obs_nudge_opt = 1
fdda_start    = 0 (obs nudging start time in minutes)
fdda_end      = 360 (obs nudging end time in minutes)
```

and in &time_control

auxinput11_interval_s = 180, 180, 180, (set the interval to be small enough so that all observations will be checked)

Look for an example to set other obs nudging namelist variables in the file examples.namelists in test/em_real/ directory. See The Observation Nudging User's Guide, http://www2.mmm.ucar.edu/wrf/users/wrfv3.1/How_to_run_obs_fdda.html, and README.obs_fdda in WRFV3/test/em_real/ for more information.

i. Global Run

WRFV3 supports global capability. To make a global run, run WPS, starting with the namelist template namelist.wps.gloabl. Set map_proj = 'lat-lon', and grid dimensions e_we and e_sn without setting dx and dy in namelist.wps. The geogrid program will calculate grid distances, and their values can be found in the global attribute section of geo_em.d01.nc file. Type ncdump -h geo_em.d01.nc to find out the grid distances, which will be needed in filling out WRF's namelist.input file. Grid distances in x and y directions may be different, but it is best that they are set similarly or the same. WRF and WPS assume the earth is a sphere, and its radius is 6370 km. There are no restrictions on what to use for grid dimensions, but for effective use of the polar filter in WRF, the east-west dimension should be set to $2^P*3^Q*5^R+1$ (where P, Q, and R are any integers, including 0).

Run the rest of the WPS programs as usual but only for one time period. This is because the domain covers the entire globe, and lateral boundary conditions are no longer needed.

Run the program real.exe as usual and for one time period only. The lateral boundary file wrfbdy_d01 is not needed.

Copy namelist.input.global to namelist.input, and edit it. Run the model as usual.

Note: since this is not a commonly-used configuration in the model, use it with caution. Not all physics and diffusion options have been tested with it, and some options may not work well with polar filters. Also, positive-definite and monotonic advection options do not work with polar filters in a global run because polar filters can generate negative values of scalars. This implies, too, that WRF-Chem cannot be run with positive-definite and monotonic options in a global WRF setup.

As an extension to the global lat-lon grid, the regional domain can also be set using a lat-lon grid. To do so, one needs to set both grid dimensions, and grid distances in degrees. Again geogrid will calculate the grid distance, assuming the earth is a sphere and its

radius is 6370 km. Find the grid distance in meters in the netCDF file, and use the value for WRF's `namelist.input` file.

j. Using Digital Filter Initialization

Digital filter initialization (DFI) is a new option in V3. It is a way to remove initial model imbalance as, for example, measured by the surface pressure tendency. This might be important when one is interested in the 0 – 6 hour simulation/forecast. It runs a digital filter during a short model integration, backward and forward, and then starts the forecast. In WRF implementation, this is all done in a single job. With the V3.3 release, DFI can be used for multiple domains with concurrent nesting, with feedback disabled.

There is no special requirement for data preparation.

Start with the namelist template `namelist.input.dfi.` This namelist file contains an extra namelist record for DFI: `&dfi_control`. Edit it to match your case configuration. For a typical application, the following options are used:

`dfi_opt` = 3 (Note: if doing a restart, this must be changed to 0)
`dfi_nfilter` = 7 (filter option: Dolph)
`dfi_cutoff_seconds` = 3600 (should not be longer than the filter window)
For time specification, it typically needs to integrate backward for 0.5 to 1 hour, and integrate forward for half of the time.

If option `dfi_write_filtered_input` is set to true, a filtered wrfinput file, `wrfinput_initialized_d01`, will be produced when you run wrf.

In Version 3.2, a constant boundary condition option is introduced for DFI. To use it, set `constant_bc = 1` in `&bdy_control`

If a different time step is used for DFI, one may use `time_step_dfi` to set it.

k. Using the sst_update option

The WRF model physics do not predict sea-surface temperature, vegetation fraction, albedo or sea ice. For long simulations, the model provides an alternative to read-in the time-varying data and to update these fields. In order to use this option, one must have access to time-varying SST and sea ice fields. Twelve monthly values of vegetation fraction and albedo are available from the `geogrid` program. Once these fields are processed via WPS, one may activate the following options in the namelist record `&time_control` before running the program `real.exe` and `wrf.exe`:

`io_form_auxinput4` = 2
`auxinput4_inname` = "wrflowinp_d<domain>" (created by `real.exe`)
`auxinput4_interval` = 360, 360, 360,

and in *&physics*

```
sst_update = 1
```

Note that this option doesn't work with sf_ocean_physics options.

l. Using bucket_mm and bucket_J options

These options are for long simulation rainfall accumulations and radiation budget accumulation terms (RAINC, RAINNC, ACSWUPT, ACLWDNBC, etc.). With 32-bit accuracy, adding small numbers to very large numbers loses accuracy as the accumulation term increases. For simulations of days to weeks, the accumulations are usually okay, but for months to years, this has the effect of truncating the additions, and especially small ones may be zeroed-out.

When these options are activated, part of the term is stored in an integer that increments by 1 each time the bucket value is reached, so we have two terms - RAINNC and I_RAINNC, where RAINNC now only contains the remainder. The total is retrieved from the output with total = RAINNC+bucket_mm*I_RAINNC. A reasonable bucket value may be based on a monthly accumulation such as 100 mm. Total precipitation equals RAINC + RAINNC, where

Total RAINNC = RAINNC+bucket_mm*I_RAINNC

Total RAINC = RAINC+bucket_mm*I_RAINC

The radiation accumulation terms (e.g., ACSWUPT) are in Joules/m^2, so that the mean value over a simulation period is the difference divided by the time between, giving W/m^2.

The bucket_J option is for these terms, and the typical value, based on a monthly accumulation, is 1.e9 J. Here the total is given by (ACSWUPT example - other radiative terms would follow the same equation concept):

total = ACSWUPT+bucket_J*I_ACSWUPT

m. Using Adaptive Time Stepping

Adaptive time stepping is a way to maximize the time step that the model can use while keeping the model numerically stable. The model time step is adjusted based on the domain-wide horizontal and vertical stability criterion (called the Courant-Friedrichs-Lewy (CFL) condition). The following set of values would typically work well.

```
use_adaptive_time_step = .true.
step_to_output_time = .true. (but nested domains may still be writing output at
```

the desired time. Try to use `adjust_output_times` = .true. to make up for this.)
`target_cfl` = 1.2, 1.2, 1.2,
`max_step_increase_pct` = 5, 51, 51, (a large percentage value for the nest allows the time step for the nest to have more freedom to adjust)
`starting_time_step` = the actual value or -1 (which means 4*DX at start time)
`max_time_step` : use fixed values for all domains, e.g. 8*DX
`min_time_step` : use fixed values for all domains, e.g. 3*DX
`adaptation_domain`: which domain is driving the adaptive time step

Also see the description of these options in the list of namelist on page 5-43.

n. Stochastic parameterization schemes

The stochastic parameterization suite comprises a number of stochastic parameterization schemes, some widely used and some developed for very specific applications. It can be used to represent model uncertainty in ensemble simulations by applying a small perturbation at every time step to each member. Each of these schemes generates its own random perturbation field characterized by spatial and temporal correlations and an overall perturbation amplitude defined in the namelist record &stoch (since version 3.6).

Random perturbations are generated on the parent domain at every time step and by default, interpolated to the nested domain(s). The namelist settings determine on which domains these perturbations are applied. By setting, e.g. sppt=0,1,1 the perturbations would be applied on the nested domains only.

Since the scheme uses Fast Fourier Transforms (FFTs) provided in the library FFTPACK, we recommend the number of gridpoints in each direction to be a product of small primes. If the number of gridpoints is a large prime in at least one of the directions, the computational cost may increase substantially.

Random perturbation field (rand_perturb=1)

This option generates a 3-D Gaussian random perturbation field for user-implemented applications.The perturbation field is saved as `rand_pert` in the history files (available starting with version 3.7).

Stochastically perturbed physics tendencies (SPPT) (sppt=1)

A random pattern is used to perturb the accumulated physics tendencies (except those from micro-physics) of potential temperature, wind and humidity. For details on the WRF implementation see Berner et al., 2015 (http://journals.ametsoc.org/doi/abs/10.1175/MWR-D-14-00091.1). The perturbation field is saved as `rstoch` in the history files (available starting with version 3.9).

Stochastic kinetic-energy backscatter scheme (SKEBS) (skebs=1)

A random pattern is used to perturb the potential temperature and rotational wind component. The perturbation fields are saved as `ru_tendf_stoch, rv_tendf_stoch, rt_tendf_stoch` in the history files for u,v and θ, respectively. For details on the WRF implementation see Berner et al., 2011 http://journals.ametsoc.org/doi/abs/10.1175/2010MWR3595.1) and. http://www.cgd.ucar.edu/~berner/skebs.html) Wind perturbations are proportional to the square root of the kinetic-energy backscatter rate, and temperature perturbations are proportional to the potential energy backscatter rate (Details available at http://www.cgd.ucar.edu/~berner/skebs.html).

Default parameters are for synoptic-scale perturbations in the mid-latitudes. Tuning strategies are discussed in Romine et al. 2014 (http://journals.ametsoc.org/doi/citedby/10.1175/MWR-D-14-00100.1) and Ha et al. 2015 (http://journals.ametsoc.org/doi/10.1175/MWR-D-14-00395.1)

Stochastically perturbed parameter scheme (SPP) (spp=1)

A random pattern is used to perturb parameters in selected physics packages, namely the GF convection scheme, the MYNN boundary layer scheme and the RUC LSM. Parameter perturbations to a single physics package can be achieved by setting `spp_conv=1, spp_pbl=1` or `spp_lsm=1`. For implementation details see Jankov et al. (http://journals.ametsoc.org/doi/abs/10.1175/MWR-D-16-0160.1). The perturbation fields are saved as `pattern_spp_conv, pattern_spp_pbl, pattern_spp_lsm` in the history files. (Available starting with version 3.9).

Stochastic Perturbations to the boundary conditions (perturb_bdy)

For `perturb_bdy=1`, the stochastic random field is used to perturb the boundary tendencies for wind and potential temperature. The `perturb_bdy` option runs independently of SKEBS and as such may be run with or without the SKEB scheme, which operates solely on the interior grid. However, selecting `perturb_bdy=1` will require the generation of a domain-size random array, thus computation time may increase.

For `perturb_bdy=2`, a user-provided pattern is used to perturb the boundary tendencies. Arrays are initialized and called: `field_u_tend_perturb, field_v_tend_perturb, field_t_tend_perturb`. These arrays will need to be filled with desired pattern in spec_bdytend_perturb in share/module_bc.F or spec_bdy_dry_perturb in dyn_em/module_bc_em.F

Stochastic perturbations to the boundary tendencies in WRF-CHEM (perturb_chem_bdy)

The random pattern created by the option `rand_perturb=1` (see above) is used to perturb the chemistry boundary tendencies in WRF-CHEM. For this application, WRF-

Chem should be compiled at the time of the WRF compilation.

The `perturb_chem_bdy` option runs independently of `rand_perturb` and as such may be run with or without the `rand_perturb` scheme, which operates solely on the interior grid. However, selecting `perturb_bdy_chem=1` will require the generation of a domain-size random array to apply the perturbations in the lateral boundary zone, thus computation time may increase. When running WRF-Chem with `have_bcs_chem` = `.true.` in &chem, chemical LBCs read from wrfbdy_d01 are perturbed with the random pattern created by `rand_perturb=1` (available from version 3.7).

o. Run-Time IO

With the release of WRF version 3.2, IO decisions may now be updated as a run-time option. Previously, any modification to the IO (such as which variable is associated with which stream) was handled via the Registry, and changes to the Registry always necessitate a cycle of `clean -a`, `configure`, and `compile`. This compile-time mechanism is still available and it is how most of the WRF IO is defined. However, should a user wish to add (or remove) variables from various streams, that capability is available as an option.

First, the user lets the WRF model know where the information for the run-time modifications to the IO is located. This is a text file (`my_file_d01.txt`), one for each domain, defined in the `namelist.input` file, located in the `time_control` namelist record.

```
&time_control
iofields_filename = "my_file_d01.txt", "my_file_d02.txt"
ignore_iofields_warning = .true.,
/
```

The contents of the text file associates a stream ID (0 is the default history and input) with a variable, and whether the field is to be added or removed. The state variables must already be defined in the Registry file. Following are a few examples:
`-:h:0:RAINC,RAINNC`
would remove the fields RAINC and RAINNC from the standard history file.

`+:h:7:RAINC,RAINNC`
would add the fields RAINC and RAINNC to an output stream #7.

The available options are:

`+` or `-`, add or remove a variable
`0-24`, integer, which stream
`i` or `h`, input or history
field name in the Registry – this is the first string in quotes. Note: do not include any spaces in between field names.

It is not necessary to remove fields from one stream to insert them in another. It is OK to have the same field in multiple streams.

If you are interested in outputting variables into a new stream (i.e., not the default history stream 0), then the following namelist variables will also be necessary (example for stream 7):

```
auxhist7_outname = "yourstreamname_d<domain>_<date>"
auxhist7_interval = 360, 360,
frames_per_auxhist7 = 1, 1,
io_form_auxhist7 = 2
```

The namelist variable, `ignore_iofields_warning`, tells the program what to do if it encounters an error in these user-specified files. The default value, .TRUE., is to print a warning message but continue the run. If set to .FALSE., the program will abort if there are errors in these user-specified files.

Note that any field that can be part of the optional IO (either the input or output streams) must already be declared as a state variable in the Registry. Care needs to be taken when specifying the names of the variables that are selected for the run-time IO. The "name" of the variable to use in the text file (defined in the namelist.input file) is the quoted string from the Registry file. Most of the WRF variables have the same string for the name of the variable used inside the WRF source code (column 3 in the Registry file, non-quoted, and not the string to use) and the name of the variable that appears in the netCDF file (column 9 in the Registry file, quoted, and that is the string to use).

p. Output Diagnostics

1. Time series output. To activate the option, a file called "`tslist`" must be present in the WRF run directory. The `tslist` file contains a list of locations defined by their latitude and longitude along with a short description and an abbreviation for each location. A sample file looks something like this:

```
#-----------------------------------------------#
# 24 characters for name | pfx |  LAT  |   LON  |
#-----------------------------------------------#
Cape Hallett             hallt -72.330  170.250
McMurdo Station          mcm   -77.851  166.713
```

The first three lines in the file are regarded as header information, and are ignored. Given a `tslist` file, for each location inside a model domain (either coarse or nested) a file containing time series variables at each model time step will be written with the name `pfx.d<domain>.TS`, where pfx is the specified prefix for the location in the tslist file. The maximum number of time series locations is controlled by the namelist variable `max_ts_locs` in the namelist record `&domains`. The default value is 5. The time

series output contains selected variables at the surface, including 2-m temperature, vapor mixing ratio, 10-m wind components, u and v, rotated to the earth coordinate, etc.. More information for time series output can be found in `WRFV3/run/README.tslist`.

Starting in V3.5, in addtion to surface variables, vertical profiles of earth-relative U and V, potential temperature, water vapor, and geopotential height will also be output. The default number of levels in the output is 15, but can be changed with namelist variable `max_ts_level`.

2. Pressure level output. This is activated by adding a namelist record `&diags`, and set `p_lev_diags` = 1. The option can output U, V, wind speed, T, dew point T, RH and geopotential height at a number of pressure levels.

```
&diags
p_lev_diags = 1
num_press_levels = 4,
press_levels = 85000, 70000, 50000, 20000,
```

The output goes to auxiliary output stream 23, so the following should be set in `&time_control`:

```
auxhist23_interval = 360, 360,
frames_per_auxhist23 = 100, 100,
io_form_auxhist23 = 2
```

3. `nwp_diagnostics` = 1 in `&time_control`. Convective storm diagnostics. This option outputs maximum 10 m wind speed, max helicity in 2 - 5 km layer, maximum vertical velocity in updraft and downdraft below 400 mb, mean vertical velocity in 2 - 5 km layer, and maximum column graupel in a time-window between history output times. The extra fields go to history file.

4. `output_diagnostics` = 1 in `&time_control`. Climate diagnostics. This option outputs 36 surface diagnostic variables: maximum and minimum, times when max and min occur, mean value, standard deviation of the mean for T2, Q2, TSK, U10, V10, 10 m wind speed, RAINCV, RAINNCV (the last two are time-step rain). The output goes to auxiliary output stream 3, and hence it needs the following:

```
auxhist3_outname = "wrfxtrm_d<domain>_<date>"
auxhist3_interval = 1440, 1440,
frames_per_auxhist3 = 100, 100,
io_form_auxhist3 = 2
```

Since this option computes the daily max and min, etc., it is advisable to do a restart at the daily interval.

5. do_avgflx_em = 1 in &dyanmics. This option outputs history-time averaged, column-pressure coupled U, V and W for downstream transport models. If Grell-type of schemes is used, do_avg_cugd = 1 will output time-averaged convective mass-fluxes.

6. afwa_diag_opt = 1 in &afwa. Main control option to turn on weather diagnostics contributed by AFWA. Output goes to auxiliary stream 2. (see full documentation at http://www2.mmm.ucar.edu/wrf/users/docs/AFWA_Diagnostics_in_WRF.pdf). NOTE: These options cannot be used with OpenMP.

afwa_ptype_opt = 1	precipitation type
afwa_severe_opt = 1	severe weather diagnostics
afwa_vil_opt = 1	vertically integrated liquid
afwa_radar_opt = 1	radar
afwa_icing_opt = 1	icing
afwa_vis_opt = 1	visibility
afwa_cloud_opt = 1	cloud
afwa_therm_opt = 1	thermal index
afwa_turb_opt = 1	turbulence
afwa_buoy_opt = 1	buoyancy

7. Others in &physics

do_radar_ref = 1: compute radar reflectivity using microphysics-specific parameters in the model. Works for mp_physics = 2,4,6,7,8,10,14,16.

prec_acc_dt = 60: Time interval for outputing precipitation variables (rain from cumulus and microphysics schemes, and snow from microphysics scheme) (unit in minutes).

q. WRF-Hydro

This is a new capability in V3.5. It couples WRF model with hydrology processes (such as routing and channeling). Using WRF-Hydro requires a separate compile by using environment variable WRF_HYDRO. In c-shell environment, do

```
setenv WRF_HYDRO 1
```

before doing 'configure' and 'compile'. Once WRF is compiled, copy files from hydro/Run/ directory to your working directory (e.g. test/em_real/). A separately prepared geogrid file is also required. Please refer the following web site for detailed information: http://www.ral.ucar.edu/projects/wrf_hydro/. (*From W. Yu*)

r. Using IO Quilting

This option allows a few processors to be set aside to be responsible for output only. It can be useful and performance-friendly if the domain size is large, and/or the time taken to write an output time is becoming significant when compared to the time taken to integrate the model in between the output times. There are two variables for setting the option:

`nio_tasks_per_group`: How many processors to use per IO group for IO quilting. Typically 1 or 2 processors should be sufficient for this purpose.
`nio_groups`: How many IO groups for IO. Default is 1.

*Note: This option is only used for wrf.exe. It does not work for real or ndown.

s. Using Physics Suites

Beginning in Version 3.9, an option to use physics suites was introduced. There are currently 2 available suites ("CONUS" and "tropical") that require a one-line specification in namelist.input, and consist of a combination of physics options that have been highly tested and have shown good and reasonable results.

To use one of these options, simply set the "physics_suite" parameter in namelist.input, within the &physics namelist record, e.g.,

```
physics_suite = 'tropical'
```

and this will set the packaged physics options for the chosen suite (specifically mp_physics, cu_physics, ra_lw_physics, ra_sw_physics, bl_pbl_physics, sf_sfclay_physics, and sf_surface_physics). At runtime, the model prints to the rsl files a summary of the physics schemes that will be used in the simulation, which are as follows (note: this is an example for a 2 domain run. All nests are assumed to use the same physics options unless the user specifically overrides these options - see example below):

```
physics_suite = 'tropical'
mp_physics =          6,  6
cu_physics =         16, 16
ra_lw_physics =       4,  4
ra_sw_physics =       4,  4
bl_pbl_physics =      1,  1
sf_sfclay_physics = 91, 91
sf_surface_physics = 2,  2
```

```
physics_suite = 'CONUS'
mp_physics =          8, 8
cu_physics =          6, 6
ra_lw_physics =       4, 4
ra_sw_physics =       4, 4
bl_pbl_physics =      2, 2
sf_sfclay_physics =   2, 2
sf_surface_physics = 2, 2
```

It is possible to override any of the above options by simply adding that particular parameter to the namelist. For example, if you wish to use the tropical physics suite but would like to turn off cu_physics for domain 3:

```
physics_suite = 'tropical'
cu_physics = -1, -1, 0
```

If you wish to use tropical suite but would like to use a different cu_physics option, and to turn cu_physics off for domain 3:

```
physics_suite = 'tropical'
cu_physics = 2, 2, 0
```

t. Hybrid Vertical Coordinate

Beginning in Version 3.9, the option is available to use either a terrain following (TF) vertical coordinate (the vertical coordinate in the WRF model that has been used for the Eulerian mass model since the initial release) or a hybrid vertical coordinate (HVC). Here, the HVC is a coordinate that is terrain following near the ground and becomes isobaric at a pre-defined user level.

The new definition of the coordinate has been implemented with a modification to the meaning of the variable "mu". Previously, this variable was both the 2d column pressure and the 2d $\delta(P_{DRY})/\delta(\eta)$. With the selection of the hybrid vertical coordinate, now the dry pressure is defined as:

$$P_{DRY}(i,j,k) = B(k)\,(P_{DRY\ SFC}(i,j) - P_{TOP}) + (\eta(k) - B(k))\,(P_0 - P_{TOP}) + P_{TOP}$$

where the B(k) field is a 1d weighting array computed internally.

> When $B(k) \equiv \eta(k)$, this definition simplifies to the current TF coordinate.
> When $B(k) \equiv 0$, this definition simplifies to an isobaric coordinate system.

The vertical value where the B(k) arrays transitions to isobaric, η_C, determines how many of the η layers (downward from the model lid) are isobaric. The default value for ETAC is set in a registry file, and is safe for usage across the globe. Figure 5.1 shows the transitioning of the coordinate surfaces from TF to HVC under several values of ETAC.

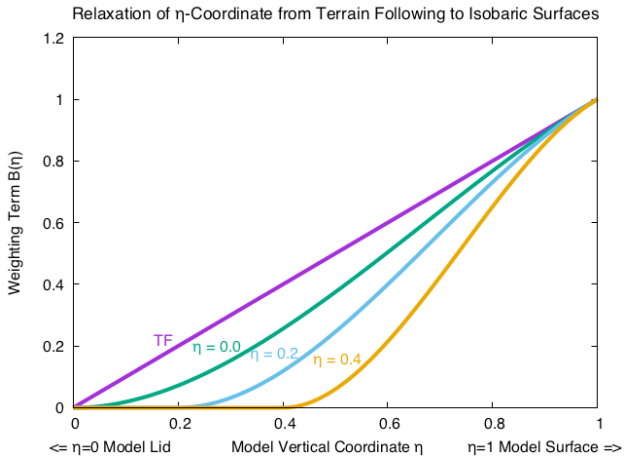
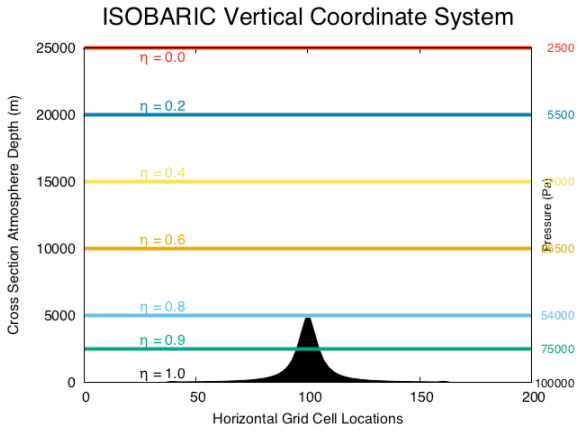
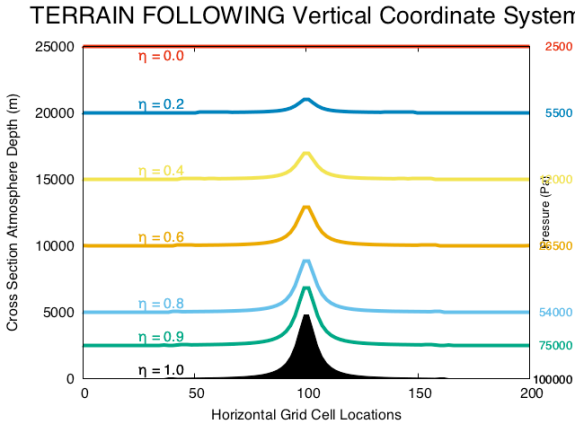


Fig. 5.1 The transition of the η coordinate surfaces from terrain following (TF) to isobaric is a function of the critical value of η at which the user requests that an isobaric surface be achieved. The fundamental property of the TF *vs*. the HVC system is seen when tracing a horizontal line from any value on the "Weighting Term B(η)" axis. The degree of model coordinate "flatness", for example, is the same in the TF system at η = 0.2 as in the HVC system for η_C = 0.4 when the approximate value of η = 0.6.

The depiction of the vertical location of an η surface for an isobaric coordinate (figure 5.2a), a terrain following coordinate (figure 5.2b), and a hybrid coordinate (figure 5.2c) is given with a simple 2d cross section. The depth of the atmosphere (m) is and the pressure are shown.





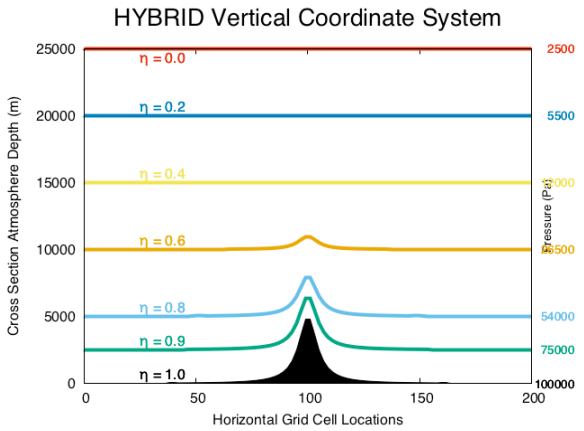


Fig. 5.2 Three cross section plots show the vertical location of the η surfaces for a given model lid (25 km is approximately 25 hPa) and for a given $\eta_C = 0.2$.

There are two steps required to select the HVC option.

1. WRF must be built for the HVC option.
   At the configure step, the user must add the "-hyb" flag
   `./configure -hyb`
2. The user must select the namelist option hybrid_opt
   ```
   &dynamics
   hybrid_opt = 2
   ```

It is important that the `real.exe` and the `wrf.exe` programs both run with the same hybrid_opt value.

The "mu" fields in the WRF model have changed meaning. Due to the large number of source lines that needed to modified, an automatic text processing method was chosen to introduce the changes. This automatic method is employed during the build process. Users are strongly warned against modifying any source code line that has any of the various "mu" arrays.

Users must also use care when pushing the HVC data through post-processors. The post-processors must know the new definition of dry pressure. It is preferable that either the hydrostatic pressure (P_HYD) or the total pressure (PB + P) be used for diagnostics and for vertical interpolations.

Examples of namelists for various applications

A few physics options sets (plus model top and the number of vertical levels) are provided here for reference. They may provide a good starting point for testing the model in your application. Also note that other factors will affect the outcome; for example, the domain setup, the distributions of vertical model levels, and input data.

a. 1 – 4 km grid distances, convection-permitting runs for a 1- 3 day run (as used for the NCAR spring real-time convection forecast over the US in 2013 and 3 km ensemble in 2015 – 2017, and this is the 'conus' physics suite without the cumulus scheme):

```
mp_physics                          = 8,
ra_lw_physics                       = 4,
ra_sw_physics                       = 4,
radt                                = 10,
sf_sfclay_physics                   = 2,
sf_surface_physics                  = 2,
bl_pbl_physics                      = 2,
bldt                                = 0,
cu_physics                          = 0,

ptop_requested                      = 5000,
e_vert                              = 40,
```

b. 10 – 20 km grid distances, 1- 3 day runs (e.g., NCAR daily real-time runs over the US):

```
mp_physics                          = 8,
ra_lw_physics                       = 4,
ra_sw_physics                       = 4,
radt                                = 15,
sf_sfclay_physics                   = 1,
sf_surface_physics                  = 2,
bl_pbl_physics                      = 1,
bldt                                = 0,
cu_physics                          = 3,
cudt                                = 0,

ptop_requested                      = 5000,
e_vert                              = 39,
```

c. Cold region 10 – 30 km grid sizes (e.g. used in NCAR's Antarctic Mesoscale Prediction System):

```
mp_physics                          = 4,
ra_lw_physics                       = 4,
ra_sw_physics                       = 2,
radt                                = 15,
sf_sfclay_physics                   = 2,
sf_surface_physics                  = 2,
bl_pbl_physics                      = 2,
bldt                                = 0,
cu_physics                          = 1,
cudt                                = 5,
fractional_seaice                   = 1,
seaice_threshold                    = 0.0,
```

```
ptop_requested                      = 1000,
e_vert                              = 44,
```

d. Hurricane applications (e.g. 36, 12, and 4 km nesting used by NCAR's real-time hurricane runs in 2012):

```
mp_physics                          = 6,
ra_lw_physics                       = 4,
ra_sw_physics                       = 4,
radt                                = 10,
sf_sfclay_physics                   = 1,
sf_surface_physics                  = 2,
bl_pbl_physics                      = 1,
bldt                                = 0,
cu_physics                          = 6,  (only on 36/12 km grid)
cudt                                = 0,
isftcflx                            = 2,

ptop_requested                      = 2000,
e_vert                              = 36,
```

e. Regional climate case at 10 – 30 km grid sizes (e.g. used in NCAR's regional climate runs):

```
mp_physics                          = 6,
ra_lw_physics                       = 3,
ra_sw_physics                       = 3,
radt                                = 30,
sf_sfclay_physics                   = 1,
sf_surface_physics                  = 2,
bl_pbl_physics                      = 1,
bldt                                = 0,
cu_physics                          = 1,
cudt                                = 5,
sst_update                          = 1,
tmn_update                          = 1,
sst_skin                            = 1,
bucket_mm                           = 100.0,
bucket_J                            = 1.e9,
ptop_requested                      = 1000,
e_vert                              = 51,

spec_bdy_width                      = 10,
spec_zone                           = 1,
relax_zone                          = 9,
spec_exp                            = 0.33,
```

Check Output

Once a model run is completed, it is good practice to check a couple of things quickly.

If you have run the model on multiple processors using MPI, you should have a number of `rsl.out.*` and `rsl.error.*` files. Type '`tail rsl.out.0000`' to see if you get '`SUCCESS COMPLETE WRF`'. This is a good indication that the model has run successfully.

The namelist options are written to a separate file: `namelist.output`.

Check the output times written to the `wrfout*` file by using the netCDF command:

```
ncdump -v Times wrfout_d01_yyyy-mm-dd_hh:00:00
```

Take a look at either the `rsl.out.0000` file or other standard-out files. This file logs the times taken to compute for one model time step, and to write one history and restart output file:

```
Timing for main: time 2006-01-21_23:55:00 on domain  2:    4.91110 elapsed seconds.
Timing for main: time 2006-01-21_23:56:00 on domain  2:    4.73350 elapsed seconds.
Timing for main: time 2006-01-21_23:57:00 on domain  2:    4.72360 elapsed seconds.
Timing for main: time 2006-01-21_23:57:00 on domain  1:   19.55880 elapsed seconds.
```

and

```
Timing for Writing wrfout_d02_2006-01-22_00:00:00 for domain 2: 1.17970 elapsed seconds.
Timing for main: time 2006-01-22_00:00:00 on domain 1: 27.66230 elapsed seconds.
Timing for Writing wrfout_d01_2006-01-22_00:00:00 for domain 1: 0.60250 elapsed seconds.
```

Trouble Shooting

- If the model aborts very quickly, it is likely that either the computer memory is not large enough to run the specific configuration, or the input data have some serious problems. For the first potential issue, try to type '`unlimit`' or '`ulimit -s unlimited`' to see if more memory and/or stack size can be obtained.
- For OpenMP (smpar-compiled code), the stack size needs to be set large, but not unlimited. Unlimited stack size may crash the computer.
- To check if the input data are the problem, use ncview or another netCDF file browser to check the fields in the wrfinput files.
- Another frequent error seen is '`module_configure: initial_config: error reading namelist`'. This is an error message from the model complaining about errors and typos in the `namelist.input` file. Edit the `namelist.input` file with caution. If unsure, always start with an available template. A namelist record where the namelist read error occurs is provided in the V3 error message, and it should help with identifying the error.

- If the model did not run to completion, one possibility is that the model may have become numerically unstatble, which means the time step used for advancing the model in time is too large for a stable solution. Even if one observes the standard rule for setting the model time step (to be ~ 6*DX in kilometers in physical space), other configurations of the model domain may affect the outcome. For example, if one has thin model layers, or if one uses a very large domain and the corners of the domain may have a very large map-scale factor that reduces the equivalent earth distance to be a lot smaller than the model grid size. One can find out whether this is the case by searching for CFL prints in the standard output/error files (e.g. the rsl files):

  `grep cfl rsl.error.*` or `grep cfl wrf.out`

  you might see something like these:

```
5 points exceeded cfl=2 in domain            1 at time   4.200000
  MAX AT i,j,k:          123          48          3 cfl,w,d(eta)= 4.165821
21 points exceeded cfl=2 in domain            1 at time   4.200000
  MAX AT i,j,k:          123          49          4 cfl,w,d(eta)= 10.66290
```

  When this happens, consider using the namelist option `w_damping`, and/or reducing the time step.

Physics and Dynamics Options

Physics Options

WRF offers multiple physics options that can be combined in any way. The options typically range from simple and efficient, to sophisticated and more computationally costly, and from newly developed schemes, to well-tried schemes such as those in current operational models.

The choices vary with each major WRF release, but here we will outline those available in WRF Version 3.

1. Microphysics (mp_physics)

a. Kessler scheme: A warm-rain (i.e. no ice) scheme used commonly in idealized cloud modeling studies (*mp_physics* = 1).

b. Lin et al. scheme: A sophisticated scheme that has ice, snow and graupel processes, suitable for real-data high-resolution simulations (2).

c. WRF Single-Moment 3-class scheme: A simple, efficient scheme with ice and snow processes suitable for mesoscale grid sizes (3).

d. WRF Single-Moment 5-class scheme: A slightly more sophisticated version of (c) that allows for mixed-phase processes and super-cooled water (4).

e. Eta microphysics: The operational microphysics in NCEP models. A simple efficient scheme with diagnostic mixed-phase processes. For fine resolutions (< 5km) use option (5) and for coarse resolutions use option (95).

f. WRF Single-Moment 6-class scheme: A scheme with ice, snow and graupel processes suitable for high-resolution simulations (6).

g. Goddard microphysics scheme. A scheme with ice, snow and graupel processes suitable for high-resolution simulations (7). New in Version 3.0.

h. New Thompson et al. scheme: A new scheme with ice, snow and graupel processes suitable for high-resolution simulations (8). This adds rain number concentration and updates the scheme from the one in Version 3.0. New in Version 3.1.

i. Milbrandt-Yau Double-Moment 7-class scheme (9). This scheme includes separate categories for hail and graupel with double-moment cloud, rain, ice, snow, graupel and hail. New in Version 3.2. (*Note*: Do not use this scheme in V3.6 and V3.6.1.)

j. Morrison double-moment scheme (10). Double-moment ice, snow, rain and graupel for cloud-resolving simulations. New in Version 3.0.

k. WRF Double-Moment 5-class scheme (14). This scheme has double-moment rain. Cloud and CCN for warm processes, but is otherwise like WSM5. New in Version 3.1.

l. WRF Double-Moment 6-class scheme (16). This scheme has double-moment rain. Cloud and CCN for warm processes, but is otherwise like WSM6. New in Version 3.1.

m. Stony Brook University (Y. Lin) scheme (13). This is a 5-class scheme with riming intensity predicted to account for mixed-phase processes. New in Version 3.3.

n. NSSL 2-moment scheme (17, 18). New since Version 3.4, this is a two-moment scheme for cloud droplets, rain drops, ice crystals, snow, graupel, and hail. It also predicts average graupel particle density, which allows graupel to span the range from frozen drops to low-density graupel. There is an additional option to predict cloud condensation nuclei (CCN, option 18) concentration (intended for idealized simulations). The scheme is intended for cloud-resolving simulations (dx <= 2km) in research applications. Since V3.5, two more one-moment schemes have been added (19 and 21). Option 19 is a single-moment version of the NSSL scheme, and option 21 is similar to Gilmore et al. (2004). Option 22 (new in V3.7) is the two moment scheme (option 17) without hail.

o. CAM V5.1 2-moment 5-class scheme.

p. Thompson aerosol-aware (28). This scheme considers water- and ice-friendly aerosols. A climatology dataset may be used to specify initial and boundary conditions for the aerosol variables (Thompson and Eidhammer, 2014, JAS.) New in Version 3.6.

q. HUJI (Hebrew University of Jerusalem, Israel) spectral bin microphysics, full (32) and ‘fast’ (30) versions are available since Version 3.6.

s. P3 (Morrison and Milbrandt): Predicted Particle Property scheme. This has one ice category that represents a combination of ice, snow and graupel, and also carries prognostic arrays for rimed ice mass and rimed ice volume. Double moment rain and

ice. P3-nc: As P3 but adds supersaturation dependent activation and double-moment cloud water.

2.1 Longwave Radiation (ra_lw_physics)

a. RRTM scheme (*ra_lw_physics* = 1): Rapid Radiative Transfer Model. An accurate scheme using look-up tables for efficiency. Accounts for multiple bands, and microphysics species. For trace gases, the volume-mixing ratio values for CO_2=330e-6, N_2O=0. and CH_4=0. in pre-V3.5 code; in V3.5, CO_2=379e-6, N_2O=319e-9 and CH4=1774e-9. See section 2.3 for time-varying option.

b. GFDL scheme (99): Eta operational radiation scheme. An older multi-band scheme with carbon dioxide, ozone and microphysics effects.

c. CAM scheme (3): from the CAM 3 climate model used in CCSM. Allows for aerosols and trace gases. It uses yearly CO_2, and constant N_2O (311e-9) and CH_4 (1714e-9). See section 2.3 for the time-varying option.

d. RRTMG scheme (4): A new version of RRTM added in Version 3.1. It includes the MCICA method of random cloud overlap. For major trace gases, CO_2=379e-6, N_2O=319e-9, CH_4=1774e-9. See section 2.3 for the time-varying option. In V3.7, a fast version is introduced as option 24.

e. New Goddard scheme (5). Efficient, multiple bands, ozone from climatology. It uses constant CO2=337e-6, N_2O=320e-9, CH_4=1790e-9. New in Version 3.3.

f. Fu-Liou-Gu scheme (7). multiple bands, cloud and cloud fraction effects, ozone profile from climatology and tracer gases. CO_2=345e-6. New in Version 3.4.

2.2 Shortwave Radiation (ra_sw_physics)

a. Dudhia scheme: Simple downward integration allowing efficiently for clouds and clear-sky absorption and scattering (*ra_sw_physics* = 1).

b. Goddard shortwave: Two-stream multi-band scheme with ozone from climatology and cloud effects (2).

c. GFDL shortwave: Eta operational scheme. Two-stream multi-band scheme with ozone from climatology and cloud effects (99).

d. CAM scheme: from the CAM 3 climate model used in CCSM. Allows for aerosols and trace gases (3).

e. RRTMG shortwave. A new shortwave scheme with the MCICA method of random cloud overlap (4). New in Version 3.1. In V3.7, a fast version is introduced as option 24.

f. New Goddard scheme (5). Efficient, multiple bands, ozone from climatology. New in Version 3.3.

g. Fu-Liou-Gu scheme (7). multiple bands, cloud and cloud fraction effects, ozone profile from climatology, can allow for aerosols. New in Version 3.4.

h. Held-Suarez relaxation. A temperature relaxation scheme designed for idealized tests only (31).

Related options:

- Slope and shading effects. *slope_rad* = 1 modifies surface solar radiation flux according to terrain slope. *topo_shad* = 1 allows for shadowing of neighboring grid cells. Use only with high-resolution runs with grid size less than a few kilometers. Since Version 3.2, these are available for all shortwave options.

- *swrad_scat*: scattering turning parameter for *ra_sw_physics* = 1. Default value is 1, which is equivalent to 1.e-5 m^2/kg. When the value is greater than 1, it increases the scattering.

- *swint_opt*: Interpolation of short-wave radiation based on the updated solar zenith angle between SW calls. Available since V3.5.1.

2.3 Input to radiation options

a. CAM Green House Gases: Provides yearly green house gases from 1765 to 2500. The option is activated by compiling WRF with the macro –DCLWRFGHG added in configure.wrf. Once compiled, CAM, RRTM and RRTMG long-wave schemes will see these gases. Five scenario files are available: from IPCC AR5: CAMtr_volume_mixing_ratio .RCP4.5, CAMtr_volume_mixing_ratio.RCP6, and CAMtr_volume_mixing_ratio.RCP8.5; from IPCC AR4: CAMtr_volume_mixing_ratio.A1B, and CAMtr_volume_mixing_ratio.A2. The default points to the RCP8.5 file. New in Version 3.5.

b. Climatological ozone and aerosol data for RRTMG: The ozone data is adapted from CAM radiation (ra_*_physics=3), and it has latitudinal (2.82 degrees), height and temporal (monthly) variation, as opposed to the default ozone used in the scheme that only varies with height. This is activated by the namelist option *o3input* = 2, which becomes the default option in V3.7. The aerosol data is based on Tegen et al. (1997), which has 6 types: organic carbon, black carbon, sulfate, sea salt, dust and stratospheric aerosol (volcanic ash, which is zero). The data also has spatial (5 degrees in longitude and 4 degrees in latitudes) and temporal (monthly) variations. The option is activated by the namelist option *aer_opt* = 1. New in Version 3.5.

c. Aerosol input for RRTMG and Goddard radiation options (*aer_opt = 2*). Either AOD or AOD plus Angstrom exponent, single scattering albedo, and cloud asymmetry parameter can be provided via constant values from namelist or 2D input fields via auxiliary input stream 15. Aerosol type can be set too. New in V3.6.

d. Aerosol input for RRTMG radiation scheme from climatological water- and ice-friendly aerosols (*aer_opt = 3*). It works with Thompson microphysics option 28. New in V3.8.

e. Effective cloud water, ice and snow radii from Thompson (since 3.5.1), WSM, WDM and NSSL microphysics schemes (new in V3.7) are used in RRTMG.

2.4 Cloud fraction option

icloud: = 1, use Xu-Randall method; = 2, use threshold method which gives either 0 or 1 cloud fraction; = 3, use a RH-based method that follows Sundqvist et al. (1989). The threshold of RH depends on grid sizes (new in V3.7, fixed in V3.8).

3.1 Surface Layer (sf_sfclay_physics)

a. MM5 similarity: Based on Monin-Obukhov with Carslon-Boland viscous sub-layer and standard similarity functions from look-up tables (*sf_sfclay_physics* = 91). In V3.7, the thermal and moisture roughness lengths (or exchange coefficients for heat and moisture) over ocean are changed to COARE 3 formula (Fairall et al. 2003)

b. Eta similarity: Used in Eta model. Based on Monin-Obukhov with Zilitinkevich thermal roughness length and standard similarity functions from look-up tables (2).

c. Pleim-Xiu surface layer. (7). New in Version 3.0.

d. QNSE surface layer. Quasi-Normal Scale Elimination PBL scheme's surface layer option (4). New in Version 3.1.

e. MYNN surface layer. Nakanishi and Niino PBL's surface layer scheme (5). New in Version 3.1.

f. TEMF surface layer. Total Energy – Mass Flux surface layer scheme. New in Version 3.3.

g. Revised MM5 surface layer scheme (option 11 prior to V3.6, renamed to option 1 since V3.6): Remove limits and use updated stability functions. New in Version 3.4. (Jimenez et al. MWR 2012). In V3.7, the code is sped up to give similar timing as with the old MM5 scheme. The thermal and moisture roughness lengths (or exchange coefficients for heat and moisture) over ocean are changed to COARE 3 formula (Fairall et al. 2003) in V3.7.

h. Other: *iz0tlnd* = 1 (works with *sf_sfclay_physics* = 1, 91, and 5), Chen-Zhang thermal roughness length over land, which depends on vegetation height, 0 = original thermal roughness length in each sfclay option. New in Version 3.2.

3.2 Land Surface (sf_surface_physics)

a. (1)5-layer thermal diffusion: Soil temperature only scheme, using five layers.

b. (2) Noah Land Surface Model: Unified NCEP/NCAR/AFWA scheme with soil temperature and moisture in four layers, fractional snow cover and frozen soil physics. New modifications are added in Version 3.1 to better represent processes over ice sheets and snow covered area.

- In V3.6, a sub-tiling option is introduced, and it is activated by namelist *sf_surface_mosaic* = 1, and the number of tiles in a grid box is defined by namelist *mosaic_cat*, with a default value of 3.

c. (3) RUC Land Surface Model: This model has a layer approach to the solution of energy and moisture budgets in that the atmospheric fluxes, as well as soil fluxes, are computed in the middle of the first atmospheric layer and the top soil layer, respectively, and these fluxes modify the heat and moisture storage in the layer

spanning the ground surface. The RUC LSM currently uses 9 levels in soil with higher resolution near the interface with the atmosphere. (NOTE: if initialized from the model with low resolution near the surface, like the Noah LSM, the top levels could be too moist causing moist/cold biases in the model forecast. Solution: cycle soil moisture and let it spin-up for at least several days to fit the vertical structure of RUC LSM).

The prognostic variable for soil moisture is volumetric soil moisture content minus the residual soil moisture tied to soil particles and therefore not participating in moisture transport. The RUC LSM takes into account freezing and thawing processes in the soil. It is able to use the explicit mixed-phase precipitation provided by the cloud microphysics schemes. It has a simple treatment of sea ice which solves heat diffusion in sea ice and allows evolving snow cover on top of sea ice. In the warm season, RUC LSM corrects soil moisture in the cropland areas to compensate for irrigation in these regions.

Snow, accumulated on top of soil, can have up to two layers depending on snow depth (ref S16). When snow layer is very thin, it is combined with the top soil layer to avoid excessive radiative cooling at night. The grid cell can be partially covered with snow, when snow water equivalent is below a threshold value of 3 cm. When this condition occurs, surface parameters, such as roughness length and albedo, are computed as a weighted average of snow-covered and snow-free areas. The energy budget utilizes an iterative snow melting algorithm. Melted water can partially refreeze and remain within the snow layer, and the rest of it percolates through the snow pack, infiltrates into soil and forms surface runoff. Snow density evolves as a function of snow temperature, snow depth and compaction parameters. Snow albedo is initialized from the maximum snow albedo for the given vegetation type, but it can also be modified depending on snow temperature and snow fraction. To obtain a better representation of snow accumulated on the ground, the RUC LSM has introduced estimation of frozen precipitation density.

The most recent modifications to RUC LSM include refinements to the interception of liquid or frozen precipitation by the canopy, and also the “mosaic” approach for patchy snow with a separate treatment of energy and moisture budgets for snow-covered and snow-free portions of the grid cell, and aggregation of the separate solutions at the end of time step.

The datasets needed to initialize RUC LSM include:

1. High-resolution dataset for soil and land-use types;
2. Climatological albedo for snow-free areas;
3. Spatial distribution of maximum surface albedo in the presence of snow cover;
4. Fraction of vegetation types in the grid cell to take into account sub-grid-scale heterogeneity in computation of surface parameters;
5. Fraction of soil types within the grid cell;
6. Climatological greenness fraction;
7. Climatological leaf area index;

8. Climatological mean temperature at the bottom of soil domain;
9. Real-time sea-ice concentration;
10. Real-time snow cover to correct cycled in RAP and HRRR snow fields.

The recommended namelist options:
sf_surface_physics = 3
num_soil_layers = 9,
usemonalb = .true.,
rdlai2d = .true.,
mosaic_lu = 1
mosaic_soil = 1

References:
Smirnova et al (2016, Mon. Wea. Rev., S16);
RAP and HRRR that use RUC LSM as their land component:
https://rapidrefresh.noaa.gov/RAP and https://rapidrefresh.noaa.gov/hrrr/HRRR.

(from Tanya Smirnova, GSD/NOAA)

d. (7) Pleim-Xiu Land Surface Model. For a more detailed description of the PX LSM, including pros/cons, best practices, and recent improvements, see http://www2.mmm.ucar.edu/wrf/users/docs/PX-ACM.pdf

Two-layer scheme with vegetation and sub-grid tiling (7). New in Version 3.0: The Pleim-Xiu land surface model (PX LSM; Pleim and Xiu 1995; Xiu and Pleim 2001) was developed and improved over the years to provide realistic ground temperature, soil moisture, and surface sensible and latent heat fluxes in mesoscale meteorological models. The PX LSM is based on the ISBA model (Noilhan and Planton 1989), and includes a 2-layer force-restore soil temperature and moisture model. the top layer is taken to be 1 cm thick, and the lower layer is 99 cm. Grid aggregate vegetation and soil parameters are derived from fractional coverage of land use categories and soil texture types. There are two indirect nudging schemes that correct biases in 2-m air temperature and moisture by dynamic adjustment of soil moisture (Pleim and Xiu, 2003) and deep soil temperature (Pleim and Gilliam, 2009).

Users should recognize that the PX LSM was primarily developed for retrospective simulation, where surface-based observations are available to inform the indirect soil nudging. While soil nudging can be disabled using the FDDA namelist.input setting "pxlsm_soil_nudge," little testing has been done in this mode, although some users have reported reasonable results. Gilliam and Pleim (2010) discuss the implementation in the WRF model and provide typical configurations for retrospective applications. If soil nudging is activated, modelers must use the Obsgrid objective re-analysis utility to produce a surface nudging file with the naming convention "wrfsfdda_d0*." Obsgrid takes WPS "met_em*" files and LittleR observation files and produces the "wrfsfdda_d0*" file. The PX LSM uses 2-m temperature and mixing ratio re-analyses from this file for the deep soil moisture and temperature nudging. If modelers want to test PX LSM in forecast mode with soil nudging activated,

forecasted 2-m temperature and mixing ratio can be used with empty observation files to produce the "wrfsfdda_d0*" files, using Obsgrid, but results will be tied to the governing forecast model.

f. (4) Noah-MP (multi-physics) Land Surface Model: uses multiple options for key land-atmosphere interaction processes. Noah-MP contains a separate vegetation canopy defined by a canopy top and bottom with leaf physical and radiometric properties used in a two-stream canopy radiation transfer scheme that includes shading effects. Noah-MP contains a multi-layer snow pack with liquid water storage and melt/refreeze capability and a snow-interception model describing loading/unloading, melt/refreeze, and sublimation of the canopy-intercepted snow. Multiple options are available for surface water infiltration and runoff, and groundwater transfer and storage including water table depth to an unconfined aquifer. Horizontal and vertical vegetation density can be prescribed or predicted using prognostic photosynthesis and dynamic vegetation models that allocate carbon to vegetation (leaf, stem, wood and root) and soil carbon pools (fast and slow). New in Version 3.4. (Niu et al. 2011)

g. (8) SSiB Land Surface Model: This is the third generation of the Simplified Simple Biosphere Model (Xue et al. 1991; Sun and Xue, 2001). SSiB is developed for land/atmosphere interaction studies in the climate model. The aerodynamic resistance values in SSiB are determined in terms of vegetation properties, ground conditions and bulk Richardson number according to the modified Monin–Obukhov similarity theory. SSiB-3 includes three snow layers to realistically simulate snow processes, including destructive metamorphism, densification process due to snow load, and snow melting, which substantially enhances the model's ability for the cold season study. To use this option, *ra_lw_physics* and *ra_sw_physics* should be set to either 1, 3, or 4. The second full model level should be set to no larger than 0.982 so that the height of that level is higher than vegetation height. New in Version 3.4.

h. Fractional sea-ice (*fractional_seaice* = 1). Treat sea-ice as fractional field. Require fractional sea-ice as input data. Data sources may include those from GFS or the National Snow and Ice Data Center (http://nsidc.org/data/seaice/index.html). Use XICE for Vtable entry instead of SEAICE. This option works with *sf_sfclay_physics* = 1, 2, 5, and 7, and *sf_surface_physics* = 2, 3, and 7 in the present release. New in Version 3.1.

i. (5) CLM4 (Community Land Model Version 4, Oleson et al. 2010; Lawrence et al. 2010): CLM4 was developed at the National Center for Atmospheric Research with many external collaborators and represents a state-of-the-science land surface process model. It contains sophisticated treatment of biogeophysics, hydrology, biogeochemistry, and dynamic vegetation. In CLM4, the land surface in each model grid cell is characterized into five primary sub-grid land cover types (glacier, lake, wetland, urban, and vegetated). The vegetated sub-grid consists of up to 4 plant functional types (PFTs) that differ in physiology and structure. The WRF input land cover types are translated into the CLM4 PFTs through a look-up table. The CLM4 vertical structure includes a single-layer vegetation canopy, a five-layer snowpack, and a ten-layer soil column. An earlier version of CLM has been quantitatively evaluated within WRF in Jin and Wen (2012; JGR-Atmosphere), Lu and Kueppers

(2012; JGR-Atmosphere), and Subin et al. (2011; Earth Interactions) (*from Jin*). New in Version 3.5. Updated for 20/21 category MODIS landuse data in V3.6.

3.3 Urban Surface (sf_urban_physics – replacing old switch ucmcall)

The orban physics options work with Noah LSM since V3.1, and with NoahMP since V3.9.

a. Urban canopy model (1): 3-category UCM option with surface effects for roofs, walls, and streets. In V3.7, a green roof option is added.

b. BEP (2). Building Environment Parameterization: Multi-layer urban canopy model that allows for buildings higher than the lowest model levels. Only works with Noah LSM and Boulac and MYJ PBL options. New in Version 3.1.

c. BEM (3). Building Energy Model. Adds to BEP, building energy budget with heating and cooling systems. Works with same options as BEP. New in Version 3.2.

3.4 Lake Physics (sf_lake_physics)

a. CLM 4.5 lake model (1). The lake scheme was obtained from the Community Land Model version 4.5 (Oleson et al. 2013) with some modifications by Gu et al. (2013). It is a one-dimensional mass and energy balance scheme with 20-25 model layers, including up to 5 snow layers on the lake ice, 10 water layers, and 10 soil layers on the lake bottom. The lake scheme is used with actual lake points and lake depth derived from the WPS, and it also can be used with user defined lake points and lake depth in WRF (lake_min_elev and lakedepth_default). The lake scheme is independent of a land surface scheme and therefore can be used with any land surface scheme embedded in WRF. The lake scheme developments and evaluations were included in Subin et al. (2012) and Gu et al. (2013) (Subin et al. 2012: Improved lake model for climate simulations, J. Adv. Model. Earth Syst., 4, M02001. DOI:10.1029/2011MS000072; Gu et al. 2013: Calibration and validation of lake surface temperature simulations with the coupled WRF-Lake model. Climatic Change, 1-13, 10.1007/s10584-013-0978-y).

4. Planetary Boundary layer (bl_pbl_physics)

a. Yonsei University scheme: Non-local-K scheme with explicit entrainment layer and parabolic K profile in unstable mixed layer (*bl_pbl_physics* = 1).

- *topo_wind*: = 1: Topographic correction for surface winds to represent extra drag from sub-grid topography and enhanced flow at hill tops (Jimenez and Dudhia, JAMC 2012). Works with YSU PBL only. New in Version 3.4. = 2: a simpler terrain variance-related correction. New in Version 3.5.

- *ysu_topdown_pblmix*: = 1: option for top-down mixing driven by radiative cooling. New in V3.7.

b. Mellor-Yamada-Janjic scheme: Eta operational scheme. One-dimensional prognostic turbulent kinetic energy scheme with local vertical mixing (2).

c. MRF scheme: Older version of (a) with implicit treatment of entrainment layer as part of non-local-K mixed layer (99).

d. ACM2 PBL: Asymmetric Convective Model with non-local upward mixing and local downward mixing (7). New in Version 3.0.

e. Quasi-Normal Scale Elimination PBL (4). A TKE-prediction option that uses a new theory for stably stratified regions (Available since 3.1). Daytime part uses eddy diffusivity mass-flux method with shallow convection (*mfshconv* = 1) which is added in Version 3.4.

f. Mellor-Yamada Nakanishi and Niino Level 2.5 PBL (5). Predicts sub-grid TKE terms. New in Version 3.1 with significant update in V3.8.

- icloud_bl: = 1, option to couple subgrid-scale clouds from MYNN to radiation;
- bl_mynn_cloudpdf: = 1, Kuwano et al (2010); = 2, Chaboureau and Bechtold (2002, JAS, with mods, default);
- bl_mynn_cloudmix: = 1, mixing cloud water and ice (qnc and qni are mixed when scalar_pblmix = 1);

The above three options are new in V3.8.

- bl_mynn_edmf = 1, activate mass-flux in MYNN (ok to try since v3.9);
- bl_mynn_mixlength = 2: 1 is from RAP/HRRR, 2 is from blending (also available from v3.9).

g. Mellor-Yamada Nakanishi and Niino Level 3 PBL (6). Predicts TKE and other second-moment terms. New in Version 3.1.

h. BouLac PBL (8): Bougeault-Lacarrère PBL. A TKE-prediction option. New in Version 3.1. Designed for use with BEP urban model.

i. UW (Bretherton and Park) scheme (9). TKE scheme from CESM climate model. New in Version 3.3.

j. Total Energy - Mass Flux (TEMF) scheme (10). Sub-grid total energy prognostic variable, plus mass-flux type shallow convection. New in Version 3.3.

k. LES PBL: A large-eddy-simulation (LES) boundary layer is available in Version 3. For this, *bl_pbl_physic* = 0, *isfflx* = 1, and *sf_sfclay_physics* and *sf_surface_physics* are selected. This uses diffusion for vertical mixing and must use *diff_opt* = 2, and *km_opt* = 2 or 3, see below. Alternative idealized ways of running the LESPBL are chosen with *isfflx* = 0 or 2. New in Version 3.0.

l. Grenier-Bretherton-McCaa scheme (12): This is a TKE scheme. Tested in cloud-topped PBL cases. New in Version 3.5.

m. Shin-Hong scheme (11): Include scale dependency for vertical transport in convective PBL. Vertical mixing in the stable PBL and free atmosphere follows YSU. This scheme also has diagnosed TKE and mixing length output. New in V3.7.

5. Cumulus Parameterization (cu_physics)

a. Kain-Fritsch scheme: Deep and shallow convection sub-grid scheme using a mass flux approach with downdrafts and CAPE removal time scale (*cu_physics* = 1).

- *kfeta_trigger* = 1 – default trigger; = 2 – moisture-advection modulated trigger function [based on Ma and Tan (2009, Atmospheric Research)]. May improve results in subtropical regions when large-scale forcing is weak.

- *cu_rad_feedback* = true – allow sub-grid cloud fraction interaction with radiation. New in V3.6. (Alapaty et al. 2012, Geophysical Research Letters)

b. Betts-Miller-Janjic scheme. Operational Eta scheme. Column moist adjustment scheme relaxing towards a well-mixed profile (2).

c. Grell-Devenyi (GD) ensemble scheme: Multi-closure, multi-parameter, ensemble method with typically 144 sub-grid members (moved to option 93 in V3.5).

d. Simplified Arakawa-Schubert (4). Simple mass-flux scheme with quasi-equilibrium closure with shallow mixing scheme (and momentum transport in NMM only). Adapted for ARW in Version 3.3.

e. Grell 3D is an improved version of the GD scheme that may also be used on high resolution (in addition to coarser resolutions) if subsidence spreading (option cugd_avedx) is turned on (5). New in Version 3.0.

f. Tiedtke scheme (U. of Hawaii version) (6). Mass-flux type scheme with CAPE-removal time scale, shallow component and momentum transport. New in Version 3.3.

g. Zhang-McFarlane scheme (7). Mass-flux CAPE-removal type deep convection from CESM climate model with momentum transport. New in Version 3.3.

h. New Simplified Arakawa-Schubert (14). New mass-flux scheme with deep and shallow components and momentum transport. New in Version 3.3.

i. New Simplified Arakawa-Schubert (84, HWRF version). New mass-flux scheme with deep and shallow components and momentum transport. New in Version 3.4.

j. Grell-Freitas (GF) scheme (3): An improved GD scheme that tries to smooth the transition to cloud-resolving scales, as proposed by Arakawa et al. (2004). New in Version 3.5.

k. Old Kain-Fritsch scheme: Deep convection scheme using a mass flux approach with downdrafts and CAPE removal time scale (99).

l. Multi-scale Kain-Fritsch scheme (11): using scale-dependent dynamic adjustment timescale, LCC-based entrainment. Also uses new trigger function based on Bechtold.

m. New Tiedtke scheme (16): this version is similar to the Tiedtke scheme used in REGCM4 and ECMWF cy40r1. New in V3.7, updated in V3.8.

n. Kain-Fritsch-Cumulus Potential scheme (10): this option modifies the KF ad-hoc trigger function with one linked to boundary layer turbulence via probability density function (PDFs) using cumulus potential scheme. The scheme also computes the cumulus cloud fraction based on the time-scale relevant for shallow cumuli. (Berg et al. 2013.) New in V3.8.

6. Shallow convection option (shcu_physics)

a. *ishallow* = 1, shallow convection option on. Works together with Grell 3D scheme (cu_physics = 5) – will move to shcu_physics category in the future.

b. UW (Bretherton and Park) scheme (2). Shallow cumulus option from CESM climate model with momentum transport. New in Version 3.3.

c. GRIMS (Global/Regional Integrated Modeling System) scheme: it represents the shallow convection process by using eddy-diffusion and the pal algorithm, and couples directly to the YSU PBL scheme. New in Version 3.5.

7. Other physics options

a. Options to use for tropical storm and hurricane applications:

- *sf_ocean_physics* = 1 (renamed from *omlcall* in previous versions): Simple ocean mixed layer model (1): 1-D ocean mixed layer model following that of Pollard, Rhines and Thompson (1972). Two other namelist options are available to specify the initial mixed layer depth (although one may ingest real mixed layer depth data) (*oml_hml0*) and a temperature lapse rate below the mixed layer (*oml_gamma*). Since V3.2, this option works with all *sf_surface_physics* options.

- *sf_ocean_physics* = 2: New in V3.5. 3D Price-Weller-Pinkel (PWP) ocean model based on Price et al. (1994). This model predicts horizontal advection, pressure gradient force, as well as mixed layer processes. Only simple initialization via namelist variables *ocean_z, ocean_t,* and *ocean_s* is available in V3.5.

- *isftcflx*: Modify surface bulk drag (Donelan) and enthalpy coefficients to be more in line with recent research results of those for tropical storms and hurricanes. This option also includes dissipative heating term in heat flux. It is only available for *sf_sfclay_physics* = 1. There are two options for computing enthalpy coefficients: *isftcflx* = 1: constant Z_{0q} (since V3.2) for heat and moisture; *isftcflx* = 2 Garratt formulation, slightly different forms for heat and moisture.

b. Other options for long simulations (new in Version 3.1):

- *tmn_update*: update deep soil temperature (1).

- *sst_skin*: calculate skin SST based on Zeng and Beljaars (2005) (1)

- *bucket_mm*: bucket reset value for water equivalent precipitation accumulations (value in mm, -1 = inactive).

- *bucket_J*: bucket reset value for energy accumulations (value in Joules, -1 = inactive). Only works with CAM and RRTMG radiation (*ra_lw_physics* = 3 and 4 and *ra_sw_physics* = 3 and 4) options.

- To drive WRF model with climate data that does not have leap year, there is a compile option to do that. Edit `configure.wrf` and add -DNO_LEAP_CALENDAR to the macro ARCH_LOCAL.

c. Land model input options:

- *usemonalb*: When set to .true., it uses monthly albedo fields from geogrid, instead of table values

- *rdlai2d*: When set to .true., it uses monthly LAI data from geogrid (new in V3.6) and the field will also go to wrflowinp file if *sst_update* is 1.

d. *gwd_opt*: Gravity wave drag option. Can be activated when grid size is greater than 10 km. May be beneficial for simulations longer than 5 days and over a large domain with mountain ranges. It is recommended that this option is used only with unrotated

lat/long (e.g. global) or Mercator projections because the input orographic sub-grid asymmetry arrays assume this grid orientation. New in Version 3.1.

e. *windfarm_opt*: Wind turbine drag parameterization scheme. It represents sub-grid effects of specified turbines on wind and TKE fields. The physical charateristics of the wind farm is read in from a file and use of the manufacturers' specification is recommeded. An example of the file is provided in run/wind-turbine-1.tbl. The location of the turbines are read in from a file, windturbines.txt. See README.windturbine in WRFV3/ directory for more detail. New in Version 3.3, and in this version it only works with 2.5 level MYNN PBL option (*bl_pbl_physics*=5), and updated in V3.6.

8. Physics sensitivity options

a. *no_mp_heating*: When set to 1, it turns off latent heating from microphysics. When using this option, *cu_physics* should be set to 0.
b. *icloud*: When set to 0, it turns off cloud effect on optical depth in shortwave radiation options 1, 4 and longwave radiation option 1, 4. Note since V3.6, this namelist also controls which cloud fraction method to use for radiation.
c. *isfflx*: When set to 0, it turns off both sensible and latent heat fluxes from the surface. This option works for *sf_sfclay_physics* = 1, 5, 7, 11.
d. *ifsnow*: When set to 0, it turns off snow effect in *sf_surface_physics* = 1.

Diffusion and Damping Options

Diffusion in WRF is categorized under two parameters: the diffusion option and the K option. The diffusion option selects how the derivatives used in diffusion are calculated, and the K option selects how the K coefficients are calculated. Note that when a PBL option is selected, vertical diffusion is done by the PBL scheme, and not by the diffusion scheme. In Version 3, vertical diffusion is also linked to the surface fluxes.

1.1 Diffusion Option (diff_opt)

a. Simple diffusion: Gradients are simply taken along coordinate surfaces (*diff_opt* = 1).

b. Full diffusion: Gradients use full metric terms to more accurately compute horizontal gradients in sloped coordinates (*diff_opt* = 2). This option can be used with real-data cases since V3.6.1.

1.2 K Option (km_opt)

Note that when using a PBL scheme, only options (a) and (d) below make sense, because (b) and (c) are designed for 3d diffusion.

a. Constant: K is specified by namelist values for horizontal and vertical diffusion (*km_opt* = 1).

b. 3d TKE: A prognostic equation for turbulent kinetic energy is used, and K is based on TKE (*km_opt* = 2).

c. 3d Deformation: K is diagnosed from 3d deformation and stability following a Smagorinsky approach (*km_opt* = 3).

d. 2d Deformation: K for horizontal diffusion is diagnosed from just horizontal deformation. The vertical diffusion is assumed to be done by the PBL scheme (*km_opt* = 4).

1.3 6th Order Horizontal Diffusion (diff_6th_opt)

6^{th}-order horizontal hyper diffusion (del^6) on all variables to act as a selective short-wave numerical noise filter. Can be used in conjunction with *diff_opt*. = 1: simple; = 2: positive definite. Option 2 is recommended.

1.4 Nonlinear Backscatter Anisotropic (NBA) (sfs_opt)

Sub-grid turbulent stress option for momentum in LES applications. New in Version 3.2. *sfs_opt* = 1 diagnostic sub-grid stress to be used with *diff_opt* = 2 and *km_opt* = 2 or 3. *sfs_opt* = TKE sub-grid stress to be used with *diff_opt* = 2 and *km_opt* = 2.

2. Damping Options

These are independently activated choices.

a. Upper Damping: Either a layer of increased diffusion (*damp_opt* =1) or a Rayleigh relaxation layer (2) or an implicit gravity-wave damping layer (3, new in Version 3.0), can be added near the model top to control reflection from the upper boundary.

b. Vertical velocity damping (*w_damping*): For operational robustness, vertical motion can be damped to prevent the model from becoming unstable with locally large vertical velocities. This only affects strong updraft cores, so has very little impact on results otherwise.

c. Divergence Damping (*sm_div*): Controls horizontally-propagating sound waves.

d. External Mode Damping (*em_div*): Controls upper-surface (external) waves.

e. Time Off-centering (*epssm*): Controls vertically-propagating sound waves.

Advection Options

a. Horizontal advection orders for momentum (*h_mom_adv_order*) and scalar (*h_sca_adv_order*) can be $2^{nd}$to 6^{th}, with 5^{th} order being the recommended one.

b. Vertical advection orders for momentum (*v_mom_adv_order*) and scalar (v_sca_adv_order) can be $2^{nd}$and 6th, with 3^{rd} order being the recommended one.

c. Monotonic transport (option 2, new in Version 3.1) and positive-definite advection option (option 1) can be applied to moisture (*moist_adv_opt*), scalar (*scalar_adv_opt*), chemistry variables (*chem_adv_opt*) and tke (*tke_adv_opt*). Option 1 replaces *pd_moist* = .true. etc. in previous versions.

d. WENO (weighted essentially non-oscillatory) (option 3 for 5th order WENO; option 4 for 5th order WENO with positive definite limiter): for moisture (*moist_adv_opt*), scalar (*scalar_adv_opt*), chemistry variables (*chem._adv_opt*) and TKE (*tke_adv_opt*). For momentum, *momentum_adv_opt* = 3.

Some notes about using monotonic and positive-definite advection options:

The positive-definite and monotonic options are available for moisture, scalars, chemical scalers and TKE in the ARW solver. Both the monotonic and positive-definite transport options conserve scalar mass locally and globally and are consistent with the ARW mass conservation equation. We recommend using the positive-definite option for moisture variables on all real-data simulations. The monotonic option may be beneficial in chemistry applications and for moisture and scalars in some instances.

When using these options there are certain aspects of the ARW integration scheme that should be considered in the simulation configuration.

(1) The integration sequence in ARW changes when the positive-definite or monotonic options are used. When the options are not activated, the timestep tendencies from the physics (excluding microphysics) are used to update the scalar mixing ratio at the same time as the transport (advection). The microphysics is computed, and moisture is updated, based on the transport+physics update. When the monotonic or positive definite options are activated, the scalar mixing ratio is first updated with the physics tendency, and the new updated values are used as the starting values for the transport scheme. The microphysics update occurs after the transport update using these latest values as its starting point. It is important to remember that for any scalars, the local and global conservation properties, positive definiteness and monotonicity depend upon each update possessing these properties.

(2) Some model filters may not be positive definite.

i. *diff_6th_opt* = 1 is not positive definite nor monotonic. Use *diff_6th_opt* = 2 if you need this diffusion option (*diff_6th_opt* = 2 is monotonic and positive-definite). We have encountered cases where the departures from monotonicity and positive-definiteness have been very noticeable.
ii. *diff_opt* = 1 and *km_opt* = 4 (a commonly-used real-data case mixing option) is not guaranteed to be positive-definite nor monotonic due to the variable eddy diffusivity, K. We have not observed significant departures from positive-definiteness or monotonicity when this filter is used with these transport options.
iii. The diffusion option that uses a user-specified constant eddy viscosity is positive definite and monotonic.
iv. Other filter options that use variable eddy viscosity are not positive definite or monotonic.

(3) Most of the model physics are not monotonic nor should they be - they represent sources and sinks in the system. All should be positive definite, although we have not

examined and tested all options for this property.

(4) The monotonic option adds significant smoothing to the transport in regions where it is active. You may want to consider turning off the other model filters for variables using monotonic transport (filters such as the second and sixth order horizontal filters). At present it is not possible to turn off the filters for the scalars but not for the dynamics using the namelist - one must manually comment out the calls in the solver.

Other Dynamics Options

a. The model can be run hydrostatically by setting the *non_hydrostatic* switch to .false.

b. The Coriolis term can be applied to wind perturbation (*pert_coriolis* = .true.) only (idealized only).

c. For *diff_opt* = 2 only, vertical diffusion may act on full fields (not just on perturbation from the 1D base profile (*mix_full_fields* = .true.; idealized only).

d. To obtain more accurate solution with moisture, one can add

use_q_diabatic: which considers moisture tendency from microphysics in small steps. This option could make time-step more restrictive.
use_theta_m: which considers moisture effect on pressure in small steps. The current implementation may cost a bit more to run.

Lateral Boundary Condition Options

a. Periodic (*periodic_x* / *periodic_y*): for idealized cases.

b. Open (*open_xs, open_xe, open_ys, open_ye*): for idealized cases.

c. Symmetric (*symmetric_xs, symmetric_xe, symmetric_ys, symmetric_ye*): for idealized cases.

d. Specified (*specified*): for real-data cases. The first row and column are specified with external model values (*spec_zone* = 1, and it should not change). The rows and columns in *relax_zone* have values blended from an external model and WRF. The value of *relax_zone* may be changed, as long as *spec_bdy_width* = *spec_zone* + *relax_zone*. This can be used with *periodic_x* in tropical channel simulations.

   spec_exp: exponential multiplier for the relaxation zone ramp, used with a *specified* boundary condition. 0. = linear ramp, default; 0.33 = ~3*dx exp decay factor. This may be useful for long simulations.

e. Nested (*nested*): for real and idealized cases.

Summary of PBL Physics Options

bl_pbl_physics	Scheme	Reference	Added
1	YSU	Hong, Noh and Dudhia (2006, MWR)	2004
2	MYJ	Janjic (1994, MWR)	2000
3	GFS	Hong and Pan (1996, MWR)	2005
4	QNSE	Sukoriansky, Galperin and Perov (2005, BLM)	2009
5	MYNN2	Nakanishi and Niino (2006, BLM)	2009
6	MYNN3	Nakanishi and Niino (2006, BLM)	2009
7	ACM2	Pleim (2007, JAMC	2008
8	BouLac	Bougeault and Lacarrere (1989, MWR)	2009
9	UW	Bretherton and Park (2009, JC)	2011
10	TEMF	Angevine, Jiang and Mauriten (2010, MWR)	2011
12	GBM	Grenier and Bretherton (2001, MWR)	2013
99	MRF	Hong and Pan (1996, MWR)	2000
11	Shin-Hong	Shin and Hong (2015, MWR)	2015

bl_pbl_physics	Scheme	Cores	sf_sfclay_physics	Prognostic variables	Diagnostic variables	Cloud mixing
1	YSU	ARW/ NMM	1, (91)*		exch_h	QC,QI
2	MYJ	ARW/ NMM	2	TKE_PBL	el_myj, exch_h	QC,QI
3	GFS (hwrf)	NMM	3			QC,QI
4	QNSE-EDMF	ARW/ NMM	4	TKE_PBL	el_pbl, exch_h, exch_m	QC,QI
5	MYNN2	ARW	1,2,5,(91)	QKE	Tsq, Qsq, Cov, exch_h, exch_m	QC

6	MYNN3	ARW	1,2,5,(91)	QKE, Tsq, Qsq, Cov	exch_h, exch_m	QC
7	ACM2	ARW	1,7,(91)			QC,QI
8	BouLac	ARW	1,2,(91)	TKE_PBL	el_pbl, exch_h, exch_m, wu_tur, wv_tur, wt_tur, wq_tur	QC
9	UW	ARW	1,2,(91)	TKE_PBL	exch_h, exch_m	QC
10	TEMF	ARW	10	TE_TEMF	*_temf	QC, QI
12	GBM	ARW	1,(91)	TKE_PBL	el_pbl, exch_tke	QC, QI
99	MRF	ARW/ NMM	1,(91)			QC, QI
11	Shin-Hong	ARW	1,(91)		exch_h, tke_diag	QC, QI

* sfclay option 11 was renamed to 1, and original option 1 to 91 in Version 3.6.

Summary of Microphysics Options

mp_physics	Scheme	Reference	Added
1	Kessler	Kessler (1969)	2000
2	Lin (Purdue)	Lin, Farley and Orville (1983, JCAM)	2000
3	WSM3	Hong, Dudhia and Chen (2004, MWR)	2004
4	WSM5	Hong, Dudhia and Chen (2004, MWR)	2004
5	Eta (Ferrier)	Rogers, Black, Ferrier, Lin, Parrish and DiMego (2001, web doc)	2000
6	WSM6	Hong and Lim (2006, JKMS)	2004
7	Goddard	Tao, Simpson and McCumber (1989, MWR)	2008

8	Thompson	Thompson, Field, Rasmussen and Hall (2008, MWR)	2009
9	Milbrandt 2-mom	Milbrandt and Yau (2005, JAS)	2010
10	Morrison 2-mom	Morrison, Thompson and Tatarskii (2009, MWR)	2008
11	CAM 5.1	Neale et al. (2012, NCAR Tech Note)	2013
13	SBU-YLin	Lin and Colle (2011, MWR)	2011
14	WDM5	Lim and Hong (2010, MWR)	2009
16	WDM6	Lim and Hong (2010, MWR)	2009
17	NSSL 2-mom	Mansell, Ziegler and Bruning (2010, JAS)	2012
18	NSSL 2-mom w/ CCN prediction	Mansell, Ziegler and Bruning (2010, JAS)	2012
19	NSSL 1-mom		2013
21	NSSL 1-momlfo		2013
22	NSSL 2-mom w/o hail		2015
28	Thompson aerosol-aware	Thompson and Eidhammer (2014, JAS)	2014
30	HUJI SBM ‘fast’	Khain et al. (2010, JAS)	2014
32	HUJI SBM full	Khain et al. (2004, JAS)	2014
50/51	P3	Morrison and Milbrandt (2015, JAS)	2017

mp_physics	**Scheme**	**Cores**	**Mass Variables**	**Number Variables**
1	Kessler	ARW	Qc Qr	
2	Lin (Purdue)	ARW (Chem)	Qc Qr Qi Qs Qg	
3	WSM3	ARW	Qc Qr	
4	WSM5	ARW/NMM	Qc Qr Qi Qs	
5	Eta (Ferrier)	ARW/NMM	Qc Qr Qs (Qt*)	
6	WSM6	ARW/NMM	Qc Qr Qi Qs Qg	

8	Thompson	ARW/NMM	Qc Qr Qi Qs Qg	Ni Nr
9	Milbrandt 2-mom	ARW	Qc Qr Qi Qs Qg Qh	Nc Nr Ni Ns Ng Nh
10	Morrison 2-mom	ARW (Chem)	Qc Qr Qi Qs Qg	Nr Ni Ns Ng
11	CAM 5.1	ARW	Qc Qr Qi Qs Qg	Nr Ni Ns Ng
13	SBU-YLin	ARW	Qc Qr Qi Qs	
14	WDM5	ARW	Qc Qr Qi Qs	Nn** Nc Nr
16	WDM6	ARW	Qc Qr Qi Qs Qg	Nn** Nc Nr
17	NSSL 2-mom	ARW	Qc Qr Qi Qs Qg Qh	Nc Nr Ni Ns Ng Nh
18	NSSL 2-mom +CCN	ARW	Qc Qr Qi Qs Qg Qh	Nc Nr Ni Ns Ng Nh Nn Vg
19	NSSL 1-mom	ARW	Qc Qr Qi Qs Qg Qh	Vg***
21	NSSL 1-momlfo	ARW	Qc Qr Qi Qs Qg	
22	/nssl 2-mom	ARW	Qc Qr Qi Qs Qg	Nc Nr Ni Ns Ng
28	Thompson aerosol-aware	ARW/NMM	Qc Qr Qi Qs Qg	Ni Nr Nwf Nif
30	HUJI fast	ARW	Qc Qr Qs Qg Qi	Nc Nr Ns Ni Ng Nn
32	HUJI full	ARW	Qc Qr Qs Qg Qh Qip Qic Qid Qnn	Nc Nr Ns Ng Nip Nic Nid Nn
50	P3	ARW	Qc Qr Qi	Nr Ni Ri^{+} Bi^{++}
51	P3-nc	ARW	Qc Qr Qi	Nc Nr Ni Ri Bi

* Advects only total condensates ** Nn = CCN number *** Vg: graupel volume
+ Rimed ice mass ++ rimed ice volume

Summary of Cumulus Parameterization Options

cu_physics	Scheme	Reference	Added
1	Kain-Fritsch	Kain (2004, JAM)	2000
2	Betts-Miller-Janjic	Janjic (1994, MWR; 2000, JAS)	2002
3	Grell-Freitas	Grell et al. (2013)	2013
4	Old Simplied Arakawa-	Pan and Wu (1995), NMC Office Note 409	2005/ 2011

	Schubert		
5	Grell-3	-	2008
6	Tiedtke	Tiedtke (1989, MWR), Zhang et al. (2011, MWR)	2011
7	Zhang-McFarlane	Zhang and McFarlane (1995, AO)	2011
10	KF-CuP	Berg et al. (2013, MWR)	2016
11	Multi-scale KF	Zheng et al. (2015, MWR)	2015
14	New SAS	Han and Pan (2011, Wea. Forecasting)	2011
16	New Tiedtke	Zhang and Wang (2016)	2015
84	New SAS (HWRF)	Han and Pan (2011, Wea. Forecasting)	2012
93	Grell-Devenyi	Grell and Devenyi (2002, GRL)	2002
99	Old Kain-Fritsch	Kain and Fritsch (1990, JAS; 1993, Meteo. Monogr.)	2000

cu_physics	**Scheme**	**Cores**	**Moisture Tendencies**	**Momentum Tendencies**	**Shallow Convection**
1	Kain-Fritsch	ARW / NMM	Qc Qr Qi Qs	no	yes
2	BMJ	ARW / NMM	-	no	yes
3	GF	ARW	Qc Qi	no	yes
4	OSAS	ARW / NMM	Qc Qi	yes (NMM)	yes (ARW)
5	G3	ARW	Qc Qi	no	yes
6	Tiedtke	ARW / NMM	Qc Qi	yes	yes
7	Zhang-McFarlane	ARW	Qc Qi	yes	no
10	KF-CuP	ARW	Qc Qr Qi Qs	no	yes
11	Multi-scale KF	ARW	Qc Qr Qi Qs	no	yes

14	NSAS	ARW	Qc Qr Qi Qs	yes	yes
16	New Tiedtke	ARW	Qc Qi	yes	yes
84	NSAS (HWRF)	NMM	Qc Qi	yes	
93	GD	ARW	Qc Qi	no	no
99	old KF	ARW	Qc Qr Qi Qs	no	no

Summary of Radiation Physics Options

ra_sw_physics	Scheme	Reference	Added
1	Dudhia	Dudhia (1989, JAS)	2000
2	Goddard	Chou and Suarez (1994, NASA Tech Memo)	2000
3	CAM	Collins et al. (2004, NCAR Tech Note)	2006
4	RRTMG	Iacono et al. (2008, JGR)	2009
24	RRTMG	Fast version	2015
5	New Goddard	Chou and Suarez (1999, NASA Tech Memo)	2011
7	FLG	Gu et al. (2011, JGR), Fu and Liou (1992, JAS)	2012
99	GFDL	Fels and Schwarzkopf (1981, JGR)	2004

ra_sw_ physics	Scheme	Cores+Chem	Microphysics Interaction	Cloud Fraction	Ozone
1	Dudhia	ARW NMM + Chem(PM2.5)	Qc Qr Qi Qs Qg	1/0	none
2	GSFC	ARW+Chem(τ)	Qc Qi	1/0	5 profiles
3	CAM	ARW	Qc Qi Qs	max-rand overlap	lat/month
4	RRTMG	ARW + Chem (τ), NMM	Qc Qr Qi Qs	max-rand overlap	1 profile or lat/month
24	RRTMG				
5	New Goddard	ARW	Qc Qr Qi Qs Qg	1/0	5 profiles
7	FLG	ARW	Qc Qr Qi Qs Qg	1/0	5 profiles
99	GFDL	ARW NMM	Qc Qr Qi Qs	max-rand	lat/date

				overlap	

ra_lw_physics	Scheme	Reference	Added
1	RRTM	Mlawer et al. (1997, JGR)	2000
3	CAM	Collins et al. (2004, NCAR Tech Note)	2006
4	RRTMG	Iacono et al. (2008, JGR)	2009
24	RRTMG	Fast version	2015
5	New Goddard	Chou and Suarez (1999, NASA Tech Memo)	2011
7	FLG	Gu et al. (2011, JGR), Fu and Liou (1992, JAS)	2012
31	Held-Suarez		2008
99	GFDL	Fels and Schwarzkopf (1981, JGR)	2004

ra_lw_ physics	Scheme	Cores+Chem	Microphysics Interaction	Cloud Fraction	Ozone	GHG
1	RRTM	ARW NMM	Qc Qr Qi Qs Qg	1/0	1 profile	constant or yearly GHG
3	CAM	ARW	Qc Qi Qs	max-rand overlap	lat/month	yearly CO2 or yearly GHG
4	RRTMG	ARW + Chem (τ), NMM	Qc Qr Qi Qs	max-rand overlap	1 profile or lat/month	constant or yearly GHG
24	RRTMG					
5	New Goddard	ARW	Qc Qr Qi Qs Qg	1/0	5 profiles	constant
7	FLG	ARW	Qc Qr Qi Qs Qg	1/0	5 profiles	constant
31	Held-Suarez	ARW	none	none		none
99	GFDL	ARW NMM	Qc Qr Qi Qs	max-rand overlap	lat/date	constant

Description of Namelist Variables

The following is a description of the namelist variables. The variables that are a function of nests are indicated by *(max_dom)* following the variable. Also see the `Registry/Registry.EM` and `run/README.namelist` files in the WRFV3/ for more detailed information.

Variable Names	Input Option	Description
&time_control		***options for time control***
run_days	0	run time in days
run_hours	0	run time in hours *note: if it is more than 1 day, you may use both run_days and run_hours or just run_hours. e.g. if the total run length is 36 hrs, you may set run_days = 1, and run_hours = 12, or run_days = 0, and run_hours = 36
run_minutes	0	run time in minutes
run_seconds	0	run time in seconds
start_year (max_dom)	2012	4 digit year of starting time
start_month (max_dom)	06	2 digit month of starting time
start_day (max_dom)	11	2 digit day of starting time
start_hour (max_dom)	12	2 digit hour of starting time
start_minute (max_dom)	00	2 digit minute of starting time
start_second (max_dom)	00	2 digit second of starting time *note: the start time is used to name the first wrfout file. It also controls the start time for nest domains, and the time to restart
end_year (max_dom)	2012	4 digit year of ending time
end_month (max_dom)	06	2 digit month of ending time
end_day (max_dom)	12	2 digit day of ending time
end_hour (max_dom)	12	2 digit hour of ending time
end_minute (max_dom)	00	2 digit minute of ending time
end_second (max_dom_	00	2 digit second of ending time *note: all end times also control when the nest domain integrations end. All start and end times are used by *real.exe*. You may use either run_days/run_hours/etc. or end_year/month/day/hour/etc. to control the length of model

		integration; but run_days/run_hours takes precedence over the end times. The program *real.exe* uses start and end times only
interval_seconds	10800	time interval between the incoming real data, which will be the interval between the lateral boundary condition file (in seconds) (for *real* only)
input_from_file (max_dom)	.true.	(logical); whether the nested run will have input files for domains other than domain 1
fine_input_stream (max_dom)		selected fields from nest input
	0	(default) all fields from nest input are used
	2	only nest input specified from input stream 2 (defined in the Registry) are used. In V3.2, this requires `io_form_auxinput2` to be set
history_interval (max_dom)	60	history output file interval in minutes (integer only)
history_interval_d (max_dom)	1	history output file interval in days (integer only); used as an alternative to `history_interval`
history_interval_h (max_dom)	1	history output file interval in hours (integer only); used as an alternative to `history_interval`
history_interval_m (max_dom)	1	history output file interval in minutes (integer only); used as an alternative to `history_interval` and is equivalent to `history_interval`
history_interval_s (max_dom)	1	history output file interval in seconds (integer only); used as an alternative to `history_interval`
frames_per_outfile (max_dom)	1	number of output times bulked into each history file; used to split output files into smaller pieces
restart	.false.	(logical); whether this run is a

		restart
restart_interval	1440	restart output file interval in minutes
override_restart_timers *(new since V3.5.1)*	.false.	(default) uses all output intervals (including history) given by the wrfrst files
	.true.	uses restart output intervals given by the namelist
write_hist_at_0h_rst	.false.	(default) does not give a history file at the initial time of restart (prevents overwriting original history file at this time)
	.true.	gives a history file at the initial time of restart
output_ready_flag *(new since V3.7)*	.true.	asks the model to write-out an empty file with the name 'wrfoutReady_d<domain>_<date>; Useful in production runs so that post-processing code can check on the completeness of this file.
reset_simulation_start	.false.	whether to overwrite the simulation start date with the forecast start time
auxinput1_inname	"met_em.d<domain><date>"	(default); name of input file from WPS
auxinput4_inname	"wrflowinp_d<domain>"	name of input file for lower boundary file; works with `sst_update = 1`
auxinput4_interval (max_dom)	360	file interval in minutes for lower boundary file; works with `sst_update = 1`
io_form_auxinput4	2	IO format for wrflowinp files; required for V3.2; works with `sst_update = 1`
io_form_history		the format in which the history output file will be
	2	netCDF
	102	split netCDF files, one per processor *note: no supported post-processing software for split files
	1	binary format *note: no supported post-processing software available
	4	PHDF5 format *note: no supported post-processing software available

	5	GRIB1
	10	GRIB2
	11	parallel netCDF
io_form_restart		the format in which the restart output files will be
	2	nedCDF
	102	split netCDF files, one per processor (must restart with the same number of processors)
io_form_input		the format of the input files
	2	netCDF
	102	allows the program *real.exe* to read in split `met_em*` files, and write split `wrfinput` files. No split file for the `wrfbdy` file.
io_form_boundary		the format for the `wrfbdy` file
	2	netCDF format
	4	PHD5 format
	5	GRIB1 format
	10	GRIB2 format
	11	pnetCDF format
ncd_nofill	.true.	(default) only a single write, not the write/read/write sequence (new in V3.6)
io_form_auxinput2		IO format for input stream 2 data
	2	netCDF format
	4	PHD5 format
	5	GRIB1 format
	10	GRIB2 format
	11	pnetCDF format
diag_print	0	(default) When set to 1 or 2, it allows some simple diagnostic fields to be output
	1	domain-averaged 3-hourly hydrostatic surface pressure tendency (Dpsfc/Dt), and dry-hydrostatic column pressure tendency (Dmu/Dt) will appear in stdout file.
	2	in addition to those listed above, domain-averaged rainfall, surface evaporation, and sensible and latent heat fluxes will be output in stdout file.
debug_level	0	giving this a larger value (50, 100,

		200, etc.) increases the debugging print-outs when running WRF
auxhist2_outname	"rainfall_d<domain>"	file name to write additional output to a different unit or output stream.. If not specified, *auxhist2_d<domain>_<date>* will be used. Also note that to write variables in output other than the history file requires either a change in the Registry.EM_COMMON file, or the use of the option `iofields_filename` option.
auxhist2_interval (max_dom)	10	the interval in minutes for the output
io_form_auxhist2		output format for using auxhist2
	2	netCDF format
	4	PHD5 format
	5	GRIB1 format
	10	GRIB2 format
	11	pnetCDF format
frames_per_auxhist2 (max_dom)	1000	how many output times will be in each output file
auxinput11_interval	10	interval in minutes for obs nudging input. It should be set as the same (or more) frequency as `obs_ionf` (with the unit of the coarse domain time step)
auxinput11_end_h	6	end of the observation time (in hours), when using the `diag_print` option
nocolons	.false.	when set to .true. this replaces the colons with underscores in the output file names
write_input	.true.	write input-formatted data as output for 3DVAR application
inputout_interval (max_dom)	180	interval in minutes when using the `write_input` option
input_outname	"wrf_3dvar_input_d<domain>_<date>"	Output file name from 3DVAR
inputout_begin_y (max_dom)	0	beginning year to write 3DVAR data
inputout_begin_d (max_dom)	0	beginning day to write 3DVAR data
inputout_begin_h (max_dom)	3	beginning hour to write 3DVAR data

inputout_begin_m (max_dom)	0	beginning minute to write 3DVAR data
inputout_begin_s (max_dom)	0	beginning second to write 3DVAR data
inputout_end_y (max_dom)	0	ending year to write 3DVAR data
inputout_end_d (max_dom)	0	ending day to write 3DVAR data
inputout_end_h (max_dom)	12	ending hour to write 3DVAR data
inputout_end_m (max_dom)	0	ending minute to write 3DVAR data
inputout_end_s (max_dom)	0	ending second to write 3DVAR data
		NOTE: The above example shows that the input-formatted data are output starting from hour 3 to hour 12 in a 180-min interval.
all_ic_times	.false.	when set to .true., allows you to output a wrfinput file for all time periods
adjust_output_times	.false.	(default); adjust output times to the nearest hour
output_ready_flag *(new since V3.6.1)*	.true.	(default = .false.); when turned on, the model will write out an empty file with the name `wrfoutReady_d<domain>_<date>`. This is useful in production runs so that post-processing code can check on the existence of this file to start doing processing.
output_diagnostics *(new since V3.3.1)*	0	set to =1 to add 36 surface diagnostic arrays (max/min/mean/std)
	1	36 surface diagnostic arrays (max/min/mean/std) in the time interval are specified. The output goes to auxiliary history output stream 3 with default file name 'wrfxtrm_d<domain>_<date>.' You must also set `io_form_auxhist3 =2, auxhist3_interval = 1440, 1440, and`

		`frames_per_auxhist3 = 1000, 1000.` **Note:** do restart only at multiple of `auxhist3_intervals`
nwp_diagnostics *(new since V3.5)*	0	set to =1 to add 7 history_interval max diagnostic fields
For automatic moving nests		
input_from_hires (max_dom) *(new since V3.6)*	.false.	When set to .true., high-resolution terrain and landuse will be used in the nests (requires special input data, and environment variable TERRAIN_AND_LANDUSE set at compile time). This optin will overwrite `input_from_file` option for nest domains.
rsmas_data_path	"*high-res-data-directory*"	Directory path where the high-res data is
	1	output 7 history-interval maximum or mean diagnostic fields in wrfout: 10 m surface wind max, max positive and negative w, max helicity in the 2-5 km layer, mean w, max column-integrated graupel
iofields_filename (max_dom)	"*my_iofields_list*.txt"	an option to request particular variables to appear in output, if they are not already, or to not appear if they do and you do not want them to. You must also create a text file (*my_iofields_list*.txt) in which you will declare the variables to be output. It will be a single line of text, e.g.: `+:h:7:RAINC,RAINNC` or `-:h:0:RAINC,RAINNC`
ignore_iofields_warning	.true.	tells the model to continue if an error is encountered in the user-specified files
	.false.	tells the model to abort if an error is encountered in the user-specified files
&domains		***dimensions, nesting, parameters***
time_step	60	time step for integration seconds (recommended 6*dx in km for a typical case)
time_step_fract_num	0	numerator for fractional time step

time_step_fract_den	1	denominator for fractional time step. E.g., if you want to use 60.3 sec as your time step, `set time_step = 60, time_step_fract_num = 3,` and `time_step_fract_den = 10.`
time_step_dfi	60	time step when setting `dfi_opt = 1,` may be different from the regular time step
max_dom	1	the number of domains over which you are running
s_we (max_dom)	1	start index in x (west-east) direction (leave as is)
e_we (max_dom)	91	end index in x (west_east) direction (staggered dimension)
s_sn (max_dom)	1	start index in y (south-north) direction (leave as is)
e_sn (max_dom)	82	end index in y (south-north) direction (staggered dimension)
s_vert (max_dom)	1	start index in z (vertical) direction (leave as is)
e_vert (max_dom)	30	end index in z (vertical) direction (staggered dimension -- this refers to full levels). Most variables are on unstaggered levels. *Note: Vertical dimensions need to be the same for all nests
dx (max_dom)	30000	grid length in x-direction (in meters)
dy (max_dom)	30000	grid length in y-direction (in meters)
ztop (max_dom)	19000	height in meters; used to define model top for idealized cases
grid_id (max_dom)	1	domain identifier
parent_id (max_dom)	0	ID of the parent domain
i_parent_start (max_dom)	1	the starting lower-left corner i-indice from the parent domain
j_parent_start (max_dom)	1	the starting lower-left corner j_indice from the parent domain
parent_grid_ratio (max_dom)	1	parent-to-nest domain grid size ratio. *Note: for real data cases the ratio must be odd; for ideal data cases, the ratio can be even if `feedback` is set to 0.

parent_time_step_ratio (max_dom)	1	parent-to-nest time step ratio; this can be different from the `parent_grid_ratio`
feedback	0	no feedback
	1	feedback from nest to its parent domain
smooth_option		smoothing option for parent domain; used only with feedback
	0	turned off
	1	1-2-1 smoothing option for parent domain; used only with `feedback=1`
	2	(default) smoothing-desmoothing option for parent domain; used only with `feedback=1`
hypsometric_opt	2 *(default changed to 2 beginning V3.4)*	(default) computes height in program *real.exe* and pressure in the model (ARW only) by using an alternative method (less biased when compared against input data)
	1	original method
max_ts_locs	5	maximum number of time series locations
max_ts_level *(new since V3.7)*	15	highest model level for profile output
wif_input_opt	0	(default is 0=off) whether to process the Water Ice Friendly Aerosol input from metgrid (set to =1 to turn on); used for `mp_physics = 28`; see run/README.namelist for additional information
num_wif_levels	27	(default) number of levels in the Thompson Water Ice Friendly Aerosols (`mp_physics = 28`); see run/README.namelist for additional information
Options for Program *real.exe*		
num_metgrid_levels	40	number of vertical levels in WPS output (type `ncdump -h` on one of the `met_em*` files to find out this number)
num_metgrid_soil_levels	4	number of soil levels or layers in WPS output (type `ncdump -h` on

		one of the `met_em*` files to find out this number)
eta_levels	1.0, 0.99, ...0.0	model *eta* levels from 1 to 0. If not given, *real* will provide a set of levels
ideal_init_method *(new since V3.8)*		method to compute albedo in idealized cases in start_em
	1	(default) albedo from phb
	2	albedo from t_init
Horizontal interpolation options, coarse grid to fine grid		
interp_method_type *(new since V3.7)*		The default is to use the Smolarkiewicz "SINT" method; however, this is known to break with the implementation inside of WRF for large refinement ratios (such as 15:1). For those extreme and rare occurrences, other schemes ar available. For options 1, 3, 4, and 12, the FG lateral boundaries use the same horizontal scheme for the lateral BC computations
	1	bi-linear interpolation
	2	(default) SINT
	3	nearest-neighbor - only to be used for testing purposes
	4	overlapping quadratic
	12	for testing only, uses SINT horizontal interpolation, and same scheme for computation of FG lateral boundaries
Vertical interpolation options		
force_sfc_in_vinterp	1	(default) use the surface level as the lower boundary when interpolating through this many eta levels
	0	perform traditional trapping interpolation
maxw_horiz_pres_diff *(new since V3.6.1)*	5000	(default) Pressure threshold (Pa). For using the level of max winds when the pressure difference between neighboring values

		exceeds this maximum, the variable is NOT inserted into the column for vertical interpolation. ARW real only.
trop_horiz_pres_diff *(new since V3.6.1)*	5000	(default) Pressure threshold (Pa). For using the tropopause level when the pressure difference between neighboring values exceeds this maximum, the variable is NOT inserted into the column for vertical interpolation. ARW real only.
maxw_above_this_level *(new since V3.6.1)*	30000	(default) minimum height (it is actually pressure in Pa) to allow using the level of max wind information in real. With a value of 300 hPa, then a max wind value at 500 hPa will be ignored. ARW real only.
use_maxw_level *(new since V3.7.1)*	1	use max wind speed level in vertical interpolation inside of the ARW real program (default = 0; do not use level)
use_trop_level *(new since V3.7.1)*	1	same as above, but with tropopause level data (default = 0; do not use)
interp_theta *(new since V3.3.1)*	.false. *(default changed to .false. beginning V3.4)*	(default) vertically interpolates temperature (which may reduce bias when compared with input data)
	.true.	vertically interpolates potential temperature
p_top_requested	5000	pressure top (in Pa) to use in the model; must be available in WPS data
interp_type	2	(default) vertical interpolation that is linear in log(pressure)
	1	vertical interpolation that is linear in pressure
extrap_type	2	(default) vertical extrapolation of non-temperature variables, using the lowest level as constant below ground
	1	vertical extrapolation of non-

		temperature variables, using the 2 lowest levels
t_extrap_type		vertical extrapolation for potential temp:
	2	(default) -6.5 K/km lapse rate for temperature
	1	isothermal
	3	constant theta
use_levels_below_ground		in vertical interpolation, whether to use levels below input surface level
	.true.	(default) use input isobaric levels below input surface
	.false.	extrapolate when WRF location is below input surface level
use_surface	.true.	(default) uses input surface level data in vertical interpolation
	.false.	do not use input surface data
lagrange_order	2 *(default changed to 2 beginning V3.4)*	(default) quadratic vertical interpolation order
	1	linear vertical interpolation order
	9	Cubic spline
lowest_lev_from_sfc	.false.	(default) use traditional interpolation
	.true.	use surface values for the lowest *eta* (u,v,t,q)
sfcp_to_sfcp	.true	optional method to compute model's surface pressure when incoming data only has surface pressure and terrain, but not sea-level pressure (default is .false.)
use_tavg_for_tsk	.true.	uses diurnally-averaged surface temp as skin temp. The diurnally-averaged surface temp can be computed using WPS utility `avg_tsfc.exe`. May use this option when SKINTEMP is not present (default is .false.)
rh2qv_wrt_liquid *(new since V3.3)*	.true.	(default) computes qv with respect to liquid water
	.false.	computes qv with respect to ice
rh2qv_method *(new since V3.3)*		which method to use to computer mixing ratio from RH:

	1	(default) old MM5 method
	2	uses a WMO recommended method (WMO-No. 49, corrigendum, August 2000)
smooth_cg_topo	.true.	smooths the outer rows and columns of the domain 1 topography with respect to the input data (default is .false.)
vert_refine_fact	1	vertical refinement factor for *ndown* (1 = same number of vertical levels as the coarse domain, 2 = double the vertical resolution, and so on); not used for current vertical grid refinement
vert_refine_method (max_dom) *(new since V3.7)*	0	(default) no vertical refinement
	1	integer vertical refinement
	2	use specified or computed eta levels for vertical refinement
Options for Preset Moving Nest		
num_moves	0	total # of moves for all domains
move_id (max_moves)	2, 2,	a list of nest domain ID's, one per move
move_interval (max_moves)	60, 120,	time in minutes since the start of this domain
move_cd_x (max_moves)	1, -1,	the # of parent domain grid cells to move in the i-direction
move_cd_y (max_moves)	-1, 1,	the # of parent domain grid cells to move in the j-direction (positive in increasing i/j directions, and negative in decreasing i/j directions. Only 1, 0, and -1 is permitted.
Options for Automatic Moving Nest		
vortex_interval (max_dom)	15	how often the new vortex position is computed (in mins)
max_vortex_speed (max_dom)	40	used to compute the search radius for the new vortex position (in m/s)
corral_dist (max_dom)	8	how close the moving nest is allowed to get to the coarse grid boundary. This # sets the

		minimum limit of grid cells allowed between them.
track_level	50000	pressure level value (Pa) at which the tropical storm vortex is tracked
time_to_move (max_dom)	0.,	time (in mins) to start moving nest
Options for Adaptive Time Step		
use_adaptive_time_step	.true.	use adaptive time step (default is .false.)
step_to_output_time	.true.	modifies the time step so that the exact history time is reached
target_cfl (max_dom)	1.2., 1.2., 1.2.,	if vertical CFL ≤ this value, then time step is increased
target_hcfl (max_dom) *(new since V3.3)*	0.84, 0.84, 0.84,	if horizontal CFL ≤ this value, the time step is increased
max_step_increase_pct (max_dom)	5, 51, 51,	percentage of previous time step to increase if the max CFL is ≤ `target_cfl`
starting_time_step (max_dom)	-1, -1, -1,	flag -1 implies 4*dx is used to start the model. Any positive integer specifies the time step the model will use to start (in seconds). *Note: when `use_adapative_time_step = .true.`, the value specified for `time_step` is ignored.
starting_time_step_den (max_dom) *(new since V3.6)*	0	denominator for starting_time_step (so that fractional time step can be used)
max_time_step (max_dom)	-1, -1, -1,	flag -1 implies the maximum time step is 8*dx. Any positive integer specifies the maximum time step (in seconds).
max_time_step_den (max_dom) *(new since V3.6)*	0	denominator for max_time_step
min_time_step (max_dom)	-1, -1, -1,	flag -1 implies the minimum time step is 3*dx. Any positive integer specifies the minimum time step (in seconds).
min_time_step_den (max_dom) *(new since V3.6)*	0	denominator for min_time_step
adaptation_domain	1	(default) specifies which domain to use to drive adaptive time stepping

Options to Control Parallel Computing		
tile_sz_x	0	number of points in tile x direction (open MP only)
tile_sz_y	0	number of points in tile y direction; can be determined automatically (open MP only)
numtiles	1	number of tiles per patch (alternative to above 2 items; open MP only)
nproc_x	-1	(default) turned off; code will do automatic decomposition (MPI only)
	>1	number of processors in x for decomposition (MPI only)
nproc_y	-1	(default) turned off; code will do automatic decomposition (MPI only)
	>1	number of processors in y for decomposition (MPI only)
Options for 3D Ocean Model		
ocean_levels	30	(default) number of ocean levels when using `sf_ocean_physics = 2`
ocean_z	(values for # of ocean_levels)	vertical profile of layer depths for for ocean (in meters). See /run/README.namelist for more details.
ocean_t	(values for # of ocean_levels)	vertical profile of ocean temps (K). See /run/README.namelist for more details
ocean_s	(values for # of ocean_levels	vertical profile of salinity. See /run/README.namelist for more details
&physics		
chem_opt (max_dom)	0	chemistry option - use WRF-Chem
mp_physics (max_dom)	0	(default) no microphysics
	1	Kessler scheme
	2	Lin et al. scheme
	3	WSM 3-class simple ice scheme
	4	WSM 5-class scheme
	5	Ferrier (new Eta) microphysics, operational High-Resolution

		Window
	6	WSM 6-class graupel scheme
	7	Goddard GCE scheme (also uses `gsfcgce_hail` and `gsfcgce_2ice`)
	8	Thompson graupel scheme (2-moment scheme in V3.1)
	9	Milbrandt-Yau 2-moment scheme
	10	Morrison 2-moment scheme
(new since V3.5)	11	CAM 5.1 5-class scheme
(new since V3.3)	13	SBU_YLin, 5-class scheme
	14	WRF double moment, 5-class scheme
	15	High-resolution Ferrier microphysics, with advection
	16	WRF double moment, 6-class scheme
(new since V3.4)	17	NSSL 2-moment 4-ice scheme (steady background CCN)
(new since V3.4)	18	NSSL 2-moment 4-ice scheme with predicted CCN (better for idealized than real cases); to set a global CCN value, use `nssl_cccn = 0.7e9` (CCN for NSSL scheme 18). Also sets same value to ccn_conc for `mp_physics = 18`.
(new since V3.5)	19	NSSL 1-moment, 6-class scheme
(new since V3.5)	21	NSSL-LFO 1-moment, 6-class; very similar to Gilmore et al. 2004; can set intercepts and particle densities in physics namelist, e.g., `nssl_cnor` for NSSL 1-moment schemes, intercept and particle densities can be set for snow, graupel, hail, and rain. For the 1- and 2-moment schemes, the shape parameters for graupel and hail can be set. See `/WRFV3/run/README.namelist` file for specifics
(new since V3.7)	22	NSSL 2-moment 3-ice scheme, no hail.
(new since V3.6)	28	aerosol-aware Thompson scheme with water- and ice-friendly

		aerosol climatology (new for V3.6); this option has 2 climatological aerosol input options: use_aero_icbs = .F. (use constant values), and use_aero_icbc = .T. (use input from WPS)
(new since V3.6)	30	HUJI (Hebrew University of Jerusalem, Israel) spectral bin microphysics, fast version
(new since V3.6)	32	HUJI spectral bin microphysics, full version
(new since V3.9)	50	P3 1-category
(new since V3.9)	51	P3 1-category plus double moment cloud water
	95	Ferrier (old Eta), operational NAM (WRF NMM)
	98	Thompson scheme in V3.0
do_radar_ref *(new since V3.4.1)*	0	allows radar reflectivity to be computed using mp-scheme-specific parameters. Currently works for `mp_physics` = 2,4,6,7,8,10,14,16 0: off 1: on
mp_zero_out		for non-zero mp_physics options, this keeps moisture variables above a threshold value ≥0. An alternative (and better) way to keep moisture variables positive is to use the `moist_adv_opt`.
	0	(default) no action taken; no adjustment to any moisture field
	1	except for Qv, all other moisture arrays are set to zero if they fall below a critical value
	2	Qv ≥ 0 and all other moisture arrays are set to zero if they fall below a critical value
mp_zero_out_thresh	1.e-8	critical value for moisture variable threshold, below which moisture arrays (except for Qv) are set to zero (unit: kg/kg)
mp_tend_lim	10.	limit on temp tendency from microphysics latent heating when

		radar data assimilation is used
gsfcgce_hail	0	(default) running gsfcgce scheme with graupel
	1	running gsfcgce scheme with hail
gsfcgce_2ice	0	(default) running gsfcgce scheme with snow, ice, and graupel/hail
	1	running gsfcgce scheme with only ice and snow (`gsfcgce_hail` is ignored)
	2	running gsfcgce scheme with only ice and graupel (used only in very extreme situation; `gsfcgce_hail` is ignored)
ccn_conc (*new name since V3.7)*	1.0E8	(default) CCN concentration; used by WDM schemes (previously afwa_ccn_conc, new in V3.6.1)
hail_opt (*new name since V3.7)*		hail/graupel switch for WSM6, WDM6, and Morrison schemes (previously afwa_hail_opt, new in V3.6.1)
The following 9 namelists are for the NSSL 1-moment scheme. For the 1- and 2-moment schemes, the shape parameters for graupel and hail can also be set.		
nssl_alphah	0	shape parameter for graupel
nssl_alphahl	2	shape parameter for hail
nssl_cnoh	4.e5	graupel intercept
nssl_cnohl	4.e4	hail intercept
nssl_cnor	8.e5	rain intercept
nssl_cnos	3.e6	snow intercept
nssl_rho_qh	500.	graupel density
nssl_rho_ghl	900.	hail density
nssl_rho_qs	100.	snow density
no_mp_heating	1	turn off latent heating from a microphysics scheme (0 is off and is default)
use_mp_re *(new since V3.8)*		whether to use effective radii computed in mp schemes in RRTMG (the mp schemes that compute effective radii are 3, 4, 6, 8, 14, 16, 17-21)
	0	off; do not use
	1	(default) on; use effective radii
ra_lw_physics (max_dom)	0	(default) no longwave radiation
	1	rrtm scheme (Default values for GHG in V3.5: co2vmr=379.e-6, n2ovmr=319.e-9,

		ch4vmr=1774.e-9; Values used in previous versions: co2vmr=330.e-6, n2ovmr=0., ch4vmr=0.)
	3	CAM scheme *Note: restart must be at 6-hourly interval; also requires `levsiz`, `paerlev`, `cam_abs_dim1(2)`; see below
	4	rrtmg scheme (Default values for GHG in V3.5: co2vmr=379.e-6, n2ovmr=319.e-9, ch4vmr=1774.e-9)
(new since V3.7)	24	fast rrtmg scheme for GPU and MIC
(new since V3.3)	5	Goddard scheme
(new since V3.4)	7	FLG (UCLA) scheme
	31	Earth Held-Suarez forcing
	99	GFDL (Eta) longwave (semi-supported); also must use `co2tf = 1` for ARW
ra_sw_physics (max_dom)	0	(default) no shortwave radiation
	1	Dudhia scheme (ptop > 50 mb)
	2	(old) Goddard shortwave scheme
	3	CAM scheme (restart must be at 6-hourly interval); must set `levsiz, paerlev, cam_abs_dim1/2`
	4	rrtmg scheme
(new since V3.7)	24	fast rrtmg scheme for GPU and MIC
(new since V3.3)	5	Goddard scheme
(new since V3.4)	7	FLG (UCLA) scheme
	99	GFDL (Eta) longwave (semi-supported); must use `co2tf = 1` for ARW
radt (max_dom)	30	minutes between radiation physics calls. Recommended 1 minute per km of dx (e.g. 10 for 10 km grid); use the same value for all nests
swint_opt *(new since V3.5.1)*		Interpolation of shortwave radiation based on the updated solar zenith angle between radiation calls
	0	no interpolation
	1	use interpolation

ra_call_offset	0	default; call radiation after output time
	-1	may call radiation just before output time.
co2tf	1	CO2 transmission function flag for GFDL radiation only. Set it to 1 for ARW, which allows generation of CO2 function internally
** Note: The following 5 variables for CAM are automatically set since V3.2*		
cam_abs_freq_s	21600	default CAM clear sky longwave absorption calculation frequency (recommended minimum value to speed scheme up)
levsiz	59	(default) number of ozone data levels for CAM radiation
paerlev	29	(default) number of aerosol data levels for CAM radiation
cam_abs_dim1	4	(default) dimension for absnxt (absorption save array) in CAM radiation
cam_abs_dim2	same as e_vert	(default) dimension for abstot (2nd absorption save array) in CAM radiation
o3input *(new since V3.5)*		ozone input option (RRTMG only)
	0	using profile inside the scheme
	2 *(became default in V3.7)*	using CAM ozone data (`ozone.formatted`)
aer_opt		aerosol input option (RRTMG only)
	0	off
(new since V3.5)	1	using Tegen climatology
(new since V3.6)	2	using J. A. Ruiz-Arias method (see other aer* options)
(new since V3.8)	3	using G. Thompson's water/ice-friendly climatological aerosol
alevsiz	12	no of vertical levels in aerosol data. Value set automatically.
no_src_types	6	no of aerosol types: organic and black carbon, sea salt, sulfate, dust and stratospheric aerosol (volcanic ash – currently 0). Value set automatically.
	0	do not interpolate (default)
	1	interpolate

**The following aerosol options allow RRTMG and new Goddard radiation schemes to see it, but the aerosols are constant during the model integration*		
aer_aod550_opt (max_dom)	1	(default) input constant value for AOD at 550 nm from namelist; in this case, the value is read from `aer_aod550_val`
	2	input value from auxiliary input 5; it is a time-varying 2D grid in netcdf wrf-compatible format.
aer_aod550_val (max_dom)	0.12	(default) value to be used with `aer_aod550_opt = 1`
aer_angexp_opt (max_dom)	1	(default) input constant value for Angstrom exponent from namelist. In this case, the value is read from `aer_angexp_val`
	2	input value from auxiliary input 5, as in `aer_aod550_opt`
	3	Angstrom exponent value estimated from the aerosol type defined in `aer_type`, and modulated with the RH in WRF.
aer_angexp_val (max_dom)	1.3	(default) value to be used with `aer_angexp_opt = 1`
aer_ssa_opt (max_dom)	1	(default) input constant value for single scattering albedo from namelist. In this case, the value is read from `aer_ssa_val`
	2	input value from auxiliary input 5, as in `aer_aod550_opt`
	3	single scattering albedo value estimated from the aerosol type defined in `aer_type`, and modulated with the RH in WRF.
aer_ssa_val (max_dom)	0.85	(default) value to be used with `aer_ssa_opt = 1`
aer_asy_opt (max_dom)	1	(default) input constant value for asymmetry parameter from namelist. In this case, the value is read from `aer_asy_val`
	2	input value from auxiliary input 5, as in `aer_aod550_opt`
	3	asymmetry parameter value estimated from the aerosol type defined in `aer_type`, and modulated with the RH in WRF.

aer_asy_val (max_dom)	0.9	(default) value to be used with `aer_asy_opt = 1`
aer_type (max_dom)		aerosol type to be used with the above aerosol options
	1	(default) rural
	2	urban
	3	maritime
sf_sfclay_physics (max_dom)		surface layer option
	0	(default) no surface-layer
(since V3.6; option 11 for V3.4 and V3.5)	1	Revised MM5 Monin-Obukhov scheme (Jimenez, renamed in v3.6)
	2	Monin-Obukhov (Janjic Eta) scheme
	3	NCEP GFS scheme (NMM only)
	4	QNSE
	5	MYNN
	7	Pleim-Xiu (ARW only), only tested with Pleim-Xiu surface and ACM2 PBL
(new since V3.3)	10	TEMF (ARW only)
(since V3.6; option 1 in earlier versions)	91	old MM5 surface layer scheme (previously option 1)
iz0tlnd *(new since V3.2)*		switch to control land thermal roughness length
	0	(default) old, or non-vegetation dependent thermal roughness length over land
	1	veg dependent Chen-Zhang Czil
sf_surface_physics (max_dom)		land-surface option (set this before running *real.exe*; also make sure `num_soil_layers` is set correctly)
	0	(default) no surface temp prediction
	1	thermal diffusion scheme
	2	unified Noah land-surface model
	3	RUC land-surface model
(new since V3.4)	4	Noah-MP land-surface model (additional options under the `&noah_mp` section)
(new since V3.5)	5	CLM4 (Community Land Model Version 4)
	7	Pleim-Xiu scheme (ARW only)
(new since V3.4)	8	SSiB land-surface model (ARW

		only). Works with `ra_lw_physics = 1, 3, or 4`, and `ra_sw_physics = 1, 3, or 4`
sf_urban_physics		activate urban canopy model (in Noah LSM only)
	0	(default) off
	1	Single-layer, UCM
	2	Multi-layer, Building Environment Parameterization (BEP) scheme (works only with the MYJ and BouLac PBL)
	3	Multi-layer, Building Environment Model (BEM) scheme (works only with MYJ and BouLac PBL)
ua_phys *(new since V3.5)*	.false.	Option to activate UA Noah LSM changes to use a different snow-cover physics. Aimed toward improving treatment of snow as it relates to the vegetation canopy.
num_soil_layers		number of soil layers in land surface model (set before running *real.exe*)
	5	(default) thermal diffusion scheme for temp only
	4	Noah land-surface model
	6 or 9	RUC land-surface model
	10	CLM4 land-surface model
	2	Pleim-Xu land-surface model
	3	SSiB land-surface model
bl_pbl_physics (max_dom)		boundary layer option
	0	(default) no boundary-layer
	1	YSU scheme; use `sf_sfclay_physics =1`
	2	Mellor-Yamada-Janjic (Eta) TKE scheme; use `sf_sfclay_physics=2`
	4	QNSE-EDMF; use `sf_sfclay_physics=4`
	5	MYNN 2.5 level TKE; use `sf_sfclay_physics=1, 2,` or `5`
	6	MYNN 3rd level TKE; use `sf_sfclay_physics=5`
	7	ACM2 (Pleim) scheme (ARW

		only); use `sf_sfclay_physics=1` or `7`
	8	Bougeault and Lacarrere (BouLac) TKE; use `sf_sfclay_physics=1` or `2`
(new since V3.3)	9	Bretherton-Park/UW TKE scheme; use `sf_sfclay_physics=1` or `2`
(new since V3.3)	10	TEMF scheme (ARW only); use `sf_sfclay_physics=10`
(new since V3.7)	11	Shin-Hong 'scale-aware' PBL scheme
(new since V3.5)	12	GBM TKE-type scheme (ARW only); use `sf_sfclay_physics=1`
	99	MRF scheme (to be removed in the future)
mfshconv (max_dom)	1	turns on day-time EDMF for QNSE (0=off)
bldt (max_dom)	0	minutes between boundary-layer physics calls (0=call every time step)
topo_wind (max_dom) *(new since V3.4)*		turns on topographic surface wind correction, and requires extra input from geogrid. YSU PBL only
	0	off
	1	Jimenez method
	2	UW method
bl_mynn_tkebudget (max_dom) *(new since V3.4.1)*	0	(default) off
	1	adds MYNN tke budget terms to output
bl_mynn_tkeadvect (max_dom) *(new since V3.5)*	.false.	(default) off; does not advect tke in MYNN scheme (default)
	.true.	do MYNN tke advection
icloud_bl *(new since V3.8)*		option to couple the subgrid-scale clouds from the PBL scheme (MYNN only) to the radiation scheme
	0	no coupling
	1	(default) activate coupling to radiation
bl_mynn_cloudmix		option to activate mixing of qc and

(max_dom) *(new since V3.8)*		qi in MYNN (NOTE: qnc and qni are mixed when `scalar_pblmix = 1`)
	0	(default) no mixing of qc and qi
	1	activates mixing of qc and qi in MYNN
bl_mynn_mixlength *(new since V3.8)*		option to change mixing length formulation in MYNN
	0	original, as in Nakanishi and Niino 2009
	1	(default) RAP/HRRR (including BouLac in free atmosphere)
	2	experimental (includes cloud-specific mixing length and a scale-aware mixing length; following Ito et al. 2015, BLM); this option has been well-tested with the edmf options
bl_mynn_cloudpdf		option to switch to diffrent cloud PDFs to represent subgrid clouds
	0	original (Sommeria and Deardorf 1977)
	1	Kuwano et al. 2010; similar to option 0, but uses resolved scale gradients, as opposed to higher order moments
	2	(default) from Chaboureau and Bechtold 2002 (JAS, with mods)
bl_mynn_edmf (max_dom) *(new since V3.8)*		option to activate mass-flux scheme in MYNN
	0	(default) regular MYNN
	1	for StEM
	2	for TEMF
bl_mynn_edmf_mom (max_dom) *(new since V3.8)*		option to activate momentum transport in MYNN mass-flux scheme (assuming bl_mynn_edmf > 0)
	0	no momentum transport
	1	(default) momentum transport activated
bl_mynn_edmf_tke (max_dom) *(new since V3.8)*		option to activate TKE transport in MYNN mass-flux scheme (assumumg bl_mynn_edmf > 0)
	0	(default) no TKE transport
	1	activate TKE transport

scalar_pblmix *(new since V3.6)*	0	(default) off
	1	mix scalar fields consistent with PBL option (exch_h)
tracer_pblmix *(new since V3.6)*	0	(default) off
	1	mix tracer fields consistent with PBL option (exch_h)
shinhong_tke_diag (max_dom) *(new since V3.7)*	0	diagnostic TKE and mixing length from Shin-Hong PBL
opt_thcnd *(new since V3.8)*		option to treat thermal conductivity in Noah LSM
	1	(default) original
	2	McCumber and Pielke for silt loam and sandy loam
sf_surface_mosaic *(new since V3.6)*		option to mosaic landuse categories for Noah LSM
	0	(default) use dominant category only
	1	use mosaic landuse categories
mosaic_lu *(new since V3.4)*	1	option to specify landuse parameters based on a mosaic approach, when using the RUC land surfce model; default is 0 (off)
mosaic_soil *(new since V3.4)*	1	option to specify soil parameters based on a masaic approach, when using the RUC land surface model; default is 0 (off)
mosaic_cat *(new since V3.6)*	3	(default) number of mosaic landuse categories in a grid cell
grav_settling (max_dom) *(new since V3.5.1)*		gravitational settling of fog/cloud droplets (Now works for any PBL scheme, since V3.5.1)
	0	(default) no settling of cloud droplets
	1	settling from Dyunkerke 1991 (in atmosphere at at surface)
	2	Fogdes (vegetation and wind speed dependent; Katata et al. 2008) at surface, and Dyunkerke in the atmosphere
ysu_topdown_pblmix *(new since V3.7)*	1	turns on top-down radiation-driven mixing (default is 0=no)

cu_physics (max_dom)		cumulus parameterization option
	0	(default) no cumulus parameterization
	1	Kain-Fritsch (new Eta) scheme
	2	Betts-Miller-Janjic scheme
(new since V3.5, replacing Grell-Devenyi scheme)	3	Grell-Freitas ensemble scheme
(new to ARW since V3.3)	4	Scale-aware GFS Simplified Arakawa-Schubert (SAS) scheme
	5	New Grell scheme (G3)
(new since V3.3)	6	Tiedtke scheme (ARW only)
(new since V3.3)	7	Zhang-McFarlane from CESM (works with MYJ and UW PBL)
(new since V3.7)	10	Modified Kain-Fritsch scheme with trigger function based on PDFs (ARW-only)
(new since V3.7)	11	Multi-scale Kain-Fritsch scheme
(new since V3.3)	14	New GFS SAS from YSU (ARW only)
(new since V3.7)	16	A newer Tiedke scheme
(option 3 before V3.5)	93	Grell-Devenyi ensemble scheme
	94	2015 GFS Simplified Arakawa-Schubert scheme (HWRF)
	95	Previous GFS Simplified Arakawa-Schubert scheme (HWRF)
	99	previous Kain-Fritsch scheme
cudt (max_dom)	0	minutes between cumulus physics calls; should be set to 0 when using all `cu_physics` except Kain-Fritsch (0 = call every time step)
kfeta_trigger	1	The way to determines whether a grid point is convective; used only with `cu_physics=1`. = 1, default, original.
(new since V3.3)	2	moisture-advection based trigger (Ma and Tan 2009; ARW only)
	3	relative humidity-dependent
ishallow	0	=1 turns on shallow convection used with `cu_physics=3 or 5` (default is 0 = off)
cu_diag (max_dom)	0	additional t-averaged stuff for cu physics (`cu_physics = 3, 5,` and `93` only)

shcu_physics (max_dom)		independent shallow cumulus option (not tied to deep convection)
	0	no independent shallow cumulus
(new since V3.3)	2	Park and Bretherton shallow cumulus from CAM5
(new since V3.5)	3	GRIMS scheme
**Note: The following 5 options show recommended #'s. If you would like to use any other number, consult the code to understand what you are doing.*		
maxiens	1	Grell-Devenyi and G3 only
maxens	3	Grell-Devenyi only
maxens2	3	Grell-Devenyi only
maxens3	16	Grell-Devenyi only
ensdim	144	Grell-Devenyi only
cugd_avedx	1	(default) number of grid boxes over which subsidence is spread, for large grid distances
	3	for small grid distances (DX < 5 km)
nsas_dx_factor *(New since V3.6)*	0	(default); off
	1	nsas grid distance dependent option
For the KF-CuP Scheme:		
shallowcu_forced_ra (max_dom) *(new since V3.8)*	.false.	radiative impact of shallow Cu by a prescribed maximum cloud fraction [cu_physics = 10 only; default = .false. (off); if =.true., radiative impact of shallow cu with a cloud fraction value of 0.36]
numbins (max_dom) *(new since V3.8)*	1	number of perturbations for potential temperature and mixing ratio in the CuP PDF (cu_physics = 10 only ; default is 1; should be an odd number - recommended value is 21)
thBinSize (max_dom) *(new since V3.8)*	1	bin size of potential temperature perturbation increment: 0.01 K (cu_physics = 10 only; default is 1)
rBinSize (max_dom) *(new since V3.8)*	1	bin size of mixing ratio perturbation increment: 1.0e-4 kg/kg (cu_physics = 10 only; default is 1)
minDeepFreq (max_dom) *(new since V3.8)*	1	minimum frequency required before deep convection is allowed:

		0.333 (cu_physics = 10 only; default is 1)
minShallowFreq (max_dom) *(new since V3.8)*	1	minimum frequency required before shallow convection is allowed: 1.0e-2 (cu_physics = 10 only; default is 1)
shcu_aerosols_opt (max_dom) *(new since V3.8)*		whether to include aerosols in shcu (cu_physics = 10 only; run with WRF-Chem)
	0	(default) none
	2	prognostic
cu_diag (max_dom)	0	Additional time-averaged diagnostics from cu_physics (use only with `cu_physics=3,5,` and `93`)
kf_edrates (max_dom) *(new since V3.8)*		option to add entrainment/detrainment rates and convective timescale output variables for KF-based cumulus schemes (cu_physics = 1, 11, and 99 only)
	0	(default) no output
	1	additional output
convtrans_avglen_m	30	averaging time for convective transport output variables (in minutes; only use with `cu_physics=3,5` and `93`)
cu_rad_feedback (max dom)	.true.	sub-grid cloud effect to the optical depth in radiation currently it works only for GF, G3, GD, and KF schemes; also need to set `cu_diag = 1` for GF, G3, and GD schemes (default is .false. = off)
isfflx		heat and moisture fluxes from the surface for real-data cases and when a PBL is used (only works with `sf_sfclay_physics=1, 5, 7, or 11`) 1 = fluxes are on 0 = fluxes are off It also controls surface fluxes when diff_opt = 2 and km_opt = 3, and a PBL isn't used

		0 = constant fluxes defined by `tke_drag_coefficient` and `tke_heat_flux` 1 = use model-computed u* and heat and moisture fluxes 2 = use model-computed u* and specified heat flux by `tke_heat_flux`
ideal_xland *(new since V3.7)*		sets XLAND for ideal cases with no input land-use run-time switch for wrf.exe physics_init
	1	land
	2	water
ifsnow		snow-cover effects (only works for `sf_surface_physics=1`)
	1	(default) with snow-cover effect;
	0	without snow-cover effect
icloud		(default) cloud effect to the optical depth in radiation (only works with `ra_sw_physics=1,4` and `ra_lw_physics=1,4`); since V3.6 this also controls the cloud fraction options
	1	(default) with cloud effect, and use cloud fraction option 1 (Xu-Randall mehod)
	0	without cloud effect
	2	with cloud effect, and use cloud fraction option 2, 0/1 based on threshold
(new since V3.7)	3	with cloud effect, and use cloud fraction option 3, a Sundqvist method (Sundqvist et al. 1989)
swrad_scat	1	scattering tuning parameter; default 1 is 1.e-5 m^{-2} kg^{-1} (only for `ra_sw_physics=1`). Increase for more scattering.
surface_input_source		where landuse and soil category data come from
	1	(default prior to V3.8) WPS/geogrid, but with dominant categories recomputed in real
	2	GRIB data from another model (only if arrays VEGCAT/SOILCAT exist)

	3	(default begining in V3.8) use dominant land and soil categories from WPS/geogrid
pxlsm_smois_init (max_dom)		Pleim-Xu land-surface model soil moisture initialization option
	0	from analysis
	1	(default) from LANDUSE.TBL (SLMO, or moisture availability)
num_land_cat		number of land categories in input data
	24	(default prior to V3.8) for USGS
	20	for MODIS
	28	for USGS if including lake category
	21	(default beginning with V3.8) for MODIS if including lake category
	40	NLCD2006 (North America only)
num_soil_cat	16	number of soil categories in input data
usemonalb	.true.	use monthly albedo map instead of table values (recommended for `sst_update=1`)
	.false.	(default) use table values
rdmaxalb	.true.	(default) use snow albedo from geogrid
	.false.	use snow albedo from table
rdlai2d *(data available to use this option since V3.6)*	.true.	use LAI (Leaf Area Index) from input data. If sst_update is 1, then LAI will also appear in wrflowinp file
	.false.	(default) use LAI from table
seaice_threshold	100. *(default value of 100 since V3.5.1; was 271 in earlier versions)*	If skin temp (TSK) is less than this value, water points are changed to sea ice. If water point + 5-layer slab scheme, set to land point and permanent ice; if water point + Noah scheme, set to land point, permanent ice, set temps from 2 m to surface, and set smois and sh2o. The default value was changed to 100. From 271. in 3.5.1 to avoid mixed-up use with fractional seaice input. Used by `sf_surface_physics = 1,2,3,4,8`

sst_update		option to use time-varying SST, seaice, vegetation fraction, and albedo during a model simulation (set before running *real.exe*)
	0	(default) no SST update
	1	*real.exe* will create wrflowinp file(s) at the same time interval as the available input data. These files contain SST, XICE, ALBEDO, and VEGFRA. Also set `auxinput4_inname = "wrflowinp_d<domain>"`, `auxinput4_interval` and (in V3.2) `io_form_auxinput4` in namelist section *&time_control*
tmn_update	1	update deep layer soil temperature, useful for long simulations (multi-year runs; default is 0 = off)
lagday	150	days over which tnm (deep layer soil temp) is computed using skin temperature
sst_skin	1	calculate skin SST, useful for long simulations (multi-year runs; default is 0 = off)
bucket_mm		bucket reset values for water accumulation (unit in mm), useful for long simulations (multi-year runs)
	-1	(default) inactive
bucket_j		bucket reset value for energy accumulations (unit in Joules); useful for long simulations (multi-year runs)
	-1	(default) inactive
slope_rad (max_dom)	1	use slope-dependent radiation; for `ra_sw_physics`
	0	(default) off
topo_shading (max_dom)	1	applies neighboring-point shadow effects for `ra_sw_physics`
	0	(default) off
shadlen	25000	maximum length of orographic shadow (in meters); use with `topo_shading=1`
sf_ocean_physics *(replacing omlcall*		activate ocean model

beginning with V3.5)		
	0	off
	1	activate a simple ocean mixed layer (oml) model
(new since V3.5)	2	activate a 3D PWP ocean model
omdt	1.	3D PWP time step (minutes). It can be set t the same as the WRF time step in corresponding nested grids, but omdt should be no less than 1.0 minute.
oml_hml0 (for sf_ocean_physics=1)	≥ 0	initial ocean mixed layer depth value (m); constant everywhere (50 is default)
	< 0	use input
oml_gamma (for sf_ocean_physics=1)	0.14	(K m^{-1}) lapse rate in deep water (below the mixed layer) for oml
oml_relaxation_time *(new since V3.8)*	0.	relaxation time (seconds) of mixed layer ocean model back to original values (e.g. value: 259200 sec - 3 days)
ocean_levels (for sf_ocean_physics=2)	30	number of vertical levels in 3D ocean model
isftcflx		alternative Ck (exchange coefficient for temp and moisture), Cd (drag coefficient for momentum) formulation for tropical storm application
	0	(default) off for Ck
	1	Donelan Cd + constant Z_{0q} for Ck
	2	Donelan Cd + Garratt Ck
fractional_seaice	1	treats seaice as a fractional field; works with `sf_sfclay_physics = 1,2,3,4,5,7 or 91` Also set `seaice_threshold=0.`
	0	(default) either ice or no ice flag
seaice_albedo_opt *(new since V3.4)*		option to set albedo over sea ice
	0	seaice albedo is a constant value from namelist option `seaice_albedo_default`
	1	seaice albedo is a function of air temp, skin temp, and snow
	2	seaice albedo read in from input variable ALBSI

seaice_albedo_default	0.65 (changed from 0.8)	default value of seaice albedo for `seaice_albedo_opt`=0
seaice_snowdepth_opt *(new since V3.5)*		method for treating snow depth on sea ice
	0	snow depth on sea ice is bounded by `seaice_snowdepth_min` and `seaice_snowdepth_max`
	1	snow depth on sea ice read in from input array SNOWSI (bounded by `seaice_snowdepth_min` and `seaice_snodepth_max`)
seaice_snowdepth_max	1.e10	maximum allowed accumulation of snow (m) on sea ice
seaice_snowdepth_min	0.001	minimum snow depth (m) on sea ice
seaice_thickness_opt		option for treating seaice thickness
	0	seaice thickness is uniform value taken from namelist variable `seaice_thickness_default`
	1	seaice_thickness is read in from input variable ICEDEPTH
seaice_thickness_default	3.0	default value of seaice thickness for `seaice_thickness_opt`=0
prec_acc_dt (max_dom)	0.	bucket reset time interval between outputs for cumulus or grid-scale precipitation (in minutes). If set >0, this will output 3 new 2d fields: *prec_acc_c*, *prec_acc_nc*, and *snow_acc_nc* (descriptions of these can be found in the Registry.EM_COMMON file)
traj_opt *(new since V3.5)*	1	activate forward trajectories (default 0)
num_traj	1000	(default) number of trajectories to be released
** The following are options for the lake model*		
sf_lake_physics (max_dom) *(new since V3.6)*	1	lake model on (default is 0 = off)
lakedepth_default (max_dom)	50	(default) lake depth (in meters). If there is no lake depth information in the input data, then lake depth is assumed to be 50m)
lake_min_elev (max_dom)	5	(default) minimum elevation of lakes; may be used to determine

		whether a water point is a lake in the absence of a lake category. If the landuse type includes 'lake' (i.e., Modis_lake andn USGS_LAKE); this variable is of no effects
use_lakedepth (max_dom)	1	(default) option to use lake depth data. Lake depth data is available beginning in the V3.6 geogrid program. If the lake depth data was not processed, but this switch is set to 1, the program will stop and tell the user to go back to geogrid program.
lightning_option (max_dom) *(new since V3.5)*		Lightning parameterization option to allow flash rate prediction without chemistry. Requires `do_radar_ref` on.
	0	off
	1	PR92 based on maximum w, redistributes flashes within dBZ > 20 (for convection resolved runs)
	2	PR92 based on 20 dBZ top, redistributes flashes within dBZ > 20 (for convection resolved runs)
(New since V3.6.1)	3	Predicting the potential for lightning activity (based on Yair et al., 2010)
	11	PR92 based on level of neutral buoyancy from convective parameterization (for scale where a CPS is used, intended for use at 10 < dx < 50 km
lightning_dt (max_dom) *(new since V3.5)*	0.	time interval (seconds) for calling lightning parameterization. Default uses model time step
lightning_start_seconds (max_dom) *(new since V3.5)*	0.	start time for calling lightning parameterization. Recommends at least 10 minutes for spin-up
flashrate_factor (max_dom) *(new since V3.5)*	1.0	Factor to adjust the predicted number of flashes. Recommends 1.0 for `lightning_option` = 11 between dx=10 and 50 km. Manual tuning recommended for all other options independently for each

		nest.
cellcount_method (max_dom)		method for counting storm cells. Used by CRM options (`lightning_options`=1,2)
	0	model determines method used
	1	tile-wide, appropriate for large domains
	2	domain-wide, appropriate for sing-storm domains
cldtop_adjustment (max_dom)	0.	adjustment from LNB in km. Used by `lightning_option`=11. Default is 0, but recommends 2 km
iccg_method (max_dom)		IC:CG partitioning method (IC: intra-cloud; CG: cloud-to-ground)
	0	Default method depending on lightning option, currently all options use `iccg_method`=2 by default
	1	Constant everywhere, set with namelist options `iccg_prescribed (num|den)`#, default is 0./1. (all CG)
	2	Coarsely prescribed 1995-1999 NLDN/OTD climatology based on Boccippio et al. (2001)
	3	Parameterization by Price and Rind (1993) based on cold-cloud depth
	4	Gridded input via arrays *iccg_in_(num|den)* from wrfinput for monthly mapped ratios. Points with 0/0 values use ratio defined by iccg_prescribed_(num|den)
iccg_prescribed_num (max_dom)	0.	Numerator of user-specified prescribed IC:CG
iccg_prescribed_den (max_dom)	1.	Denominator of user-specified prescribed IC:CG
For Wind Turbine Drag Parameterization		
windfarm_opt (max_dom) *(new since V3.3)*	1	simulates the effets of wind turbines in the atmospheric evolution (default is 0 = off)
windfarm_ij *(new since V3.3)*		whether to use lat-lon or i-j coordinate as wind turbine

		locations
	0	(default) the coordinates of the turbines are defined in terms of lat-lon
	1	the coordinates of the turbines are defined in terms of grid points
hailcast_opt (max_dom)	0	whether to use the hailcasting option (=1 to turn on)

&stoch		***For Stochastic Kinetic-Energy Backscatter Scheme (SKEB; used to perturb a forecast)*** ***See pages 5-26 – 5-27***
rand_perturb (max_dom)		Whether to turn on random perturbations
	0	(default) no random perturbations
	1	create random perturbation field
lengthscale_rand_pert (max_dom)	500000	(default) perturbation correlation lengthscale (in meters)
timescale_rand_pert (max_dom)	21600	(default) temporal decorrelation of random field (in seconds)
gridpt_stddev_rand_pert (max_dom)	0.03	(default) standard deviation of random perturbation field at each grid point
stddev_cutoff_rand_pert (max_dom)	3.0	(default) cutoff tails of perturbation pattern above this threshold standard deviation
rand_pert_vertstruc		vertical structure for random perturbation field
	0	(default) constant
	1	random phase with tilt
nens	1	(default) seed for random number stream. For ensemble forecasts this parameter needs to be different for each member. The seed is a function of initial start time to ensure different random number streams are created for forecasts starting from different intial times. Changing this seed changes the random number streams for all activated stochastic parameterization schemes.
iseed_rand_pert	17	(default) seed for random number

		stream for `rand_perturb`. Will be combined with seed `nens`, signifying ensemble member number and initial start time to ensure different random number streams are created for forecasts starting from different initial times and for different ensemble members.
** The following are stochastically perturbed physical tendencies (SPPT) (sppt=1)*		
sppt (max_dom)		Whether to turn on stochastically perturbed physics tendencies (SPPT)
	0	(default) off
	1	on
lengthscale_sppt (max_dom)	150000	(default) random perturbation lengthscale (in meters)
timescale_sppt (max_dom)	21600	(default) temporal decorrelation of random field (in seconds)
gridpt_stddev_sppt (max_dom)	0.5	(default) standard deviation of random perturbation field at each grid point
stddev_cutoff_sppt (max_dom)	2.0	(default) cutoff tails of perturbation pattern above this threshold standard deviation
nens	1	(default) seed for random number stream. For ensemble forecasts this parameter needs to be different for each member. The seed is a function of initial start time to ensure different random number streams for forecasts starting from different initial times. Changing this seed changes the random number streams for all activated stochastic parameterization schemes.
iseed_sppt	53	(default) seed for random number stream for `sppt`. Will be combined with parameter `nens`, signifying ensemble member number and initial start time to ensure different random number streams for forecasts starting from different initial times and for

		different ensemble members.
** The following are for stochastic kinetic-energy backscatter scheme (SKEBS) (skebs=1)*		
skebs (max_dom)		Whether to turn on the stochastic kinetic-energy backscatter scheme (SKEBS) **Note: this replaces the namelist parameter `stoch_forc_opt` which was used up to V3.6. Latter is still maintained, but obsolete*
	0	(default) no stochastic parameterization
	1	stochastic kinetic-energy backscatter scheme (SKEBS) turned on
tot_backscat_psi (max_dom)	1.0E-05	(default) total backscattered dissipation rate for streamfunction; controls amplitude of rotational wind perturbations (in m^2/s^2)
tot_backscat_t (max_dom)	1.0E	(default) total backscattered dissipation rate for potential temperature; controls amplitude of potential temperature perturbations (in m^2/s^2)
ztau_psi	10800.0	(default) decorrelation time (in seconds) for streamfunction perturbations
ztau_t	10800.0	(default) decorrelation time (in seconds) for potential temperature perturbations
rexponent_psi	-1.83	(default for a kinetic-energy forcing spectrum with slope -5/3) spectral slope for streamfunction perturbations
rexponent_t	-1.83	(default for a potential energy forcing spectrum with slope -1.83^2) spectral slope of potential temperature perturbations
kminforc	1	(default) minimal forcing wavenumber in longitude for streamfunction perturbations
lminforc	1	(default) minimal forcing wavenumber in latitude for streamfunction perturbations
kminforct	1	(default) minimal forcing

		wavenumber in longitude for potential temperature perturbations
lminforct	1	(default) minimal forcing wavenumber in latitude for potential temperature perturbations
kmaxforc	1000000	(default is maximal possible wavenumbers determined by number of gridpoints in longitude) maximal forcing wavenumber in longitude for streamfunction perturbations
lmaxforc	1000000	(default is maximal possible wavenumbers determined by number of gridpoints in latitude) maximal forcing wavenumber in latitude for streamfunction perturbations
kmaxforct	1000000	(default is maximal possible wavenumbers determined by number of gridpoints in longitude) maximal forcing wavenumber in longitude for potential temperature perturbations
lmaxforct	1000000	(default is maximal possible wavenumbers determined by number of gridpoints in latitude) maximal forcing wavenumber in latitude for potential temperature perturbations
zsigma2_eps	0.0833	(default) noise variance in autoregressive process defining streamfunction perturbations
zsigma2_eta	0.0833	(default) noise variance in autoregressive process defining potential temperature perturbations
skebs_vertstruc (max_dom)		defines the vertical structure of random pattern generator **Note: this replaces the namelist parameter* `stoch_vertstruc_opt` *which was used up to V3.6. Latter is still maintained, but obsolete*
	0	(default) constand vertical structure of random pattern

		generator
	1	random phase vertical structure with westward tilt
nens	1	(default) Seed for random number stream for both stochastic schemes. For ensemble forecasts this parameter needs to be different for each member. The seed is a function of initial start time to ensure different random number streams for forecasts starting from different initial times. Changing this seed changes the random number streams for all activated stochastic parameterization schemes
iseed_skebs	811	(default) seed for random number stream for skebs. Will be combined with seed nens, signifying ensemble member number and initial start time to ensure different random number streams for forecasts starting from different initial times and for different ensemble members
** The following are for stochastically perturbed parameter scheme (SPP) (spp=1)*		
spp (max_dom)		whether to turn on stochastically perturbed parameter scheme (SPP) for GF convection schemes, MYNN boundary layer scheme, and RUC LSM
	0	(default) off
	1	on
spp_conv (max_dom)		whether to perturb parameters of GF convective scheme
	0	(default) off
	1	on
lengthscale_spp_conv (max_dom)	150000	(default) perturbation length scale (in meters)
timescale_spp_conv (max_dom)	21600	(default) temporal decorrelation of random field (in seconds)
gridpt_stddev_spp_conv (max_dom)	0.3	(default) standard deviation of random perturbation feild at each grid point
stddev_cutoff_spp_conv	3.0	(default) cutoff tails of

(max_dom)		perturbation pattern above this threshold standard deviation
iseed_spp_conv	171	(default) seed for random number stream for `spp_conv`
spp_pbl (max_dom)		whether to perturb parameters of MYNN convection scheme
	0	(default) off
	1	on
lengthscale_spp_pbl (max_dom)	700000	(default) perturbation length scale (in meters)
timescale_spp_pbl (max_dom)	21600	(default) temporal decorrelation of random field (in seconds)
gridpt_stddev_spp_pbl (max_dom)	0.15	(default) standard deviation of random perturbation field at each gridpoint
stddev_cutoff_spp_pbl (max_dom)	2.0	(default) cutoff tails of perturbation pattern above this threshold standard deviation
iseed_spp_pbl	217	(default) seed for random number stream for `spp_pbl`
spp_lsm (max_dom)		whether to perturb parameters of RUC LSM
	0	(default) off
	1	on
lengthscale_spp_lsm (max_dom)	50000	(default) perturbation length scale (in meters)
timescale_spp_lsm (max_dom)	86400	(default) temporal decorrelation of random field (in seconds)
gridpt_stddev_spp_lsm (max_dom)	0.3	(default) standard deviation of random perturbation field at each grid point
stddev_cutoff_spp_lsm (max_dom)	3.0	(default) cutoff tails of perturbation pattern above this threshold standard deviation
iseed_spp_lsm	317	(default) seed for random number stream for `spp_lsm`
nens	1	(default) Seed for random number stream for both stochastic schemes. For ensemble forecasts this parameter needs to be different for each member. The seed is a function of initial start time to ensure different random number streams for forecasts starting from different initial times. Changing

		this seed changes the random number streams for all activated stochastic parameterization schemes
&noah_mp		Options for NoahMP LSM
dveg		dynamic vegetation option
	1	off [LAI (Leaf Area Index) from table; FVEG (veg fraction) = shdfac (model variable for veg fraction)]
	2	on (LAI predicted; FVEG calculated)
	3	off (LAI from table; FVEG calculated)
	4	(default) off (LAI from table; FVEG = maximum veg. fraction)
(new since V3.7)	5	on (LAI predicted; FVEG = maximum veg. fraction)
	6	on; use FVEG - SHDFAC from input
	7	off; use input LAI; use FVEG - SHDFAC from input
	8	off; use input LAI; calculate FVEG
	9	off; use input LAI; use maximum vegetation fraction
	10	crop model on; use maximum vegetation fraction
opt_crs		stomatal resistance option
	1	(default) Ball-Berry
	2	Jarvis
opt_sfc		surface layer drag coefficient calculation
	1	(default) Monin-Obukhov
	2	original Noah
(option removed in 3.7)	3	MYJ consistent
(option removed in 3.7)	4	YSU consistent
opt_btr		soil moisture factor for stomatal resistance
	1	Noah
	2	CLM
	3	SSiB
opt_run		Noah-MP runoff and groundwater option
	1	TOPMODEL with groundwater

	2	TOPMODEL with equilibrium water table
	3	(default) original surface and subsurface runoff (free drainage)
	4	BATS (Biosphere-Atmosphere Transfer Scheme) surface and subsurface runoff (free drainage)
opt_frz		supercooled liquid water option
	1	(default) no iteration
	2	Koren's iteration
opt_inf		soil permeability option
	1	(default) linear effect, more permeable
	2	non-linear effect, less permeable
opt_rad		radiative transfer option
	1	modified two-stream
	2	two-stream applied to grid cell
	3	(default) two-stream applied to vegetated fraction
opt_alb		ground surface albedo option
	1	BATS
	2	(default) CLASS (Canadian Land Surface Scheme)
opt_snf		precipitation partitioning between snow and rain
	1	(default) Jordan (1991)
	2	BATS; snow when SFCTMP < TFRZ+2.2
	3	show when SFCTMP < TFRZ
(new since V3.7)	4	use WRF precipitation partitioning
opt_tbot		soil temp lower boundary condition
	1	zero heat flux
	2	(default) TBOT at 8 m from input file
opt_stc		snow/soil temperature time scheme
	1	(default) semi-implicit
	2	fully-implicit
opt_gla *(new since V3.8)*		Noah-MP glacier treatment option
	1	(default) includes phase change
	2	slab ice (Noah)
opt_rsf *(new since V3.8)*		Noah-MP surface evaporation resistence option
	1	Sakaguchi and Zeng 2009
	2	Sellers 1992

	3	adjusted Sellers to decrease RSURF for wet soil
	4	option 1 for non-snow; rsurf = rsurf_snow for snow (set in MPTABLE -added in V3.8)
(new since V3.7)	3	semi-implicit where Ts uses snow cover fraction
&fdda		***options for grid, obs and spectral nudging***
(For Grid Nudging)		
grid_fdda (max_dom)	0	(default) off
	1	grid analysis nudging on
	2	spectral analysis nudging option
gfdda_inname	"wrffdda_d<domain>"	name of fdda input file that will be produced when running real
gfdda_interval_m (max_dom)	360	time interval (in mins) between analysis times
gfdda_end_h (max_dom)	6	time (hr) to stop nudging after the start of the forecast
io_form_gfdda		analysis data format
	2	netCDF format
	4	PHD5 format
	5	GRIB1 format
	10	GRIB2 format
	11	pnetCDF format
fgdt (max_dom)	0	calculation frequency (in mins) for anlaysis nudging; 0=every time step (which is recommended)
if_no_pbl_nudging_uv (max_dom)	0	(default) nudging in the PBL
	1	no nudging of u and v in the PBL
if_no_pbl_nudging_t (max_dom)	0	(default) nudging in the PBL
	1	no nudging of temp in the PBL
if_no_pbl_nudging_q (max_dom)	0	(default) nudging in the PBL
	1	no nudging of qvapor in the PBL
if_zfac_uv (max_dom)	0	(default) nudge u and v in all layers
	1	limit nudging to levels above `k_zfac_uv`
k_zfac_uv	10	model level below which nudging is switched off for u and v
if_zfac_t (max_dom)	0	(default) nudge temp in all layers

	1	limit nudging to levels above `k_zfac_t`
k_zfac_t	10	model level below which nudging is switched off for temp
if_zfac_q (max_dom)	0	(default) nudge qvapor in all layers
	1	limit nudging to levels above `k_zfac_q`
k_zfac_q	10	model level below which nudging is switched off for qvapor
guv (max_dom)	0.0003	nudging coefficient for u and v (s^{-1})
gt (max_dom)	0.0003	nudging coefficient for temp (s^{-1})
gq (max_dom)	0.0003	nudging coefficient for qvaopr (s^{-1})
if_ramping	0	(default) nudging ends as a step function
	1	ramping nudging down at the end of the period
dtramp_min	0.	time (min) for ramping function;
grid_sfdda (max_dom)		surface fdda switch
	0	(default) off
	1	nudging selected surface fields
(new since V3.8)	2	FASDAS (flux-adjusted surface data assimilation system)
sgfdda_inname	"wrfsfdda_d<domain>"	defined name for surface nuding input file (from program *obsgrid*)
sgfdda_interval_m (max_dom)	360	time interval (in mins) between surface analsysis times
sgfdda_end_h (max_dom)	6	time (in hours) to stop surface nudging after start of the forecast
io_form_sgfdda	2	surface analysis format (2=netCDF)
guv_sfc (max_dom)	0.0003	nudging coefficient for u and v (s^{-1})
gt_sfc (max_dom)	0.0003	nudging coefficient for temp (s^{-1})
gq_sfc (max_dom)	0.0003	nudging coefficient for qvapor (s^{-1})
rinblw (max_dom)	0.	radius of influence used to determine the confidence (or weights) for the analysis, which is based on the distance between the grid point to the nearest obs. The analysis without nearby observation is used at a reduced weight.
(For Spectral Nudging)		
fgdtzero (max_dom)	1	nudging tendencies are set to zero

		in between fdda calls
	0	(default) not active
if_no_pbl_nudging_ph (max_dom)	1	no nudging of ph in the PBL
	0	(default) nudging of ph in the PBL
if_zfac_ph (max_dom)	0	(default) nudge ph in all layers
	1	limit nudging to levels above `k_zfac_ph`
k_zfac_ph	10	model level below which nudging is switched off for water ph
gph (max_dom)	0.0003	nudging coefficient for ph (s^{-1})
dk_zfac_uv (max_dom)	1	depth in k between `k_zfac_uv` to `dk_zfac_uv` where nuding increases linearly to full strength
dk_zfac_t (max_dom)	1	depth in k between `k_zfac_t` to `dk_zfac_t` where nuding increases linearly to full strength
dk_zfac_ph (max_dom)	1	depth in k between `k_zfac_ph` to `dk_zfac_ph` where nuding increases linearly to full strength
xwavenum	3	top wave number to nudge in x-direction (0 is default)
ywavenum	3	top wave number to nudge in y-direction (0 is default)
(For Obs Nudging)		
obs_nudge_opt (max_dom)	1	obs-nudging fdda on for each domain (default is 0=off); also must set `auxinput11_interval` and `auxinput11_end_h` under **&time_control**
max_obs	0	max number of observations used on a domain during any given time windown (default is 0)
(max_dom)	0.	obs nudging start time (min)
fdda_end (max_dom)	0.	obs nudging end time (min)
obs_nudge_wind (max_dom)	1	nudge wind on
	0	(default) off
obs_coef_wind (max_dom)	0	nudging coefficient for wind (s^{-1})
obs_nudge_temp (max_dom)	0	set to =1 to nudge temperatures (default is 0=off)
obs_coef_temp (max_dom)	0	nudging coefficient for temp (s^{-1})
obs_nudge_mois	0	set to =1 to nudge water vapor

(max_dom)		mixing ratio (default is 0=off)
obs_coef_mois (max_dom)	6.e-4	nudging coefficient for water vapor mixing ratio (s^{-1})
obs_rinxy (max_dom)	0.	horizontal radius of influence (km;
obs_rinsig	0	vertical radius of influence in eta
obs_twindo (max_dom)	0.666667	half-period time window over which an observation will be used for nudging (hrs)
obs_npfi	0	frequency in coarse grid timesteps for diagnostic prints
obs_ionf (max_dom)	1	frequency in coarse grid timesteps for obs input and err calc
obs_idynin	1	for dynamic initialization using a ramp-down function to gradually turn off the FDDA before the pure forecast (default is 0=off)
obs_dtramp	0.	time period (mins) over which the nudging is ramped down from one to zero
obs_prt_max	1000	maximum allowed obs entries in diagnostic printout
obs_prt_freq (max_dom)	1000	frequency in obs index for diagnostic printout
obs_ipf_in4dob	.true.	print obs input diagnostics (default is .false.=off)
obs_ipf_errob	.true.	print obs error diagnostics (default is .false.=off)
obs_ipf_nudob	.true.	print obs nudge diagnostics (default is .false.=off)
obs_ipf_init	.true.	(default) enable obs printed warning messages
obs_no_pbl_nudge_uv (max_dom)	1	no wind-nudging within the PBL
	0	(default) wind-nudging within the PBL
obs_no_pbl_nudge_t (max_dom)	1	no temperature-nudging within the PBL
	0	(default) temperature-nudging within the PBL
obs_no_pbl_nudge_q (max_dom)	1	no moisture-nudging within the PBL
	0	(default) no moisture-nudging within the PBL
obs_nudgezfullr1_uv	50	Vertical influence full weight height for LML obs, regime 1,

		winds
obs_nudgezrampr1_uv	50	vertical influence ramp-to-zero height for LML obs, regime 1, winds
obs_nudgezfullr2_uv	50	Vertical influence full weight height for LML obs, regime 2, winds
obs_nudgezrampr2_uv	50	vertical influence ramp-to-zero height for LML obs, regime 2, winds
obs_nudgezfullr4_uv	-5000	Vertical influence full weight height for LML obs, regime 4, winds
obs_nudgezrampr4_uv	50	Vertical influence ramp-to-zero height for LML obs, regime 4, winds
obs_nudgezfullr1_t	50	Vertical influence full weight height for LML obs, regime 1, temperature
obs_nudgezrampr1_t	50	Vertical influence ramp-to-zero height for LML obs, regime 1, temperature
obs_nudgezfullr2_t	50	Vertical influence full weight height for LML obs, regime 2, temperature
obs_nudgezrampr2_t	50	Vertical influence ramp-to-zero height for LML obs, regime 2, temperature
obs_nudgezfullr4_t	-5000	Vertical influence full weight height for LML obs, regime 4, temperature
obs_nudgezrampr4_t	50	Vertical influence ramp-to-zero height for LML obs, regime 4, temperature
obs_nudgezfullr1_q	50	Vertical influence full weight height for LML obs, regime 1, temperature
obs_nudgezrampr1_q	50	Vertical influence ramp-to-zero height for LML obs, regime 1, temperature
obs_nudgezfullr2_q	50	Vertical influence full weight height for LML obs, regime 2, temperature
obs_nudgezrampr2_q	50	Vertical influence ramp-to-zero height for LML obs, regime 2,

		temperature
obs_nudgezfullr4_q	-5000	Vertical influence full weight height for LML obs, regime 4, temperature
obs_nudgezrampr4_q	50	Vertical influence ramp-to-zero height for LML obs, regime 4, temperature
obs_nudgefullmin	50	minimum depth (m) through which vertical influence function remains 1.0
obs_nudgezrampmin	50	minimum depth (m) through which vert infl fcn decreases from 1 to 0
obs_nudgezmax	3000	max depth (m) in which vert infl function is non-zero
obs_sfcfact	1.0	scale factor applied to time window for surface obs
obs_sfcfacr	1.0	scale factor applied to horiz radius of influence for surface obs
obs_dpsmx	7.5	max pressure change (cb) allowed within horiz radius of influence
obs_sfc_scheme_horiz		horizontal spreading scheme for surface obs
	0	(default) WRF scheme
	1	original MM5 scheme
obs_sfc_scheme_vert		vertical spreading scheme for surface obs
	0	(default) regime vif scheme
	1	original scheme (simple scheme)
obs_max_sndng_gap	20	max allowed pressure gap between soundings for interpolation (cb)
obs_scl_neg_qv_innov *(new since V3.6)*	0	0: default behavior 1: prevent nudging toward negative Qv
&dynamics		***Diffusion, damping options, advection options***
rk_ord		time-integration scheme option
	2	Runge-Kutta 2nd order
	3	(default/recommended) Runge-Kutta 3rd order
diff_opt (max_dom)		turbulence and mixing option
	0	no turbulence or explicit spatial numerical filters (km_opt is ignored)
	1	(default) evaluates 2nd order

		diffusion term on coordinate surfaces, uses kvdif for vertical diffusion unless PBL option is used, may be used with `km_opt = 1` (recommended for real-data case) and 4
	2	evaluates mixing terms in physical space (stress form) (x,y,z); turbulence parameterization is chosen by specifying `km_opt`
km_opt (max_dom)		eddy coefficient option
	1	(default) constant (use `khdif` and `kvdif`)
	2	1.5 order TKE closure (3D) ** Not recommended for DX > 2 km
	3	Smagorinsky first order closure (3D) **Not recommended for DX > 2 km
	4	horizontal Smagorinsky first order closure (recommended for real-data case)
diff_6th_opt (max_dom)		6th-order numerical diffusion
	0	(default) no 6th-order diffusion
	1	6th-order numerical diffusion
	2	6th-order numerical diffusion, but prohibit up-gradient diffusion
diff_6th_factor (max_dom)	0.12	6th-order numerical diffusion non-dimensional rate (max value 1.0 corresponds to complete removal of 2dx wave in one timestep)
damp_opt		upper-level damping flag
	0	(default) no damping
	1	with diffusive damping; maybe used for real-data cases (`dampcoef` nondimensional ~ 0.01 to 0.1)
	2	with Rayleigh damping (`dampcoef` inverse time scale [1/s], e.g. 0.003)
	3	with Rayleigh damping (`dampcoef` inverse time scale [1/s], e.g. 0.2; for real-data cases)
use_theta_m *(new since V3.7)*	1	uses theta(1+1.61Qv); (default 0=off)
use_q_diabatic *(new since*	1	includes QV and QC tendencies in

V3.7)		advection; this helps to produce correct solution in an idealized 'moist benchmark' test case (Bryan, 2014). In real data testing, time step needs to be reduced to maintain a stable solution (default 0=off)
c_s (max_dom) *(new since V3.7)*	0.25	(default) Smagorinsky coeff
c_k (max_dom) *(new since V3.7)*	0.15	(default) TKE coeff
zdamp (max_dom)	5000	damping depth (m) from model top
dampcoef (max_dom)	0.	damping coefficient (see `damp_opt`)
w_damping		vertical velocity damping flag (for operational use)
	0	(default) no damping
	1	with damping
base_pres	100000	base state surface pressure (Pa); real only., not recommended to change.
base_temp	290.	base state temperature (K); real only
base_lapse	50.	real-data ONLY, lapse rate (K), not recommended to change
iso_temp	200. *(default value changed to 200 in V3.5)*	isothermal temperature in statosphere; enables model to be extended to 5 mb; real only. Default value changed to 200 since V3.5
base_pres_strat *(New since V3.6.1)*	0. *(default value set to 0 mb in V3.7)*	real data, em ONLY, base state pressure (Pa) at bottom of the stratosphere, US Standard atmosphere 55 hPa.
base_lapse_strat *(new since V3.6.1)*	-11.	(default) real-data; em ONLY, base state lapse rate (dT/d(lnP)) in stratosphere, approx to US standard atmosphere -12K
use_baseparm_fr_nml	.false.	for backward compatibility; to use with old wrfinput file produced prior to V3.4
use_input_w *(new since V3.3.1)*	. false.	whether to use vertical velocity from input file
khdif (max_dom)	0.	horizontal diffusion constant (m^2/s)

kvdif (max_dom)	0.	vertical diffusion constant (m^2/s)
smdiv (max_dom)	0.1	divergence damping (0.1 is typical)
emdiv (max_dom)	0.01	external-mode filter coef for mass coordinate model (0.01 is typical for real-data cases)
epssm (max_dom)	0.1	time off-centering for vertical sound waves
non-hydrostatic (max_dom)	.true.	(default) running the model in non-hydrostatic mode
	.false.	running the model in hydrostatic mode
pert_coriolis (max_dom)	.false.	coriolis only acts on wind perturbation (only for idealized)
top_lid (max_dom)	.false.	zero vertical motion at top of domain (only for idealized)
mix_full_fields	.false.	used with `diff_opt = 2`; value of .true. is recommended, except for highly idealized numerical tests; `damp_opt` must not be =1 if .true. is chosen; .false. means subtract 1D base-state profile before mixing (only for idealized)
mix_isotropic (max_dom)	0	(default) anistropic vertical/horizontal diffusion
	1	isotropic; for `km_opt = 2, 3`
mix_upper_bound (max_dom)	0.1	non-dimensional upper limit for diffusion coefficients; for `km_opt = 2, 3`
h_mom_adv_order (max_dom)	5	horizontal momentum advection order; 5 (default) = 5th, etc.
v_mom_adv_order (max_dom)	3	vertical momentum advection order; 3 (default) = 3rd, etc.
h_sca_adv_order (max_dom)	5	horizontal scalar advection order; 5 (default) = 5th, etc
v_sca_adv_order (max_dom)	3	vertical scalar advection order; 3 (default) = 3rd, etc.
time_step_sound (max_dom)	4	number of sound steps per timestep (if using a time_step much larger than 6*DX (in km), increase number of sound steps (default is 0)
moist_adv_opt (max_dom)		advection options for moisture
	0	simple
	1	(default) positive-definite

	2	monotonic
	3	5th-order WENO (Weighted Essentially Non-Oscillatory)
(new since V3.4)	4	5th-order WENO with positive definite
scalar_adv_opt (max_dom)		advection options for scalars
	0	simple
	1	(default) positive-definite
	2	monotonic
	3	5th-order WENO
	4	5th-order WENO with positive definite
tke_adv_opt (max_dom)		advection options for TKE
	0	simple
	1	(default) positive-definite
	2	monotonic
	3	5th-order WENO
	4	5th-order WENO with positive definite
chem_adv_opt (max_dom)		advection options for chem variables
	0	simple
	1	(default) positive definite
	2	monotonic
	3	5th-order WENO
	4	5th-order WENO with positive definite
tracer_adv_opt (max_dom)		advection options for tracer variables
	0	simple
	1	(default) positive definite
	2	monotonic
	3	5th-order WENO
	4	5th-order WENO with positive definite
momentum_adv_opt		advection options for momentum
	1	(default) standard
(new since V3.4)	3	5th-order WENO
tke_drag_coefficient (max_dom)	0	surface drag coefficient (Cd, dimensionless) for `diff_opt = 2` only
tke_heat_flux (max_dom)	0	surface thermal flux (H/rho*cp), K ms^{-1}, for `diff_opt = 2` only
fft_filter_lat	91.	the latitude above which the polar

		filter is turned on (degrees) for global model; -45 is a reasonable latitude to start using polar filters
coupled_filtering *(new since V3.7)*	.true.	(default) mu coupled scalar arrays are run through the polar filters
pos_def *(new since V3.7)*	.false.	(default) remove negative values of scalar arrays by setting minimum value to zero
swap_pole_with_next_j *(new since V3.7)*	.false.	(default) replace the entire j=1 (jds-1) with the values from j=2 (jds-2)
actual_distance_average *(new since V3.7)*	.false.	(default) average the field at each i location in the j-loop with a number of grid points based on a map-factor ratio
gwd_opt	1	gravity wave drag option; use when grid size > 10 km (default is 0=off)
do_avgflx_em (max_dom)	1	outputs time-averaged mass-coupled advective velocities (default is 0 = off)
do_avgflx_cugd (max_dom)	1	outputs time_averaged convective mass-fluxes from the Grell-Devenyi ensemble scheme (default is 0 = off; only takes effect if `do_avgflx_em =1,` and `cu_physics = 93`
sfs_opt (max_dom)		nonlinear backscatter and anisotrophy (NBA)
	0	(default) off
	1	NBA, using diagnostic stress terms (`km_opt` = 2, 3 for scalars)
	2	NBA, using tke-based stress terms (`km_opt` = 2, 3 needed)
m_opt (max_dom)	1	adds output of Mij stress terms when NBA is not used (default is 0 = off)
tracer_opt (max_dom)	2	activates 8 pre-defined tracers in the Registry (default is 0 = off)
rad_nudge	1	option to nudge toward initial sounding in idealized TC case (default is 0 = off)
&bdy_control		***boundary condition control***
spec_bdy_width	5	total number of rows for specified

		boundary value nudging (real only)
spec_zone	1	number of points in specified zone (specified b.c. option; real only)
relax_zone	4	number of points in relaxation zone (spec b.c. option; real only)
specified	.true.	specified boundary condition; only can be used for domain 1 (default is .false.; real only)
spec_exp	0.	exponential multiplier for relaxation zone ramp for specified = .true.; default is 0. = linear ramp; 0.33 = ~3*DX exp decay factor (real only)
periodic_x (max_dom)	.true.	periodic boundary conditions in x-direction (default is .false.)
symmetric_xs (max_dom)	.true.	symmetric boundary conditions at x start (west; default is .false.)
symmetric_xe (max_dom)	.true.	symmetric boundary conditions at x end (east; default is .false.)
open _xs (max_dom)	.true.	open boundary conditions at x start (west; default is .false.)
open _xe (max_dom)	.true.	open boundary conditions at x end (east; default is .false.)
periodic_y (max_dom)	.true.	periodic boundary conditions in y-direction (default is .false.)
symmetric_ys (max_dom)	.true.	symmetric boundary conditions at y start (south; default is .false.)
symmetric_ye (max_dom)	.true.	symmetric boundary conditions at y end (north; default is .false.)
open_ys (max_dom)	.true.	open boundary conditions at y start (south; default is .false.)
open_ye (max_dom)	.true.	open boundary conditions at y end (north; default is .false.)
nested (max_dom)	.false., .true., .true.	nested boundary conditions (must be set to .true for nests)
polar (max_dom)	.true.	polar boundary condition (v=0 at polarward-most v-point) for global application (default is .false.)
constant_bc	.true.	constant boundary condition used with DFI (default is .false.)
spec_bdy_final_mu *(new since V3.7)*	1	call spec_bdy_final for mu (default is 0=off); this may cause different restart results in V3.8
have_bcs_moist (max_dom) *(new since*	.false.	do not use microphysics variables in boundary file in model run after

V3.5.1)		ndown (default)
	.true.	use microphysics variables in boundary file
have_bcs_scalar (max_dom) *(new since V3.5.1)*	.false.	do not use scalar variables in boundary file in model run after ndown (default)
	.true.	use scalar variables in boundary file
&namelist_quilt		***options for asynchronized I/O for MPI applications***
nio_tasks_per_group	0	(default) no quilting
	>0	# of processors used for IO quilting per IO group
nio_groups	1	default; may be set to higher value for nesting IO or history and restart IO
&grib2		
background_proc_id	255	(default); background generating process identifier, typically defined by the originating center to identify the background data that was used in creating the data; this is octet 13 of Section 4 in the grib2 message
forecast_proc_id	255	(default) analysis or generating forecast process identifier, typically defined by the originating center to identify the forecast process that was used to generate the data; this is octet 14 of Section 4 in the grib2 message
production_status	255	(default) production status of processed data in the grib2 message; see Code Table 1.3 of the grib2 manual; this is octect 20 of Section 1 in the grib2 record.
compression		the compression method to encode the output grib2 message; only jpeg2000 and PNG are supported.
	40	(default) for jpeg2000
	41	PNG
&dfi_control		***digital filter options control (does***

		not yet support nesting)
dfi_opt	0	(default) no digital filter initialization
	1	digital filter launch (DFL)
	2	diabatic DFI (DDFI)
	3	(recommended) twice DFI (TDFI)
dfi_nfilter	0	uniform filter
	1	Lanczos filter
	2	Hamming filter
	3	Blackman filter
	4	Kaiser filter
	5	Potter filter
	6	Dolph window filter
	7	(default; recommended) Dolph filter
	8	recursive high-order filter
dfi_write_filtered_input	.true.	whether to write wrfinput file with filtered model state before beginning forecast
dfi_write_dfi_history	.false.	whether to write wrfout files during filtering integration
dfi_cutoff_seconds	3600	cutoff period (s) for the filter; should not be longer than the filter window
dfi_time_dim	1000	maximum number of time steps for filtering period; this value can be larger than necessary
		for a model that starts from 2001061112, the below setup specifies 1 hour backward integration
dfi_bckstop_year	2001	4-digit year of stop time for backward DFI integration
dfi_bckstop_month	06	2-digit month of stop time for backward DFI integration
dfi_bckstop_day	11	2-digit day of stop time for backward DFI integration
dfi_bckstop_hour	11	2-digit hour of stop time for backward DFI integration
dfi_bckstop_minute	00	2-digit minute of stop time for backward DFI integration
dfi_bckstop_second	00	2-digit second of stop time for backward DFI integration
		for a model that starts at 2001061112, the below setup

		specifies 30 minutes of forward integration
dfi_fwdstop_year	2001	4-digit year of stop time for forward DFI integration
dfi_fwdstop_month	06	2-digit month of stop time for forward DFI integration
dfi_fwdstop_day	11	2-digit day of stop time for forward DFI integration
dfi_fwdstop_hour	12	2-digit hour of stop time for forward DFI integration
dfi_fwdstop_minute	30	2-digit minute of stop time for forward DFI integration
dfi_fwdstop_second	00	2-digit second of stop time for forward DFI integration
dfi_radar	0	DFI radar data assimilation switch
&scm		***for the single-column model (SCM) option only***
scm_force	0	(default) single column forcing turned off
	1	single column forcing on
scm_force_dx	4000.	DX for SCM forcing (m)
num_force_layers	8	number of SCM input forcing layers
scm_lu_index	2	SCM landuse category (2 = dryland, cropland, and pasture; others can be found in the LANDUSE.TBL)
scm_isltyp	4	SCM soil category (4 = silt loam; others can be found in the SOILPARM.TBL)
scm_vegfra	0.5	SCM vegetation fraction
scm_canwat	0.0	SCM canopy water (kg m^{-2})
scm_lat	36.605	SCM latitude
scm_lon	-97.485	SCM longitude
scm_th_adv	.true.	turn on theta advection in SCM
scm_wind_adv	.true.	turn on wind advection in SCM
scm_qv_adv	.true.	turn on moisture advection in SCM
scm_vert_adv	.true.	turn on vertical advection in SCM
scm_ql_adv	.true.	turn on liquid advection in SCM (default is .false. = off)
num_force_soil_layers	5	number of SCM soil forcing layers
scm_soilt_force	.true.	turn on soil temperature forcing in SCM (default is .false. = off)
scm_soilq_force	.true.	turn on soil moisture forcing in

		SCM (default is .false. = off)
scm_force_th_largescale	.true.	turn on large-scale theta forcing in SCM (default is .false. = off)
scm_force_qv_largescale	.true.	turn on large-scale qv forcing in SCM (default is .false. = off)
scm_force_ql_largescale	.true.	turn on large-scale ql forcing in SCM (default is .false. = off)
scm_force_wind_largescale	.true.	turn on large-scale wind forcing in SCM (default is .false. = off)
&tc		***controls for tc_em.exe only***
insert_bogus_storm	.false.	T/F for inserting a bogus tropical storm
remove_storm	.false.	T/F for only removing the original TC
num_storm	1	number of bogus TC
latc_loc	-999.	center latitude of the bogus TC
lonc_loc	-999.	center longitude of the bogus TC
vmax_meters_per_second (max_dom)	-999.	wind max of bogus storm (m s^{-1})
rmax	-999.	maximum radius outward from storm center of bogus TC
vmax_ratio (max_dom)	-999.	ratio for representative maximum winds, 0.75 for 45 km grid, and 0.9 for 15 kim grid
rankine_lid	-999.	top pressure limit for the TC bogus scheme
&diags *(new since V3.4.1)*		***output fields on pressure levels*** Also need to set auxhist23_outname="wrfpress_d<domain>_<date>" io_form_auxhist23 = 2, auxhist23_interval = 180, 180, frames_per_auxhist23 = 100, 100,
p_lev_diags	0	0/1 whether to output pressure level diagnostics
num_press_levels	4	Number of pressure levels
press_levels (max_plevs)	0	Pressure levels in Pa
use_tot_or_hyd_p	2	1: use total pressure 2: use hydrostatic pressure
z_lev_diags *(new since V3.7.1)*	0	switch to vertically interpolate diagnostics to z-levels; (default is off)
num_z_levels *(new since*	0	number of height levels to

V3.7.1)		interpolate to
z_levels *(new since V3.7.1)*	0	list of height values (m) to interpolate data to; positive numbers are for height above mean sea level (i.e., a flight level), negative numbers are for level above ground
p_lev_missing	-999.	Missing value below ground
&afwa *(new since V3.6) Cannot be used with OpenMP*		
afwa_diag_opt (max_dom)	0	(default) AFWA diagnostic opton (1 = on)
afwa_ptype_opt (max_dom)	0	(default) precip type option (1 = on)
afwa_vil_opt (max_dom)	0	(default) vertical int liquid option (1 = on)
afwa_radar_opt (max_dom)	0	(default) radar option (1 = on)
afwa_severe_opt (max_dom)	0	(default) severe weather option (1 = on)
afwa_icing_opt (max_dom)	0	(default) icing option (1 = on)
afwa_vis_opt (max_dom)	0	(default) visibility option (1 = on)
afwa_cloud_opt (max_dom)	0	(default) cloud option (1 = on)
afwa_therm_opt (max_dom) *(new since V3.6.1)*	0	thermal indices option (default is 0=off)
afwa_turb_opt (max_dom) *(new since V3.6.1)*	0	turbulence option (default is 0=off)
afwa_buoy_opt (max_dom) *(new since V3.6.1)*	0	buoyancy option (default is 0=off)
afwa_ptype_ccn_tmp	264.15	(default) CCN temperature for precipitation type calculation
afwa_ptype_tot_melt	50	(default) total melting energy for precipitation type calculation
	1	(default) hail
	0	graupel
progn (max_dom) *(new since V3.7)*	0	(default) switch to use mix-activate scheme (only for Morrison, WDM6, WDM5, and NSSL_2MOMCCN/NSSL_2MOM

WRF Output Fields

List of Fields

The following is an edited output list from the netCDF command *'ncdump -h'*. Note that valid output fields will depend on the model options used. If the fields have zero values, then the fields are not computed by the model options selected.

```
ncdump -h wrfout_d<domain>_<date>
```

```
netcdf wrfout_d01_2000-01-24_12:00:00

dimensions:
        Time = UNLIMITED ; // (1 currently)
        DateStrLen = 19 ;
        west_east = 73 ;
        south_north = 60 ;
        bottom_top = 29 ;
        bottom_top_stag = 30 ;
        soil_layers_stag = 4 ;
        west_east_stag = 74 ;
        south_north_stag = 61 ;

variables:
 char Times(Time, DateStrLen) ;
 float LU_INDEX(Time, south_north, west_east) ;
        LU_INDEX:description = "LAND USE CATEGORY" ;
        LU_INDEX:units = "" ;
 float ZNU(Time, bottom_top) ;
        ZNU:description = "eta values on half (mass) levels" ;
        ZNU:units = "" ;
 float ZNW(Time, bottom_top_stag) ;
        ZNW:description = "eta values on full (w) levels" ;
        ZNW:units = "" ;
 float ZS(Time, soil_layers_stag) ;
        ZS:description = "DEPTHS OF CENTERS OF SOIL LAYERS" ;
        ZS:units = "m" ;
 float DZS(Time, soil_layers_stag) ;
        DZS:description = "THICKNESSES OF SOIL LAYERS" ;
        DZS:units = "m" ;
 float U(Time, bottom_top, south_north, west_east_stag) ;
        U:description = "x-wind component" ;
        U:units = "m s-1" ;
 float V(Time, bottom_top, south_north_stag, west_east) ;
        V:description = "y-wind component" ;
        V:units = "m s-1" ;
 float W(Time, bottom_top_stag, south_north, west_east) ;
        W:description = "z-wind component" ;
        W:units = "m s-1" ;
 float PH(Time, bottom_top_stag, south_north, west_east) ;
        PH:description = "perturbation geopotential" ;
        PH:units = "m2 s-2" ;
 float PHB(Time, bottom_top_stag, south_north, west_east) ;
        PHB:description = "base-state geopotential" ;
        PHB:units = "m2 s-2" ;
 float T(Time, bottom_top, south_north, west_east) ;
        T:description = "perturbation potential temperature (theta-t0)" ;
        T:units = "K" ;
 float MU(Time, south_north, west_east) ;
```

```
       MU:description = "perturbation dry air mass in column" ;
       MU:units = "Pa" ;
float MUB(Time, south_north, west_east) ;
       MUB:description = "base state dry air mass in column" ;
       MUB:units = "Pa" ;
float NEST_POS(Time, south_north, west_east) ;
       NEST_POS:description = "-" ;
       NEST_POS:units = "-" ;
float P(Time, bottom_top, south_north, west_east) ;
       P:description = "perturbation pressure" ;
       P:units = "Pa" ;
float PB(Time, bottom_top, south_north, west_east) ;
       PB:description = "BASE STATE PRESSURE" ;
       PB:units = "Pa" ;
float FNM(Time, bottom_top) ;
       FNM:description = "upper weight for vertical stretching" ;
       FNM:units = "" ;
float FNP(Time, bottom_top) ;
       FNP:description = "lower weight for vertical stretching" ;
       FNP:units = "" ;
float RDNW(Time, bottom_top) ;
       RDNW:description = "inverse d(eta) values between full (w) levels" ;
       RDNW:units = "" ;
float RDN(Time, bottom_top) ;
       RDN:description = "inverse d(eta) values between half (mass) levels" ;
       RDN:units = "" ;
float DNW(Time, bottom_top) ;
       DNW:description = "d(eta) values between full (w) levels" ;
       DNW:units = "" ;
float DN(Time, bottom_top) ;
       DN:description = "d(eta) values between half (mass) levels" ;
       DN:units = "" ;
float CFN(Time) ;
       CFN:description = "extrapolation constant" ;
       CFN:units = "" ;
float CFN1(Time) ;
       CFN1:description = "extrapolation constant" ;
       CFN1:units = "" ;
 float P_HYD(Time, bottom_top, south_north, west_east) ;
       P_HYD:description = "hydrostatic pressure" ;
       P_HYD:units = "Pa" ;
float Q2(Time, south_north, west_east) ;
       Q2:description = "QV at 2 M" ;
       Q2:units = "kg kg-1" ;
float T2(Time, south_north, west_east) ;
       T2:description = "TEMP at 2 M" ;
       T2:units = "K" ;
float TH2(Time, south_north, west_east) ;
       TH2:description = "POT TEMP at 2 M" ;
       TH2:units = "K" ;
float PSFC(Time, south_north, west_east) ;
       PSFC:description = "SFC PRESSURE" ;
       PSFC:units = "Pa" ;
float U10(Time, south_north, west_east) ;
       U10:description = "U at 10 M" ;
       U10:units = "m s-1" ;
float V10(Time, south_north, west_east) ;
       V10:description = "V at 10 M" ;
       V10:units = "m s-1" ;
float RDX(Time) ;
       RDX:description = "INVERSE X GRID LENGTH" ;
       RDX:units = "" ;
float RDY(Time) ;
       RDY:description = "INVERSE Y GRID LENGTH" ;
```

```
       RDY:units = "" ;
float RESM(Time) ;
       RESM:description = "TIME WEIGHT CONSTANT FOR SMALL STEPS" ;
       RESM:units = "" ;
float ZETATOP(Time) ;
       ZETATOP:description = "ZETA AT MODEL TOP" ;
       ZETATOP:units = "" ;
float CF1(Time) ;
       CF1:description = "2nd order extrapolation constant" ;
       CF1:units = "" ;
float CF2(Time) ;
       CF2:description = "2nd order extrapolation constant" ;
       CF2:units = "" ;
float CF3(Time) ;
       CF3:description = "2nd order extrapolation constant" ;
       CF3:units = "" ;
int ITIMESTEP(Time) ;
       ITIMESTEP:description = "" ;
       ITIMESTEP:units = "" ;
float XTIME(Time) ;
       XTIME:description = "minutes since simulation start" ;
       XTIME:units = "" ;
float QVAPOR(Time, bottom_top, south_north, west_east) ;
       QVAPOR:description = "Water vapor mixing ratio" ;
       QVAPOR:units = "kg kg-1" ;
float QCLOUD(Time, bottom_top, south_north, west_east) ;
       QCLOUD:description = "Cloud water mixing ratio" ;
       QCLOUD:units = "kg kg-1" ;
float QRAIN(Time, bottom_top, south_north, west_east) ;
       QRAIN:description = "Rain water mixing ratio" ;
       QRAIN:units = "kg kg-1" ;
float LANDMASK(Time, south_north, west_east) ;
       LANDMASK:description = "LAND MASK (1 FOR LAND, 0 FOR WATER)" ;
       LANDMASK:units = "" ;
float TSLB(Time, soil_layers_stag, south_north, west_east) ;
       TSLB:description = "SOIL TEMPERATURE" ;
       TSLB:units = "K" ;
float SMOIS(Time, soil_layers_stag, south_north, west_east) ;
       SMOIS:description = "SOIL MOISTURE" ;
       SMOIS:units = "m3 m-3" ;
float SH2O(Time, soil_layers_stag, south_north, west_east) ;
       SH2O:description = "SOIL LIQUID WATER" ;
       SH2O:units = "m3 m-3" ;
float SEAICE(Time, south_north, west_east) ;
       SEAICE:description = "SEA ICE FLAG" ;
       SEAICE:units = "" ;
float XICEM(Time, south_north, west_east) ;
       XICEM:description = "SEA ICE FLAG (PREVIOUS STEP)" ;
       XICEM:units = "" ;
float SFROFF(Time, south_north, west_east) ;
       SFROFF:description = "SURFACE RUNOFF" ;
       SFROFF:units = "mm" ;
float UDROFF(Time, south_north, west_east) ;
       UDROFF:description = "UNDERGROUND RUNOFF" ;
       UDROFF:units = "mm" ;
int IVGTYP(Time, south_north, west_east) ;
       IVGTYP:description = "DOMINANT VEGETATION CATEGORY" ;
       IVGTYP:units = "" ;
int ISLTYP(Time, south_north, west_east) ;
       ISLTYP:description = "DOMINANT SOIL CATEGORY" ;
       ISLTYP:units = "" ;
float VEGFRA(Time, south_north, west_east) ;
       VEGFRA:description = "VEGETATION FRACTION" ;
       VEGFRA:units = "" ;
```

```
float GRDFLX(Time, south_north, west_east) ;
       GRDFLX:description = "GROUND HEAT FLUX" ;
       GRDFLX:units = "W m-2" ;
float SNOW(Time, south_north, west_east) ;
       SNOW:description = "SNOW WATER EQUIVALENT" ;
       SNOW:units = "kg m-2" ;
float SNOWH(Time, south_north, west_east) ;
       SNOWH:description = "PHYSICAL SNOW DEPTH" ;
       SNOWH:units = "m" ;
float RHOSN(Time, south_north, west_east) ;
       RHOSN:description = " SNOW DENSITY" ;
       RHOSN:units = "kg m-3" ;
float CANWAT(Time, south_north, west_east) ;
       CANWAT:description = "CANOPY WATER" ;
       CANWAT:units = "kg m-2" ;
float SST(Time, south_north, west_east) ;
       SST:description = "SEA SURFACE TEMPERATURE" ;
       SST:units = "K" ;
float SSTSK(Time, south_north, west_east) ;
       SSTSK:description = "SKIN SEA SURFACE TEMPERATURE" ;
       SSTSK:units = "K" ;
float MAPFAC_M(Time, south_north, west_east) ;
       MAPFAC_M:description = "Map scale factor on mass grid" ;
       MAPFAC_M:units = "" ;
float MAPFAC_U(Time, south_north, west_east_stag) ;
       MAPFAC_U:description = "Map scale factor on u-grid" ;
       MAPFAC_U:units = "" ;
float MAPFAC_V(Time, south_north_stag, west_east) ;
       MAPFAC_V:description = "Map scale factor on v-grid" ;
       MAPFAC_V:units = "" ;
float MAPFAC_MX(Time, south_north, west_east) ;
       MAPFAC_MX:description = "Map scale factor on mass grid, x direction" ;
       MAPFAC_MX:units = "" ;
float MAPFAC_MY(Time, south_north, west_east) ;
       MAPFAC_MY:description = "Map scale factor on mass grid, y direction" ;
       MAPFAC_MY:units = "" ;
float MAPFAC_UX(Time, south_north, west_east_stag) ;
       MAPFAC_UX:description = "Map scale factor on u-grid, x direction" ;
       MAPFAC_UX:units = "" ;
float MAPFAC_UY(Time, south_north, west_east_stag) ;
       MAPFAC_UY:description = "Map scale factor on u-grid, y direction" ;
       MAPFAC_UY:units = "" ;
float MAPFAC_VX(Time, south_north_stag, west_east) ;
       MAPFAC_VX:description = "Map scale factor on v-grid, x direction" ;
       MAPFAC_VX:units = "" ;
float MF_VX_INV(Time, south_north_stag, west_east) ;
       MF_VX_INV:description = "Inverse map scale factor on v-grid, x direction"
       MF_VX_INV:units = "" ;
float MAPFAC_VY(Time, south_north_stag, west_east) ;
       MAPFAC_VY:description = "Map scale factor on v-grid, y direction" ;
       MAPFAC_VY:units = "" ;
float F(Time, south_north, west_east) ;
       F:description = "Coriolis sine latitude term" ;
       F:units = "s-1" ;
float E(Time, south_north, west_east) ;
       E:description = "Coriolis cosine latitude term" ;
       E:units = "s-1" ;
float SINALPHA(Time, south_north, west_east) ;
       SINALPHA:description = "Local sine of map rotation" ;
       SINALPHA:units = "" ;
float COSALPHA(Time, south_north, west_east) ;
       COSALPHA:description = "Local cosine of map rotation" ;
       COSALPHA:units = "" ;
float HGT(Time, south_north, west_east) ;
```

```
       HGT:description = "Terrain Height" ;
       HGT:units = "m" ;
 float HGT_SHAD(Time, south_north, west_east) ;
       HGT_SHAD:description = "Height of orographic shadow" ;
       HGT_SHAD:units = "m" ;
 float TSK(Time, south_north, west_east) ;
       TSK:description = "SURFACE SKIN TEMPERATURE" ;
       TSK:units = "K" ;
 float P_TOP(Time) ;
       P_TOP:description = "PRESSURE TOP OF THE MODEL" ;
       P_TOP:units = "Pa" ;
 float T00(Time) ;
       T00:description = "BASE STATE TEMPERATURE" ;
       T00:units = "K" ;
 float P00(Time) ;
       P00:description = "BASE STATE PRESURE" ;
       P00:units = "Pa" ;
 float TLP(Time) ;
       TLP:description = "BASE STATE LAPSE RATE" ;
       TLP:units = "" ;
 float TISO(Time) ;
       TISO:description = "TEMP AT WHICH THE BASE T TURNS CONST" ;
       TISO:units = "K" ;
 float MAX_MSTFX(Time) ;
       MAX_MSTFX:description = "Max map factor in domain" ;
       MAX_MSTFX:units = "" ;
 float MAX_MSTFY(Time) ;
       MAX_MSTFY:description = "Max map factor in domain" ;
       MAX_MSTFY:units = "" ;
 float RAINC(Time, south_north, west_east) ;
       RAINC:description = "ACCUMULATED TOTAL CUMULUS PRECIPITATION" ;
       RAINC:units = "mm" ;
float RAINSH(Time, south_north, west_east) ;
       RAINSH:description = "ACCUMULATED SHALLOW CUMULUS PRECIPITATION" ;
       RAINSH:units = "mm" ;
 float RAINNC(Time, south_north, west_east) ;
       RAINNC:description = "ACCUMULATED TOTAL GRID SCALE PRECIPITATION" ;
       RAINNC:units = "mm" ;
 float PRATEC(Time, south_north, west_east) ;
       PRATEC:description = "PRECIP RATE FROM CUMULUS SCHEME" ;
       PRATEC:units = "mm s-1" ;
 float RAINCV(Time, south_north, west_east) ;
       RAINCV:description = "TIME-STEP CUMULUS PRECIPITATION" ;
       RAINCV:units = "mm" ;
 float SNOWNC(Time, south_north, west_east) ;
       SNOWNC:description = "ACCUMULATED TOTAL GRID SCALE SNOW AND ICE" ;
       SNOWNC:units = "mm" ;
 float GRAUPELNC(Time, south_north, west_east) ;
       GRAUPELNC:description = "ACCUMULATED TOTAL GRID SCALE GRAUPEL" ;
       GRAUPELNC:units = "mm" ;
 float SWDOWN(Time, south_north, west_east) ;
       SWDOWN:description = "DOWNWARD SHORT WAVE FLUX AT GROUND SURFACE" ;
       SWDOWN:units = "W m-2" ;
 float GLW(Time, south_north, west_east) ;
       GLW:description = "DOWNWARD LONG WAVE FLUX AT GROUND SURFACE" ;
       GLW:units = "W m-2" ;
float SWNORM(Time, south_north, west_east) ;
       SWNORM:description = "NORMAL SHORT WAVE FLUX AT GROUND SURFACE" ;
       SWNORM:units = "W m-2" ;
 float OLR(Time, south_north, west_east) ;
       OLR:description = "TOA OUTGOING LONG WAVE" ;
       OLR:units = "W m-2" ;
 float XLAT(Time, south_north, west_east) ;
       XLAT:description = "LATITUDE, SOUTH IS NEGATIVE" ;
```

```
       XLAT:units = "degree_north" ;
 float XLONG(Time, south_north, west_east) ;
       XLONG:description = "LONGITUDE, WEST IS NEGATIVE" ;
       XLONG:units = "degree_east" ;
 float XLAT_U(Time, south_north, west_east_stag) ;
       XLAT_U:description = "LATITUDE, SOUTH IS NEGATIVE" ;
       XLAT_U:units = "degree_north" ;
 float XLONG_U(Time, south_north, west_east_stag) ;
       XLONG_U:description = "LONGITUDE, WEST IS NEGATIVE" ;
       XLONG_U:units = "degree_east" ;
 float XLAT_V(Time, south_north_stag, west_east) ;
       XLAT_V:description = "LATITUDE, SOUTH IS NEGATIVE" ;
       XLAT_V:units = "degree_north" ;
 float XLONG_V(Time, south_north_stag, west_east) ;
       XLONG_V:description = "LONGITUDE, WEST IS NEGATIVE" ;
       XLONG_V:units = "degree_east" ;
 float ALBEDO(Time, south_north, west_east) ;
       ALBEDO:description = "ALBEDO" ;
       ALBEDO:units = "-" ;
 float ALBBCK(Time, south_north, west_east) ;
       ALBBCK:description = "BACKGROUND ALBEDO" ;
       ALBBCK:units = "" ;
 float EMISS(Time, south_north, west_east) ;
       EMISS:description = "SURFACE EMISSIVITY" ;
       EMISS:units = "" ;
  float NOAHRES(Time, south_north, west_east) ;
       NOAHRES:description = "RESIDUAL OF THE NOAH SURFACE ENERGY BUDGET" ;
       NOAHRES:units = "W m{-2}" ;
 float TMN(Time, south_north, west_east) ;
       TMN:description = "SOIL TEMPERATURE AT LOWER BOUNDARY" ;
       TMN:units = "K" ;
 float XLAND(Time, south_north, west_east) ;
       XLAND:description = "LAND MASK (1 FOR LAND, 2 FOR WATER)" ;
       XLAND:units = "" ;
float ZNT(Time, south_north, west_east) ;
       ZNT:description = "TIME-VARYING ROUGHNESS LENGTH" ;
       ZNT:units = "m" ;
 float UST(Time, south_north, west_east) ;
       UST:description = "U* IN SIMILARITY THEORY" ;
       UST:units = "m s-1" ;
 float PBLH(Time, south_north, west_east) ;
       PBLH:description = "PBL HEIGHT" ;
       PBLH:units = "m" ;
 float HFX(Time, south_north, west_east) ;
       HFX:description = "UPWARD HEAT FLUX AT THE SURFACE" ;
       HFX:units = "W m-2" ;
 float QFX(Time, south_north, west_east) ;
       QFX:description = "UPWARD MOISTURE FLUX AT THE SURFACE" ;
       QFX:units = "kg m-2 s-1" ;
 float LH(Time, south_north, west_east) ;
       LH:description = "LATENT HEAT FLUX AT THE SURFACE" ;
       LH:units = "W m-2" ;
 float SNOWC(Time, south_north, west_east) ;
       SNOWC:description = "FLAG INDICATING SNOW COVERAGE (1 FOR SNOW COVER)" ;
       SNOWC:units = "" ;
int SAVE_TOPO_FROM_REAL(Time) ;
       SAVE_TOPO_FROM_REAL:description = "1=original topo from real/0=topo
                 modified by WRF" ;
       SAVE_TOPO_FROM_REAL:units = "flag" ;
```

List of Global Attributes

```
// global attributes:

       :TITLE = " OUTPUT FROM WRF V3.6 MODEL" ;
       :START_DATE = "2000-01-24_12:00:00" ;
       :SIMULATION_START_DATE = "2000-01-24_12:00:00" ;
       :WEST-EAST_GRID_DIMENSION = 74 ;
       :SOUTH-NORTH_GRID_DIMENSION = 61 ;
       :BOTTOM-TOP_GRID_DIMENSION = 28 ;
       :DX = 30000.f ;
       :DY = 30000.f ;
       :STOCH_FORCE_OPT = 0 ;
       :GRIDTYPE = "C" ;
       :DIFF_OPT = 1 ;
       :KM_OPT = 4 ;
       :DAMP_OPT = 0 ;
       :DAMPCOEF = 0.2f ;
       :KHDIF = 0.f ;
       :KVDIF = 0.f ;
       :MP_PHYSICS = 3 ;
       :RA_LW_PHYSICS = 1 ;
       :RA_SW_PHYSICS = 1 ;
       :SF_SFCLAY_PHYSICS = 1 ;
       :SF_SURFACE_PHYSICS = 2 ;
       :BL_PBL_PHYSICS = 1 ;
       :CU_PHYSICS = 1 ;
      :SF_LAKE_PHYSICS = 0 ;
      :SURFACE_INPUT_SOURCE = 1 ;
      :SST_UPDATE = 0 ;
      :GRID_FDDA = 0 ;
      :GFDDA_INTERVAL_M = 0 ;
      :GFDDA_END_H = 0 ;
      :GRID_SFDDA = 0 ;
      :SGFDDA_INTERVAL_M = 0 ;
      :SGFDDA_END_H = 0 ;
      :HYPSOMETRIC_OPT = 2 ;
      :SF_URBAN_PHYSICS = 0 ;
      :SHCU_PHYSICS = 0 ;
      :MFSHCONV = 0 ;
      :FEEDBACK = 1 ;
      :SMOOTH_OPTION = 0 ;
      :SWRAD_SCAT = 1.f ;
      :W_DAMPING = 0 ;
      :DT = 180.f ;
      :RADT = 30.f ;
      :BLDT = 0.f ;
      :CUDT = 5.f ;
      :AER_OPT = 0 ;
      :SWINT_OPT = 0 ;
      :AER_TYPE = 1 ;
      :AER_AOD550_OPT = 1 ;
      :AER_ANGEXP_OPT = 1 ;
      :AER_SSA_OPT = 1 ;
      :AER_ASY_OPT = 1 ;
      :AER_AOD550_VAL = 0.12f ;
      :AER_ANGEXP_VAL = 1.3f ;
      :AER_SSA_VAL = 0.f ;
      :AER_ASY_VAL = 0.f ;
      :MOIST_ADV_OPT = 1 ;
      :SCALAR_ADV_OPT = 1 ;
      :TKE_ADV_OPT = 1 ;
      :DIFF_6TH_OPT = 0 ;
      :DIFF_6TH_FACTOR = 0.12f ;
      :OBS_NUDGE_OPT = 0 ;
```

```
:BUCKET_MM = -1.f ;
:BUCKET_J = -1.f ;
:PREC_ACC_DT = 0.f ;
:SF_OCEAN_PHYSICS = 0 ;
:ISFTCFLX = 0 ;
:ISHALLOW = 0 ;
:ISFFLX = 1 ;
:ICLOUD = 1 ;
:ICLOUD_CU = 0 ;
:TRACER_PBLMIX = 1 ;
:SCALAR_PBLMIX = 0 ;
:GRAV_SETTLING = 0 ;
:DFI_OPT = 0 ;
:WEST-EAST_PATCH_START_UNSTAG = 1 ;
:WEST-EAST_PATCH_END_UNSTAG = 73 ;
:WEST-EAST_PATCH_START_STAG = 1 ;
:WEST-EAST_PATCH_END_STAG = 74 ;
:SOUTH-NORTH_PATCH_START_UNSTAG = 1 ;
:SOUTH-NORTH_PATCH_END_UNSTAG = 60 ;
:SOUTH-NORTH_PATCH_START_STAG = 1 ;
:SOUTH-NORTH_PATCH_END_STAG = 61 ;
:BOTTOM-TOP_PATCH_START_UNSTAG = 1 ;
:BOTTOM-TOP_PATCH_END_UNSTAG = 27 ;
:BOTTOM-TOP_PATCH_START_STAG = 1 ;
:BOTTOM-TOP_PATCH_END_STAG = 28 ;
:GRID_ID = 1 ;
:PARENT_ID = 0 ;
:I_PARENT_START = 1 ;
:J_PARENT_START = 1 ;
:PARENT_GRID_RATIO = 1 ;
:DT = 180.f ;
:CEN_LAT = 34.83002f ;
:CEN_LON = -81.03f ;
:TRUELAT1 = 30.f ;
:TRUELAT2 = 60.f ;
:MOAD_CEN_LAT = 34.83002f ;
:STAND_LON = -98.f ;
:POLE_LAT = 90.f ;
:POLE_LON = 0.f ;
:GMT = 12.f ;
:JULYR = 2000 ;
:JULDAY = 24 ;
:MAP_PROJ = "Lambert Conformal"   ;
:MMINLU = "USGS" ;
:NUM_LAND_CAT = 24 ;
:ISWATER = 16 ;
:ISLAKE = -1 ;
:ISICE = 24 ;
:ISURBAN = 1 ;
:ISOILWATER = 14 ;
```

Special WRF Output Variables

The WRF model outputs the state variables defined in the Registry file, and these state variables are used in the model's prognostic equations. Some of these variables are perturbation fields; therefore the following definitions for reconstructing meteorological variables are necessary:

total geopotential	`PH + PHB`
total geopotential height in m	`( PH + PHB ) / 9.81`
total potential temperature in_ K	`T + 300`
total pressure in mb	`( P + PB ) * 0.01`
wind compoments, grid relative	`U, V`
surface pressure in Pa	`psfc`
surface winds, grid relative	`U10, V10 (valid at mass points)`
surface temperature and mixing ratio	`T2, Q2`

The definitions for map projection options:

`map_proj` = 1: Lambert Conformal
2: Polar Stereographic
3: Mercator
6: latitude and longitude (including global)

Chapter 6: WRF Data Assimilation (WRFDA)

Table of Contents

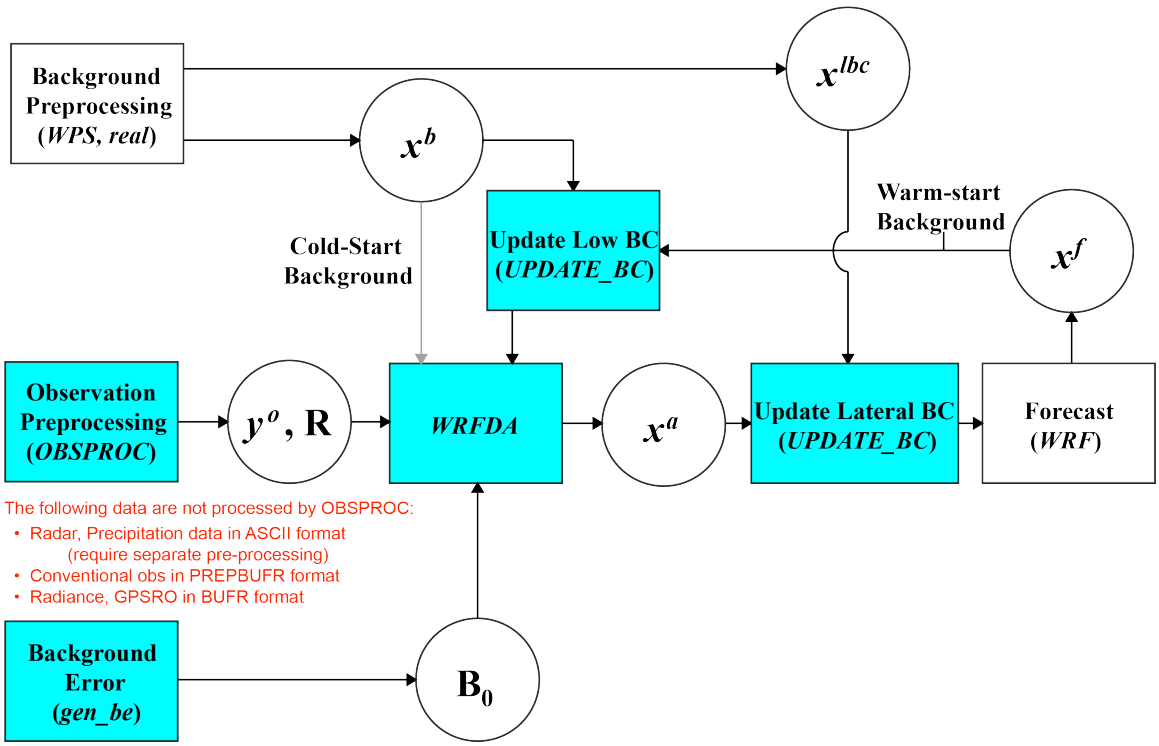
Introduction

Data assimilation is the technique by which **observations** are combined with an NWP product (the **first guess** or background forecast) and their respective error statistics to provide an improved estimate (the **analysis**) of the atmospheric (or oceanic, Jovian, etc.) state. Variational (Var) data assimilation achieves this through the iterative minimization of a prescribed cost (or penalty) function. Differences between the analysis and observations/first guess are penalized (damped) according to their perceived error. The difference between three-dimensional (3D-Var) and four-dimensional (4D-Var) data assimilation is the use of a numerical forecast model in the latter.

The MMM Laboratory of NCAR supports a unified (global/regional, multi-model, 3/4D-Var) model-space data assimilation system (WRFDA) for use by the NCAR staff and collaborators, and is also freely available to the general community, together with further documentation, test results, plans etc., from the WRFDA web-page (http://www2.mmm.ucar.edu/wrf/users/wrfda/index.html).

Various components of the WRFDA system are shown in blue in the sketch below, together with their relationship with the rest of the WRF system.

WRFDA in the WRF Modeling System



x^b first guess, either from a previous WRF forecast or from WPS/real.exe output.
x^{lbc} lateral boundary from WPS/real.exe output.

x^a	analysis from the WRFDA data assimilation system.
x^f	WRF forecast output.
y^o	observations processed by OBSPROC. (note: PREPBUFR input, radar, radiance, and rainfall data do not go through OBSPROC)
$\mathbf{B_0}$	background error statistics from generic BE data (CV3) or gen_be.
$\mathbf{R}$	observational and representative error statistics.

In this chapter, you will learn how to install and run the various components of the WRFDA system. For training purposes, you are supplied with a test case, including the following input data:

- observation files,
- a netCDF background file (WPS/real.exe output, the first guess of the analysis)
- background error statistics (estimate of errors in the background file).
- This tutorial dataset can be downloaded from the WRFDA Users Page (http://www2.mmm.ucar.edu/wrf/users/wrfda/download/testdata.html), and will be described later in more detail. In your own work, however, you will have to create all these input files yourself. See the section "Running Observation Preprocessor" for creating your observation files. See the section "Background Error and running GEN_BE" for generating your background error statistics file, if you want to use cv_options=5, 6, or 7.

Before using your own data, we suggest that you start by running through the WRFDA-related programs using the supplied test case. This serves two purposes: First, you can learn how to run the programs with data we have tested ourselves, and second you can test whether your computer is capable of running the entire data assimilation system. After you have done the tutorial, you can try running other, more computationally intensive case studies, and experimenting with some of the many namelist variables.

WARNING: It is impossible to test every permutation of computer, compiler, number of processors, case, namelist option, etc. for every WRFDA release. The namelist options that are supported are indicated in the "`WRFDA/var/README.namelist`", and these are the default options.

Hopefully, our test cases will prepare you for the variety of ways in which you may wish to run your own WRFDA experiments. Please inform us about your experiences.

As a professional courtesy, we request that you include the following references in any publication that uses any component of the community WRFDA system:

Barker, D.M., W. Huang, Y.R. Guo, and Q.N. Xiao., 2004: A Three-Dimensional (3DVAR) Data Assimilation System For Use With MM5: Implementation and Initial Results. *Mon. Wea. Rev.*, **132**, 897-914.

Huang, X.Y., Q. Xiao, D.M. Barker, X. Zhang, J. Michalakes, W. Huang, T. Henderson, J. Bray, Y. Chen, Z. Ma, J. Dudhia, Y. Guo, X. Zhang, D.J. Won, H.C. Lin, and Y.H.

Kuo, 2009: Four-Dimensional Variational Data Assimilation for WRF: Formulation and Preliminary Results. *Mon. Wea. Rev.*, 137, 299–314.

Barker, D., X.-Y. Huang, Z. Liu, T. Auligné, X. Zhang, S. Rugg, R. Ajjaji, A. Bourgeois, J. Bray, Y. Chen, M. Demirtas, Y.-R. Guo, T. Henderson, W. Huang, H.-C. Lin, J. Michalakes, S. Rizvi, and X. Zhang, 2012: The Weather Research and Forecasting Model's Community Variational/Ensemble Data Assimilation System: WRFDA. *Bull. Amer. Meteor. Soc.*, 93, 831–843.

Running WRFDA requires a Fortran 90 compiler. The WRFDA system can be compiled on the following platforms: Linux (ifort, gfortran, pgf90), Macintosh (gfortran, ifort), IBM (xlf), and SGI Altix (ifort). Please let us know if this does not meet your requirements, and we will attempt to add other machines to our list of supported architectures, as resources allow. Although we are interested in hearing about your experiences in modifying compiler options, we do not recommend making changes to the configure file used to compile WRFDA.

Installing WRFDA for 3DVAR Run

a. Obtaining WRFDA Source Code

Users can download the WRFDA source code from http://www2.mmm.ucar.edu/wrf/users/wrfda/download/get_source.html.

Note: **Although the WRFDA package also contains the WRF source code, they can not be built together. WRF should be downloaded and compiled separately.**

After the tar file is unzipped (`gunzip WRFDAV3.9.TAR.gz`) and untarred (`tar -xf WRFDAV3.9.TAR`), the directory `WRFDA` should be created. This directory contains the WRFDA source, external libraries, and fixed files. The following is a list of the system components and content for each subdirectory:

Directory Name	Content
var/da	WRFDA source code
var/run	Fixed input files required by WRFDA, such as background error covariance, radiance-related files, CRTM coefficients and VARBC.in
var/external	Libraries needed by WRFDA, includes CRTM, BUFR, LAPACK, BLAS
var/obsproc	OBSPROC source code, namelist, and observation error files
var/gen_be	Source code of gen_be, the utility to create background error statistics files

var/build	Builds all .exe files.

b. Compile WRFDA and Libraries

Some external libraries (e.g., LAPACK, BLAS, and NCEP BUFR) are included in the WRFDA tar file. To compile the WRFDA code, the only mandatory library is the netCDF library. You should set an environment variable NETCDF to point to the directory where your netCDF library is installed

```
> setenv NETCDF your_netcdf_path
```

The source code for BUFRLIB 10.2.3 (with minor modifications) is included in the WRFDA tar file, and is compiled automatically. This library will be used for assimilating files in PREPBUFR and NCEP BUFR format.

Starting with WRFDA version 3.8, AMSR2 data can be assimilated in HDF5 format, which requires the use of HDF5 libraries. If you wish to make use of this capability, you should ensure that HDF5 libraries are installed on your system (or download and install them yourself; the source code is available from https://www.hdfgroup.org/HDF5/). To use HDF5 in WRFDA, you should set the environment variable "HDF5" to the parent path of your HDF5 build:

```
> setenv HDF5 your_hdf5_path
```

The HDF5 path should contain the directories "include" and "lib".

For some platforms, you may have to also add the HDF5 "lib" directory to your environment variable LD_LIBRARY_PATH:

```
> setenv LD_LIBRARY_PATH ${LD_LIBRARY_PATH}:your_hdf5_path/lib
```

If satellite radiance data are to be used, a Radiative Transfer Model (RTM) is required. The current RTM versions that WRFDA supports are CRTM V2.2.3 and RTTOV V11.1–11.3 .

The CRTM V2.2.3 source code is included in the WRFDA tar file, and is compiled automatically. No action is needed from the user.

If the user wishes to use RTTOV, download and install the RTTOV v11 library before compiling WRFDA. This library can be downloaded from http://nwpsaf.eu/deliverables/rtm/index.html. **The RTTOV libraries must be compiled with the "emis_atlas" option in order to work with WRFDA; see the RTTOV "readme.txt" for instructions on how to do this.** After compiling RTTOV (see the

RTTOV documentation for detailed instructions), set the "RTTOV" environment variable to the path where the `lib` directory resides. For example, if the library files can be found in `/usr/local/rttov11/gfortran/lib/librttov11.*.a`, you should set RTTOV as:

```
> setenv RTTOV /usr/local/rttov11/gfortran
```

Note: **Make sure the required libraries were all compiled using the same compiler that will be used to build WRFDA**, since the libraries produced by one compiler may not be compatible with code compiled with another.

Assuming all required libraries are available and the WRFDA source code is ready, you can start to build WRFDA using the following steps:

Enter the `WRFDA` directory and run the configure script:

```
> cd WRFDA
> ./configure wrfda
```

A list of configuration options should appear. Each option combines an operating system, a compiler type, and a parallelism option. Since the configuration script doesn't check which compilers are *actually* installed on your system, be sure to select only among the options that you have available to you. The available parallelism options are single-processor (serial), shared-memory parallel (smpar), distributed-memory parallel (dmpar), and distributed-memory with shared-memory parallel (sm+dm). **However, shared-memory (smpar and sm+dm) options are not supported as of WRFDA Version 3.9, so we do not recommend selecting any of these options.**

For example, on a Linux machine such as NCAR's Yellowstone, the above steps will look similar to the following:

```
checking for perl5... no
checking for perl... found /usr/bin/perl (perl)
Will use NETCDF in dir: /glade/apps/opt/netcdf/4.3.0/gnu/4.8.2/
Will use HDF5 in dir: /glade/u/apps/opt/hdf5/1.8.12/gnu/4.8.2/
PHDF5 not set in environment. Will configure WRF for use without.
Will use 'time' to report timing information
$JASPERLIB or $JASPERINC not found in environment, configuring to build without grib2
I/O...
------------------------------------------------------------------------
Please select from among the following Linux x86_64 options:

  1. (serial)   2. (smpar)   3. (dmpar)   4. (dm+sm)   PGI (pgf90/gcc)
  5. (serial)   6. (smpar)   7. (dmpar)   8. (dm+sm)   PGI (pgf90/pgcc): SGI MPT
  9. (serial)  10. (smpar)  11. (dmpar)  12. (dm+sm)   PGI (pgf90/gcc): PGI accelerator
 13. (serial)  14. (smpar)  15. (dmpar)  16. (dm+sm)   INTEL (ifort/icc)
                                         17. (dm+sm)   INTEL (ifort/icc): Xeon Phi (MIC
architecture)
 18. (serial)  19. (smpar)  20. (dmpar)  21. (dm+sm)   INTEL (ifort/icc): Xeon (SNB with
AVX mods)
 22. (serial)  23. (smpar)  24. (dmpar)  25. (dm+sm)   INTEL (ifort/icc): SGI MPT
 26. (serial)  27. (smpar)  28. (dmpar)  29. (dm+sm)   INTEL (ifort/icc): IBM POE
 30. (serial)               31. (dmpar)                 PATHSCALE (pathf90/pathcc)
 32. (serial)  33. (smpar)  34. (dmpar)  35. (dm+sm)   GNU (gfortran/gcc)
 36. (serial)  37. (smpar)  38. (dmpar)  39. (dm+sm)   IBM (xlf90_r/cc_r)
 40. (serial)  41. (smpar)  42. (dmpar)  43. (dm+sm)   PGI (ftn/gcc): Cray XC CLE
```

```
 44. (serial)  45. (smpar)  46. (dmpar)  47. (dm+sm)   CRAY CCE (ftn/cc): Cray XE and XC
 48. (serial)  49. (smpar)  50. (dmpar)  51. (dm+sm)   INTEL (ftn/icc): Cray XC
 52. (serial)  53. (smpar)  54. (dmpar)  55. (dm+sm)   PGI (pgf90/pgcc)
 56. (serial)  57. (smpar)  58. (dmpar)  59. (dm+sm)   PGI (pgf90/gcc): -f90=pgf90
 60. (serial)  61. (smpar)  62. (dmpar)  63. (dm+sm)   PGI (pgf90/pgcc): -f90=pgf90
 64. (serial)  65. (smpar)  66. (dmpar)  67. (dm+sm)   INTEL (ifort/icc): HSW/BDW
 68. (serial)  69. (smpar)  70. (dmpar)  71. (dm+sm)   INTEL (ifort/icc): KNL MIC

Enter selection [1-71] : 34
------------------------------------------------------------------------

Configuration successful!
------------------------------------------------------------------------
... ...
```

After entering the option that corresponds to your machine/compiler combination, the configure script should print the message "`Configuration successful!`" followed by a large amount of configuration information. Depending on your system, you may see a warning message mentioning that some Fortran 2003 features have been removed: this message is normal and can be ignored. However, if you see a message "`One of compilers testing failed! Please check your compiler`", configuration has probably failed, and you should make sure you have selected the correct option.

After running the configuration script and choosing a compilation option, a `configure.wrf` file will be created. Because of the variety of ways that a computer can be configured, if the WRFDA build ultimately fails, there is a chance that minor modifications to the `configure.wrf` file may be needed.

To compile WRFDA, type

```
> ./compile all_wrfvar >& compile.out
```

Successful compilation will produce 44 executables: 43 of which are in the `var/build` directory and linked in the `var/da` directory, with the 44th, `obsproc.exe`, found in the `var/obsproc/src` directory. You can list these executables by issuing the command:

```
>ls -l var/build/*exe var/obsproc/src/obsproc.exe
-rwxr-xr-x 1 user   885143 Apr  4 17:22 var/build/da_advance_time.exe
-rwxr-xr-x 1 user  1162003 Apr  4 17:24 var/build/da_bias_airmass.exe
-rwxr-xr-x 1 user  1143027 Apr  4 17:23 var/build/da_bias_scan.exe
-rwxr-xr-x 1 user  1116933 Apr  4 17:23 var/build/da_bias_sele.exe
-rwxr-xr-x 1 user  1126173 Apr  4 17:23 var/build/da_bias_verif.exe
-rwxr-xr-x 1 user  1407973 Apr  4 17:23 var/build/da_rad_diags.exe
-rwxr-xr-x 1 user  1249431 Apr  4 17:22 var/build/da_tune_obs_desroziers.exe
-rwxr-xr-x 1 user  1186368 Apr  4 17:24 var/build/da_tune_obs_hollingsworth1.exe
-rwxr-xr-x 1 user  1083862 Apr  4 17:24 var/build/da_tune_obs_hollingsworth2.exe
-rwxr-xr-x 1 user  1193390 Apr  4 17:24 var/build/da_update_bc_ad.exe
-rwxr-xr-x 1 user  1245842 Apr  4 17:23 var/build/da_update_bc.exe
-rwxr-xr-x 1 user  1492394 Apr  4 17:24 var/build/da_verif_grid.exe
-rwxr-xr-x 1 user  1327002 Apr  4 17:24 var/build/da_verif_obs.exe
-rwxr-xr-x 1 user 26031927 Apr  4 17:31 var/build/da_wrfvar.exe
-rwxr-xr-x 1 user  1933571 Apr  4 17:23 var/build/gen_be_addmean.exe
-rwxr-xr-x 1 user  1944047 Apr  4 17:24 var/build/gen_be_cov2d3d_contrib.exe
-rwxr-xr-x 1 user  1927988 Apr  4 17:24 var/build/gen_be_cov2d.exe
-rwxr-xr-x 1 user  1945213 Apr  4 17:24 var/build/gen_be_cov3d2d_contrib.exe
-rwxr-xr-x 1 user  1941439 Apr  4 17:24 var/build/gen_be_cov3d3d_bin3d_contrib.exe
-rwxr-xr-x 1 user  1947331 Apr  4 17:24 var/build/gen_be_cov3d3d_contrib.exe
-rwxr-xr-x 1 user  1931820 Apr  4 17:24 var/build/gen_be_cov3d.exe
-rwxr-xr-x 1 user  1915177 Apr  4 17:24 var/build/gen_be_diags.exe
-rwxr-xr-x 1 user  1947942 Apr  4 17:24 var/build/gen_be_diags_read.exe
```

```
-rwxr-xr-x 1 user  1930465 Apr  4 17:24 var/build/gen_be_ensmean.exe
-rwxr-xr-x 1 user  1951511 Apr  4 17:24 var/build/gen_be_ensrf.exe
-rwxr-xr-x 1 user  1994167 Apr  4 17:24 var/build/gen_be_ep1.exe
-rwxr-xr-x 1 user  1996438 Apr  4 17:24 var/build/gen_be_ep2.exe
-rwxr-xr-x 1 user  2001400 Apr  4 17:24 var/build/gen_be_etkf.exe
-rwxr-xr-x 1 user  1942988 Apr  4 17:24 var/build/gen_be_hist.exe
-rwxr-xr-x 1 user  2021659 Apr  4 17:24 var/build/gen_be_stage0_gsi.exe
-rwxr-xr-x 1 user  2012035 Apr  4 17:24 var/build/gen_be_stage0_wrf.exe
-rwxr-xr-x 1 user  1973193 Apr  4 17:24 var/build/gen_be_stage1_1dvar.exe
-rwxr-xr-x 1 user  1956835 Apr  4 17:24 var/build/gen_be_stage1.exe
-rwxr-xr-x 1 user  1963314 Apr  4 17:24 var/build/gen_be_stage1_gsi.exe
-rwxr-xr-x 1 user  1975042 Apr  4 17:24 var/build/gen_be_stage2_1dvar.exe
-rwxr-xr-x 1 user  1938468 Apr  4 17:24 var/build/gen_be_stage2a.exe
-rwxr-xr-x 1 user  1952538 Apr  4 17:24 var/build/gen_be_stage2.exe
-rwxr-xr-x 1 user  1202392 Apr  4 17:22 var/build/gen_be_stage2_gsi.exe
-rwxr-xr-x 1 user  1947836 Apr  4 17:24 var/build/gen_be_stage3.exe
-rwxr-xr-x 1 user  1928353 Apr  4 17:24 var/build/gen_be_stage4_global.exe
-rwxr-xr-x 1 user  1955622 Apr  4 17:24 var/build/gen_be_stage4_regional.exe
-rwxr-xr-x 1 user  1924416 Apr  4 17:24 var/build/gen_be_vertloc.exe
-rwxr-xr-x 1 user  2057673 Apr  4 17:24 var/build/gen_mbe_stage2.exe
-rwxr-xr-x 1 user  2110993 Apr  4 17:32 var/obsproc/src/obsproc.exe
```

The main executable for running WRFDA is `da_wrfvar.exe`. Make sure it has been created after the compilation: it is fairly common that all the executables will be successfully compiled except this main executable. If this occurs, please check the compilation log file carefully for any errors.

The basic gen_be utility for the regional model consists of `gen_be_stage0_wrf.exe`, `gen_be_stage1.exe`, `gen_be_stage2.exe`, `gen_be_stage2a.exe`, `gen_be_stage3.exe`, `gen_be_stage4_regional.exe`, and `gen_be_diags.exe`.

`da_update_bc.exe` is used for updating the WRF lower and lateral boundary conditions before and after a new WRFDA analysis is generated. This is detailed in the section on Updating WRF Boundary Conditions.

`da_advance_time.exe` is a very handy and useful tool for date/time manipulation. Type `$WRFDA_DIR/var/build/da_advance_time.exe` to see its usage instructions.

`obsproc.exe` is the executable for preparing conventional observations for assimilation by WRFDA. Its use is detailed in the section on Running Observation Preprocessor.

If you plan on using CRTM for radiance assimilation, check `$WRFDA_DIR/var/external/crtm_2.2.3/libsrc` to ensure that `libCRTM.a` was generated.

c. Clean old compilation

To remove all object files and executables, type:

```
./clean
```

To remove all build files, including `configure.wrf`, type:

```
./clean -a
```

The `clean –a` command is recommended if your compilation fails, or if the configuration file has been changed and you wish to restore the default settings.

Installing WRFPLUS and WRFDA for 4DVAR Run

If you intend to run WRFDA 4DVAR, it is necessary to have WRFPLUS installed. WRFPLUS contains the adjoint and tangent linear models based on a simplified WRF model, which includes a few simplified physics packages, such as surface drag, large scale condensation and precipitation, and cumulus parameterization.

> **Note: if you intend to run both 3DVAR and 4DVAR experiments, it is not necessary to compile the code twice.** The `da_wrfvar.exe` executable compiled for 4DVAR can be used for both 3DVAR and 4DVAR assimilation**.**

To install WRFPLUS:

- Get the WRFPLUS zipped tar file from http://www2.mmm.ucar.edu/wrf/users/wrfda/download/wrfplus.html

- Unzip and untar the WRFPLUS file, then run the `configure` script

```
> gunzip WRFPLUSV3.9.tar.gz
> tar -xf WRFPLUSV3.9.tar
> cd WRFPLUSV3
> ./configure wrfplus
```

As with 3D-Var, “serial” means single-processor, and “dmpar” means Distributed Memory Parallel (MPI). Be sure to select the same option for WRFPLUS as you will use for WRFDA.

- Compile WRFPLUS

```
> ./compile wrf >& compile.out
> ls -ls main/*.exe
```

If compilation was successful, you should see the WRFPLUS executable (named `wrf.exe`):

```
53292 -rwxr-xr-x 1 user man 54513254 Apr  6 22:43 main/wrf.exe
```

Finally, set the environment variable `WRFPLUS_DIR` to the appropriate directory:

```
>setenv WRFPLUS_DIR ${your_source_code_dir}/WRFPLUSV3
```

To install WRFDA for the 4D-Var run:

- If you intend to use RTTOV to assimilate radiance data, you will need to set the appropriate environment variable at compile time. See the previous 3DVAR section for instructions.

  ```
  >./configure 4dvar

  >./compile all_wrfvar >& compile.out

  >ls -ls var/build/*.exe var/obsproc/*.exe
  ```

  You should see the same 44 executables as are listed in the above 3DVAR section, including `da_wrfvar.exe`

Running Observation Preprocessor (OBSPROC)

The OBSPROC program reads observations in LITTLE_R format (a text-based format, in use since the MM5 era). We have provided observations for the tutorial case, but for your own applications, you will have to prepare your own observation files. Please see http://www2.mmm.ucar.edu/wrf/users/wrfda/download/free_data.html for the sources of some freely-available observations. Because the raw observation data files have many possible formats, such as ASCII, BUFR, PREPBUFR, MADIS (***note***: a converter for MADIS data to LITTLE_R is available on the WRFDA website: http://www2.mmm.ucar.edu/wrf/users/wrfda/download/madis.html), and HDF, the free data site also contains instructions for converting the observations to LITTLE_R format. To make the WRFDA system as general as possible, the LITTLE_R format was adopted as an intermediate observation data format for the WRFDA system, however, *the conversion of the user-specific source data to LITTLE_R format is the user's task*. A more complete description of the LITTLE_R format, as well as conventional observation data sources for WRFDA, can be found by reading The LITTLE_R for WRFDA help page, the "Observation Pre-processing" tutorial found at http://www2.mmm.ucar.edu/wrf/users/wrfda/Tutorials/2016_Aug/tutorial_presentations_summer_2016.html, or by referencing Chapter 7 of this User's Guide.

The purpose of OBSPROC is to:

- Remove observations outside the specified temporal and spatial domains
- Re-order and merge duplicate (in time and location) data reports
- Retrieve pressure or height based on observed information using the hydrostatic assumption
- Check multi-level observations for vertical consistency and superadiabatic conditions
- Assign observation errors based on a pre-specified error file

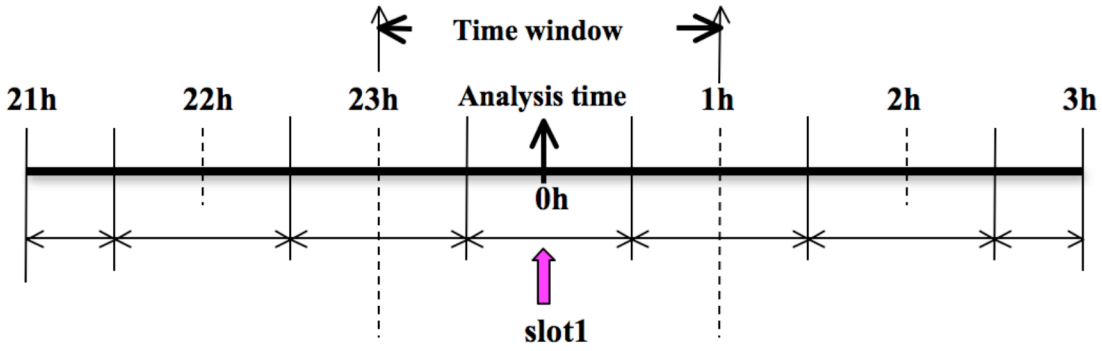
- Write out the observation file to be used by WRFDA in ASCII or BUFR format

The OBSPROC program (`obsproc.exe`) should be found under the directory `$WRFDA_DIR/var/obsproc/src` if "`compile all_wrfvar`" completed successfully.

If you haven't already, you should download the tutorial case, which contains example files for all the exercises in this User's Guide. The case can be found at the WRFDA website (http://www2.mmm.ucar.edu/wrf/users/wrfda/download/testdata.html).

a. OBSPROC for 3DVAR

As an example, to prepare the observation file at the analysis time, all the observations in the range ±1h will be processed, which means that (in the example case) the observations between 23h and 1h are treated as the observations at 0h. This is illustrated in the following figure:



OBSPROC requires at least 3 files to run successfully:

- A namelist file (`namelist.obsproc`)
- An observation error file (`obserr.txt`)
- One or more observation files
- Optionally, a table for specifying the elevation information for marine observations over the US Great Lakes (`msfc.tbl`)

The files `obserr.txt` and `msfc.tbl` are included in the source code under `var/obsproc`. To create the required namelist file, we have provided an example file (`namelist_obsproc.3dvar.wrfvar-tut`) in the `var/obsproc` directory. Thus, proceed as follows.

```
> cd $WRFDA_DIR/var/obsproc
> cp namelist.obsproc.3dvar.wrfvar-tut namelist.obsproc
```

Next, edit the namelist file, `namelist.obsproc`, to accommodate your experiments.

You will likely only need to change variables listed under records 1, 2, 6, 7, and 8. See `$WRFDA_DIR/var/obsproc/README.namelist`, or the section OBSPROC namelist variables for details. You should pay special attention to the record 7 and record 8 variables: these will determine the domain for which observations will be written to the output observation file. Alternatively, if you do not wish to filter the observations spatially, you can set `domain_check_h = .false.` under `&record4`.

If you are running the tutorial case, you should copy or link the sample observation file (`ob/2008020512/obs.2008020512`) to the `obsproc` directory. Alternatively, you can edit the namelist variable `obs_gts_filename` to point to the observation file's full path.

To run OBSPROC, type

```
> ./obsproc.exe >& obsproc.out
```

Once `obsproc.exe` has completed successfully, you will see an observation data file, with the name formatted `obs_gts_YYYY-MM-DD_HH:NN:SS.3DVAR`, in the `obsproc` directory. For the tutorial case, this will be `obs_gts_2008-02-05_12:00:00.3DVAR`. This is the input observation file to WRFDA. It is an ASCII file that contains a header section (listed below) followed by observations. The meanings and format of observations in the file are described in the last six lines of the header section.

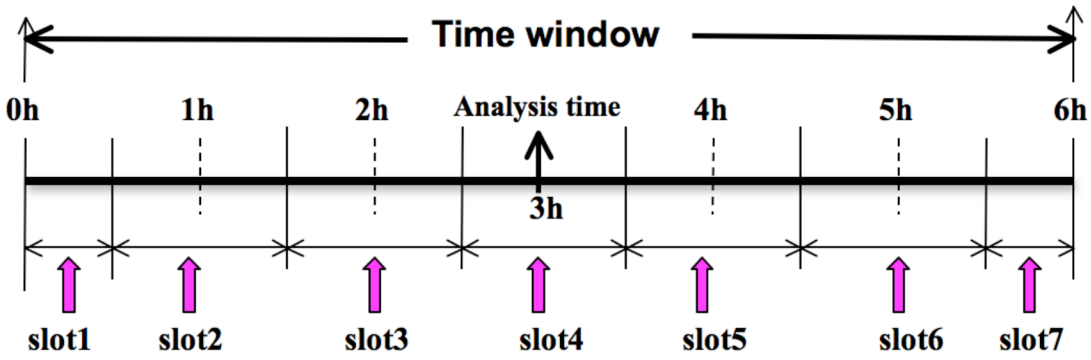
```
TOTAL =   9066, MISS. =-888888.,
SYNOP =    757, METAR =   2416, SHIP  =    145, BUOY  =    250, BOGUS =      0, TEMP  =
86,
AMDAR =     19, AIREP =    205, TAMDAR=      0, PILOT =     85, SATEM =    106, SATOB =
2556,
GPSPW =    187, GPSZD =      0, GPSRF =      3, GPSEP =      0, SSMT1 =      0, SSMT2 =
0,
TOVS  =      0, QSCAT =   2190, PROFL =     61, AIRSR =      0, OTHER =      0,
PHIC  =  40.00, XLONC = -95.00, TRUE1 =  30.00, TRUE2 =  60.00, XIM11 =   1.00, XJM11 =
1.00,
base_temp= 290.00, base_lapse=  50.00, PTOP  =  1000., base_pres=100000.,
base_tropo_pres= 20000., base_strat_temp=   215.,
IXC   =     60, JXC   =     90, IPROJ =      1, IDD   =      1, MAXNES=      1,
NESTIX=     60,
NESTJX=     90,
NUMC  =      1,
DIS   =  60.00,
NESTI =      1,
NESTJ =      1,
INFO  = PLATFORM, DATE, NAME, LEVELS, LATITUDE, LONGITUDE, ELEVATION, ID.
SRFC  = SLP, PW (DATA,QC,ERROR).
EACH  = PRES, SPEED, DIR, HEIGHT, TEMP, DEW PT, HUMID (DATA,QC,ERROR)*LEVELS.
INFO_FMT = (A12,1X,A19,1X,A40,1X,I6,3(F12.3,11X),6X,A40)
SRFC_FMT = (F12.3,I4,F7.2,F12.3,I4,F7.3)
EACH_FMT = (3(F12.3,I4,F7.2),11X,3(F12.3,I4,F7.2),11X,3(F12.3,I4,F7.2))
#------------------------------------------------------------------------------#
…… observations ……
```

Before running WRFDA, you may find it useful to learn more about various types of data that will be processed (e.g., their geographical distribution). This file is in ASCII format and so you can easily view it. For a graphical view of the file's content, there are NCL scripts available which can display the distribution and type of observations. In the WRFDA Tools package (can be downloaded at http://www2.mmm.ucar.edu/wrf/users/wrfda/download/tools.html), the relevant script is located at

`$TOOLS_DIR/var/graphics/ncl/plot_ob_ascii_loc.ncl`. You will need to have NCL installed in your system to use this script; for more information on NCL, the NCAR Command Language, see http://www.ncl.ucar.edu/.

b. OBSPROC for 4DVAR

To prepare the observation file, for example, at the analysis time 0h for 4D-Var, all observations from 0h to 6h will be processed and grouped in 7 sub-windows (slot1 through slot7) as illustrated in the following figure:



NOTE: The "Analysis time" in the above figure is not the actual analysis time (0h). It indicates the time_analysis setting in the namelist file, which in this example is three hours later than the actual analysis time. The actual analysis time is still 0h.

An example namelist (`namelist_obsproc.4dvar.wrfvar-tut`) has already been provided in the `var/obsproc` directory. Thus, proceed as follows:

```
> cd $WRFDA_DIR/var/obsproc
> cp namelist.obsproc.4dvar.wrfvar-tut namelist.obsproc
```

In the namelist file, you need to change the following variables to accommodate your experiments. In this tutorial case, the actual analysis time is `2008-02-05_12:00:00`, **but in the namelist, `time_analysis` should be set to 3 hours later**. The different values of `time_analysis`, `num_slots_past`, and `time_slots_ahead` contribute to the actual times analyzed. For example, if you set `time_analysis` = 2008-02-05_16:00:00, and set the `num_slots_past` = 4 and `time_slots_ahead`=2, the final results will be the same as before.

Edit all the domain settings according to your own experiment; a full list of namelist options and descriptions can be found in the section Description of Namelist Variables. You should pay special attention to the record 7 and record 8 variables: these will determine the domain for which observations will be written to the output observation file. Alternatively, if you do not wish to filter the observations spatially, you can set `domain_check_h = .false.` under `&record4`.

If you are running the tutorial case, you should copy or link the sample observation file (`ob/2008020512/obs.2008020512`) to the `obsproc` directory. Alternatively, you can edit the namelist variable `obs_gts_filename` to point to the observation file's full path.

To run OBSPROC, type

```
> obsproc.exe >& obsproc.out
```

Once `obsproc.exe` has completed successfully, you will see 7 observation data files, which for the tutorial case are named

```
obs_gts_2008-02-05_12:00:00.4DVAR
obs_gts_2008-02-05_13:00:00.4DVAR
obs_gts_2008-02-05_14:00:00.4DVAR
obs_gts_2008-02-05_15:00:00.4DVAR
obs_gts_2008-02-05_16:00:00.4DVAR
obs_gts_2008-02-05_17:00:00.4DVAR
obs_gts_2008-02-05_18:00:00.4DVAR
```

They are the input observation files to WRF 4D-Var.

Running WRFDA

a. Download Test Data

The WRFDA system requires three input files to run:

a) WRF *first guess* file, output from either WPS/real.exe (cold-start) or a WRF forecast (warm-start)

b) Observations (in ASCII format, PREPBUFR or BUFR for radiance)

c) A background error statistics file (containing background error covariance)

The following table summarizes the above info:

Input Data	*Format*	*Created By*
First Guess	NETCDF	WRF Preprocessing System (WPS) and real.exe or WRF
Observations	ASCII (PREPBUFR also possible)	Observation Preprocessor (OBSPROC)
Background Error Statistics	Binary	WRFDA gen_be utility or generic CV3

In the test case, you will store data in a directory defined by the environment variable `$DAT_DIR`. This directory can be in any location, and it should have read access. Type

```
> setenv DAT_DIR your_choice_of_dat_dir
```

Here, `your_choice_of_dat_dir` is the directory where the WRFDA input data is stored.

If you have not already done so, download the sample data for the tutorial case, valid at 12 UTC 5th February 2008, from
http://www2.mmm.ucar.edu/wrf/users/wrfda/download/testdata.html

Once you have downloaded the `WRFDAV3.9-testdata.tar.gz` file to `$DAT_DIR`, extract it by typing

```
> gunzip WRFDAV3.9-testdata.tar.gz
> tar -xvf WRFDAV3.9-testdata.tar
```

Now you should find the following four files under "`$DAT_DIR`"

```
ob/2008020512/ob.2008020512      #  Observation data in "little_r" format
rc/2008020512/wrfinput_d01       #  First guess file
rc/2008020512/wrfbdy_d01         #  lateral boundary file
be/be.dat                        #  Background error file
......
```

At this point you should have three of the input files (first guess, observations from OBSPROC, and background error statistics files in the directory `$DAT_DIR`) required to run WRFDA, and have successfully downloaded and compiled the WRFDA code. If this is correct, you are ready to run WRFDA.

b. Run 3DVAR test case

The data for the tutorial case is valid at 12 UTC 5 February 2008. The first guess comes from the NCEP FNL (Final) Operational Global Analysis data, passed through the WRF-WPS and real.exe programs.

To run WRF 3D-Var, first create and enter into a working directory (for example, `$WRFDA_DIR/workdir`), and set the environment variable `WORK_DIR` to this directory (e.g., `setenv WORK_DIR $WRFDA_DIR/workdir`). Then follow the steps below:

```
> cd $WORK_DIR
> cp $DAT_DIR/namelist.input.3dvar namelist.input
> ln -sf $WRFDA_DIR/run/LANDUSE.TBL .
> ln -sf $DAT_DIR/rc/2008020512/wrfinput_d01 ./fg
> ln -sf $DAT_DIR/ob/2008020512/obs_gts_2008-02-05_12:00:00.3DVAR
./ob.ascii  (note the different name!)
> ln -sf $DAT_DIR/be/be.dat .
> ln -sf $WRFDA_DIR/var/da/da_wrfvar.exe .
```

Now edit the file `namelist.input`, which is a very basic namelist for the tutorial test case, and is shown below.

```
&wrfvar1
```

```
var4d=false,
print_detail_grad=false,
/
&wrfvar2
/
&wrfvar3
ob_format=2,
/
&wrfvar4
/
&wrfvar5
/
&wrfvar6
max_ext_its=1,
ntmax=50,
orthonorm_gradient=true,
/
&wrfvar7
cv_options=5,
/
&wrfvar8
/
&wrfvar9
/
&wrfvar10
test_transforms=false,
test_gradient=false,
/
&wrfvar11
/
&wrfvar12
/
&wrfvar13
/
&wrfvar14
/
&wrfvar15
/
&wrfvar16
/
&wrfvar17
/
&wrfvar18
analysis_date="2008-02-05_12:00:00.0000",
/
&wrfvar19
/
&wrfvar20
/
&wrfvar21
time_window_min="2008-02-05_11:00:00.0000",
/
&wrfvar22
time_window_max="2008-02-05_13:00:00.0000",
/
&time_control
start_year=2008,
start_month=02,
start_day=05,
start_hour=12,
end_year=2008,
end_month=02,
end_day=05,
end_hour=12,
/
&fdda
/
&domains
e_we=90,
e_sn=60,
e_vert=41,
dx=60000,
```

```
dy=60000,
/
&dfi_control
/
&tc
/
&physics
mp_physics=3,
ra_lw_physics=1,
ra_sw_physics=1,
radt=60,
sf_sfclay_physics=1,
sf_surface_physics=1,
bl_pbl_physics=1,
cu_physics=1,
cudt=5,
num_soil_layers=5,
mp_zero_out=2,
co2tf=0,
/
&scm
/
&dynamics
/
&bdy_control
/
&grib2
/
&fire
/
&namelist_quilt
/
&perturbation
/
```

No edits should be needed if you are running the tutorial case without radiance data. If you plan to use the PREPBUFR-format data, change the `ob_format=1` in `&wrfvar3` in `namelist.input` and link the data as `ob.bufr`,

```
> ln -fs $DAT_DIR/ob/2008020512/gdas1.t12z.prepbufr.nr  ob.bufr
```

Once you have changed any other necessary namelist variables, run WRFDA 3D-Var:

```
> da_wrfvar.exe >& wrfda.log
```

The file `wrfda.log` (or `rsl.out.0000`, if run in distributed-memory mode) contains important WRFDA runtime log information. Always check the log after a WRFDA run:

```
*** VARIATIONAL ANALYSIS ***
    WRFDA V3.9

DYNAMICS OPTION: Eulerian Mass Coordinate
   alloc_space_field: domain            1 ,             499448408  bytes allocated
hybrid_opt =  0

 Tile Strategy is not specified. Assuming 1D-Y
WRF TILE   1 IS      1 IE     89 JS      1 JE     59
WRF NUMBER OF TILES =   1
Domain mapping info:
map_proj =     1
cen_lat   =    0.400000E+02
cen_lon   =   -0.950000E+02
truelat1  =    0.300000E+02
truelat2  =    0.600000E+02
```

```
start_lat =    0.207406E+02
start_lon =   -0.119501E+03
pole_lat  =    0.900000E+02
dsm       =    0.600000E+02

Set up observations (ob)

Using ASCII format observation input

Observation summary
   ob time  1
      sound                 86 global,      86 local
      synop                750 global,     750 local
      pilot                 85 global,      85 local
      satem                105 global,     105 local
      geoamv              2499 global,    2499 local
      airep                221 global,     221 local
      gpspw                187 global,     187 local
      gpsrf                  3 global,       3 local
      metar               2408 global,    2408 local
      ships                140 global,     140 local
      qscat               2126 global,    2126 local
      profiler              61 global,      61 local
      buoy                 247 global,     247 local
      sonde_sfc             86 global,      86 local

Set up background errors for regional application for cv_options =   5


   Using the averaged regression coefficients for unbalanced part

   cloud_cv_options =  0
   WRFDA dry control variables are: psi, chi_u, t_u and ps_u
   WRFDA Humidity control variable is rh


Vertical truncation for psi    =  15(  99.00%)

Vertical truncation for chi_u  =  20(  99.00%)

Vertical truncation for t_u    =  29(  99.00%)

Vertical truncation for rh     =  22(  99.00%)


   Scaling: var, len, ds:   0.100000E+01   0.100000E+01   0.600000E+05
   Scaling: var, len, ds:   0.100000E+01   0.100000E+01   0.600000E+05
   Scaling: var, len, ds:   0.100000E+01   0.100000E+01   0.600000E+05
   Scaling: var, len, ds:   0.100000E+01   0.100000E+01   0.600000E+05
   Scaling: var, len, ds:   0.100000E+01   0.100000E+01   0.600000E+05
Calculate innovation vector(iv)

Minimize cost function using CG method

Starting outer iteration :   1
Starting cost function:  5.366048535905661D+04, Gradient=  8.134548965597619D+02
For this outer iteration gradient target is:        8.134548965597618D+00
-------------------------------------------------------------------------
            Loop Iter Cost Function          Gradient               Step
minimize_cg   1    0  5.366048535905661D+04  8.134548965597619D+02  0.000000000000000D+00
minimize_cg   1    1  4.160895118661885D+04  4.087246011996226D+02  3.642548782952763D-02
minimize_cg   1    2  3.684015367850271D+04  3.371798989064126D+02  5.709227119079368D-02
minimize_cg   1    3  3.374263324064368D+04  2.579817263649239D+02  5.449050389717097D-02
minimize_cg   1    4  3.163760162325043D+04  1.959172950097825D+02  6.325731144809946D-02
minimize_cg   1    5  3.069560214937115D+04  1.426201418835412D+02  4.908345259881822D-02
minimize_cg   1    6  2.994553670826729D+04  1.016946487735333D+02  7.375091679036799D-02
minimize_cg   1    7  2.963703986213524D+04  8.614527420925806D+01  5.966017496500481D-02
minimize_cg   1    8  2.944840596364260D+04  5.586898886231801D+01  5.083780846639206D-02
minimize_cg   1    9  2.932974897428447D+04  4.810455663750825D+01  7.602966851781012D-02
minimize_cg   1   10  2.925909806811914D+04  3.154639503336832D+01  6.106260102681394D-02
```

```
minimize_cg   1   11  2.922595474924949D+04  2.511864257306522D+01  6.660801879172493D-02
minimize_cg   1   12  2.920702117122884D+04  1.953264766296704D+01  6.001645744010778D-02
minimize_cg   1   13  2.919536455912784D+04  1.421581370380062D+01  6.110547268188220D-02
minimize_cg   1   14  2.918931706353119D+04  1.000448731094664D+01  5.984971814842433D-02
minimize_cg   1   15  2.918568177329574D+04  7.457040724273403D+00  7.264059789587740D-02
---------------------------------------------------------------------

Inner iteration stopped after   15 iterations

Final:  15 iter, J= 2.918568177329574D+04, g= 7.457040724273385D+00
---------------------------------------------------------------------

Diagnostics
   Final cost function J       =     29185.68

   Total number of obs.        =    37570
   Final value of J            =     29185.68177
   Final value of Jo           =     23086.99122
   Final value of Jd           =         0.00000
   Final value of Jb           =      6098.69056
   Final value of Jc           =         0.00000
   Final value of Je           =         0.00000
   Final value of Jp           =         0.00000
   Final value of Jl           =         0.00000
   Final J / total num_obs     =         0.77683
   Jb factor used(1)           =         1.00000
   Jb factor used(2)           =         1.00000
   Jb factor used(3)           =         1.00000
   Jb factor used(4)           =         1.00000
   Jb factor used(5)           =         1.00000
   Jb factor used              =         1.00000
   Je factor used              =         1.00000
   VarBC factor used           =        10.00000

*** WRF-Var completed successfully ***
```

The file `namelist.output.da` (which contains the complete namelist settings) will be generated after a successful run of `da_wrfvar.exe`. The settings appearing in `namelist.output.da`, but not specified in your `namelist.input`, are the default values from `$WRFDA_DIR/Registry/registry.var`.

After successful completion, `wrfvar_output` (the WRFDA analysis file, i.e. the new initial condition for WRF) should appear in the working directory along with a number of diagnostic files. Text files containing various diagnostics will be explained in the WRFDA Diagnostics section.

To understand the role of various important WRFDA options, try re-running WRFDA by changing different namelist options. Some examples are listed below:

1. Response of convergence criteria:

Run the tutorial case with

```
&wrfvar6
eps = 0.0001,
/
```

You may wish to compare various diagnostics with an earlier run.

2. Response of outer loop on minimization:

Run the tutorial case with

```
&wrfvar6
max_ext_its = 2,
/
```

With this setting, the "outer loop" for the minimization procedure will be activated. You may wish to compare various diagnostics with an earlier run.

Note that when running multiple outer loops with the CV3 background error option, you must specify the scaling factors which are called as1, as2, as3, as4, and as5. More details can be found in the section "Modifying CV3 length scales and variance".

3. Response of suppressing particular types of data in WRFDA:

The types of observations that WRFDA gets to use actually depend on what is included in the observation file and the WRFDA namelist settings. For example, if you have SYNOP data in the observation file, you can suppress its usage in WRFDA by setting `use_synopobs=false` in record `&wrfvar4` of `namelist.input`. It is OK if there are no SYNOP data in the observation file and `use_synopobs=true.`

Turning on and off certain types of observations is widely used for assessing the impact of observations on data assimilations.

Note: It is important to go through the default "use_*" settings in record `&wrfvar4` in `WRFDA/Registry/registry.var` to know what observations are activated in default.

For example, try making the WRFDA convergence criterion more stringent. This is achieved by reducing the value of "`EPS`" to e.g. 0.0001 by adding "`EPS=0.0001`" in the `namelist.input` record `&wrfvar6`. See the section Additional Background Error options for more namelist options.

c. Run 4DVAR test case

To run WRF 4D-Var, first create and enter a working directory, such as `$WRFDA_DIR/workdir`. Set the `WORK_DIR` environment variable (e.g. `setenv WORK_DIR $WRFDA_DIR/workdir`)

For the tutorial case, the analysis date is 2008020512 and the test data directories are:

```
> setenv DAT_DIR {directory where data is stored}
> ls –lr $DAT_DIR
ob/2008020512
ob/2008020513
ob/2008020514
ob/2008020515
ob/2008020516
```

```
ob/2008020517
ob/2008020518
rc/2008020512
be
```

***Note*:** WRFDA 4D-Var is able to assimilate conventional observational data, satellite radiance BUFR data, and precipitation data. The input data format can be PREPBUFR format data or ASCII observation data, processed by OBSPROC.

Now follow the steps below:

1) Link the executable file

```
> cd $WORK_DIR
> ln -fs $WRFDA_DIR/var/da/da_wrfvar.exe .
```

2) Link the observational data, first guess, BE and `LANDUSE.TBL`, `etc`.

```
> ln -fs $DAT_DIR/ob/2008020512/ob01.ascii ob01.ascii
> ln -fs $DAT_DIR/ob/2008020513/ob02.ascii ob02.ascii
> ln -fs $DAT_DIR/ob/2008020514/ob03.ascii ob03.ascii
> ln -fs $DAT_DIR/ob/2008020515/ob04.ascii ob04.ascii
> ln -fs $DAT_DIR/ob/2008020516/ob05.ascii ob05.ascii
> ln -fs $DAT_DIR/ob/2008020517/ob06.ascii ob06.ascii
> ln -fs $DAT_DIR/ob/2008020518/ob07.ascii ob07.ascii

> ln -fs $DAT_DIR/rc/2008020512/wrfinput_d01 .
> ln -fs $DAT_DIR/rc/2008020512/wrfbdy_d01 .
> ln -fs wrfinput_d01 fg

> ln -fs $DAT_DIR/be/be.dat .
> ln -fs $WRFDA_DIR/run/LANDUSE.TBL .
> ln -fs $WRFDA_DIR/run/GENPARM.TBL .
> ln -fs $WRFDA_DIR/run/SOILPARM.TBL .
> ln -fs $WRFDA_DIR/run/VEGPARM.TBL .
> ln –fs $WRFDA_DIR/run/RRTM_DATA_DBL RRTM_DATA
```

3) Copy the sample namelist

```
> cp $DAT_DIR/namelist.input.4dvar namelist.input
```

4) Edit necessary namelist variables, link optional files

WRFDA 4D-Var has the capability to consider lateral boundary conditions as control variables as well during minimization. The namelist variable `var4d_lbc=true` turns on this capability. To enable this option, WRF 4D-Var needs not only the first guess at the beginning of the time window, but also the first guess at the end of the time window.

```
> ln -fs $DAT_DIR/rc/2008020518/wrfinput_d01 fg02
```

Please note: WRFDA beginners should not use this option until you have a good understanding of the 4D-Var lateral boundary conditions control. To disable this feature, make sure `var4d_lbc` in namelist.input is set to false.

If you use PREPBUFR format data, set `ob_format=1` in `&wrfvar3` in `namelist.input`.

Because 12UTC PREPBUFR data only includes the data from 9UTC to 15UTC, for 4D-Var you should include 18UTC PREPBUFR data as well:

```
> ln -fs $DAT_DIR/ob/2008020512/gdas1.t12z.prepbufr.nr  ob01.bufr
> ln -fs $DAT_DIR/ob/2008020518/gdas1.t18z.prepbufr.nr  ob02.bufr
```

Edit `namelist.input` to match your experiment settings. The most important namelist variables related to 4D-Var are listed below. Please refer to `README.namelist` under the `$WRFDA_DIR/var` directory. A common mistake users make is in the time information settings. The rules are: `analysis_date`, `time_window_min` and `start_xxx` in `&time_control` should always be equal to each other; `time_window_max` and `end_xxx` should always be equal to each other; and `run_hours` is the difference between `start_xxx` and `end_xxx`, which is the length of the 4D-Var time window.

```
&wrfvar1
var4d=true,
var4d_lbc=false,
var4d_bin=3600,
……
/
……
&wrfvar18
analysis_date="2008-02-05_12:00:00.0000",
/
……
&wrfvar21
time_window_min="2008-02-05_12:00:00.0000",
/
……
&wrfvar22
time_window_max="2008-02-05_18:00:00.0000",
/
……
&time_control
run_hours=6,
start_year=2008,
start_month=02,
start_day=05,
start_hour=12,
end_year=2008,
end_month=02,
end_day=05,
end_hour=18,
interval_seconds=21600,
debug_level=0,
/
……
```

5) Run WRF 4D-Var

```
> cd $WORK_DIR
> ./da_wrfvar.exe >& wrfda.log
```

4DVAR is much more computationally expensive than 3DVAR, so running may take a while; you can set `ntmax` to a lower value so that WRFDA uses fewer minimization steps. You can also MPI with multiple processors to speed up the execution:

```
> mpirun –np 4 ./da_wrfvar.exe >& wrfda.log &
```

The "mpirun" command may be different depending on your machine. The output logs will be found in files named `rsl.out.####` and `rsl.error.####` for MPI runs.

Please note: If you utilize the lateral boundary conditions option (`var4d_lbc=true`), in addition to the analysis at the beginning of the time window (`wrfvar_output`), the analysis at the end of the time window will also be generated as `ana02`, which will be used in subsequent updating of boundary conditions before the forecast.

Radiance Data Assimilation in WRFDA

This section gives a brief description for various aspects related to radiance assimilation in WRFDA. Each aspect is described mainly from the viewpoint of usage, rather than more technical and scientific details, which will appear in a separate technical report and scientific paper. Namelist parameters controlling different aspects of radiance assimilation will be detailed in the following sections. It should be noted that this section does not cover general aspects of the assimilation process with WRFDA; these can be found in other sections of chapter 6 of this user's guide, or other WRFDA documentation.

a. Running WRFDA with radiances

In addition to the basic input files (`LANDUSE.TBL, fg, ob.ascii, be.dat`) mentioned in the "Running WRFDA" section, the following additional files are required for radiances: radiance data (typically in NCEP BUFR format), `radiance_info` files, `VARBC.in` (if you plan on using variational bias correction VARBC, as described in the section on bias correction), and RTM (CRTM or RTTOV) coefficient files.

Edit `namelist.input` (Pay special attention to `&wrfvar4, &wrfvar14, &wrfvar21, and &wrfvar22` for radiance-related options. A very basic namelist.input for running the radiance test case is provided in `WRFDA/var/test/radiance/namelist.input`)

```
> ln -sf $DAT_DIR/gdas1.t00z.1bamua.tm00.bufr_d   ./amsua.bufr
> ln -sf $DAT_DIR/gdas1.t00z.1bamub.tm00.bufr_d   ./amsub.bufr
> ln -sf $WRFDA_DIR/var/run/radiance_info  ./radiance_info  # (radi-
ance_info is a directory)
> ln -sf $WRFDA_DIR/var/run/VARBC.in  ./VARBC.in
(CRTM only)  > ln -sf $WRFDA_DIR/var/run/crtm_coeffs ./crtm_coeffs
#(crtm_coeffs is a directory)
(RTTOV only) > ln -sf your_RTTOV_path/rtcoef_rttov11/rttov7pred54L
./rttov_coeffs     #   (rttov_coeffs is a directory)
(HDF5 only) > ln –sf $WRFDA_DIR/var/run/leapsec.dat .
```

See the following sections for more details on each aspect of radiance assimilation.

Note: You can also specify the path of the "`crtm_coeffs`" directory via the namelist; see the following section for more details

b. Reading radiance data in WRFDA

Currently, the ingest interface for NCEP BUFR radiance data is implemented in WRFDA. The radiance data are available through NCEP's public ftp server (ftp://ftp.ncep.noaa.gov/pub/data/nccf/com/gfs/prod/gdas.${yyyymmddhh}) in near real-time (with a 6-hour delay) and can meet requirements for both research purposes and some real-time applications.

As of Version 3.9, WRFDA can read data from NOAA ATOVS instruments (HIRS, AMSU-A, AMSU-B and MHS), EOS Aqua instruments (AIRS, AMSU-A), DMSP instruments (SSMIS), METOP instruments (HIRS, AMSU-A, MHS, IASI), Meteosat instruments (SEVIRI), and JAXA GCOM-W1 instruments (AMSR2). Note that NCEP radiance BUFR files are separated by instrument names (i.e., one file for each type of instrument), and each file contains global radiance (generally converted to brightness temperature) within a 6-hour assimilation window, from multi-platforms. For running WRFDA, users need to rename NCEP corresponding BUFR files (table 1) to `hirs3.bufr` (including HIRS data from NOAA-15/16/17), `hirs4.bufr` (including HIRS data from NOAA-18/19, METOP-2), `amsua.bufr` (including AMSU-A data from NOAA-15/16/18/19, METOP-1 and -2), `amsub.bufr` (including AMSU-B data from NOAA-15/16/17), `mhs.bufr` (including MHS data from NOAA-18/19 and METOP-1 and -2), `airs.bufr` (including AIRS and AMSU-A data from EOS-AQUA) `ssmis.bufr` (SSMIS data from DMSP-16, AFWA provided) `iasi.bufr` (IASI data from METOP-1 and -2) and `seviri.bufr` (SEVIRI data from Meteosat 8-10) for WRFDA filename convention. Note that the `airs.bufr` file contains not only AIRS data but also AMSU-A, which is collocated with AIRS pixels (1 AMSU-A pixel collocated with 9 AIRS pixels). Users must place these files in the working directory where the WRFDA executable is run. It should also be mentioned that WRFDA reads these BUFR radiance files directly without the use of any separate pre-processing program. All processing of radiance data, such as quality control, thinning, bias correction, etc., is carried out within WRFDA. This is different from conventional observation assimilation, which requires a pre-processing package (OBSPROC) to generate WRFDA readable ASCII files. For reading the radiance BUFR files, WRFDA must be compiled with the NCEP BUFR library (see http://www.nco.ncep.noaa.gov/sib/decoders/BUFRLIB/).

Table 1: NCEP and WRFDA radiance BUFR file naming convention

NCEP BUFR file names	WRFDA naming convention
gdas1.t00z.airsev.tm00.bufr_d	airs.bufr
gdas1.t00z.1bamua.tm00.bufr_d	amsua.bufr
gdas1.t00z.1bamub.tm00.bufr_d	amsub.bufr
gdas1.t00z.atms.tm00.bufr_d	atms.bufr
gdas1.t00z.1bhrs3.tm00.bufr_d	hirs3.bufr
gdas1.t00z.1bhrs4.tm00.bufr_d	hirs4.bufr
gdas1.t00z.mtiasi.tm00.bufr_d	iasi.bufr
gdas1.t00z.1bmhs.tm00.bufr_d	mhs.bufr
gdas1.t00z.sevcsr.tm00.bufr_d	seviri.bufr

Namelist parameters are used to control the reading of corresponding BUFR files into WRFDA. For instance, USE_AMSUAOBS, USE_AMSUBOBS, USE_HIRS3OBS, USE_HIRS4OBS, USE_MHSOBS, USE_AIRSOBS, USE_EOS_AMSUAOBS, USE_SSMISOBS, USE_ATMSOBS, USE_IASIOBS, and USE_SEVIRIOBS control whether or not the respective file is read. These are logical parameters that are assigned to .FALSE. by default; therefore they must be set to .TRUE. to read the respective observation file. Also note that these parameters only control whether the data is read, not whether the data included in the files is to be assimilated. This is controlled by other namelist parameters explained in the next section.

Sources for downloading these and other data can be found on the WRFDA website: http://www2.mmm.ucar.edu/wrf/users/wrfda/download/free_data.html.

Other data formats

Most of the above paragraphs describe NCEP BUFR data, but some of the satellite data supported by WRFDA are in alternate formats. Level-1R AMSR2 data from the JAXA GCOM-W1 satellite are available in HDF5 format, which requires compiling WRFDA with HDF5 libraries, as described in the "Compile WRFDA and Libraries" section.

HDF5 file naming conventions are different than those for BUFR files. For AMSR2 data, WRFDA will look for two data files: L1SGRTBR.h5 (brightness temperature) and L2SGCLWLD.h5 (cloud liquid water). Only the brightness temperature file is mandatory (you will also need to copy or link the "leapsec.dat" file from WRFDA/var/run). If you have multiple data files for your assimilation window, you should name them L1SGRTBR-01.h5, L1SGRTBR-02.h5, etc. and L2SGCLWLD-01.h5, L2SGCLWLD-02.h5, etc.

c. Radiative Transfer Models

The core component for direct radiance assimilation is to incorporate a radiative transfer model (RTM) into the WRFDA system as one part of observation operators. Two widely used RTMs in the NWP community, RTTOV (developed by ECMWF and UKMET in Europe), and CRTM (developed by the Joint Center for Satellite Data Assimilation (JCSDA) in US), are already implemented in the WRFDA system with a flexible and consistent user interface. WRFDA is designed to be able to compile with or without RTTOV by the definition of the "RTTOV" environment variable at compile time (see the "Compile WRFDA and Libraries" section). At runtime the user must select which RTM they intend to use via the namelist parameter RTM_OPTION (1 for RTTOV, the default, and 2 for CRTM).

Both RTMs can calculate radiances for almost all available instruments aboard the various satellite platforms in orbit. An important feature of the WRFDA design is that all data structures related to radiance assimilation are dynamically allocated during running time, according to a simple namelist setup. The instruments to be assimilated are controlled at

run-time by four integer namelist parameters: RTMINIT_NSENSOR (the total number of sensors to be assimilated), RTMINIT_PLATFORM (the platforms IDs array to be assimilated with dimension RTMINIT_NSENSOR, e.g., 1 for NOAA, 9 for EOS, 10 for METOP and 2 for DMSP), RTMINIT_SATID (satellite IDs array) and RTMINIT_SENSOR (sensor IDs array, e.g., 0 for HIRS, 3 for AMSU-A, 4 for AMSU-B, etc.). The full list of instrument triplets can be found in the table below:

Instrument	Satellite	Format	(PLATFORM, SATID, SENSOR)
AIRS	EOS-Aqua	BUFR	(9,2,11)
AMSR2	GCOM-W1	HDF5	(29,1,63)
AMSU-A	EOS-Aqua	BUFR	(9,2,3)
AMSU-A	METOP-A	BUFR	(10,2,3)
AMSU-A	NOAA 15–19	BUFR	(1,15–19,3)
AMSU-B	NOAA 15–17	BUFR	(1,15–17,4)
ATMS	Suomi-NPP	BUFR	(17,0,19)
HIRS-3	NOAA 15–17	BUFR	(1,15–17,0)
HIRS-4	METOP-A	BUFR	(10,2,0)
HIRS-4	NOAA 18–19	BUFR	(1,18–19,0)
IASI	METOP-A	BUFR	(10,2,16)
MHS	METOP-A	BUFR	(10,2,15)
MHS	NOAA 18–19	BUFR	(1,18–19,15)
MWHS	FY-3A–FY-3B	Binary	(23,1–2,41)
MWTS	FY-3A–FY-3B	Binary	(23,1–2,40)
SEVIRI	Meteosat 8–10	BUFR	(12,1–3,21)
SSMIS	DMSP 16–18	BUFR	(2,16–18,10)

Here's an example of this section of the namelist for a user assimilating IASI observations from METOP-A, utilizing RTTOV as their RTM:

```
&wrfvar14
 rtminit_nsensor = 1
 rtminit_platform = 10,
 rtminit_satid = 2,
 rtminit_sensor = 16,
 rtm_option = 1,
/
```

Here's another example of this section of the namelist, this time for a user assimilating AMSU-A from NOAA 18–19 and EOS-Aqua, MHS from NOAA 18–19, and AIRS from EOS-Aqua, utilizing CRTM as their RTM:

```
&wrfvar14
 rtminit_nsensor = 6
 rtminit_platform = 1, 1, 9, 1, 1, 9
 rtminit_satid = 18, 19, 2, 18, 19, 2
 rtminit_sensor = 3, 3, 3, 15, 15, 11
 rtm_option = 2,
/
```

The instrument triplets (platform, satellite, and sensor ID) in the namelist can be ranked in any order. More detail about the convention of instrument triples can be found in tables 2 and 3 in the RTTOV v11 User's Guide (http://nwpsaf.eu/deliverables/rtm/docs_rttov11/users_guide_11_v1.4.pdf)

CRTM uses a different instrument-naming method, however, a conversion routine inside WRFDA is implemented such that the user interface remains the same for RTTOV and CRTM, using the same instrument triplet for both.

When running WRFDA with radiance assimilation switched on, a set of RTM coefficient files need to be loaded. For the RTTOV option, RTTOV coefficient files are to be copied or linked to a sub-directory `rttov_coeffs/` under the working directory. For the CRTM option, CRTM coefficient files are to be copied or linked to a sub-directory `crtm_coeffs/` under the working directory, or the location of this directory can be specified in the namelist:

```
&wrfvar14
 crtm_coef_path = WRFDA/var/run/crtm_coeffs  (Can be a relative or absolute path)
/
```

Only coefficients for instruments listed in the namelist are needed. Potentially WRFDA can assimilate all sensors as long as the corresponding coefficient files are provided. In addition, necessary developments on the corresponding data interface, quality control, and bias correction are important to make radiance data assimilate properly; however, a modular design of radiance relevant routines already facilitates the addition of more instruments in WRFDA.

The RTTOV package is not distributed with WRFDA, due to licensing restrictions. Users need to follow the instructions at http://nwpsaf.eu/site/software/rttov/ to download the RTTOV source code and supplement coefficient files and the emissivity atlas dataset. Only RTTOV v11 (11.1—11.3) can be used in WRFDA version 3.9, so if you have an older version of RTTOV you must upgrade. RTTOV v12 is not yet supported.

As mentioned in a previous paragraph, the CRTM package is distributed with WRFDA, and is located in `$WRFDA_DIR/var/external/crtm_2.2.3`. The CRTM code in WRFDA is the same as the source code that users can download from ftp://ftp.emc.ncep.noaa.gov/jcsda/CRTM, with only minor modifications (mainly for ease of compilation).

To use one or both of the above radiative transfer models, you will have to set the appropriate environment variable(s) at compile time. See the section "Compile WRFDA and Libraries" for details.

d. Channel Selection

Channel selection in WRFDA is controlled by radiance 'info' files, located in the sub-

directory `radiance_info`, under the working directory. These files are separated by satellites and sensors; e.g., `noaa-15-amsua.info`, `noaa-16-amsub.info`, `dmsp-16-ssmis.info` and so on. An example of 5 channels from `noaa-15-amsub.info` is shown below. The fourth column is used by WRFDA to control when to use a corresponding channel. Channels with the value "-1" in the fourth column indicate that the channel is "not assimilated," while the value "1" means "assimilated." The sixth column is used by WRFDA to set the observation error for each channel. Other columns are not used by WRFDA. It should be mentioned that these error values might not necessarily be optimal for your applications. It is the user's responsibility to obtain the optimal error statistics for his/her own applications.

```
Sensor channel  IR/MW  use  idum   varch    polarization(0:vertical;1:horizontal)

415    1        1      -1   0      0.5500000000E+01   0.0000000000E+00
415    2        1      -1   0      0.3750000000E+01   0.0000000000E+00
415    3        1       1   0      0.3500000000E+01   0.0000000000E+00
415    4        1      -1   0      0.3200000000E+01   0.0000000000E+00
415    5        1       1   0      0.2500000000E+01   0.0000000000E+00
```

e. Bias Correction

Satellite radiance is generally considered to be biased with respect to a reference (e.g., background or analysis field in NWP assimilation) due to systematic error of the observation itself, the reference field, and RTM. Bias correction is a necessary step prior to assimilating radiance data. There are two ways of performing bias correction in WRFDA. One is based on the Harris and Kelly (2001) method, and is carried out using a set of coefficient files pre-calculated with an off-line statistics package, which was applied to a training dataset for a month-long period. The other is Variational Bias Correction (VarBC). Only VarBC is introduced here, and recommended for users because of its relative simplicity in usage.

Variational Bias Correction

To use VarBC, set the namelist option `USE_VARBC` to TRUE and have the `VARBC.in` file in the working directory. `VARBC.in` is a VarBC setup file in ASCII format. A template is provided with the WRFDA package (`$WRFDA_DIR/var/run/VARBC.in`).

All VarBC input is passed through a single ASCII file called `VARBC.in`. Once WRFDA has run with the VarBC option switched on, it will produce a `VARBC.out` file in a similar ASCII format. This output file will then be used as the input file for the next assimilation cycle.

VarBC Coldstart

Coldstarting means starting the VarBC from scratch; i.e. when you do not know the values of the bias parameters.

The Coldstart is a routine in WRFDA. The bias predictor statistics (mean and standard deviation) are computed automatically and will be used to normalize the bias parameters.

All coldstart bias parameters are set to zero, except the first bias parameter (= simple offset), which is set to the mode (=peak) of the distribution of the (uncorrected) innovations for the given channel.

A threshold of a number of observations can be set through the namelist option VARBC_NOBSMIN (default = 10), under which it is considered that not enough observations are present to keep the Coldstart values (i.e. bias predictor statistics and bias parameter values) for the next cycle. In this case, the next cycle will do another Coldstart.

Background constraint for bias parameters

The background constraint controls the inertia you want to impose on the predictors (i.e. the smoothing in the predictor time series). It corresponds to an extra term in the WRFDA cost function.

It is defined in the namelist via the option VARBC_NBGERR; the default value is 5000. This number is related to a number of observations; the bigger the number, the more inertia constraint. If these numbers are set to zero, the predictors can evolve without any constraint.

Scaling factor

The VarBC uses a specific preconditioning, which can be scaled through the namelist option VARBC_FACTOR (default = 1.0).

Offline bias correction

The analysis of the VarBC parameters can be performed "offline" ; i.e. independently from the main WRFDA analysis. No extra code is needed. Just set the following MAX_VERT_VAR* namelist variables to be 0, which will disable the standard control variable and only keep the VarBC control variable.

```
MAX_VERT_VAR1=0.0
MAX_VERT_VAR2=0.0
MAX_VERT_VAR3=0.0
MAX_VERT_VAR4=0.0
MAX_VERT_VAR5=0.0
```

Freeze VarBC

In certain circumstances, you might want to keep the VarBC bias parameters constant in time (="frozen"). In this case, the bias correction is read and applied to the innovations, but it is not updated during the minimization. This can easily be achieved by setting the namelist options:

```
USE_VARBC=false
FREEZE_VARBC=true
```

Passive observations

Some observations are useful for preprocessing (e.g. Quality Control, Cloud detection) but you might not want to assimilate them. If you still need to estimate their bias correction, these observations need to go through the VarBC code in the minimization. For this purpose, the VarBC uses a separate threshold on the QC values, called "qc_varbc_bad". This threshold is currently set to the same value as "qc_bad", but can easily be changed to any ad hoc value.

f. Other radiance assimilation options

RAD_MONITORING (30)
Integer array of dimension RTMINIT_NSENSOR, 0 for assimilating mode, 1 for monitoring mode (only calculates innovation).

THINNING
Logical, TRUE will perform thinning on radiance data.

THINNING_MESH (30)
Real array with dimension RTMINIT_NSENSOR, values indicate thinning mesh (in km) for different sensors.

QC_RAD
Logical, controls if quality control is performed, always set to TRUE.

WRITE_IV_RAD_ASCII
Logical, controls whether to output observation-minus-background (O-B) files, which are in ASCII format, and separated by sensors and processors.

WRITE_OA_RAD_ASCII
Logical, controls whether to output observation-minus-analysis (O-A) files (including also O-B information), which are in ASCII format, and separated by sensors and processors.

USE_ERROR_FACTOR_RAD
Logical, controls use of a radiance error tuning factor file (`radiance_error.factor`) which is created with empirical values, or generated using a variational tuning method (Desroziers and Ivanov, 2001).

ONLY_SEA_RAD
Logical, controls whether only assimilating radiance over water.

TIME_WINDOW_MIN
String, e.g., "2007-08-15_03:00:00.0000", start time of assimilation time window

TIME_WINDOW_MAX
String, e.g., "2007-08-15_09:00:00.0000", end time of assimilation time window

USE_ANTCORR (30)
Logical array with dimension RTMINIT_NSENSOR, controls if performing Antenna Correction in CRTM.

USE_CLDDET_MMR
Logical, controls whether using the MMR scheme to conduct cloud detection for infrared radiance.

USE_CLDDET_ECMWF
Logical, controls whether using the ECMWF scheme to conduct cloud detection for infrared radiance.

AIRS_WARMEST_FOV
Logical, controls whether using the observation brightness temperature for AIRS Window channel #914 as criterion for GSI thinning.

USE_CRTM_KMATRIX
Logical, controls whether using the CRTM K matrix rather than calling CRTM TL and AD routines for gradient calculation.

CRTM_CLOUD
Logical, include cloud effects in CRTM calculations.
Further information on this capability can be found in the following publication:

Chun Yang, Zhiquan Liu, Jamie Bresch, Syed R. H. Rizvi, Xiang-Yu Huang and Jinzhong Min, 2016: AMSR2 all-sky radiance assimilation and its impact on the analysis and forecast of Hurricane Sandy with a limited-area data assimilation system. *Tellus A*, **68**, 30917, doi:10.3402/tellusa.v68.30917.

USE_RTTOV_KMATRIX
Logical, controls whether using the RTTOV K matrix rather than calling RTTOV TL and AD routines for gradient calculation.

RTTOV_EMIS_ATLAS_IR
Integer, controls the use of the IR emissivity atlas.
Emissivity atlas data (should be downloaded separately from the RTTOV web site) need to be copied or linked under a sub-directory of the working directory (`emis_data`) if RTTOV_EMIS_ATLAS_IR is set to 1.

RTTOV_EMIS_ATLAS_MW
Integer, controls the use of the MW emissivity atlas.
Emissivity atlas data (should be downloaded separately from the RTTOV web site) need to be copied or linked under a sub-directory of the working directory (`emis_data`) if RTTOV_EMIS_ATLAS_MW is set to 1 or 2.

g. Diagnostics and Monitoring

Monitoring capability within WRFDA

Run WRFDA with the `rad_monitoring` namelist parameter in record `wrfvar14` in `namelist.input`.

0 means assimilating mode. Innovations (O minus B) are calculated and data are used in minimization.
1 means monitoring mode: innovations are calculated for diagnostics and monitoring. Data are not used in minimization.

The value of `rad_monitoring` should correspond to the value of `rtminit_nsensor`. If `rad_monitoring` is not set, then the default value of 0 will be used for all sensors.

Outputting radiance diagnostics from WRFDA

Run WRFDA with the following namelist options in record `wrfvar14` in `namelist.input`.

`write_iv_rad_ascii`
Logical. TRUE to write out (observation-background, etc.) diagnostics information in plain-text files with the prefix 'inv,' followed by the instrument name and the processor id. For example, 01_inv_noaa-17-amsub.0000 (01 is outerloop index, 0000 is processor index)

`write_oa_rad_ascii`
Logical. TRUE to write out (observation-background, observation-analysis, etc.) diagnostics information in plain-text files with the prefix 'oma,' followed by the instrument name and the processor id. For example, `01_oma_noaa-18-mhs.0001`

Each processor writes out the information for one instrument in one file in the WRFDA working directory.

Radiance diagnostics data processing

One of the 44 executables compiled as part of the WRFDA system is the file `da_rad_diags.exe`. This program can be used to collect the `01_inv*` or `01_oma*` files and write them out in netCDF format (one instrument in one file with prefix `diags` followed by the instrument name, analysis date, and the suffix `.nc`) for eas-

ier data viewing, handling and plotting with netCDF utilities and NCL scripts. See `WRFDA/var/da/da_monitor/README` for information on how to use this program.

Radiance diagnostics plotting

Two NCL scripts (available as part of the WRFDA Tools package, which can be downloaded at http://www2.mmm.ucar.edu/wrf/users/wrfda/download/tools.html) are used for plotting: `$TOOLS_DIR/var/graphics/ncl/plot_rad_diags.ncl` and `$TOOLS_DIR/var/graphics/ncl/advance_cymdh.ncl`. The NCL scripts can be run from a shell script, or run alone with an interactive `ncl` command (the NCL script and set the plot options must be edited, and the path of `advance_cymdh.ncl`, a date-advancing script loaded in the main NCL plotting script, may need to be modified).

Steps (3) and (4) can be done by running a single ksh script (also in the WRFDA Tools package: `$TOOLS_DIR/var/scripts/da_rad_diags.ksh`) with proper settings. In addition to the settings of directories and what instruments to plot, there are some useful plotting options, explained below.

`setenv OUT_TYPE=ncgm`	ncgm or pdf pdf will be much slower than ncgm and generate huge output if plots are not split. But pdf has higher resolution than ncgm.
`setenv PLOT_STATS_ONLY=false`	true or false true: only statistics of OMB/OMA vs channels and OMB/OMA vs dates will be plotted. false: data coverage, scatter plots (before and after bias correction), histograms (before and after bias correction), and statistics will be plotted.
`setenv PLOT_OPT=sea_only`	all, sea_only, land_only
`setenv PLOT_QCED=false`	true or false true: plot only quality-controlled data false: plot all data
`setenv PLOT_HISTO=false`	true or false: switch for histogram plots
`setenv PLOT_SCATT=true`	true or false: switch for scatter plots
`setenv PLOT_EMISS=false`	true or false: switch for emissivity plots
`setenv PLOT_SPLIT=false`	true or false true: one frame in each file false: all frames in one file
`setenv PLOT_CLOUDY=false`	true or false true: plot cloudy data. Cloudy data to be plotted are defined by PLOT_CLOUDY_OPT (si or clwp), CLWP_VALUE, SI_VALUE settings.
`setenv PLOT_CLOUDY_OPT=si`	si or clwp clwp: cloud liquid water path from model si: scatter index from obs, for amsua, amsub and

	mhs only
`setenv CLWP_VALUE=0.2`	only plot points with clwp >= clwp_value (when clwp_value > 0) clwp > clwp_value (when clwp_value = 0)
`setenv SI_VALUE=3.0`	

Evolution of VarBC parameters

NCL scripts (also in the WRFDA Tools package: `$TOOLS_DIR/var/graphics/ncl/plot_rad_varbc_param.ncl` and `$TOOLS_DIR/var/graphics/ncl/advance_cymdh.ncl`) are used for plotting the evolution of VarBC parameters.

Radar Data Assimilation in WRFDA

WRFDA has the ability to assimilate Doppler radar data, either for 3DVAR or 4DVAR assimilation. Both Doppler velocity and reflectivity can be assimilated, and there are several different reflectivity operator options available.

a. Preparing radar observations

Radar observations are read by WRFDA in a text-based format. This format is described in the radar tutorial presentation available on the WRFDA website (http://www2.mmm.ucar.edu/wrf/users/wrfda/Tutorials/2015_Aug/docs/WRFDA_Radar.pdf). Because radar data comes in a variety of different formats, it is the user's responsibility to convert their data into this format. For 3DVAR, these observations should be placed in a file named `ob.radar`. For 4DVAR, they should be placed in files named `ob01.radar`, `ob02.radar`, etc., with one observation file per time slot, as described in the earlier 4DVAR section.

b. Running WRFDA for radar assimilation

Once your observations are prepared, you can run WRFDA the same as you would normally (see the previous sections on how to run either 3DVAR or 4DVAR). For guidance, there is an example 3DVAR case available for download at http://www2.mmm.ucar.edu/wrf/users/wrfda/download/V38/wrfda_radar_testdata.tar.gz.

Edit `namelist.input` and pay special attention to the radar options listed below. Further details on some of these options can be found in the following sections

`&wrfvar4`	
`use_radarobs`	true: radar observation files will be read by WRFDA
`use_radar_rv`	true: Assimilate radar velocity observations
`use_radar_rf`	true: Assimilate radar reflectivity using total mixing ratio

use_radar_rhv	true: Assimilate retrieved hydrometeors (qr, qs, qg) from radar reflectivity
use_radar_rqv	true: Assimilate estimated humidity (qv) from radar reflectivity

/

…

&wrfvar7

cloud_cv_options	0 (default): no hydrometeor control variables 1: use total water (water vapor+cloud liquid water+rain water) control variable 3: use individual hydrometeor control variables (use_radar_rhv = true only)
use_cv_w	false (default): use ω (vertical velocity with respect to pressure) control variable true: use W (vertical velocity with respect to height) control variable. For cloud_cv_options = 3 only

/

…

&radar_da

radar_non_precip_opt	0 (default): no null-echo assimilation 1: KNU null-echo scheme
radar_non_precip_rf	Reflectivity flag value (dBz) in observation file indicating non-precipitation echoes (default: -999.99)

The following options apply for use_radar_rqv only:

radar_non_precip_rh_w	RH (%) with respect to water for non-precip retrieved Q_vapor (rqv) (default: 95)
radar_non_precip_rh_i	RH (%) with respect to ice for non-precip retrieved rqv (default: 85)
cloudbase_calc_opt	Option for calculating cloud-base height: below this height retrieved humidity will not be assimilated for the use_radar_rqv option 0: fixed value of 1500 meters 1 (default): KNU scheme 2: NCAR scheme
radar_saturated_rf	rf value (dBz) used to indicate precipitation for rqv (default 25.0)
radar_rqv_thresh1	rf value (dBz) used to scale down retrieved rqv (default 40.0)
radar_rqv_thresh2	rf value (dBz) used to scale down retrieved rqv (default 50.0)
radar_rqv_rh1	RH (%) for radar_saturated_rf < rf < radar_rqv_thresh1 (default 85)
radar_rqv_rh2	RH (%) for radar_rqv_thresh1 < rf < radar_rqv_thresh2 (default 95)
radar_rqv_h_lbound	height (meters) lower bound for assimilating rqv (default -999.0)
radar_rqv_h_ubound	height (meters) upper bound for assimilating rqv (default -999.0) NOTE: **both** namelist settings radar_rqv_h_lbound and radar_rqv_h_ubound must be set and greater than zero for **either** to have an impact

c. Reflectivity assimilation options

There are two different options for assimilating radar reflectivity data. The first (use_radar_rf) directly assimilates the observed reflectivity using a reflectivity operator to convert the model rainwater mixing ratio into reflectivity and the total mixing ratio as the control variable, as described in Xiao and Sun, 2007 (http://journals.ametsoc.org/doi/full/10.1175/MWR3471.1); this is the only option available in WRFDA prior to version 3.7. For this option, the hydrometeors are partitioned using a warm rain scheme described in the above reference.

The second (use_radar_rhv) is a scheme described in Wang et al, 2013

(http://journals.ametsoc.org/doi/full/10.1175/JAMC-D-12-0120.1), which assimilates rainwater mixing ratio that is estimated from radar reflectivity, described as an "indirect method" in the paper. This second option also includes an option (`use_radar_rqv`) that allows the assimilation of in-cloud humidity estimated from reflectivity using a method described in Wang et al, 2013. It also includes the assimilation of snow and graupel converted from reflectivity using formulas as described in Gao and Stensrud, 2012 (http://journals.ametsoc.org/doi/abs/10.1175/JAS-D-11-0162.1).

There are many tunable parameters that go along with the `use_radar_rqv` option, which retrieves a value of cloud humidity for assimilation. There are three possible options for cloud base height (below which cloud humidity will not be assimilated) as specified by cloudbase_calc_opt (0 is the previous default behavior and is not recommended). There are also a few thresholds for scaling the calculated cloud humidity by certain amounts, as well as an upper and lower altitude bound for assimilating cloud humidity.

d. Null-echo assimilation options

New for version 3.9, WRFDA includes the capability to assimilate null-echo observations: reflectivity values with a set flag value will be assimilated as non-precipitation points. This can be an important radar assimilation technique, as normally you can not remove precipitation from your analysis without using the retrieved water vapor option (`use_radar_rqv`). This capability was developed by Ki-Hong Min from Kyungpook National University, South Korea (WRF Workshop abstract: http://www2.mmm.ucar.edu/wrf/users/workshops/WS2016/short_abstracts/P78.pdf).

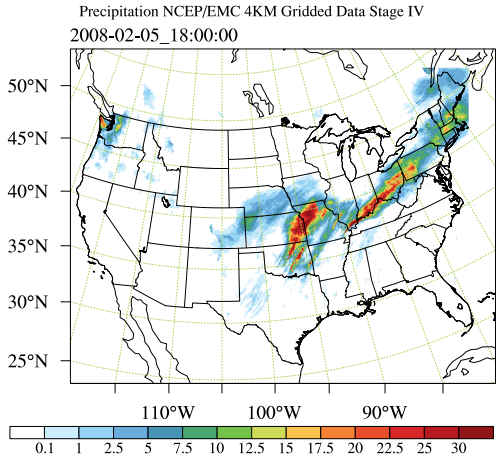
Precipitation Data Assimilation in WRFDA 4DVAR

The assimilation of precipitation observations in WRFDA 4D-Var is described in this section. Currently, WRFPLUS has already included the adjoint and tangent linear codes of large-scale condensation and cumulus scheme, therefore precipitation data can be assimilated directly in 4D-Var. Users who are interested in the scientific detail of 4D-Var assimilation of precipitation should refer to related scientific papers, as this section is only a basic guide to running WRFDA Precipitation Assimilation. This section instructs users on data processing, namelist variable settings, and how to run WRFDA 4D-Var with precipitation observations.

a. Preparing precipitation observations

WRFDA 4D-Var can assimilate NCEP Stage IV radar and gauge precipitation data. NCEP Stage IV archived data are available on the NCAR CODIAC web page at: http://data.eol.ucar.edu/codiac/dss/id=21.093 (for more information, please see the NCEP Stage IV Q&A Web page at http://www.emc.ncep.noaa.gov/mmb/ylin/pcpanl/QandA/). The original precipitation data are at 4-km resolution on a polar-stereographic grid. Hourly, 6-hourly and

24-hourly analyses are available. The following image shows the accumulated 6-h precipitation for the tutorial case.



It should be mentioned that the NCEP Stage IV archived data is in GRIB1 format and it cannot be ingested into the WRFDA directly. A tool "precip_converter" is provided to reformat GRIB1 observations into the WRFDA-readable ASCII format. It can be downloaded from the WRFDA users page at http://www2.mmm.ucar.edu/wrf/users/wrfda/download/precip_converter.tar.gz. The NCEP GRIB libraries, w3 and g2 are required to compile the precip_converter utility. These libraries are available for download from NCEP at http://www.nco.ncep.noaa.gov/pmb/codes/GRIB2/. The output file to the precip_converter utility is named in the format `ob.rain.yyyymmddhh.xxh`; The '`yyyymmddhh`' in the file name is the ending hour of the accumulation period, and '`xx`' (=01,06 or 24) is the accumulating time period.

For users wishing to use their own observations instead of NCEP Stage IV, it is the user's responsibility to write a Fortran main program and call subroutine writerainobs (in write_rainobs.f90) to generate their own precipitation data. For more information please refer to the README file in the `precip_converter` directory.

b. Running WRFDA with precipitation observations

WRFDA 4D-Var is able to assimilate hourly, 3-hourly and 6-hourly precipitation data. According to experiments and related scientific papers, 6-hour precipitation accumulations are the ideal observations to be assimilated, as this leads to better results than directly assimilating hourly data.

The tutorial example is for assimilating 6-hour accumulated precipitation. In your working directory, link all the necessary files as follows,

```
> ln -fs $WRFDA_DIR/var/da/da_wrfvar.exe .
> ln -fs $DAT_DIR/rc/2008020512/wrfinput_d01 .
```

```
> ln -fs $DAT_DIR/rc/2008020512/wrfbdy_d01 .
> ln -fs $DAT_DIR/rc/2008020518/wrfinput_d01 fg02 (only necessary
for var4d_lbc=true)
> ln -fs wrfinput_d01 fg
> ln -fs $DAT_DIR/be/be.dat .
> ln -fs $WRFDA_DIR/run/LANDUSE.TBL .
> ln -fs $WRFDA_DIR/run/RRTM_DATA_DBL ./RRTM_DATA
> ln -fs $DAT_DIR/ob/2008020518/ob.rain.2008020518.06h ob07.rain
```

Note: The reason why the observation `ob.rain.2008020518.06h` is linked as `ob07.rain` will be explained in section c.

Edit `namelist.input` (you can start with the same namelist as for the 4dvar tutorial case) and pay special attention to `&wrfvar1` and `&wrfvar4` for precipitation-related options.

`&wrfvar1`	
`var4d`	true: Run WRFDA for 4DVAR. This is the only supported option for precipitation assimilation (default value is false)
`var4d_bin_rain`	length (seconds) of the precipitation assimilation window (default 3600). This can be different from `var4d_bin`, which controls the assimilation window for all other observation types
/	
…	
`&wrfvar4`	
`use_rainobs`	true (default) : read precipitation data
`thin_rainobs`	true (default): thin precipitation observations
`thin_mesh_conv`	Size of thinning mesh (in km) for non-radiance observations, including precipitation observations (default value 20.0)
/	

Then, run 4D-Var in serial or parallel mode,

```
>./da_wrfvar.exe >& wrfda.log
```

c. Properly linking observation files

In section b, `ob.rain.2008020518.06h` is linked as `ob07.rain.` The number `07` is assigned according to the following rule:

```
x=i*(var4d_bin_rain/var4d_bin)+1,
```

Here, `i` is the sequence number of the observation.
for `x<10`, the observation file should be renamed as `ob0x.rain`;
for `x>=10`, it should be renamed as `obx.rain`

In the example above, 6-hour accumulated precipitation data is assimilated in 6-hour time window. In the namelist, values should be set at `var4d_bin=3600` and `var4d_bin_rain=21600`, and there is one observation file (i.e., `i=1`) in the time window, Thus the value of `x` is 7. The file `ob.rain.2008020518.06h` should be renamed as `ob07.rain.`

Let us take another example for how to rename observation files for 3-hourly precipitation data in 6-hour time window. The sample namelist is as follows,

```
&wrfvar1
var4d=true,
var4d_lbc=true,
var4d_bin=3600,
var4d_bin_rain=10800,
……
/
```

There are two observation files, `ob.rain.2008020515.03h` and `ob.rain.2008020518.03h`. For the first file (`i=1`) `ob.rain.2008020515.03h`, it should be renamed as `ob04.rain`,and the second file (`i=2`) renamed as `ob07.rain`.

Updating WRF Boundary Conditions

a. Lateral boundary conditions

When using WRFDA output to run a WRF forecast, it is essential that you update the WRF lateral boundary conditions (contained in the file `wrfbdy_01`, created by `real.exe`) to match your new analysis. Domain-1 (`wrfbdy_d01`) must be updated to be consistent with the new WRFDA initial condition (analysis). This is absolutely essential. For nested domains, domain-2, domain-3, etc., the lateral boundary conditions are provided by their parent domains, so no lateral boundary update is needed for these domains. The update procedure is performed by the WRFDA utility called `da_update_bc.exe`, and after compilation can be found in `$WRFDA_DIR/var/build`.

`da_update_bc.exe` requires three input files: the WRFDA analysis (`wrfvar_output`), the wrfbdy file from `real.exe`, and a namelist file: `parame.in`. To run `da_update_bc.exe` to update lateral boundary conditions, follow the steps below:

```
> cd $WRFDA_DIR/var/test/update_bc
> cp –p $DAT_DIR/rc/2008020512/wrfbdy_d01 .
```

(IMPORTANT: make a copy of `wrfbdy_d01`, as the `wrf_bdy_file` will be overwritten by `da_update_bc.exe`)

```
> vi parame.in
&control_param
 da_file            = '../tutorial/wrfvar_output'
 wrf_bdy_file       = './wrfbdy_d01'
 domain_id          = 1
 debug              = .true.
 update_lateral_bdy = .true.
 update_low_bdy     = .false.
 update_lsm         = .false.
 iswater            = 16
 var4d_lbc          = .false.
/
```

```
> ln -sf $WRFDA_DIR/var/da/da_update_bc.exe .
> ./da_update_bc.exe
```

At this stage, you should have the files `wrfvar_output` and `wrfbdy_d01` in your WRFDA working directory. They are the WRFDA updated initial and boundary condition files for any subsequent WRF model runs. To use, link a copy of `wrfvar_output` and `wrfbdy_d01` to `wrfinput_d01` and `wrfbdy_d01`, respectively, in your WRF working directory.

You should also see two additional output files: fort.11 and fort.12. These contain information about the changes made to wrfbdy_01.

b. Cycling with WRF and WRFDA (warm-start)

In cycling mode (warm-start), the lower boundary in the first guess file also needs to be updated based on the information from the wrfinput file, generated by WPS/real.exe at analysis time. If in cycling mode (especially if you are doing radiance data assimilation and there are SEA ICE or SNOW in your domain), it is recommended that before you run WRFDA, you run da_update_bc.exe with the following namelist options:

```
da_file            = './fg'
wrf_input          = './wrfinput_d01'
update_lateral_bdy = .false.
update_low_bdy     = .true.
iswater            = 16
```

Note: "`iswater`" (water point index) is 16 for USGS LANDUSE and 17 for MODIS LANDUSE.

This creates a lower-boundary updated first guess (`da_file` will be overwritten by `da_update_bc` with updated lower boundary conditions from `wrf_input`). Then, after WRFDA has finished, run `da_update_bc.exe` again with the following namelist options:

```
da_file            = './wrfvar_output'
wrf_bdy_file       = './wrfbdy_d01'
update_lateral_bdy = .true.
update_low_bdy     = .false.
```

This updates the lateral boundary conditions (`wrf_bdy_file` will be overwritten by `da_update_bc` with lateral boundary conditions from `da_file`).

As mentioned previously, lateral boundary conditions for child domains (wrfinput_02, wrfinput_03, etc.) come from the respective parent domains, so update_bc is not necessary after running WRFDA. However, in a cycling procedure, the lower boundaries in each of the nested domains' WRFDA analysis files still need to be updated. In these cases, you must set the namelist variable, `domain_id` > 1 (default is 1 for domain-1) and provide the appropriate wrfinput file (`wrf_input = './wrfinput_d02'` for domain 2, for instance).

c. WRFDA 4DVAR with lateral boundary conditions as control variables

If you activate the `var4d_lbc` option in a WRF 4D-Var run, in addition to the above-mentioned files you will also need the `ana02` file from the WRFDA working directory. In `parame.in`, set `var4d_lbc` to TRUE and use "`da_file_02`" to point to the location of the `ana02` file.

```
da_file_02          = './ana02'
var4d_lbc           = .true.
```

Background Error and running GEN_BE

Quick-start guide: running WRFDA with different BE options

To run WRFDA with the generic CV3 option, simply link the provided be.dat file in the var/run directory:

```
> cp –p $WRFDA_DIR/var/run/be.dat.cv3 $WORK_DIR/be.dat
```

To run WRFDA with any other option, you will have to run GEN_BE first. GEN_BE takes a series of forecasts initialized at different times, and compares the forecasts that are valid at the same time (e.g., compare a 24-hour forecast initialized at 00Z with a 12-hour forecast initialized at 12Z) to get an estimate of the background error statistics.

You will use the wrapper script `gen_be_wrapper.ksh` to run GEN_BE. For instructions on how to set up your experiment to run GEN_BE, reference the test case as described in the section "Domain-specific background error options: Running GEN_BE" below.

Background error options in WRFDA

Users have four choices to define the background error covariance (BE). We call them CV3, CV5, CV6, and CV7. Each of these has different properties, which are outlined in the table below:

CV option	*Data source*	*Control variables*	*cv_options =*
CV3	Provided be.dat file	ψ, χ_u, T_u, q, $P_{s,u}$	3
CV5	GEN_BE	ψ, χ_u, T_u, RH_s, $P_{s,u}$	5
CV6	GEN_BE	ψ, χ_u, T_u, $RH_{s,u}$, $P_{s,u}$	6
CV7	GEN_BE	u, v, T, RH_s, P_s	7

With CV3, the control variables are in physical space while with CV5, CV6, and CV7, the control variables are in eigenvector space. The major difference between these two

kinds of BE is the vertical covariance; CV3 uses the vertical recursive filter to model the vertical covariance but the others use an empirical orthogonal function (EOF) to represent the vertical covariance. The recursive filters to model the horizontal covariance are also different with these BEs. We have not conducted the systematic comparison of the analyses based on these BEs. However, CV3 (a BE file provided with our WRFDA system) is a global BE and can be used for any regional domain, while CV5, CV6, and CV7 BE's are domain-dependent, and so should be generated based on forecast or ensemble data from the same domain.

As summarized in the above table, CV5, CV6, and CV7 differ in the control variables they use. CV5 utilizes streamfunction (ψ), unbalanced velocity potential (χ_u), unbalanced temperature (T_u), pseudo relative humidity (RH_s), and unbalanced surface pressure ($P_{s,u}$). The pseudo relative humidity is defined as $Q/Q_{b,s}$, where $Q_{b,s}$ is the saturated specific humidity from the background field. For CV6 the moisture control variable is the unbalanced portion of the pseudo relative humidity ($RH_{s,u}$). Additionally, CV6 introduces six additional correlation coefficients in the definition of the balanced part of analysis control variables. See the section GEN_BE for CV6 for more details on this option. Finally, CV7 uses a different set of control variables: u, v, temperature, pseudo relative humidity (RH_s), and surface pressure (P_s).

Generic BE option: CV3

CV3 is the NCEP background error covariance. It is estimated in grid space by what has become known as the NMC method (Parrish and Derber 1992) . The statistics are estimated with the differences of 24 and 48-hour GFS forecasts with T170 resolution, valid at the same time for 357 cases, distributed over a period of one year. Both the amplitudes and the scales of the background error have to be tuned to represent the forecast error in the estimated fields. The statistics that project multivariate relations among variables are also derived from the NMC method.

The variance of each variable, and the variance of its second derivative, are used to estimate its horizontal scales. For example, the horizontal scales of the stream function can be estimated from the variance of the vorticity and stream function.

The vertical scales are estimated with the vertical correlation of each variable. A table is built to cover the range of vertical scales for the variables. The table is then used to find the scales in vertical grid units. The filter profile and the vertical correlation are fitted locally. The scale of the best fit from the table is assigned as the scale of the variable at that vertical level for each latitude. Note that the vertical scales are locally defined so that the negative correlation further away, in the vertical direction, is not included.

Theoretically, CV3 BE is a generic background error statistics file which can be used for any case. It is quite straightforward to use CV3 in your own case. To use the CV3 BE file in your case, set `cv_options=3` in `&wrfvar7` in `namelist.input` in your working directory, and use the `be.dat` is located in `WRFDA/var/run/be.dat.cv3`.

Modifying CV3 length scales and variance

Because CV3 is a generic background error option, it is necessary to tune the default background error scale length and variance values for each experiment. These can be controlled at run time with a series of namelist variables described below.

The scaling factors for CV3 are stored as an array of values for each individual control variable:

```
as1: stream function
as2: unbalanced velocity potential
as3: unbalanced temperature
as4: pseudo relative humidity
as5: unbalanced surface pressure
```

These variables are all 3-element vectors. The first element is the variance scaling factor. The second is the horizontal length scale factor. The third is the vertical length scale factor. So setting the default values in your namelist would look like this:

```
&wrfvar7
 cv_options = 3,
 as1     =  0.25,   1.00,   1.50,
 as2     =  0.25,   1.00,   1.50,
 as3     =  0.25,   1.00,   1.50,
 as4     =  0.25,   1.00,   1.50,
 as5     =  0.25,   1.00,   1.50,
/
```

The first column is the variance, the second is the horizontal length scale factor, and the third is the vertical length scale factor.

For multiple outer loops, the next 3 elements of each vector must be filled in. So for 2 outer loops (max_ext_its=2), to use the default values, the namelist should look like this:

```
&wrfvar7
 cv_options = 3,
 as1     =  0.25,   1.00,   1.50,   0.25,   1.00,   1.50,
 as2     =  0.25,   1.00,   1.50,   0.25,   1.00,   1.50,
 as3     =  0.25,   1.00,   1.50,   0.25,   1.00,   1.50,
 as4     =  0.25,   1.00,   1.50,   0.25,   1.00,   1.50,
 as5     =  0.25,   1.00,   1.50,   0.25,   1.00,   1.50,
/
```

Again, the first column is the variance, the second is the horizontal length scale factor, and the third is the vertical length scale factor for the first outer loop. The fourth column is the variance, the fifth is the horizontal length scale factor, and the sixth is the vertical length scale factor for the second outer loop.

Continue in this manner for more outer loops. The values listed above are the default values, but can be adjusted for each individual experiment.

Domain-specific background error options: Running GEN_BE

To use CV5, CV6 or CV7 background error covariance, it is necessary to generate your domain-specific background error statistics with the `gen_be` utility. The default CV3 background error statistics file, supplied with the WRFDA source code, can NOT be used with these control variable options.

The main source code for the various `gen_be` stages can be found in `WRFDA/var/gen_be`. The executables of `gen_be` should have been created when you compiled the WRFDA code (as described earlier). The scripts to run these codes are in `WRFDA/var/scripts/gen_be`. The user can run gen_be using the wrapper script `WRFDA/var/scripts/gen_be/gen_be_wrapper.ksh`.

The input data for `gen_be` are WRF forecasts, which are used to generate model perturbations, used as a proxy for estimates of forecast error. For the NMC-method, the model perturbations are differences between forecasts (e.g. T+24 minus T+12 is typical for regional applications, T+48 minus T+24 for global) valid at the same time. Climatological estimates of background error may then be obtained by averaging these forecast differences over a period of time (e.g. one month). Given input from an ensemble prediction system (EPS), the inputs are the ensemble forecasts, and the model perturbations created are the transformed ensemble perturbations. The gen_be code has been designed to work with either forecast difference or ensemble-based perturbations. The former is illustrated in this tutorial example.

It is important to include forecast differences valid at different parts of the day (for example, forecasts valid at 00Z and 12Z through the forecast period) to remove contributions from the diurnal cycle (i.e. do not run `gen_be` using model perturbations valid for a single time each day).

The inputs to `gen_be` are netCDF WRF forecast output ("wrfout") files at specified forecast ranges. To avoid unnecessary large single data files, it is assumed that all forecast ranges are output to separate files. For example, if we wish to calculate BE statistics using the NMC-method with (T+24)-(T+12) forecast differences (default for regional) then by setting the WRF `namelist.input` options `history_interval=720`, and `frames_per_outfile=1` we get the necessary output datasets. Then the forecast output files should be arranged as follows: directory name is the forecast initial time, time info in the file name is the forecast valid time. `2008020512/wrfout_d01_2008-02-06_00:00:00` means a 12-hour forecast valid at `2008020600`, initialized at `2008020512`.

Example dataset for a test case (90 x 60 x 41 gridpoints) can be downloaded from http://www2.mmm.ucar.edu/wrf/users/wrfda/download/testdata.html. Untar the `gen_be_forecasts_20080205.tar.gz` file. You will have:

```
>ls $FC_DIR

-rw-r--r--  1   users  11556492 2008020512/wrfout_d01_2008-02-06_00:00:00
-rw-r--r--  1   users  11556492 2008020512/wrfout_d01_2008-02-06_12:00:00
```

```
-rw-r--r--  1   users  11556492 2008020600/wrfout_d01_2008-02-06_12:00:00
-rw-r--r--  1   users  11556492 2008020600/wrfout_d01_2008-02-07_00:00:00
-rw-r--r--  1   users  11556492 2008020612/wrfout_d01_2008-02-07_00:00:00
-rw-r--r--  1   users  11556492 2008020612/wrfout_d01_2008-02-07_12:00:00
```

In the above example, only 1 day (12Z 05 Feb to 12Z 06 Feb. 2008) of forecasts, every 12 hours is supplied to `gen_be_wrapper` to estimate forecast error covariance. It is only for demonstration. The minimum number of forecasts required depends on the application, number of grid points, etc. Month-long (or longer) datasets are typical for the NMC-method. Generally, at least a 1-month dataset should be used.

Under `WRFDA/var/scripts/gen_be`, `gen_be_wrapper.ksh` is used to generate the BE data. The following variables need to be set to fit your case:

```
export WRFVAR_DIR=/glade/p/work/wrfhelp/PRE_COMPILED_CODE/WRFDA
export NL_CV_OPTIONS=5        # 5 for CV5, 7 for CV7
export START_DATE=2008020612  # the first perturbation valid date
export END_DATE=2008020700    # the last perturbation valid date
export NUM_LEVELS=40          # e_vert - 1
export BIN_TYPE=5             # How data is binned for calculating statistics
export FC_DIR=/glade/p/work/wrfhelp/WRFDA_DATA/fc   # where wrf forecasts are
export RUN_DIR=`pwd`/gen_be   # Where GEN_BE will run and output files
```

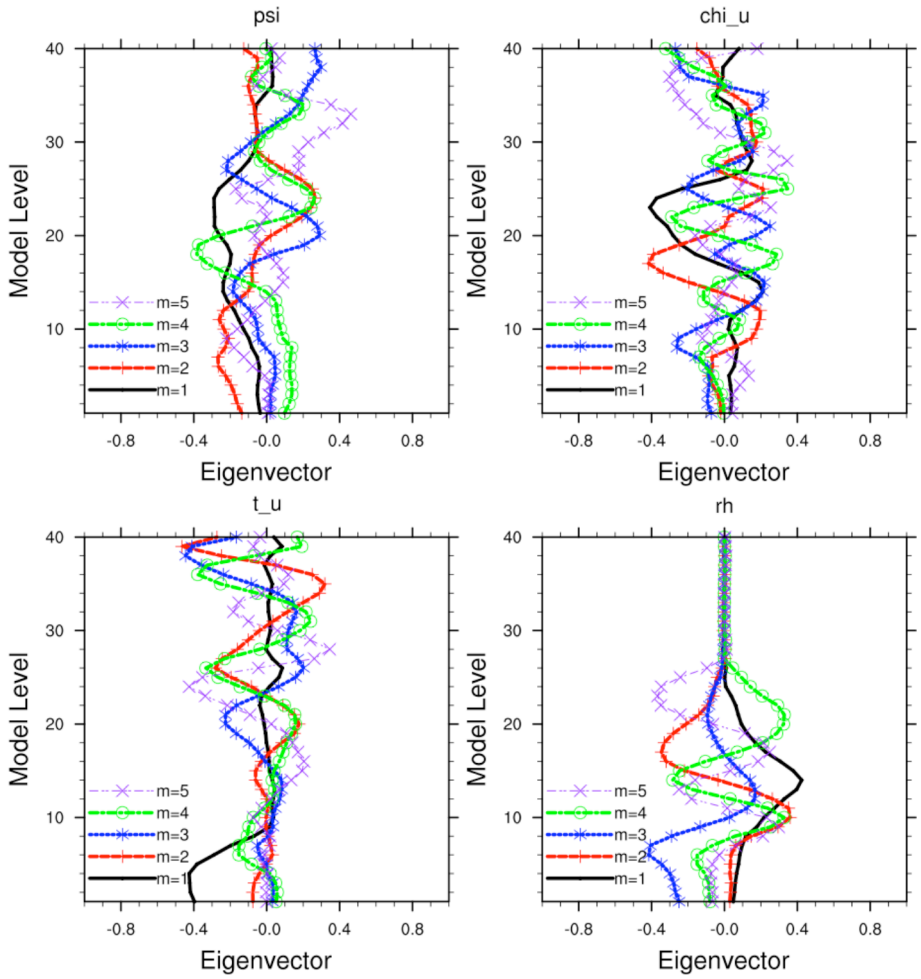
Note: The START_DATE and END_DATE are perturbation valid dates. As shown in the forecast list above, when you have 24-hour and 12-hour forecasts initialized at 2008020512, through 2008020612, the first and final forecast difference valid dates are 2008020612 and 2008020700, respectively.

Note: The forecast dataset should be located in `$FC_DIR`. Then type:

```
> gen_be_wrapper.ksh
```

Once the `gen_be_wrapper.ksh` run is completed, the `be.dat` can be found under the `$RUN_DIR` directory.

To get a clear idea about what is included in `be.dat`, the script `gen_be_plot_wrapper.ksh` may be used. This plots various data in `be.dat`; for example:



GEN_BE for CV6

CV6 is a multivariate background error statistics option in WRFDA. It may be activated by setting the namelist variable `cv_options=6`. This option introduces six additional correlation coefficients in the definition of the balanced part of analysis control variables. Thus with this implementation, moisture analysis is multivariate, in the sense that temperature and wind may lead to moisture increments, and vice-versa. Further details may be seen at: http://www2.mmm.ucar.edu/wrf/users/wrfda/Docs/WRFDA_updated_for_cv6.pdf

How to generate CV6 background error statistics for WRFDA

CV6 background error statistics for WRFDA are generated by executing a top-level script, `gen_be/wrapper_gen_mbe.ksh`, residing under `SCRIPTS_DIR` via a suitable wrapper script. The rest of the procedure remains the same as with normal running of the `gen_be` utility. A successful run will create a `be.dat` file in the `RUN_DIR` directory.

How to run WRFDA with CV6 background error statistics

After successfully generating the CV6 background error statistics file `be.dat`, the procedure for running WRFDA is straight-forward: Include `cv_options=6` in the `namelist.input` file under the `&wrfvar7` list of namelist options.

How to tune CV6 background error statistics

Below is a list of nine tuning parameters available in WRFDA; these can be specified under `&wrfvar7` in the namelist. Default values for these variables are set as "1.0". Setting corresponding values > 1.0 (< 1.0) will increase (decrease) the corresponding contributions:

Variable name	Description
`psi_chi_factor`	Parameter to control contribution of stream function in defining balanced part of velocity potential
`psi_t_factor`	Parameter to control contribution of stream function in defining balanced part of temperature
`psi_ps_factor`	Parameter to control contribution of stream function in defining balanced part of surface pressure
`psi_rh_factor`	Parameter to control contribution of stream function in defining balanced part of moisture
`chi_u_t_factor`	Parameter to control contribution of unbalanced part of velocity potential in defining balanced part of temperature
`chi_u_ps_factor`	Parameter to control contribution of unbalanced part of velocity potential in defining balanced part of surface pressure
`chi_u_rh_factor`	Parameter to control contribution of unbalanced part of velocity potential in defining balanced part of moisture
`t_u_rh_factor`	Parameter to control contribution of unbalanced part of temperature in defining balanced part of moisture
`ps_u_rh_factor`	Parameter to control contribution of unbalanced part of surface pressure in defining balanced part of moisture

Additional Background Error options

a. Single Observation response in WRFDA

With the single observation test, you may get some ideas of how the background and observation error statistics work in the model variable space. A single observation test is done in WRFDA by setting `num_pseudo=1`, along with other pre-specified values in record `&wrfvar15` and `&wrfvar19` of `namelist.input`.

With the settings shown below, WRFDA generates a single observation with a pre-

specified *innovation* (Observation − First Guess) value at the desired location; e.g. at (in terms of grid coordinate) 23x23, level 14 for "U" observation with error characteristics 1 m/s, and innovation size = 1.0 m/s.

```
&wrfvar15
num_pseudo = 1,
pseudo_x = 23.0,
pseudo_y = 23.0,
pseudo_z = 14.0,
pseudo_err = 1.0,
pseudo_val = 1.0,
/
&wrfvar19
pseudo_var = 'u',
/
```

You may wish to repeat this exercise for other observation types. "`pseudo_var`" can take any of the following values:

Variable name	Description	Units
u	East-west wind	m/s
v	North-south wind	m/s
t	Temperature	K
p	Pressure	Pa
q	Water vapor mixing ratio	*unitless* (kg/kg)
tpw	Total precipitable water	cm
ztd	GPS zenith total delay	cm
ref	GPS Refractivity	*Unitless*

b. Response of BE length scaling parameter

Run the single observation test with the following additional parameters in record `&wrfvar7` of `namelist.input`.

```
&wrfvar7
len_scaling1 = 0.5, # reduce psi length scale by 50%
len_scaling2 = 0.5, # reduce chi_u length scale by 50%
len_scaling3 = 0.5, # reduce T length scale by 50%
len_scaling4 = 0.5, # reduce q length scale by 50%
len_scaling5 = 0.5, # reduce Ps length scale by 50%
/
```

Note: You may wish to try the response of an individual variable by setting one parameter at a time. Note the spread of analysis increment.

c. Response of changing BE variance

Run the single observation test with the following additional parameters in record `&wrfvar7` of `namelist.input`.

```
&wrfvar7
var_scaling1 = 0.25,   # reduce psi variance by 75%
var_scaling2 = 0.25,   # reduce chi_u variance by 75%
var_scaling3 = 0.25,   # reduce T variance by 75%
var_scaling4 = 0.25,   # reduce q variance by 75%
var_scaling5 = 0.25,   # reduce Ps variance by 75%
/
```

Note: You may wish to try the response of individual variable by setting one parameter at a time. Note the magnitude of analysis increments.

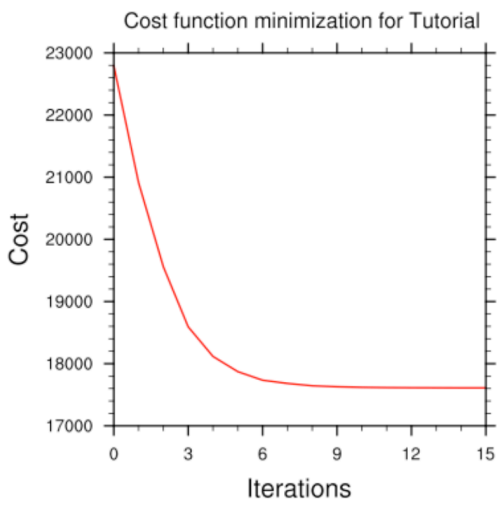
WRFDA Diagnostics

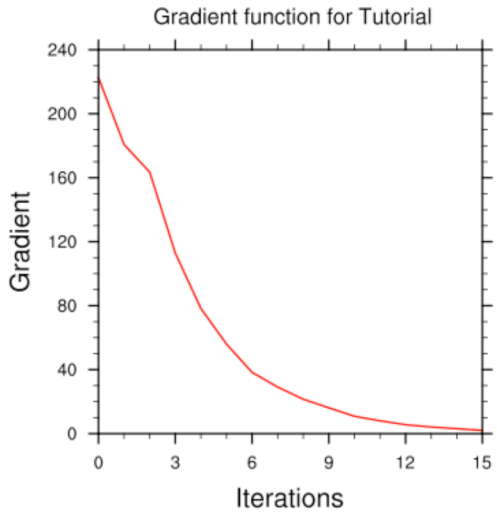
WRFDA produces a number of diagnostic files that contain useful information on how the data assimilation has performed. This section will introduce you to some of these files, and what to look for.

After running WRFDA, it is important to check a number of output files to see if the assimilation appears sensible. The WRFDA package, which includes several useful scripts, may be downloaded from http://www2.mmm.ucar.edu/wrf/users/wrfda/download/tools.html

The content of some useful diagnostic files are as follows:

`cost_fn` and `grad_fn`: These files hold (in ASCII format) WRFDA cost and gradient function values, respectively, for the first and last iterations. If you run with `calculate_cg_cost_fn=true` and `write_detail_grad_fn=true`, however, these values will be listed for each iteration; this can be helpful for visualization purposes. The NCL script in the WRFDA TOOLS package located at `var/graphics/ncl/plot_cost_grad_fn.ncl` may be used to plot the content of `cost_fn` and `grad_fn`, if these files are generated with `calculate_cg_cost_fn=true` and `write_detail_grad_fn=true`.





Note: Make sure that you remove the first two lines (header) in `cost_fn` and `grad_fn` before you plot. You also need to specify the directory name for these two files.

`gts_omb_oma_01`: It contains (in ASCII format) information on all of the observations used by the WRFDA run. Each observation has its observed value, quality flag, observation error, observation minus background (OMB), and observation minus analysis (OMA). This information is very useful for both analysis and forecast verification purposes.

`namelist.input`: This is the WRFDA input namelist file, which contains all the user-defined non-default options. Any namelist-defined options that do not appear in this file should have their names checked against the values in `$WRFDA_DIR/Registry/registry.var`.

`namelist.output.da`: A list of all the namelist options used. If an option was not specified in `namelist.input`, the default listed in the registry value will be used.

`rsl*`: Files containing information for standard WRFDA output from individual processors when multiple processors are used. It contains a host of information on a number of observations, minimization, timings, etc. Additional diagnostics may be printed in these files by including various "print" WRFDA namelist options. To learn more about these additional "print" options, search for the "print_" string in `$WRFDA_DIR/Registry/registry.var`.

`statistics`: Text file containing OMB (OI) and OMA (OA) statistics (minimum, maximum, mean and standard deviation) for each observation type and variable. This information is very useful in diagnosing how WRFDA has used different components of the observing system. Also contained are the analysis minus background (A-B) statistics, i.e. statistics of the analysis increments for each model variable at each model level. This information is very useful in checking the range of analysis increment values found in the analysis, and where they are in the WRF-model grid space.

The WRFDA analysis file is `wrfvar_output`. It is in WRF (netCDF) format. It will become the input file `wrfinput_d01` of any subsequent WRF run after lateral boundary and/or lower boundary conditions are updated by another WRFDA utility (See the section Updating WRF boundary conditions).

An NCL script, `$TOOLS_DIR/var/graphics/ncl/WRF-Var_plot.ncl`, is provided in the tools package for plotting. You need to specify the `analysis_file` name, its full path, etc. Please see the in-line comments in the script for details.

As an example, if you are aiming to display the U-component of the analysis at level 18, use the script `WRF-Var_plot.ncl`, and make sure the following pieces of codes are uncommented:

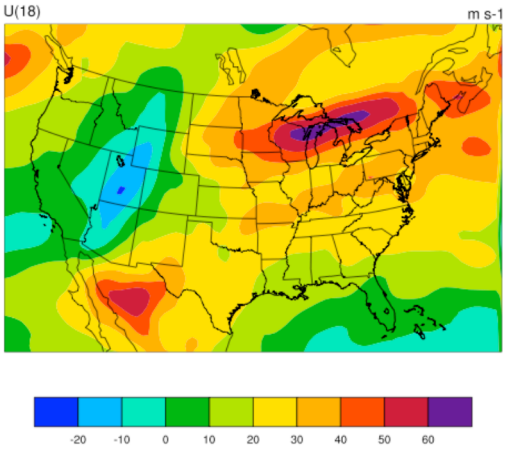
```
var = "U"
```

```
fg = first_guess->U
an = analysis->U
plot_data = an
```

When you execute the following command from `$WRFDA_DIR/var/graphics/ncl`.

```
> ncl WRF-Var_plot.ncl
```

The plot should look like:



You may change the variable name, level, etc. in this script to display the variable of your choice at the desired eta level.

Take time to look through the text output files to ensure you understand how WRFDA works. For example:

How closely has WRFDA fit individual observation types? Look at the `statistics` file to compare the O-B and O-A statistics.

How big are the analysis increments? Again, look in the `statistics` file to see minimum/maximum values of A-B for each variable at various levels. It will give you a feel for the impact of the input observation data you assimilated via WRFDA by modifying the input analysis first guess.

How long did WRFDA take to converge? Does it really converge? You will get the answers of all these questions by looking into the `rsl.*` -files, as it indicates the number of iterations taken by WRFDA to converge. If this is the same as the maximum number of iterations specified in the namelist (`NTMAX`), or its default value (=200) set in `$WRFDA_DIR/Registry/registry.var`, then it means that the analysis solution did not converge. If this is the case, you may need to increase the value of "`NTMAX`" and rerun your case to ensure that the convergence is achieved. On the other hand, a normal WRFDA run should usually converge within 100 iterations. If it still doesn't converge in 200 iterations, that means there

may be a problem in the observations or first guess.

A good way to visualize the impact of assimilation of observations is to plot the analysis increments (i.e. analysis minus the first guess difference). Many different graphics packages (e.g. RIP4, NCL, GRADS etc) can do this.

You need to modify this script to fix the full path for `first_guess and analysis` files. You may also use it to modify the display level by setting `kl` and the name of the variable to display by setting `var`. Further details are given in this script.

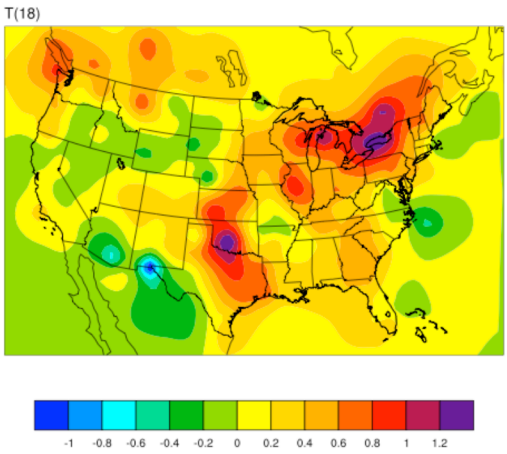
If you are aiming to display the increment of potential temperature at level 18, after modifying `$WRFDA_DIR/var/graphics/ncl/WRF-Var_plot.ncl`, make sure the following pieces of code are uncommented:

```
var = "T"
fg = first_guess->T ;Theta- 300
an = analysis->T    ;Theta- 300
plot_data = an - fg
```

When you execute the following command from `WRFDA_DIR/var/graphics/ncl`.

```
> ncl WRF-Var_plot.ncl
```

The plot created will look as follows:



Note: Larger analysis increments indicate a larger data impact in the corresponding region of the domain.

Generating ensembles with RANDOMCV

In addition to the variational methods previously mentioned, the WRFDA system supports both ensemble and hybrid ensemble/variational assimilation methods. To utilize these methods, having an ensemble of forecasts is necessary. WRFDA has a built-in

method for generating ensemble initial conditions known as RANDOMCV. RANDOMCV works by adding random noise to the analysis in control variable space.

a. Running WRFDA for RANDOMCV

RANDOMCV is a capability of the main WRFDA executable, so you will run it by setting the following variables in namelist.input and then running da_wrfvar.exe as you would with any data assimilation run:

`&wrfvar5`	
`put_rand_seed`	true: enter your own seed numbers to generate random background perturbations. The advantage of this setting is that the same seed numbers will always produce the same perturbation false: (default behavior) perturbations will be generated "randomly" and give new perturbations each time
`&wrfvar11`	
`seed_array1`	First integer for seeding the random function (default: 1)
`seed_array2`	Second integer for seeding the random function (default: 1) It is not necessary to change both seeds to get different perturbations
`&wrfvar17`	
`analysis_type`	Set this to 'RANDOMCV' to use the RANDOMCV capability

When setting your own random seeds, a common good practice is to set the first seed as the experiment date/time in integer form, and the second seed as the ensemble member number. *The seeds should not be set to zero.*

Because the perturbations are made in control variable space, the general pattern of perturbations will depend on your background error. You should be able to use any background error option with RANDOMCV (CV3, CV5, CV6, or CV7). Additionally, this means you can control their magnitude and lengthscales by modifying the background error variance and length scaling variables respectively:

For CV5, CV6, or CV7

```
&wrfvar7
var_scaling1 = 0.25,  # reduce psi perturbation magnitude by 75%
var_scaling2 = 0.25,  # reduce chi_u perturbation magnitude by 75%
var_scaling3 = 0.0,   # reduce T perturbation by 100% (there will be no
                        T perturbation!)
var_scaling4 = 2.0,   # increase q perturbation by 100%
var_scaling5 = 1.0,   # Keep Ps perturbation magnitude the same
len_scaling1 = 0.5,   # reduce psi perturbation length scale by 50%
len_scaling2 = 0.5,   # reduce chi_u perturbation length scale by 50%
len_scaling3 = 1.0,   # Keep T perturbation length scale the same
len_scaling4 = 2.0,   # increase q perturbation length scale by 100%
len_scaling5 = 1.5,   # increase Ps perturbation length scale by 50%
/
```

For CV3, see the section "Modifying CV3 length scales and variance".

Hybrid Data Assimilation in WRFDA

The WRFDA system also includes hybrid data assimilation techniques—both 3DEnVar and 4DEnVar (new for version 3.9), which is based on the previously-described variational capability.

The difference between hybrid and variational schemes is that WRFDA 3DVAR and 4DVAR rely solely on a static covariance model to specify the background errors, while the hybrid system uses a combination of static error covariances and ensemble-estimated error covariances to incorporate a flow-dependent estimate of the background error statistics. The following sections will give a brief introduction to using the hybrid system. Please refer to these papers for a detailed description of the methodology used in the WRFDA hybrid system:

> Xuguang Wang, Dale M. Barker, Chris Snyder, and Thomas M. Hamill, 2008: A hybrid ETKF–3DVAR data assimilation scheme for the WRF model. Part I: Observing system simulation experiment. *Mon. Wea. Rev.*, **136**, 5116–5131.
>
> Xuguang Wang, Dale M. Barker, Chris Snyder, and Thomas M. Hamill, 2008: A Hybrid ETKF–3DVAR Data Assimilation Scheme for the WRF Model. Part II: Real Observation Experiments. *Mon. Wea. Rev.*, **136**, 5132–5147.

Four executables are used in the hybrid system. If you have successfully compiled the WRFDA system, the following executables will exist in the `WRFDA/var/build` directory:

```
WRFDA/var/build/gen_be_ensmean.exe
WRFDA/var/build/gen_be_ep2.exe
WRFDA/var/build/da_wrfvar.exe
WRFDA/var/build/gen_be_vertloc.exe
```

`gen_be_ensmean.exe` is used to calculate the ensemble mean, while `gen_be_ep2.exe` is used to calculate the ensemble perturbations. `gen_be_vertloc.exe` is used for vertical localization. As with 3DVAR/4DVAR, `da_wrfvar.exe` is the main WRFDA program. However, in this case, `da_wrfvar.exe` will run in hybrid mode.

a. Running the hybrid system for 3DEnVar

The procedure is the same as running 3DVAR, with the exception of some extra input files and namelist settings. The basic input files for WRFDA are LANDUSE.TBL, `ob.ascii` or `ob.bufr` (depending on which observation format you use), and `be.dat` (static background errors). Additional input files required for 3DEnVar are a single ensemble mean file (used as the fg for the hybrid application) and a set of ensemble perturbation files (used to represent flow-dependent background errors).

A set of initial ensemble members must be prepared before the hybrid application can be started. The ensemble can be obtained from other ensemble model outputs, or you can

generate them yourself. This can be done, for example, adding random noise to the initial conditions at a previous time and integrating each member to the desired time. A tutorial case with a test ensemble can be found at http://www2.mmm.ucar.edu/wrf/users/wrfda/download/V38/wrfda_hybrid_etkf_testdata.tar.gz. In this example, the ensemble forecasts were initialized at 2015102612 and valid 2015102712. A hybrid analysis at 2015102712 will be performed using the ensemble valid 2015102712 as input. Once you have the initial ensemble, the ensemble mean and perturbations can be calculated following the steps below:

1) Set an environment variable for your working directory and your data directory

```
> setenv WORK_DIR your_hybrid_path
> setenv DAT_DIR your_data_path
> cd $WORK_DIR
```

2) Calculate the ensemble mean

   a) From your working directory, copy or link the ensemble forecasts to your working directory. The ensemble members are identified by the characters ".e###" at the end of the file name, where ### represents three-digit numbers following the valid time.

```
> ln –sf $DAT_DIR/Hybrid/fc/2015102612/wrfout_d01_2015-10-
27_12:00:00.e* .
```

   b) Provide two template files (ensemble mean and variance files) in your working directory. These files will be overwritten with the ensemble mean and variance as discussed below.

```
> cp $DAT_DIR/Hybrid/fc/2015102612/wrfout_d01_2015-10-
27_12:00:00.e001 ./wrfout_d01_2015-10-27_12:00:00.mean
> cp $DAT_DIR/Hybrid/fc/2015102612/wrfout_d01_2015-10-
27_12:00:00.e001 ./wrfout_d01_2015-10-27_12:00:00.vari
```

   c) Copy `gen_be_ensmean_nl.nl` (`cp $DAT_DIR/Hybrid/gen_be_ensmean_nl.nl .`) You will need to set the information in this script as follows:

```
&gen_be_ensmean_nl
directory = '.'
filename = 'wrfout_d01_2015-10-27_12:00:00'
num_members = 10
nv = 7
cv = 'U', 'V', 'W', 'PH', 'T', 'MU', 'QVAPOR'
/
```

where `directory` is the folder containing the ensemble members and template files, `filename` is the name of the files before their suffixes (e.g., `.mean`, `.vari`, etc), `num_members` is the number of ensemble members you are using, `nv` is the number of variables, and `cv` is the name of variables used in the hybrid system. Be sure `nv` and

cv are consistent!

d) Link gen_be_ensmean.exe to your working directory and run it.

```
> ln –sf  $WRFDA_DIR/var/build/gen_be_ensmean.exe .
> ./gen_be_ensmean.exe
```

Check the output files. wrfout_d01_2015-10-27_12:00:00.mean is the ensemble mean; wrfout_d01_2015-10-27_12:00:00.vari is the ensemble variance

3) Calculate ensemble perturbations

a) Create a sub-directory in which you will be working to create ensemble perturbations.

```
> mkdir –p ./ep
> cd ./ep
```

b) Run gen_be_ep2.exe. The executable requires four command-line arguments (DATE, NUM_MEMBER, DIRECTORY, and FILENAME) as shown below for the tutorial example:

```
> ln –sf $WRFDA_DIR/var/build/gen_be_ep2.exe  .
> ./gen_be_ep2.exe  2015102712  10  .  ../wrfout_d01_2015-10-
27_12:00:00
```

c) Check the output files. A list of binary files should now exist. Among them, tmp.e* are temporary scratch files that can be removed.

4) Back in the working directory, create the input file for vertical localization. This program requires one command-line argument: the number of vertical levels of the model configuration (same value as e_vert in the namelist; for the tutorial example, this should be 42).

```
> cd $WORK_DIR
> ln –sf $WRFDA_DIR/var/build/gen_be_vertloc.exe .
> ./gen_be_vertloc.exe 42
```

The output is ./be.vertloc.dat in your working directory.

5) Run WRFDA in hybrid mode

a) In your hybrid working directory, link all the necessary files and directories as follows:

```
> ln -fs ./wrfout_d01_2015-10-27_12:00:00.mean ./fg  (first
guess is the ensemble mean for this test case)
> ln -fs $WRFDA_DIR/run/LANDUSE.TBL .
> ln -fs $DAT_DIR/Hybrid/ob/2015102712/ob.ascii ./ob.ascii
> ln -fs $DAT_DIR/Hybrid/be/be.dat ./be.dat
```

```
> ln –fs $WRFDA_DIR/var/build/da_wrfvar.exe .
> cp $DAT_DIR/Hybrid/namelist.input .
```

b) Edit `namelist.input`, paying special attention to the following hybrid-related settings:

```
&wrfvar7
je_factor = 2.0
/
&wrfvar16
ensdim_alpha = 10
alphacv_method = 2
alpha_corr_type=3
alpha_corr_scale = 500.0
alpha_std_dev=1.000
alpha_vertloc = .true.
/
```

c) Finally, execute the WRFDA file, running in hybrid mode

```
> ./da_wrfvar.exe >& wrfda.log
```

Check the output files; the output file lists are the same as when you run WRF 3D-Var.

b. Running the hybrid system for 4DEnVar

The procedure for 4DEnVar is very similar to the procedure for 3DEnVar. Unlike 4DVAR, 4DEnVar does not require WRFPLUS, the tangent linear/adjoint model. It is more analogous to the First Guess at Appropriate Time (FGAT) method than full 4DVAR. Like FGAT, 4DEnVar requires multiple first guess files, one for each assimilation time window. In addition, you must have ensemble output for each of the first guess times, and generate ensemble perturbations from each of these sets of ensemble forecasts.

To activate the 4DEnVar option, set the namelist variable `use_4denvar=.true.` under `&wrfvar16`. A tutorial case with a test ensemble can be found at http://www2.mmm.ucar.edu/wrf/users/wrfda/download/V39/WRFDA_4denvar_test_data.tar.gz. In this example, the ensemble forecasts were initialized at 2005071512 and valid for 2005071521—2005071603. The 4DEnVar hybrid analysis (wrfvar_output) will be valid for 2005071600.

c. Dual-resolution hybrid

WRFDA has an option for dual-resolution hybrid data assimilation, where a high-resolution background can make use of a lower-resolution ensemble for extracting the flow-dependent contribution to the background error. The lower-resolution ensemble should be the parent domain of the higher-resolution child domain that the analysis is performed on.

Performing dual-resolution hybrid assimilation is similar to the process for regular

assimilation described above. The main difference is that you must include some settings in the &domains section of the namelist in a different way: The setting max_dom=2 must be used, and for each column of settings, **the low-resolution domain settings must be listed first**, even though the second column will be the domain on which assimilation is being performed. An example of the &domains namelist section is shown below; in this case, the low-resolution ensemble domain is 222x128 grid points at 45 km resolution, and the high-resolution analysis domain is 184x196 grid points at 15 km resolution:

```
&domains
 time_step            = 90,
 max_dom              = 2,
 s_we                 =   1,   1,
 e_we                 = 222, 184,
 s_sn                 =   1,   1,
 e_sn                 = 128, 196,
 s_vert               =   1,   1,
 e_vert               =  45,  45,
 dx                   = 45000, 15000,
 dy                   = 45000, 15000,
 grid_id              = 1,  2,
 parent_id            = 0,  1,
 i_parent_start       = 0, 89,
 j_parent_start       = 0, 22,
 parent_grid_ratio    = 1,  3,
/
```

For further details about any of the above settings, see Chapter 5 of this User's Guide.

In addition to the above, you must set the namelist variable **`hybrid_dual_res=true`**, as well as providing a file named "fg_ens" in the working directory. This file can be any WRF input or wrfout file that has the same domain as the low-resolution ensemble; it is merely used for reading in mapping parameters for the low-resolution ensemble domain.

The dual-resolution hybrid capability is described in more detail in the following publication:

Schwartz, C. S., Z. Liu, X.-Y. Huang, 2015: Sensitivity of Limited-Area Hybrid Variational-Ensemble Analyses and Forecasts to Ensemble Perturbation Resolution. *Mon. Wea. Rev.* , **143**, 3454-3477.

d. Hybrid namelist options

`&wrfvar7`

`je_factor`

ensemble covariance weighting factor. This factor controls the weighting component of ensemble and static covariances. The corresponding jb_factor = je_factor/(je_factor - 1).

`&wrfvar16`

use_4denvar
.true. will activate 4DEnVar
hybrid_dual_res
.true. will activate dual-resolution mode
ep_para_read
Method for reading ensemble perturbation files
0 (default): Serial read
1: Parallel read.
rden_bin
bins for parallel reading of ensemble perturbation files. Default is 1. Lower numbers use more memory, but are faster. If memory use becomes too large, increase this value.
ensdim_alpha
the number of ensemble members. Hybrid mode is activated when ensdim_alpha is larger than zero
alphacv_method
2 (default): perturbations in model space ("u","v","t","q","ps"). Option 2 is extensively tested and recommended to use.
1: perturbations in control variable space ("psi","chi_u","t_u","rh","ps_u")
alpha_corr_type
correlation function. 1=Exponential; 2=SOAR; 3=Gaussian.
alpha_corr_scale
hybrid covariance localization scale in km unit. Default value is 200.
alpha_std_dev
alpha standard deviation. Default value is 1.0
alpha_vertloc
true: use vertical localization
false (default): no vertical localization

ETKF Data Assimilation

The WRFDA system also includes a ETKF assimilation technique. The ETKF system updates the ensemble perturbations. Please refer to Bishop et al. (2001) and Wang et al. (2003) for a detailed description of the methodology. The following section will give a brief introduction of some aspects of using the ETKF system.

a. Source Code

Three executables are used in the ETKF system. If you have successfully compiled the WRFDA system, you will see the following:

```
WRFDA/var/build/gen_be_etkf.exe

WRFDA/var/build/gen_be_addmean.exe

WRFDA/var/build/da_wrfvar.exe
```

The file `gen_be_etkf.exe` is used to update the ensemble perturbations, while `gen_be_addmean.exe` is used to combine the ensemble mean and the ensemble perturbations. As with 3D-Var/4D-Var, `da_wrfvar.exe` is the main WRFDA program. However, in this case, `da_wrfvar.exe` will create filtered observations and prepare formatted omb files for ETKF.

b. Running the ETKF System

The first procedure is to update the ensemble perturbations. A set of initial ensemble members must be prepared before the ETKF application can be started. The ensemble can be obtained from a previous ensemble forecast. A tutorial case with a test ensemble can be found at http://www2.mmm.ucar.edu/wrf/users/wrfda/download/V38/wrfda_hybrid_etkf_testdata.tar.gz. In this example, the ensemble forecasts were initialized at 2015102612 and valid 2015102712. ETKF will be performed using the ensemble valid 2015102712 as input. Once you have the initial ensemble, the ensemble perturbations can be updated by following the steps below:

1) Set environment variables for convenience

```
> setenv WORK_DIR_ETKF your_etkf_path
> setenv DAT_DIR your_data_path
> setenv WRFDA_DIR your_WRFDA_path
> cd $WORK_DIR_ETKF
```

2) Prepare the filtered observations

a) In your ETKF working directory, make a subdirectory to prepare the filtered observations and link all the necessary files and directories as follows:

```
> mkdir obs_filter
> cd obs_filter
> ln -fs $DAT_DIR/Hybrid/fc/2015102612/wrfout_d01_2015-10-
27_12:00:00.mean ./fg  (first guess is the ensemble mean)
> ln -fs $WRFDA_DIR/run/LANDUSE.TBL .
 > ln -fs $DAT_DIR/Hybrid/ob/2015102712/ob.ascii ./ob.ascii
> ln -fs $DAT_DIR/Hybrid/be/be.dat ./be.dat
> ln -fs $WRFDA_DIR/var/build/da_wrfvar.exe .
> cp $DAT_DIR/ETKF/namelist.input .
```

b) Edit namelist.input, paying special attention to the following 'QC-OBS'-related settings:

```
&wrfvar17
analysis_type                       = 'QC-OBS',
/
```

c) Execute the WRFDA file, running in QC-OBS mode

```
> ./da_wrfvar.exe >& wrfda.log
```

Check the output files; you should see a 'filtered_obs_01' file which contains the filtered observations.

3) Prepare omb files for ETKF

a) In your ETKF working directory, make a subdirectory to prepare the omb files for each ensemble member and link all the necessary files and directories as follows:

```
> cd $WORK_DIR_ETKF
> mkdir -p omb/working.e001
> cd omb/working.e001
> ln -fs $DAT_DIR/Hybrid/fc/2015102612/wrfout_d01_2015-10-
27_12:00:00.e001 ./fg  (first guess is the ensemble member)
> ln -fs $WRFDA_DIR/run/LANDUSE.TBL .
> ln -fs $WORK_DIR_ETKF/obs_filter/filtered_obs_01 ./ob.ascii
> ln -fs $DAT_DIR/Hybrid/be/be.dat ./be.dat
> ln -fs $WRFDA_DIR/var/build/da_wrfvar.exe .
> cp $DAT_DIR/ETKF/namelist.input .
```

b) Edit namelist.input, paying special attention to the following 'VERIFY'-related settings:

```
&wrfvar17
analysis_type                       = 'VERIFY',
/
```

c) Execute the WRFDA file, running in VERIFY mode

```
> ./da_wrfvar.exe >& wrfda.log
```

Check the output files. The output files are the same as when you run WRF 3D-Var (except `wrfvar_output` will NOT be created), and the 'ob.etkf.0*' files are omb files.

d) Combine the ob.etkf.0* files and add the observation number in the head of ob.etkf.e0*

```
> cat ob.etkf.0* > ob.all
> wc -l ob.all > ob.etkf.e001
> cat ob.all >> ob.etkf.e001
```

e) Likewise, prepare ob.etkf.e0* files for other ensemble members

4) Run ETKF

a) Copy or link the ensemble mean and forecasts and ob.etkf.e0* files to your working directory and make a parameter directory to save the parameter files.

```
   > cd $WORK_DIR_ETKF
   > setenv PAR_DIR_ETKF $WORK_DIR_ETKF/param
   > mkdir $PAR_DIR_ETKF
   > ln -sf $DAT_DIR/Hybrid/fc/2015102612/wrfout_d01_2015-10-
27_12:00:00.mean ./etkf_input
   > ln -sf $DAT_DIR/Hybrid/fc/2015102612/wrfout_d01_2015-10-
27_12:00:00.e001 ./etkf_input.e001
  ...
   > ln -sf $DAT_DIR/Hybrid/fc/2015102712/wrfout_d01_2015-10-
27_12:00:00.e010 ./etkf_input.e010

   > ln -sf omb/working.e001/ob.etkf.e001 .
  ...
   > ln -sf omb/working.e010/ob.etkf.e010 .
```

b) Provide template files. These files will be overwritten with the ensemble perturbations.

```
   > cp $DAT_DIR/Hybrid/fc/2015102612/wrfout_d01_2015-10-
27_12:00:00.e001 ./etkf_output.e001
  ...
   > cp $DAT_DIR/Hybrid/fc/2015102612/wrfout_d01_2015-10-
27_12:00:00.e010 ./etkf_output.e010
```

c) Copy gen_be_etkf_nl.nl (cp $DAT_DIR/ETKF/gen_be_etkf_nl.nl .)
You will need to set the information in this script as follows:

```
&gen_be_etkf_nl
  num_members = 10,
  nv = 7,
  cv = 'U', 'V', 'W', 'PH', 'T', 'QVAPOR', 'MU',
  naccumt1 = 20,
  naccumt2 = 20,
  nstartaccum1 = 1,
  nstartaccum2 = 1,
  nout = 1,
  tainflatinput = 1,
  rhoinput = 1,
  infl_fac_file = '$PAR_DIR_ETKF/inflation_factor.dat',
  infl_let_file = '$PAR_DIR_ETKF/inflation_letkf.dat',
  eigen_val_file = '$PAR_DIR_ETKF/eigen_value.dat',
  inno2_val_file = '$PAR_DIR_ETKF/innovation_value.dat',
  proj2_val_file = '$PAR_DIR_ETKF/projection_value.dat',
  infl_fac_TRNK = .false.,
  infl_fac_WG03 = .false.,
  infl_fac_WG07 = .true.,
  infl_fac_BOWL = .false.,
  letkf_flg=.false.,
  rand_filt = .false.,
  rnd_seed = 2015102712,
  rnd_nobs = 5000
  etkf_erro_max = 20.
  etkf_erro_min = .00001
  etkf_inno_max = 20.
  etkf_inno_min = .00001
  etkf_erro_flg = .true.
```

```
  etkf_inno_flg = .true.
  etkf_wrfda = .false.
/
```

Important note: since environment variables are not parsed when reading namelists, you MUST manually change $PAR_DIR_ETKF to its actual value in the namelist

Where the various namelist parameters are as follows:

- `num_members` is the ensemble members size
- `nv` is the number of variables
- `cv` the name of variables
- `naccumt1` and `naccumt1` are number of previous cycles used to accumulate for inflation and rho factor
- `nstartaccumt1` and `nstartaccumt2` are not used for ordinary ETKF
- nout is the cycle index
- `tainflatinput` and `rhoinput` are prescribed factors for inflation and rho factor
- `infl_fac_file`, `eigen_val_file`, `inno2_val_file` and `proj2_val_file` are files to save template parameters
- `infl_fac_TRNK`, `infl_fac_WG03`, `infl_fac_WG07`, and `infl_fac_BOWL` are options for different adaptive inflation schemes
- `rand_filt`, `rnd_seed` and `rnd_nobs` are options for using filtered observation and random observations
- `etkf_erro_max`, `etkf_erro_min`, `etkf_inno_max`, `etkf_inno_min`, `etkf_erro_flg`, `etkf_inno_flg`, and `etkf_wrfda` are options to conduct further observation filtering.

d) Link gen_be_etkf.exe to your working directory and run it.

```
> ln -sf  $WRFDA_DIR/var/build/gen_be_etkf.exe .
> ./gen_be_etkf.exe
```

Check the output files. etkf_output.* files are updated ensemble perturbations.

5) Add updated ensemble perturbations to the ensemble mean to get new ensemble members

```
> cd $WORK_DIR_ETKF
```

a) Copy add_mean_nl.nl (cp $DAT_DIR/ETKF/add_mean_nl.nl .)
You will need to set the information in this script as follows for each member:

```
&add_mean_nl
num_members = 10
cv          = 'U', 'V', 'W', 'PH', 'T', 'QVAPOR', 'MU'
nv          = 7
```

```
  path        = '$WORK_DIR_ETKF'
  file_mean   = 'etkf_input'
  file_pert   = 'etkf_output.e001' (for each member,
etkf_output.e0*...)
 /
```

Again, be sure to substitute the actual path in the place of $WORK_DIR_ETKF

b) Run gen_be_addmean.exe.

```
> ln -sf $WRFDA_DIR/var/build/gen_be_addmean.exe  .
> ./gen_be_addmean.exe
```

Check the output files. etkf_output.e0* files are the new ensemble members.

Additional WRFDA Options

1. Wind speed/direction assimilation

If observations containing wind speed/direction information are provided to WRFDA, you can assimilate these observations directly, rather than converting the wind to its u- and v-components prior to assimilation.

Wind speed/direction assimilation is controlled by the following namelist options:

`&wrfvar2`	
`wind_sd`	true: all wind values which are reported as speed/direction will be assimilated as such false: (default behavior) all wind obs are converted to u/v prior to assimilation
`wind_stats_sd`	Assimilate wind in u/v format, but output speed/direction statistics

The following settings only matter if `check_max_iv=true` (if innovation is greater than observation error times the error factor listed below, the observation will be rejected):

`&wrfvar2`	
`qc_rej_both`	true: if either u or v (spd or dir) do not pass quality control, both obs are rejected false: (default behavior) qc on wind obs is handled individually
`&wrfvar5`	
`max_omb_spd`	Max absolute value of innovation for wind speed obs in m/s; greater than this and the innovation will be set to zero (default: 100.0)
`max_omb_dir`	Max absolute value of innovation for wind direction obs in degrees; greater than this and the innovation will be set to zero (default: 1000.0)
`max_error_spd`	Speed error factor (default: 5.0)
`max_error_dir`	Direction error factor (default: 5.0)

The assimilation of wind speed/direction can also be controlled by observation type, using the following variables (note: setting `wind_sd = .true.` as above will override these individual settings):

```
&wrfvar2
```

wind_sd_airep	Aircraft reports
wind_sd_buoy	Buoy reports
wind_sd_geoamv	Geostationary satellite atmospheric motion vectors
wind_sd_metar	METAR reports
wind_sd_mtgirs	Meteosat Third Generation
wind_sd_pilot	Pilot reports
wind_sd_polaramv	Polar satellite atmospheric motion vectors
wind_sd_profiler	Wind profiler reports
wind_sd_qscat	QuikScat reports
wind_sd_ships	Ship reports
wind_sd_sound	Sounding reports
wind_sd_synop	Synoptic reports
wind_sd_tamdar	TAMDAR reports

true: wind values which are reported as speed/direction will be assimilated as such
false: (default behavior) all wind obs are converted to u/v prior to assimilation

Further details about this method can be found in the following publications:

Huang, X.-Y., F. Gao, N. A. Jacobs, and H. Wang, 2013: Assimilation of wind speed and direction observations: a new formulation and results from idealised experiments. *Tellus A*, **65**, 19936, doi:10.3402/tellusa.v65i0.19936.

Gao, Feng, Xiang-Yu Huang, Neil A. Jacobs, and Hongli Wang, 2015: Assimilation of wind speed and direction observations: results from real observation experiments. *Tellus A*, **67**, 27132, doi:10.3402/tellusa.v67.27132.

2. The Weak Penalty Constraint option

For Version 3.8, a new "weak penalty constraint" (WPEC) option has been added to WRFDA which aims to enforce quasi-gradient balance on a WRFDA analysis. It was designed with the specific aim of improving assimilation of radar data within tropical cyclones, but may be useful for other weather phenomena of similar scales. It can be used with 3DVAR or hybrid 3DVAR (4DVAR is not compatible with this new capability).

Further details about this method can be found in the following publication:

Li, X., J. Ming, M. Xue, Y. Wang, and K. Zhao, 2015: Implementation of a dynamic equation constraint based on the steady state momentum equations within the WRF hybrid ensemble-3DVar data assimilation system and test with radar T-TREC wind assimilation for tropical Cyclone Chanthu (2010). *J. Geophys. Res. Atmos.*, 120, 4017–4039, doi: 10.1002/2014JD022706.

This new option is controlled by the following set of namelist options:

```
&wrfvar12
```

use_wpec	true: enables the constraint term false: (default behavior) disables the constraint term
wpec_factor	The constraint's weighting factor (1/Γ) as described in the paper
balance_type	1 = geostrophic term 2 = cyclostrophic term 3 = geostrophic + cyclostrophic terms (default; recommended)

3. Options for improving surface data assimilation

There are a number of options in WRFDA that are specifically for surface observations (e.g. METAR, SYNOP). Surface observations should be handled especially cautiously, as their impact can vary widely based on vertical and horizontal resolution, as well as other factors. Adjusting the options listed below can help investigate the assimilation of surface observations, especially in mountainous terrain.

&wrfvar11

These two options work for BUOY, METAR, SHIP, and SYNOP observations, as well as surface-level sounding and TAMDAR observations.

sfc_assi_options	1 (default): surface observations will be assimilated based on the lowest model level first guess. Observations are not used when the elevation difference between the observing site and the lowest model level is larger than max_stheight_diff 2: surface observations will be assimilated based on surface similarity theory in PBL. Innovations are computed based on 10-m wind, 2-m temperature and 2-m moisture.
max_stheight_diff	Stations whose model-interpolated elevation is different from the actual observation elevation by greater than this value (default: 100.0) in meters will be rejected.

The following options apply only for SYNOP observations

sfc_hori_intp_options	Specifies the method of interpolating the background to observation space 1 (default): 4-point interpolation 2: Chooses values from neighboring model gridpoint with smallest height difference (among land points: grid points over water will not be used).
obs_err_inflate	false (default): Observation error will be used as specified from observation files true: Inflate observation error values by a factor of e^(|Zdiff|/stn_ht_diff_scale)
stn_ht_diff_scale	If obs_err_inflate=true, observation error will be inflated by a factor of e^(|Zdiff|/stn_ht_diff_scale). Default is 200.0

Description of Namelist Variables

a. WRFDA namelist variables

&wrfvar1

Variable Name	Default Value	Description
write_increments	false	.true.: write out a binary analysis increment file
var4d	false	.true.: 4D-Var mode

var4d_lbc	true	.true.: on/off for lateral boundary control in 4D-Var
var4d_bin	3600	seconds, observation sub-window length for 4D-Var
var4d_bin_rain	3600	seconds, precipitation observation sub-window length for 4D-Var
multi_inc	0	> 0: multi-incremental run
print_detail_radar	false	print_detail_xxx: output extra (sometimes can be too many) diagnostics for debugging; not recommended to turn these on for production runs
print_detail_xa	false	
print_detail_xb	false	
print_detail_obs	false	
print_detail_grad	false	.true.: to print out a detailed gradient of each observation type at each iteration
check_max_iv_print	true	obsolete (used only by Radar)
update_sfc_diags	false	.true.: update T2/Q2/U10/V10/TH2 with WRFDA re-diagnosed values. Use only with sf_sfclay_physics=91 in WRF

&wrfvar2

Variable Name	Default Value	Description
analysis_accu	900	in seconds: if the time difference between the namelist date (analysis_date) and date info read-in from the first guess is larger than analysis_accu, WRFDA will abort.
calc_w_increment	false	.true.: the increment of the vertical velocity, W, will be diagnosed based on the increments of other fields. .false.: the increment of the vertical velocity W is zero if no W information is assimilated. If there is information on the W from observations assimilated, such as radar radial velocity, the W increments are always computed, whether calc_w_increment=true. or .false.
wind_sd	false	true: wind values which are reported as speed/direction will be assimilated as such false: (default behavior) all wind obs are converted to u/v prior to assimilation
qc_rej_both	false	true: if either u or v (spd or dir) do not pass quality control, both obs are rejected false: (default behavior) qc on wind obs is handled individually

&wrfvar3

Variable Name	Default Value	Description
fg_format	1	1: fg_format_wrf_arw_regional (default) 3: fg_format_wrf_arw_global 4: fg_format_kma_global

		Options 3 and 4 are untested; use with caution!
ob_format	2	1: read in NCEP PREPBUFR data from ob.bufr 2: read in data from ob.ascii (default)
ob_format_gpsro	2	1: read in GPSRO data from gpsro.bufr 2: read in GPSRO data from ob.ascii (default)
num_fgat_time	1	1: 3DVar > 1: number of time slots for FGAT and 4DVAR

&wrfvar4

Variable Name	Default Value	Description
thin_conv	true	Turns on observation thinning for ob_format=1 (NCEP PREPBUFR) only. thin_conv can be set to .false., but this is not recommended.
thin_conv_ascii	false	Turns on observation thinning for ob_format=2 (ASCII from OBSPROC) only.
thin_mesh_conv	20. (max_instrumerand the index/order follows the definition in ts)	km, each observation type can set its thinning mesh WRFDA/var/da/da_control/da_control.f90
use_synopobs	true	use_xxxobs - .true.: assimilate xxx obs if available .false.: do not assimilate xxx obs even available
use_shipsobs	true	
use_metarobs	true	
use_soundobs	true	
use_pilotobs	true	
use_airepobs	true	
use_geoamvobs	true	
use_polaramvobs	true	
use_bogusobs	true	
use_buoyobs	true	
use_profilerobs	true	
use_satemobs	true	
use_gpspwobs	true	
use_gpsztdobs	**false**	Note: unlike most use_*obs variables, the default for use_gpsztdobs is false. This is because PW and ZTD observations can not be assimilated simultaneously, so one of them must be false.
use_gpsrefobs	true	
use_qscatobs	true	
use_radarobs	false	.true.: Assimilate radar data
use_radar_rv	false	Assimilate radar velocity observations
use_radar_rf	false	Assimilate radar reflectivity using original reflectivity operator (total mixing ratio)
use_radar_rhv	false	Assimilate retrieved hydrometeors (qr, qs, qg) from radar reflectivity

use_radar_rqv	false	Assimilate estimated humidity (qv) from radar reflectivity
use_rainobs	false	.true.: Assimilate precipitation data
thin_rainobs	true	.true.: perform thinning on precipitation data
use_airsretobs	true	

; use_hirs2obs, use_hirs3obs, use_hirs4obs, use_mhsobs, use_msuobs,
; use_amsuaobs, use_amsubobs, use_airsobs, use_eos_amsuaobs, use_ssmisobs are
; radiance-related variables that only control if corresponding BUFR files are read
; into WRFDA or not, but do not control if the data is assimilated or not. Additional
; variables have to be set in &wrfvar14 in order to assimilate radiance data.

use_hirs2obs	false	.true.: read in data from hirs2.bufr
use_hirs3obs	false	.true.: read in data from hirs3.bufr
use_hirs4obs	false	.true.: read in data from hirs4.bufr
use_mhsobs	false	.true.: read in data from mhs.bufr
use_msuobs	false	.true.: read in data from msu.bufr
use_amsuaobs	false	.true.: read in data from amsua.bufr
use_amsubobs	false	.true.: read in data from amsub.bufr
use_airsobs	false	.true.: read in data from airs.bufr
use_eos_amsuaobs	false	.true.: read in data EOS-AMSUA data from airs.bufr
use_ssmisobs	false	.true.: to read in data from ssmis.bufr
use_atmsobs	false	.true.: to read in data from atms.bufr
use_iasiobs	false	.true.: to read in data from iasi.bufr
use_seviriobs	false	.true.: to read in data from seviri.bufr
use_amsr2obs	false	.true.: to read in data from AMSR2 files (see section "Other data formats" for file names)
use_obs_errfac	false	.true.: apply obs error tuning factors if errfac.dat is available for conventional data only

&wrfvar5

Variable Name	Default Value	Description
check_max_iv	true	.true.: reject the observations whose innovations (O-B) are larger than a maximum value defined as a multiple of the observation error for each observation. i.e., inv > (obs_error*factor) --> fails_error_max; the default maximum value is 5 times the observation error ; the factor of 5 can be changed through max_error_* settings.
max_error_t	5.0	maximum check_max_iv error check factor for t
max_error_uv	5.0	maximum check_max_iv error check factor for u and v
max_error_pw	5.0	maximum check_max_iv error check factor for precipitable water
max_error_ref	5.0	maximum check_max_iv error check factor for gps refractivity
max_error_q	5.0	maximum check_max_iv error check factor for specific humidity

max_error_p	5.0	maximum check_max_iv error check factor for pressure
max_error_thickness	5.0	maximum check_max_iv error check factor for thickness
max_error_rv	5.0	maximum check_max_iv error check factor for radar radial velocity
max_error_rf	5.0	maximum check_max_iv error check factor for radar reflectivity
max_error_rain	5.0	maximum check_max_iv error check factor for precipitation
max_error_spd	5.0	maximum check_max_iv error check factor for wind speed (wind_sd=.true. only)
max_error_dir	5.0	maximum check_max_iv error check factor for wind direction (wind_sd=.true. only)
put_rand_seed	false	For RANDOMCV: setting to "true" allows you to enter your own seed numbers (see &wrfvar11) to generate random background perturbations.

&wrfvar6 (for minimization options)

Variable Name	Default Value	Description
max_ext_its	1	number of outer loops
ntmax	200 (max_ext_its)	maximum number of iterations in an inner loop criterion (uses dimension: max_ext_its)
eps	0.01 (max_ext_its)	minimization convergence criterion (uses dimension: max_ext_its); minimization stops when the norm of the gradient of the cost function gradient is reduced by a factor of eps. inner minimization stops either when the criterion is met or when inner iterations reach ntmax.
orthonorm_gradient	false	.true.: the gradient vectors are stored during the Conjugate Gradient for each iteration and used to re-orthogonalize the new gradient. This requires extra storage of large vectors (each one being the size of the control variable) but results in a better convergence of the Conjugate Gradient after around 20 iterations.

&wrfvar7

Variable Name	Default Value	Description
cv_options	5	3: NCEP Background Error model 5: NCAR Background Error model (default) 6: Use of moisture-multivariate background error statistics (CV6) 7: New NCAR Background Error model (CV7)
cloud_cv_options	0	0: no hydrometeor/cloud control variables 1: Q_total control variable 3: Use individual cloud/hydrometeor control variables: Q_cloud, Q_rain, Q_ice, Q_snow, Q_graupel

use_cv_w	false	true: turns on W (vertical velocity) as a control variable. Works for cloud_cv_options=3 only
as1(3)	0.25, 1.0, 1.5	tuning factors for variance, horizontal and vertical scales for control variable 1 = stream function. For cv_options=3 only.
as2(3)	0.25, 1.0, 1.5	tuning factors for variance, horizontal and vertical scales for control variable 2 - unbalanced potential velocity. For cv_options=3 only.
as3(3)	0.25, 1.0, 1.5	tuning factors for variance, horizontal and vertical scales for control variable 3 - unbalanced temperature. For cv_options=3 only.
as4(3)	0.25, 1.0, 1.5	tuning factors for variance, horizontal and vertical scales for control variable 4 - pseudo relative humidity. For cv_options=3 only.
as5(3)	0.25, 1.0, 1.5	tuning factors for variance, horizontal and vertical scales for control variable 5 - unbalanced surface pressure. For cv_options=3 only.
rf_passes	6	number of passes of recursive filter.
var_scaling1	1.0	tuning factor of background error covariance for control variable 1 - stream function. For cv_options=5, 6, and 7 only.
var_scaling2	1.0	tuning factor of background error covariance for control variable 2 - unbalanced velocity potential. For cv_options=5, 6, and 7 only.
var_scaling3	1.0	tuning factor of background error covariance for control variable 3 - unbalanced temperature. For cv_options=5, 6, and 7 only.
var_scaling4	1.0	tuning factor of background error covariance for control variable 4 - pseudo relative humidity. For cv_options=5, 6, and 7 only.
var_scaling5	1.0	tuning factor of background error covariance for control variable 5 - unbalanced surface pressure. For cv_options=5, 6, and 7 only.
len_scaling1	1.0	tuning factor of scale-length for stream function. For cv_options=5, 6, and 7 only.
len_scaling2	1.0	tuning factor of scale-length for unbalanced velocity potential. For cv_options=5, 6, and 7 only.
len_scaling3	1.0	tuning factor of scale-length for unbalanced temperature. For cv_options=5, 6, and 7 only.
len_scaling4	1.0	tuning factor of scale-length for pseudo relative humidity. For cv_options=5, 6, and 7 only.
len_scaling5	1.0	tuning factor of scale-length for unbalanced surface pressure. For cv_options=5, 6, and 7 only.
je_factor	1.0	ensemble covariance weighting factor

&wrfvar8 not used

&wrfvar9 (for program tracing)

Variable Name	Default Value	Description
stdout	6	unit number for standard output
stderr	0	unit number for error output
trace_unit	7	Unit number for tracing output. Note that units 10 and 9 are reserved for reading namelist.input and writing namelist.output respectively.
trace_pe	0	Currently, statistics are always calculated for all processors, and output by processor 0.
trace_repeat_head	10	the number of times any trace statement will produce output for any particular routine. This stops overwhelming trace output when a routine is called multiple times. Once this limit is reached a 'going quiet' message is written to the trace file, and no more output is produced from the routine, though statistics are still gathered.
trace_repeat_body	10	see trace_repeat_head description
trace_max_depth	30	define the deepest level to which tracing writes output
trace_use	false	.true.: activate tracing. Tracing gives additional performance diagnostics (calling tree, local routine timings, overall routine timings, & memory usage). It does not change results, but does add runtime overhead.
trace_use_frequent	false	.true.: activate tracing for **all** subroutines, even frequently called ones. Adds significant runtime overhead
trace_use_dull	false	
trace_memory	true	.true.: calculate allocated memory using a mallinfo call. On some platforms (Cray and Mac), mallinfo is not available and no memory monitoring can be done.
trace_all_pes	false	.true.: tracing is output for all pes. As stated in trace_pe, this does not change processor statistics.
trace_csv	true	.true.: tracing statistics are written to a xxxx.csv file in CSV format
use_html	true	.true.: tracing and error reporting routines will include HTML tags.
warnings_are_fatal	false	.true.: warning messages that would normally allow the program to continue are treated as fatal errors.

&wrfvar10 (for code developers)

Variable Name	Default Value	Description
test_transforms	false	.true.: perform adjoint tests
test_gradient	false	.true.: perform gradient test

&wrfvar11

Variable Name	Default Value	Description
check_rh	0	0 --> No supersaturation check after minimization. 1 --> supersaturation (rh> 100%) and minimum rh (rh<10%) check, and make the local adjustment of q. 2 --> supersaturation (rh> 95%) and minimum rh (rh<11%) check and make the multi-level q adjustment under the constraint of conserved column integrated water vapor
sfc_assi_options	1	1 --> surface observations will be assimilated based on the lowest model level first guess. Observations are not used when the elevation difference between the observing site and the lowest model level is larger than max_stheight_diff. 2 --> surface observations will be assimilated based on surface similarity theory in PBL. Innovations are computed based on 10-m wind, 2-m temperature and 2-m moisture.
max_stheight_diff	100.0	Height difference in meters. Stations whose model-interpolated height is different from the actual observation station height by more than this value will be rejected.
sfc_hori_intp_options	1	(SYNOP only) Specifies the method of interpolating the background to observation space 1: 4-point interpolation 2: Chooses values from neighboring model gridpoint with smallest height difference (among land points: grid points over water will not be used).
q_error_options	1	(SYNOP only) Method for calculating Q error values from RH error values 1 (default): original method 2: new method
obs_err_inflate	false	(SYNOP only) Observation error will be used as specified from observation files true: Inflate observation error values by a factor of e^(|Zdiff|/stn_ht_diff_scale)
stn_ht_diff_scale	200.0	(SYNOP only) If obs_err_inflate=true, observation error will be inflated by a factor of e^(|Zdiff|/stn_ht_diff_scale). Default is 200.0
psfc_from_slp	false	.true.: when sfc_assi_options=1, re-calculates Psfc from SLP when the observation elevation is below the lowest model level height. This was the behavior prior to V3.8, but is not recommended.
calculate_cg_cost_fn	false	conjugate gradient algorithm does not require the

		computation of cost function at every iteration during minimization. .true.: Compute and write out cost function for each iteration into file `cost_fn` for diagnostic purposes false.: Only the initial and final cost functions are computed and output.
`write_detail_grad_fn`	false	.true.: Write out gradient for each iteration into file `grad_fn` for diagnostic purposes
`seed_array1`	1	For RANDOMCV when `put_rand_seed=true`, first integer for seeding the random function
`seed_array2`	1	For RANDOMCV when `put_rand_seed=true`, second integer for seeding the random function

&wrfvar12

Variable Name	Default Value	Description
`use_wpec`	false	true: enables the WPEC dynamic constraint term
`wpec_factor`	0.001	WPEC dynamic constraint weighting factor
`balance_type`	3	1 = geostrophic term only 2 = cyclostrophic term only 3 = geostrophic + cyclostrophic terms

&wrfvar13

Variable Name	Default Value	Description
`max_vert_var1`	99.0	specify the maximum truncation value (percentage) to explain the variance of stream function in eigenvector decomposition
`max_vert_var2`	99.0	specify the maximum truncation value (percentage) to explain the variance of unbalanced potential velocity in eigenvector decomposition
`max_vert_var3`	99.0	specify the maximum truncation value (percentage) to explain the variance of the unbalanced temperature in eigenvector decomposition
`max_vert_var4`	99.0	specify the maximum truncation value (percentage) to explain the variance of pseudo relative humidity in eigenvector decomposition
`max_vert_var5`	99.0	for unbalanced surface pressure, it should be a non-zero positive number. set max_vert_var5=0.0 only for offline VarBC applications.
`psi_chi_factor`	1.0	Contribution of stream function in defining balanced part of velocity potential. For cv_options=6 only.
`psi_t_factor`	1.0	Contribution of stream function in defining balanced part of temperature. For cv_options=6 only.
`psi_ps_factor`	1.0	Contribution of stream function in defining balanced part of surface pressure. For cv_options=6 only.
`psi_rh_factor`	1.0	Contribution of stream function in defining balanced part of moisture. For cv_options=6 only.

chi_u_t_factor	1.0	Contribution of the unbalanced part of velocity potential in defining balanced part of temperature. For cv_options=6 only.
chi_u_ps_factor	1.0	Contribution of the unbalanced part of velocity potential in defining balanced part of surface pressure. For cv_options=6 only.
chi_u_rh_factor	1.0	Contribution of the unbalanced part of velocity potential in defining balanced part of moisture. For cv_options=6 only.
t_u_rh_factor	1.0	Contribution of the unbalanced part of temperature in defining balanced part of moisture. For cv_options=6 only.
ps_u_rh_factor	1.0	Contribution of the unbalanced part of surface pressure in defining balanced part of moisture. For cv_options=6 only.

&wrfvar14 (radiance options)

Variable Name	Default Value	Description
rtminit_nsensor	1	total number of sensors to be assimilated
rtminit_platform	-1 (max_instruments)	platforms IDs array (used dimension: rtminit_nsensor); e.g., 1 for NOAA, 9 for EOS, 10 for METOP and 2 for DMSP
rtminit_satid	-1.0 (max_instruments)	satellite IDs array (used dimension: rtminit_nsensor)
rtminit_sensor	-1.0 (max_instruments)	sensor IDs array (used dimension: rtminit_nsensor); e.g., 0 for HIRS, 3 for AMSU-A, 4 for AMSU-B, 15 for MHS, 10 for SSMIS, 11 for AIRS
rad_monitoring	0 (max_instruments)	integer array (used dimension: rtminit_nsensor); 0: assimilating mode; 1: monitoring mode (only calculate innovations)
thinning_mesh	60.0 (max_instruments)	real array (used dimension: rtminit_nsensor); specify thinning mesh size (in km) for different sensors.
thinning	false	.true.: perform thinning on radiance data
qc_rad	true	.true.: perform quality control. Do not change.
write_iv_rad_ascii	false	.true.: output radiance Observation minus Background files, which are in ASCII format and separated by sensor and processor.
write_oa_rad_ascii	false	.true.: output radiance Observation minus Analysis files (Observation minus Background information is also included), which are in ASCII format and separated by sensor and processor.
use_error_factor_rad	false	.true.: use a radiance error tuning factor file radiance_error.factor, which can be created with empirical values or generated using variational tuning method (Desroziers and Ivanov,

		2001)
use_antcorr	false (max_instruments)	.true.: perform Antenna Correction in CRTM
rtm_option	1	which RTM (Radiative Transfer Model) to use (To use RTTOV, WRFDA must be compiled to include RTTOV libraries; see first section for details) 1: RTTOV 2: CRTM
only_sea_rad	false	.true.: assimilate radiance over water only
use_varbc	false	.true.: perform Variational Bias Correction. A parameter file in ASCII format called VARBC.in (a template is provided with the source code tar ball) is required.
freeze_varbc	false	.true: together with use_varbc=.false., keep the VarBC bias parameters constant in time. In this case, the bias correction is read and applied to the innovations, but it is not updated during the minimization.
varbc_factor	1.0	for scaling the VarBC preconditioning
varbc_nobsmin	10	defines the minimum number of observations required for the computation of the predictor statistics during the first assimilation cycle. If there are not enough data (according to "VARBC_NOBSMIN") on the first cycle, the next cycle will perform a coldstart again.
use_clddet_mmr	false	.true. :use the MMR scheme to conduct cloud detection for infrared radiance
use_clddet_ecmwf	false	.true. :use the ECMWF operational scheme to conduct cloud detection for infrared radiance.
airs_warmest_fov	false	.true.: uses the observation brightness temperature for AIRS Window channel #914 as criterion for GSI thinning (with a higher amplitude than the distance from the observation location to the nearest grid point).
use_crtm_kmatrix	true	.true. use CRTM K matrix rather than calling CRTM TL and AD routines for gradient calculation, which reduces runtime noticeably.
crtm_cloud	false	.true. include cloud effects in CRTM calculations (AMSR2 instrument only) .false. do not include cloud effects (non-clear-sky pixels will be rejected)
use_rttov_kmatrix	false	.true. use RTTOV K matrix rather than calling RTTOV TL and AD routines for gradient calculation, which reduces runtime noticeably.
rttov_emis_atlas_ir	0	0: do not use IR emissivity atlas

		1: use IR emissivity atlas (recommended)
rttov_emis_atlas_mw	0	0: do not use MW emissivity atlas 1: use TELSEM MW emissivity atlas (recommended) 2: use CNRM MW emissivity atlas
use_blacklist_rad	true	true.: switch off the assimilation of known problematic channels (up to year 2012) that are hard-coded in var/da/da_radiance/da_blacklist_rad.inc. false.: users need to specify proper channel selections in the radiance_info files.

&wrfvar15 (needs to be set together with &wrfvar19)

Variable Name	Default Value	Description
num_pseudo	0	Set the number of pseudo observations, either 0 or 1 (single ob)
pseudo_x	1.0	Set the x-position (I) of the OBS in unit of grid-point.
pseudo_y	1.0	Set the y-position (J) of the OBS in unit of grid-point.
pseudo_z	1.0	Set the z-position (K) of OBS with the vertical level index, in bottom-up order.
pseudo_val	1.0	Set the innovation of the ob; wind in m/s, pressure in Pa, temperature in K, specific humidity in kg/kg
pseudo_err	1.0	set the error of the pseudo ob. Unit the same as pseudo_val.; if pseudo_var="q", pseudo_err=0.001 is more reasonable.

&wrfvar16 (hybrid DA options)

Variable Name	Default Value	Description
use_4denvar	.false.	.true.: activate 4DEnVar capability .false.: No 4DEnVar
hybrid_dual_res	.false.	.true.: activate dual-resolution hybrid capability .false.: No dual-resolution hybrid
ensdim_alpha	0	ensemble size
alphacv_method	2	1: ensemble perturbations in control variable space 2: ensemble perturbations in model variable space
alpha_corr_type	3	1: alpha_corr_type_exp 2: alpha_corr_type_soar 3: alpha_corr_type_gaussian (default)
alpha_corr_scale	200.0	Hybrid covariance localization (km)
alpha_std_dev	1.0	Alpha standard deviation
alpha_vertloc	.false.	.true.: use vertical localization (recommended) .false.: no vertical localization

&wrfvar17

Variable Name	Default Value	Description
analysis_type	“3D-VAR”	"3D-VAR": 3D-VAR mode (default);

		"QC-OBS": 3D-VAR mode plus extra filtered_obs output; "VERIFY": verification mode. WRFDA resets check_max_iv=.false. and ntmax=0; "RANDOMCV": for creating ensemble perturbations
adj_sens	false	.true.: write out gradient of Jo for adjoint sensitivity

&wrfvar18

Variable Name	Default Value	Description
analysis_date	"2002-08-03_00:00:00.0000"	specify the analysis time. It should be consistent with the first guess time; if time difference between analysis_date and date info read in from first guess is larger than the &wrfvar2 setting "analysis_accu", WRFDA will abort.

&wrfvar19 (needs to be set together with &wrfvar15)

Variable Name	Default Value	Description
pseudo_var	"t"	Set the name of the OBS variable: 'u' = X-direction component of wind, 'v' = Y-direction component of wind, 't' = Temperature, 'p' = Pressure, 'q' = Specific humidity "tpw": total precipitable water "ref": refractivity "ztd": zenith total delay

&wrfvar20

documentation_url	"http://www.mmm.ucar.edu/people/wrfhelp/wrfvar/code/trunk"	

&wrfvar21

time_window_min	"2002-08-02_21:00:00.0000"	start time of assimilation time window used for ob_format=1 and radiances to select observations inside the defined time_window. Note: Start from V3.1, this variable is also used for ob_format=2 to double-check if the obs are within the specified time window.

&wrfvar22

time_window_max	"2002-08-03_03:00:00.0000"	end time of assimilation time window used for ob_format=1 and radiances to select observations inside the defined time_window. Note: this variable is also used for ob_format=2 to double-check if the obs are within the specified time window.

&perturbation (settings related to 4DVAR options)

jcdfi_use	false	.true.: Include JcDF term in cost function.

		.false.: Ignore JcDF term in cost function.
jcdfi_diag	1	0: Doesn't print out the value of Jc. 1:Print out the value of Jc.
jcdfi_penalty	10	The weight to Jc term.
enable_identity	.false.	.true.: use identity adjoint and tangent linear model in 4D-Var. .false.: use full adjoint and tangent linear model in 4D-Var.
trajectory_io	.true.	.true.: use memory I/O in 4D-Var for data exchange **NOTE:** `trajectory_io=false` **is depreciated and should not be used.** .false.: use disk I/O in 4D-Var for data exchange
var4d_detail_out	false	.true.: output extra diagnostics for debugging 4D-Var
&radar_da (settings related to radar options)		
radar_non_precip_opt	0	0 (default): no null-echo assimilation 1: KNU null-echo scheme
radar_non_precip_rf	-999.99	Reflectivity flag value (dBz) in observation file indicating non-precipitation echoes
radar_non_precip_rh_w	95	RH (%) with respect to water for non-precip retrieved Q_vapor (rqv)
radar_non_precip_rh_i	85	RH (%) with respect to water for non-precip rqv
cloudbase_calc_opt	1	Option for calculating cloud-base height: below this height retrieved humidity will not be assimilated for the use_radar_rqv option 0 (not recommended): fixed value of 1500 meters 1 (default): KNU scheme 2: NCAR scheme
radar_saturated_rf	25.0	rf value (dBz) used to indicate precipitation for rqv
radar_rqv_thresh1	40.0	rf value (dBz) used to scale down retrieved rqv
radar_rqv_thresh2	50.0	rf value (dBz) used to scale down retrieved rqv
radar_rqv_rh1	85	RH (%) for radar_saturated_rf < rf < radar_rqv_thresh1
radar_rqv_rh2	95	RH (%) for radar_rqv_thresh1 < rf < radar_rqv_thresh2
radar_rqv_h_lbound	-999.0	height (meters) lower bound for assimilating rqv
radar_rqv_h_ubound	-999.0	height (meters) upper bound for assimilating rqv

b. OBSPROC namelist variables

Variable Names	Description
&record1	
obs_gts_filename	name and path of decoded observation file
fg_format	'MM5' for MM5 application, 'WRF' for WRF application
obserr.txt	name and path of observational error file

first_guess_file	name and path of the first guess file
&record2	
time_window_min	The earliest time edge as ccyy-mm-dd_hh:mn:ss
time_analysis	The analysis time as ccyy-mm-dd_hh:mn:ss
time_window_max	The latest time edge as ccyy-mm-dd_hh:mn:ss ** Note : Only observations between [time_window_min, time_window_max] will kept.
&record3	
max_number_of_obs	Maximum number of observations to be loaded, i.e. in domain and time window, this is independent of the number of obs actually read.
fatal_if_exceed_max_obs	.TRUE.: will stop when more than max_number_of_obs are loaded .FALSE.: will process the first max_number_of_obs loaded observations.
&record4	
qc_test_vert_consistency	.TRUE. will perform a vertical consistency quality control check on sounding
qc_test_convective_adj	.TRUE. will perform a convective adjustment quality control check on sounding
qc_test_above_lid	.TRUE. will flag the observation above model lid
remove_above_lid	.TRUE. will remove the observation above model lid
domain_check_h	.TRUE. will discard the observations outside the domain
Thining_SATOB	.FALSE.: no thinning for SATOB data. .TRUE.: thinning procedure applied to SATOB data.
Thining_SSMI	.FALSE.: no thinning for SSMI data. .TRUE.: thinning procedure applied to SSMI data.
Thining_QSCAT	.FALSE.: no thinning for SATOB data. .TRUE.: thinning procedure applied to SSMI data.
&record5	
print_gts_read	TRUE. will write diagnostic on the decoded obs reading in file obs_gts_read.diag
print_gpspw_read	.TRUE. will write diagnostic on the gpsppw obs reading in file obs_gpspw_read.diag
print_recoverp	.TRUE. will write diagnostic on the obs pressure recovery in file obs_recover_pressure.diag
print_duplicate_loc	.TRUE. will write diagnostic on space duplicate removal in file obs_duplicate_loc.diag
print_duplicate_time	.TRUE. will write diagnostic on time duplicate removal in file obs_duplicate_time.diag
print_recoverh	.TRUE will write diagnostic on the obs height recovery in file obs_recover_height.diag
print_qc_vert	.TRUE will write diagnostic on the vertical consistency check in file obs_qc1.diag
print_qc_conv	.TRUE will write diagnostic on the convective adjustment check in file obs_qc1.diag

print_qc_lid	.TRUE. will write diagnostic on the above model lid height check in file obs_qc2.diag
print_uncomplete	.TRUE. will write diagnostic on the uncompleted obs removal in file obs_uncomplete.diag
user_defined_area	.TRUE.: read in the record6: x_left, x_right, y_top, y_bottom, .FALSE.: not read in the record6.
&record6	
x_left	West border of sub-domain, not used
x_right	East border of sub-domain, not used
y_bottom	South border of sub-domain, not used
y_top	North border of sub-domain, not used
ptop	Reference pressure at model top
ps0	Reference sea level pressure
base_pres	Same as ps0. User must set either ps0 or base_pres.
ts0	Mean sea level temperature
base_temp	Same as ts0. User must set either ts0 or base_temp.
tlp	Temperature lapse rate
base_lapse	Same as tlp. User must set either tlp or base_lapse.
pis0	Tropopause pressure, the default = 20000.0 Pa
base_tropo_pres	Same as pis0. User must set either pis0 or base_tropo_pres
tis0	Isothermal temperature above tropopause (K), the default = 215 K.
base_start_temp	Same as tis0. User must set either tis0 or base_start_temp.
&record7	
IPROJ	Map projection (0 = Cylindrical Equidistance, 1 = Lambert Conformal, 2 = Polar stereographic, 3 = Mercator)
PHIC	Central latitude of the domain
XLONC	Central longitude of the domain
TRUELAT1	True latitude 1
TRUELAT2	True latitude 2
MOAD_CEN_LAT	The central latitude for the Mother Of All Domains
STANDARD_LON	The standard longitude (Y-direction) of the working domain.
&record8	
IDD	Domain ID (1=< ID =< MAXNES), Only the observations geographically located on that domain will be processed. For WRF application with XLONC /= STANDARD_LON, set IDD=2, otherwise set 1.
MAXNES	Maximum number of domains as needed.
NESTIX	The I(y)-direction dimension for each of the domains
NESTJX	The J(x)-direction dimension for each of the domains
DIS	The resolution (in kilometers) for each of the domains. For WRF application, always set NESTIX(1),NESTJX(1), and DIS(1) based on the information in wrfinput.
NUMC	The mother domain ID number for each of the domains
NESTI	The I location in its mother domain of the nest domain's low left corner -- point (1,1)

NESTI	The J location in its mother domain of the nest domain's low left corner -- point (1,1). For WRF application, NUMC(1), NESTI(1), and NESTJ(1) are always set to be 1.
&record9	
prep-bufr_output_filename	Name of the PREPBUFR OBS file.
prep-bufr_table_filename	'prepbufr_table_filename' ; do not change
output_ob_format	output 1, PREPBUFR OBS file only; 2, ASCII OBS file only; 3, Both PREPBUFR and ASCII OBS files.
use_for	'3DVAR' obs file, same as before, default 'FGAT ' obs files for FGAT '4DVAR' obs files for 4DVAR
num_slots_past	the number of time slots before time_analysis
num_slots_ahead	the number of time slots after time_analysis
write_synop	If keep synop obs in obs_gts (ASCII) files.
write_ship	If keep ship obs in obs_gts (ASCII) files.
write_metar	If keep metar obs in obs_gts (ASCII) files.
write_buoy	If keep buoy obs in obs_gts (ASCII) files.
write_pilot	If keep pilot obs in obs_gts (ASCII) files.
write_sound	If keep sound obs in obs_gts (ASCII) files.
write_amdar	If keep amdar obs in obs_gts (ASCII) files.
write_satem	If keep satem obs in obs_gts (ASCII) files.
write_satob	If keep satob obs in obs_gts (ASCII) files.
write_airep	If keep airep obs in obs_gts (ASCII) files.
write_gpspw	If keep gpspw obs in obs_gts (ASCII) files.
write_gpsztd	If keep gpsztd obs in obs_gts (ASCII) files.
write_gpsref	If keep gpsref obs in obs_gts (ASCII) files.
write_gpseph	If keep gpseph obs in obs_gts (ASCII) files.
write_ssmt1	If keep ssmt1 obs in obs_gts (ASCII) files.
write_ssmt2	If keep ssmt2 obs in obs_gts (ASCII) files.
write_ssmi	If keep ssmi obs in obs_gts (ASCII) files.
write_tovs	If keep tovs obs in obs_gts (ASCII) files.
write_qscat	If keep qscat obs in obs_gts (ASCII) files.
write_profl	If keep profile obs in obs_gts (ASCII) files.
write_bogus	If keep bogus obs in obs_gts (ASCII) files.
write_airs	If keep airs obs in obs_gts (ASCII) files.

Chapter 7: Objective Analysis (OBSGRID)

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Introduction

The goal of objective analysis in meteorological modeling is to improve meteorological analyses (the *first guess*) on the mesoscale grid by incorporating information from observations. Traditionally, these observations have been "direct" observations of temperature, humidity, and wind from surface and radiosonde reports. As remote sensing techniques come of age, more and more "indirect" observations are available for researchers and operational modelers. Effective use of these indirect observations for objective analysis is not a trivial task. Methods commonly employed for indirect observations include three-dimensional or four-dimensional variational techniques ("3DVAR" and "4DVAR", respectively), which can be used for direct observations as well.

This chapter discusses the objective analysis program, OBSGRID. Discussion of variational techniques (*WRFDA*) can be found in Chapter 6 of this User's Guide.

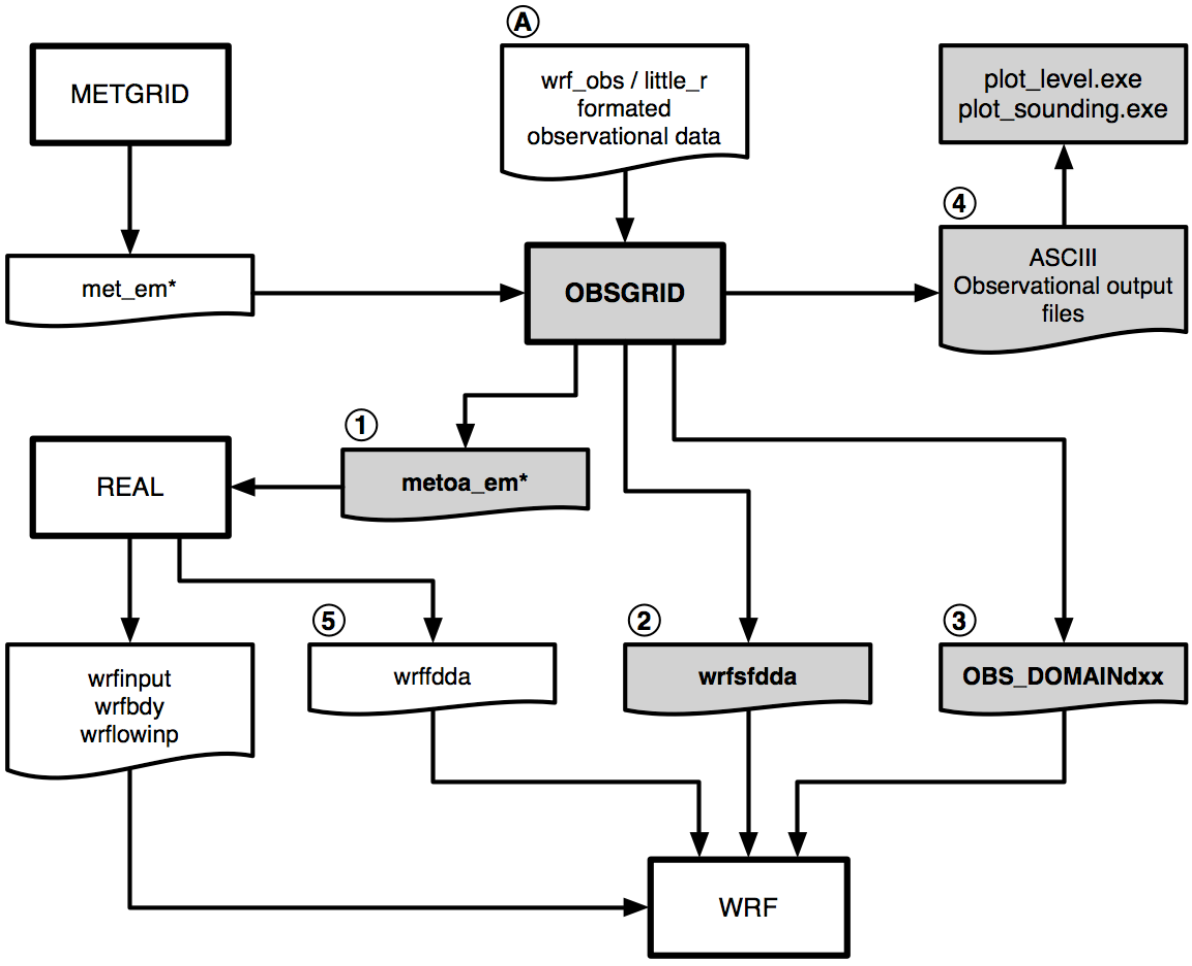
The analyses input to OBSGRID as the first guess are analyses output from the METGRID part of the WPS package (*see Chapter 3 of this User's Guide for details regarding the WPS package*).

OBSGRID capabilities include:

- Choice of Cressman-style or Multiquadric objective analysis.
- Various tests to screen the data for suspect observations.
- Procedures to input bogus data.
- Expanded Grid: OBSGRID has the capability to cut the input model domain down on output. This feature allows you to incorporate data from outside your intended grid to improve analyses near the boundaries. To use this feature, a user must create a larger domain than the final intended domain when running WPS.

Program Flow

OBSGRID is run directly after `metgrid.exe`, and uses the *met_em** output files from `metgrid.exe` as input. OBSGRID also requires additional observations (**A**) as input. The format of these observational files is described in the Observations Format section of this chapter.



Output from the objective analysis programs can be used to:

- Provide fields for Initial and Boundary conditions (1). Note that the files *metoa_em** are formatted identically to the *met_em** files from `metgrid.exe`. The only difference is that the fields in these files now incorporate observational information.
- Provide surface fields for surface-analysis-nudging *FDDA (2)*. Note, when using the *wrfsfdda* file as input to WRF, it is also recommended to use the 3-D fdda file *(wrffdda (5) – which is an optional output created when running `real.exe`)* as input to WRF.
- Provide data for observational nudging (3). Note: since version 3.1.1 of OBSGRID this file can be read directly by the observational nudging code and no longer needs to pass through an additional perl script.
- Provide ASCII and netCDF output (4). These files provide information regarding the observations used and the quality control flags assigned. The information in these files can also be plotted with the provided plotting utilities.

Source of Observations

OBSGRID reads observations provided by the user in formatted ASCII text files. This allows users to adapt their own data to use as input to the OBSGRID program. This format (*wrf_obs / little_r format*) is the same format used in the MM5 objective analysis program LITTLE_R (*hence the name*).

Programs are available to convert NMC ON29 and NCEP BUFR formatted files (*see below*) into the `wrf_obs / little_r` format. Users are responsible for converting other observations they may want to provide to OBSGRID into this format. A user-contributed (*i.e., unsupported*) program is available in the `utils/` directory for converting observation files from the GTS to `wrf_obs / little_r` format.

NCEP operational global surface and upper-air observation subsets, as archived by the Data Support Section (DSS) at *NCAR*.

- Upper-air data in NMC ON29 format *(from early 1970s to early 2000)* *http://rda.ucar.edu/datasets/ds353.4/*
- Surface data in NMC ON29 format *(from early 1970s to early 2000)* *http://rda.ucar.edu/datasets/ds464.0/*
- Upper-air data in NCEP BUFR format *(from 1999 to present)* *http://rda.ucar.edu/datasets/ds351.0/*
- Surface data in NCEP BUFR format *(from 1999 to present)* *http://rda.ucar.edu/datasets/ds461.0/*

The newer data *(ds351.0 and ds461.0)* is also available in the little_r format. From outside NCAR, this data can be download from the web, while it is available on the NCAR /glade

system for NCAR supercomputer users. This data is sorted into 6-hourly windows, which are typically too large for use in OBSGRID. To reorder this into 3-hourly windows:

- Get the little_r 6-hourly data
  - Non-NCAR super-computer users. Get the data directly from the above web sites. Combine (by using the Unix 'cat' command) all the surface and upper-air data into one large file called `rda_obs`.
  - NCAR super-computer users. Use the script `util/get_rda_data.csh`, to get the data and create the file `rda_obs`. You will need to edit this script to supply the date range that you are interested in.
- Compile the Fortran program `util/get_rda_data.f`. Place `rda_obs` file the in the top OBSGRID directory. Run the `util/get_rda_data.exe` executable. This executable will use the date range from namelist.oa, and create 3-hourly OBS:<date> files which are ready to use in OBSGRID.

NMC Office Note 29 can be found in many places on the World Wide Web, including: http://www.emc.ncep.noaa.gov/mmb/data_processing/on29.htm

Another method of obtaining little_r observations is to download observations from the Meteorological Assimilation Data Ingest System (MADIS; https://madis.noaa.gov/) and convert them to little_r format using the MADIS2LITTLER tool provided by NCAR (http://www2.mmm.ucar.edu/wrf/users/wrfda/download/madis.html). Note that to allow single-level above-surface observations to be properly dealt with by OBSGRID, MADIS2LITTLER must be modified to mark such observations as soundings (in module_output.F, subroutine write_littler_onelvl must be modified to set is_sound = .TRUE.).

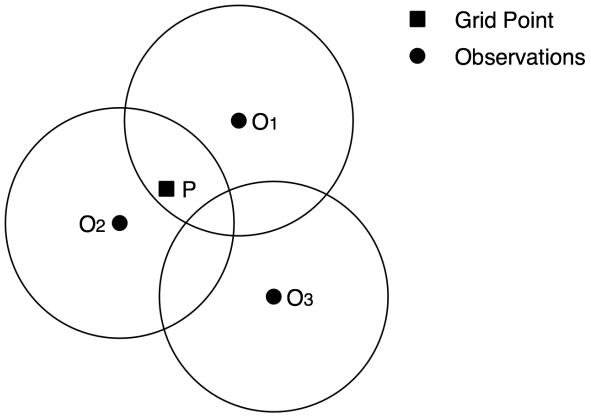
Objective Analysis techniques in OBSGRID

Cressman Scheme

Three of the four objective analysis techniques used in OBSGRID are based on the Cressman scheme, in which several successive scans nudge a first-guess field toward the neighboring observed values.

The standard Cressman scheme assigns to each observation a circular radius of influence, R. The first-guess field at each grid point, P, is adjusted by taking into account all the observations that influence P.

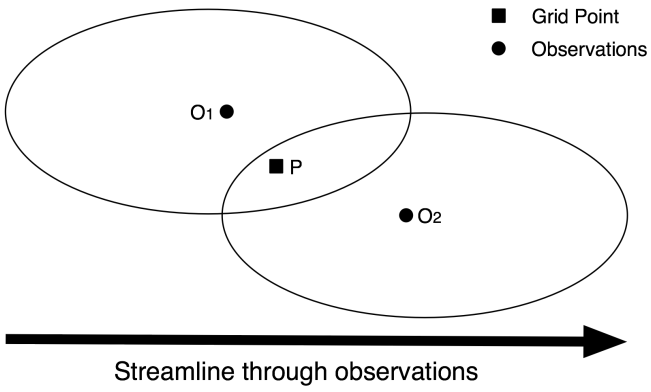
The differences between the first-guess field and the observations are calculated, and a distance-weighted average of these difference values is added to the value of the first-guess at P. Once all grid points have been adjusted, the adjusted field is used as the first guess for another adjustment cycle. Subsequent passes each use a smaller radius of influence.



Observations O_1 and O_2 influence grid point P, O_3 does not.

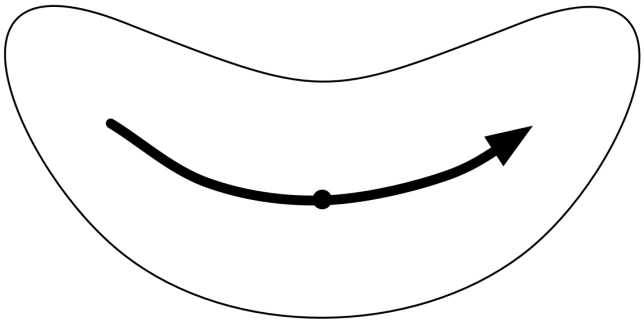
Ellipse Scheme

In analyses of wind and relative humidity (fields strongly deformed by the wind) at pressure levels, the circles from the standard Cressman scheme are elongated into ellipses, oriented along the flow. The stronger the wind, the greater the eccentricity of the ellipses. This scheme reduces to the circular Cressman scheme under low-wind conditions.



Banana Scheme

In analyses of wind and relative humidity at pressure levels, the circles from the standard Cressman scheme are elongated in the direction of the flow, and curved along the streamlines. The result is a banana shape. This scheme reduces to the Ellipse scheme under straight-flow conditions, and the standard Cressman scheme under low-wind conditions.



Multiquadric scheme

The Multiquadric scheme uses hyperboloid radial basis functions to perform the objective analysis. Details of the multiquadric technique may be found in Nuss and Titley, 1994: "Use of multiquadric interpolation for meteorological objective analysis." *Mon . Wea . Rev .*, 122, 1611-1631. Use this scheme with caution, as it can produce some odd results in areas where only a few observations are available.

Quality Control for Observations

A critical component of OBSGRID is the screening for bad observations. Many of these QC checks are optional in OBSGRID.

Quality Control on Individual Reports

- Gross Error Checks (same values, pressure decreases with height, etc.)
- Remove spikes from temperature and wind profiles.
- Adjust temperature profiles to remove superadiabatic layers.
- No comparisons to other reports or to the first-guess field.

The ERRMAX test

The ERRMAX quality-control check is optional, but highly recommended.

- Limited user control over data removal. The user may set thresholds, which vary the tolerance of the error check.
- Observations are compared to the first-guess field.
- If the difference value (obs - first-guess) exceeds a certain threshold, the observation is discarded.
- Threshold varies depending on the field, level, and time of day.
- Works well with a good first-guess field.

The Buddy test

The Buddy check is optional, but highly recommended.

- Limited user control over data removal. The user may set weighting factors, which vary the tolerance of the error check.
- Observations are compared to both the first guess and neighboring observations.
- If the difference value of an observation (obs - first-guess) varies significantly from the distance-weighted average of the difference values of neighboring observations, the observation is discarded.
- Works well in regions with good data density.

Additional Observations

Input of additional observations, or modification of existing (*and erroneous*) observations, can be a useful tool at the objective analysis stage.

In OBSGRID, additional observations are provided to the program the same way (*in the same wrf_obs / little_r format*) as standard observations. Additional observations must be in the same file as the rest of the observations. Existing (*erroneous*) observations can be modified easily, as the observations input format is ASCII text. Identifying an observation report as "bogus" simply means that it is assumed to be good data, but no quality control is performed for that report.

Surface FDDA option

The surface FDDA option creates additional analysis files for the surface only, usually with a smaller time interval between analyses (*i.e., more frequently*) than the full upper-air analyses. The purpose of these surface analysis files is for later use in WRF with the surface analysis nudging option.

The LAGTEM option controls how the first-guess field is created for surface analysis files. Typically, the surface and upper-air first-guess (*analysis times*) is available at twelve-hour or six-hour intervals, while the surface analysis interval may be 3 hours (*10800 seconds*). So at analysis times, the available surface first-guess is used. If LAGTEM is set to .**FALSE**., the surface first-guess at other times will be temporally interpolated from the first-guess at the analysis times. If

LAGTEM is set to .**TRUE**., the surface first guess at other times is the objective analysis from the previous time.

Objective Analysis on Model Nests

OBSGRID has the capability to perform the objective analysis on a nest. This is done manually with a separate OBSGRID process, performed on met_em_d0x files for the particular nest. Often, however, such a step is unnecessary; it complicates matters for the user and may introduce errors into the forecast. At other times, extra information available to the user, or extra detail that objective analysis may provide on a nest, makes objective analysis on a nest a good option.

The main reason to do objective analysis on a nest is if you have observations available with horizontal resolution somewhat greater than the resolution of your coarse domain. There may also be circumstances in which the representation of terrain on a nest allows for better use of surface observations (*i.e., the model terrain better matches the real terrain elevation of the observation*).

The main problem introduced by doing objective analysis on a nest is inconsistency in initial conditions between the coarse domain and the nest. Observations that fall just outside a nest will be used in the analysis of the coarse domain, but discarded in the analysis of the nest. With different observations used right at a nest boundary, one can get very different analyses.

How to run OBSGRID

Get the source code

The source code can be downloaded from: http://www2.mmm.ucar.edu/wrf/users/download/get_source.html. Once the tar file is gunzipped (gunzip OBSGRID.TAR.gz), and untared (untar OBSGRID.TAR), it will create an OBSGRID/ directory.

```
cd OBSGRID
```

Generate the executable

The only library that is required to build the WRF model is netCDF. The user can find the source code, precompiled binaries, and documentation at the UNIDATA home page (http://www.unidata.ucar.edu/software/netcdf/).

To successfully compile the utilities `plot_level.exe` and `plot_sounding.exe`, NCAR Graphics needs to be installed on your system. These routines are not necessary to run OBSGRID, but are useful for displaying observations. Since version 3.7.0 NCL scripts are available and therefore these two utilities are no longer needed to plot the data.

To configure, type:

```
./configure
```

Choose one of the configure options, then compile.

```
./compile
```

If successful, this will create the executable `obsgrid.exe`. Executables `plot_level.exe` and `plot_sounding.exe`, will be created if NCAR Graphics is installed.

Prepare the observations files

Preparing observational files is a user responsibility. Some data are available from NCAR's RDA web site. Data from the early 1970's are in ON29 format, while data from 1999 to present are in NCEP BUFR format. Help using these datasets are available. For more information see the section **Source of Observations** on page 7-3 of this Users' Guide.

A program is also available for reformatting observations from the GTS stream (*unsupported*). This can be found in OBSGRID/util, and is called *gts_cleaner.f*. The code expects to find one observational input file per analysis time. Each file should contain both surface and upper-air data *(if available)*.

Edit the namelist for your specific case

The most critical information you'll be changing most often is the start date, end date, and file names.

Pay particularly careful attention to the file name settings. Mistakes in observation file names can go unnoticed because OBSGRID will happily process the wrong files, and if there are no data in the (*wrongly-specified*) file for a particular time, OBSGRID will happily provide you with an analysis of no observations.

Run the program

Run the program by invoking the command:

```
./obsgrid.exe >& obsgrid.out
```

Check the `obsgrid.out` file for information and runtime errors.

Check your output

Examine the `obsgrid.out` file for error messages or warning messages. The program should have created the files called `metoa_em*.` Additional output files containing information about observations found, used and discarded will probably be created, as well.

Important things to check include the number of observations found for your objective analysis, and the number of observations used at various levels. This can alert you to possible problems in specifying observation files or time intervals. This information is included in the printout file.

You may also want to experiment with a couple of simple plot utility programs, discussed below.

There are a number of additional output files, which you might find useful. These are discussed below.

Output Files

The OBSGRID program generates some ASCII/netCDF files to detail the actions taken on observations through a time cycle of the program. In support of users wishing to plot the observations used for each variable (at each level, at each time), a file is created with this information. Primarily, the ASCII/netCDF files are for consumption by the developers for diagnostic purposes. The main output of the OBSGRID program is the gridded, pressure-level data set to be passed to the `real.exe` program (files `metoa_em`*).

In each of the files listed below, the text ".d*n*.YYYY-MM-DD_HH:mm:ss.tttt" allows each time period that is processed by OBSGRID to output a separate file. The only unusual information in the date string is the final four letters "tttt" which is the decimal time to ten thousandths of a second. These files will be dependent on the domain being processed.

metoa_em*

These are the final analysis files at surface and pressure levels. Generating this file is the primary goal of running OBSGRID.

These files can now be used in place of the *met_em** files from WPS to generate initial and boundary conditions for WRF. To use these files when running `real.exe` you can do one of two things:

1. Rename or link the *metoa_em** files back to *met_em**. This way `real.exe` will read the files automatically.
2. Use the *auxinput1_inname* namelist option in WRF's `namelist.input` file to overwrite the default filename `real.exe` uses. To do this, add the following to the *&time_control* section of the WRF `namelist.input` file before running `real.exe` *(use the exact syntax as below – do not substitute the <domain> and <date> for actual numbers)*:

   ```
   auxinput1_inname = "metoa_em.d<domain>.<date>"
   ```

wrfsfdda_d*n*

Use of the surface FDDA option in OBSGRID creates a file called `wrfsfdda_dn`. This file contains the surface analyses at INTF4D intervals, analyses of T, TH, U, V, RH, QV, PSFC, PMSL, and a count of observations within 250 km of each grid point.

Due to the input requirements of the WRF model, data at the current time (_OLD) and data for the next time (_NEW) are supplied at each time interval. *Due to this requirement, users must take care to specify the same interval in the WRF fdda section for surface nudging as the interval used in OBSGRID to create the wrfsfdda_dn file*. This also means that the user may need to have data available for OBSGRID to create a surface analysis beyond the last analysis actually used by WRF surface analysis nudging. With a positive value for the length of rampdown, even though the _OLD field at the beginning of the rampdown will be nudged throughout the rampdown, WRF still requires a _NEW field at the beginning of the rampdown period.

OBS_DOMAIN*dxx*

These files can be used in WRF for observational nudging. The format of this file is slightly different from the standard *wrf_obs / little_r* format. *See the Observation Nudging User's Guide or Chapter 5 of this User's Guide for details on observational nudging.*

The "*d*" in the file name represents the domain number. The "*xx*" is just a sequential number.

These files contain a list of all of the observations available for use by the OBSGRID program.

- The observations have been sorted and the duplicates have been removed.
- Observations outside of the analysis region have been removed.

- Observations with no information have been removed.
- All reports for each separate location *(different levels, but at the same time)* have been combined to form a single report.
- Data that has had the "discard" flag internally set *(data which will not be sent to the quality control or objective analysis portions of the code)* are not listed in this output.
- The data have gone through an expensive test to determine if the report is within the analysis region, and the data have been given various quality control flags. Unless a blatant error in the data is detected *(such as a negative sea-level pressure),* the observation data are not typically modified, but only assigned quality control flags.
- Data with qc flags higher than a specified value *(user controlled, via the namelist),* will be set to missing data.

The WRF observational nudging code requires that all observational data are available in a single file called OBS_DOMAINd01 *(where d is the domain number),* whereas OBSGRID creates one file per time. Therefore, to use these files in WRF, they should first be concatenated to a single file. A script *(run_cat_obs_files.csh)* is provided for this purpose. By running this script, the original OBS_DOMAINd01 files will be moved to OBS_DOMAINd01_sav, and a new OBS_DOMAINd01 file (containing all the observations for all times) will be created. This new file can be used directly in the WRF observational nudging code.

qc_obs_raw.d*n*.YYYY-MM-DD_HH:mm:ss.tttt(.nc)

This file contains a listing of all of the observations available for use by the OBSGRID program.

- The observations have been sorted and the duplicates have been removed.
- Observations outside of the analysis region have been removed.
- Observations with no information have been removed.
- All reports for each separate location *(different levels, but at the same time)* have been combined to form a single report.
- Data that has had the "discard" flag internally set *(data which will not be sent to the quality control or objective analysis portions of the code)* are not listed in this output.
- The data have gone through an expensive test to determine if the report is within the analysis region, and the data have been given various quality control flags. Unless a blatant error in the data is detected *(such as a negative sea-level pressure),* the observation data are not typically modified, but only assigned quality control flags.
- Two files are available, both containing identical information. One is the older ASCII format, while the other is in netCDF format.
- *The data in the ASCII file can be used as input to the plotting utility* `plot_sounding.exe`
- *The netCDF file can be used to plot both station data (util/station.ncl) and sounding data (util/sounding.ncl). This is available since version 3.7 and is the recommended option.*

qc_obs_used.d*n*.YYYY-MM-DD_HH:mm:ss.tttt(.nc)

These files are similar to the above "raw" files, and can be used in the same way. But in this case it contains the data used by the OBSGRID program, which are also the data saved to the OBS_DOMAINdxx files.

qc_obs_used_earth_relative.dn.YYYY-MM-DD_HH:mm:ss.tttt(.nc)

These files are identical to the above "qc_obs_used" files except that the winds are in an earth-relative framework rather than a model-relative framework. The non-netCDF version of these files can be used as input for the Model Evaluation Tools (MET; http://www.dtcenter.org/met/users/).

plotobs_out.d*n*.YYYY-MM-DD_HH:mm:ss.tttt

This file lists data by variable and by level, where each observation that has gone into the objective analysis is grouped with all of the associated observations for plotting or some other diagnostic purpose. The first line of this file is the necessary FORTRAN format required to input the data. There are titles over the data columns to aid in the information identification. Below are a few lines from a typical file. *This data can be used as input to the plotting utility* `plot_level.exe`. *But since version 3.7, it is recommended to use the* `station.ncl` *script that uses the data in the new netCDF data files.*

```
( 3x,a8,3x,i6,3x,i5,3x,a8,3x,2(g13.6,3x),2(f7.2,3x),i7 )
Number of Observations 00001214
Variable Press  Obs    Station Obs        Obs-1st   X         Y         QC
Name     Level  Number ID      Value      Guess     Location  Location  Value
U        1001   1      CYYT    6.39806    4.67690   161.51    122.96    0
U        1001   2      CWRA    2.04794    0.891641  162.04    120.03    0
U        1001   3      CWVA    1.30433   -1.80660   159.54    125.52    0
U        1001   4      CWAR    1.20569    1.07567   159.53    121.07    0
U        1001   5      CYQX    0.470500  -2.10306   156.58    125.17    0
U        1001   6      CWDO    0.789376  -3.03728   155.34    127.02    0
U        1001   7      CWDS    0.846182   2.14755   157.37    118.95    0
```

Plot Utilities

The OBSGRID package provides two utility programs for plotting observations. These programs are called `plot_soundings.exe` and `plot_levels.exe`. These optional programs use NCAR Graphics to build, which is often problematic. Two new NCL scripts are provided instead, `sounding.ncl` and `station.ncl`. Using these as opposed to the Fortran code are recommended.

sounding.ncl / plot_soundings.exe

The script `util/sounding.ncl` plots soundings. This script generates soundings from the netCDF files qc_obs_raw.d*n*.YYYY-MM-DD_HH:mm:ss.tttt.nc and qc_obs_used.d*n*.YYYY-MM-DD_HH:mm:ss.tttt.nc. Only data that are on the requested analysis levels are processed.

By default the script will plot the data from **all** the "qc_obs_used" files in the directory. This can be customized through the use of command line setting. For example:

ncl ./util/sounding.ncl 'qcOBS="raw"'
    will plot data from the "qc_obs_raw" files
ncl util/sounding.ncl YYYY=2010 MM=6
    will plot data from the "qc_obs_used" files for June 2010

Available command line options are:

qcOBS	Dataset to use. Options are "raw" or "used". Default is "used"
YYYY	Integer year to plot. Default is all available years.
MM	Integer month to plot. Default is all available months.
DD	Integer day to plot. Default is all available days.
HH	Integer hour to plot. Default is all available hours.
outTYPE	Output type. Default is plotting to the screen, i.e., "x11". Other options are "pdf" or "ps". The script creates the following output files(s): `qc_obs_<qcOBS>.sounding.<date>.<outTYPE>` for instance: qc_obs_used.sounding.2010-03-06_09.pdf

The older program `plot_soundings.exe` also plots soundings. This program generates soundings from the qc_obs_raw.d*n*.YYYY-MM-DD_HH:mm:ss.tttt and qc_obs_used.d*n*.YYYY-MM-DD_HH:mm:ss.tttt data files. Only data that are on the requested analysis levels are processed. The program uses information from `&record1, &record2` and `&plot_sounding` in the `namelist.oa` file to generate the required output. The program creates output file(s): `sounding_<file_type>_<date>.cgm`

plot_level.exe

The script `util/station.ncl` creates station plots for each analysis level. These plots contain both observations that have passed all QC tests and observations that have failed the QC tests. Observations that have failed the QC tests are plotted in various colors according to which test failed. This script generates soundings from the netCDF files qc_obs_raw.d*n*.YYYY-MM-DD_HH:mm:ss.tttt.nc and qc_obs_used.d*n*.YYYY-MM-DD_HH:mm:ss.tttt.nc.

By default the script will plot the data from **all** the "qc_obs_used" files in the directory. This can be customized through the use of command line setting. For example:

ncl ./util/station.ncl 'qcOBS="raw"'
will plot data from the "qc_obs_raw" files
ncl util/station.ncl YYYY=2010 MM=6
will plot data from the "qc_obs_used" files for June 2010

Available command line options are:

qcOBS	Dataset to use. Options are "raw" or "used". Default is "used"
YYYY	Integer year to plot. Default is all available years.
MM	Integer month to plot. Default is all available months.
DD	Integer day to plot. Default is all available days.
HH	Integer hour to plot. Default is all available hours.
outTYPE	Output type. Default is plotting to the screen, i.e., "x11". Other options are "pdf" or "ps". The script creates the following output files(s): `qc_obs_<qcOBS>.station.<date>.<outTYPE>` for instance: qc_obs_used.station.2010-03-06_09.pdf

The older program `plot_level.exe` creates station plots for each analysis level. These plots contain both observations that have passed all QC tests and observations that have failed the QC tests. Observations that have failed the QC tests are plotted in various colors according to which test failed. The program uses information from `&record1` and `&record2` in the `namelist.oa` file to generate plots from the observations in the file `plotobs_out.dn.YYYY-MM-DD_HH:mm:ss.tttt`. The program creates the file(s): `levels_<date>.cgm`.

Observations Format

To make the best use of the OBSGRID program, it is important for users to understand the *wrf_obs/little_r* Observations Format.

Observations are conceptually organized in terms of reports. A report consists of a single observation or set of observations associated with a single latitude/longitude coordinate.

Examples

- a surface station report including observations of temperature, pressure, humidity, and winds.
- an upper-air station's sounding report with temperature, humidity, and wind observations at many height or pressure levels.

- an aircraft report of temperature at a specific lat/lon/height.
- a satellite-derived wind observation at a specific lat/lon/height.

Each report in the *wrf_obs/little_r* Observations Format consists of at least four records:

- A *report header record*
- one or more *data records*
- an *end data record*
- an *end report record* .

The *report header record* is a 600-character-long record (*much of which is unused and needs only dummy values*) that contains certain information about the station and the report as a whole (location, station id, station type, station elevation, etc.). The report header record is described fully in the following table. Shaded items in the table are unused:

Report header format

Variable	Fortran I/O Format	Description
latitude	F20.5	station latitude (north positive)
longitude	F20.5	station longitude (east positive)
id	A40	ID of station
name	A40	Name of station
platform	A40	Description of the measurement device
source	A40	GTS, NCAR/ADP, BOGUS, etc.
elevation	F20.5	station elevation (m)
num_vld_fld	I10	Number of valid fields in the report
num_error	I10	Number of errors encountered during the decoding of this observation
num_warning	I10	Number of warnings encountered during decoding of this observation.
seq_num	I10	Sequence number of this observation
num_dups	I10	Number of duplicates found for this observation
is_sound	L10	T/F Above-surface or surface (i.e., all non-surface observations should use T, even above-surface single-level obs)
bogus	L10	T/F bogus report or normal one
discard	L10	T/F Duplicate and discarded (or merged) report.
sut	I10	Seconds since 0000 UTC 1 January 1970

julian	I10	Day of the year
date_char	A20	YYYYMMDDHHmmss
slp, qc	F13.5, I7	Sea-level pressure (Pa) and a QC flag
ref_pres, qc	F13.5, I7	Reference pressure level (for thickness) (Pa) and a QC flag
ground_t, qc	F13.5, I7	Ground Temperature (T) and QC flag
sst, qc	F13.5, I7	Sea-Surface Temperature (K) and QC
psfc, qc	F13.5, I7	Surface pressure (Pa) and QC
precip, qc	F13.5, I7	Precipitation Accumulation and QC
t_max, qc	F13.5, I7	Daily maximum T (K) and QC
t_min, qc	F13.5, I7	Daily minimum T (K) and QC
t_min_night, qc	F13.5, I7	Overnight minimum T (K) and QC
p_tend03, qc	F13.5, I7	3-hour pressure change (Pa) and QC
p_tend24, qc	F13.5, I7	24-hour pressure change (Pa) and QC
cloud_cvr, qc	F13.5, I7	Total cloud cover (oktas) and QC
ceiling, qc	F13.5, I7	Height (m) of cloud base and QC

Following the report header record are the *data records*. These data records contain the observations of pressure, height, temperature, dewpoint, wind speed, and wind direction. There are a number of other fields in the data record that are not used on input. Each data record contains data for a single level of the report. For report types that have multiple levels (*e.g., upper-air station sounding reports*), each pressure or height level has its own data record. For report types with a single level (*such as surface station reports or a satellite wind observation*), the report will have a single data record. The data record contents and format are summarized in the following table

Format of data records		
Variable	**Fortran I/O**	**Description**

	Format	
pressure, qc	F13.5, I7	Pressure (Pa) of observation, and QC
height, qc	F13.5, I7	Height (m MSL) of observation, and QC
temperature, qc	F13.5, I7	Temperature (K) and QC
dew_point, qc	F13.5, I7	Dewpoint (K) and QC
speed, qc	F13.5, I7	Wind speed (m/s) and QC
direction, qc	F13.5, I7	Wind direction (degrees) and QC
u, qc	F13.5, I7	u component of wind (m/s), and QC
v, qc	F13.5, I7	v component of wind (m/s), and QC
rh, qc	F13.5, I7	Relative Humidity (%) and QC
thickness, qc	F13.5, I7	Thickness (m), and QC

The *end data record* is simply a data record with pressure and height fields both set to -777777.

After all the data records and the end data record, an *end report record* must appear. The end report record is simply three integers, which really aren't all that important.

Format of end_report records		
Variable	**Fortran I/O Format**	**Description**
num_vld_fld	I7	Number of valid fields in the report
num_error	I7	Number of errors encountered during the decoding of the report
num_warning	I7	Number of warnings encountered during the decoding the report

QCFlags

In the observation files, most of the meteorological data fields also have space for an additional integer quality-control flag. The quality-control values are of the form 2n, where n takes on positive integer values. This allows the various quality control flags to be additive, yet permits the decomposition of the total sum into constituent components. Following are the current quality control flags that are applied to observations:

```
pressure interpolated from first-guess height      = 2 **  1 =      2
pressure int. from std. atmos. and 1st-guess height= 2 **  3 =      8
temperature and dew point both = 0                 = 2 **  4 =     16
wind speed and direction both = 0                  = 2 **  5 =     32
```

```
wind speed negative                                  = 2 **  6 =     64
wind direction < 0 or > 360                          = 2 **  7 =    128
level vertically interpolated                        = 2 **  8 =    256
value vertically extrapolated from single level      = 2 **  9 =    512
sign of temperature reversed                         = 2 ** 10 =   1024
superadiabatic level detected                        = 2 ** 11 =   2048
vertical spike in wind speed or direction            = 2 ** 12 =   4096
convective adjustment applied to temperature field = 2 ** 13 =   8192
no neighboring observations for buddy check          = 2 ** 14 =  16384
-----------------------------------------------------------------------
data outside normal analysis time and not QC-ed      = 2 ** 15 =  32768
-----------------------------------------------------------------------
fails error maximum test                             = 2 ** 16 =  65536
fails buddy test                                     = 2 ** 17 = 131072
observation outside of domain detected by QC         = 2 ** 18 = 262144
```

OBSGRID Namelist

The OBSGRID namelist file is called "`namelist.oa`", and must be in the directory from which OBSGRID is run. The namelist consists of nine namelist records, named "record1" through "record9", each having a loosely related area of content. Each namelist record, which extends over several lines in the `namelist.oa` file, begins with "&record<#>" (where <#> is the namelist record number) and ends with a slash "/".

The namelist record `&plot_sounding` is only used by the corresponding utility.

Namelist record1

The data in namelist record1 define the analysis times to process:

Namelist Variable	Value	Description
start_year	2000	4-digit year of the starting time to process
start_month	01	2-digit month of the starting time to process
start_day	24	2-digit day of the starting time to process
start_hour	12	2-digit hour of the starting time to process
end_year	2000	4-digit year of the ending time to process
end_month	01	2-digit month of the ending time to process
end_day	25	2-digit day of the ending time to process
end_hour	12	2-digit hour of the ending time to process
interval	21600	Time interval (s) between consecutive times to process

Namelist record2

The data in record2 define the model grid and names of the input files:

Namelist Variable	Value	Description
grid_id	1	ID of domain to process
obs_filename	CHARACTER	Root file name (*may include directory information*) of the observational files. All input files must have the format obs_filename:<YYYY-MM-DD_HH>. One file required for each time period. If a wrfsfdda is being created, then similar input data files are required for each surface fdda time.
remove_data_above_qc_flag	200000	Data with qc flags higher than this will not be output to the OBS_DOMAIN*dxx* files. Default is to output all data. Use 65536 to remove data that failed the buddy and error max tests. To also exclude data outside analysis times that could not be QC-ed use **32768** *(recommended).* This does not affect the data used in the OA process.

remove_unverified_data	.FALSE.	By setting this parameter to **.TRUE.** *(recommended)* any observations that could not be QC'd due to having a pressure insufficiently close to an analysis level will be removed from the *OBS_DOMAINdxx* files. Obs QC'd by adjusting them to a nearby analysis level or by comparing them to an analysis level within a user-specified tolerance will be included in the OBS_DOMAINdxx files. See use_p_tolerance_one_lev in &record4.
trim_domain	.FALSE.	Set to .TRUE. if this domain must be cut down on output
trim_value	5	Value by which the domain will be cut down in each direction

The *met_em** files which are being processed must be available in the OBSGRID/ directory.

The *obs_filename* and interval settings can get confusing, and deserve some additional explanation. Use of the *obs_filename* files is related to the times and time interval set in namelist &record1, and to the F4D options set in namelist &record8. The *obs_filename* files are used for the analyses of the full 3D dataset, both at upper levels and the surface. They are also used when F4D=.TRUE.; that is, if surface analyses are being created for surface FDDA nudging. The *obs_filename* files should contain all observations (upper-air and surface) to be used for a particular analysis at a particular time.

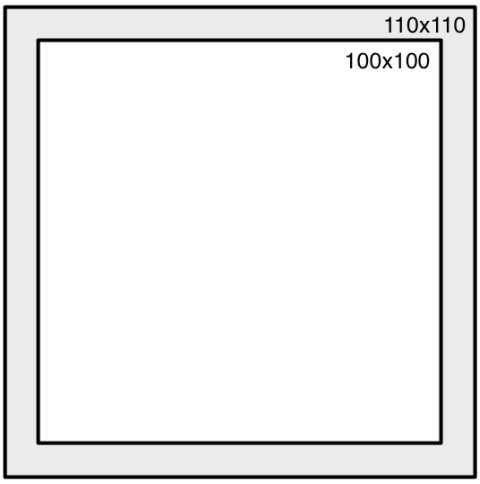
Ideally there should be an *obs_filename* for each time period for which an objective analysis is desired. Time periods are processed sequentially from the starting date to the ending date by the time interval, all specified in namelist &record1. All observational files must have a date associated with them. If a file is not found, the code will process as if this file contains zero observations, and then continue to the next time period.

If the F4D option is selected, the *obs_filename* files are similarly processed for surface analyses, this time with the time interval as specified by INTF4D.

If a user wishes to include observations from outside the model domain of interest, geogrid.exe (WPS) needs to be run over a slightly larger domain than the domain of interest. Setting

trim_domain to .TRUE. will cut all 4 directions of the input domain down by the number of grid points set in trim_value.

In the example below, the domain of interest is the inner white domain with a total of 100x100 grid points. geogrid.exe has been run for the outer domain (110x110 grid points). By setting the trim_value to 5, the output domain will be trimmed by 5 grid points in each direction, resulting in the white 100x100 grid point domain.



Namelist record3

The data in the &record3 concern space allocated within the program for observations. These are values that should not frequently need to be modified:

Namelist Variable	Value	Description
max_number_of_obs	10000	Anticipated maximum number of reports per time period
fatal_if_exceed_max_obs	.TRUE.	T/F flag allows the user to decide the severity of not having enough space to store all of the available observation

Namelist record4

The data in &record4 set the quality control options. There are four specific tests that may be activated by the user: An error max test; a buddy test; removal of spike, and; the removal of super-adiabatic lapse rates. For some of these tests, the user has control over the tolerances, as well.

Namelist Variable	Value	Description
qc_psfc	.FALSE.	Execute error max and buddy check tests for surface pressure observations (temporarily converted to sea level pressure to run QC)
Error Max Test: For this test there is a threshold for each variable. These values are scaled for time of day, surface characteristics and vertical level.		
qc_test_error_max	.TRUE.	Check the difference between the first-guess and the observation
max_error_t	10	Maximum allowable temperature difference (K)
max_error_uv	13	Maximum allowable horizontal wind component difference (m/s)
max_error_z	*8*	*Not used*
max_error_rh	50	Maximum allowable relative humidity difference (%)
max_error_p	600	Maximum allowable sea-level pressure difference (Pa
max_error_dewpoint	20	Maximum allowable dewpoint difference (K)
Buddy Check Test: For this test there is a threshold for each variable. These values are similar to standard deviations.		
qc_test_buddy	.TRUE.	Check the difference between a single observation and neighboring observations
max_buddy_t	8	Maximum allowable temperature difference (K)
max_buddy_uv	8	Maximum allowable horizontal wind component difference (m/s)
max_buddy_z	*8*	*Not used*
max_buddy_rh	40	Maximum allowable relative humidity difference (%)
max_buddy_p	800	Maximum allowable sea-level pressure difference (Pa)
max_buddy_dewpoint	20	Maximum allowable dewpoint difference (K)

buddy_weight	1.0	Value by which the buddy thresholds are scaled
Spike removal		
qc_test_vert_consistency	.FALSE.	Check for vertical spikes in temperature, dew point, wind speed and wind direction
Removal of super-adiabatic lapse rates		
qc_test_convective_adj	.FALSE.	Remove any super-adiabatic lapse rate in a sounding by conservation of dry static energy
For satellite and aircraft observations, data are often horizontally spaced with only a single vertical level. The following entries determine how such data are dealt with and are described in more detail below the table.		
use_p_tolerance_one_lev	.FALSE.	Should single-level above-surface observations be directly QC'd against nearby levels (.TRUE.) or extended to nearby levels (.FALSE.)
max_p_tolerance_one_lev_qc	700	Pressure tolerance within which QC can be applied directly (Pa)
max_p_extend_t	1300	Pressure difference (Pa) through which a single temperature report may be extended
max_p_extend_w	1300	Pressure difference (Pa) through which a single wind report may be extended

Dewpoint quality control:
Note that the dewpoint error max check and buddy check are using the same moisture field as the relative humidity checks. The dewpoint checks are to allow for an additional level of quality control on the moisture fields and may be helpful for dry observations where RH differences may be small but dewpoint differences are much larger. The maximum dewpoint thresholds are scaled based on the observed dewpoint to increase the threshold for dry conditions where larger dewpoint variations are expected. If the user does not wish to use dewpoint error checks, simply set the thresholds to very large values.

Quality control of single-level above-surface observations:

Option 1: `use_p_tolerance_one_lev = .FALSE.`:

For single-level above-surface observations marked as 'FM-88 SATOB' or 'FM-97 AIREP', the observations are adjusted to the nearest pressure level. If the observation's pressure is within max_p_extend_t Pa of the nearest first-guess level, the temperature of the observation is adjusted to the first-guess level using a standard lapse rate, otherwise the temperature is marked as missing. If the observation's pressure is within max_p_extend_w Pa of the nearest first-guess level, the winds are used without adjustment. The dewpoint is marked as missing regardless of the pressure of the observation. The pressure of the observation is changed to be the pressure of the pressure level against which it is being quality controlled.
If a single-level above-surface observation is marked as anything other than 'FM-88 SATOB' or 'FM-97 AIREP', it appears that it will not be quality controlled unless its pressure happens to exactly match one of the pressure levels in the first guess field. Note that max_p_tolerance_one_lev_qc is ignored if use_p_tolerance_one_lev = .FALSE.

Option 2: use_p_tolerance_one_lev = .TRUE.:
For all single-level above-surface observations, the observations will be quality controlled as long as the closest first-guess field is within max_p_tolerance_one_lev_qc Pa of the observation. In order to allow all single-level above-surface observations to be close enough to a first-guess pressure level that quality control directly comparing the closest pressure level to the observation is valid, the user may need to interpolate the first guess to additional pressure levels prior to ingestion into OBSGRID. OBSGRID will print out the pressure ranges for which error max quality control is not available (i.e., the pressures for which single-level above-surface observations will not be quality controlled). See max_p_tolerance_one_lev_oa in namelist record9 for the equivalent pressure tolerance for creating objective analyses. Note that max_p_extend_t and max_p_extend_w are ignored if use_p_tolerance_one_lev = .TRUE.

Namelist record5

The data in &record5 control the enormous amount of printout that may be produced by the OBSGRID program. These values are all logical flags, where TRUE will generate output and FALSE will turn off output.

```
print_obs_files ; print_found_obs ; print_header ;
print_analysis ;print_qc_vert ; print_qc_dry ;
print_error_max ; print_buddy ;print_oa
```

Namelist record7

The data in &record7 concern the use of the first-guess fields and surface FDDA analysis options. Always use the first guess.

Namelist Variable	Value	Description
use_first_guess	.TRUE.	Always use first guess (use_first_guess=.TRUE.)
f4d	.TRUE.	Turns on (.TRUE.) or off (.FALSE.) the creation of surface analysis files.
intf4d	10800	Time interval in seconds between surface analysis times
lagtem	.FALSE.	Use the previous time-period's final surface analysis for this time-period's first guess (lagtem=.TRUE.); or Use a temporal interpolation between upper-air times as the first guess for this surface analysis (lagtem = .FALSE.)

Namelist record8

The data in `&record8` concern the smoothing of the data after the objective analysis. Note, only the differences fields (*observation minus first-guess*) of the analyzed are smoothed, not the full fields.

Namelist Variable	Value	Description
smooth_type	1	1 = five point stencil of 1-2-1 smoothing; 2 = smoother-desmoother
smooth_sfc_wind	0	Number of smoothing passes for surface winds
smooth_sfc_temp	0	Number of smoothing passes for surface temperature
smooth_sfc_rh	0	Number of smoothing passes for surface relative humidity
smooth_sfc_slp	0	Number of smoothing passes for sea-level pressure
smooth_upper_wind	0	Number of smoothing passes for upper-air winds
smooth_upper_temp	0	Number of smoothing passes for upper-air temperature
smooth_upper_rh	0	Number of smoothing passes for upper-air relative humidity

Namelist record9

The data in &record9 concern the objective analysis options. There is no user control to select the various Cressman extensions for the radius of influence (*circular, elliptical or banana*). If the Cressman option is selected, ellipse or banana extensions will be applied as the wind conditions warrant.

Namelist Variable	Value	Description
oa_type	"Cressman"	"MQD" for multiquadric; "Cressman" for the Cressman-type scheme, "None" for no analysis, this string is case sensitive
oa_3D_type	"Cressman"	Set upper-air scheme to "Cressman", regardless of the scheme used at the surface
oa_3D_option	0	How to switch between "MQD" and "Cressman" if not enough observations are available to perform "MQD"
mqd_minimum_num_obs	30	Minimum number of observations for MQD
mqd_maximum_num_obs	1000	Maximum number of observations for MQD
radius_influence	5,4,3,2	Radius of influence in grid units for Cressman scheme
radius_influence_sfc_mult	1.0	Multiply above-surface radius of influence by this value to get surface radius of influence
oa_min_switch	.TRUE.	T = switch to Cressman if too few observations for MQD; F = no analysis if too few observations
oa_max_switch	.TRUE.	T = switch to Cressman if too many observations for MQD; F = no analysis if too many observation
scale_cressman_rh_decreases	.FALSE.	T = decrease magnitude of drying in Cressman analysis; F = magnitude of

		drying in Cressman analysis unmodified
oa_psfc	.FALSE.	T = perform surface pressure objective analysis; F = surface pressure only adjusted by sea level pressure analysis
max_p_tolerance_one_lev_oa	700	Pressure tolerance within which single-level above-surface observations can be used in the objective analysis (Pa)

When oa_type is set to *Cressman*, then the *Cressman* scheme will be performed on all data.

When oa_type is set to *None,* then no objective analysis will be performed on any data.

When oa_type is set to *MQD*, there are a wide variety of options available that control when the code will revert back to the *Cressman* scheme.

- oa_max_switch ; mqd_maximum_num_obs
  The code will revert back to *Cressman* if the switch is set to true and the maximum number of observations is exceeded.
  This is to reduce the time the code runs and not for physical reasons.
  Recommended to leave switch set to true and just set the maximum number large.

- oa_min_switch ; mqd_minimum_num_obs
  The code will revert back to *Cressman* if the switch is set to true and there are too few observations. How and when the code reverts back to Cressman under these conditions are controlled by the oa_3D_option parameter.
  Recommended to leave switch set to true and start with the default minimum settings.

- oa_3D_type="Cressman"
  All upper-air levels will use the *Cressman* scheme, regardless of other settings.

  The surface will use *MQD* as long as there are enough observations to do so (mqd_maximum_num_obs ; mqd_minimum_num_obs), otherwise it will revert to the *Cressman* scheme.
  Note that if some time periods have enough observations and others do not, the code will only revert to *Cressman* for the times without sufficient observations.

- oa_3D_option
  There are three options (0,1,2). For all these options the surface will use *MQD* as long as

there are enough observations to do so (`mqd_maximum_num_obs ; mqd_minimum_num_obs`), otherwise it will revert to the *Cressman* scheme. Note that if some time periods have enough observations and others do not, the code will only revert to *Cressman* for the times without sufficient observations.

The upper-air will react as follows:
0 (default): MQD is performed in the upper-air as long as there are enough observations to do so (`mqd_maximum_num_obs ; mqd_minimum_num_obs`). As soon as this is no longer the case, the code will STOP, with suggestions as to which parameters to set to run the code correctly.

1: The code will first check to see if, for a given time, all levels and variables in the upper-air have sufficient observations for the *MQD* scheme. If not, the code will revert to Cressman for that time period. Note that if some time periods have enough observations and others do not, the code will only revert to *Cressman* for the times without sufficient observations.

2: The code will check if sufficient observations are available per time, level, and variable for the *MQD* scheme. If not, the code will revert to the *Cressman* scheme for that particular time, level and variable. Note this can result in uncontrolled switching between *MQD* and *Cressman*. Therefore this option is not recommended.

`radius_influence`
There are three ways to set the radius of influence (RIN) for the *Cressman* scheme:

- Manually: Set the RIN and number of scans directly. E.g., 5,4,3,2, will result in 4 scans. The first will use 5 grid points for the RIN and the last, 2 points.
- Automatically 1: Set RIN to 0 and the code will calculate the RIN based on the domain size and an estimated observation density of 325 km. By default there will be 4 scans.
- Automatically 2: Set RIN to a negative number and the code will calculate the RIN based on the domain size and an estimated observation density of 325 km. The number of scans is controlled by the value of the set number. E.g, -5 will result in 5 scans.

`radius_influence_sfc_mult`
The RIN calculated as described above is multiplied by this value to determine the RIN for surface observations. This allows the finer scale structures observed at the surface to be retained. If this multiplication results in a RIN greater than 100 model grid points, then the RIN on the first scan is scaled to be 100 model grid points and all subsequent scans are scale by that same ratio. This is to prevent features from being washed out on fine-scale domains. In order to minimize "spots" on the solution, any scan with a RIN less than 4.5 model grid points is skipped. If this is set to 1.0 then the RIN for surface observations will match the RIN for above-surface observations.

`scale_cressman_rh_decreases`

This option is meant to mitigate overdrying that can occur when the need for drying diagnosed via an observation at one point is spread to another point where the first guess is already drier than the first guess at the location of the observation If this option is set to true then drying applied to a point where the first guess is drier than the first guess at the observation location is scaled by the ratio first guess relative humidity at the point the drying is being applied to divided by the first guess relative humidity at the location of the observation.

Note that this scaling is applied on each Cressman scan. See Reen et al. 2016 (http://dx.doi.org/10.1175/JAMC-D-14-0301.1) for further details.

`oa_psfc`
An objective analysis of surface pressure may allow Obsgrid surface analyses of other fields to be more effectively utilized in WRF if the first-guess surface pressure field is sufficiently coarse compared to the WRF domains (e.g., Reen 2015; http://www.arl.army.mil/arlreports/2015/ARL-TR-7447.pdf). This is because the surface pressure analysis may provide a better estimate of the pressure of the surface analyses and thus WRF is less likely to erroneously reject the surface analyses as being too distant from the actual surface. If there are an insufficient number of observations or if the first-guess surface pressure is not much coarser than WRF, this capability is less likely to add value.

`max_p_tolerance_one_lev_oa`
`If use_p_tolerance_one_lev = .TRUE.` in record4, then `max_p_tolerance_one_lev_oa` is the pressure tolerance (Pa) allowed between single-level above-surface observations and the pressure level they are being used in an objective analysis. If `use_p_tolerance_one_lev = .FALSE.` in record4, then `max_p_tolerance_one_lev_oa` is not used by OBSGRID.

Namelist plot_sounding

Only used for the utility plot_sounding.exe

Namelist Variable	Value	Description
`file_type`	`"raw"`	`File to read to produce the plots. Options are "raw" or "used"`
`read_metoa`	`.TRUE.`	`If set to .TRUE., the model domain information in the metoa_em files will be used to add location information on the plot.`

Chapter 8: WRF Software

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WRF Build Mechanism

The WRF build mechanism provides a uniform apparatus for configuring and compiling the WRF model, WRF-Var system and the WRF pre-processors over a range of platforms, with a variety of options. This section describes the components and functioning of the build mechanism. For information on building the WRF code, see the chapter on Software Installation.

Required software:

The WRF build relies on Perl (version 5 or later) and a number of UNIX utilities: csh and Bourne shell, make, M4, sed, awk, and the uname command. A C compiler is needed to compile programs and libraries in the tools and external directories. The WRF code, itself, is mostly standard Fortran (and uses a few 2003 capabilities). For distributed-memory processing, MPI and related tools and libraries should be installed.

Build Mechanism Components:

Directory structure: The directory structure of WRF consists of the top-level directory, plus directories containing files related to the WRF software framework (**`frame`**), the WRF model (**`dyn_em`**, **`phys`**, **`chem`**, **`share`**), WRF-Var (**`da`**), configuration files (**`arch`**, **`Registry`**), helper and utility programs (**`tools`**), and packages that are distributed with the WRF code (**`external`**).

Scripts: The top-level directory contains three user-executable scripts: **`configure`**, **`compile`**, and **`clean`**. The configure script relies on the Perl script in **`arch/Config_new.pl`**.

Programs: A significant number of WRF lines of code are automatically generated at compile time. The program that does this is **`tools/registry`** and it is distributed as part of the source code with the WRF model.

Makefiles: The main **`Makefile`** (input to the UNIX make utility) is in the top-level directory. There are also makefiles in most of the subdirectories that come with WRF. Make is called recursively over the directory structure. Make is not directly invoked by the user to compile WRF; the **`compile`** script is provided for this purpose. The WRF build has been structured to allow "parallel make". Before the compile command, the user sets an environment variable, J, to the number of processors to use. For example, to use two processors (in csh syntax):

```
setenv J "-j 2"
```

On some machines, this parallel **`make`** causes troubles (a typical symptom is a missing **`mpif.h`** file in the frame directory). The user can force that only a single processor to be used with the command:

```
setenv J "-j 1"
```

Configuration files: The **`configure.wrf`** contains compiler, linker, and other build settings, as well as rules and macro definitions used by the make utility. The **`configure.wrf`** file is included by the Makefiles in most of the WRF source distribution (Makefiles in tools and external directories do not include **`configure.wrf`**). The **`configure.wrf`** file, in the top-level directory, is generated each time the configure script is invoked. It is also deleted by **`clean -a`**. Thus, **`configure.wrf`** is the place to make temporary changes, such as optimization levels and compiling with debugging, but permanent changes should be made in the file **`arch/configure_new.defaults`**. The **`configure.wrf`** file is composed of three files: **`arch/preamble_new`**, **`arch/postamble_new`** and **`arch/configure_new.defaults`**.

The **`arch/configure_new.defaults`** file contains lists of compiler options for all the supported platforms and configurations. Changes made to this file will be permanent. This file is used by the **`configure`** script to generate a temporary **`configure.wrf`** file in the top-level directory. The **`arch`** directory also contains the files **`preamble_new`** and **`postamble_new`**, which constitute the generic parts (non-architecture specific) of the **`configure.wrf`** file that is generated by the **`configure`** script.

The **`Registry`** directory contains files that control many compile-time aspects of the WRF code. The files are named **`Registry.`*`core`*** (where ***`core`*** is, for example, ***`EM`***). The **`configure`** script copies one of these to **`Registry/Registry`**, which is the file that **`tools/registry`** will use as input. The choice of ***`core`*** depends on settings to the **`configure`** script. Changes to **`Registry/Registry`** will be lost; permanent changes should be made to **`Registry.`*`core`***. For the WRF ARW model, the file is typically **`Registry.EM`**. One of the keywords that the registry program understands is

include. The ARW Registry files make use of the **REGISTRY.EM_COMMON** file. This reduces the amount of replicated registry information. When searching for variables previously located in a **Registry.EM*** file, now look in **Registry.EM_COMMON**.

Environment variables: Certain aspects of the configuration and build are controlled by environment variables: the non-standard locations of NetCDF libraries or the Perl command, which dynamic core to compile, machine-specific features, and optional build libraries (such as Grib Edition 2, HDF, and parallel netCDF).

In addition to WRF-related environment settings, there may also be settings specific to particular compilers or libraries. For example, local installations may require setting a variable like **MPICH_F90** to make sure the correct instance of the Fortran 90 compiler is used by the **mpif90** command.

How the WRF build works:

There are two steps in building WRF: configuration and compilation.

Configuration: The **configure** script configures the model for compilation on your system. The configuration first attempts to locate needed libraries, such as netCDF or HDF, and tools, such as Perl. It will check for these in normal places, or will use settings from the user's shell environment. The **configure** file then calls the UNIX **uname** command to discover what platform you are compiling on. It then calls the Perl script **arch/Config_new.pl**, which traverses the list of known machine configurations and displays a list of available options to the user. The selected set of options is then used to create the **configure.wrf** file in the top-level directory. This file may be edited but changes are temporary, since the file will be deleted by **clean -a,** or overwritten by the next invocation of the **configure** script. About the only typical option that is included on the **configure** command is "**-d**" (for debug). The code builds relatively quickly and has the debugging switches enabled, but the model will run very slowly since all of the optimization has been deactivated. This script takes only a few seconds to run.

Compilation: The **compile** script is used to compile the WRF code after it has been configured using the **configure** script. This csh script performs a number of checks, constructs an argument list, copies to **Registry/Registry** the correct **Registry.*core*** file for the core being compiled, and the invokes the UNIX **make** command in the top-level directory. The core to be compiled is determined from the user's environment; if no core is specified in the environment (by setting **WRF_*core*_CORE** to **1**) the default core is selected (currently the Eulerian Mass core for ARW). The **Makefile,** in the top-level directory, directs the rest of the build, accomplished as a set of recursive invocations of **make** in the subdirectories of WRF. Most of these makefiles include the **configure.wrf** file from the top-level directory. The order of a complete build is as follows:

1. Make in **`external`** directory

    a. make in **`external/io_{grib1,grib_share,int,netcdf}`** for Grib Edition 1, binary, and netCDF implementations of I/O API

    b. make in **`RSL_LITE`** directory to build communications layer (DM_PARALLEL only)

    c. make in **`external/esmf_time_f90`** directory to build ESMF time manager library

    d. make in **`external/fftpack`** directory to build FFT library for the global filters

    e. make in other external directories, as specified by "**`external:`**" target in the **`configure.wrf`** file

2. Make in the **`tools`** directory to build the program that reads the **`Registry/Registry`** file and auto-generates files in the **`inc`** directory

3. Make in the **`frame`** directory to build the WRF framework specific modules

4. Make in the **`share`** directory to build the non-core-specific mediation layer routines, including WRF I/O modules that call the I/O API

5. Make in the **`phys`** directory to build the WRF model layer routines for physics (non core-specific)

6. Make in the **`dyn_`*`core`*** directory for core-specific mediation-layer and model-layer subroutines

7. Make in the **`main`** directory to build the main programs for WRF, symbolic link to create executable files (location depending on the build case that was selected as the argument to the compile script)

Source files (**`.F`** and, in some of the external directories, **`.F90`**) are preprocessed to produce **`.f90`** files, which are input to the compiler. As part of the preprocessing, Registry-generated files from the **`inc`** directory may be included. Compiling the **`.f90`** files results in the creation of object (**`.o`**) files that are added to the library **`main/libwrflib.a`**. Most of the **`external`** directories generate their own library file. The linking step produces the **`wrf.exe`** executable and other executables, depending on the case argument to the compile command: **`real.exe`** (a preprocessor for real-data cases) or **`ideal.exe`** (a preprocessor for idealized cases), and the **`ndown.exe`** program, for one-way nesting of real-data cases.

The **.o** files and **.f90** files from a compile are retained until the next invocation of the **clean** script. The **.f90** files provide the true reference for tracking down run time errors that refer to line numbers or for sessions using interactive debugging tools such as **dbx** or **gdb**.

Registry

Tools for automatic generation of application code from user-specified tables provide significant software productivity benefits in development and maintenance of large applications, such as WRF. Just for the WRF model, hundreds of thousands of lines of WRF code are automatically generated from a user-edited table, called the Registry. The Registry provides a high-level single-point-of-control over the fundamental structure of the model data, and thus provides considerable utility for developers and maintainers. It contains lists describing state data fields and their attributes: dimensionality, binding to particular solvers, association with WRF I/O streams, communication operations, and run time configuration options (namelist elements and their bindings to model control structures). Adding or modifying a state variable to WRF involves modifying a single line of a single file; this single change is then automatically propagated to scores of locations in the source code the next time the code is compiled.

The WRF Registry has two components: the Registry file (which the user may edit), and the Registry program.

The Registry file is located in the **Registry** directory and contains the entries that direct the auto-generation of WRF code by the Registry program. There is more than one Registry in this directory, with filenames such as **Registry.EM_COMMON** (for builds using the Eulerian Mass/ARW core) and **Registry.NMM** (for builds using the NMM core). The WRF Build Mechanism copies one of these to the file **Registry/Registry** and this file is used to direct the Registry program. The syntax and semantics for entries in the Registry are described in detail in "WRF Tiger Team Documentation: The Registry" on **http://www2.mmm.ucar.edu/wrf/WG2/Tigers/Registry/**. The use of the keyword **include** has greatly reduced the replicated information that was inside the **Registry.EM_COMMON** file. The Registry program is distributed as part of WRF in the **tools** directory. It is built automatically (if necessary) when WRF is compiled. The executable file is **tools/registry**. This program reads the contents of the Registry file, **Registry/Registry**, and generates files in the **inc** directory. These include files are inserted (with **cpp #include** commands) into WRF Fortran source files prior to compilation. Additional information on these is provided as an appendix to "WRF Tiger Team Documentation: The Registry (DRAFT)". The Registry program itself is written in C. The source files and **makefile** are in the **tools** directory.

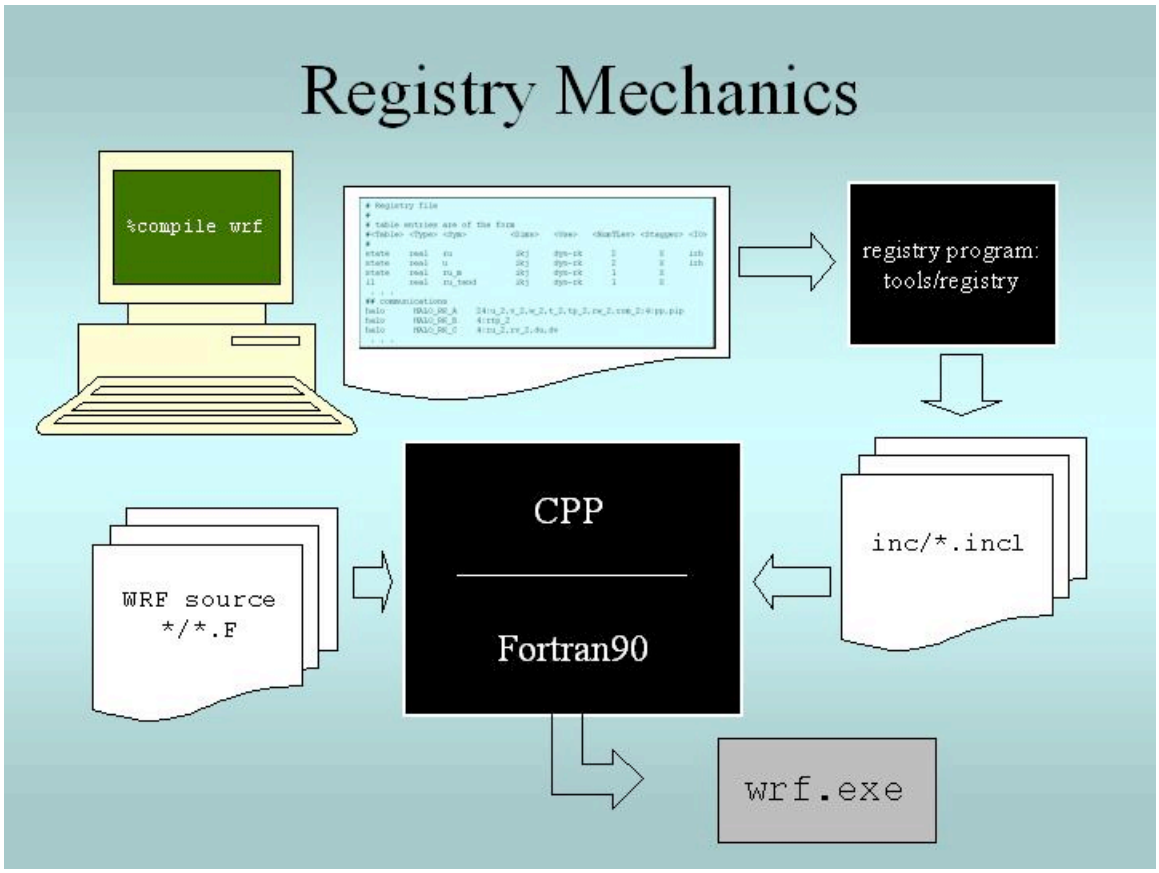


Figure 8.1. When the user compiles WRF, the Registry Program reads Registry/Registry, producing auto-generated sections of code that are stored in files in the **`inc`** directory. These are included into WRF using the CPP preprocessor and the Fortran compiler.

In addition to the WRF model itself, the **`Registry/Registry`** file is used to build the accompanying preprocessors such as **`real.exe`** (for real data) or **`ideal.exe`** (for ideal simulations), and the **`ndown.exe`** program (used for one-way, off-line nesting).

Every variable that is an input or an output field is described in the Registry. Additionally, every variable that is required for parallel communication, specifically associated with a physics package, or needs to provide a tendency to multiple physics or dynamics routines is contained in the Registry. For each of these variables, the index ordering, horizontal and vertical staggering, feedback and nesting interpolation requirements, and the associated IO are defined. For most users, to add a variable into the model requires, regardless of dimensionality, only the addition of a single line to the Registry (make sure that changes are made to the correct **`Registry.`*`core`*** file, as changes to the **`Registry`** file itself are overwritten). Since the Registry modifies code for compile-time options, any change to the Registry REQUIRES that the code be returned to the original unbuilt status with the **`clean -a`** command.

The other very typical activity for users is to define new run-time options, which are handled via a Fortran namelist file **`namelist.input`** in WRF. As with the model state arrays and variables, the entire model configuration is described in the Registry. As with the model arrays, adding a new namelist entry is as easy as adding a new line in the Registry.

While the model state and configuration are, by far, the most commonly used features in the Registry, the data dictionary has several other powerful uses. The Registry file provides input to generate all of the communications for the distributed memory processing (halo interchanges between patches, support for periodic lateral boundaries, and array transposes for FFTs to be run in the X, Y, or Z directions). The Registry associates various fields with particular physics packages so that the memory footprint reflects the actual selection of the options, not a maximal value.

Together, these capabilities allow a large portion of the WRF code to be automatically generated. Any code that is automatically generated relieves the developer of the effort of coding and debugging that portion of software. Usually, the pieces of code that are suitable candidates for automation are precisely those that are fraught with "hard to detect" errors, such as communications, indexing, and IO, which must be replicated for hundreds of variables.

Registry Syntax:

Each entry in the Registry is for a specific variable, whether it is for a new dimension in the model, a new field, a new namelist value, or even a new communication. For readability, a single entry may be spread across several lines with the traditional "\" at the end of a line to denote that the entry is continuing. When adding to the Registry, most users find that it is helpful to copy an entry that is similar to the anticipated new entry, and then modify that Registry entry. The Registry is not sensitive to spatial formatting. White space separates identifiers in each entry.

Note: Do not simply remove an identifier and leave a supposed token blank, use the appropriate default value (currently a dash character "-").

Registry Entries:

The WRF Registry has the following types of entries (not case dependent):

Dimspec – Describes dimensions that are used to define arrays in the model
State – Describes state variables and arrays in the domain structure
I1 – Describes local variables and arrays in solve
Typedef – Describes derived types that are subtypes of the domain structure
Rconfig – Describes a configuration (e.g. namelist) variable or array
Package – Describes attributes of a package (e.g. physics)
Halo – Describes halo update interprocessor communications
Period – Describes communications for periodic boundary updates

Xpose – Describes communications for parallel matrix transposes
include – Similar to a CPP #include file

These ***keywords*** appear as the first word in a line of the file **`Registry`** to define which type of information is being provided. Following are examples of the more likely Registry types that users will need to understand.

Registry Dimspec:

The first set of entries in the Registry is the specifications of the dimensions for the fields to be defined. To keep the WRF system consistent between the dynamical cores and Chemistry, a unified **`registry.dimspec`** file is used (located in the **`Registry`** directory). This single file is included into each Registry file, with the keyword **`include`**. In the example below, three dimensions are defined: i, j, and k. If you do an "**`ncdump -h`**" on a WRF file, you will notice that the three primary dimensions are named as "**`west_east`**", "**`south_north`**", and "**`bottom_top`**". That information is contained in this example (the example is broken across two lines, but interleaved).

```
#<Table>  <Dim>  <Order> <How defined>
dimspec    i      1     standard_domain
dimspec    j      3     standard_domain
dimspec    k      2     standard_domain

<Coord-axis>  <Dimname in Datasets>
x           west_east
y           south_north
z           bottom_top
```

The WRF system has a notion of horizontal and vertical staggering, so the dimension names are extended with a "**`_stag`**" suffix for the staggered sizes. The list of names in the <Dim> column may either be a single unique character (for release 3.0.1.1 and prior), or the <Dim> column may be a string with no embedded spaces (such as **`my_dim`**). When this dimension is used later to dimension-ize a **`state`** or **`i1`** variable, it must be surrounded by curly braces (such as **`{my_dim}`**). This <Dim> variable is not case specific, so for example "**`i`**" is the same as an entry for "**`I`**".

Registry State and I1:

A **`state`** variable in WRF is a field that is eligible for IO and communications, and exists for the duration of the model forecast. The **`I1`** variables (intermediate level one) are typically thought of as tendency terms, computed during a single model time-step, and then discarded prior to the next time-step. The space allocation and de-allocation for these **`I1`** variables is automatic (on the stack for the model solver). In this example, for readability, the column titles and the entries are broken into multiple interleaved lines, with the user entries in a **`bold font`**.

Some fields have simple entries in the **Registry** file. The following is a **state** variable that is a Fortran type **real**. The name of the field inside the WRF model is **u_gc**. It is a three dimension array (**igj**). This particular field is only for the ARW core (**dyn_em**). It has a single time level, and is staggered in the **X** and **Z** directions. This field is input only to the real program (**i1**). On output, the netCDF name is **UU**, with the accompanying description and units provided.

```
#<Table> <Type> <Sym> <Dims>
state    real   u_gc   igj

<Use>  <NumTLev> <Stagger> <IO>
dyn_em     1          XZ     i1

<DNAME>  <DESCRIP>              <UNITS>
"UU"    "x-wind component"    "m s-1"
```

If a variable is not staggered, a "**-**" (dash) is inserted instead of leaving a blank space. The same dash character is required to fill in a location when a field has no IO specification. The variable description and units columns are used for post-processing purposes only; this information is not directly utilized by the model.

When adding new variables to the **Registry** file, users are warned to make sure that variable names are unique. The <Sym> refers to the variable name inside the WRF model, and it is not case sensitive. The <DNAME> is quoted, and appears exactly as typed. Do not use imbedded spaces. While it is not required that the <Sym> and <DNAME> use the same character string, it is highly recommended. The <DESCRIP> and the <UNITS> are optional, however they are a good way to supply self-documenation to the Registry. Since the <DESCRIP> value is used in the automatic code generation, restrict the variable description to 40 characters or less.

From this example, we can add new requirements for a variable. Suppose that the variable to be added is not specific to any dynamical core. We would change the <Use> column entry of **dyn_em** to **misc** (for miscellaneous). The **misc** entry is typical of fields used in physics packages. Only dynamics variables have more than a single time level, and this introductory material is not suitable for describing the impact of multiple time periods on the registry program. For the <Stagger> option, users may select any subset from {**X**, **Y**, **Z**} or {**-**}, where the dash character "**-**" signifies "no staggering". For example, in the ARW model, the x-direction wind component, u, is staggered in the **X** direction, and the y-direction wind component, v, is staggered in the **Y** direction.

The <IO> column handles file input and output, and it handles the nesting specification for the field. The file input and output uses three letters: **i** (input), **r** (restart), and **h** (history). If the field is to be in the input file to the model, the restart file from the model, and the history file from the model, the entry would be **irh**. To allow more flexibility,

the input and history fields are associated with streams. The user may specify a digit after the **i** or the **h** token, stating that this variable is associated with a specified stream (**1** through **9**) instead of the default (**0**). A single variable may be associated with multiple streams. Once any digit is used with the **i** or **h** tokens, the default **0** stream must be explicitly stated. For example, <IO> entry **i** and <IO> entry **i0** are the same. However, <IO> entry **h1** outputs the field to the first auxiliary stream, but does not output the field to the default history stream. The <IO> entry **h01** outputs the field to both the default history stream and the first auxiliary stream. For streams larger than a single digit, such as stream number thirteen, the multi-digit numerical value is enclosed inside braces: **i{13}**. The maximum stream is currently 24 for both input and history.

Nesting support for the model is also handled by the <IO> column. The letters that are parsed for nesting are: **u** (*up* as in feedback up), **d** (*down*, as in downscale from coarse to fine grid), **f** (*forcing*, how the lateral boundaries are processed), and **s** (*smoothing*). As with other entries, the best coarse of action is to find a field nearly identical to the one that you are inserting into the **Registry** file, and copy that line. The user needs to make the determination whether or not it is reasonable to smooth the field in the area of the coarse grid, where the fine-grid feeds back to the coarse grid. Variables that are defined over land and water, non-masked, are usually smoothed. The lateral boundary forcing is primarily for dynamics variables, and is ignored in this overview presentation. For non-masked fields (such as wind, temperature, & pressure), the downward interpolation (controlled by **d**) and the feedback (controlled by **u**) use default routines. Variables that are land fields (such as soil temperature **TSLB**) or water fields (such as sea ice **XICE**) have special interpolators, as shown in the examples below (again, interleaved for readability):

```
#<Table> <Type> <Sym> <Dims>
state    real   TSLB   ilj
state    real   XICE   ij

<Use>  <NumTLev> <Stagger>
misc       1          Z
misc       1          -

<IO>
i02rhd=(interp_mask_land_field:lu_index)u=(copy_fcnm)
i0124rhd=(interp_mask_water_field:lu_index)u=(copy_fcnm)

<DNAME>  <DESCRIP>           <UNITS>
"TSLB"   "SOIL TEMPERATURE"   "K"
"SEAICE" "SEA ICE FLAG"       ""
```

Note that the **d** and **u** entries in the <IO> section are followed by an "**=**" then a parenthesis-enclosed subroutine, and a colon-separated list of additional variables to pass to the routine. It is recommended that users follow the existing pattern: **du** for non-

masked variables, and the above syntax for the existing interpolators for masked variables.

Registry Rconfig:

The **Registry** file is the location where the run-time options to configure the model are defined. Every variable in the ARW namelist is described by an entry in the **Registry** file. The default value for each of the namelist variables is as assigned in the Registry. The standard form for the entry for two namelist variables is given (broken across lines and interleaved):

```
#<Table>  <Type>    <Sym>
rconfig  integer    run_days
rconfig  integer    start_year

     <How set>           <Nentries>   <Default>
namelist,time_control      1            0
namelist,time_control  max_domains     1993
```

The keyword for this type of entry in the **Registry** file is **rconfig** (run-time configuration). As with the other model fields (such as **state** and **i1**), the <Type> column assigns the Fortran kind of the variable: **integer**, **real**, or **logical**. The name of the variable in ARW is given in the <Sym> column, and is part of the derived data type structure, as are the **state** fields. There are a number of Fortran namelist records in the file **namelist.input**. Each namelist variable is a member of one of the specific namelist records. The previous example shows that **run_days** and **start_year** are both members of the **time_control** record. The <Nentries> column refers to the dimensionality of the namelist variable (number of entries). For most variables, the <Nentries> column has two eligible values, either **1** (signifying that the scalar entry is valid for all domains) or **max_domains** (signifying that the variable is an array, with a value specified for each domain). Finally, a default value is given. This permits a namelist entry to be removed from the **namelist.input** file if the default value is acceptable.

The registry program constructs two subroutines for each namelist variable: one to retrieve the value of the namelist variable, and the other to set the value. For an integer variable named **my_nml_var**, the following code snippet provides an example of the easy access to the namelist variables.

```
INTEGER :: my_nml_var, dom_id
CALL nl_get_my_nml_var ( dom_id , my_nml_var )
```

The subroutine takes two arguments. The first is the input integer domain identifier (for example, **1** for the most coarse grid, **2** for the second domain), and the second argument is the returned value of the namelist variable. The associated subroutine to set the namelist variable, with the same argument list, is **nl_set_my_nml_var**. For namelist variables that are scalars, the grid identifier should be set to **1**.

The **rconfig** line may also be used to define variables that are convenient to pass around in the model, usually part of a derived configuration (such as the number of microphysics species associated with a physics package). In this case, the <How set> column entry is **derived**. This variable does not appear in the namelist, but is accessible with the same generated **nl_set** and **nl_get** subroutines.

Registry Halo, Period, and Xpose:

The distributed memory, inter-processor communications are fully described in the **Registry** file. An entry in the Registry constructs a code segment which is included (with **cpp**) in the source code. Following is an example of a **halo** communication (split across two lines and interleaved for readability).

```
#<Table>  <CommName>   <Core>
halo      HALO_EM_D2_3 dyn_em

<Stencil:varlist>
24:u_2,v_2,w_2,t_2,ph_2;24:moist,chem,scalar;4:mu_2,al
```

The keyword is **halo**. The communication is named in the <CommName> column, so that it can be referenced in the source code. The entry in the <CommName> column is case sensitive (the convention is to start the name with **HALO_EM**). The selected dynamical core is defined in the <Core> column. There is no ambiguity, as every communication in each **Registry** file will have the exact same <Core> column option. The last set of information is the <Stencil:varlist>. The portion in front of the "**:**" is the stencil size, and the comma-separated list afterwards defines the variables that are communicated with that stencil size. Different stencil sizes are available, and are "**;**" -separated in the same <Stencil:varlist> column. The stencil sizes **8**, **24**, **48** all refer to a square with an odd number of grid cells on a side, with the center grid cell removed (**8** = 3x3-1, **24** = 5x5-1, **48** = 7x7-1). The special small stencil **4** is just a simple north, south, east, west communication pattern.

The convention in the WRF model is to provide a communication immediately after a variable has been updated. The communications are restricted to the mediation layer (an intermediate layer of the software that is placed between the framework level and the model level). The model level is where developers spend most of their time. The majority of users will insert communications into the **dyn_em/solve_em.F** subroutine. The **HALO_EM_D2_3** communication, defined in the **Registry** file in the

example above, is activated by inserting a small section of code that includes an automatically generated code segment into the solve routine, via standard **cpp** directives.

```
#ifdef DM_PARALLEL
#    include "HALO_EM_D2_3.inc"
#endif
```

The parallel communications are only required when the ARW code is built for distributed-memory parallel processing, which accounts for the surrounding **#ifdef**.

The **period** communications are required when periodic lateral boundary conditions are selected. The Registry syntax is very similar for **period** and **halo** communications, but the stencil size refers to how many grid cells to communicate, in a direction that is normal to the periodic boundary.

```
#<Table>     <CommName>          <Core>   <Stencil:varlist>
period   PERIOD_EM_COUPLE_A    dyn_em    2:mub,mu_1,mu_2
```

The **xpose** (a data transpose) entry is used when decomposed data is to be re-decomposed. This is required when doing FFTs in the x-direction for polar filtering, for example. No stencil size is necessary.

```
#<Table>     <CommName>          <Core>      <Varlist>
xpose    XPOSE_POLAR_FILTER_T  dyn_em   t_2,t_xxx,dum_yyy
```

It is anticipated that many users will add to the the parallel communications portion of the Registry file (**halo** and **period**. It is unlikely that users will add **xpose** fields.

Registry Package:

The **package** option in the **Registry** file associates fields with particular physics packages. Presently, it is mandatory that all 4-D arrays be assigned. Any 4-D array that is not associated with the selected physics option at run-time is neither allocated, used for IO, nor communicated. All other 2-D and 3-D arrays are eligible for use with a **package** assignment, but that is not required.

The purpose of the **package** option is to allow users to reduce the memory used by the model, since only "necessary" fields are processed. An example for a microphysics scheme is given below.

```
#<Table>  <PackageName>  <NMLAssociated>    <Variables>
package   kesslerscheme   mp_physics==1   - moist:qv,qc,qr
```

The entry keyword is **package**, and is associated with the single physics option listed under <NMLAssociated>. The package is referenced in the code in Fortran **IF** and

CASE statements by the name given in the <PackageName> column, instead of the more confusing and typical **IF (mp_physics == 1)** approach. The <Variables> column must start with a dash character and then a blank "**- **" (for historical reasons of backward compatibility). The syntax of the <Variables> column then is a 4-D array name, followed by a colon, and then a comma-separated list of the 3-D arrays constituting that 4-D amalgamation. In the example above, the 4-D array is **moist**, and the selected 3-D arrays are **qv**, **qc**, and **qr**. If more than one 4-D array is required, a "**;**" separates those sections from each other in the <Variables> column.

In addition to handling 4-D arrays and their underlying component, 3-D arrays, the **package** entry is able to associate generic **state** variables, as shown in the example following. If the namelist variable **use_wps_input** is set to **1**, then the variables **u_gc** and **v_gc** are available to be processed.

```
#<Table>   <PackageName> <NMLAssociated>      <Variables>
package      realonly    use_wps_input==1   - state:u_gc,v_gc
```

I/O Applications Program Interface (I/O API)

The software that implements WRF I/O, like the software that implements the model in general, is organized hierarchically, as a "software stack" (**http://www2.mmm.ucar.edu/wrf/WG2/Tigers/IOAPI/IOStack.html**). From top (closest to the model code itself) to bottom (closest to the external package implementing the I/O), the I/O stack looks like this:

- Domain I/O (operations on an entire domain)
- Field I/O (operations on individual fields)
- Package-neutral I/O API
- Package-dependent I/O API (external package)

The lower-levels of the stack, associated with the interface between the model and the external packages, are described in the I/O and Model Coupling API specification document on **http://www2.mmm.ucar.edu/wrf/WG2/Tigers/IOAPI/index.html**.

Timekeeping

Starting times, stopping times, and time intervals in WRF are stored and manipulated as Earth System Modeling Framework (ESMF, http://www.cisl.ucar.edu/research/2005/esmf.jsp) time manager objects. This allows exact representation of time instants and intervals as integer numbers of years, months,

hours, days, minutes, seconds, and fractions of a second (numerator and denominator are specified separately as integers). All time computations involving these objects are performed exactly by using integer arithmetic, with the result that there is no accumulated time step drift or rounding, even for fractions of a second.

The WRF implementation of the ESMF Time Manger is distributed with WRF in the **`external/esmf_time_f90`** directory. This implementation is entirely Fortran90 (as opposed to the ESMF implementation in C++) and it is conformant to the version of the ESMF Time Manager API that was available in 2009.

WRF source modules and subroutines that use the ESMF routines do so by use-association of the top-level ESMF Time Manager module, esmf_mod:

```
USE esmf_mod
```

The code is linked to the library file **`libesmf_time.a`** in the **`external/esmf_time_f90`** directory.

ESMF timekeeping is set up on a domain-by-domain basis in the routine setup_timekeeping (**`share/set_timekeeping.F`**). Each domain keeps track of its own clocks and alarms. Since the time arithmetic is exact there is no problem with clocks on separate domains getting out of synchronization.

Software Documentation

Detailed and comprehensive documentation aimed at WRF software is available at http://www2.mmm.ucar.edu/wrf/WG2/software_2.0.

Performance

Benchmark information is available at http://www2.mmm.ucar.edu/wrf/bench

Chapter 9: Post-Processing Utilities

Table of Contents

Introduction

There are a number of visualization tools available to display WRF-ARW *(http://http://www2.mmm.ucar.edu/wrf/users)* model data. Model data in netCDF format can essentially be displayed using any tool capable of displaying this data format.

Currently the following post-processing utilities are supported: NCL, RIP4, ARWpost *(converter to GrADS)*, UPP, and VAPOR.

NCL, RIP4, ARWpost and VAPOR can currently only read data in netCDF format, while UPP can read data in netCDF and binary format.

Required software
The only library that is always required is the netCDF package from Unidata (***http://www.unidata.ucar.edu/***: login > Downloads > NetCDF - *registration login required*).

netCDF stands for **Net**work **C**ommon **D**ata **F**orm. This format is platform independent, i.e., data files can be read on both big-endian and little-endian computers, regardless of where the file was created. To use the netCDF libraries, ensure that the paths to these libraries are set correct in your login scripts as well as all Makefiles.

Additional libraries required by each of the supported post-processing packages:

- NCL (*http://www.ncl.ucar.edu*)
- GrADS (*http://grads.iges.org/home.html*)
- GEMPAK (*http://www.unidata.ucar.edu/software/gempak/*)
- VAPOR (*http://www.vapor.ucar.edu*)

NCL

With the use of **NCL Libraries** *(http://www.ncl.ucar.edu)*, WRF-ARW data can easily be displayed.

The information on these pages has been put together to help users generate NCL scripts to display their WRF-ARW model data.

Some example scripts are available online *(http://www2.mmm.ucar.edu/wrf/OnLineTutorial/Graphics/NCL/NCL_examples.htm)*, but in order to fully utilize the functionality of the NCL Libraries, users should adapt these for their own needs, or write their own scripts.

NCL can process WRF-ARW static, input and output files, as well as WRFDA output data. Both single and double precision data can be processed.

WRF and NCL

In July 2007, the **WRF-NCL** processing scripts have been incorporated into the **NCL Libraries**, thus only the **NCL Libraries** are now needed.

Major WRF-ARW-related upgrades have been added to the NCL libraries in version 6.1.0; therefore, in order to use many of the functions, NCL version 6.1.0 or higher is required.

Special **functions** are provided to simplify the plotting of WRF-ARW data. These functions are located in:
"$NCARG_ROOT/lib/ncarg/nclscripts/wrf/WRFUserARW.ncl".
Users are encouraged to view and edit this file for their own needs. If users wish to edit this file, but do not have write permission, they should simply copy the file to a local directory, edit and load the new version, when running NCL scripts.

Special **NCL built-in functions** have been added to the NCL libraries to help users calculate basic diagnostics for WRF-ARW data.

All the **FORTRAN subroutines** used for diagnostics and interpolation *(previously located in wrf_user_fortran_util_0.f)* has been re-coded into NCL in-line functions. This means users no longer need to compile these routines.

What is NCL

The NCAR Command Language (NCL) is a free, interpreted language designed specifically for scientific data processing and visualization. NCL has robust file input and output. It can read in netCDF, HDF4, HDF4-EOS, GRIB, binary and ASCII data. The graphics are world-class and highly customizable.

It runs on many different operating systems including Solaris, AIX, IRIX, Linux, MacOSX, Dec Alpha, and Cygwin/X running on Windows. The NCL binaries are freely available at: *http://www.ncl.ucar.edu/Download/*

To read more about NCL, visit: *http://www.ncl.ucar.edu/overview.shtml*

Necessary software

NCL libraries, *version 6.1.0 or higher.*

Environment Variable

Set the environment variable NCARG_ROOT to the location where you installed the NCL libraries. Typically *(for cshrc shell):*

```
setenv NCARG_ROOT /usr/local/ncl
```

.hluresfile

Create a file called **.hluresfile** in your $HOME directory. This file controls the color, background, fonts, and basic size of your plot. For more information regarding this file, see: *http://www.ncl.ucar.edu/Document/Graphics/hlures.shtml.*

NOTE: *This file must reside in your $HOME directory and not where you plan on running NCL.*

Below is the **.hluresfile** used in the example scripts posted on the web *(scripts are available at: http://www2.mmm.ucar.edu/wrf/users/graphics/NCL/NCL.htm*). If a different color table is used, the plots will appear different. Copy the following to your **~/.hluresfile**. *(A copy of this file is available at: http://www2.mmm.ucar.edu/wrf/OnLineTutorial/Graphics/NCL/NCL_basics.htm)*

```
*wkColorMap : BlAqGrYeOrReVi200
*wkBackgroundColor : white
*wkForegroundColor : black
*FuncCode : ~
*TextFuncCode : ~
```

```
*Font : helvetica
*wkWidth : 900
*wkHeight : 900
```

NOTE:

If your image has a black background with white lettering, your ***.hluresfile*** *has not been created correctly, or it is in the wrong location.*
wkColorMap*, as set in your* ***.hluresfile*** *can be overwritten in any NCL script with the use of the function "****gsn_define_colormap****", so you do not need to change your* ***.hluresfile*** *if you just want to change the color map for a single plot.*

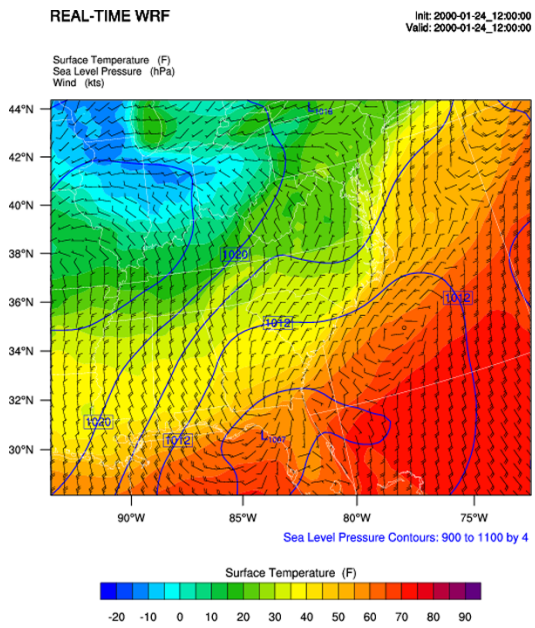
Create NCL scripts

The basic outline of any NCL script will look as follows:

```
load external functions and procedures

begin
      ; Open input file(s)
      ; Open graphical output
      ; Read variables
      ; Set up plot resources & Create plots
      ; Output graphics
end
```

For example, let's create a script to plot Surface Temperature, Sea Level Pressure and Wind as shown in the picture below.



```
; load functions and procedures
load "$NCARG_ROOT/lib/ncarg/nclscripts/csm/gsn_code.ncl"
load "$NCARG_ROOT/lib/ncarg/nclscripts/wrf/WRFUserARW.ncl"

begin

; WRF ARW input file (NOTE, your wrfout file does not need
; the .nc, but NCL needs it so make sure to add it in the
; line below)
a = addfile("../wrfout_d01_2000-01-24_12:00:00.nc","r")


; Output on screen. Output will be called "plt_Surface1"
type = "x11"
wks = gsn_open_wks(type,"plt_Surface1")


; Set basic resources
res = True
res@MainTitle = "REAL-TIME WRF"          ; Give plot a main title
res@Footer = False                             ; Set Footers off
pltres = True                                ; Plotting resources
mpres = True                                      ; Map resources

;---------------------------------------------------------------
times = wrf_user_getvar(a,"times",-1)    ; get times in the file
it = 0                                ; only interested in first time
res@TimeLabel = times(it)                ; keep some time information

;---------------------------------------------------------------
; Get variables

slp = wrf_user_getvar(a,"slp",it)                            Get slp
   wrf_smooth_2d( slp, 3 )                                ; Smooth slp

t2 = wrf_user_getvar(a,"T2",it)                    ; Get T2 (deg K)
   tc2 = t2-273.16                                 ; Convert to deg C
   tf2 = 1.8*tc2+32.                               ; Convert to deg F
   tf2@description = "Surface Temperature"
   tf2@units = "F"

u10 = wrf_user_getvar(a,"U10",it)                           ; Get U10
v10 = wrf_user_getvar(a,"V10",it)                           ; Get V10
   u10 = u10*1.94386                               ; Convert to knots
   v10 = v10*1.94386
   u10@units = "kts"
   v10@units = "kts"

;---------------------------------------------------------------
```

```
; Plotting options for T
opts = res                                      ; Add basic resources
opts@cnFillOn = True                                  ; Shaded plot
opts@ContourParameters = (/ -20., 90., 5./)    ; Contour intervals
opts@gsnSpreadColorEnd = -3
contour_tc = wrf_contour(a,wks,tf2,opts)              ; Create plot
delete(opts)


; Plotting options for SLP
opts = res                                      ; Add basic resources
opts@cnLineColor = "Blue"                          ; Set line color
opts@cnHighLabelsOn = True                          ; Set labels
opts@cnLowLabelsOn = True
opts@ContourParameters = (/ 900.,1100.,4./)    ; Contour intervals
contour_psl = wrf_contour(a,wks,slp,opts)             ; Create plot
delete(opts)


; Plotting options for Wind Vectors
opts = res                                      ; Add basic resources
opts@FieldTitle = "Winds"                 ; Overwrite the field title
opts@NumVectors = 47                         ; Density of wind barbs
vector = wrf_vector(a,wks,u10,v10,opts)               ; Create plot
delete(opts)


; MAKE PLOTS
plot = wrf_map_overlays(a,wks,  \
      (/contour_tc,contour_psl,vector/),pltres,mpres)

;---------------------------------------------------------------


end
```

Extra sample scripts are available at:
http://www2.mmm.ucar.edu/wrf/OnLineTutorial/Graphics/NCL/NCL_examples.htm

Run NCL scripts

1. Ensure NCL is successfully installed on your computer.

2. Ensure that the environment variable NCARG_ROOT is set to the location where NCL is installed on your computer. Typically *(for cshrc shell),* the command will

look as follows:

```
setenv NCARG_ROOT /usr/local/ncl
```

3. Create an NCL plotting script.

4. Run the NCL script you created:

```
ncl  NCL_script
```

The output type created with this command is controlled by the line:
wks = gsn_open_wk (type,"Output") ; inside the NCL script
where *type* can be *x11, pdf, ncgm, ps,* or *eps*

For high quality images, create pdf , ps, or eps images directly via the ncl scripts **(*type* = *pdf / ps / eps*)**

See the **Tools** section in Chapter 10 of this User's Guide for more information concerning other types of graphical formats and conversions between graphical formats.

Functions / Procedures under "$NCARG_ROOT/lib/ncarg/nclscripts/wrf/" *(WRFUserARW.ncl)*

wrf_user_getvar (*nc_file, fld, it*)
Usage: *ter = wrf_user_getvar (a, "HGT", 0)*

Get fields from a netCDF file for:

- Any given time by setting **it** to the time required.
- For all times in the input file(s), by setting **it = -1**
- A list of times from the input file(s), by setting **it** to *(/start_time,end_time,interval/)* (e.g. *(/0,10,2/)*).
- A list of times from the input file(s), by setting **it** to the list required (e.g. *(/1,3,7,10/)*).

Any field available in the netCDF file can be extracted.
fld is case sensitive. The policy adapted during development was to set all diagnostic variables, calculated by NCL, to lower-case to distinguish them from fields directly available from the netCDF files.

List of available diagnostics:

avo	Absolute Vorticity [10-5 s-1]
pvo	Potential Vorticity [PVU]
eth	Equivalent PotentialTtemperature [K]
cape_2d	Returns 2D fields mcape/mcin/lcl/lfc
cape_3d	Returns 3D fields cape/cin
dbz	Reflectivity [dBZ]
mdbz	Maximum Reflectivity [dBZ]
geopt/geopotential	Full Model Geopotential [m2 s-2]
helicity	Storm Relative Helicity [m-2/s-2]
updraft_helicity	Updraft Helicity [m-2/s-2]
lat	Latitude (will return either XLAT or XLAT_M, depending on which is available)
lon	Longitude (will return either XLONG or XLONG_M, depending on which is available)
omg	Omega
p/pres	Full Model Pressure [Pa]
pressure	Full Model Pressure [hPa]
pw	Precipitable Water
rh2	2m Relative Humidity [%]
rh	Relative Humidity [%]
slp	Sea Level Pressure [hPa]
ter	Model Terrain Height [m] (will return either HGT or HGT_M, depending on which is available)
td2	2m Dew Point Temperature [C]
td	Dew Point Temperature [C]
tc	Temperature [C]
tk	Temperature [K]
th/theta	Potential Temperature [K]
tv	Virtual Temperature
twb	Wetbulb Temperature
times	Times in file *(note this return strings - recommended)*
Times	Times in file *(note this return characters)*
ua	U component of wind on mass points
va	V component of wind on mass points
wa	W component of wind on mass points
uvmet10	10m U and V components of wind rotated to earth coordinates
uvmet	U and V components of wind rotated to earth coordinates
z/height	Full Model Height [m]

wrf_user_list_times (*nc_file*)
Usage: *times* = wrf_user_list_times *(a)*

Obtain a list of times available in the input file. The function returns a 1D array containing the times *(type: character)* in the input file.
This is an outdated function – best to use *wrf_user_getvar(nc_file,"times",it)*

wrf_contour (*nc_file, wks, data, res*)
Usage: *contour* = wrf_contour *(a, wks, ter, opts)*

Returns a graphic (contour), of the data to be contoured. This graphic is only created, but not plotted to a wks. This enables a user to generate many such graphics and overlay them, before plotting the resulting picture to the wks.

The returned graphic (*contour*) does not contain map information, and can therefore be used for both real and idealized data cases.

This function can plot both line contours and shaded contours. *Default is line contours.*

Many resources are set for a user, and most can be overwritten. Below is a list of resources you may want to consider changing before generating your own graphics:

Resources unique to ARW WRF Model data
opts@MainTitle : Controls main title on the plot.
opts@MainTitlePos : Main title position – Left/Right/Center. Default is Left.
opts@NoHeaderFooter : Switch off all Headers and Footers.
opts@Footer : Add some model information to the plot as a footer. Default is True.
opts@InitTime : Plot initial time on graphic. Default is True. If True, the initial time will be extracted from the input file.
opts@ValidTime : Plot valid time on graphic. Default is True. A user must set opts@TimeLabel to the correct time.
opts@TimeLabel : Time to plot as valid time.
opts@TimePos : Time position – Left/Right. Default is "Right".
opts@ContourParameters : A single value is treated as an interval. Three values represent: Start, End, and Interval.
opts@FieldTitle : Overwrite the field title - if not set the field description is used for the title.
opts@UnitLabel : Overwrite the field units - seldom needed as the units associated with the field will be used.
opts@PlotLevelID : Use to add level information to the field title.

General NCL resources *(most standard NCL options for **cn** and **lb** can be set by the user to overwrite the default values)*
opts@cnFillOn : Set to True for shaded plots. Default is False.
opts@cnLineColor : Color of line plot.

opts@lbTitleOn : Set to False to switch the title on the label bar off. Default is True.
opts@cnLevelSelectionMode ; *opts @cnLevels* ; *opts@cnFillColors* ;
optr@cnConstFLabelOn : Can be used to set contour levels and colors manually.

wrf_vector (*nc_file, wks, data_u, data_v, res*)
Usage: *vector* = wrf_vector *(a, wks, ua, va, opts)*

Returns a graphic (*vector*) of the data. This graphic is only created, but not plotted to a wks. This enables a user to generate many graphics, and overlay them, before plotting the resulting picture to the wks.

The returned graphic (*vector*) does not contain map information, and can therefore be used for both real and idealized data cases.

Many resources are set for a user, and most can be overwritten. Below is a list of resources you may want to consider changing before generating your own graphics:

Resources unique to ARW WRF Model data
opts@MainTitle : Controls main title on the plot.
opts@MainTitlePos : Main title position – Left/Right/Center. Default is Left.
opts@NoHeaderFooter : Switch off all Headers and Footers.
opts@Footer : Add some model information to the plot as a footer. Default is True.
opts@InitTime : Plot initial time on graphic. Default is True. If True, the initial time will be extracted from the input file.
opts@ValidTime : Plot valid time on graphic. Default is True. A user must set opts@TimeLabel to the correct time.
opts@TimeLabel : Time to plot as valid time.
opts@TimePos : Time position – Left/Right. Default is “Right”.
opts@ContourParameters : A single value is treated as an interval. Three values represent: Start, End, and Interval.
opts@FieldTitle : Overwrite the field title - if not set the field description is used for the title.
opts@UnitLabel : Overwrite the field units - seldom needed as the units associated with the field will be used.
opts@PlotLevelID : Use to add level information to the field title.
opts@NumVectors : Density of wind vectors.

General NCL resources *(most standard NCL options for vc can be set by the user to overwrite the default values)*
opts@vcGlyphStyle : Wind style. “WindBarb” is default.

wrf_map_overlays (*nc_file, wks, (/graphics/), pltres, mpres*)
Usage: *plot = wrf_map_overlays (a, wks, (/contour,vector/), pltres, mpres)*

Overlay contour and vector plots generated with *wrf_contour* and *wrf_vector*. Can overlay any number of graphics. Overlays will be done in the order given, so always list shaded plots before line or vector plots, to ensure the lines and vectors are visible and not hidden behind the shaded plot.

A map background will automatically be added to the plot. Map details are controlled with the *mpres* resource. Common map resources you may want to set are:
mpres@mpGeophysicalLineColor ; mpres@mpNationalLineColor ;
mpres@mpUSStateLineColor ; mpres@mpGridLineColor ;
mpres@mpLimbLineColor ; mpres@mpPerimLineColor

If you want to zoom into the plot, set *mpres@ZoomIn* to True, and *mpres@Xstart, mpres@Xend, mpres@Ystart, and mpres@Yend* to the corner x/y positions of the zoomed plot.

pltres@NoTitles : Set to True to remove all field titles on a plot.
pltres@CommonTitle : Overwrite field titles with a common title for the overlaid plots.
Must set *pltres@PlotTitle* to desired new plot title.

If you want to generate images for a panel plot, set *pltres@PanelPot* to True.

If you want to add text/lines to the plot before advancing the frame, set *pltres@FramePlot* to False. Add your text/lines directly after the call to the *wrf_map_overlays* function. Once you are done adding text/lines, advance the frame with the command "***frame (wks)***".

wrf_overlays (nc_file, *wks, (/graphics/), pltres*)
Usage: *plot = wrf_overlays (a, wks, (/contour,vector/), pltres)*

Overlay contour and vector plots generated with *wrf_contour* and *wrf_vector*. Can overlay any number of graphics. Overlays will be done in the order given, so always list shaded plots before line or vector plots, to ensure the lines and vectors are visible and not hidden behind the shaded plot.

Typically used for idealized data or cross-sections, which does not have map background information.

pltres@NoTitles : Set to True to remove all field titles on a plot.
pltres@CommonTitle : Overwrite field titles with a common title for the overlaid plots.
Must set *pltres@PlotTitle* to desired new plot title.

If you want to generate images for a panel plot, set *pltres@PanelPot* to True.

If you want to add text/lines to the plot before advancing the frame, set *pltres@FramePlot* to False. Add your text/lines directly after the call to the *wrf_overlays* function. Once you are done adding text/lines, advance the frame with the command "***frame (wks)***".

wrf_map (*nc_file, wks, res*)
Usage: *map = wrf_map (a, wks, opts)*

Create a map background.
As maps are added to plots automatically via the *wrf_map_overlays* function, this function is seldom needed as a stand-alone.

wrf_user_intrp3d (*var3d, H, plot_type, loc_param, angle, res*)

This function is used for both horizontal and vertical interpolation.

var3d: The variable to interpolate. This can be an array of up to 5 dimensions. The 3 right-most dimensions must be *bottom_top* **x** *south_north* **x** *west_east*.
H: The field to interpolate to. Either pressure *(hPa or Pa),* or z *(m)*. Dimensionality must match **var3d**.
plot_type: "h" for horizontally- and "v" for vertically-interpolated plots.
loc_param: Can be a scalar, or an array, holding either 2 or 4 values.
For plot_type = "h":
This is a scalar representing the level to interpolate to.
Must match the field to interpolate to (H).
When interpolating to pressure, this can be in hPa or Pa *(e.g. 500., to interpolate to 500 hPa)*. When interpolating to height this must in in *m (e.g. 2000., to interpolate to 2 km).*
For plot_type = "v":
This can be a pivot point though which a line is drawn – in this case a single x/y point *(2 values)* is required. Or this can be a set of x/y points *(4 values),* indicating start x/y and end x/y locations for the cross-section.
angle:
Set to 0., for *plot_type = "h",* or *for plot_type = "v"* when start and end locations of cross-section are supplied in *loc_param*.
If a single pivot point was supplied in *loc_param*, angle is the angle of the line that will pass through the pivot point. Where: 0. is SN, and 90. is WE.
res:
Set to False for *plot_type = "h",* or for *plot_type = "v"* when a single pivot point is supplied. Set to True if start and end locations are supplied.

wrf_user_intrp2d (*var2d, loc_param, angle, res*)

This function interpolates a 2D field along a given line.

var2d: The 2D field to interpolate. This can be an array of up to 3 dimensions. The 2 right-most dimensions must be *south_north* **x** *west_east*.

loc_param:

An array holding either 2 or 4 values.
This can be a pivot point though which a line is drawn - in this case a single x/y point *(2 values)* is required. Or this can be a set of x/y points *(4 values),* indicating start x/y and end x/y locations for the cross-section.

angle:

Set to 0 when start and end locations of the line are supplied in *loc_param*.
If a single pivot point is supplied in *loc_param*, angle is the angle of the line that will pass through the pivot point. Where: 0. is SN, and 90. is WE.

res:

Set to False when a single pivot point is supplied. Set to True if start and end locations are supplied.

wrf_user_ll_to_ij (nc_file, lons, lats, res)
Usage: *loc = wrf_user_latlon_to_ij (a, 100., 40., res)*
Usage: *loc = wrf_user_latlon_to_ij (a, (/100., 120./), (/40., 50./), res)*

Converts a lon/lat location to the nearest x/y location. This function makes use of map information to find the closest point; therefore this returned value may potentially be outside the model domain.

lons/lats can be scalars or arrays.

Optional resources:
res@returnInt - If set to False, the return values will be real (default is True with integer return values)
res@useTime - Default is 0. Set if you want the reference longitude/latitudes to come from a specific time - one will only use this for moving nest output, which has been stored in a single file.

loc(0,:) is the x (WE) locations, and loc(1,:) the y (SN) locations.

wrf_user_ij_to_ll (nc_file, i, j, res)
Usage: *loc = wrf_user_latlon_to_ij (a, 10, 40, res)*
Usage: *loc = wrf_user_latlon_to_ij (a, (/10, 12/), (/40, 50/), res)*

Convert an i/j location to a lon/lat location. This function makes use of map information to find the closest point, so this returned value may potentially be outside the model domain.

i/j can be scalars or arrays.

Optional resources:
res@useTime - Default is 0. Set if you want the reference longitude/latitudes to come from a specific time - one will only use this for moving nest output, which has been stored in a single file.

loc(0,:) is the lons locations, and loc(1,:) the lats locations.

wrf_user_unstagger (varin, unstagDim)

This function unstaggers an array, and returns an array on ARW WRF mass points.

varin: Array to be unstaggered.
unstagDim: Dimension to unstagger. Must be either "X", "Y", or "Z". This is case sensitive. If you do not use one of these strings, the returning array will be unchanged.

wrf_wps_dom (wks, mpres, lnres, txres)

A function has been built into NCL to preview where a potential domain will be placed *(similar to plotgrids.exe from WPS).*

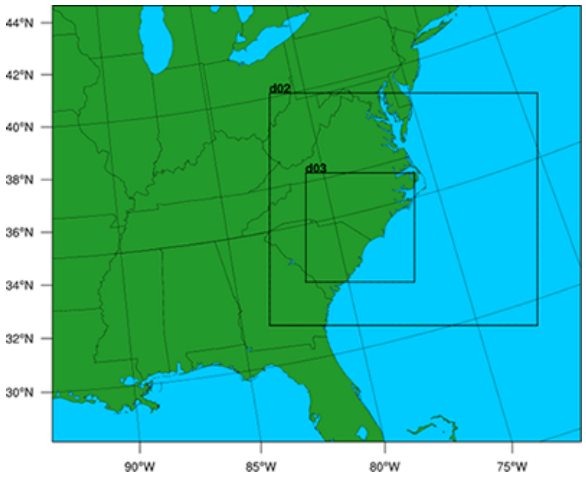
The **lnres** and **txres** resources are standard NCL Line and Text resources. These are used to add nests to the preview.

The **mpres** are used for standard map background resources like:
mpres@mpFillOn ; mpres@mpFillColors ; mpres@mpGeophysicalLineColor ; mpres@mpNationalLineColor ; mpres@mpUSStateLineColor ; mpres@mpGridLineColor ; mpres@mpLimbLineColor ; mpres@mpPerimLineColor

Its main function, however, is to set map resources to preview a domain. These resources are similar to the resources set in WPS. Below is an example of how to display 3 nested domains on a Lambert projection. *(The output is shown below).*

```
mpres@max_dom           = 3
mpres@parent_id         = (/ 1,    1,   2 /)
mpres@parent_grid_ratio = (/ 1,    3,   3 /)
mpres@i_parent_start    = (/ 1,   31,  15 /)
mpres@j_parent_start    = (/ 1,   17,  20 /)
```

```
mpres@e_we              = (/ 74, 112, 133/)
mpres@e_sn              = (/ 61,  97, 133 /)
mpres@dx                = 30000.
mpres@dy                = 30000.
mpres@map_proj          = "lambert"
mpres@ref_lat           = 34.83
mpres@ref_lon           = -81.03
mpres@truelat1          = 30.0
mpres@truelat2          = 60.0
mpres@stand_lon         = -98.0
```



NCL built-in Functions

A number of NCL built-in functions have been created to help users calculate simple diagnostics. Full descriptions of these functions are available on the NCL web site (http://www.ncl.ucar.edu/Document/Functions/wrf.shtml).

wrf_avo	Calculates absolute vorticity.
wrf_cape_2d	Computes convective available potential energy (CAPE), convective inhibition (CIN), lifted condensation level (LCL), and level of free convection (LFC).
wrf_cape_3d	Computes convective available potential energy (CAPE) and convective inhibition (CIN).
wrf_dbz	Calculates the equivalent reflectivity factor.
wrf_eth	Calculates equivalent potential temperature
wrf_helicity	Calculates storm relative helicity
wrf_ij_to_ll	Finds the longitude, latitude locations to the specified model grid indices (i,j).

wrf_ll_to_ij	Finds the model grid indices (i,j) to the specified location(s) in longitude and latitude.
wrf_omega	Calculates omega
wrf_pvo	Calculates potential vorticity.
wrf_rh	Calculates relative humidity.
wrf_slp	Calculates sea level pressure.
wrf_smooth_2d	Smooth a given field.
wrf_td	Calculates dewpoint temperature in [C].
wrf_tk	Calculates temperature in [K].
wrf_updraft_helicity	Calculates updraft helicity
wrf_uvmet	Rotates u,v components of the wind to earth coordinates.
wrf_virual_temp	Calculates virtual temperature
wrf_wetbulb	Calculates wetbulb temperature

Adding diagnostics using FORTRAN code

It is possible to link your favorite FORTRAN diagnostics routines to NCL. It is easier to use FORTRAN 77 code, but NCL also recognizes basic FORTRAN 90 code.

Let's use a routine that calculates temperature (K) from theta and pressure.

FORTRAN 90 routine called myTK.f90

```
subroutine compute_tk (tk, pressure, theta, nx, ny, nz)
implicit none

!! Variables
   integer  :: nx, ny, nz
   real, dimension (nx,ny,nz) :: tk, pressure, theta

!! Local Variables
   integer :: i, j, k
   real, dimension (nx,ny,nz):: pi

   pi(:,:,:) = (pressure(:,:,:) / 1000.)**(287./1004.)
   tk(:,:,:) = pi(:,:,:)*theta(:,:,:)

return
end subroutine compute_tk
```

For simple routines like this, it is easiest to re-write the routine into a FORTRAN 77 routine.

FORTRAN 77 routine called myTK.f

```
      subroutine compute_tk (tk, pressure, theta, nx, ny, nz)
      implicit none

C     Variables
      integer  nx, ny, nz
      real   tk(nx,ny,nz) , pressure(nx,ny,nz), theta(nx,ny,nz)

C     Local Variables
      integer  i, j, k
      real   pi

      DO k=1,nz
        DO j=1,ny
          DO i=1,nx
            pi=(pressure(i,j,k) / 1000.)**(287./1004.)
            tk(i,j,k) = pi*theta(i,j,k)
          ENDDO
        ENDDO
      ENDDO

    return
    end
```

Add the markers **NCLFORTSTART** and **NCLEND** to the subroutine as indicated below. Note, that local variables are outside these block markers.

FORTRAN 77 routine called myTK.f, with NCL markers added

```
C NCLFORTSTART
      subroutine compute_tk (tk, pressure, theta, nx, ny, nz)
      implicit none

C     Variables
      integer  nx, ny, nz
      real   tk(nx,ny,nz) , pressure(nx,ny,nz), theta(nx,ny,nz)

C NCLEND

C     Local Variables
      integer  i, j, k
      real   pi

      DO k=1,nz
        DO j=1,ny
          DO i=1,nx
            pi=(pressure(i,j,k) / 1000.)**(287./1004.)
            tk(i,j,k) = pi*theta(i,j,k)
          ENDDO
        ENDDO
      ENDDO

    return
    end
```

Now compile this code using the NCL script WRAPIT.

```
WRAPIT myTK.f
```

NOTE: If WRAPIT cannot be found, make sure the environment variable *NCARG_ROOT* has been set correctly.

If the subroutine compiles successfully, a new library will be created, called **myTK.so.** This library can be linked to an NCL script to calculate TK. See how this is done in the example below:

```
load "$NCARG_ROOT/lib/ncarg/nclscripts/csm/gsn_code.ncl"
load "$NCARG_ROOT/lib/ncarg/nclscripts/wrf/WRFUserARW.ncl"
external myTK "./myTK.so"

begin

        t = wrf_user_getvar (a,"T",5)
        theta = t + 300
        p = wrf_user_getvar (a,"pressure",5)

        dim = dimsizes(t)
        tk = new( (/ dim(0), dim(1), dim(2) /), float)

      myTK :: compute_tk (tk, p, theta, dim(2), dim(1), dim(0))

end
```

Want to use the FORTRAN 90 program? It is possible to do so by providing an interface block for your FORTRAN 90 program. Your FORTRAN 90 program may also not contain any of the following features:

- pointers or structures as arguments,
- missing/optional arguments,
- keyword arguments, or
- if the procedure is recursive.

Interface block for FORTRAN 90 code, called myTK90.stub

```
C NCLFORTSTART
      subroutine compute_tk (tk, pressure, theta, nx, ny, nz)

      integer  nx, ny, nz
      real   tk(nx,ny,nz) , pressure(nx,ny,nz), theta(nx,ny,nz)

C NCLEND
```

Now compile this code using the NCL script WRAPIT.

```
WRAPIT myTK90.stub myTK.f90
```

NOTE: You may need to copy the WRAPIT script to a locate location and edit it to point to a FORTRAN 90 compiler.

If the subroutine compiles successfully, a new library will be created, called **myTK90.so** *(note the change in name from the FORTRAN 77 library).* This library can similarly be linked to an NCL script to calculate TK. See how this is done in the example below:

```
load "$NCARG_ROOT/lib/ncarg/nclscripts/csm/gsn_code.ncl"
load "$NCARG_ROOT/lib/ncarg/nclscripts/wrf/WRFUserARW.ncl”
external myTK90 "./myTK90.so"

begin
        t = wrf_user_getvar (a,”T”,5)
        theta = t + 300
        p = wrf_user_getvar (a,”pressure”,5)

        dim = dimsizes(t)
        tk = new( (/ dim(0), dim(1), dim(2) /), float)

      myTK90 :: compute_tk (tk, p, theta, dim(2), dim(1), dim(0))

end
```

RIP4

RIP (which stands for Read/Interpolate/Plot) is a Fortran program that invokes NCAR Graphics routines for the purpose of visualizing output from gridded meteorological data sets, primarily from mesoscale numerical models. It was originally designed for sigma-coordinate-level output from the PSU/NCAR Mesoscale Model (MM4/MM5), but was generalized in April 2003 to handle data sets with any vertical coordinate, and in particular, output from the Weather Research and Forecast (WRF) modeling system. It can also be used to visualize model input or analyses on model grids. It has been under continuous development since 1991, *primarily by Mark Stoelinga at both NCAR and the University of Washington.*

The RIP **users' guide** (*http://www2.mmm.ucar.edu/wrf/users/docs/ripug.htm*) is essential reading.

Code history

Version 4.0: reads WRF-ARW real output files
Version 4.1: reads idealized WRF-ARW datasets
Version 4.2: reads all the files produced by WPS
Version 4.3: reads files produced by WRF-NMM model
Version 4.4: add ability to output different graphical types
Version 4.5: add configure/compiler capabilities
Version 4.6: current version – only bug fix changes between 4.5 and 4.6
(This document will only concentrate on running RIP4 for WRF-ARW. For details on running RIP4 for WRF-NMM, see the WRF-NMM User's Guide: http://www.dtcenter.org/wrf-nmm/users/docs/overview.php)

Necessary software

RIP4 only requires low-level NCAR Graphics libraries. These libraries have been merged with the NCL libraries since the release of NCL version 5 (*http://www.ncl.ucar.edu/*), so if you don't already have NCAR Graphics installed on your computer, install NCL version 5.

Obtain the code from the WRF-ARW user's web site:
http://www2.mmm.ucar.edu/wrf/users/download/get_source.html

Unzip and untar the RIP4 tar file. The tar file contains the following directories and files:

- *CHANGES*, a text file that logs changes to the RIP tar file.
- *Doc/*, a directory that contains documentation of RIP, most notably the Users' Guide (*ripug*).

- *README*, a text file containing basic information on running RIP.
- *arch/*, directory containing the default compiler flags for different machines.
- *clean*, script to clean compiled code.
- *compile*, script to compile code.
- *configure*, script to create a configure file for your machine.
- *color.tbl*, a file that contains a table, defining the colors you want to have available for RIP plots.
- *eta_micro_lookup.dat*, a file that contains "look-up" table data for the Ferrier microphysics scheme.
- *psadilookup.dat*, a file that contains "look-up" table data for obtaining temperature on a pseudoadiabat.
- *sample_infiles/*, a directory that contains sample user input files for RIP and related programs.
- *src/*, a directory that contains all of the source code files for RIP, RIPDP, and several other utility programs.
- *stationlist*, a file containing observing station location information.

Environment Variables

An important environment variable for the RIP system is **RIP_ROOT**. RIP_ROOT should be assigned the path name of the directory where all your RIP program and utility files (*color.tbl*, *stationlist*, lookup tables, etc.) reside. Typically *(for cshrc shell):*

```
setenv RIP_ROOT /my-path/RIP4
```

The RIP_ROOT environment variable can also be overwritten with the variable *rip_root* in the RIP user input file (UIF).

A second environment variable you need to set is **NCARG_ROOT**.
Typically *(for cshrc shell):*

```
setenv NCARG_ROOT /usr/local/ncarg     ! for NCARG V4
setenv NCARG_ROOT /usr/local/ncl       ! for NCL V5
```

Compiling RIP and associated programs

Since the release of version 4.5, the same configure/compile scripts available in all other WRF programs have been added to RIP4. To compile the code, first configure for your machine by typing:

```
./configure
```

You will see a list of options for your computer *(below is an example for a Linux machine)*:

```
Will use NETCDF in dir: /usr/local/netcdf-pgi
------------------------------------------------------------
Please select from among the following supported platforms.
1.  PC Linux i486 i586 i686 x86_64, PGI compiler
2.  PC Linux i486 i586 i686 x86_64, g95 compiler
3.  PC Linux i486 i586 i686 x86_64, gfortran compiler
4.  PC Linux i486 i586 i686 x86_64, Intel compiler

Enter selection [1-4]
```

Make sure the netCDF path is correct.
Pick compile options for your machine.

This will create a file called `configure.rip`. Edit compile options/paths, if necessary.

To compile the code, type:

```
./compile
```

After a successful compilation, the following new files should be created.

rip	RIP post-processing program. Before using this program, first convert the input data to the correct format expected by this program, using the program **ripdp**
ripcomp	This program reads-in two rip data files and compares their content.
ripdp_mm5	RIP Data Preparation program for MM5 data
ripdp_wrfarw **ripdp_wrfnmm**	RIP Data Preparation program for WRF data
ripinterp	This program reads-in model output (in rip-format files) from a coarse domain and from a fine domain, and creates a new file which has the data from the coarse domain file interpolated (bi-linearly) to the fine domain. The header and data dimensions of the new file will be that of the fine domain, and the case name used in the file name will be the same as that of the fine domain file that was read-in.
ripshow	This program reads-in a rip data file and prints out the contents of the header record.
showtraj	Sometimes, you may want to examine the contents of a trajectory position file. Since it is a binary file, the trajectory position file cannot simply be printed out. showtraj, reads the trajectory position file and prints out its contents in a readable form. When you run showtraj, it prompts you for the name of the trajectory position file to be printed out.

tabdiag	If fields are specified in the plot specification table for a trajectory calculation run, then RIP produces a **.diag** file that contains values of those fields along the trajectories. This file is an unformatted Fortran file; so another program is required to view the diagnostics. **tabdiag** serves this purpose.
upscale	This program reads-in model output (in rip-format files) from a coarse domain and from a fine domain, and replaces the coarse data with fine data at overlapping points. Any refinement ratio is allowed, and the fine domain borders do not have to coincide with coarse domain grid points.

Preparing data with RIPDP

RIP does not ingest model output files directly. First, a preprocessing step must be executed that converts the model output data files to RIP-format data files. The primary difference between these two types of files is that model output data files typically contain all times and all variables in a single file (or a few files), whereas RIP data has each variable at each time in a separate file. The preprocessing step involves use of the program RIPDP (which stands for RIP Data Preparation). RIPDP reads-in a model output file (or files), and separates out each variable at each time.

Running RIPDP

The program has the following usage:

```
ripdp_XXX [-n namelist_file] model-data-set-name [basic|all]
data_file_1 data_file_2 data_file_3 ...
```

Above, the "XXX" refers to "mm5", "wrfarw", or "wrfnmm".
The argument model-data-set-name can be any string you choose, that uniquely defines this model output data set.

The use of the namelist file is optional. The most important information in the namelist is the times you want to process.

As this step will create a large number of extra files, creating a new directory to place these files in will enable you to manage the files easier *(`mkdir RIPDP`)*.

e.g. `ripdp_wrfarw RIPDP/arw all wrfout_d01_*`

The RIP user input file

Once the RIP data has been created with RIPDP, the next step is to prepare the user input file (UIF) for RIP *(see Chapter 4 of the RIP users' guide for details)*. This file is a text file, which tells RIP what plots you want, and how they should be plotted. A sample UIF, called *rip_sample.in*, is provided in the RIP tar file. This sample can serve as a template for the many UIFs that you will eventually create.

A UIF is divided into two main sections. The first section specifies various general parameters about the set-up of RIP, in a namelist format (***userin*** - *which controls the general input specifications; and* ***trajcalc*** - *which controls the creation of trajectories*). The second section is the plot specification section, which is used to specify which plots will be generated.

namelist: userin

Variable	Value	Description
idotitle	1	Controls first part of title.
title	'auto'	Defines your own title, or allow RIP to generate one.
titlecolor	'def.foreground'	Controls color of the title.
iinittime	1	Prints initial date and time *(in UTC)* on plot.
ifcsttime	1	Prints forecast lead-time *(in hours)* on plot.
ivalidtime	1	Prints valid date and time (*in both UTC and local time*) on plot.
inearesth	0	This allows you to have the hour portion of the initial and valid time be specified with two digits, rounded to the nearest hour, rather than the standard 4-digit HHMM specification.
timezone	-7.0	Specifies the offset from Greenwich time.
iusdaylightrule	1	Flag to determine if US daylight saving should be applied.
ptimes	9.0E+09	Times to process. This can be a string of times *(e.g. 0,3,6,9,12,)* or a series in the form of *A,-B,C,* which means "times from hour *A*, to hour *B*, every *C* hours" *(e.g. 0,-12,3,)*. Either *ptimes* or *iptimes* can be used, but not both. *You can plot all available times, by omitting both ptimes and iptimes from the namelist, or by setting the first value negative.*
ptimeunits	'h'	Time units. This can be 'h' *(hours)*, 'm' *(minutes)*, or 's' *(seconds)*. *Only valid with ptimes.*

iptimes	99999999	Times to process. This is an integer array that specifies desired times for RIP to plot, but in the form of 8-digit "mdate" times *(i.e. YYMMDDHH)*. Either *ptimes* or *iptimes* can be used, but not both. *You can plot all available times by omitting both ptimes and iptimes from the namelist, or by setting the first value negative.*
tacc	1.0	Time tolerance in seconds. Any time in the model output that is within *tacc* seconds of the time specified in *ptimes/iptimes* will be processed.
flmin, flmax, fbmin, ftmax	.05, .95,.10, .90	Left, right, bottom and top frame limit
ntextq	0	Text quality specifier (0=high; 1=medium; 2=low).
ntextcd	0	Text font specifier [0=complex (Times); 1=duplex (Helvetica)].
fcoffset	0.0	This is an optional parameter you can use to "tell" RIP that you consider the start of the forecast to be different from what is indicated by the forecast time recorded in the model output. Examples: *fcoffset*=12 means you consider hour 12 in the model output to be the beginning of the true forecast.
idotser	0	Generates time-series output files *(no plots);* only an ASCII file that can be used as input to a plotting program.
idescriptive	1	Uses more descriptive plot titles.
icgmsplit	0	Splits metacode into several files.
maxfld	10	Reserves memory for RIP.
ittrajcalc	0	Generates trajectory output files (use namelist *trajcalc* when this is set).
imakev5d	0	Generate output for Vis5D
ncarg_type	‘cgm’	Outputs type required. Options are ‘cgm’ *(default)*, ‘ps’, ‘pdf’, ‘pdfL’, ‘x11’. Where ‘pdf’ is portrait and ‘pdfL’ is landscape.
istopmiss	1	This switch determines the behavior for RIP when a user-requested field is not available. *The default is to stop*. Setting the switch to 0 tells RIP to ignore the missing field and to continue plotting.
rip_root	‘/dev/null’	Overwrites the environment variable RIP_ROOT.

Plot Specification Table

The second part of the RIP UIF consists of the Plot Specification Table. The PST provides all of the user control over particular aspects of individual frames and overlays.

The basic structure of the PST is as follows:

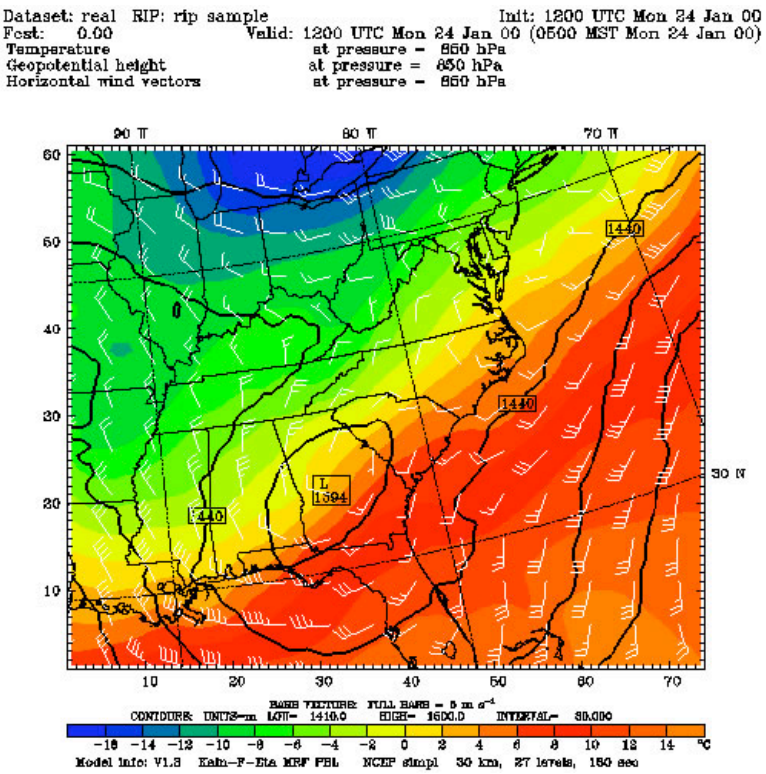
- The first line of the PST is a line of consecutive equal signs. This line, as well as the next two lines, is ignored by RIP. It is simply a banner that says this is the start of the PST section.
- After that, there are several groups of one or more lines, separated by a full line of equal signs. Each group of lines is a frame specification group (FSG), and it describes what will be plotted in a single frame of metacode. Each FSG must end with a full line of equal signs, so that RIP can determine where individual frames start and end.
- Each line within a FGS is referred to as a plot specification line (PSL). An FSG that consists of three PSL lines will result in a single metacode frame with three over-laid plots.

Example of a frame specification groups (FSG's):

```
==================================================
 feld=tmc; ptyp=hc; vcor=p; levs=850; >
  cint=2; cmth=fill; cosq=-32,light.violet,-24,
  violet,-16,blue,-8,green,0,yellow,8,red,>
  16,orange,24,brown,32,light.gray
 feld=ght; ptyp=hc; cint=30; linw=2
 feld=uuu,vvv; ptyp=hv; vcmx=-1; colr=white; intv=5
 feld=map; ptyp=hb
 feld=tic; ptyp=hb
==================================================
```

This **FSG** will generate 5 frames to create a single plot (as shown below):

- Temperature in degrees C (*feld=**tmc***). This will be plotted as a horizontal contour plot (*ptyp=hc*), on pressure levels (*vcor=p*). The data will be interpolated to 850 hPa. The contour intervals are set to 2 (*cint=2*), and shaded plots (*cmth=fill*) will be generated with a color range from light violet to light gray.
- Geopotential heights (*feld=**ght***) will also be plotted as a horizontal contour plot. This time the contour intervals will be 30 (*cint=30*), and contour lines with a line width of 2 (*linw=2*) will be used.
- Wind vectors (*feld=**uuu,vvv***), plotted as barbs (*vcmax=-1*).
- A map background will be displayed (*feld=**map***), and
- Tic marks will be placed on the plot (*feld=tic*).



Running RIP

Each execution of RIP requires three basic things: a RIP executable, a model data set and a user input file (UIF). The syntax for the executable, *rip*, is as follows:

`rip [-f] model-data-set-name rip-execution-name`

In the above, model-data-set-name is the same model-data-set-name that was used in creating the RIP data set with the program *ripdp*.

rip-execution-name is the unique name for this RIP execution, and it also defines the name of the UIF that RIP will look for.

The *–f* option causes the standard output *(i.e., the textual print out)* from RIP to be written to a file called *rip-execution-name.out*. Without the *–f* option, the standard output is sent to the screen.

e.g. `rip -f RIPDP/arw rip_sample`

If this is successful, the following files will be created:

rip_sample.*TYPE*	- metacode file with requested plots
rip_sample.out	- log file *(if –f used)* ; view this file if a problem occurred

The default output *TYPE* is a 'cgm', metacode file. To view these, use the command 'idt'.

```
e.g.  idt   rip_sample.cgm
```

For high quality images, create pdf or ps images directly **(ncarg_*type* = *pdf / ps*).**

See the **Tools** section in Chapter 10 of this User's Guide for more information concerning other types of graphical formats and conversions between graphical formats.

Examples of plots created for both idealized and real cases are available from:
http://www2.mmm.ucar.edu/wrf/users/graphics/RIP4/RIP4.htm

ARWpost

The ARWpost package reads-in WRF-ARW model data and creates GrADS output files. *Since version 3.0 (released December 2010), vis5D output is no longer supported. More advanced 3D visualization tools, like VAPOR and IDV, have been developed over the last couple of years, and users are encouraged to explore those for their 3D visualization needs.*

The converter can read-in WPS geogrid and metgrid data, and WRF-ARW input and output files in netCDF format. *Since version 3.0 the ARWpost code is no longer dependant on the WRF IO API. The advantage of this is that the ARWpost code can now be compiled and executed anywhere without the need to first install WRF. The disadvantage is that GRIB1 formatted WRF output files are no longer supported.*

Necessary software

GrADS software - you can download and install GrADS from *http://grads.iges.org/*. The GrADS software is not needed to compile and run ARWpost, but is needed to display the output files.

Obtain the ARWpost TAR file from the WRF Download page (*http://www2.mmm.ucar.edu/wrf/users/download/get_source.html*)

Unzip and untar the ARWpost tar file.

The tar file contains the following directories and files:

- *README*, a text file containing basic information on running ARWpost.
- *arch/,* directory containing configure and compilation control.
- *clean,* a script to clean compiled code.
- *compile*, a script to compile the code.
- *configure*, a script to configure the compilation for your system.
- *namelist.ARWpost,* namelist to control the running of the code.
- *src/*, directory containing all source code.
- *scripts/*, directory containing some grads sample scripts.
- *util/*, a directory containing some utilities.

Environment Variables

Set the environment variable NETCDF to the location where your netCDF libraries are installed. Typically *(for cshrc shell):*

```
setenv NETCDF /usr/local/netcdf
```

Configure and Compile ARWpost

To configure - Type:

```
./configure
```

You will see a list of options for your computer *(below is an example for a Linux machine)*:

```
Will use NETCDF in dir: /usr/local/netcdf-pgi
------------------------------------------------------------
Please select from among the following supported platforms.
1. PC Linux i486 i586 i686, PGI compiler
2. PC Linux i486 i586 i686, Intel compiler

Enter selection [1-2]
```

Make sure the netCDF path is correct.
Pick the compile option for your machine

To compile - Type**:**

```
./compile
```

If successful, the executable `ARWpost.exe` will be created.

Edit the namelist.ARWpost file

Set input and output file names and fields to process (***&io***)

Variable	Value	Description
&datetime		
start_date; *end_date*		Start and end dates to process. Format: YYYY-MM-DD_HH:00:00
interval_seconds	0	Interval in seconds between data to process. If data is available every hour, and this is set to every 3 hours, the code will skip past data not required.
tacc	0	Time tolerance in seconds. Any time in the model output that is within *tacc* seconds of the time specified will be processed.
debug_level	0	Set this higher for more print-outs that can be useful for debugging later.
&io		
input_root_name	./	Path and root name of files to use as input. All files starting with the root name will be processed. Wild characters are allowed.
output_root_name	./	Output root name. When converting data to GrADS, *output_root_name*.ctl and *output_root_name*.dat will be created.
output_title	Title as in WRF file	Use to overwrite title used in GrADS .ctl file.
mercator_defs	.False.	Set to true if mercator plots are distorted.
split_output	.False.	Use if you want to split our GrADS output files into a number of smaller files *(a common .ctl file will be used for all .dat files).*
frames_per_outfile	1	If *split_output* is .True., how many time periods are required per output *(.dat)* file.

plot	'all'	Which fields to process. 'all' – all fields in WRF file 'list' – only fields as listed in the *'fields'* variable. 'all_list' – all fields in WRF file and all fields listed in the *'fields'* variable. Order has no effect, i.e., *'all_list'* and *'list_all'* are similar. If '*list*' is used, a list of variables must be supplied under '*fields*'. Use *'list'* to calculate diagnostics.
fields		Fields to plot. Only used if '*list'* was used in the '*plot*' variable.
&interp		
interp_method	0	0 - sigma levels, -1 - code-defined "nice" height levels, 1 - user-defined height or pressure levels
interp_levels		Only used if interp_method=1 Supply levels to interpolate to, in hPa (pressure) or km (height). Supply levels bottom to top.
extrapolate	.false.	Extrapolate the data below the ground if interpolating to either pressure or height.

Available diagnostics:

cape - 3d cape
cin - 3d cin
mcape - maximum cape
mcin - maximum cin
clfr - low/middle and high cloud fraction
dbz - 3d reflectivity
max_dbz - maximum reflectivity
geopt - geopotential
height - model height in km
lcl - lifting condensation level
lfc - level of free convection
pressure - full model pressure in hPa
rh - relative humidity
rh2 - 2m relative humidity
theta - potential temperature
tc - temperature in degrees C
tk - temperature in degrees K

td - dew point temperature in degrees C
td2 - 2m dew point temperature in degrees C
slp - sea level pressure
umet and **vmet** - winds rotated to earth coordinates
u10m and **v10m** - 10m winds rotated to earth coordinates
wdir - wind direction
wspd - wind speed coordinates
wd10 - 10m wind direction
ws10 - 10m wind speed

Run ARWpost

Type:

```
./ARWpost.exe
```

This will create the *output_root_name*.**dat** and *output_root_name*.**ctl** files required as input by the GrADS visualization software.

NOW YOU ARE READY TO VIEW THE OUTPUT

For general information about working with GrADS, view the GrADS home page: *http://grads.iges.org/grads/*

To help users get started, a number of GrADS scripts have been provided:

- The scripts are all available in the *scripts/* directory.
- The scripts provided are only examples of the type of plots one can generate with GrADS data.
- The user will need to modify these scripts to suit their data (e.g., if you do not specify 0.25 km and 2 km as levels to interpolate to when you run the "bwave" data through the converter, the "bwave.gs" script will not display any plots, since it will specifically look for these levels).
- Scripts must be copied to the location of the input data.

GENERAL SCRIPTS

cbar.gs	Plot color bar on shaded plots (from GrADS home page)
rgbset.gs	Some extra colors *(Users can add/change colors from color number 20 to 99)*

skew.gs Program to plot a skewT

TO RUN TYPE: run skew.gs (needs pressure level TC,TD,U,V as input)
User will be prompted if a hardcopy of the plot must be created (- 1 for yes and 0 for no).
If 1 is entered, a GIF image will be created.
Need to enter lon/lat of point you are interested in
Need to enter time you are interested in
Can overlay 2 different times

plot_all.gs Once you have opened a GrADS window, all one needs to do is run this script.
It will automatically find all .ctl files in the current directory and list them so one can pick which file to open.
Then the script will loop through all available fields and plot the ones a user requests.

SCRIPTS FOR REAL DATA

real_surf.gs Plot some surface data
Need input data on model levels

plevels.gs Plot some pressure level fields
Need model output on pressure levels

rain.gs Plot total rainfall
Need a model output data set (any vertical coordinate), that contain fields "RAINC" and "RAINNC"

cross_z.gs Need z level data as input
Will plot a NS and EW cross section of RH and T (C)
Plots will run through middle of the domain

zlevels.gs Plot some height level fields
Need input data on height levels
Will plot data on 2, 5, 10 and 16km levels

input.gs Need WRF INPUT data on height levels

SCRIPTS FOR IDEALIZED DATA

bwave.gs Need height level data as input
Will look for 0.25 and 2 km data to plot

grav2d.gs Need normal model level data

hill2d.gs Need normal model level data

qss.gs Need height level data as input.
Will look for heights 0.75, 1.5, 4 and 8 km to plot

sqx.gs Need normal model level data a input

sqy.gs Need normal model level data a input

Examples of plots created for both idealized and real cases are available from:
http://www2.mmm.ucar.edu/wrf/OnLineTutorial/Graphics/ARWpost/

Trouble Shooting

The code executes correctly, but you get ***"NaN"*** *or* ***"Undefined Grid"*** *for all fields when displaying the data.*

Look in the .ctl file.

a) If the second line is:

> **options byteswapped**
>
> Remove this line from your .ctl file and try to display the data again.
> If this SOLVES the problem, you need to remove the **-Dbytesw** option from *configure.arwp*

b) If the line below does NOT appear in your .ctl file:

> **options byteswapped**
>
> ADD this line as the second line in the .ctl file.
> Try to display the data again.
> If this SOLVES the problem, you need to ADD the **-Dbytesw** option for *configure.arwp*

The line "options byteswapped" is often needed on some computers (DEC alpha as an example). It is also often needed if you run the converter on one computer and use another to display the data.

NCEP Unified Post Processor (UPP)

UPP Introduction

The NCEP Unified Post Processor has replaced the WRF Post Processor (WPP). The UPP software package is based on WPP but has enhanced capabilities to post-process output from a variety of NWP models, including WRF-NMM, WRF-ARW, Non-hydrostatic Multi-scale Model on the B grid (NMMB), Global Forecast System (GFS), and Climate Forecast System (CFS). At this time, community user support is provided for the WRF-based systems and NMMB.

In addition to the option to output fields on the model's native vertical levels, UPP interpolates output from the model's native grids to National Weather Service (NWS) standard levels (pressure, height, etc.) and standard output grids (AWIPS, Lambert Conformal, polar-stereographic, etc.) in NWS and World Meteorological Organization (WMO) GRIB format. With the release of UPPv3.0, preliminary capabilities to output in GRIB Edition 2 (GRIB2) format for select models has been included and a simple template is available for users to modify to fit their needs. Caution should be taken when utilizing GRIB2; exhaustive testing has not been conducted and it is recommend to use this feature in testing/exploratory mode at this time. Updates will be provided as GRIB2 output capabilities become available and more comprehensive information will be included in the Users' Guide.

UPP incorporates the Joint Center for Satellite Data Assimilation (JCSDA) Community Radiative Transfer Model (CRTM) to compute model derived brightness temperature (T_B) for various instruments and channels. This additional feature enables the generation of a number of simulated satellite products including GOES and AMSRE products for WRF-NMM, Hurricane WRF (HWRF), WRF-ARW and GFS. For CRTM documentation, refer to http://www.orbit.nesdis.noaa.gov/smcd/spb/CRTM.

UPP Software Requirements

The Community Unified Post Processor requires the same Fortran and C compilers used to build the WRF model. In addition, the netCDF library, the JasPer library, the PNG library, Zlib, and the WRF I/O API libraries, which are included in the WRF model tar file, are also required. UPP uses WRF I/O libraries for data processing of all models and as a result UPP is dependent on a WRF build. The JasPer library, PNG library, and Zlib are new requirements with the release of UPPv2.0 and higher, due to the addition GRIB2 capabilities. NCEP provides these necessary codes for download: http://www.nco.ncep.noaa.gov/pmb/codes/GRIB2/

The UPP has some sample visualization scripts included to create graphics using either GrADS (http://grads.iges.org/grads/grads.html) or GEMPAK (http://www.unidata.ucar.edu/software/gempak/index.html). These are not part of the UPP installation and need to be installed separately if one would like to use either plotting package.

UPP has been tested on LINUX platforms (with PGI, Intel and GFORTRAN compilers).

Obtaining the UPP Code

The UPP package can be downloaded from:
http://www.dtcenter.org/upp/users/downloads/index.php

UPP Functionalities

The UPP,

- is compatible with WRF v3.3 and higher.
- can be used to post-process WRF-ARW, WRF-NMM, NMMB, GFS, and CFS forecasts (community support provided for WRF-based and NMMB forecasts).
- can ingest WRF history files (***wrfout****) in two formats: netCDF and binary.
- can ingest NMMB history files (*nmmb_hist**) in binary.

The UPP is divided into two parts:

Unipost

i. Interpolates the forecasts from the model's native vertical coordinate to NWS standard output levels (e.g., pressure, height) and computes mean sea level pressure. If the requested parameter is on a model's native level, then no vertical interpolation is performed.
ii. Computes diagnostic output quantities (e.g., convective available potential energy, helicity, relative humidity).
iii. Outputs the results in NWS and WMO standard GRIB1 format (for GRIB documentation, see http://www.nco.ncep.noaa.gov/pmb/docs/).
iv. Destaggers the WRF-ARW forecasts from a C-grid to an A-grid.
v. Outputs two navigation files, ***copygb_nav.txt*** (for WRF-NMM output only) and ***copygb_hwrf.txt*** (for WRF-ARW and WRF-NMM). These files can be used as input for ***copygb***.

1. ***copygb_nav.txt:*** This file contains the GRID GDS of a Lambert Conformal Grid similar in domain and grid spacing to the one used to run the WRF-NMM. The Lambert Conformal map projection works well for mid-latitudes.
2. ***copygb_hwrf.txt***: This file contains the GRID GDS of a Latitude-

Longitude Grid similar in domain and grid spacing to the one used to run the WRF model. The latitude-longitude grid works well for tropics.

Copygb

1. Destaggers the WRF-NMM forecasts from the staggered native E-grid to a regular non-staggered grid. (Since ***unipost*** destaggers WRF-ARW output from a C-grid to an A-grid, WRF-ARW data can be displayed directly without going through ***copygb***.)
2. Destaggers the NMMB forecasts from the staggered native B-grid to a regular non-staggered grid.
3. Interpolates the forecasts horizontally from their native grid to a standard AWIPS or user-defined grid (for information on AWIPS grids, see http://www.nco.ncep.noaa.gov/pmb/docs/on388/tableb.html).
4. Outputs the results in NWS and WMO standard GRIB1 format (for GRIB documentation, see http://www.nco.ncep.noaa.gov/pmb/docs/).

Full UPP documentation available at:

http://www.dtcenter.org/upp/users/docs/user_guide/V3/upp_users_guide.pdf
http://www.dtcenter.org/upp/users/index.php

VAPOR

VAPOR is the **V**isualization and **A**nalysis **P**latform for **O**cean, Atmosphere, and Solar **R**esearchers. VAPOR was developed at NCAR to provide interactive visualization and analysis of numerically simulated fluid dynamics. The current (2.3) version of VAPOR has many capabilities for 3D visualization of WRF-ARW simulation output, including the ability to directly import wrfout files, and support for calculating derived variables that are useful in visualizing WRF output.

Basic capabilities of VAPOR with WRF-ARW output

- *Direct Volume rendering (DVR)*
  Any 3D variable in the WRF data can be viewed as a density. Users control transparency and color to view temperature, water vapor, clouds, etc. in 3D.

- *Flow*
  - Display barbs associated with 2D or 3D field magnitudes. Barbs can also be positioned at a specified height above the terrain and aligned to the WRF data grid.

- Draw 2D and 3D streamlines and flow arrows, showing the wind motion and direction, and how wind changes in time.
- Path tracing (unsteady flow) enables visualization of trajectories that particles take over time. Users control when and where the particles are released.
- Flow images (image based flow visualization) can be used to provide an animated view of wind motion in a planar section, positioned anywhere in the scene.
- Field line advection can be used to animate the motion of streamlines of any vector field in a moving wind field.

- *Isosurfaces*
  The isosurfaces of variables are displayed interactively. Users can control iso-values, color and transparency of the isosurfaces. Isosurfaces can be colored according to the values of another variable.

- *Contour planes and Probes*
  3D variables can be intersected with arbitrarily oriented planes. Contour planes can be interactively positioned. Users can interactively pinpoint the values of a variable and establish seed points for flow integration. Wind and other vector fields can be animated in the probe plane.

- *Two-dimensional variable visualization*
  2D (horizontal) WRF variables can be color-mapped and visualized in the 3D scene. They can be viewed on a horizontal plane in the scene, or mapped onto the terrain surface.

- *Animation*
  Control the time-stepping of the data, for interactive replaying and for recording animated sequences.

- *Image display*
  Tiff images can be displayed in the 3D scene. If the images are georeferenced (i.e. geotiffs) then they can be automatically positioned at the correct latitude/longitude coordinates. Images can be mapped to the terrain surface, or aligned to an axis-aligned plane. Several useful georeferenced images are preinstalled with VAPOR, including political boundary maps, and the NASA Blue Marble earth image. VAPOR also provides several utilities for obtaining geo-referenced images from the Web. Images with transparency can be overlaid on the terrain images, enabling combining multiple layers of information.

- *Analysis capabilities*
  VAPOR (versions 2.1+) has an embedded Python calculation engine. Derived variables can be easily calculated with Python expressions or programs and these will be evaluated as needed for use in visualization. VAPOR provides Python scripts to calculate the following variables from WRF output:
  CTT: Cloud-top temperature

DBZ: 3D radar reflectivity
DBZ_MAX: radar reflectivity over vertical column
ETH: equivalent potential temperature
RH: relative humidity
PV: potential vorticity
SHEAR: horizontal wind hear
SLP: 2D sea-level pressure
TD: dewpoint temperature
TK: temperature in degrees Kelvin

Instructions for calculating and visualizing these and other variables are provided in the document, "Using Python with VAPOR" on the VAPOR website.
.

Derived variables can also be calculated in IDL and imported into the current visualization session. Variables can also be calculated in other languages (e.g. NCL) and adjoined to the Vapor Data Collection. Documentation of these capabilities can be found in the Documentation menu on the VAPOR website http://www.vapor.ucar.edu.

VAPOR requirements

VAPOR is supported on Linux, Mac, and Windows systems. VAPOR works best with a recent graphics card (say 1-2 years old). The advanced features of VAPOR perform best with nVidia™, ATI™ or AMD™ graphics accelerators.

VAPOR is installed on NCAR visualization systems. Users with UCAR accounts can connect their (Windows, Linux or Mac) desktops to the NCAR visualization systems using NCAR's VNC-based remote visualization services, to run VAPOR and visualize the results remotely. Instructions for using NCAR visualization services are at:
https://www2.cisl.ucar.edu/resources/geyser_caldera/visualization
Contact *dasg@ucar.edu* or vapor@ucar.edu for assistance.

VAPOR support resources

The VAPOR website*:* *http://www.vapor.ucar.edu* includes software, documentation, example data, and links to other resources. The document "*Getting started with VAPOR and WRF*"
(http://www.vapor.ucar.edu/docs/getting-started-vapor/getting-started-vapor-and-wrf)
has an overview of the various capabilities that are useful in visualizing WRF data with VAPOR.

The VAPOR Sourceforge website (*http://sourceforge.net/projects/vapor*) enables users to post bugs, request features, download software, etc.

Users of VAPOR on NCAR visualization systems should contact *dasg@ucar.edu* for support.

Users are encouraged to provide feedback. Questions, problems, bugs etc. should be reported to *vapor@ucar.edu*. The VAPOR development priorities are set by users as well as by the VAPOR steering committee, a group of turbulence researchers who are interested in improving the ability to analyze and visualize time-varying simulation results. Post a feature request to the VAPOR SourceForge website *(http://sourceforge.net/projects/vapor),* or e-mail *vapor@ucar.edu* if you have requests or suggestions about improving VAPOR capabilities.

Basic steps for using VAPOR to visualize WRF-ARW data

1. Install VAPOR

VAPOR installers for Windows, Macintosh and Linux are available on the VAPOR home page, http://www.vapor.ucar.edu/.
For most users, a binary installation is fine. Installation instructions are also provided in the VAPOR documentation pages, *http://www.vapor.ucar.edu/docs/install*.

After VAPOR is installed, it is necessary to perform user environment setup on Unix or Mac, before executing any VAPOR software. These setup instructions are provided on the VAPOR binary install documentation pages:
http://www.vapor.ucar.edu/docs/install.

2. **(Optional) Convert WRF output data to VAPOR Data Collection**

Starting with VAPOR 2.0, you can directly load WRF-ARW output files into VAPOR. From the VAPOR menu select "Import data into current session---WRF-ARW". Alternately, if your data is very large, you will be able to visualize it more interactively by converting it to a Vapor Data Collection (VDC).

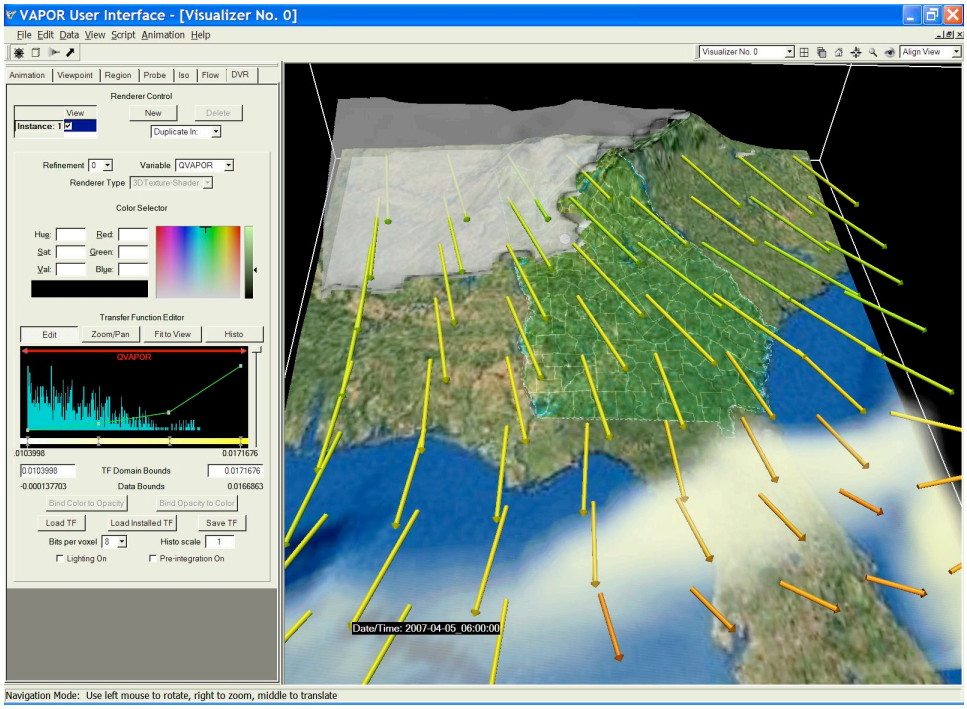
A VAPOR VDC consists of (1) a metadata file (file type .vdf) that describes an entire VAPOR data collection, and (2) a directory of multi-resolution data files where the actual data is stored. The metadata file is created by the command *wrfvdfcreate*, and the multi-resolution data files are written by the command *wrf2vdf*. The simplest way to create a VAPOR data collection is using the vdcwizard application, which is installed with VAPOR. Also there are command-line tools *wrfvdfcreate* and *wrf2vdf* that can be used to convert the WRF-ARW output data to a VDC.

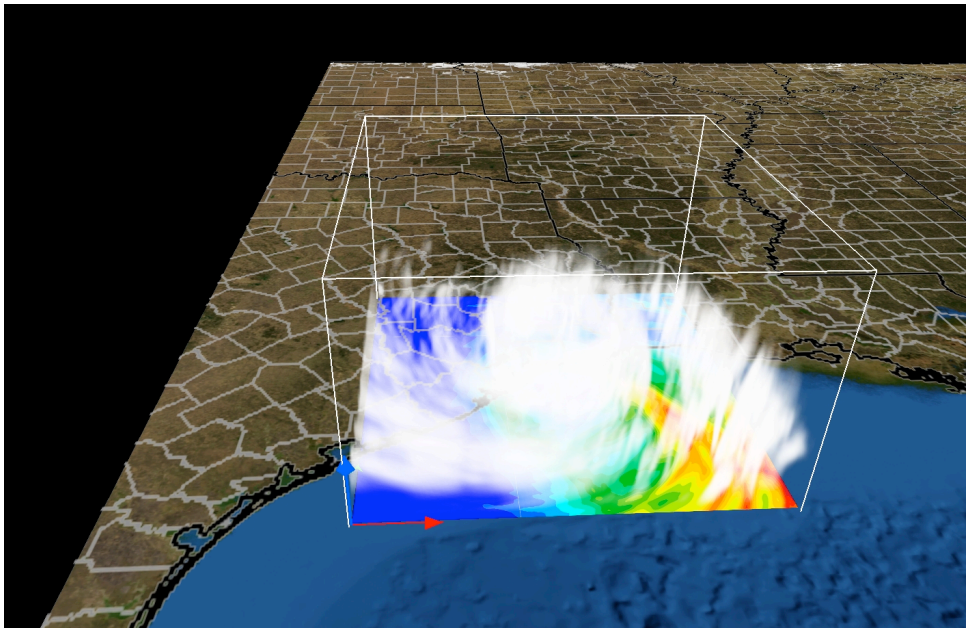
Using vdcwizard, you specify the name of the .vdf file and all the wrfout files that are to be used. First the .vdf file is created, then all the wrfout files are processed creating a VDC.

3. Visualize the WRF data

From the command line, issue the command "*vaporgui*", or double-click the VAPOR desktop icon (on Windows or Mac). This will launch the VAPOR user interface.

To directly import WRF-ARW (NetCDF) output files, click on the Data menu, and select "Import WRF output files into default session". Then select all the wrfout files you want to visualize and click "open". If instead you converted your data to a VAPOR Data Collection, then, from the Data menu, choose "Load a dataset into default session", and select the metadata file that you associated with your converted WRF data.





To visualize the data, select a renderer tab (DVR, Iso, Flow, 2D, Image, Barbs, or Probe), chose the variable(s) to display, and then, at the top of the tab, check the box labeled "Instance:1", to enable the renderer. For example, the above top image combines volume, flow and isosurface visualization with a terrain image. The bottom image illustrates hurricane Ike, as it made landfall in 2008. The Texas terrain has a map of US Counties applied to it, and an NCL image of accumulated rainfall is shown at ground level in the current region.

4. Read the VAPOR Documentation

VAPOR documentation is provided on the Website http://www.vapor.ucar.edu. For a quick overview of capabilities of VAPOR with WRF data, see "Getting started with VAPOR and WRF": *http://www.vapor.ucar.edu/docs/getting-started-vapor/getting-started-vapor-and-wrf*.

A short tutorial, showing how to use VAPOR to visualize hurricane Katrina WRF output files, is provided at http://docs.vapor.ucar.edu/tutorials/hurricane-katrina.

Additional documents on the VAPOR website *(http://www.vapor.ucar.edu)* provide more information about visualization of WRF data. Information is also available in the VAPOR user interface to help users quickly get the information they need, and showing how to obtain the most useful visualizations. Note the following resources:

- The *Georgia Weather Case Study (http://www.vapor.ucar.edu/sites/default/files/docs/GeorgiaCaseStudy.pdf)* provides a step-by-step tutorial, showing how to use most of the VAPOR features that are useful

in WRF visualization. However this material is based on an older version of VAPOR.

- Creation of geo-referenced images to use with WRF data is discussed in the web document "Preparation of Georeferenced Images". *(http://www.vapor.ucar.edu/docs/vapor-data-preparation/preparation-georeferenced-images)*

- "*Using NCL with VAPOR to visualize WRF-ARW data*": *(http://www.vapor.ucar.edu/sites/default/files/docs/VAPOR-WRF-NCL.pdf)* is a tutorial that shows how to create geo-referenced images from NCL plots, and to insert them in VAPOR scenes.

- Fuller documentation of the capabilities of the VAPOR user interface is provided in the *VAPOR GUI General Guide*: *(http://www.vapor.ucar.edu/docs/vaporgui-help)*.

- The *VAPOR Users' Guide for WRF Typhoon Research*: *(http://www.vapor.ucar.edu/sites/default/files/docs/Typhoon.pdf)* provides a tutorial for using VAPOR on typhoon data, including instructions for preparing satellites images and NCL plots to display in the scene. This document is also fairly old.

To understand the meaning or function of an element in the VAPOR user interface: *Tool tips*: Place the cursor over a widget for a couple of seconds and a one-sentence description will be provided.

Context-sensitive help: From the Help menu, click on "?Explain This", and then click with the left mouse button on a GUI element, to obtain a longer technical explanation of the functionality.

Web help: From the vaporgui Help menu, various help topics associated with the current context can be selected. These will launch a Web browser displaying detailed information about the selected topic.

Chapter 10: Utilities and Tools

Table of Contents

Introduction

This chapter contains a number of short utilities to read and manipulate WRF-ARW data.

Also included in this chapter are references to some basic third party software, which can be used to view/change input and output data files.

read_wrf_nc

This utility allows a user to look at a WRF netCDF file at a glance.

What is the difference between this utility and the netCDF utility ncdump?

- This utility has a large number of options, to allow a user to look at the specific part of the netCDF file in question.
- The utility is written in Fortran 90, which will allow users to add options.
- This utility can be used for both WRF-ARW and WRF-NMM cores.
  It can be used for geogrid, metgrid and wrf input / output files.
  Only 3 basic diagnostics are available, pressure / height / tk, these can be activated with the -diag option *(these are only available for wrfout files)*

Obtain the **read_wrf_nc** utility from the WRF Download page (*http://www2.mmm.ucar.edu/wrf/users/download/get_source.html*)

Compile

The code should run on any machine with a netCDF library *(If you port the code to a different machine, please forward the compile flags to wrfhelp@ucar.edu)*

To compile the code, use the compile flags at the top of the utility.

e.g.*, for a LINUX machine you need to type:*

```
pgf90  read_wrf_nc.f  -L/usr/local/netcdf/lib
   -lnetcdf  -lm  -I/usr/local/netcdf/include
   -Mfree  -o read_wrf_nc
```

If successful, this will create the executable: `read_wrf_nc`

Run

```
./read_wrf_nc  wrf_data_file_name  [-options]

options : [-h / help] [-att] [-m] [-M z] [-s]
          [-S x y z] [-v VAR] [-V VAR] [-w VAR]
          [-t t1 [t2]] [-times]
          [-ts xy X  Y  VAR VAR ....]
          [-ts ll  lat lon VAR VAR ....]
          [-lev z] [-rot] [-diag]
          [-EditData VAR]
```

Options:	*(Note: options [-att] ; [-t] and [-diag] can be used with other options)*
-h / help	Print help information.
-att	Print global attributes.
-m	Print list of fields available for each time, plus the min and max values for each field.
-M **z**	Print list of fields available for each time, plus the min and max values for each field. The min and max values of 3d fields will be for the **z** level of the field.
-s	Print list of fields available for each time, plus a sample value for each field. Sample value is taken from the middle of model domain.
-S **x y z**	Print list of fields available for each time, plus a sample value for each field. Sample value is at point **x y z** in the model domain.
-t **t1 [t2]**	Apply options only to times **t1** to **t2**.

	t2 is optional. If not set, options will only apply to **t1**.
-times	Print only the times in the file.
-ts	Generate time series output. A full vertical profile for each variable will be created. -ts xy X Y VAR VAR ….. will generate time series output for all VAR's at location X/Y -ts ll lat lon VAR VAR ….. will generate time series output for all VAR's at x/y location nearest to lat/lon
-lev **z**	Work only with option **–ts** Will only create a time series for level **z**
-rot	Work only with option **–ts** Will rotate winds to Earth coordinates
-diag	Add if you want to see output for the diagnostics temperature (K), full model pressure and model height *(tk, pressure, height)*
-v **VAR**	Print basic information about field **VAR**.
-V **VAR**	Print basic information about field **VAR**, and dump the full field out to the screen.
-w **VAR**	Write the full field out to a file **VAR.out**
	Default Options are [-att –s]

SPECIAL option: -EditData VAR

This option allows a user to **read** a WRF netCDF file, **change** a specific field, and **write** it BACK into the WRF netCDF file.
This option will CHANGE your CURRENT WRF netCDF file so TAKE CARE when using this option.
ONLY one field at a time can be changed; therefore, if you need 3 fields changed, you will need to run this program 3 times, each with a different "VAR"
IF you have multiple times in your WRF netCDF file – **by default ALL times** for variable "VAR" WILL be changed. *If you only want to change one time period, also use the "-t" option.*

HOW TO USE THIS OPTION:

Make a COPY of your WRF netCDF file before using this option

EDIT the subroutine USER_CODE

ADD an IF-statement block for the variable you want to change. This is to prevent a variable getting overwritten by mistake.

For REAL data arrays, work with the array "data_real" and for INTEGER data arrays, work with the array "data_int".

Example 1:
If you want to change all (all time periods too) values of U to a constant 10.0 m/s, you would **add** the following IF-statement:

```
  else if ( var == 'U') then
    data_real = 10.0
```

Example 2:
If you want to change a section of the LANDMASK data to SEA points:

```
  else if ( var == 'LANDMASK') then
    data_real(10:15,20:25,1) = 0
```

Example 3:
Change **all** ISLTYP category 3 values into category 7 values (NOTE this is an INTEGER field):

```
  else if ( var == 'ISLTYP') then
    where (data_int == 3 )
      data_int = 7
    end where
```

Compile and run the program.
You will be asked if this is really what you want to do.
ONLY the answer "yes" will allow the change to take effect.

iowrf

This utility allows a user to do some basic manipulation on WRF-ARW netCDF files.

- The utility allows a user to thin the data; de-stagger the data; or extract a box from the data file.

Obtain the **iowrf utility** from the WRF Download page: (http://www2.mmm.ucar.edu/wrf/users/download/get_source.html).

Compile

The code should run on any machine with a netCDF *library (If you port the code to a different machine, please forward the compile flags to wrfhelp@ucar.edu).*

To compile the code, use the compile flags at the top of the utility.

e.g.*, for a LINUX machine you need to type:*

```
pgf90 iowrf.f  -L/usr/local/netcdf/lib  -lnetcdf  -lm
      -I/usr/local/netcdf/include  -Mfree  -o iowrf
```

If successful, this will create the executable: `iowrf`

Run

```
./iowrf  wrf_data_file_name  [-options]

options : [-h / help] [-thina X] [-thin X] [-box {}]
          [-A] [-64bit]
```

-thina **X**	Thin the data with a ratio of 1:X Data will be averaged before being fed back
-thin **X**	Thin the data with a ratio of 1:X No averaging will be done
-box {}	Extract a box from the data file. X/Y/Z can be controlled independently. e.g., -box **x** 10 30 **y** 10 30 **z** 5 15 -box **x** 10 30 **z** 5 15 -box **y** 10 30 -box **z** 5 15
-A	De-stagger the data – no thinning will take place
-64bit	Allow large files (> 2GB) to have read / write access

p_interp

This utility interpolates WRF-ARW netCDF output files to user-specified pressure levels. Several new capabilities have been supported in **p_interp** since October 2010. These includes:

- The ability to output fields needed to create *met_em* files, which can be used as input to *real.exe.* This output can be used to change the vertical resolution of WRF input files. Output from **p_interp** can also be used as input to TC bogusing or OBSGRID.
- A new namelist option is included to split input files containing multiple times into multiple output files, each with a separate time.
- **p_interp** can be compiled and ran in parallel to improve the time needed to processes large input files.
- Output from **p_interp** can now also be read directly by MET (*http://www.dtcenter.org/met/users/index.php*), removing the requirement to first run WPP before WRF-ARW data can be processed by the MET toolkit.

Obtain the **p_interp utility** from the WRF Download page: (*http://www2.mmm.ucar.edu/wrf/users/download/get_source.html*).

Compile

The code should run on any machine with a netCDF *library (If you port the code to a different machine, please forward the compile flags to wrfhelp@ucar.edu)*

To compile the code, use the compile flags at the top of the utility.

e.g.*, for a serial compile on a LINUX machine you need to type:*

```
pgf90 p_interp.F90  -L/usr/local/netcdf/lib
      -lnetcdf  -lm  -I/usr/local/netcdf/include
      -Mfree  -o p_interp
```

e.g.*, for a parallel compile on an IBM machine you need to type:*

```
mpxlf_r -qfree=f90 -L/usr/local/netcdf/lib -lnetcdf
      -lm -I/usr/local/netcdf/include -o p_interp
      p_interp.F90 -WF,-D_MPI
```

If successful, this will create the executable: `p_interp`

Edit the Namelist

Edit the associated *namelist.pinterp* file. *(see namelist options below).*

&io	Default value	Description
path_to_input	`./`	Path to input data
input_name	None – must be set in namelist	File name(s) of wrfout files. *Use wild character if more than one file is processed.*
path_to_output	`./`	Path where output data will be written
output_name	`' '`	If no name is specified, the output will be written to *input_name_PLEV*
process	`'all'`	Indicate which fields to process. 'all' fields in wrfout file *(diagnostics PRES, TT, HGT & RH will automatically be calculated)*; 'list' of fields as indicated in 'fields'
fields	`' '`	List of fields to process, if *'list'* is used in parameter *'process'*
debug	`.false.`	Set to `.true.` for more debugging
mpi_debug	`.false.`	Set to `.true.` for additional output that may be helpful when debugging parallel code.
bit64	`.false.`	Allow large files (> 2GB) to have read / write access.
met_em_output	`.false.`	Set to `.true.` to calculate the output fields needed in a *met_em* file. These files are used as input to *real.exe*.
split_output	`.false.`	`.true.` will output each time in the input file to a separate output file.

&interp_in	Default Value	Description
interp_levels	`-99999.`	List of pressure levels to interpolate data to

extrapolate	`0`	`0` - set values below ground and above model top to missing values *(default)* `1` - extrapolate below ground, and set above model top to model top values
interp_method	`1`	`1` - linear in p-interpolation *(default)* `2` - linear in log-p-interpolation
unstagger_grid	`.false.`	Set to `.true.` to unstagger the data on output

If `met_em_output` is set to `.true.` in the namelist, other options also need to be set:

```
split_output   = .true.
unstagger_grid = .false.
extrapolate    = 1
process        = 'all'
```

If you do not set any of the first 3 options as shown above, they will be reset automatically in the code. If `process` is set to `'list'`, the code will stop and the user will have to set `process` to `'all'`.

Also note that **p_interp** will stop if *met_em** files already exist in the `path_to_output` directory. This is to reduce the change of overwriting any *met_em** files created by `metgrid.exe`.

Run

To run **p_interp** compiled with the serial options, type

```
./p_interp
```

For distributed memory systems, some form of **mpirun** will be needed to run the executable. To run **p_interp** *(compiled with parallel options)* interactively, and using *x* processors, the command may look like:

```
mpirun -np x ./p_interp
```

On some systems, parallel interactive jobs may not be an option, in which case the command would be

```
mpirun ./p_interp
```

to run in a batch script. On some IBM systems, the parallel job launcher may be **poe** or **mpirun.lsf,** rather than **mpirun**.

TC Bogus Scheme

The ARW core for the WRF modeling system provides a simple Tropical Cyclone (TC) Bogussing scheme. It can remove an existing tropical storm, and may optionally bogus in a Rankine vortex for the new tropical storm. The input to the program is a single time-period and single domain of **`metgrid`** data, and a few namelist variables from the **`namelist.input`** file that describes the bogus TC's location and strength. The output is also a **`metgrid`**-like file. The scheme is currently only set up to process isobaric data. After running the tc.exe program, the user must manually rename the files so that the **`real.exe`** program can read the modified input.

Namelist Options

The namelist information for the TC scheme is located in an optional namelist record **`&tc`**. Only a single domain is processed. Users with multiple domains should horizontally-interpolate the generated meteorological fields to the fine-grid domains. Alternatively, users may run the **`tc.exe`** program on separate **`metgrid`** output files for different domains, though this is not recommended.

insert_bogus_storm	logical, insert a bogus storm
remove_storm	logical, removes an existing storm
num_storm	integer, number of storms to bogus, currently must be set to 1
latc_loc	real, latitude of bogus storm (+ north, - south)
lonc_loc	real, longitude of bogus storm (+ east, - west)
vmax_meters_per_second	real, maximum observed sustained wind speed (m/s)
rmax	real, radius from the cyclone center to where the maximum wind speed occurs (m)
vmax_ratio	real, scale factor for model's Rankine vortex

Note: If **`insert_bogus_storm`** is set to *true* then **`remove_storm`** should be set to *false*. If **`remove_storm`** is set to *true* then **`insert_bogus_storm`** should be set to *false*.

The value for **`vmax_ratio`** should be about 0.75 for a 45-km domain and about 0.90 for a 15-km domain (use these values to interpolate other for other resolutions). This is a representativeness scale factor. The observed maximum wind speed is not appropriate for an entire grid cell when the domain is fairly coarse.

For example, assume that a cyclone report came in with the storm centered at 25^{o} N and 75^{o} W, where the maximum sustained winds were observed to be 120 kts, with the maximum winds about 90 km from the storm center. With a 45-km coarse grid model domain, the **`namelist.input`** file would be:

```
&tc
insert_bogus_storm = .true.
remove_storm = .false.
latc_loc = 25.0
lonc_loc = -75.0
vmax_meters_per_second = 61.7
rmax = 90000.0
vmax_ratio = 0.75
/
```

Program tc.exe

The program **tc.exe** is automatically built along with the rest of the ARW executables. This, however, is a serial program. For the time being, it is the best to build this program using serial and no-nesting options.

Running tc.exe

1) Run all of the WPS programs as normal (**geogrid**, **ungrib**, and **metgrid**).
2) As usual, link-in the metgrid output files into either the **test/em_real** or the **run** directory.
3) Edit the **namelist.input** file for usage with the **tc.exe** program. Add-in the required fields from the **&tc** record, and only process a single time period.
4) Run **tc.exe**
5) Rename the output file, **auxinput1_d01_<date>** to the name that the **real.exe** program expects, **met_em.d01.<date>**, note that this will overwrite your original **metgrid.exe** output file for the initial time period.
6) Edit the **namelist.input** file to process all of the time periods for the **real.exe** program.

v_interp

This utility can be used to add vertical levels in WRF-ARW netCDF input. An example of the usage would be one-way nesting, via the program `ndown`. Since the program `ndown` does not do 'vertical nesting' prior to Version 3.2, namely adding vertical levels, this program can be used after running `ndown` to achieve the same results. Starting from Version 3.2, vertical levels may be added in the program `ndown`, via the namelist option '`vert_refine_fact`', which allows one to refine vertical levels by an integer factor.

The **v_interp** utility program can be obtained from the WRF Download page: (*http://www2.mmm.ucar.edu/wrf/users/download/get_source.html*)

Compile

The code should be easily built and ran on any machine with a netCDF library. To compile the code, use the compile flags shown at the top of the utility program.

e.g.*, for a LINUX machine and pgf90 compiler, one may type:*

```
pgf90 v_interp.f  -L/usr/local/netcdf/lib -lnetcdf \
      -I/usr/local/netcdf/include  \
      -Mfree  -o v_interp
```

If successful, this will create the executable: `v_interp`

Run

Edit the namelist file `namelist.v_interp` *(see namelist options below)* for the number of new vertical levels (`nvert`) and the new set of levels (`nlevels`). To find out the existing model levels, check the original WRF `namelist.input` file used to create the input files, or type the following:

```
ncdump –v ZNW wrfinput_d01
```

The executable takes two arguments on the command line:

```
./v_interp file file_new
```

where `file` is the input file you want to add the vertical levels to, and `file_new` is the output file that contains more vertical levels. To run the program for `wrfinput` file, type

```
./v_interp wrfinput_d01 wrfinput_d01_new
```

For the `wrfbdy` file, type

```
./v_interp wrfbdy_d01 wrfbdy_d01_new
```

namelists:

&newlevels	
nvert	Number of new vertical levels (staggered)
nlevels	Values of new model levels

Program Notes:

When adding vertical levels, please keep the first- and the last-half levels the same as in the input file, itself. A problem may occur if levels are added outside the range.

For the wrfbdy file, please keep the input file name as wrfbdy_* since the program keys-in on the file name in order to do the interpolation for special boundary arrays.

proc_oml.f

This utility may be used to process 3D HYCOM (http://www.hycom.org) ocean model temperature data in netCDF format to produce initial ocean mixed layer depth field (`H0ML`) for use in a WRF simulation that uses the simple ocean mixed layer model option (`omlcall = 1`, and `oml_hml0 < 0`). The program estimates two fields from the HYCOM data: 1) effective mixed layer depth based on the idea of ocean heat content (`H0ML`); and 2) mean ocean temperature in the top 200 m depth (`TMOML`). This is used as the lower limit for cooling SST's in the wake of a hurricane.

To download the **proc_oml.f** utility, please see:
http://www2.mmm.ucar.edu/wrf/users/hurricanes/util.html

Compile

To compile the code, use the compile flags shown at the top of the utility program. For example, for a LINUX machine and pgf90 compiler one may type:

```
pgf90 proc_oml.f  -L/usr/local/netcdf/lib -lnetcdf \
      -I/usr/local/netcdf/include -Mfree  -o proc_oml.f
```

If successful, this will create the executable: `proc_oml`

Run

To run the program, type

```
./proc_oml ocean-data-file.nc yyyymmddhh
```

where '`ocean-data-file.nc`' is the HYCOM ocean data file, and `yyyymmddhh` is the 10-digit date when the data is valid for (e.g. `2005082700`). Successfully running the program will produce an output file, `MLD`, which is in intermediate format as if it were produced by the `WPS/ungrib` program.

To use this field in `WPS/metgrid`, add it to '`constant_name`' as below:

```
constant_name = 'MLD',
```

V3.2 `WPS/metgrid` has the additional fields in METGRID.TBL for proper horizontal interpolation. For more information, please refer to the following presentation, at http://www2.mmm.ucar.edu/wrf/users/tutorial/hurricanes/AHW_nest_ocean.pdf

Tools

Below is a list of tools that are freely available, and can be used very successfully to manipulate model data (both WRF model data, as well as other GRIB and netCDF datasets).

Converting Graphics

ImageMagick

ImageMagick is a software suite to create, edit, and compose bitmap images. It can read, convert and write images in a variety of formats (over 100) including DPX, EXR, GIF, JPEG, JPEG-2000, PDF, PhotoCD, PNG, Postscript, SVG, and TIFF. Use ImageMagick to translate, flip, mirror, rotate, scale, shear and transform images, adjust image colors, apply various special effects, or draw text, lines, polygons, ellipses and B_zier curves.

The software package is freely available from, *http://www.imagemagick.org*. Download and installation instructions are also available from this site.

Examples of converting data with ImageMagick software:

```
convert  file.pdf     file.png
convert  file.png     file.bmp
convert  file.pdf     file.gif
convert  file.ras     file.png
```

ImageMagick cannot convert ncgm (NCAR Graphics) file format to other file formats.

Converting ncgm (NCAR Graphics) file format

NCAR Graphics has tools to convert ncgm files to raster file formats. Once files are in raster file format, ImageMagick can be used to translate the files into other formats.

For *ncgm* files containing a single frame, use ***ctrans***.

```
ctrans  -d sun  file.ncgm  file.ras
```

For *ncgm* files containing multiple frames, first use ***med*** (metafile frame editor) and then *ctrans*. ***med*** will create multiple single frame files called *medxxx.ncgm*

```
med -e '1,$ split $' file.ncgm
ctrans  -d sun_ med001.ncgm > med001.ras
```

Basic Unix Commands

The WRF model is run on any Unix/Linux machine. Some basic Unix commands are required to work in this environment. There are numerous web sites one can visit to learn more about basic and advanced Unix commands. A couple of basic Unix commands are listed below, as well as some web sites where users can obtain more information.

mkdir / rmdir	To make *(mkdir)* or remove *(rmdir)* directories.
cd	To change to a new directory.
ls	List the files and directories in a directory .
ls -l	Lists your files in 'long format', which contains lots of useful information, e.g. the exact size of the file, who owns the file and who has the right to look at it, and when it was last modified.
ls –lrt	Lists your files in 'long format', in order of time stamp, and reverse order.
rm	Remove files.
more	Shows the first part of a file, just as much as will fit on one screen. Just hit the space bar to see more or **q** to quit.
cat	Shows the entire file on the screen.
head	Shows the first couple of lines of a file on screen.
tail	Shows the last couple of lines of a file on screen.
grep	Find lines that match patterns in files.
mv	Rename or move a file.
cp	Copy a file to a different name or location.
pwd	Shows the directory path you are currently in.
ln -sf	Makes a symbolic *(-s)* link *(ln)* of a file. The file will appear to be in two locations, but is only physically in one location. *(The –f option ensures that if the target file already exists, then it will first be unlink so that the link may occur correctly.)*
vi / emacs	File editors. For new users, ***emacs*** may be an easier editor to work with, as ***vi*** requires some extra understanding to navigate between the *command* and *insert* modes, whereas ***emacs*** functions more like a conventional editor.

http://mally.stanford.edu/~sr/computing/basic-unix.html
http://pangea.stanford.edu/computing/unix/shell/commands.php
http://www.math.harvard.edu/computing/unix/unixcommands.html
http://www.washington.edu/computing/unix/unixqr.html
http://en.wikipedia.org/wiki/List_of_Unix_utilities
http://www.cs.colostate.edu/helpdocs/vi.html

Design WRF model domains

WPS/util/plotgrids.ncl
Is an NCL script, which can either plot the domain on screen, or create a variety of different output types (pdf, ps, ncgm). This script must be ran in the same directory where the `namelist.wps` resides. This script only works with NCL version 6.1.0 or newer. If you still have an older version of NCL you can still use the plotgrids_old.ncl script.

Read more about this utility in Chapter 3 of this Users Guide.

Display ungrib (intermediate) files

WPS/util/plotfmt.ncl
Is an NCL script that can be used to display intermediate files created by `WPS/ungrib.exe`.

If you have created intermediate files manually, it is a very good practice to use this utility to display the data in your files first before running `WPS/metgrid.exe`.
***Note**: If you plan on manually creating intermediate files, refer to http://www2.mmm.ucar.edu/wrf/OnLineTutorial/Basics/IM_files/index.html for detailed information about the file formats and sample programs.*

This script reads intermediate files and can output the graphics in a variety of different output formats (on the screen, pdf, ps, ncgm). The script requires NCL version 6.2.0 or newer. An input file much be supplied, e.g:

```
ncl plotfmt.ncl 'filename="FILE:2005-06-01_00"'
```

WPS/util/int2nc.exe, can be used to convert intermediate files created by `WPS/ungrib.exe` into netCDF files.

WPS/util/plotfmt_nc.ncl
Is an NCL script, which can plot the netCDF output files created by int2nc.exe. This script must be run in the same directory where the netCDF files reside. The file to be plotted should be entered on the command line, e.g.,

```
ncl plotfmt_nc.ncl 'inputFILE="FILE:2005-06-01_00.nc"'
```

Read more about these utilities in **Chapter 3** of this Users Guide.

netCDF data

netCDF stands for **ne**twork **C**ommon **D**ata **F**orm.
Most of the information below can be used for WRF netCDF data, as well as other netCDF datasets.
netCDF is one of the current supported data formats chosen for WRF I/O API.

Advantages of using netCDF?
Most graphical packages support netCDF file formats
netCDF files are platform-independent (big-endian / little-endian)
A lot of software already exists that can be used to process/manipulate netCDF data

Documentation:
http://www.unidata.ucar.edu/ (General netCDF documentation)
http://www.unidata.ucar.edu/software/netcdf/docs/netcdf-f90/ (NETCDF User's Guide for FORTRAN)

Utilities:
ncdump
This is part of the netCDF libraries. Reads a netCDF file and prints information about the dataset. e.g.

`ncdump -h` *file (print header information)*
`ncdump -v` *VAR file (print header information and the full field VAR)*
`ncdump -v Times file` *(a handy way to see how many times are available in a WRF output file)*

ncview
Displays netCDF data graphically. No overlays, no maps and no manipulation of data possible.
http://meteora.ucsd.edu/~pierce/ncview_home_page.html

ncBrowse
Displays netCDF data graphically. Some overlays, maps and manipulation of data are possible.
http://www.epic.noaa.gov/java/ncBrowse/

read_wrf_nc
A utility to display basic information about WRF netCDF files.

iowrf
A utility to do some basic file manipulation on WRF-ARW netCDF files.

p_interp
A utility to interpolate WRF-ARW netCDF output files to user specified pressure levels.

netCDF operators
http://nco.sourceforge.net/
Stand-alone programs that can be used to manipulate data (by performing grid point averaging / file differencing / file 'appending'). *A couple of available programs are listed below, see the above link for a list of all available programs.*

ncdiff
Difference between two files; e.g.

```
ncdiff  input1.nc input2.nc output.nc
```

ncrcat
Writes specified variables / times to a new file; e.g.

```
ncrcat -v RAINNC wrfout* RAINNC.nc
ncrcat -d Time,0,231 -v  RAINNC  wrfout* RAINNC.nc
```

ncra
Averages variables and writes to a new file; e.g.

```
ncra -v OLR  wrfout* OLR.nc
```

ncks (nc kitchen sink)
Combination of NCO tools all in one (handy: one tool for multiple operations). An especially handy use of this tool is to split large files into smaller files, e.g.

```
ncks -A -F -d Time,1,1 wrfout* -o wrfout_time1.nc
```

GRIB data

Documentation and Decoders

Documentation and decoders for both GRIB1 and GRIB2 can be found here: http://rda.ucar.edu/#!GRIB
Some of the utilities that are worth looking at is the unpackgrib2.c and grib2to1.c code.

GRIB codes

It is important to understand the GRIB codes to know which fields are available in your dataset. For instance, NCEP uses the GRIB1 code 33 for the U-component of the wind, and 34 for the V-component. *Other centers may use different codes, so always obtain the GRIB codes from the center you get your data from.*

GRIB2 uses 3 codes for each field - **product**, **category** and **parameter**. We would most often be interested in **product 0** (*Meteorological products*). **Category** refers to the type of field; e.g., category 0 is temperature, category 1 is moisture and category 2 is momentum. **Parameter** is the field number.
So whereas GRIB1 only uses code 33 for the U-component of the wind, GRIB2 will use 0,2,2, for the U-component, and 0,2,3 for the V-component.

Display GRIB header/field information

GRIB1 data

WPS/util/g1print.exe
wgrib

GRIB2 data

WPS/util/g2print.exe
wgrib2

Both wgrib and wgrib2 are available from the http://rda.ucar.edu/#!GRIB web site.

Convert GRIB data to netCDF format

ncl_grib2nc *(http://www.ncl.ucar.edu/Document/Tools/ncl_convert2nc.shtml)*

Displaying GRIB files

GRIB data can, *amongst other*, be displayed with GrADS with the use of the grib2ctl.pl script *(http://www.cpc.ncep.noaa.gov/products/wesley/grib2ctl.html)* and Panoply *(http://www.giss.nasa.gov/tools/panoply/)*.

Model Verification

MET is designed to be a highly configurable, state-of-the-art suite of verification tools. It was developed using output from the Weather Research and Forecasting (WRF) modeling system, but may be applied to the output of other modeling systems as well.

MET provides a variety of verification techniques, including:

- Standard verification scores, comparing gridded model data to point-based observations
- Standard verification scores, comparing gridded model data to gridded observations
- Object-based verification method, comparing gridded model data to gridded observations

http://www.dtcenter.org/met/users/index.php

Appendix A: WRF-Fire

Table of Contents

Introduction

A wildland fire module named WRF-Fire has been added to WRF ARW to allow users to model the growth of a wildland fire and the dynamic feedbacks with the atmosphere. It is implemented as a physics package with two-way coupling between the fire behavior and the atmospheric environment allowing the fire to alter the atmosphere surrounding it, i.e. 'create its own weather'. Here we address the mechanics, options, parameters, and datasets for using this module.

The wildland fire module is currently a simple two-dimensional model of a surface fire, that is, a fire that spreads through fuels on the ground, such as grass, shrubs, and the litter from trees that has fallen to the surface. It does not yet contain the algorithms needed to represent crown fires, which consume and spread through the tree canopies. The user specifies the time, location, and shape of a fire ignition. The evolution of the fireline, the interface enclosing the burning region, is implemented by the level set method. The level set function is advanced by the Runge-Kutta method of order 2, with spatial discretization

by the Godunov method. The rate at which this interface expands is calculated at all points along it using a point-based semi-empirical formula for estimating the rate of spread of the surface fire based upon the Rothermel (1972) formula, which calculates the fire rate of spread as a function of local fuel conditions, wind, and terrain slope. A semi-empirical formula is used as a parameterization since turbulent combustion cannot be resolved at the spatial scales of atmospheric models; thus, all physical processes involved in propagating the fire are assumed to be represented in this relationship. Importantly, the winds used to drive the fire are interpolated from nearby low-level wind velocities, which are themselves perturbed by the fire. Once the fireline has passed by, the ignited fuel continues to burn - the mass of fuel is assumed to decay exponentially with time after ignition, the rate depending on the size of the fuel particles making up the fuel complex: fine fuels such as grass are consumed rapidly, while fuels with larger diameters such as twigs and downed logs are consumed slowly. The fuel burned in each time step is converted to sensible and latent heat source terms for the lowest levels of the WRF atmospheric model state, where the water vapor source arises from the release of the intrinsic moisture in cellulosic fuels and the additional moisture absorbed by fuels from their environment, the fuel moisture content. The e-folding depth over which the heat and vapor distributed is set by the user, based on results from wildland fire measurements. The fire may not progress to locations where the local fuel moisture content is greater than the moisture content of extinction.

Additional parameters and datasets beyond a standard WRF atmospheric simulation are required and are described here. The surface fuel available to be burned at each point is categorized using the Anderson classification system for "fuel models" (3 grass-dominated types, 4 shrub-dominated types, 3 types of forest litter, and 3 levels of logging slash) which we will henceforth refer to as "fuel categories" to limit confusion. Each of these fuel categories is assigned a set of typical properties consisting of the fuel load (the mass per unit area) and numerous physical properties having to do with fuel geometry, arrangement, and physical makeup. The user may make the fuels spatially homogeneous by using one fuel category for the whole domain, alter fuel properties, add custom fuel categories, or (for real data experiments) project a spatially heterogeneous map of fuel categories onto the domain from fuel mapping datasets. The user also sets the number of ignitions, their time, location, and shape, and the fuel moisture content, an important factor in fire behavior.

One time step of the fire model is performed for every WRF time step. The fire model runs on a refined grid that covers the same region as the innermost WRF domain. The fire module supports both distributed and shared memory parallel execution.

Other References

- Users may wish to review Anderson's fuel classification system (Anderson, H. E. 1982. *Aids to determining fuel models for estimating fire behavior.* USDA For. Serv. Gen. Tech. Rep. INT-122, 22p. Intermt. For. and Range Exp. Stn., Ogden, Utah 84401) at http://www.fs.fed.us/rm/pubs_int/int_gtr122.pdf (verified 1/4/10).

- The original report introducing Rothermel's semi-empirical formulas (Rothermel, R. C. 1972. *A mathematical model for predicting fire spread in wildland fuels.* Res. Pap. INT-115. Ogden, UT: U.S. Department of Agriculture, Intermountain Forest and Range Experiment Station. 40 p.) is available at http://www.treesearch.fs.fed.us/pubs/32533 (verified 1/4/10).

- The following paper describes the WRF-Fire module and applies WRF with WRF-Fire in simulations to test the sensitivity of fire growth to environmental factors such as wind speed, fuel load and moisture, and fuel model in the daytime convective boundary layer:

  Coen, J. L. , M. Cameron, J. Michalakes, E. Patton, P. Riggan, and K. Yedinak, 2013: WRF-Fire: Coupled Weather-Wildland Fire Modeling with the Weather Research and Forecasting Model. *J. Appl. Meteor. Climatol.,* **52**, 16-38. http://journals.ametsoc.org/doi/abs/10.1175/JAMC-D-12-023.1

WRF-Fire in idealized cases

To perform a simulation including a fire, follow the installation instructions in Chapter 5 to configure WRF and set up the environment. For an idealized case, use

```
./compile em_fire
```

to build WRF for one of the several supplied ideal examples. This will create the links `wrf.exe` and `ideal.exe` in the directory `test/em_fire`.

The directory `test/em_fire` contains two fire test cases - `hill_simple` and `two_fires`. The files necessary for running these are in the top-level `em_fire` directory. To run a fire case, it will be necessary to have files named `'namelist.input'` and `'input_sounding'` in the `em_fire/` directory. If you wish to use one of the provided test cases, you will need to link them to their generic names (for example, for the `two_fires` case):

```
ln -sf namelist.input_two_fires namelist.input

ln -sf input_sounding_two_fires input_sounding
```

Currently the default `namelist.input` file is linked to the `hill_simple` case. If you wish to make your own test case, you will simply need to create the files `namelist.input` and `input_sounding` that will correspond to your case (it is advised to start by modifying an existing copy from another case).

Once you have the `namelist.input` and `input_sounding` linked to the correct case files, you can run by typing:

```
./ideal.exe

./wrf.exe
```

The file `namelist.input` contains an additional section `&fire` with parameters of the fire model and ignition coordinates. The file `namelist.fire` contains an additional namelist used to enter custom fuel properties.

Fire variables in namelist.input

Variable names	Value	Description
`&domains`		Domain definition
`sr_x`	10	The fire mesh is 10 times finer than the innermost atmospheric mesh in the *x* direction. This number must be even.
`sr_y`	10	The fire mesh is 10 times finer than the innermost atmospheric mesh in the *y* direction. This number must be even.
`&fire`		Fire ignition and fuel parameters
`ifire`	0	No fires will be simulated.
	1	Fires will be simulated, using the tracer scheme to represent the flaming front interface (not active).
	2	Fires will be simulated, using the level set method to represent the movement of the interface.
`fire_fuel_read`	0	How to set the fuel data -1: real data from WPS 0: set to a homogeneous distribution of `fire_fuel_cat` everywhere 1: The spatial distribution of fuel categories is to be specified as a function of terrain altitude. (The user specifies a custom function.)

fire_num_ignitions	3	Number of ignition lines, max. 5 allowed
fire_ignition_start_x1	1000.	*x* coordinate of the start point of the ignition line 1. All ignition coordinates are given in m from the lower left corner of the innermost domain
fire_ignition_start_y1	500.	*x* coordinate of the start point of the ignition line 1
fire_ignition_end_x1	1000.	*y* coordinate of the end point of the ignition line 1. Point ignition (actually a small circle) is obtained by specifying the end point the same as the start point.
fire_ignition_end_y1	1900.	*y* coordinate of the end point of the ignition line 1
fire_ignition_radius1	18.	Everything within fire_ignition_radius1 meters from the ignition location will be ignited.
fire_ignition_time1	2.	Time of ignition in s since the start of the run
fire_ignition_start_x2 … fire_ignition_time5		Up to 5 ignition lines may be given. Ignition parameters with the number higher than fire_num_ignitions are ignored.
fire_print_msg	1	0: no messages from the fire scheme 1: progress messages from the fire scheme
fire_print_file	0	0: no files written (leave as is) 1: fire model state written every 10 s into files that can be read in Matlab.

There are several more variables in the namelist for developers' use only to further develop and tune the numerical methods. Do not alter unless directed to do so.

namelist.fire

This file serves to redefine the fuel categories if the user wishes to alter the default fuel properties.

Variable names	Description
&fuel_scalars	Scalar fuel constants

cmbcnst	The energy released per unit fuel burned for cellulosic fuels (constant, 1.7433e7 J kg^{-1}).
hfgl	The threshold heat flux from a surface fire at which point a canopy fire is ignited above (in W m^{-2}).
fuelmc_g	Surface fuel, fuel moisture content (in percent expressed in decimal form, from 0.00 – 1.00).
nfuelcats	Number of fuel categories defined (default: 13)
no_fuel_cat	The number of the dummy fuel category specified to be used where there is no fuel
&fuel_categories	Domain specifications
fgi	The initial mass loading of surface fuel (in kg m^{-2}) in each fuel category
fueldepthm	Fuel depth (m)
savr	Fuel surface-area-to-volume-ratio (m^{-1})
fuelmce	Fuel moisture content of extinction (in percent expressed in decimal form, from 0.00 – 1.00).
fueldens	Fuel particle density lb ft^{-3} (32 if solid, 19 if rotten)
st	Fuel particle total mineral content. (kg minerals/kg wood)
se	Fuel particle effective mineral content. (kg minerals – kg silica)/kg wood
weight	Weighting parameter that determines the slope of the mass loss curve. This can range from about 5 (fast burn up) to 1000 (i.e. a 40% decrease in mass over 10 minutes).
ichap	Is this a chaparral category to be treated differently using an empirical rate of spread relationship that depends only on wind speed? (1: yes, this is a chaparral category and should be treated differently; 0: no, this is not a chaparral category or should not be treated differently). Primarily used for Fuel Category 4.

Running WRF-Fire on real data

Building the code

Running WRF with real data is a complicated process of converting data formats and interpolating to the model grid. This process is simplified by the WRF Preprocessing System (WPS). The purpose of this section is to summarize the use of this system and to highlight the differences in its use between fire and ordinary atmospheric simulations.

For more complete documentation of WPS, see Chapter 3 of the WRF-ARW User's Guide.

WPS consists of three utility programs: `geogrid.exe`, `ungrib.exe`, and `metgrid.exe`. Each program is designed to take existing data sets and convert/interpolate them into an intermediate format. The build system for WPS is similar to that of WRF. NetCDF must be installed and the environment variable NETCDF should be set to the installation prefix. Run the configure script in the main WPS directory, pick a configuration option from the list, and then run compile. Note that WRF itself must be built prior to compiling WPS. In addition, the build process assumes that WRF exists in `../WRFV3/`. WRF should be configured as described in Section 3 and compiled with the command

```
./compile em_real >& compile.log
```

The WPS can be configured from inside the top level directory wrf-fire/WPS with the command

```
./configure
```

and compiled in the same directory with the command

```
./compile >& compile.log
```

Upon successful completion the three binaries listed above should exist in the current directory.
Because the WPS programs are, for the most part, not processor intensive, it is not generally necessary to compile these programs for parallel execution, even if they do support it. Typical usage of WRF with real data involves doing all of the preprocessing work either locally on a workstation or on the head node of a supercomputer. The intermediate files are all architecture independent, so they can be transferred between computers safely. If you intend to use a supercomputer for the main simulation, it is advisable to generate the WPS output locally and transfer the met_em files to the computer you will be using for WRF-Fire. The met_em files are much smaller than the wrfinput and wrfbdy files and can be transported easily. This also eases the process of dealing with the dependencies of the python scripts described below because it may not be easy or even possible to meet these requirements on a shared parallel computer.

Fire variables in namelist.wps

The simulation domain is described in the file `namelist.wps`. This namelist contains four sections, one for each of the main binaries created in WPS and one shared among them all. This file, as distributed with WRF-Fire, is set up for a test case useful for

testing, but in general one needs to modify it for each simulation domain. The following table lists namelist options that can be modified. Other options in this file are generally not necessary to change for WRF-Fire simulations. See the WRF-ARW User's Guide for more information.

Variable names	Description
`&share`	Shared name list options
`max_dom`	Number of nested domains to use
`start_date/end_date`	Starting/ending date and time to process atmospheric data in the format YYYY-MM-DD_hh:mm:ss. These times should coincide with reanalysis cycles for your atmospheric data (hours 00,03,06,09,12, etc. for 3 hour NARR data). The simulation window in which you are interested in running must be inside this interval.
`Subgrid_ratio_[xy]`	The refinement ratio from the atmospheric grid to the fire grid.
`interval_seconds`	Number of seconds between each atmospheric dataset. (10800 for 3 hour NARR data)
`&geogrid`	Domain specifications
`parent_id`	When using nested grids, the parent of the current grid, or 0 if it is the highest level.
`parent_grid_ratio`	The refinement ratio from the parent grid (ignored for top level grid) (only 3 or 5 is supported by WRF)
`[ij]_parent_start`	The indices on the parent grid of the lower left corner of the current grid (ignored for top-level grid)
`E_we/e_sn`	The size of the grid in the x/y axis
`dx/dy`	Resolution of the grid in the x/y axis
`map_proj, true_lat[12], stand_lon`	Projection specifications. Lambert is typically used for central latitudes such as the continental US. For small domains, the projection used does not matter much.
`ref_x/ref_y`	Grid index of a reference point with known geographic location. Defaults to the center of the domain.
`ref_lon/ref_lat`	The location (longitude/latitude) of the reference point.
`geog_data_path`	Absolute or relative path to geogrid data released with WPS (http://www2.mmm.ucar.edu/wrf/src/wps_files/geog_v3.1.tar.gz)

Geogrid

The geogrid executable acts exclusively on static datasets (those that don't change from day to day) such as surface elevation and land use. Because these datasets are static, they can be obtained as a single set of files from the main WPS distribution website in resolutions of 10 minutes, 2 minutes, and 30 seconds. The geogrid executable extracts from these global data sets what it needs for the current domain. While resolutions of this magnitude are acceptable for ordinary atmospheric simulations, these datasets are too

coarse for a high-resolution fire simulation. In particular, a WRF-Fire simulation will require two additional data sets not present in the standard data.

NFUEL_CAT

The variable NFUEL_CAT contains Anderson 13 fuel category data. This data can be obtained for the US from the USGS seamless data access server at: http://landfire.cr.usgs.gov/viewer/. Using the zooming and panning controls, the user can select the desired region with LANDFIRE 13 Anderson Fire Behavior Fuel Models box selected. This will open a new window where the user can request the data in specific projections and data formats.

ZSF

The variable ZSF contains high resolution terrain height information similar to that in the HGT variable present in atmospheric simulations; however, the standard topographical data set is only available at a maximum resolution of 30 arc seconds (about 900 meters). For a simulation using the WRF-Fire routines, data resolution of at least 1/3 of an arc second is desirable to include the effect of local terrain slope on the rate of spread. Such a dataset is available for the US at http://seamless.usgs.gov/. This is another USGS seamless data access server similar to that of LANDFIRE. The desired dataset on this server is listed under elevation and is called 1/3" NED.

Conversion to geogrid format

Once one has collected the necessary data from USGS servers or elsewhere, it is necessary to convert it from the given format (such as geotiff, Arcgrid, etc.) into geogrid format. The format specification of the geogrid format is given in the WPS section of the WRF users guide. The process of this conversion is somewhat technical; however, work is in progress to automate it.

Editing GEOGRID.TBL

In order to include your custom data into the WPS output, you must add a description of it in the GEOGRID.TBL file, which is located, by default, in the geogrid subdirectory of the main WPS distribution. In addition to the standard options described in the WPS users guide, there is one additional option that is necessary for defining data for fire grid variables. For them, there is a subgrid option, which is off by default. For fire grid data, one should add the option subgrid=yes to indicate that the variable should be defined on a refined subgrid with a refinement ratio defined by the subgrid_ratio_[xy] option in the WPS namelist. For example, typical table entries would appear as follows:

```
==============================
name=NFUEL_CAT
        priority=1
        dest_type=categorical
        dominant_only=NFUEL_CAT
        z_dim_name=fuel_cat
        halt_on_missing=yes

interp_option=default:nearest_neighbor+average_16pt+search
        rel_path=default:landfire/
        subgrid=yes
==============================
name = ZSF
        priority = 1
        dest_type = continuous
        halt_on_missing=yes
        interp_option = default:four_pt
        rel_path=default:highres_elev/
        subgrid=yes
```

This table assumes that the converted data resides as a subdirectory of the standard data directory given in the namelist under the option geog_data_path. The NFUEL_CAT data should reside in landfire/ and ZSF in highres_elev/. In general, the only options that should be modified by the user are the rel_path or abs_path options.
Once the data has been obtained and converted and the geogrid table has been properly set up, the user can run:
./geogrid.exe
which will create files such as geo_em.d01.nc that contain the interpolated static data fields.

Ungrib and Metgrid

The ungrib executable performs initial processing on atmospheric data. There are many different datasets that can be used as input to ungrib. One must obtain this data manually for a given simulation. Because fire simulations will be at a much higher resolution than most atmospheric simulations, it is advisable to get as high resolution data as possible. The 32 km resolution data from the North American Regional Reanalysis (NARR) is likely a good choice. This data is available freely from https://dss.ucar.edu/datazone/dsszone/ds608.0/NARR/3HRLY_TAR/. For real data WRF runs, three individual datasets from this website are required: 3d, flx, and sfc. To use them, download the files for the appropriate date/time and extract them somewhere on your file system. The files have the naming convention, NARR3D_200903_0103.tar. NARR indicates it comes from the NARR model, 3D indicates that it is the atmospheric data fields, and 200903_0103 indicates that it contains data from March 1st through 3rd of 2009. Once these files are extracted, they must be linked into the main WPS directory with the command link_grib.csh. It takes as arguments all of the files extracted from the dataset. For example, if you extracted these files to `/home/joe/mydata`, then you would issue the command:

```
./link_grib.csh /home/joe/mydata/*
```
into the top level WPS directory. Each atmospheric dataset requires a descriptor table known as a variable table to be present. WPS comes with several variable tables that work with most major data sources. These files reside in `WPS/ungrib/Variable_Tables/`. The appropriate file must be linked into the top level WPS directory as the file Vtable. For NARR data, type:

```
ln -sf ungrib/Variable_Tables/Vtable.NARR Vtable
```

Once this has been done, everything should be set up properly to run the ungrib command:

```
./ungrib.exe
```

Finally, the program metgrid combines the output of ungrib and geogrid to create a series of files, which can be read by WRF's real.exe. This is accomplished by

```
./metgrid.exe
```

Assuming everything completed successfully, you should now have a number of files named something like `met_em.d01.2009-03-01_12:00:00.nc`. These should be copied or linked to your `WRFV3/test/em_real` directory. If any errors occur during execution of ungrib or metgrid, then make sure you have downloaded all of the necessary atmospheric data and that the variable table and namelist are configured properly.

Running real case and WRF-Fire

First copy or link the met_em files generated by metgrid into test/em_real. If the simulation is being done locally, this can be accomplished by running in `wrf-fire/WRFV3/test/em_real`

```
ln -sf ../../../WPS/met_em* .
```

The namelist for WRF in the file `namelist.input` must now be edited to reflect the domain configured in WPS. In addition to the fire-specific settings listed in Section 4.3 regarding the ideal simulation, a number of other settings must be considered as listed below. See Chapter 5 for more details on these settings.

Variable	Description
`&time_control`	

start_xxx/end_xxx	These describe the starting and ending date and time of the simulation. They must coincide with the start_date/end_date given in namelist.wps.
run_xxx	The amount of time to run the simulation.
interval_seconds	Must coincide with interval seconds from namelist.wps.
restart_interval	A restart file will be generated every x minutes. The simulation can begin from a restart file rather than wrfinput. This is controlled by the namelist variable 'restart'.
&domains	All grid settings must match those given in the geogrid section of namelist.wps.
num_metgrid_levels	The number of vertical levels of the atmospheric data being used. This can be determined from the met_em files: ncdump -h met_em* | grep 'num_metgrid_levels ='
sr_x/sr_y	Fire grid refinement. This must match that given in namelist.wps as subgrid_ratio_x/subgrid_ratio_y.
p_top_requested	The default is 5000, but may need to be edited if there is an error executing real. If so, just set this to whatever it tells you in the error message.

Once the namelist is properly configured, run the real executable:

```
./real.exe
```

and then run wrf:

```
./wrf.exe
```

Fire state variables

A number of array variables were added to the registry to the WRF state in order to support the fire model. They are available in the `wrfout*` files created when running WRF. All fire array variables are based at the centers of the fire grid cells. Their values in the strips at the upper end of width `sr_x` in the *x* direction and `sr_y` in the *y* direction are unused and are set to zero by WRF.

The following variables can be used to interpret the fire model output.

LFN	level set function. Node (i,j) is on fire if LFN(i,j)<=0
FXLONG, FXLAT	longitude and latitude of the nodes

FGRNHFX	ground heat flux from the fire (W/m^2), averaged over the cell
FGRNQFX	ground heat flux from the fire (W/m^2), averaged over the cell
ZSF	terrain elevation above sea level (m)
UF,VF	surface wind
FIRE_AREA	approximate part of the area of the cell that is on fire, between 0 and 1

WRF-Fire software

This section is intended for programmers who wish to modify or extend the fire module.

WRF-Fire coding conventions

The fire module resides in WRF physics layer and conforms to *WRF Coding Conventions*. The wildland fire-related subroutines maintain the conventions as they apply to on atmospheric grids, adapts them to 2D surface-based computations, and follows analogous conventions on the fire grid. In particular, these routines may not maintain any variables or arrays that persist between calls, and may not use common blocks, allocatable variables, or pointer variables. Work arrays with variable bounds may be declared only as automatic; thus, they are freed between on exit from the subroutine where they are declared. All grid-sized arrays that should persist between calls to the wildland fire-related subroutines must be created in WRF through the registry mechanism, and passed to these as arguments.

In addition, the wildland fire-related subroutines may not call any WRF routines directly but only through a utility layer. All variables in the wildland fire-related subroutines are based at grid centers. Grid dimensions are passed in argument lists as

```
ifds,ifde,jfds,jfde, & ! fire domain dims
ifms,ifme,jfms,jfme, & ! fire memory dims
ifps,ifpe,jfps,jfpe, & ! fire patch dims (may be omitted)
ifts,ifte,jfts,jfte, & ! fire tile dims
```

Atmosphere grid 2D variables are declared with `dimension(ims:ime, jms:jme)`. Fire grid variables are declared with `dimension(ifms:ifme, jfms:jfme)`. Loops on the fire grid are always over a tile. The index variable names, the order of the loops, and the bounds are required exactly as in the code fragment below.

```
do j=jfts,jfte
     do i=ifts,ifte
               fire_variable(i,j)=…
```

In loops that need to index more than one grid at the same time (such as computations on a submesh, or interpolation between atmosphere and fire) the index variable names must always begin with `i j`.

Parallel execution

In these routines, all computational subroutines are called from a thread that services a single tile. There is no code running on a patch. Loops may update only array entries within in the tile but they may read other array entries in adjacent tiles, for example for interpolation or finite differences. The values of arrays that may be read between adjacent tiles are synchronized outside of the computational routines. Consequently, the values of a variable that was just updated may be used from an adjacent tile only in the next call to the computational subroutines, after the required synchronization was done outside. Synchronization within a patch is by exiting the OpenMP loop. Synchronization of the values between patches is by explicit HALO calls on the required variables and with the required width. HALOs are provided by the WRF infrastructure and specified in the registry.

The overall structure of the parallelism is spread over multiple software layers, subroutines and source files. The computation is organized in stages, controlled by the value of `ifun`.

```
! the code executes on a single patch
! if distributed memory, we are one of the MPI processes

do ifun=ifun_start,ifun_end ! what to do

  if(ifun.eq.1)then  ! this HALO needed before stage ifun=1
     #include "SOME_HALO.inc" ! communicate between patches
  endif
...
!$OMP PARALLEL DO
  do ij=1,num_tiles ! parallel loop over tiles

     if(ifun.eq.1)then   ! one of the initialization stages
          call some_atmosphere_to_fire_interpolation(…)
     endif
     ...
     call fire_model(…,ifun,…) ! call the actual model
     ! for some values of ifun, fire_model may do nothing

     if(ifun.eq.6)then   ! fire step done
```

```
          call some_fire_to_atmosphere_computation(…)
      endif

  enddo ! end parallel loop over tiles
  ! array variables are synchronized between tiles now

enddo ! end ifun loop
```

Software layers

The wildland fire-related subroutines are called from WRF file `dyn_em/module_first_rk_step_part1`. The output of these routines (the heat and moisture tendencies) are stored on exit from these routines and added to the tendencies in WRF later in a call to `update_phy_ten` from `dyn_em/module_first_rk_step_part2`
The wildland fire-related subroutines themselves consist of the following files in the `phys` directory, each constituting a distinct software layer:

`module_fr_fire_driver.F` **Fire driver** layer. These subroutines are called directly from WRF. All parallelism is contained here. The rest of the routines are called on a single tile.

`module_fr_fire_atm.F` **Atmosphere-fire interaction** layer. These routines are the interface between the fire and the atmosphere and interpolate between them.

`module_fr_fire_model.F` **Fire front representation and advancement** layer. This routine calls the core and the physics layers. Formulated in terms of the fire grid only, it is intended to be independent of particular mathematical methods used in the core layer.

`module_fr_fire_core.F` **Core** layer: This contains numerical algorithms for fire front advancement and the rate of fuel consumption calculation. It calls the physics layer for the fire spread rate.

`module_fr_fire_phys.F` **Fire physics** layer. This contains algorithms for calculating the rate of spread of the fire front in terms of the fire environment and associated initialization.

`module_fr_fire_util.F` **Utilities** layer. This layer is used by all other layers. It declares scalar switches and parameters and contains all interpolation and other service routines that may be general in nature and the interface to WRF routines such as messages and error exits. To maintain independence in WRF, this is the only layer that may call any WRF routines.

`fr_fire_params_args.h` This include file contains subroutine argument lists to pass through all arguments that are needed in the fire rate of spread algorithm in the physics layer. It is only necessary to write this long argument list once given the WRF requirement that arrays may be passed as arguments only, and not shared globally, say, as pointers. Also, it maintains the independence of the core layer from the physics layer and the modularity of the wildland fire-related subroutines in WRF.

`fr_fire_params_decl.h` Include file with the matching declarations.

Initialization in idealized case

The initialization of model arrays in the idealized case is done in the file `dyn_em/module_initialize_fire.F`

This file was adapted from other initialization files in the same directory and extended to deal with wildland fire-related variables.

a. Vertically stretched grid

Because of the fine meshes used in fire modeling, the user may wish to search for the text `grid%znw(k)` and modify the following loop to assure a desired refinement of the vertical atmospheric grid near the Earth surface:

```
DO k=1, kde
     grid%znw(k) = (exp(-(k-1)/float(kde-1)/z_scale) &
     - exp(-1./z_scale))/(1.-exp(-1./z_scale)
ENDDO
```

b Topography

The relevant code is found by searching for the text

```
!******* set terrain height
```

The terrain height needs to be set consistently in the atmosphere model in the array `grid%ht` and in the fire model array `grid%zsf` at the finer resolution. In the supplied examples, controlled by namelist.input variables `fire_mountain_type`, `fire_mountain_start_x`, `fire_mountain_start_y`, `fire_mountain_end_x`, `fire_mountain_end_y`, and `fire_mountain_height`, both arrays are set consistently from an algebraic formula (a cosine hill or a cosine ridge).

It is possible, though not recommended, to set only `grid%ht` and have the fire module interpolate the terrain height from the atmosphere mesh by specifying `fire_topo_from_atm=1` in namelist.input. This will result in blocky terrain with discontinuous terrain gradients, which will affect fire spread patterns.

Note that in a real run, the user should leave `fire_topo_from_atm=0` and both terrain height arrays are set consistently at the best available resolution from the WPS.

The user should not modify the code immediately after the setting of the terrain height arrays, which initializes a number of atmosphere variables consistently with the terrain height.