Numerical Weather Prediction (NWP) and the WRF Model

Jason Knievel

Material contributed by: George Bryan, Jimy Dudhia, Dave Gill, Josh Hacker, Joe Klemp, Bill Skamarock, Wei Wang, and The COMET Program
Q: What is NWP?

A: A method of weather forecasting that employs:
   – A set of equations that describe the flow of fluids,
   – Which is translated into computer code,
   – Combined with parameterizations of other processes,
   – Then applied on a specific domain,
   – And integrated, based on initial conditions and conditions at the domains’ boundaries
Numerical weather prediction

- Almost every step in NWP includes
  - Omissions
  - Estimations
  - Approximations
  - Compromises
Numerical weather prediction

Q: What is NWP?

A: A method of weather forecasting that employs:
   – A set of equations that describe the flow of fluids,
   – Which is translated into computer code,
   – Combined with parameterizations of other processes,
   – Then applied on a specific domain,
   – And integrated, based on initial conditions and conditions at the domains’ boundaries.
Q: What is NWP?

A: A method of weather forecasting that employs:
   – Governing equations
   – Numerical methods
   – Parameterizations
   – Domains
   – Initial and boundary conditions
Q: What is NWP?

A: A method of weather forecasting that employs:
   – Governing equations
   – Numerical methods
   – Parameterizations
   – Domains
   – Initial and boundary conditions
Governing equations

- Conservation of momentum (Newton’s laws)
  - 3 equations for accelerations of 3-d wind \((F = Ma)\)

- Conservation of mass
  - 1 equation for conservation of air (mass continuity)
  - 1 equation for conservation of water

- Conservation of energy
  - 1 equation for the first law of thermodynamics

- Relationship among \(p\), \(V\), and \(T\)
  - 1 equation of state (ideal gas law)
Almost every model uses a slightly different set of equations.

Why?
- Application to different parts of the world
- Focus on different atmospheric processes
- Application to different time and spatial scales
- Ambiguity and uncertainty in formulations
- Tailoring to different uses
The WRF Model is one of the first cloud-scale models designed to conserve mass, momentum, and energy.

But…
- Water is not yet perfectly conserved
- There is still debate about whether momentum is perfectly conserved
- Internal energy is conserved for dry processes, not moist
Governing equations

- An example of one momentum equation: 1-d wind accelerated by only the pressure gradient force

\[
\frac{Du}{Dt} = -\frac{1}{\rho} \frac{\partial p}{\partial x}
\]

Computers cannot deal with even this very simple equation!
Governing equations

- **The problem:** computers can perform arithmetic but not calculus

- **The solution:** numerical methods

\[ \frac{df}{dx} \quad \int f \, dx \]
Q: What is NWP?

A: A method of weather forecasting that employs:
   - Governing equations
   - Numerical methods
   - Parameterizations
   - Domains
   - Initial and boundary conditions
Goal: convert spatial and temporal derivatives into algebraic equations that computers can solve

Examples of methods:
- Finite difference (based on Taylor series)
- Finite volume (based on fluxes in and out of volume)
- Spectral (calculated in Fourier space)
Numerical methods

- WRF Model uses finite differences
- Taylor series:

\[ f(x_i + \Delta x) = f(x_i) + \Delta x \frac{\partial f}{\partial x} \bigg|_{x_i} + \frac{\Delta x^2}{2!} \frac{\partial^2 f}{\partial x^2} \bigg|_{x_i} + \cdots + \frac{\Delta x^n}{n!} \frac{\partial^n f}{\partial x^n} \bigg|_{x_i} \]

Equality only true if series is infinite… an impossibility!

Truncation is always necessary
  - What gets cut (truncation error) defines order of scheme
Numerical methods

- Numerical methods directly affect model output, mostly at small scales

- Some model features are real, but some are due to numerical techniques. In the WRF Model:
  - Larger than 6\( \Delta x \), it may be real
  - Smaller than 6\( \Delta x \), it’s not to be trusted
Numerical methods

- MM5: leapfrog (t) and 2nd-order centered (x)

From George Bryan
Numerical methods

- WRF: Runge-Kutta (t) and 6th-order centered (x)

From George Bryan
Introduction to numerical weather prediction

Q: What is NWP?

A: A method of weather forecasting that employs:
  – Governing equations
  – Numerical methods
  – Parameterizations
  – Domains
  – Initial and boundary conditions
Parameterizations

- Parameterizations approximate the bulk effects of physical processes too small, too brief, too complex, or too poorly understood to be explicitly represented.
In the WRF Model, parameterizations include:
- Cumulus convection
- Microphysics of clouds and precipitation
- Radiation (short-wave and long-wave)
- Turbulence and diffusion
- Planetary boundary layer and surface layer
- Interaction with Earth’s surface

Some of the biggest future improvements in the WRF Model will be in parameterizations
Q: What is NWP?

A: A method of weather forecasting that employs:
   – Governing equations
   – Numerical methods
   – Parameterizations
   – Domains
   – Initial and boundary conditions
Domains

- Number of dimensions
- Degree and kind of structure
- Shape
- Vertical coordinate
- Resolution
Domains

- **Number of dimensions**
  - 1D: Single-column model
  - 2D: Simulation of density current
  - 3D: Simulation of thunderstorm

From Josh Hacker

From Joe Klemp
Domains

- Degree and kind of structure

MM5 and others

WRF and others

From Randall (1994)
Domains

- Degree and kind of structure

Hexagonal

Triangular

From ccrma.standford.edu/~bilbao
Domains

- Degree and kind of structure

Unstructured: Omega Model

From Boybeyi et al. (2001)
Domains

- **Shape**

  Spherical

  ![Spherical domain](From mitgcm.org (2006))

  Flat

  ![Flat domain](From Rife et al. (2004))
Key features of WRF Model

- **Nesting of domains**
  - One-way and two-way communication

Diagram:

- Parent domain
- Nested domain
  - Information flows only to finer grid
  - Information flows both directions between grids
Domains

- Vertical coordinate

Fig. 6-2. Schematic illustrations of (a) rectangular, (b) isobaric, (c) isentropic, and (d) sigma coordinate representations as viewed in a rectangular coordinate framework.

From Pielke (2002)
Domains

- Vertical coordinate

In WRF Model, vertical coordinate is normalized hydrostatic pressure, \( \eta \)

From Wei Wang
Domains

- Resolution

RTFDDA terrain elevation on different domains

\[ \Delta x = 30 \text{ km} \]  
\[ \Delta x = 3.3 \text{ km} \]

From Rife and Davis (2005)
Introduction to numerical weather prediction

Q: What is NWP?

A: A method of weather forecasting that employs:
   – Governing equations
   – Numerical methods
   – Parameterizations
   – Domains
   – Initial and boundary conditions
Initial conditions define the atmosphere’s current state…the starting point

Boundary conditions define the atmosphere’s state at domains’ edges
Initial and boundary conditions

- **Idealized lateral boundary conditions**
  - Open
  - Rigid
  - Periodic

- **Operational lateral boundary conditions**
  - Generally updated during simulations
  - Not needed for global models, only for limited-area models (LAMs), such as RTFDDA
  - Can come from larger domains of same/different model or from global model
    - For RTFDDA, source is NAM (was Eta, now NMM-WRF)
Introduction to WRF Model

- **Weather Research and Forecasting Model**

- The term *WRF Model* does not mean the same thing to all people

- Different WRF Models with same architecture but different core codes
  - ARW (Advanced Research WRF) at NCAR
  - NMM (Non-Hydrostatic Mesoscale Model) at NCEP
    - Based on Eta Model’s code
    - Is now the source of NAM simulations
  - Other cores may be coming soon
Architecture of WRF Model

- Based on an innovative software architecture that makes it easy for users to contribute and modify code

- **DRIVER**
  - Manages execution over nested grids
  - Controls input/output
  - Top-level control over parallel processing

- **MEDIATOR**
  - Makes calls to parallel mechanisms

- **MODEL**
  - Contains numerics and physics
  - Performs model computations
The WRF Model is replacing MM5 as the forecast engine in RT-FDDA
- MM5-RTFDDA will be run in parallel as back-up

MM5 will not be turned off until ATEC is ready, or until maintenance becomes impossible
WRF Model is young

Releases
- 2000: V1.0 (beta release of EH core)
- 2002: V1.2 (beta release of EM core)
- 2004: V2.0 (first official release)

Current version: 2.1 (released in August 2005)

Version 2.2 is scheduled for later this summer
Importance of age

- WRF Model is based on more recent technology and techniques

- *But…* The WRF Model has not benefited from many years of trouble-shooting and input from users
Grand vision for WRF Model

- From the start, WRF was intended to be used for both research and operations
  - Shorten time between research developments in NWP and application to operations
  - Increase communication and understanding between research and operational communities

- MM5 started as a research model and was later adopted by some operational forecasters
Platforms for WRF Model

- Can be run on a variety of platforms on single processor or with shared or distributed memory
The WRF Model’s numerics are higher order than MM5’s, so they contain more terms and better approximate the governing equations:

- Horizontal advection: 5\textsuperscript{th} order
- Vertical advection: 3\textsuperscript{rd} order
- Temporal integration: 3\textsuperscript{rd} order
Higher order advection schemes, which lead to a higher effective resolution than in many other NWP models.
• Numerical weather prediction models are:
  – Powerful and useful
  – Founded on basic physics
  – The result of many compromises and approximations
  – Always wrong — at least a little…this includes the WRF Model

• The WRF Model is state-of-the-art in operational mesoscale NWP
Additional reading


- [WRF Tutorial presentations in PPT and PDF](http://www.mmm.ucar.edu/wrf/users/supports/tutorial.html)

- [WRF technical paper](http://www.mmm.ucar.edu/wrf/users/pub-doc.html)