Scope of Tutorial

- What's in the modeling system
  - Pre-processing programs and model
- How to run the modeling system
- Hints on choosing options
- Advanced usage
  - Adding your own input or output data
  - Changing the code

Scope of Tutorial

- Note: we cover a wide range of topics in much detail due to having a wide range of new users
  - New users can focus on areas of their own interest
  - Don't feel you have to learn everything in the lectures now
  - Minimum you need to learn is how to run the programs and what they do
    - Daily practice sessions (~2 hr) are a basic part

WRF Modeling System Overview

Jimy 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

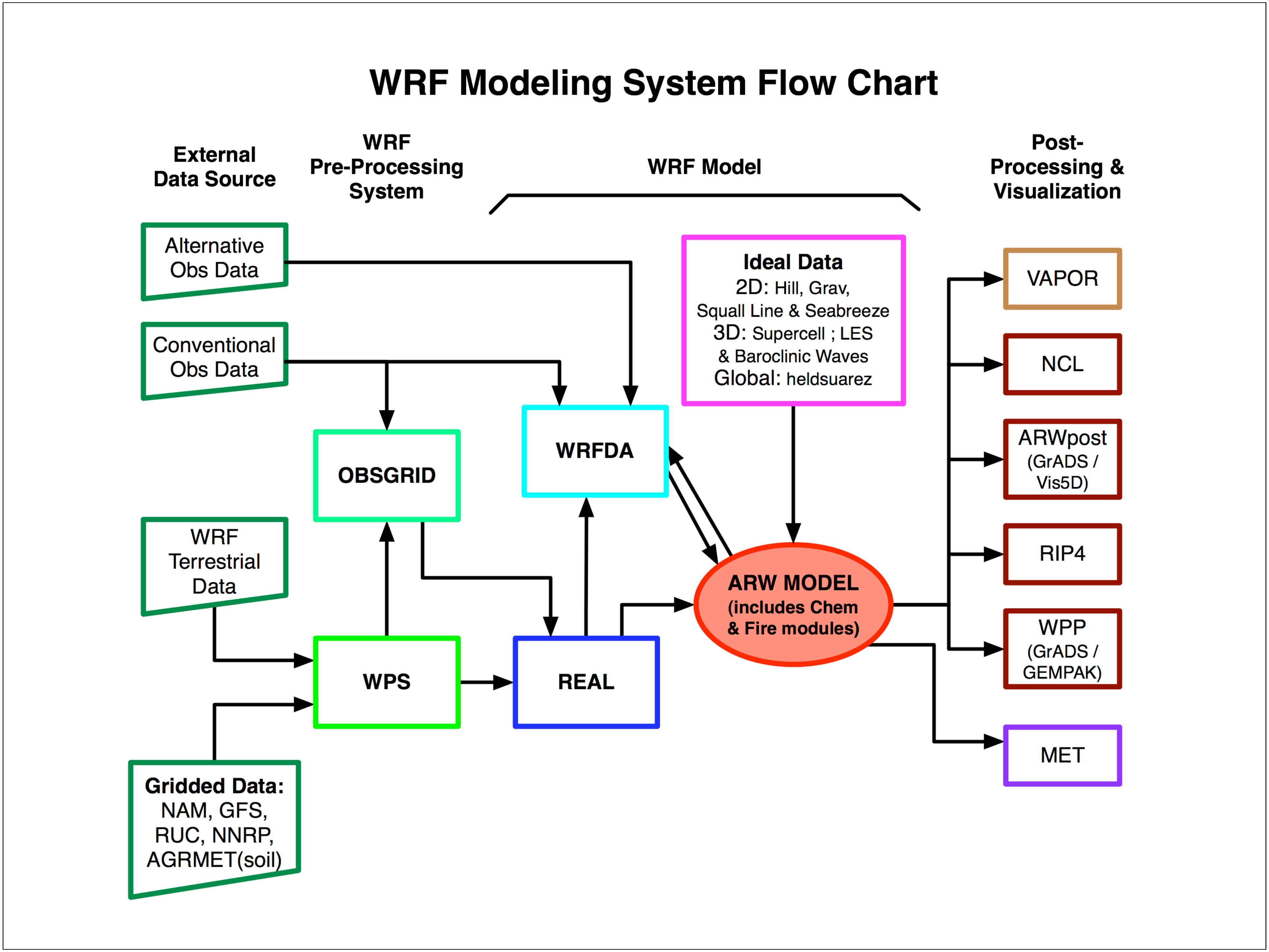
WRF Community Model

- 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 3.7: April 2015
    - Version 3.7.1: August 2015
- Version 3.8: April 2016
    - Version 3.8.1 (current 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)

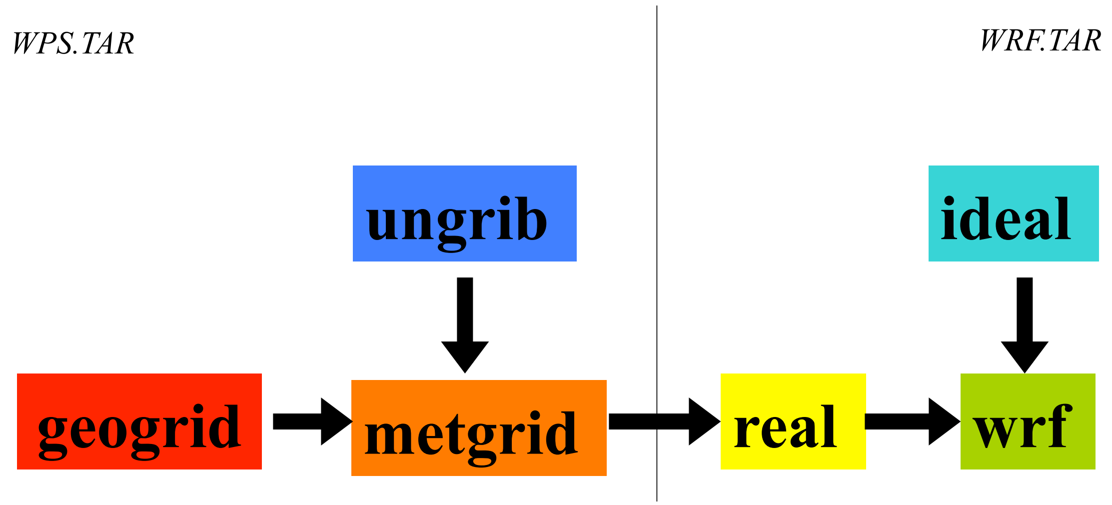


WRF Modeling System Flow Chart
External Data Source
WRF Pre-Processing System
WRF Model
Post-Processing & Visualization
Alternative Obs Data
Conventional Obs Data
Ideal Data
2D: Hill, Grav, Squall Line & Seabreeze
3D: Supercell ; LES & Baroclinic Waves
Global: heldsuarez
VAPOR
NCL
ARWpost (GrADS / Vis5D)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

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

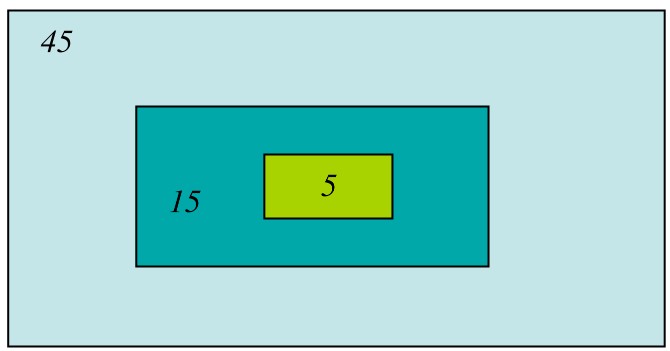
Real-Data Applications

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

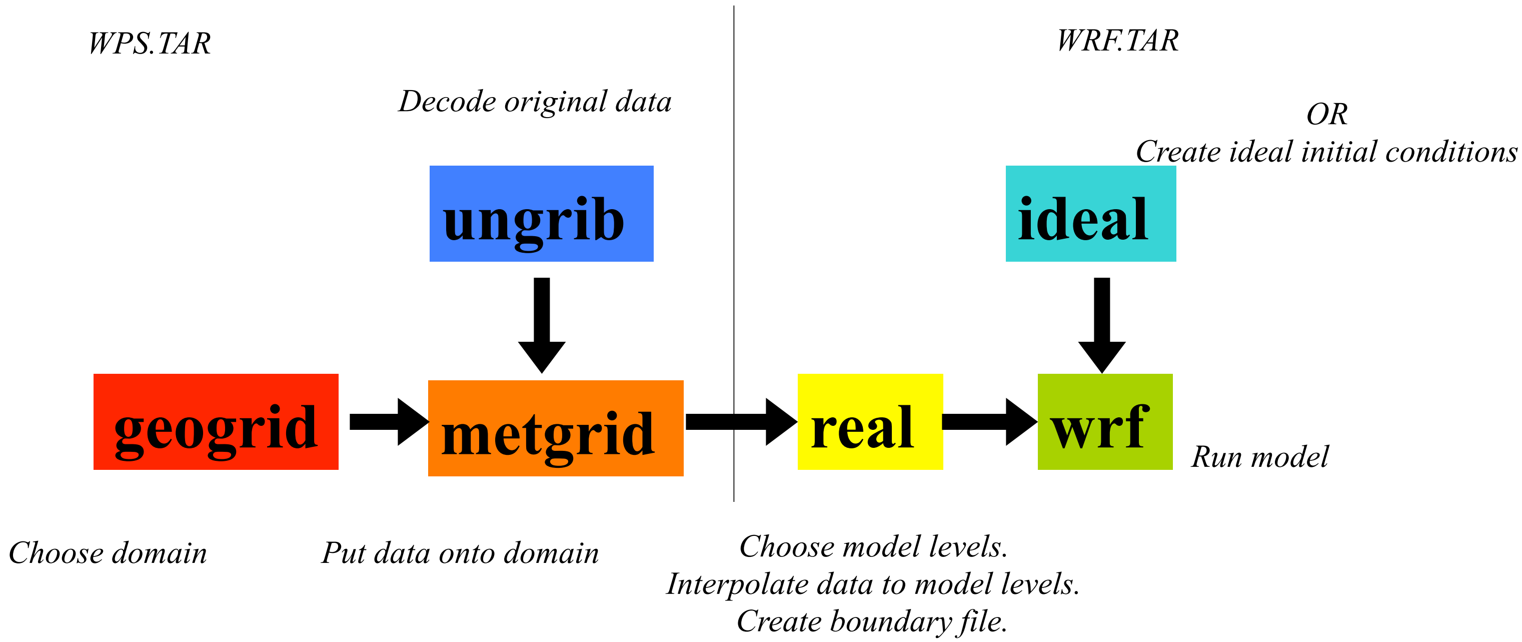
WPS Functions

- 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)

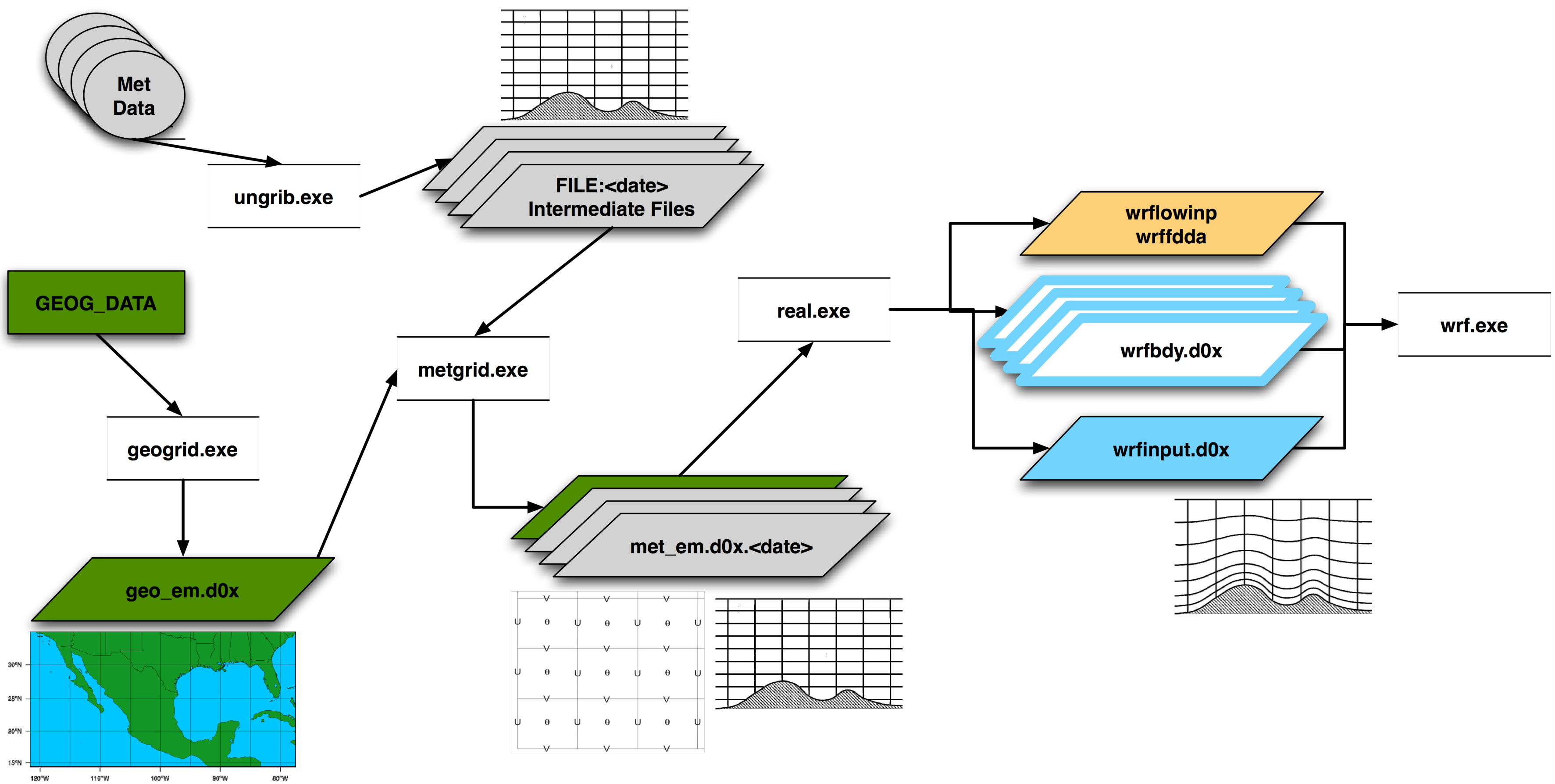
WPS Data

- 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



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

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

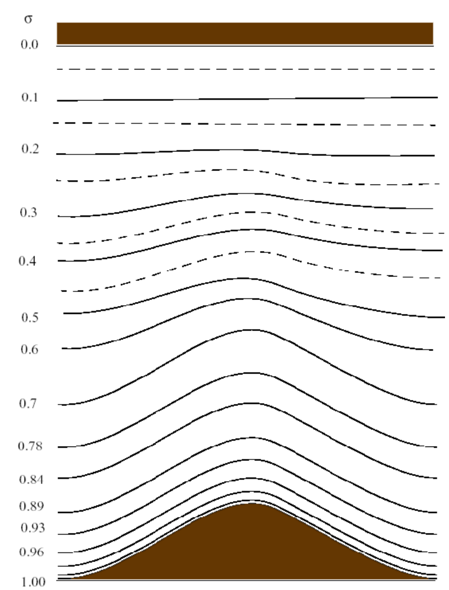
Key features:

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

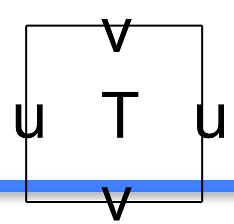
$$\eta = \frac{(\pi - \pi_t)}{\mu}, \qquad \mu = \pi_s - \pi_t$$

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

Graphics and Verification Tools

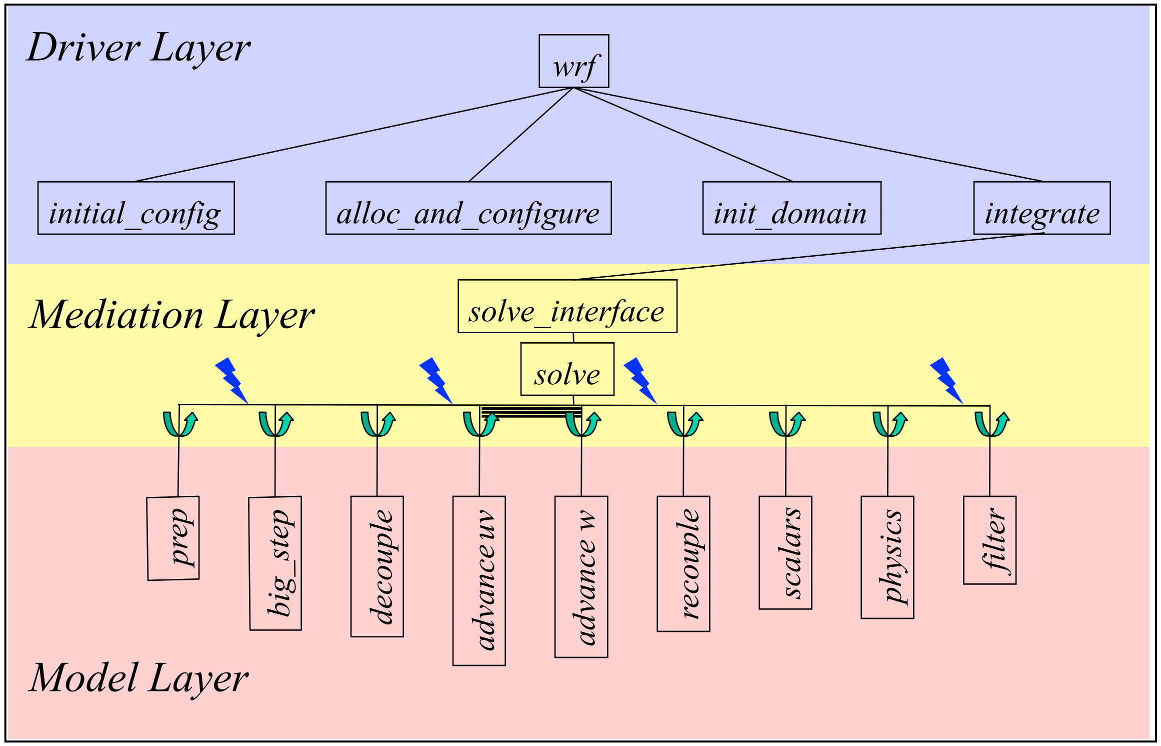
- ARW and NMM
  - RIP4 (Read, Interpolate and Plot)
  - Unified Post-Processor (UPP)
    - Conversion to GriB (for GrADS and GEMPAK)
  - MET (Model Evaluation Toolkit)
- ARW
  - NCAR Graphics Command Language (NCL)
  - ARWpost
    - Conversion program for GrADS
  - VAPOR (3D visualization tool)
  - IDV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

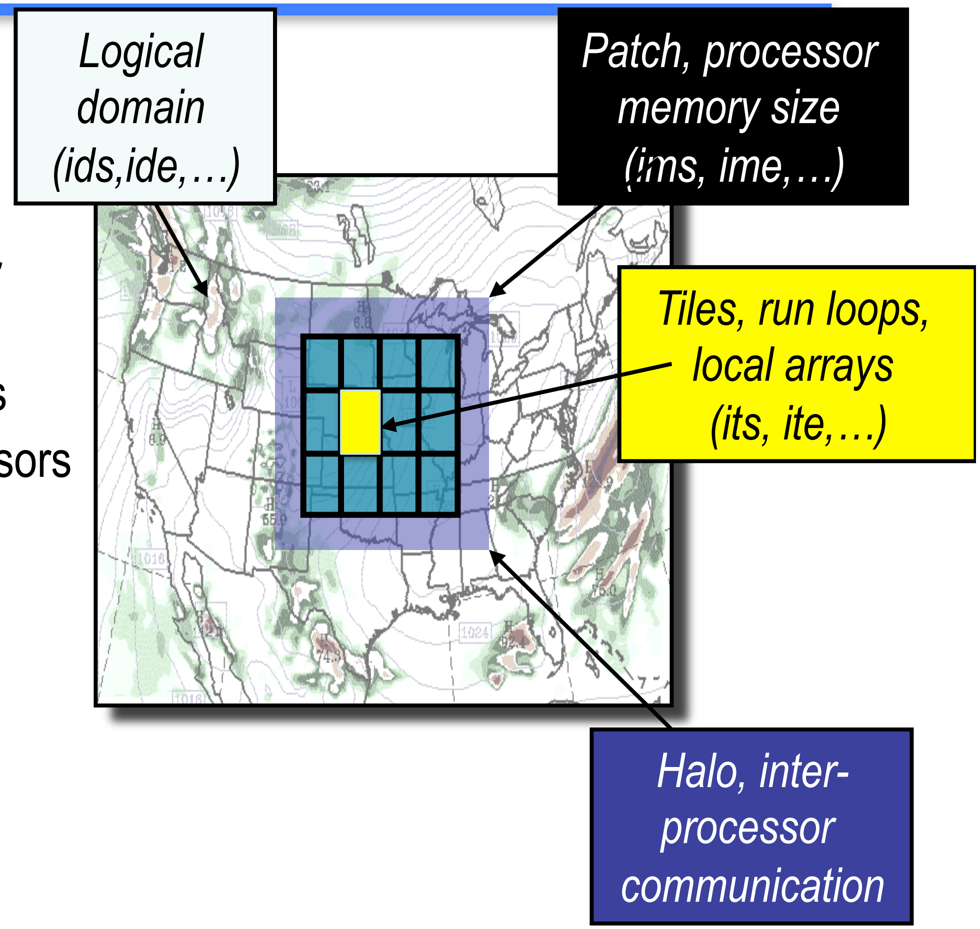
WRF Hierarchical Software Architecture

- 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

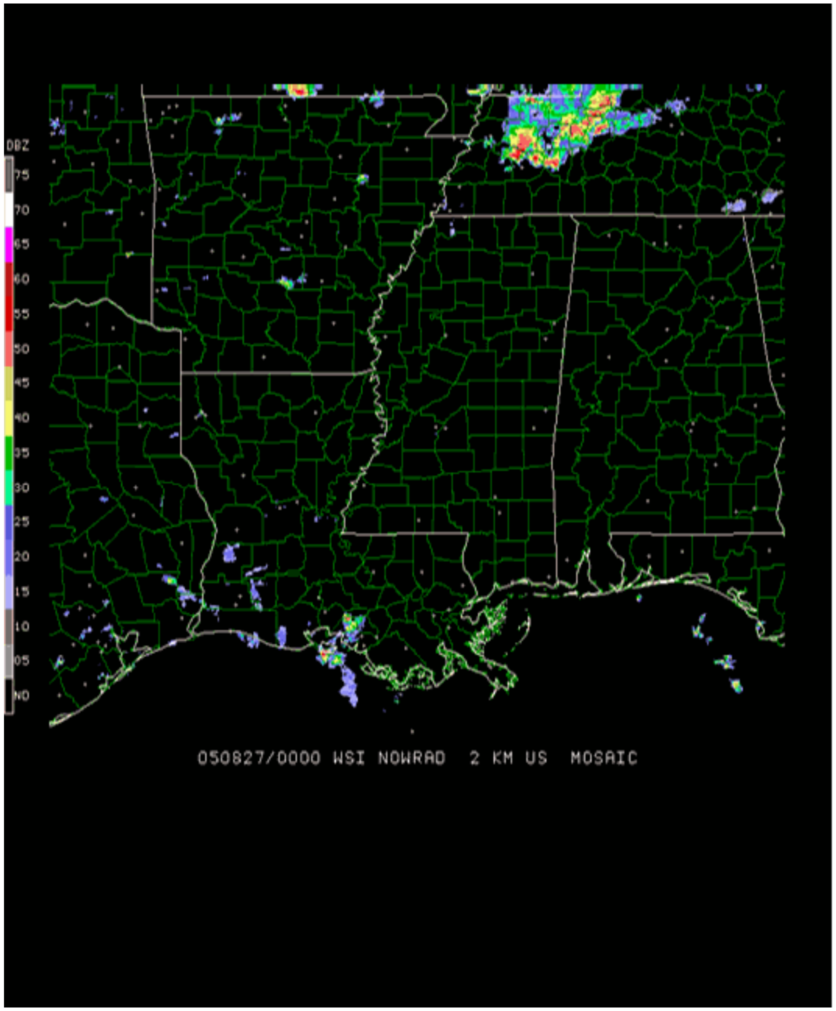
(1) Hurricane Katrina (August, 2005)

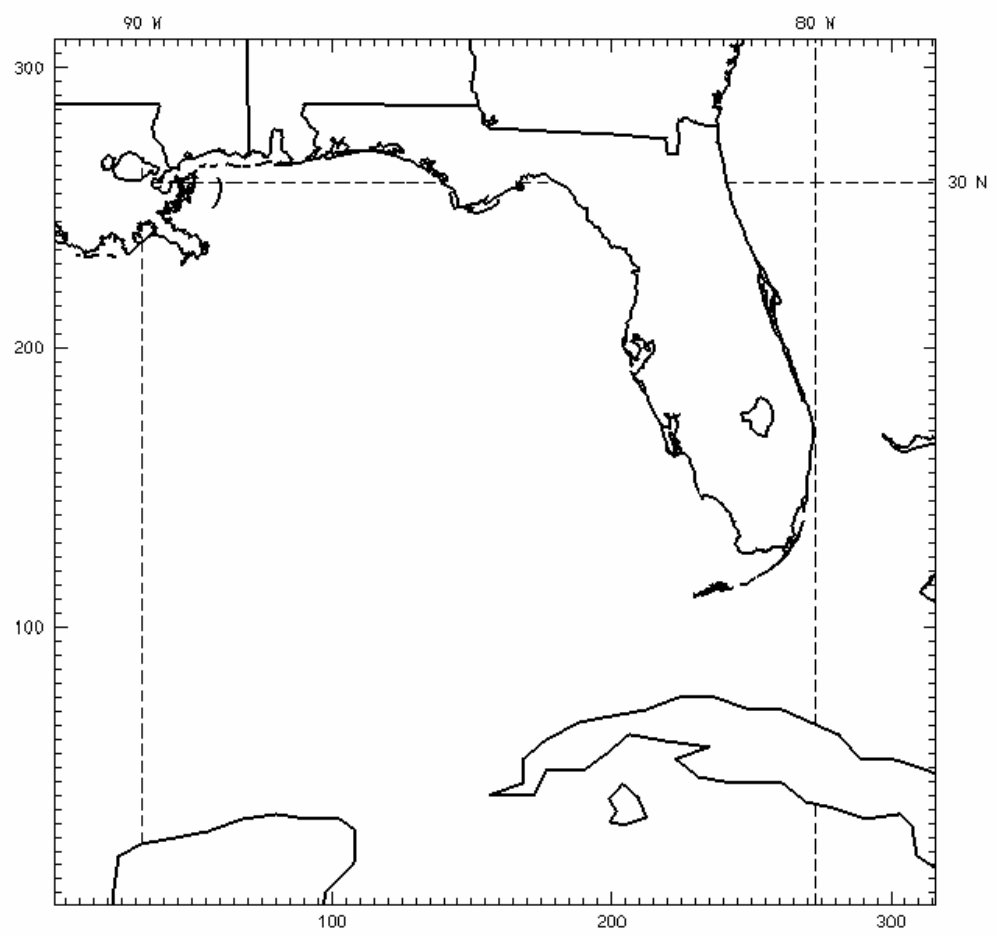
- Moving 4 km nest in a 12 km outer domain

(2) US Convective System (June, 2005)

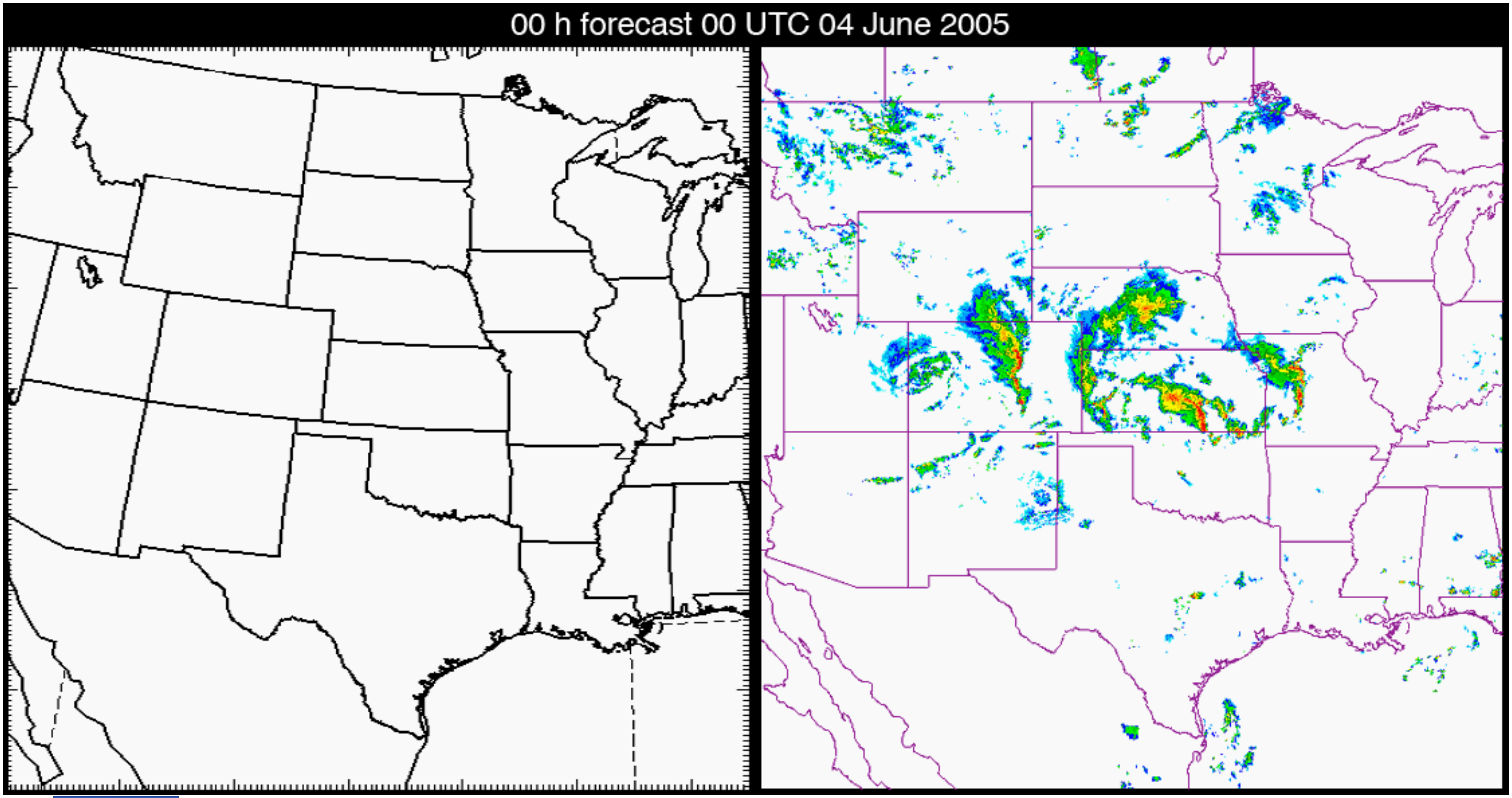
- Single 4 km central US domain

ARW Hurricane Katrina Simulation (4km)





ARW Convective-scale Forecasting (4km)



Mesoscale & Microscale Meteorology Laboratory / NCAR