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

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

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 (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)
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 \textit{specified} boundary conditions from \texttt{wrfbdy} file
- \textit{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 $t+\Delta t$
  - Nest boundaries from beginning and end of time-step interpolated
  - Nest runs typically three steps ($\Delta t/3$) using time-interpolated parent info at nest boundaries
  - After nest reaches $t+\Delta t$, feedback overwrites parent in overlapped region
  - Repeat

One-Way Nesting

- As two-way nesting but no feedback
- Can also be done with \texttt{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, landuse, 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

1. Decode original data (using ungrib)
2. Choose domain (geogrid)
3. Put data onto domain (metgrid)
4. Choose model levels, interpolate data to model levels, create boundary file (real)
5. Run model (wrf)
6. OR
   - Create ideal initial conditions

Data Flow

- Input data (grids, observations)
- Process data (geogrid, metgrid)
- Create boundary file
- Run model
- Output data
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, $\eta$
  \[ \eta = \frac{\pi - \pi_i}{\mu} \]
  \[ \mu = \pi - \pi_i \]
  where $\pi$ is hydrostatic pressure, $\mu$ 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:
    - 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)