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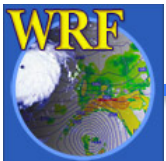
WRF Modeling System Overview

Jimmy Dudhia



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, DOE/PNNL 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 (operationally now only used for HWRF)
- This tutorial is for only 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



WRF Community Model

- Version 1.0 WRF was released December 2000
- Version 2.0: May 2004 (add nesting)
- Version 3.0: April 2008 (add global ARW version)
- ... (major releases in April, minor releases in summer)
- Version 3.8: April 2016
 - Version 3.8.1: August 2016
- Version 3.9: April 2017
 - Version 3.9.1 (later in 2017)

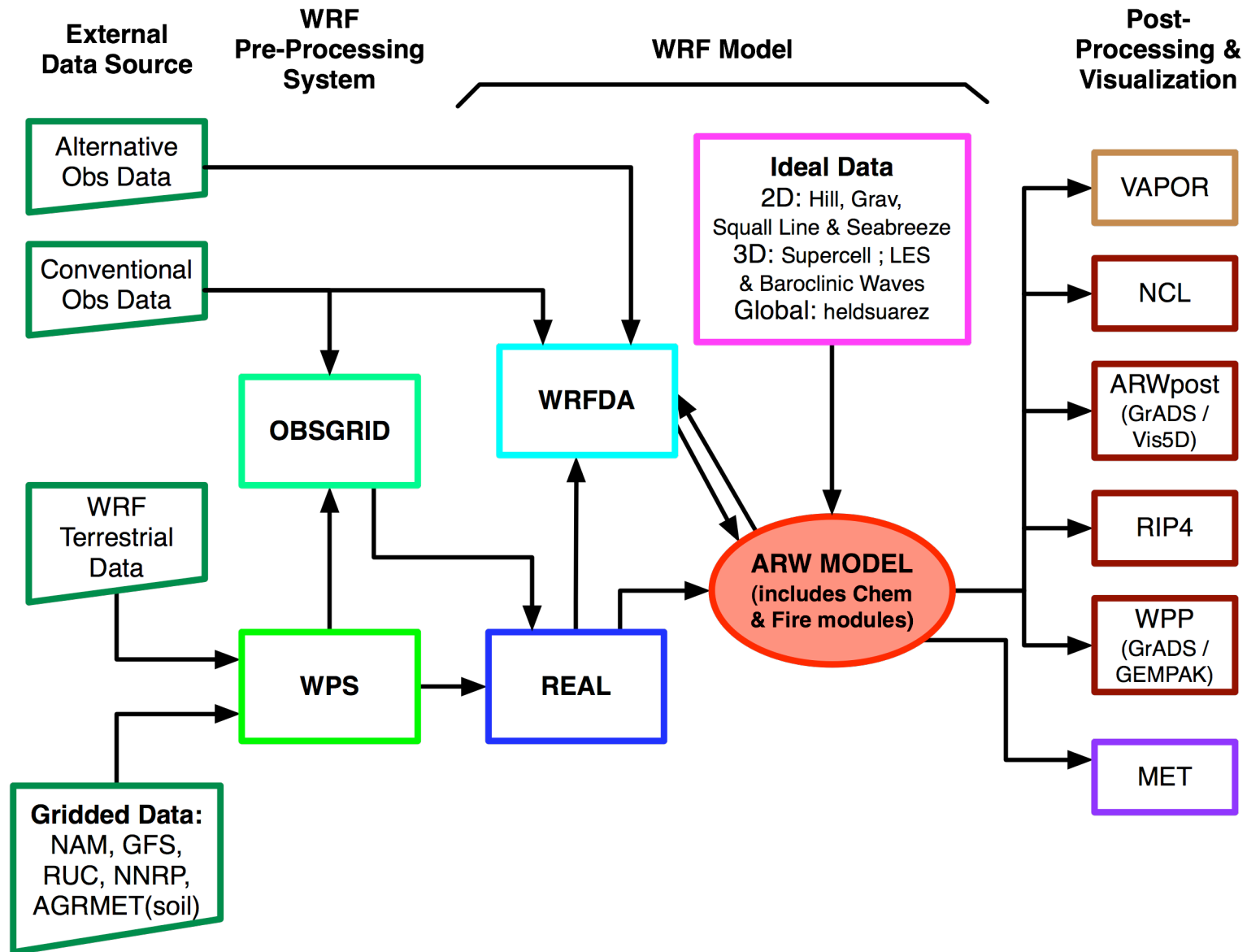


What can WRF be used for?

- 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)



WRF Modeling System Flow Chart

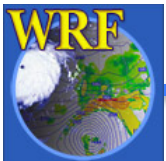
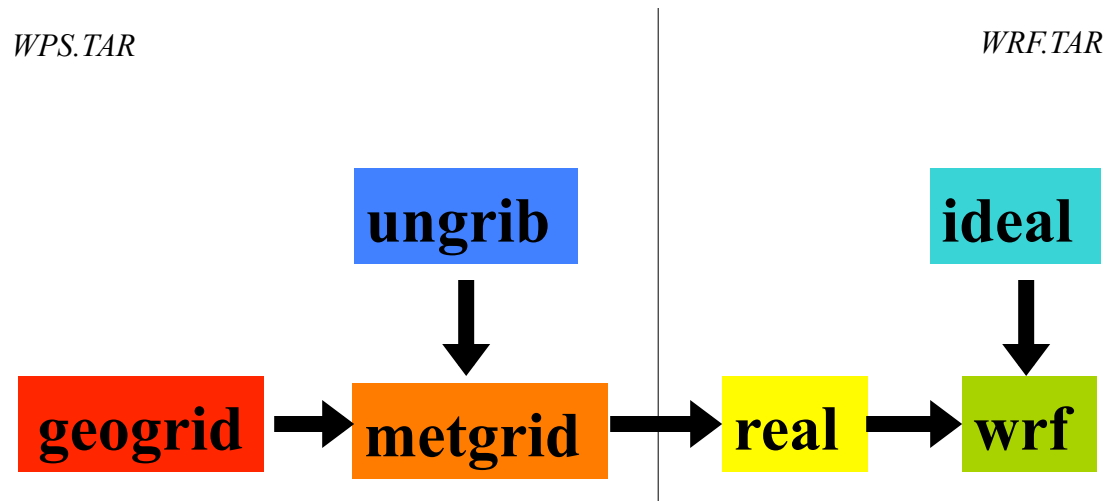


Modeling System Components

- 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-Hydro – hydrology model coupled to WRF
- 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 time-dependent information
- Initial conditions (initial analysis time)
- Boundary conditions (later times)
 - except if running WRF globally
- 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 times
 - 2d fields of sea-surface temperature, sea-ice, vegetation fraction



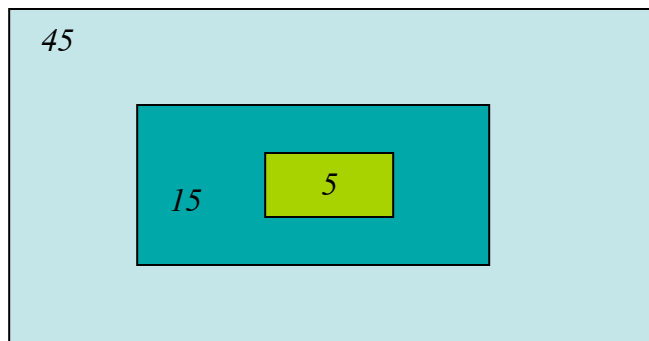
Real-Data Applications

- 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



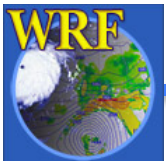
Nesting

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



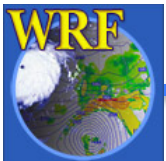
Nesting (Two-Way)

- 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



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 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)

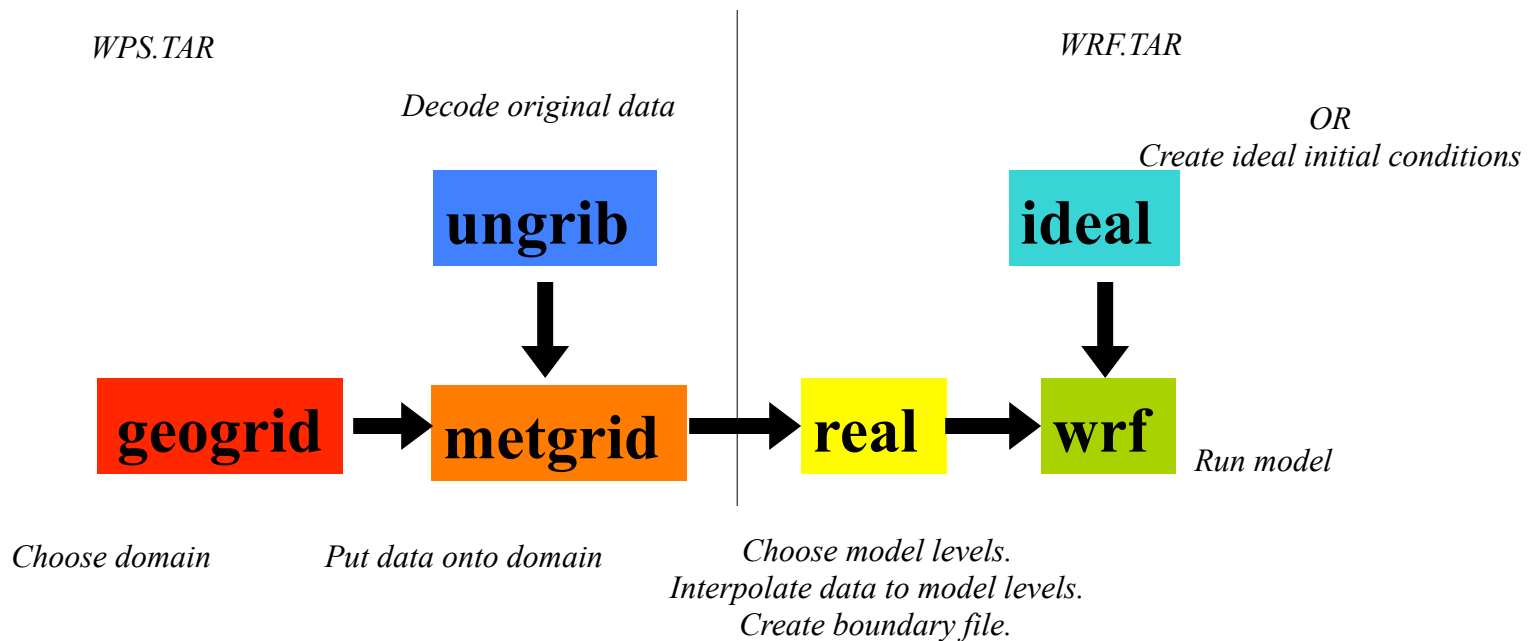


WPS Data

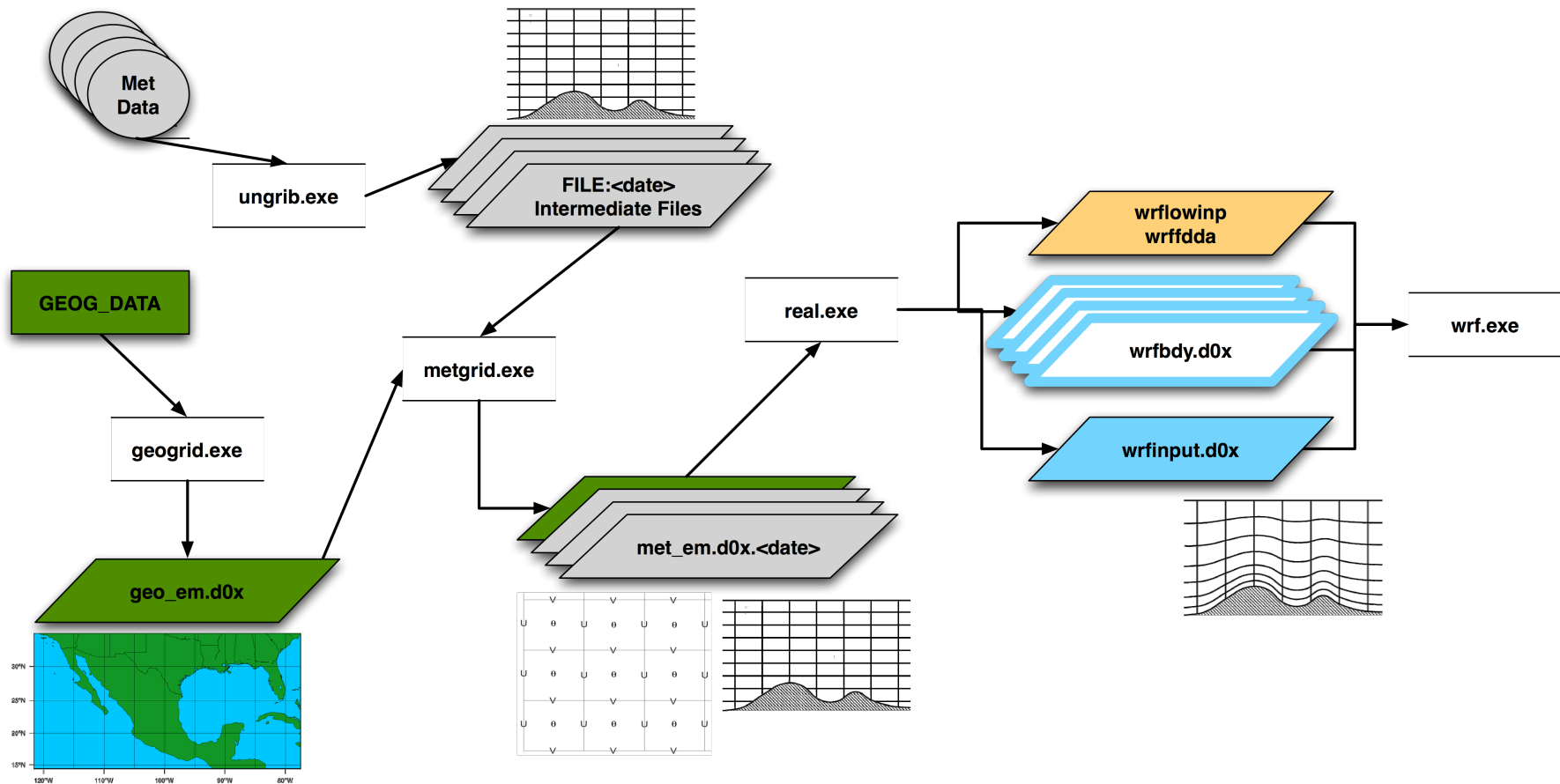
- Geogrid: We provide elevation, land-use, soil type data (static fields)
 - Or user can input own static data in same easy-to-write format
- Metgrid: Supports input of time-dependent data (dynamic fields)
 - UNGRIB can provide these from GriB files
 - Or user can input own data in same “intermediate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



WPS and WRF Program Flow

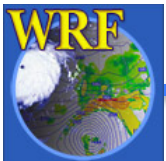


Data Flow



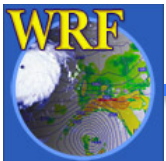
WRF real and ideal functions

- 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



ARW Dynamics

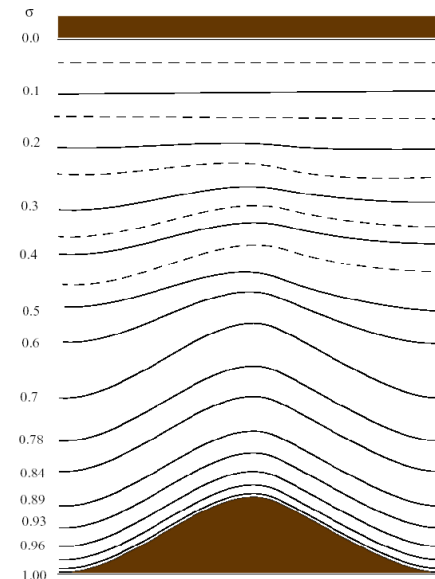
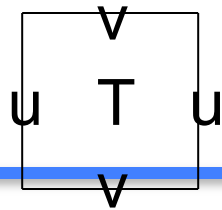
Key features:

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

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

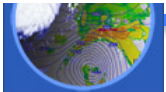
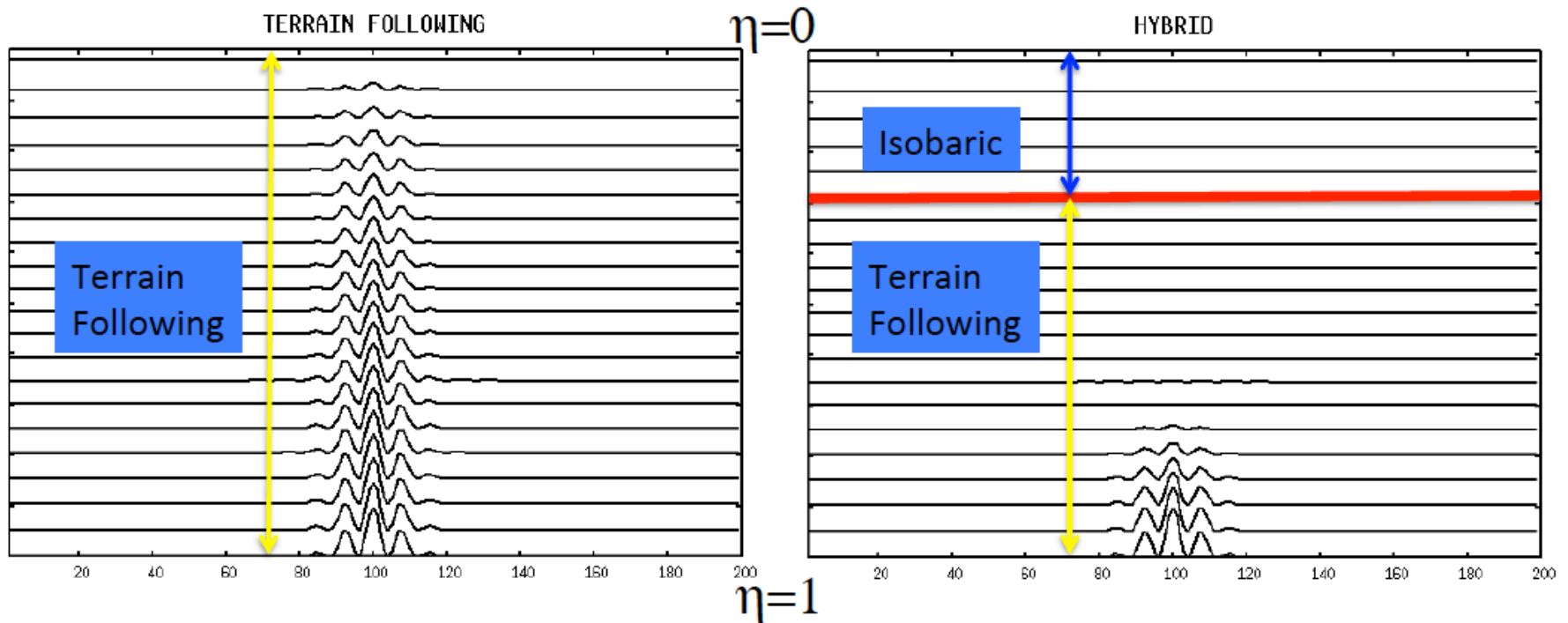
where π is hydrostatic pressure,
 μ is column mass

- Arakawa C-grid staggering



ARW Model

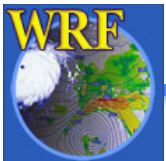
- New hybrid vertical coordinate option in V3.9
- Isobaric at top means less noise in upper-air output over mountains



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



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)



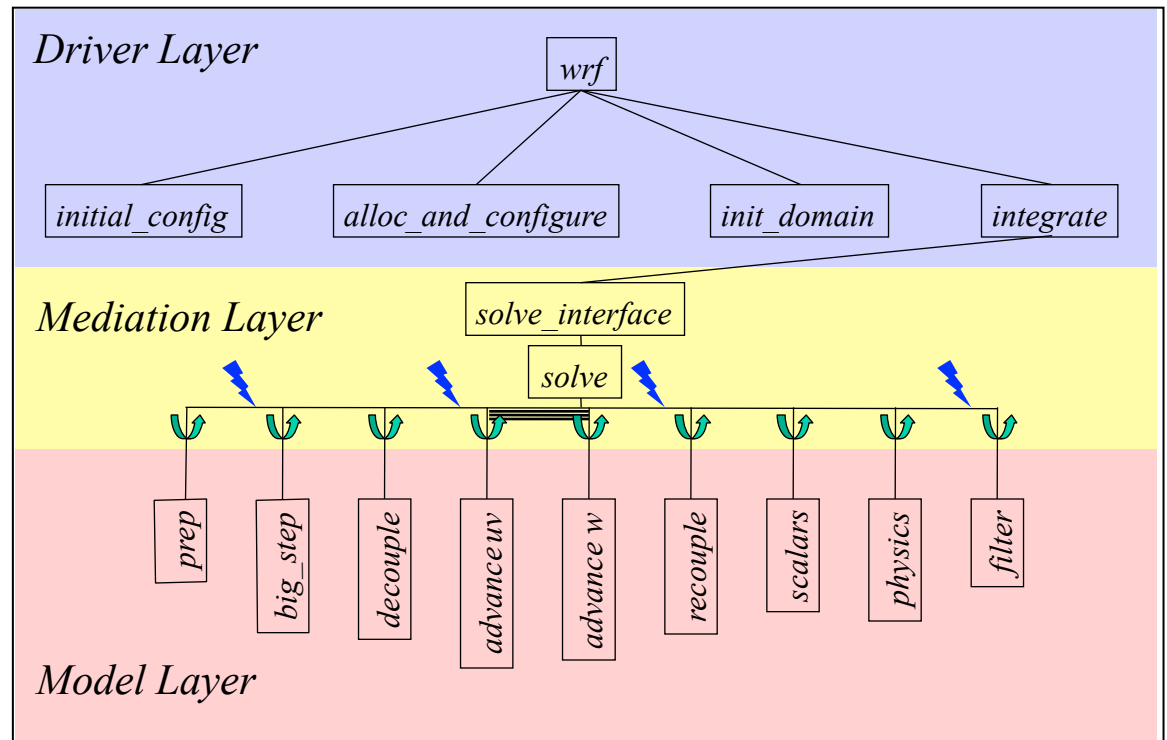
Basic Software Requirement

- 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



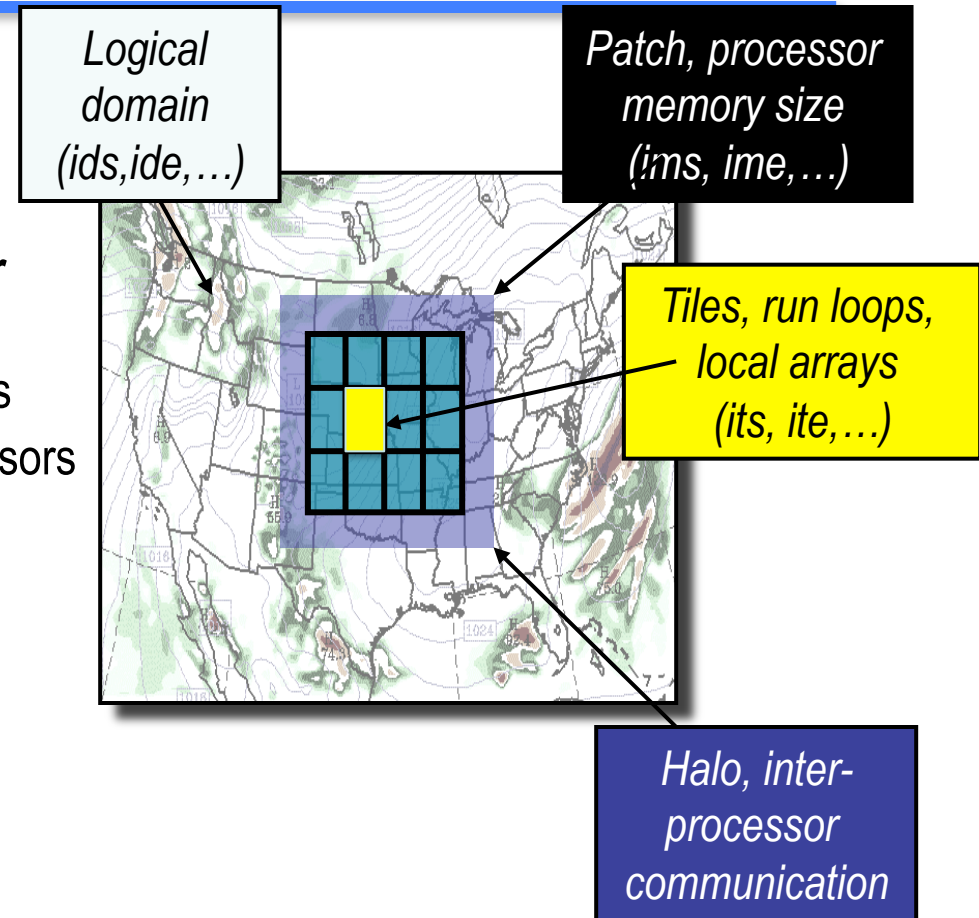
WRF Hierarchical Software Architecture

- Driver Layer
 - Memory allocation, nest starting, time-stepping, I/O
- Mediation Layer
 - Solver
- Model Layer
 - Dynamics, physics



WRF Two-Layer Domain Decomposition (patches, tiles, halo)

- **Single version of code enabled for efficient execution on:**
 - Shared-memory multiprocessors
 - Distributed-memory multiprocessors
 - Distributed clusters of SMPs
 - Vector and scalar processors



Registry File

- Input for automatic code generation
- Designed to make adding arrays or new namelist parameters easy
- 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
- Also can add them to “halo” for MPI communications (only sometimes needed)



WRFDA (Data Assimilation)

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

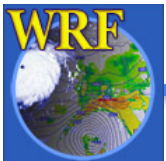
Function

- 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



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



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)



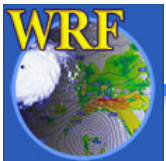
Examples of WRF Forecasts

(1) Hurricane Katrina (August, 2005)

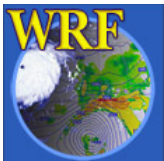
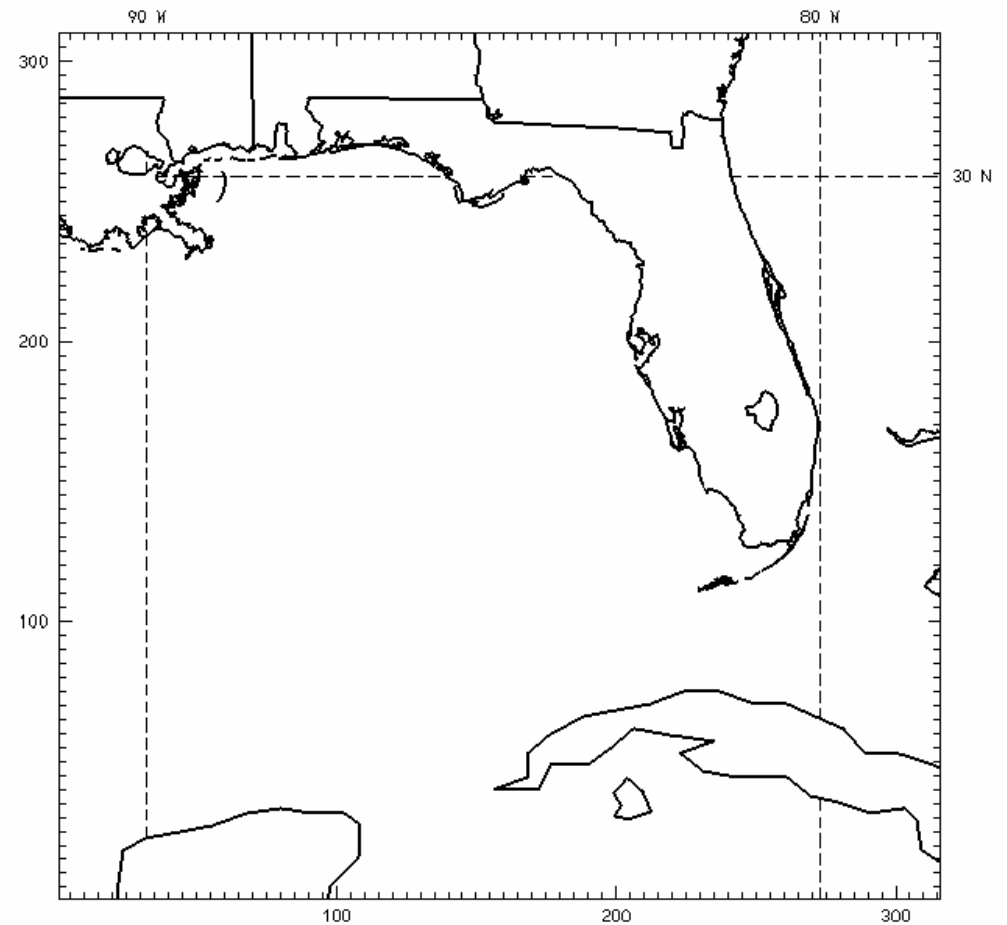
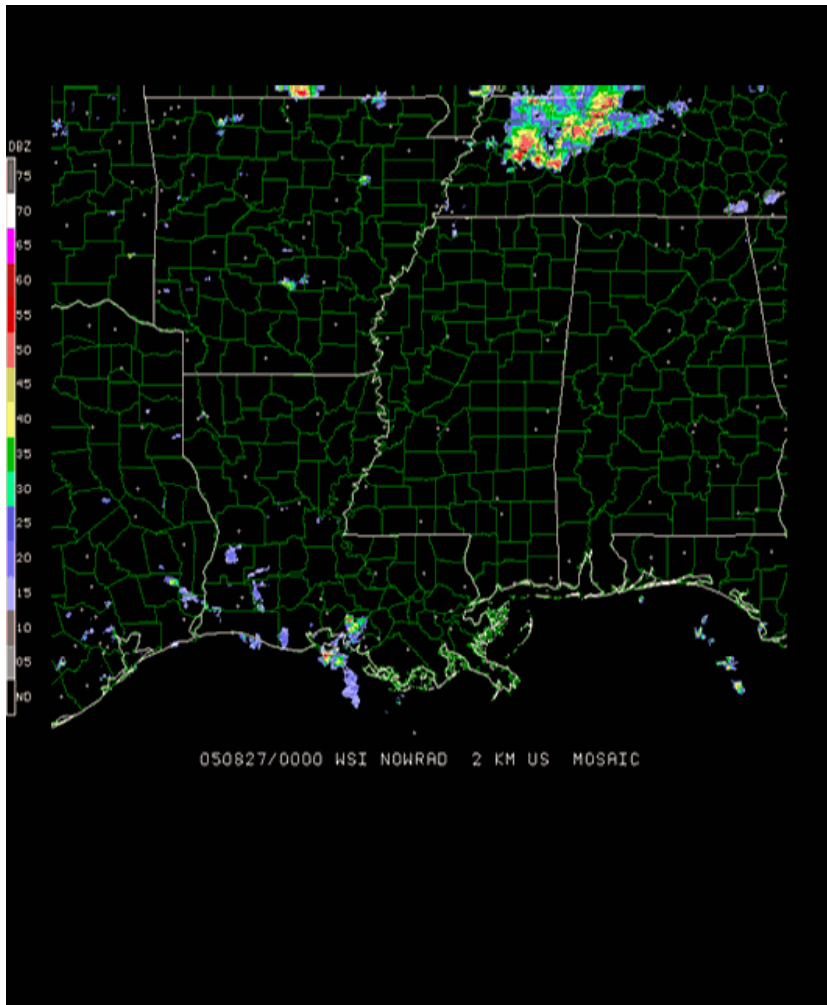
- Moving 4 km nest in a 12 km outer domain

(2) US Convective System (June, 2005)

- Single 4 km central US domain



ARW Hurricane Katrina Simulation (4km)



ARW Convective-scale Forecasting (4km)

00 h forecast 00 UTC 04 June 2005

