Numerical Weather Prediction (NWP) and the WRF Model

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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

Numerical weather prediction

- Almost every step in NWP includes
  - Omissions
  - Estimations
  - Approximations
  - Compromises

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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)

Governing equations

- 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

Governing equations

- 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

- <u>The problem:</u> computers can perform arithmetic but not calculus

✓ $+ \quad - \quad \times \quad \div$

✗ $\frac{d(f)}{dx} \quad \int (f)dx$

- <u>The solution:</u> numerical methods

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Numerical methods

- 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:

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

Equality only true if series is infinite… an impossibility!

Truncation is always necessary

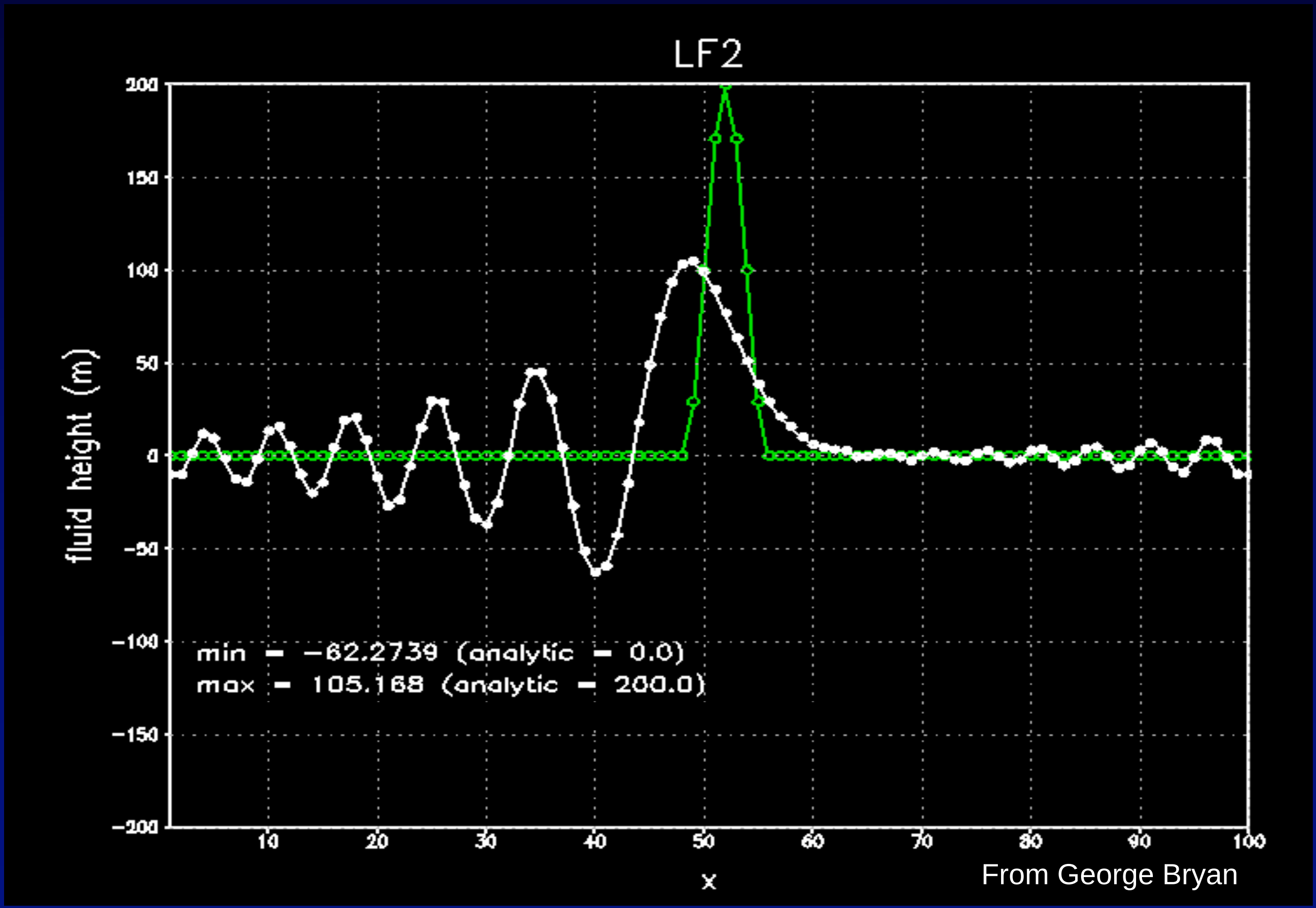
- – What gets cut (truncation error) defines order of scheme

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 6Δx, it may be real
  - Smaller than 6Δx, it's not to be trusted

Numerical methods

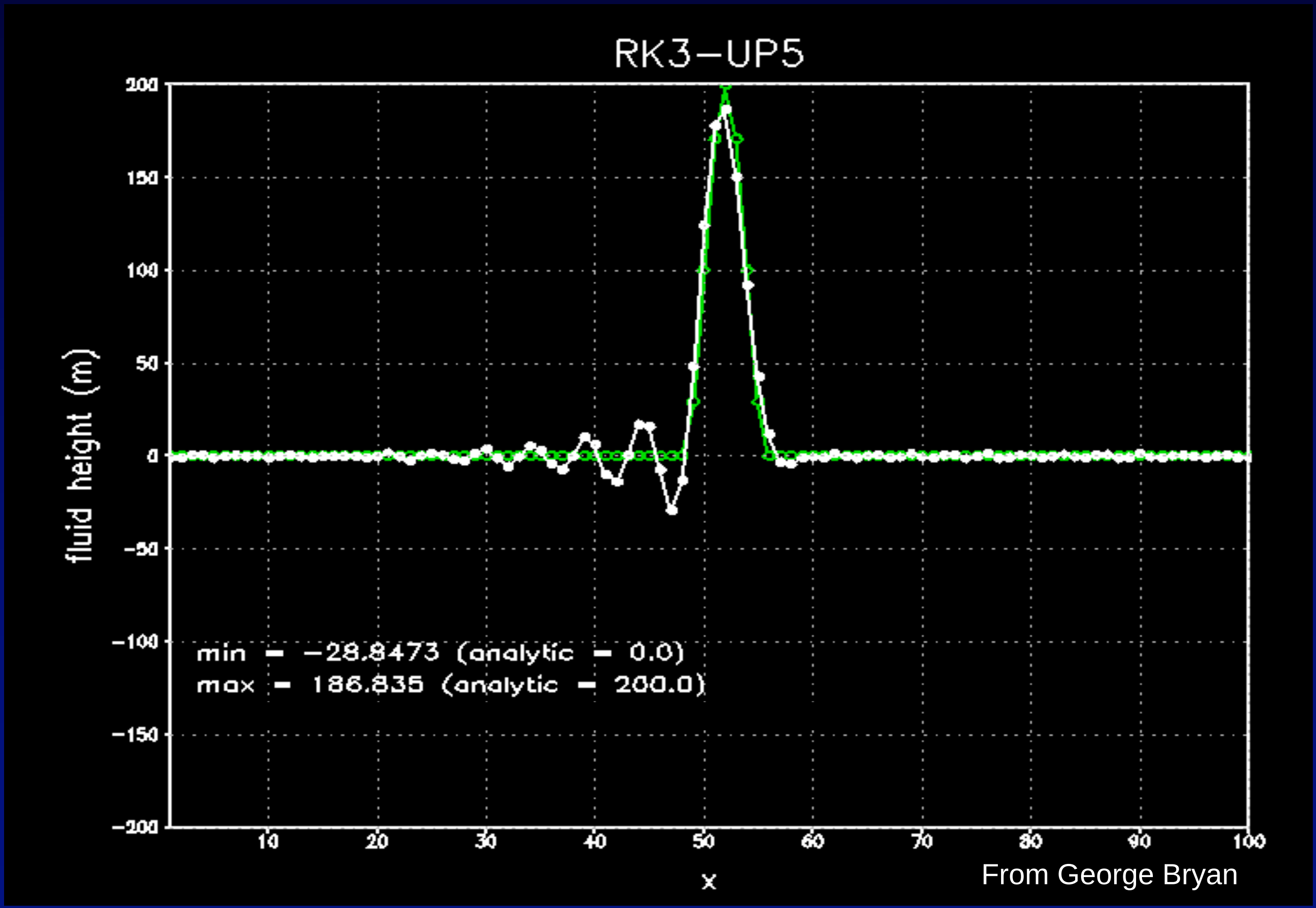
- MM5: leapfrog (t) and 2nd-order centered (x)



From George Bryan

Numerical methods

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



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Introduction to numerical weather prediction

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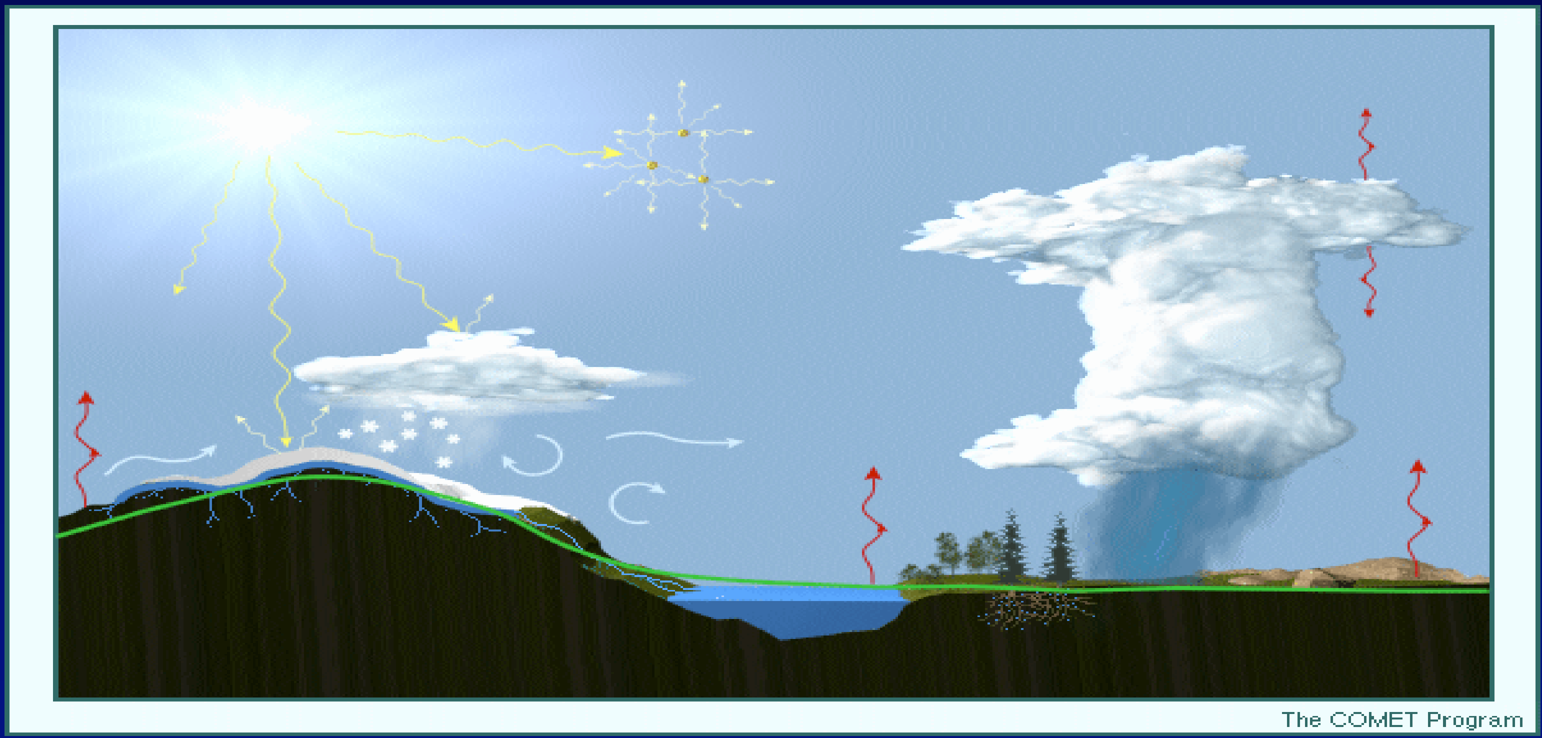
Parameterizations

- Parameterizations approximate the bulk effects of physical processes too small, too brief, too complex, or too poorly understood to be explicitly represented



Parameterizations

- 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

Introduction to numerical weather prediction

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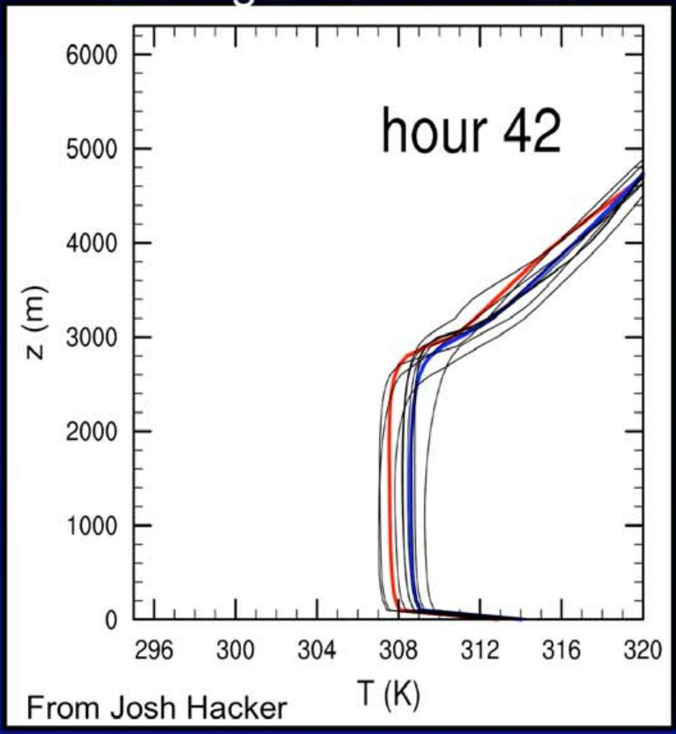
Domains

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

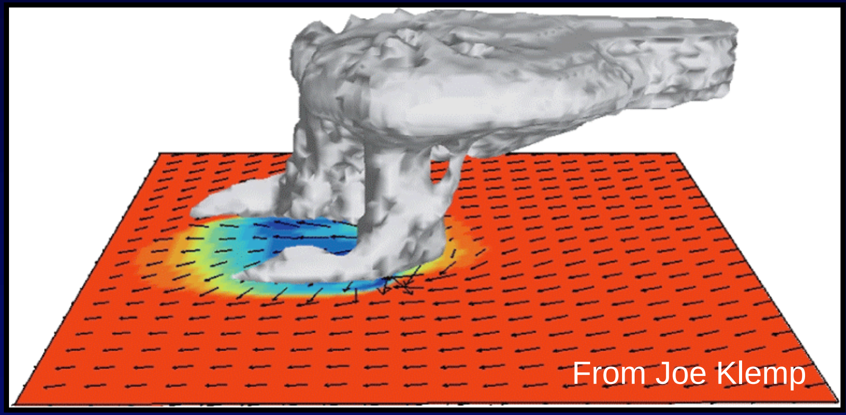
Domains

- Number of dimensions

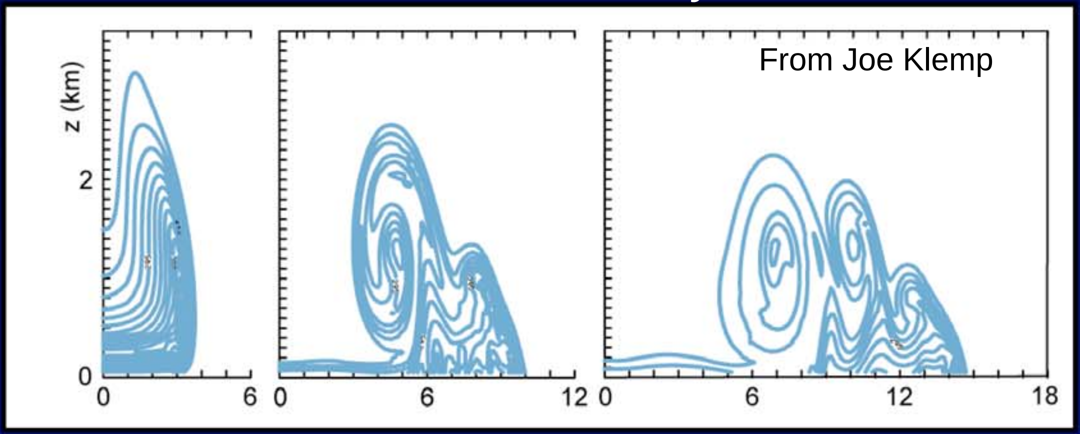
1D: Single-column model



3D: Simulation of thunderstorm

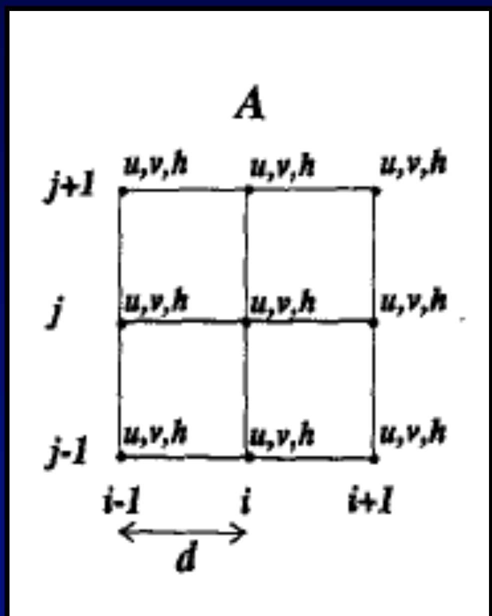


2D: Simulation of density current

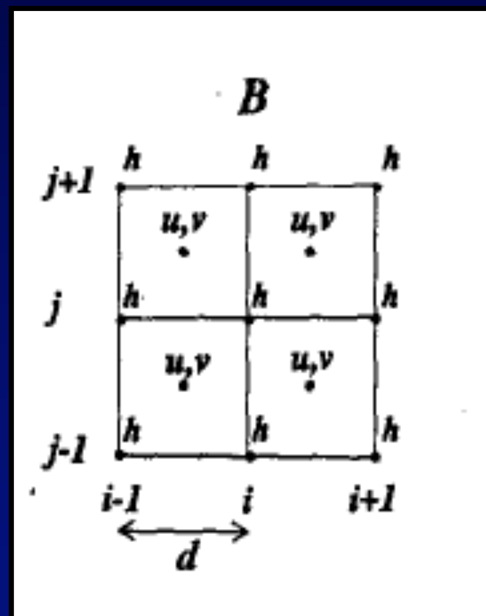


Domains

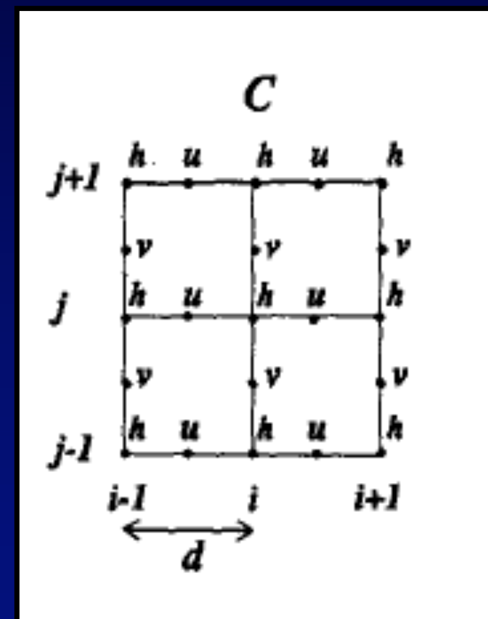
- Degree and kind of structure



MM5 and others



WRF and others

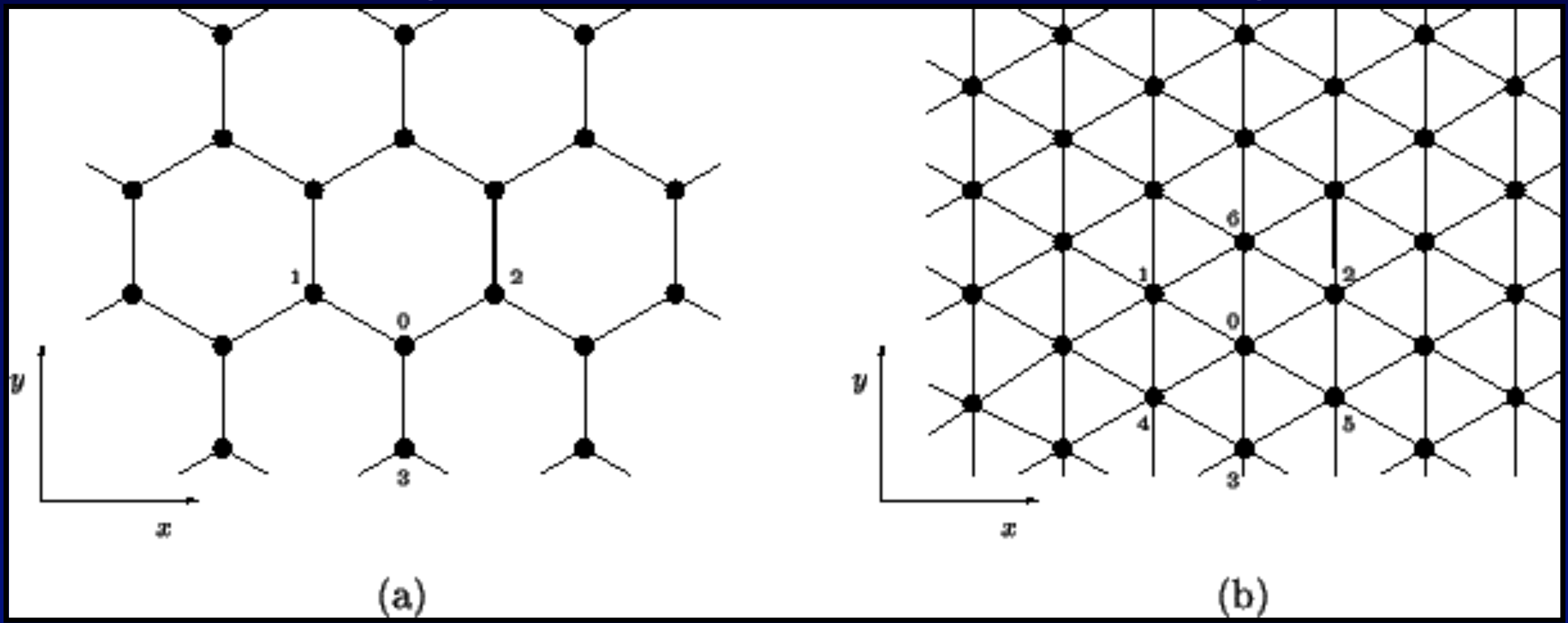


From Randall (1994)

Domains

- Degree and kind of structure

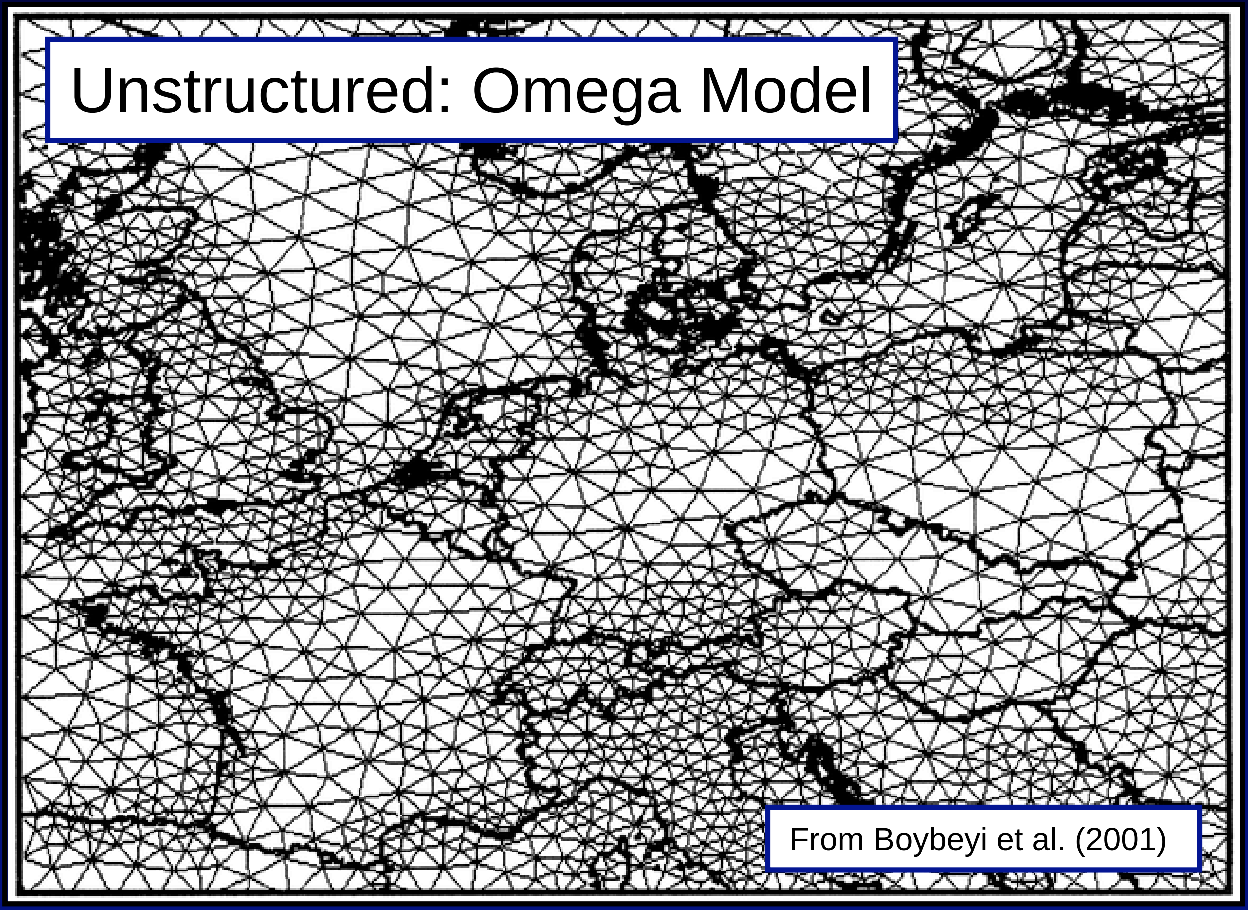
Hexagonal Triangular



From ccrma.standford.edu/~bilbao

Domains

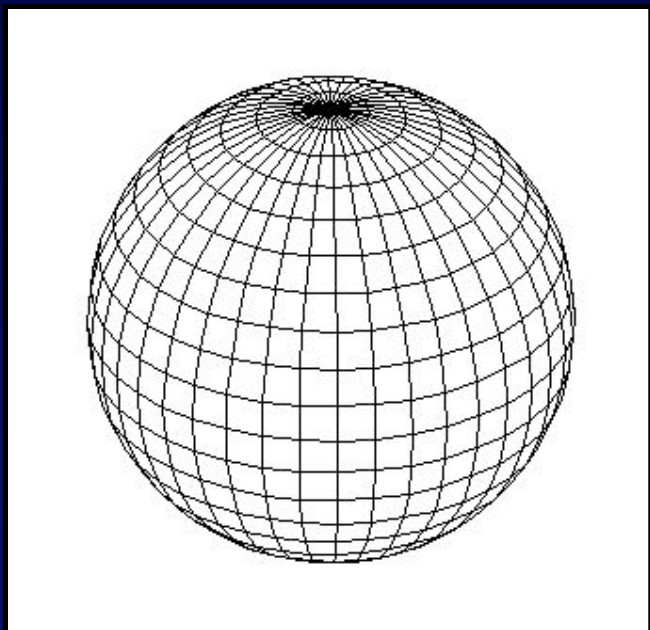
- Degree and kind of structure



Domains

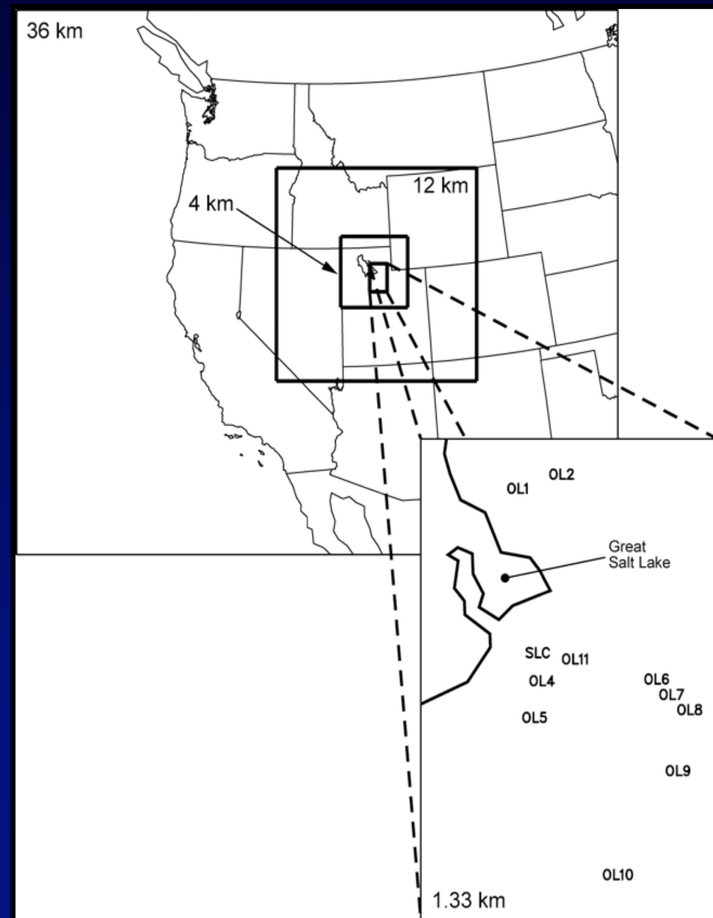
- Shape

Spherical



From mitgcm.org (2006)

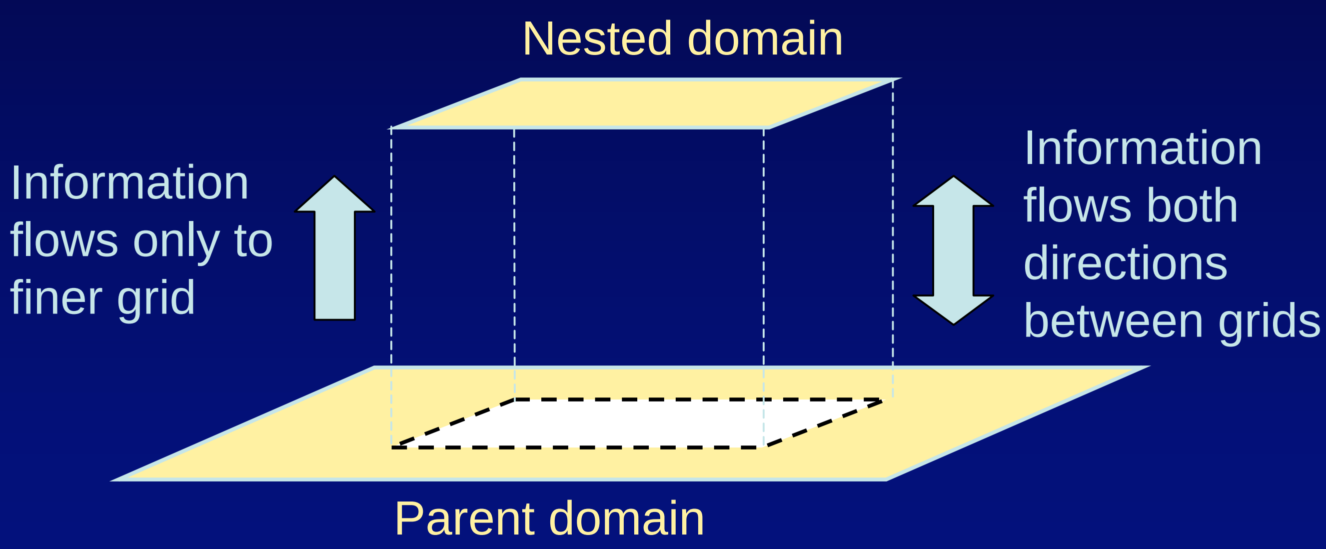
Flat



From Rife et al. (2004)

Key features of WRF Model

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



Domains

- Vertical coordinate

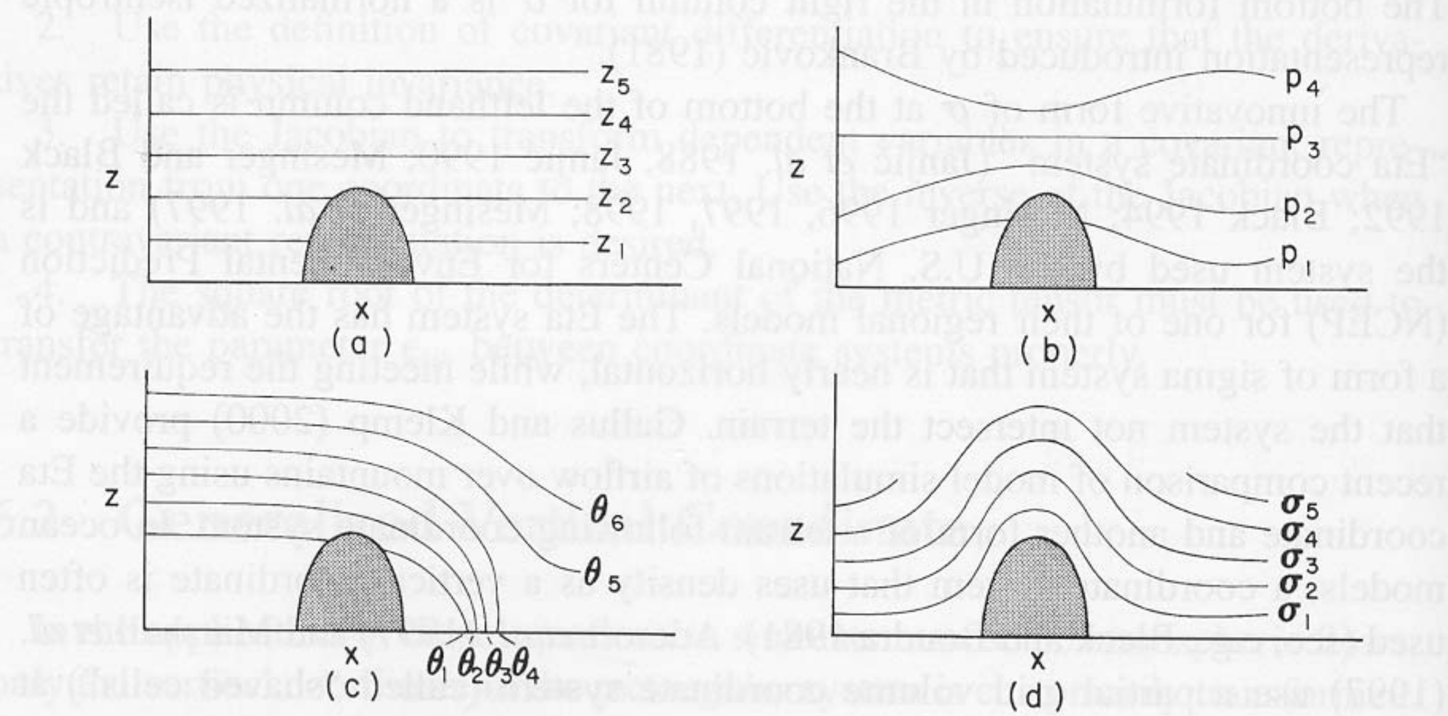


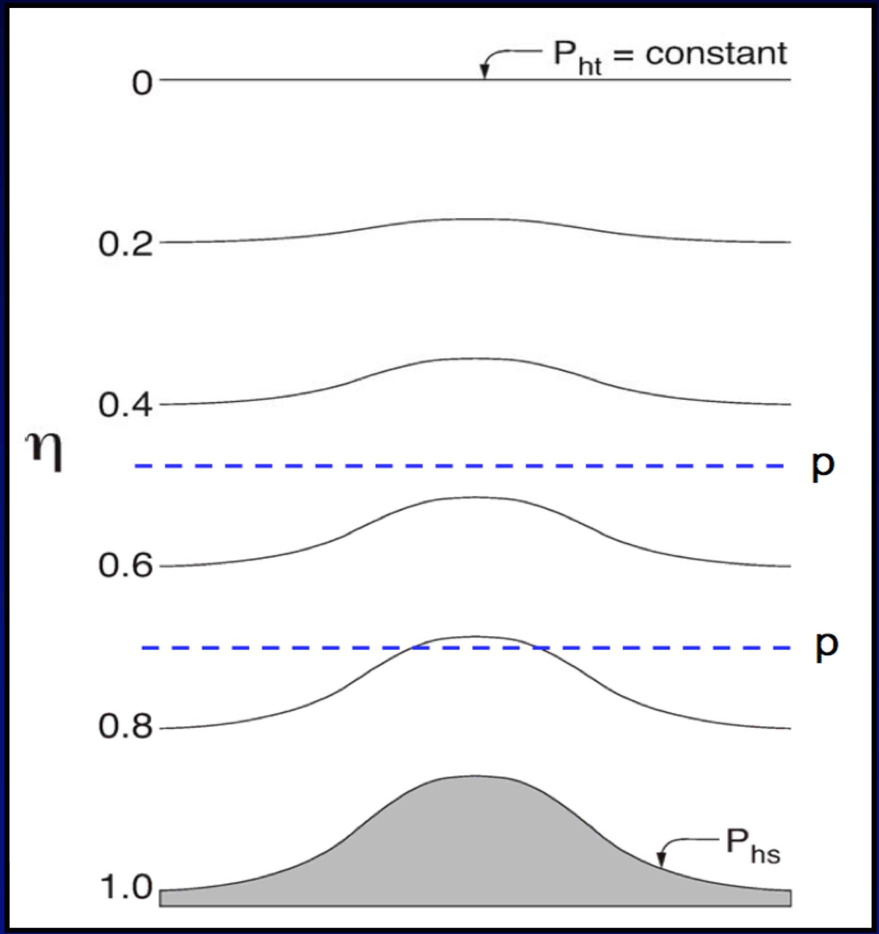
Fig. 6-2. Schematic illustrations of (a) rectangular, (b) isobaric, (c) isentropic, and (d) sigma coordinate representations as viewed in a rectangular coordinate framework.

From Pielke (2002)

Domains

- Vertical coordinate

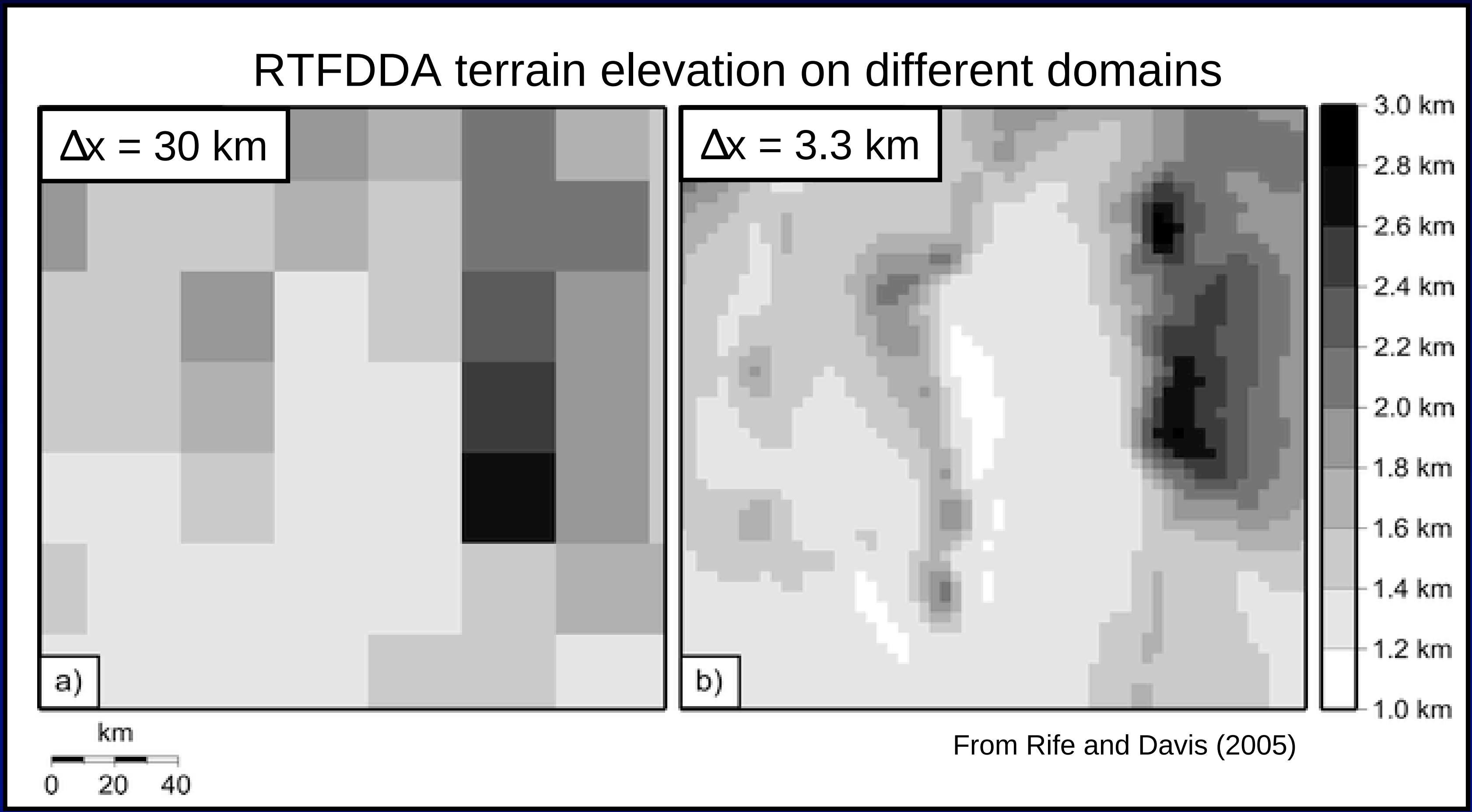
In WRF Model, vertical coordinate is normalized hydrostatic pressure, η



From Wei Wang

Domains

- Resolution



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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

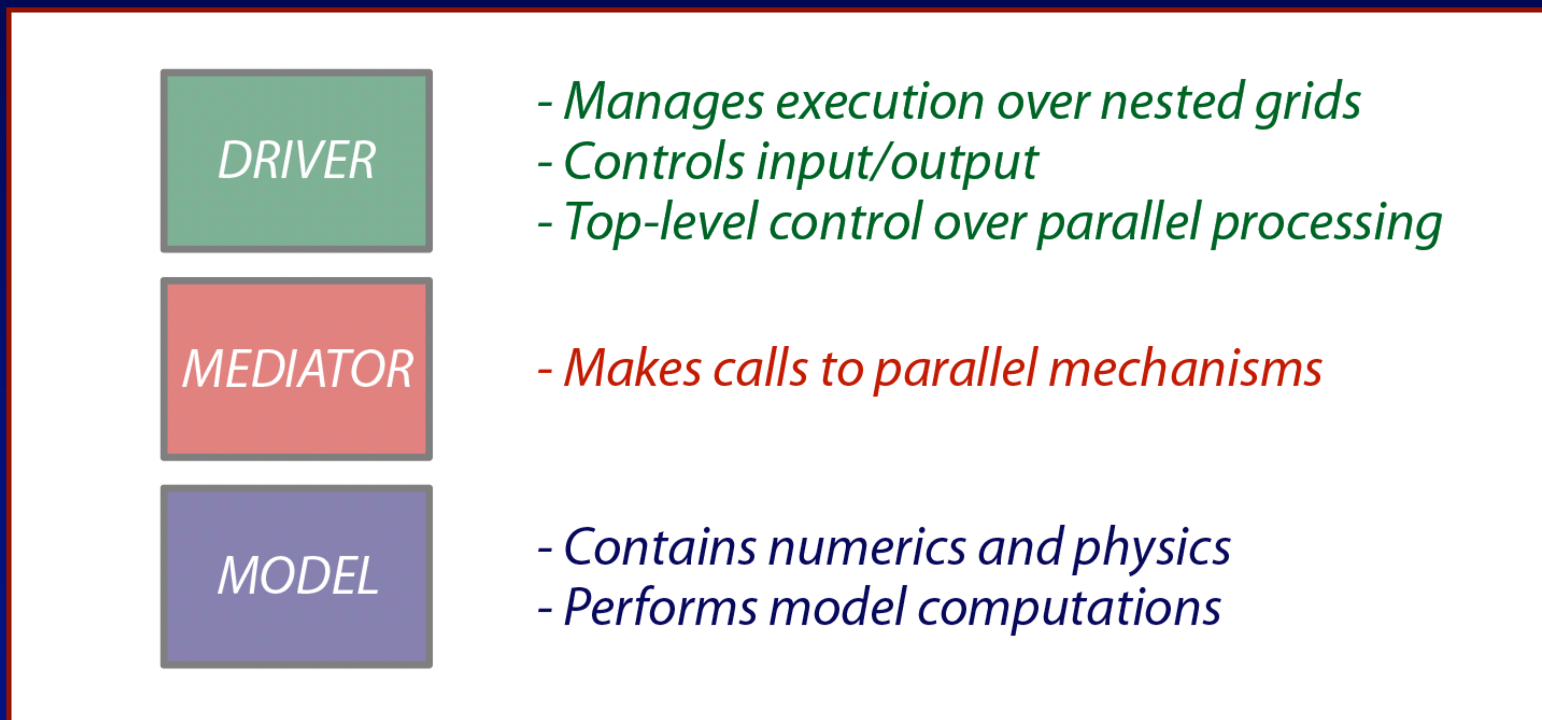
- Idealized lateral boundary conditions
  - Open
  - Rigid
  - Periodic
- Operational lateral boundary conditions
  - Generally updated during simulations
  - Not needed for global models, only for limited-area models (LAMs), such as RTFDDA
  - Can come from larger domains of same/different model or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

Introduction to WRF Model

- **<u>W</u>**eather **<u>R</u>**esearch and **<u>F</u>**orecasting 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



WRF Model in RTFDDA

- 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

History of WRF Model

- 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

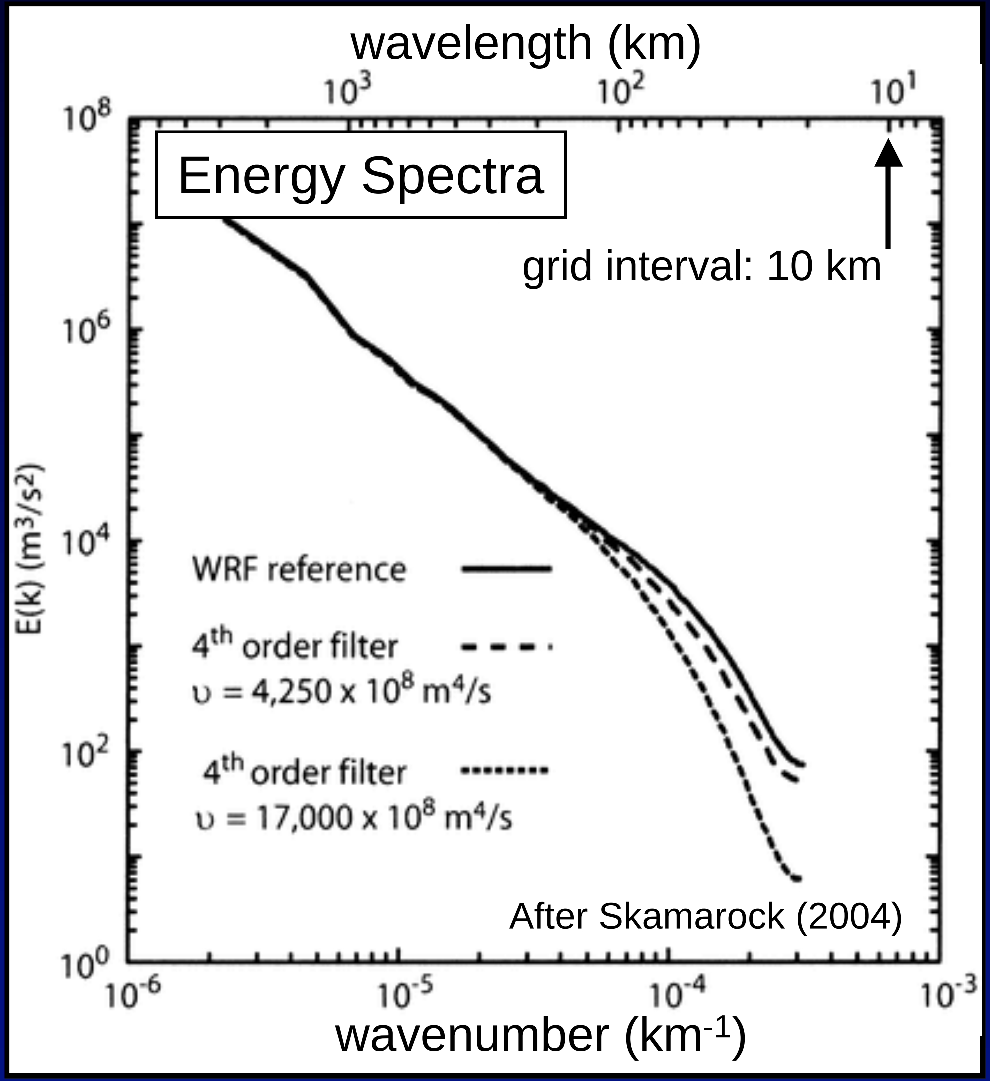
- Can be run on a variety of platforms on single processor or with shared or distributed memory

Numerics in WRF Model

- 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^{th} order
  - Vertical advection: 3^{rd} order
  - Temporal integration: 3^{rd} order

Numerics in WRF Model

- Higher order advection schemes, which lead to a higher effective resolution than in many other NWP models



Closing comments

- 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

- Kalnay, E., 2003: *Atmospheric Modeling, Data Assimilation, and Predictability.* Cambridge University Press, 341 pp.
- Klemp, J. B., and R. B. Wilhelmson, 1978: The simulation of three-dimensional convective storm dynamics. *J. Atmos. Sci.,* **35,** 1070–1096.
- Pielke, R. A., Sr., 2002: *Mesoscale Meteorological Modeling,* 2nd edition. Academic Press, 676 pp.
- Skamarock, W. C., 2004: Evaluating Mesoscale NWP Models Using Kinetic Energy Spectra. *Monthly Weather Review:* 132, 3019–3032.
- 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