Weather Research and Forecasting Model

Melissa Goering       Glen Sampson
ATMO 595E
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Outline

• What does WRF model do?
• WRF Standard Initialization
• WRF Dynamics
  – Conservation Equations
  – Grid staggering
  – Time integration
  – Boundary conditions
• WRF Physics Options
  – Turbulence/Diffusion
  – Radiation
  – Surface
  – PBL
  – Cumulus parameterization
  – Microphysics
• Testing, Verification, and Computational Efficiency
What does WRF model do?

• Developed by:
  NCAR/MMM and NOAA/FSL with partnership at NCEP, AFWA, FAA, NRL and collaborations with other universities.

• Latest version: WRF version 2.0

• Developed for:
  – Idealized simulations (convection, baroclinic waves, large eddy simulations)
  – Parameterization research
  – Data assimilation research
  – Forecast research
  – Real-time NWP
  – Coupled-model applications
WRF Standard Initialization

- Provides all required initial and time-varying boundary conditions
- De-grib GRIB files for meteorological data
- Provides method to define and localize WRF domain, nests, and subnests
- Produces terrain, landuse, etc on domain:
  - USGS 30 sec (~1km) topography
  - USGS 24 category landuse
  - WMO/FAO 16 category 2-layer soil types
  - Annual mean deep soil temperatures
  - Monthly greenness fraction
  - Albedo
  - Terrain slope index
  - Max Snow Albedo
User Hints & Information

- Create new domain: test

Variables are used as input to grigen_model, check paths to geographical files.
See documentation on parameters SILAWWT_PARM_WRF and TOPTWVL_PARM_WRF.
User Hints & Information

- Create new domain: test
- Initial Data - controls the execution of grib_prep which decodes GRIB files.
WRF Dynamics

- Terrain Representation
- Vertical Coordinate
- Grid Staggering
- Time integration scheme
- Conservation Equations
- Advection Scheme
- Boundary conditions
Terrain Representation

- Lower boundary condition for geopotential specifies the terrain elevation

Vertical Coordinate

- Hydrostatic pressure
- Vertical resolution set by user in WRFSI (default: 31 levels)
- Can choose option for vertical interpolation (log, linear, square root)
Grid Staggering

- C grid spacing

Time-split Leap Frog and Runge-Kutta scheme

- 3rd order RK generally stable using timestep twice as large in leapfrog model
- Courant number limited to
  \[ C_r = \frac{U \Delta t}{\Delta x} < 1.73 \]
• RK3 method excellent scheme for integrating the compressible equations and is ideal candidate for NWP

• RK3 best combination of accuracy and simplicity

<table>
<thead>
<tr>
<th>Time scheme</th>
<th>3rd</th>
<th>4th</th>
<th>5th</th>
<th>6th</th>
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<tbody>
<tr>
<td>Leapfrog</td>
<td>U</td>
<td>0.72</td>
<td>U</td>
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<tr>
<td>RK2</td>
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<td>U</td>
<td>0.30</td>
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<tr>
<td>RK3</td>
<td>1.61</td>
<td>1.26</td>
<td>1.42</td>
<td>1.08</td>
</tr>
</tbody>
</table>

**TABLE 1. Maximum stable Courant number for one-dimensional linear advection. Here, U indicates the scheme is unstable.**

**Fig. 1.** One-dimensional advection tests for RK3 and leapfrog integration schemes using (a) 4th, (b) 5th, and (c) 6th order spatial discretization schemes. TRER errors for each solution are listed at the top of each box. Unless otherwise noted, the Courant number equals 0.4.
Advection equation analysis

$$\phi_t = U \phi_x$$

5\textsuperscript{th} and 6\textsuperscript{th} order upwind-biased and centered schemes. Analysis for $4\Delta x$ wave.
Phase and Amplitude errors for LF and RK3

Oscillation equation analysis

\[ \phi_t = i k \phi \]
Conservation Equations Mass Coordinate (Flux)

\[ \frac{\partial U}{\partial t} + u \frac{\partial p}{\partial x} + \frac{\partial p}{\partial \eta} \frac{\partial \phi}{\partial x} = - \frac{\partial U u}{\partial x} - \frac{\partial \Omega u}{\partial \eta} \]

\[ \frac{\partial W}{\partial t} + g \left( \mu - \frac{\partial p}{\partial \eta} \right) = - \frac{\partial U w}{\partial x} - \frac{\partial \Omega w}{\partial \eta} \]

\[ \frac{\partial \Theta}{\partial t} + \frac{\partial U \Theta}{\partial x} + \frac{\partial \Omega \Theta}{\partial \eta} = \mu Q \]

\[ \frac{\partial \mu}{\partial t} + \frac{\partial U}{\partial x} + \frac{\partial \Omega}{\partial \eta} = 0 \]

\[ \text{geopotential (} \phi = gz) \quad \frac{d\phi}{dt} = gw \]

Hydrostatic pressure

\[ \frac{\partial \phi}{\partial \eta} = -u \alpha, \quad p = \left( \frac{R \Theta}{p_0 \alpha} \right)^r, \quad \Omega = \mu \eta \]

Momentum

Heat

Continuity

Diagnostic Relations

Ideal Gas Law
Conservation Equation Height Coordinates (Flux)

\[ U = \rho u, \quad V = \rho v, \quad W = \rho w, \quad \Theta = \rho \theta \]

\[ \frac{\partial U}{\partial t} + \gamma R \pi \frac{\partial \Theta}{\partial x} - fV = - \frac{\partial U}{\partial x} - \frac{\partial W}{\partial z} \]

\[ \frac{\partial W}{\partial t} + \gamma R \pi \frac{\partial \Theta}{\partial z} + g \rho = - \frac{\partial W}{\partial x} - \frac{\partial W}{\partial z} \]

\[ \frac{\partial \Theta}{\partial t} + \frac{\partial U \Theta}{\partial x} + \frac{\partial W \Theta}{\partial z} = \rho Q \]

\[ \frac{\partial \rho}{\partial t} + \frac{\partial U}{\partial x} + \frac{\partial W}{\partial z} = 0 \]

\[ \gamma R \pi \nabla \Theta = c_p \Theta \nabla \pi = \nabla p \]
Moist Equations

Momentum

\[
\frac{\partial U}{\partial t} + \alpha \mu_d \frac{\partial p}{\partial x} + \frac{\alpha}{\alpha_d} \frac{\partial p}{\partial \eta} \frac{\partial \phi}{\partial x} = - \frac{\partial U u}{\partial x} - \frac{\partial \Omega u}{\partial \eta}
\]

\[
\frac{\partial W}{\partial t} + g \left( \mu_d - \frac{\alpha}{\alpha_d} \frac{\partial p}{\partial \eta} \right) = - \frac{\partial U w}{\partial x} - \frac{\partial \Omega w}{\partial \eta}
\]

\[
\frac{\partial \mu_d}{\partial t} + \frac{\partial U}{\partial x} + \frac{\partial \Omega}{\partial \eta} = 0
\]

\[
\frac{\partial (\mu_d q_{v,l})}{\partial t} + \frac{\partial U q_{v,l}}{\partial x} + \frac{\partial \Omega q_{v,l}}{\partial \eta} = \mu_d Q_{v,l}
\]

Continuity

Heat

Diagnostic Relations

Hydrostatic Pressure

\[
\frac{\partial \phi}{\partial \eta} = -\alpha_d \mu_d, \quad p = \left( \frac{R \Theta}{P_0 \mu_d \alpha_v} \right)^{y}
\]

Ideal Gas Law
Advection

- 2nd, 3rd, 4th, 5th, and 6th order centered and upwind biased schemes

Example: 5th order scheme

\[
\frac{\partial (U \phi)}{\partial x} = \frac{1}{\Delta x} \left( F_{i+\frac{1}{2}} (U \phi) - F_{i-\frac{1}{2}} (U \phi) \right)
\]

where

\[
F_{i-\frac{1}{2}} (U \phi) = U_{i-\frac{1}{2}} \left\{ \frac{37}{60} (\phi_i + \phi_{i-1}) - \frac{2}{15} (\phi_{i+1} + \phi_{i-2}) + \frac{1}{60} (\phi_{i+2} + \phi_{i-3}) \right\}
\]

\[- \text{sign}(1,U) \frac{1}{60} \left\{ (\phi_{i+2} - \phi_{i-3}) - 5(\phi_{i+1} - \phi_{i-2}) + 10(\phi_i - \phi_{i-1}) \right\}
\]

For constant U

\[
\Delta t \frac{\delta (U \phi)}{\Delta x} \bigg|_{5th} = \Delta t \frac{\delta (U \phi)}{\Delta x} \bigg|_{6th} - \left| \frac{U \Delta t}{\Delta x} \right| \frac{1}{60} \left( -\phi_{i-3} + 6\phi_{i-2} - 15\phi_{i-1} + 20\phi_i - 15\phi_{i+1} + 6\phi_{i+2} - \phi_{i+3} \right)
\]

\[
\frac{C_r}{60} \frac{\partial^6 \phi}{\partial x^6} + H.O.T
\]
Boundary Conditions

Top
1. Constant pressure
2. Absorbing upper layer (increased horizontal diffusion)

Bottom
1. Free Slip
2. Variety BL implementations on surface drag and fluxes

Lateral
1. Specified
2. Open (perturbations can pass into/out of model domain)
3. Symmetric
4. Periodic (values of dependent variables are assumed identically equal to values of another boundary)
5. Nested
WRF Physics

- Subgrid Eddy diffusion
- PBL
- Cumulus parameterization
- Radiation
- Microphysics
- Surface
Parameterizations Interactions

Direct Interactions of Parameterizations

- **Microphysics**
  - Cloud effects
  - Cloud detrainment

- **Cumulus**
  - Cloud fraction

- **Radiation**
  - Surface fluxes (SH, LH)
  - Downward (SW, LW)
  - Surface emission/albedo

- **Surface**
  - Surface T, Qv, wind

- **PBL**
  - Surface T, Qv, wind
• It appears that the physic options are done within each RK loop EXCEPT the microphysics

• Microphysics:
  – Heat/moisture tendencies
  – Microphysics rates
  – Surface rainfall

```
Begin time step

Runge-Kutta loop (steps 1, 2, and 3)
  (i) advection, p-grad, buoyancy using \((\phi^, \phi^*, \phi^{**})\)
  (ii) physics if step 1, save for steps 2 and 3
  (iii) mixing, other non-RK dynamics, save...
  (iv) assemble dynamics tendencies

Acoustic step loop
  (i) advance U,V, then \(\mu, \Theta\), then w, \(\phi\)
  (ii) time-average U,V, \(\Omega\)

End acoustic loop
Advance scalars using time-averaged U,V, \(\Omega\)

End Runge-Kutta loop
Adjustment physics (currently microphysics)

End time step
```
<table>
<thead>
<tr>
<th>Physics</th>
<th>Options</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subgrid eddy diffusion</td>
<td>• Constant diffusion</td>
<td>• Const khdif and kvdif</td>
</tr>
<tr>
<td></td>
<td>• Level 2.5 TKE</td>
<td>• Based on K</td>
</tr>
<tr>
<td></td>
<td>• Stress/deformation Smagorinsky</td>
<td>• Based on horiz wind for horiz diffusion only</td>
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<tr>
<td></td>
<td>• 2D Horizontal Smagorinsky</td>
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<tr>
<td>Boundary Layer*</td>
<td>• YSU</td>
<td>• Non-local K mixing in dry convective BL, vertical diffusion depends on Ri</td>
</tr>
<tr>
<td></td>
<td>• MRF</td>
<td>• 1.5 order, level 2.5, TKE prediction with Local K vertical mixing</td>
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<tr>
<td></td>
<td>• Mellor-Yamada-Janjic (Eta)</td>
<td></td>
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<tr>
<td>* Includes surface similarity</td>
<td></td>
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<tr>
<td>theory</td>
<td></td>
<td></td>
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<tr>
<td>Convective parameter.</td>
<td>• new Kain-Fritsch</td>
<td>• shallow convect, mass flux up/down draft</td>
</tr>
<tr>
<td></td>
<td>• Betts-Miller-Janjic (Eta)</td>
<td>• no explicit up/downdraft</td>
</tr>
<tr>
<td></td>
<td>• Grell Ensemble</td>
<td>• multiple closure and parameter, explicit up/downdraft</td>
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</table>

* Includes surface similarity theory
<table>
<thead>
<tr>
<th>Physics</th>
<th>Options</th>
<th>Comments</th>
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<tr>
<td>Longwave Radiation</td>
<td>• RRTM (MM5)</td>
<td>• Spectral scheme with K distribution and a look up table</td>
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<td></td>
<td>• Eta (GFDL)</td>
<td>• Spectral scheme from global model used in Eta</td>
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<td>Shortwave Radiation</td>
<td>• Dudhia (MM5)</td>
<td>• Simple downward calculation, clear scattering</td>
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<td>• Goddard</td>
<td>• Spectral method</td>
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<tr>
<td></td>
<td>• Eta (GFDL)</td>
<td>• Used in Eta, ozone effects and interacts with clouds</td>
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<tr>
<td>Land-Surface</td>
<td>• 5 layer thermal diffusion</td>
<td>• layers 1,2,4,8,and 16 cm thick</td>
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<td>• NOAH Land Surface</td>
<td>• soil temp and moisture 4 layers</td>
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<tr>
<td></td>
<td>• RUC Land Surface</td>
<td>• soil temp and moisture 6 layers</td>
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<td>Micro-physics</td>
<td>• Kessler</td>
<td>• warm rain, no ice, idealized</td>
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<tr>
<td></td>
<td>• Lin et al.</td>
<td>• 5 class including graupel</td>
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<tr>
<td></td>
<td>• WSM3</td>
<td>• 3 class with ice, ice processes</td>
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<tr>
<td></td>
<td>• WSM5</td>
<td>• 5 class with ice, supercooled H₂O</td>
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<td>• Eta (Ferrier)</td>
<td>• one prognostic total condensate</td>
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<td>• WSM6</td>
<td>• 6 class with graupel</td>
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</tbody>
</table>
Testing and Verification

- Simulations run to target specific facets of research or forecasting.
Testing and Verification

Height Coordinate

Mass Coordinate

5 min

10 min

15 min
Testing and Verification

a = 1 km, dx = 200 m

a = 100 km, dx = 20 km

- Height Coordinate
- Mass Coordinate
Verification

Weisman et al.

- Although the 4 km is typically minimum grid resolution, there was significant improvement in representing the system scale structure for larger convective systems.
- Isolated convective outbreaks were not as well represented.
- During International H2O project (IHOP)
Verification

Baldwind and Wandishin

- Found that WRF reproduced the observed spectra much better than higher resolution Eta
- 10 km WRF model forecast maintains the variance in precip field down to at least 4 times grid spacing (40km)
- Variance of Eta drops off sooner and at greater than 10 times grid spacing

3 hr accumulated precipitation valid at 18Z from 12Z 4 June 2002 model run.
Computational Efficiency

Michalakes et al.

- WRF is more costly in terms of time-per-time step
- BUT the RK3 allows for considerably longer time step (200sec WRF vs. 81sec MM5)
- Time-to-solution performance for WRF slightly better than MM5
- Authors feel this will improve with tuning and optimization

36km resolution on a 136 x 112 x 33 grid
Summary of WRF

- Fully compressible, non-hydrostatic (with hydrostatic option)
- Eulerian mass/height based terrain following coordinate
- Arakawa C staggering
- Runge-Kutta time integration scheme
- Higher order advections
- Scalar-conserving
- Complete Coriolis and curvature
- Two-way and one-way nesting
- Lateral boundary conditions for ideal or real data
- Full physics options
Questions?

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References

Michalakes et al.: Development of a Next-Generation Regional Weather Research and Forecast Model
http://www.mmm.ucar.edu/mm5/mpp/ecmwf01.htm

Shamarock et al., 2001: Prototypes for the WRF Model


WRF model Users Web site: http://www.wrf-model.org