WRF Modeling System Overview

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What is WRF?

- WRF: Weather Research and Forecasting Model
  - Used for both research and operational forecasting
- It is a supported “community model”, i.e. a free and shared resource with distributed development and centralized support
- Its development is led by NCAR, NOAA/ESRL and NOAA/NCEP/EMC with partnerships at AFWA, FAA, and collaborations with universities and other government agencies in the US and overseas

What is ARW?

- WRF has two dynamical cores: The Advanced Research WRF (ARW) and Nonhydrostatic Mesoscale Model (NMM)
  - Dynamical core includes mostly advection, pressure-gradients, Coriolis, buoyancy, filters, diffusion, and time-stepping
- Both are Eulerian mass dynamical cores with terrain-following vertical coordinates
- ARW support and development are centered at NCAR/MMM
- NMM development is centered at NCEP/EMC and support is provided by NCAR/DTC
- This tutorial is for the ARW core
- Both are downloadable in the same WRF tar file
- Physics, the software framework, and parts of data pre- and post-processing are shared between the dynamical cores

What are ARW and NMM?

- The Advanced Research WRF (ARW) and Nonhydrostatic Mesoscale Model (NMM) are dynamical cores
  - Dynamical core includes mostly advection, pressure-gradients, Coriolis, buoyancy, filters, diffusion, and time-stepping
- Both are nonhydrostatic Eulerian dynamical cores with terrain-following pressure-based vertical coordinates
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- This tutorial is for ARW dynamical core
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WRF as a Community Model

- Version 1.0 WRF was released December 2000
- Version 2.0: May 2004 (NMM added, EM nesting released)
- Version 2.1: August 2005 (EM becomes ARW)
- Version 2.2: December 2006 (WPS released)
- Version 3.0: April 2008 (includes global ARW version)
- Version 3.1: April 2009
- Version 3.2: April 2010
  - Version 3.2.1 August 2010
- Version 3.3 April 2011
  - Version 3.3.1 September 2011
- *Version 3.4 April 2012 (new version)*

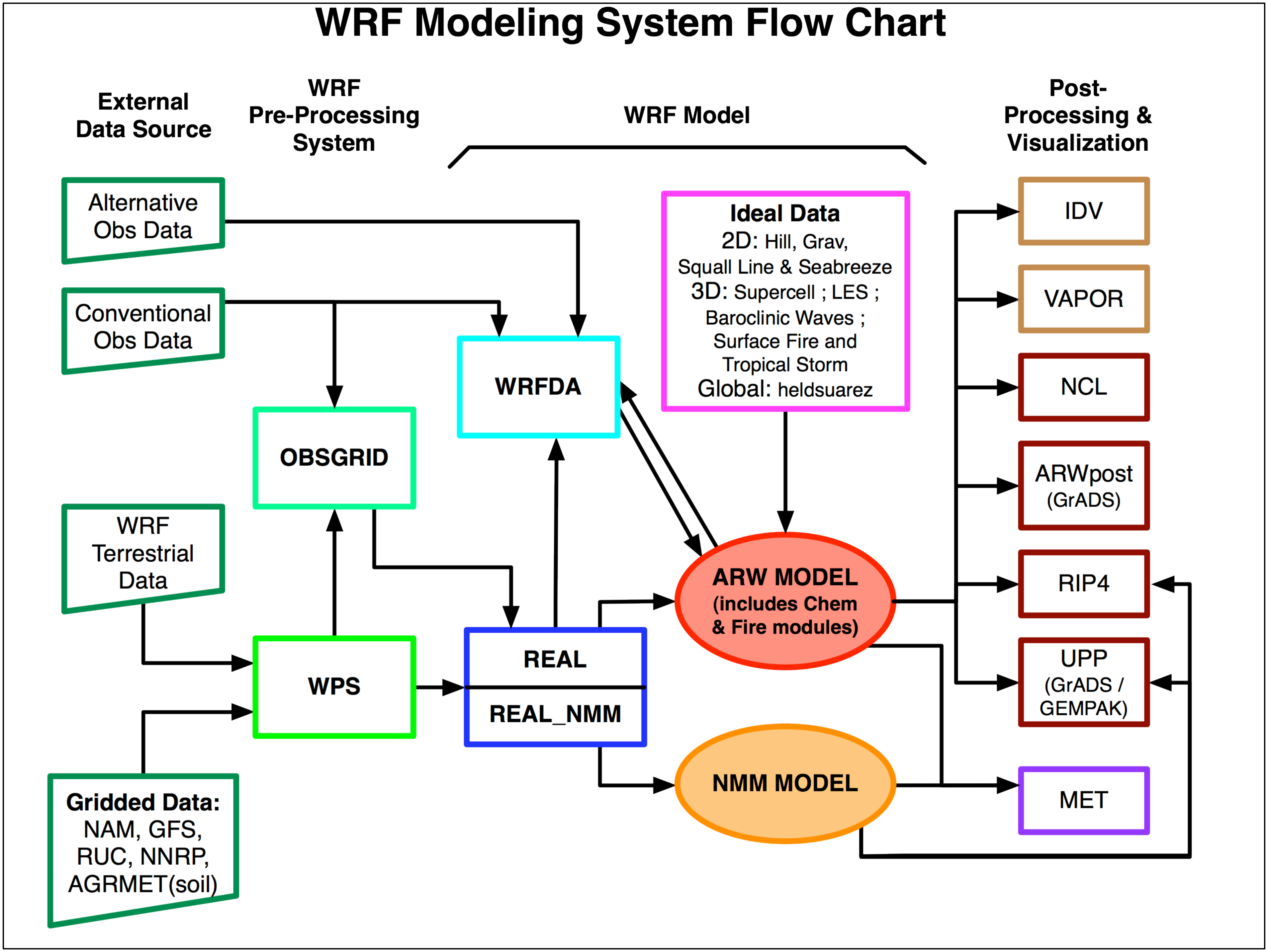
What can WRF be used for?

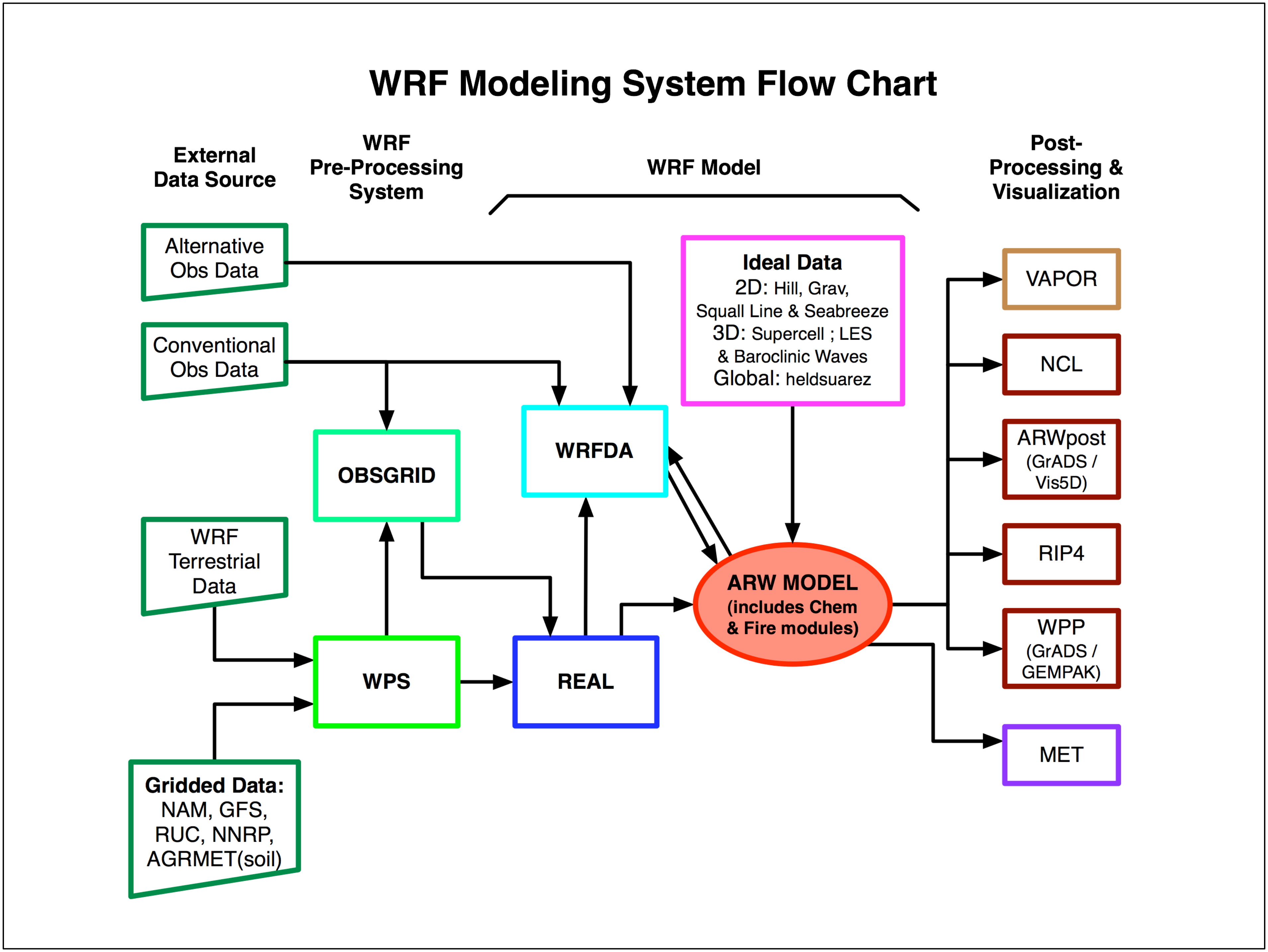
- ARW and NMM
  - Atmospheric physics/parameterization research
  - Case-study research
  - Real-time NWP and forecast system research
  - Data assimilation research
  - Teaching dynamics and NWP

- ARW only
  - Regional climate and seasonal time-scale research
  - Coupled-chemistry applications
  - Global simulations
  - Idealized simulations at many scales (e.g. convection, baroclinic waves, large eddy simulations)

Who uses WRF?

- Academic atmospheric scientists (dynamics, physics, weather, climate research)
- Forecast teams at operational centers
- Applications scientists (e.g. Air Quality, Hydrology, Utilities)


WRF Modeling System Flow Chart
External Data Source
WRF Pre-Processing System
WRF Model
Post-Processing & Visualization
Alternative Obs Data
Conventional Obs Data
WRF Terrestrial Data
Gridded Data: NAM, GFS, RUC, NNRP, AGRMET(soil)
OBSGRID
WPS
WRFDA
REAL
REAL_NMM
Ideal Data
2D: Hill, Grav, Squall Line & Seabreeze
3D: Supercell ; LES ; Baroclinic Waves ; Surface Fire and Tropical Storm
Global: heldsuarez
ARW MODEL (includes Chem & Fire modules)
NMM MODEL
IDV
VAPOR
NCL
ARWpost (GrADS)
RIP4
UPP (GrADS / GEMPAK)
MET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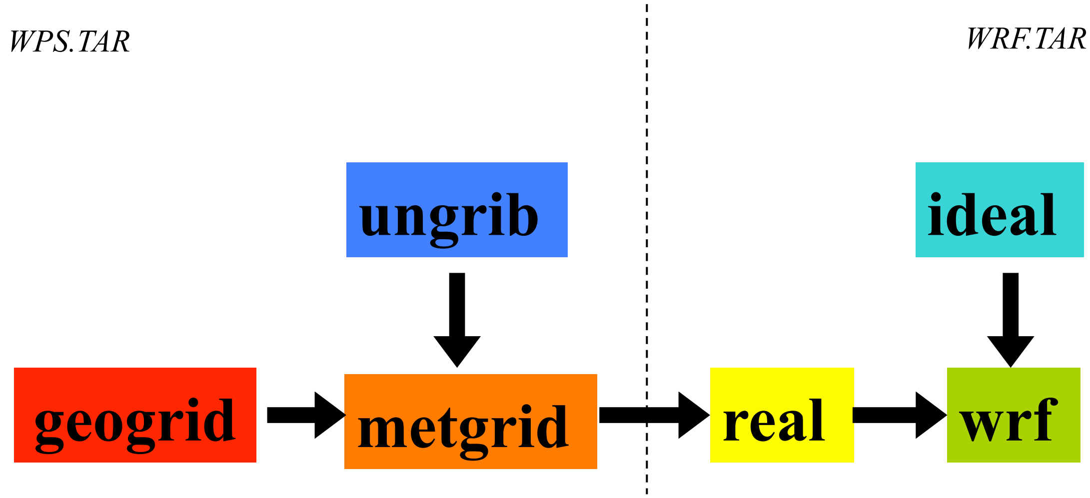
ARW MODEL (includes Chem & Fire modules)
VAPOR
NCL
ARWpost (GrADS / Vis5D)
RIP4
WPP (GrADS / GEMPAK)
MET

Modeling System Components

- WRF Pre-processing System
  - Real-data interpolation for NWP runs (WPS)
  - Program for adding more observations to analysis (obsgrid)
- WRF Model (ARW and NMM dynamical cores)
  - Initialization programs for real and (for ARW) idealized data (real.exe/ideal.exe)
  - Numerical integration program (wrf.exe)
- Graphics and verification tools including MET
- WRFDA (separate tutorial)
- WRF-Chem (separate tutorial)
- WRF-Fire – wildland model for forest fires

WPS and WRF Program Flow



Real-Data Applications

- Numerical weather prediction
- Meteorological case studies
- Regional climate
- Applications: air quality, wind energy, hydrology, etc.

Real-Data Applications

- Need time-independent information for chosen *domain* (simulation grid area)
- GEOGRID program
  - Map projection information
    - 2d gridded latitude, longitude, Coriolis parameter, map-scale factors, etc.
  - Topographic information
    - 2d gridded elevation, vegetation and soil categories, etc.

Real-Data Applications

- Need initial conditions (initial analysis time)
- UNGRIB and METGRID programs
  - 3d fields of horizontal wind, temperature, geopotential height, relative humidity
  - 2d fields of surface or sea-level pressure, surface temperature, relative humidity, horizontal winds
  - Time-sensitive land-surface fields: snow-cover, soil temperature, soil moisture

Real-Data Applications

- Regional domains need *specified* lateral boundary conditions at later times (e.g. every 6 hours) through forecast period
  - 3d fields of horizontal wind, temperature, geopotential height, water vapor
  - 2d field of surface pressure
- Long simulations (> 1 week) also need lower boundary condition at later analysis times
  - 2d fields of sea-surface temperature, sea-ice

Real-Data Applications

- Lateral Boundary Conditions (linear in time)
  - The *wrfbdy* file contains later gridded information at model points in a zone (e.g.) 5 points wide around the domain
  - The boundary fields are linearly time-interpolated from boundary times to the current model time
  - This specifies the outer values, and is used to nudge the next 4 interior points
- Lower Boundary Condition (step-wise)
  - New SSTs are read in and overwritten at each analysis time from *wrflowinp* file

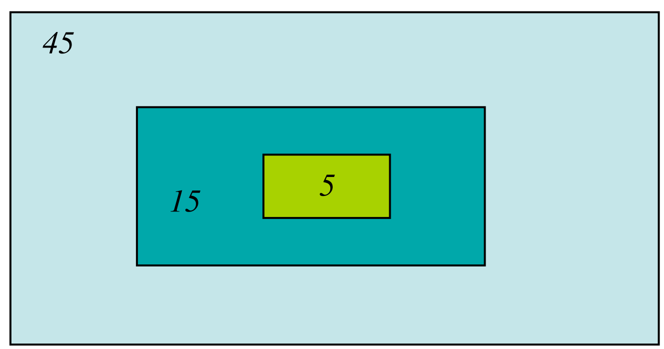
Real-Data Applications

Summary

- Pre-processing for regional domains therefore needs multiple times for lateral boundary conditions during whole forecast period (UNGRIB and METGRID should be run for all needed analysis times)
  - Note: Global models only need initial analysis
  - Real-time regional NWP often uses global forecast for boundary conditions
- Long simulations also need lower boundary information on SST and sea ice to update them over periods of weeks, months, years

Nesting

- Running multiple domains with increasing resolution in nested areas
- Parent has *specified* boundary conditions from *wrfbdy* fie
- *Nested* boundary conditions come from parent



Nesting (Two-Way)

- Lateral boundary condition is provided by parent domain at every parent step
- Method is same as for outer domain (specified and relaxation zones)
- Additional fields include vertical motion and microphysics species
- Feedback: Interior of nest overwrites overlapped parent area

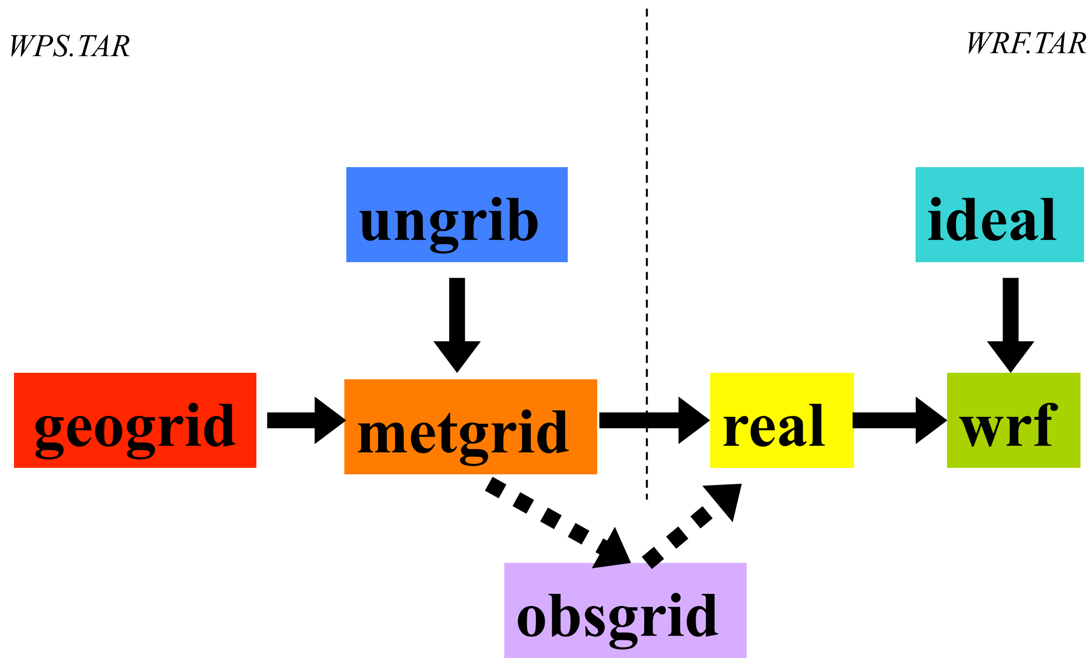
Nesting (Two-Way)

- Sequence
  - Parent domain runs a time-step to t+dt
  - Nest boundaries from beginning and end of time-step interpolated
  - Nest runs typically three steps (dt/3) using time-interpolated parent info at nest boundaries
  - After nest reaches t+dt, feedback overwrites parent in overlapped region
  - Repeat

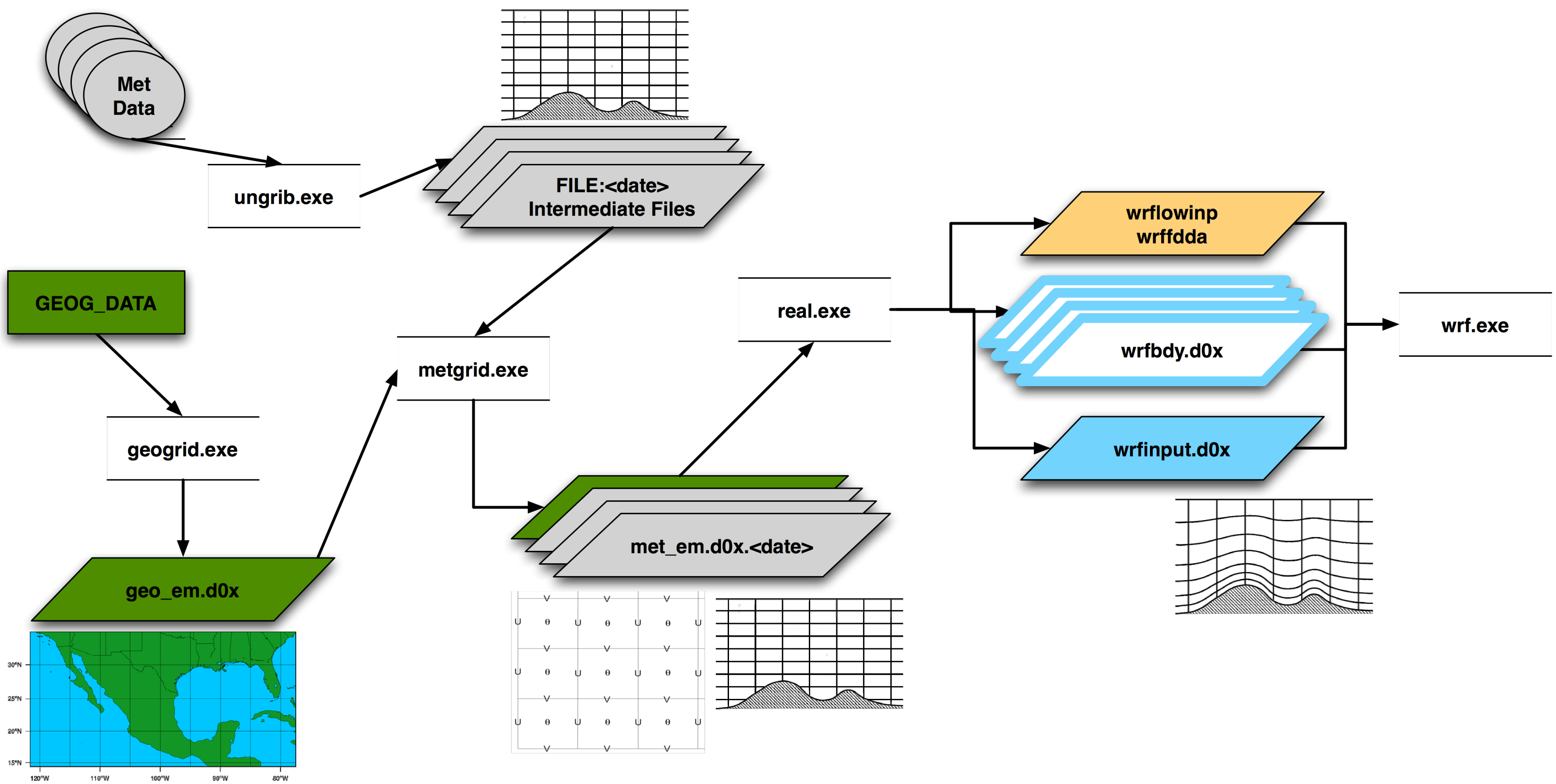
One-Way Nesting

- As two-way nesting but no feedback
- Can also be done with NDOWN program to take a previous WRF run output and provide nest boundary conditions at parent output frequency
  - Uses parent WRF run instead of analysis for initial and lateral boundary conditions

WPS and WRF Program Flow



Data Flow


Met
Data
ungrib.exe
FILE:<date>
Intermediate Files
GEOG_DATA
geogrid.exe
geo_em.d0x
metgrid.exe
met_em.d0x.<date>
real.exe
wrflowinp
wrffdda
wrfbdy.d0x
wrfinput.d0x
wrf.exe

WPS Functions

- Define simulation domain area (and nests)
- Produce terrain, landuse, soil type etc. on the simulation domain (“static” fields)
- De-grib GRIB files for meteorological data (u, v, T, q, surface pressure, soil data, snow data, sea-surface temperature, etc.)
- Interpolate meteorological data to WRF model grid (horizontally)
- Optionally add more observations to analysis (separate obsgrid program)

WPS Data

- Geogrid: We provide elevation, land-use, soil type data (static fields)
  - Or user can input own static data in same easy-to-write format
- Metgrid: Supports input of time-dependent data (dynamic fields)
  - UNGRIB can provide these from GriB files
  - Or user can input own data in same "intermediate format" (simple binary files)

WPS

Function (cont)

- Support WRF nesting
- Map projections:
  – ARW
    - Lambert conformal, Polar stereographic, Mercator, rotated lat/long
  – NMM
    - Rotated lat/long
- Two grid-staggerings
  – ARW C-grid
  – NMM E-grid

WPS and WRF

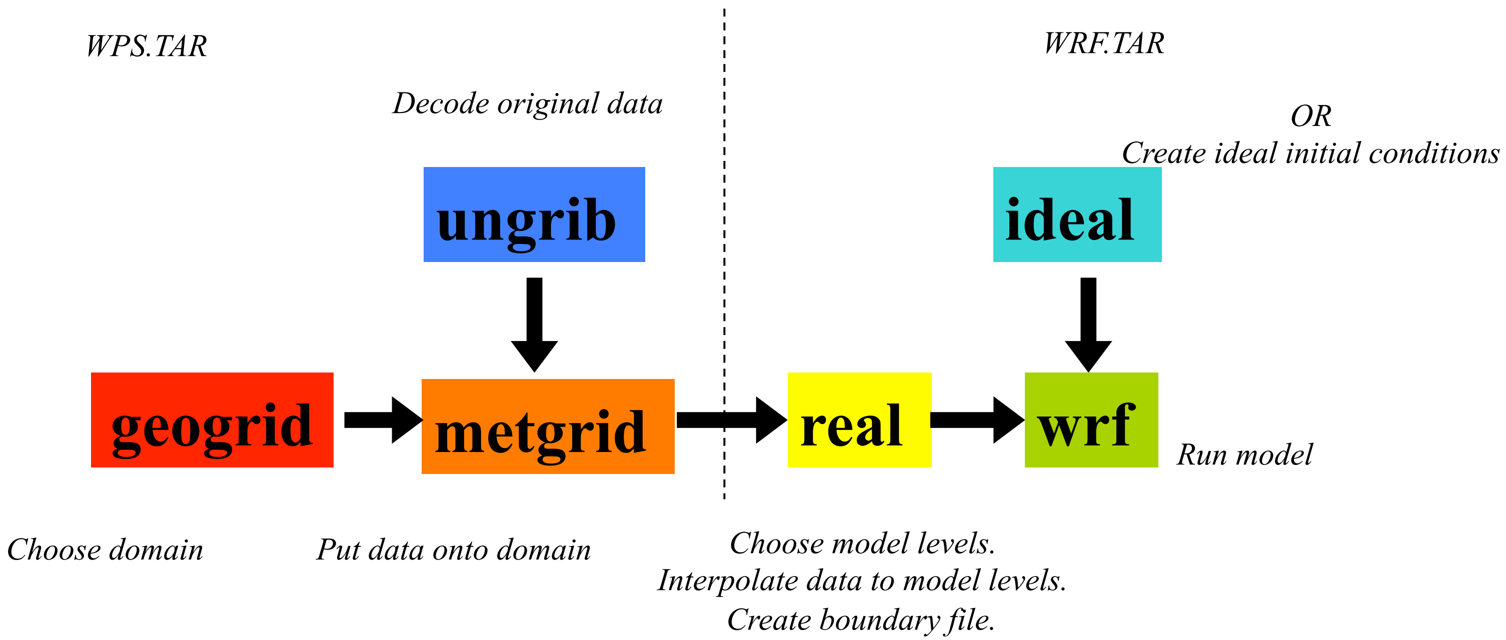
Running WPS

- Several executable stages with namelist input
  - geogrid.exe (interpolate maps and time-independent fields)
  - ungrib.exe (convert time-dependent Grib-formatted data to simple binary format)
  - metgrid.exe (interpolate time-dependent initial and boundary data)
  - obsgrid.exe (optional stage to add more observations)

Running WRF

- Two executable stages with namelist input
  - real.exe or real_nmm.exe (set up vertical model levels for model input and boundary files)
  - wrf.exe (run model)

WPS and WRF Program Flow



WRF real and ideal functions

- REAL
  - Creates initial and boundary condition files for real-data cases
  - Does vertical interpolation to model levels (when using WPS)
  - Does vertical dynamic (hydrostatic) balance
  - Does soil vertical interpolations and land-use mask checks
- IDEAL (ARW only)
  - Programs for setting up idealized case
  - Simple physics and usually single sounding
  - Initial conditions and dynamic balance

WRF Model

- WRF
  – Dynamical core (ARW or NMM) is compile-time selectable
  – Uses initial conditions from REAL or IDEAL (ARW)
  – Real-data cases use boundary conditions from REAL
  – Runs the model simulation with run-time selected namelist switches (such as physics choices, timestep, length of simulation, etc.)
  – Outputs history and restart files

Dynamical Cores

- Dynamical cores include
  - Basic Dynamical Equations: Advection, Coriolis, pressure gradient terms, buoyancy, diffusion
  - Finite differencing: Staggered grid-structure, time-stepping method and numerical filters
- ARW dynamical core
  - Designed for research as well as NWP
  - Idealized cases, regional climate, WRF-Chem, more options
- NMM dynamical core
  - Used in NCEP operational regional models (i.e. NAM and HWRF)
  - Focused on NWP applications, more limited options

WRFDA (Data Assimilation)

- Variational data assimilation (3D-Var and 4D-Var)
- Ensemble DA
- Hybrid variational/ensemble DA

Function

- Ingest observations to improve WRF input analysis from WPS
- May be used in cycling mode for updating WRF initial conditions after WRF run
- Also used for observation impact data studies

WRFDA

- Supported for data types
  - Conventional surface and upper air, wind profiler, aircraft
  - Remote sensing data: Cloud-tracked winds, satellite-retrieved profiles, ground-based/satellite GPS, scatterometer ocean surface winds, radar radial velocity and reflectivity, satellite radiance
- Background error covariance for ARW from
  - NMC method
  - Ensemble method

WRF-Chem

- Supported by NOAA/ESRL
- Includes chemistry species and processes, many chemistry options
- Also needs emissions data
- Included in WRF tar file, but requires special compilation option

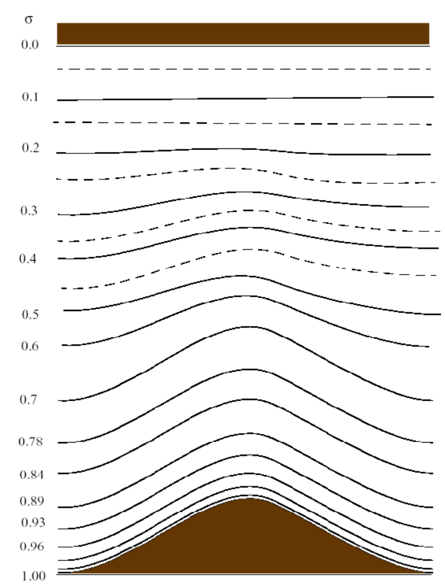
ARW Dynamics

Key features:

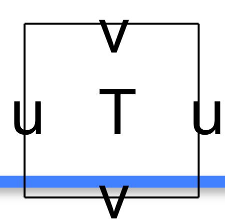
- Fully compressible, non-hydrostatic (with hydrostatic option)
- Mass-based terrain following coordinate, η

$$\eta = \frac{(\pi - \pi_t)}{\mu}, \qquad \mu = \pi_s - \pi_t$$

where π is hydrostatic pressure, μ is column mass



- Arakawa C-grid staggering



ARW Model

Key features:

- 3rd-order Runge-Kutta time integration scheme
- High-order advection scheme
- Scalar-conserving (positive definite option)
- Complete Coriolis, curvature and mapping terms
- Two-way and one-way nesting

ARW Model

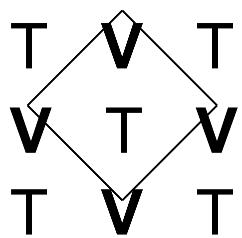
Key features:

- Choices of lateral boundary conditions suitable for real-data and idealized simulations
  - Specified, Periodic, Open, Symmetric, Nested
- Full physics options to represent atmospheric radiation, surface and boundary layer, and cloud and precipitation processes
- Grid-nudging and obs-nudging (FDDA)
- Digital Filter Initialization option

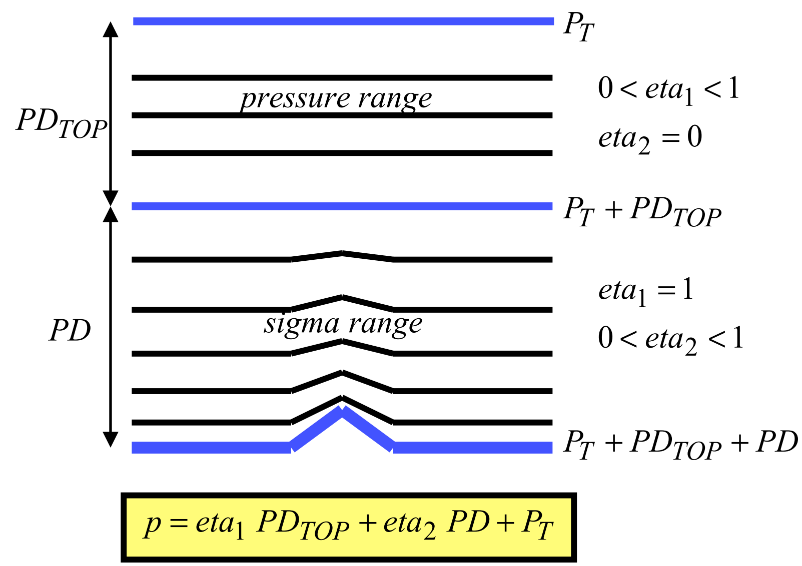
NMM Dynamics

Key features:

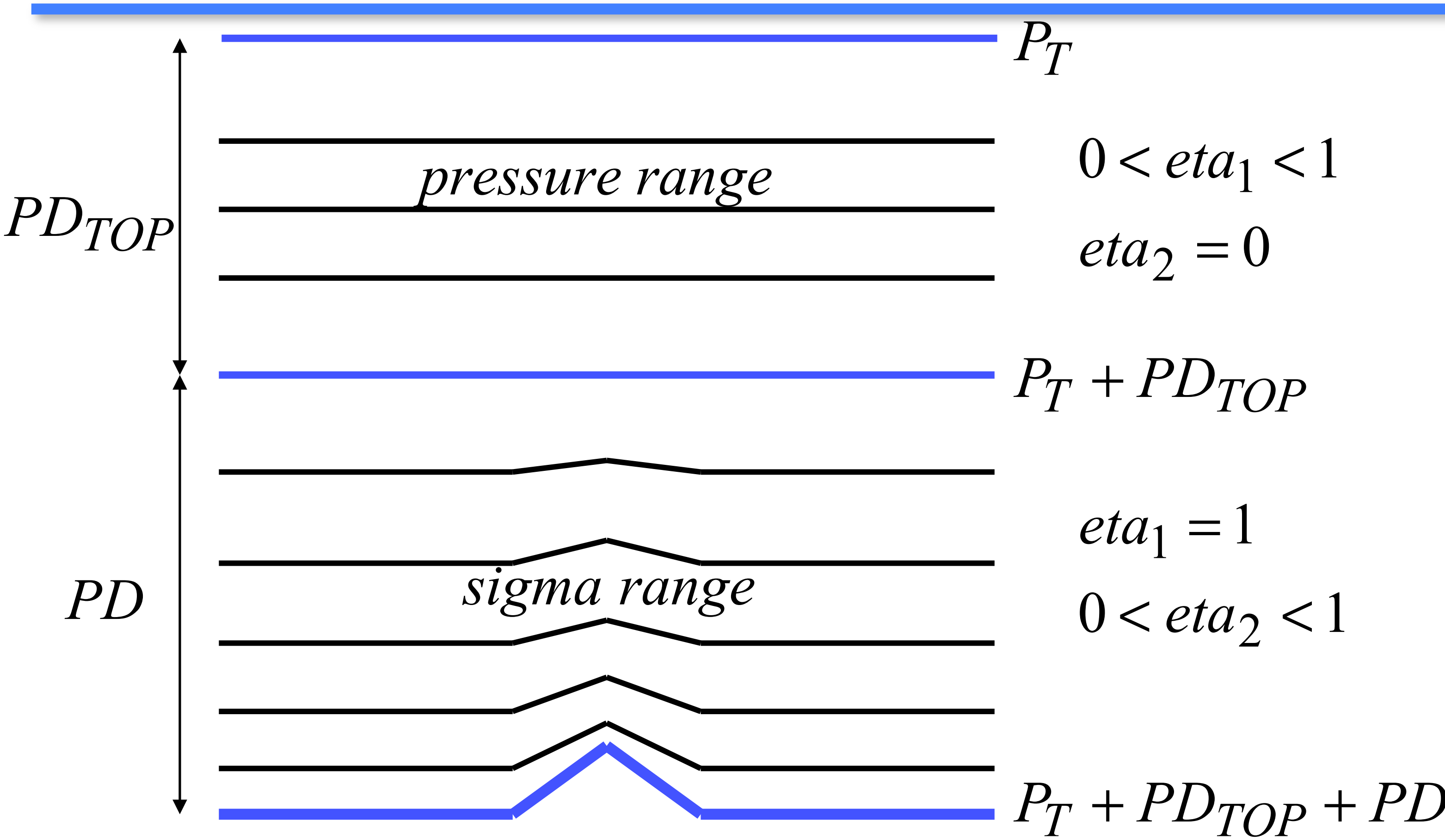
- Fully compressible, non-hydrostatic or hydrostatic
- Mass-based sigma-pressure hybrid terrain following coordinate similar to ARW but with constant pressure surfaces above 400 hPa
- Arakawa E-grid staggering



where **V** is u and v



NMM Dynamics



$$p = eta_1\, PD_{TOP} + eta_2\, PD + P_T$$

NMM Model

Key features:

- Adams-Bashforth and Crank-Nicholson time integration schemes
- High-order advection scheme
- Scalar and energy conserving
- Coriolis, curvature and mapping terms
- One-way and two-way nesting

NMM Model

Key features:

- Lateral boundary conditions suitable for real-data and nesting
- Full physics options to represent atmospheric radiation, surface and boundary layer, and cloud and precipitation processes

Graphics and Verification Tools

- ARW and NMM
  - – RIP4 (Read, Interpolate and Plot)
  - – Unified Post-Processor (UPP)
    - Conversion to GriB (for GrADS and GEMPAK)
  - – MET (Model Evaluation Toolkit)
- ARW
  - – NCAR Graphics Command Language (NCL)
  - – ARWpost
    - Conversion program for GrADS
  - – VAPOR (3D visualization tool)
  - – IDV (3D visualization tool)

Basic Software Requirement

- Fortran 90/95 compiler
  - Code uses standard f90 (very portable)
- C compiler
  - “Registry”-based automatic Fortran code generation (for argument lists, declarations, nesting functions, I/O routines)
- Perl
  - configure/compile scripts
- netcdf library
  - for I/O (other I/O formats semi-supported)
- Public domain mpich for MPI
  - if using distributed memory option

Code Layers

- Top-level (framework): allocates space, handles nested domains and interpolation/feedback functions, time-stepping, solver calls, and i/o file contents and calls
- Intermediate level: “start” routine for initial calls, “solve” routine for run-time advancing, MPI handling
- Low-level: science code in plain Fortran (no MPI or I/O calls)

Registry File

- Designed to make adding arrays or new namelist parameters easy
- Also can add them to “halo” for MPI communications (only sometimes needed)
- Allocates, passes, and declares, listed arrays for nesting, i/o and “solver” routines
    - Solver advances one domain by one time step
  - From solver, it can be passed to parts of the low-level code via argument lists

Portability

- Runs on Unix single, OpenMP and MPI platforms:
  - IBM SP AIX (xlf)
  - Linux (PGI, Intel, g95, gfortran, Pathscale compilers)
  - SGI Altix (Intel)
  - Cray XT (PGI, Pathscale)
  - Mac Darwin (xlf, PGI, Intel, g95 compilers)
  - Others (HP, Sun, SGI Origin, Compaq)

User Support

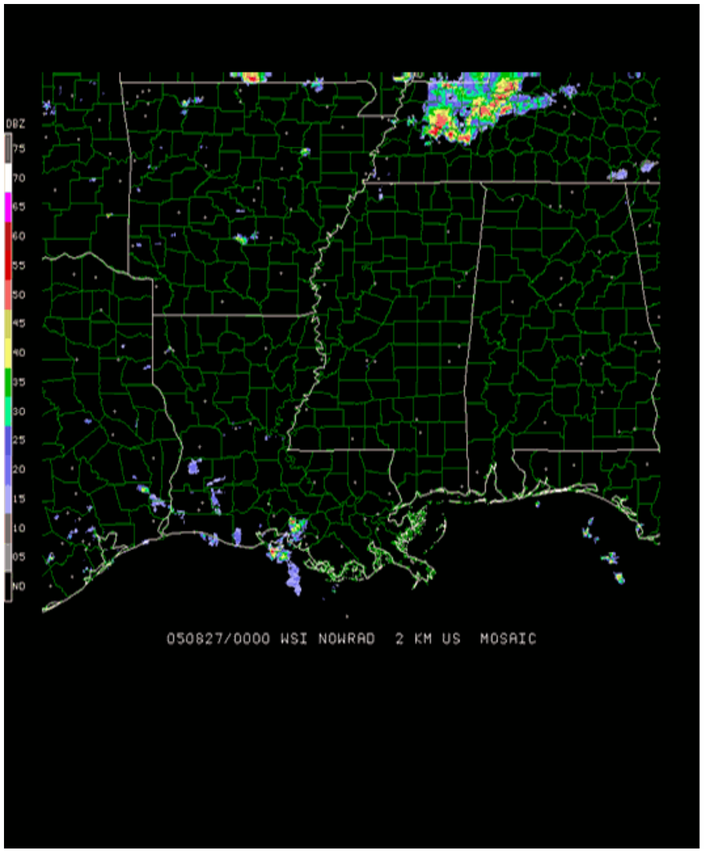
- Email: wrfhelp@ucar.edu
- User Web pages:

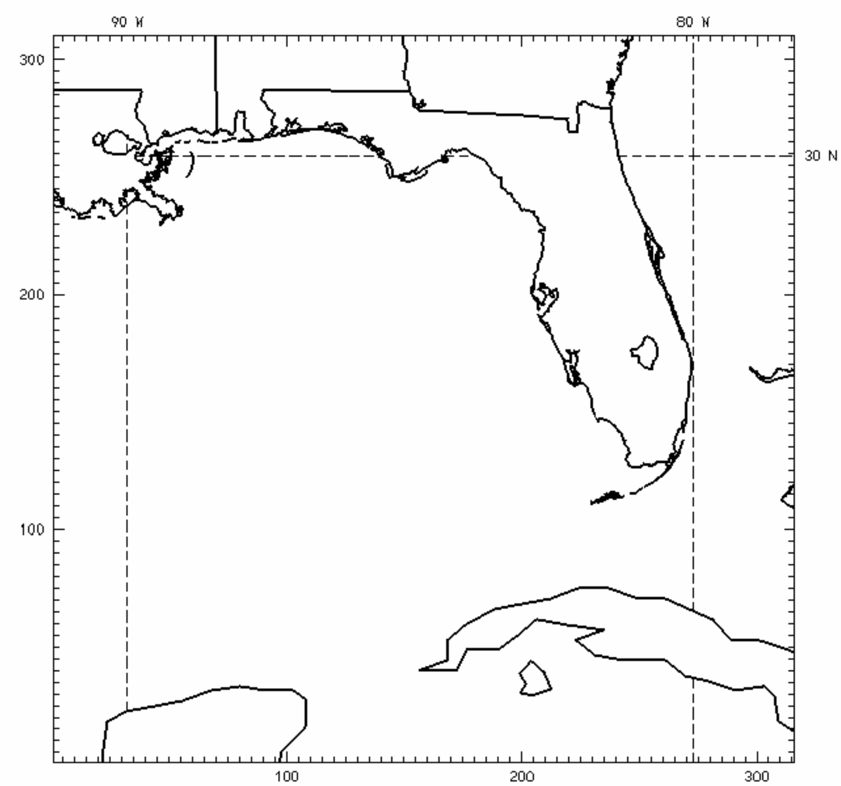
  ARW:http://www.mmm.ucar.edu/wrf/users/

  NMM:http://www.dtcenter.org/wrf-nmm/users/

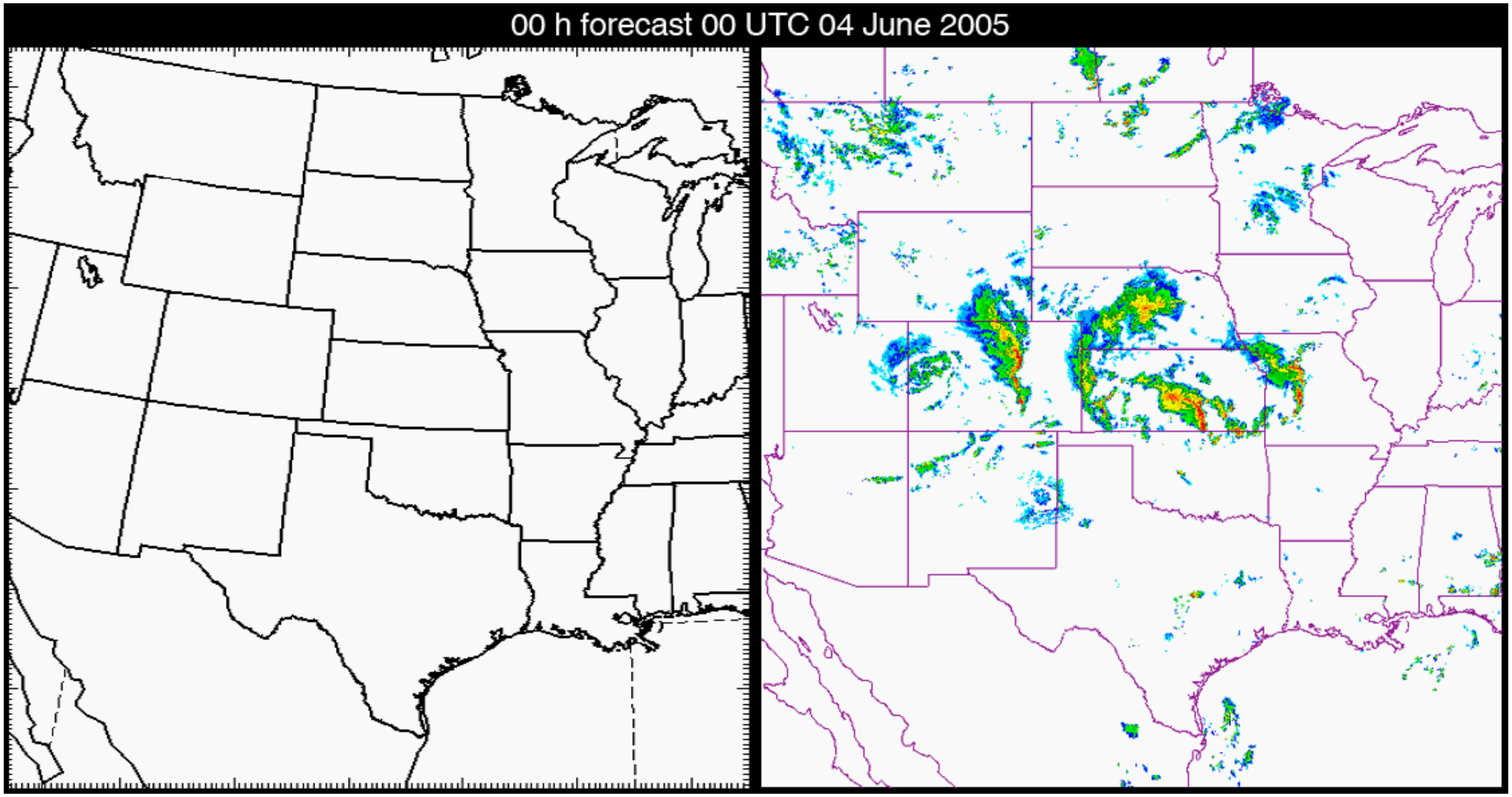
  – Latest update for the modeling system
  – WRF software download
  – Various documentation
    - Users' Guides (both cores)
    - Technical Note (ARW Description)
    - Technical Note (NMM Description)

ARW Hurricane Katrina Simulation (4km)





ARW Convective-scale Forecasting (4km)



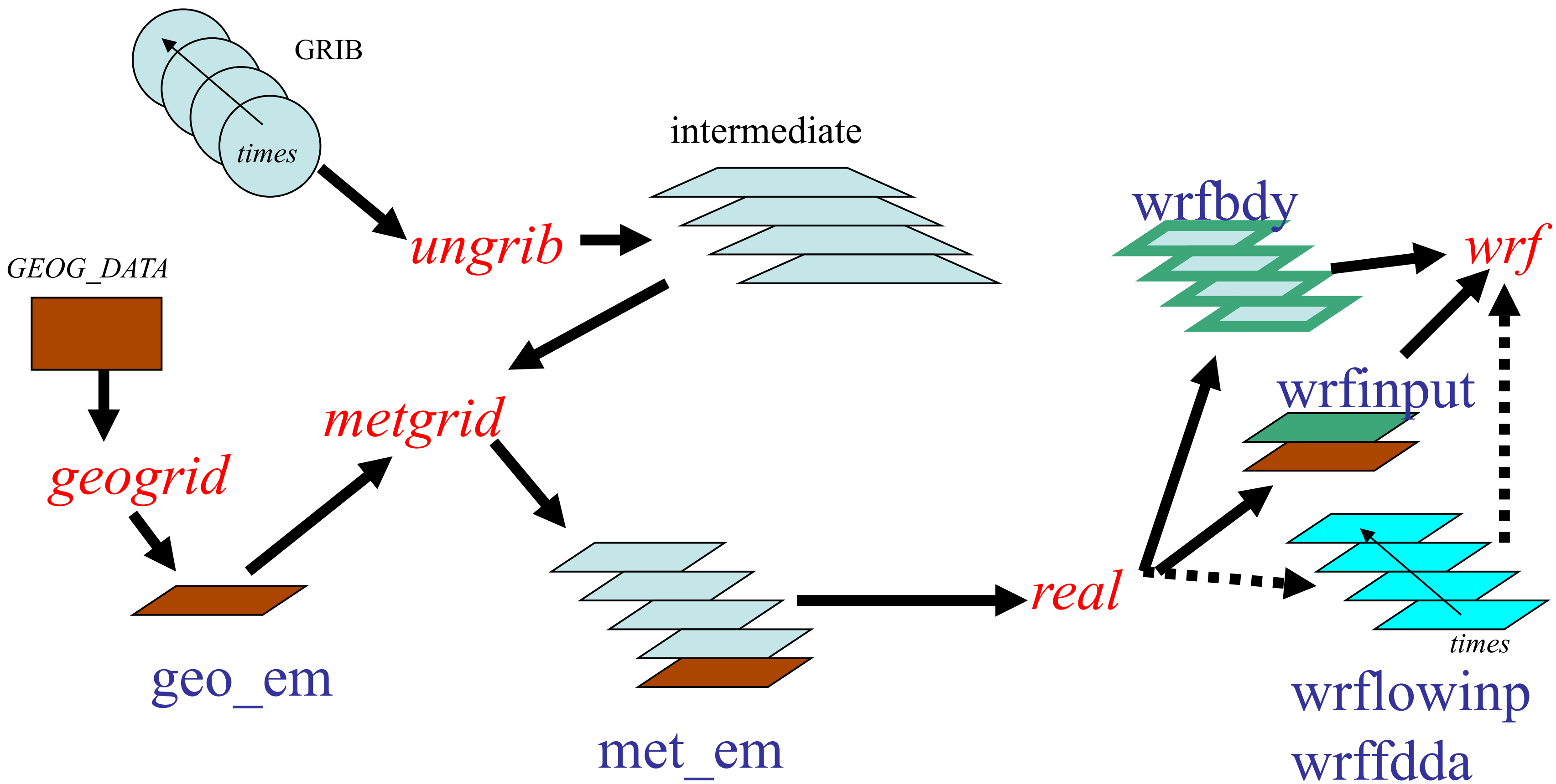
Tutorial Schedule

- Lectures for WRF: Mon.-Fri.
- Practice for WRF: Mon.-Fri.
  - 2 Groups (a.m./p.m.)
- MET tutorial: Next Mon.-Tue.

Tutorial Schedule

- Lectures for WRF: Mon.-Fri.
- Practice for WRF: Mon.-Fri.
  - 2 Groups (a.m./p.m.), 3 sessions
- WRFDA tutorial and practice: starts next Monday
- WRF-Chem tutorial and practice: starts next Wednesday

Data Flow



GRIB
times
intermediate
ungrib
GEOG_DATA
metgrid
geogrid
geo_em
met_em
real
wrfbdy
wrf
wrfinput
times
wrflowinp
wrffdda