Weather Research and Forecasting Model

Melissa Goering Glen Sampson

ATMO 595E

November 18, 2004

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

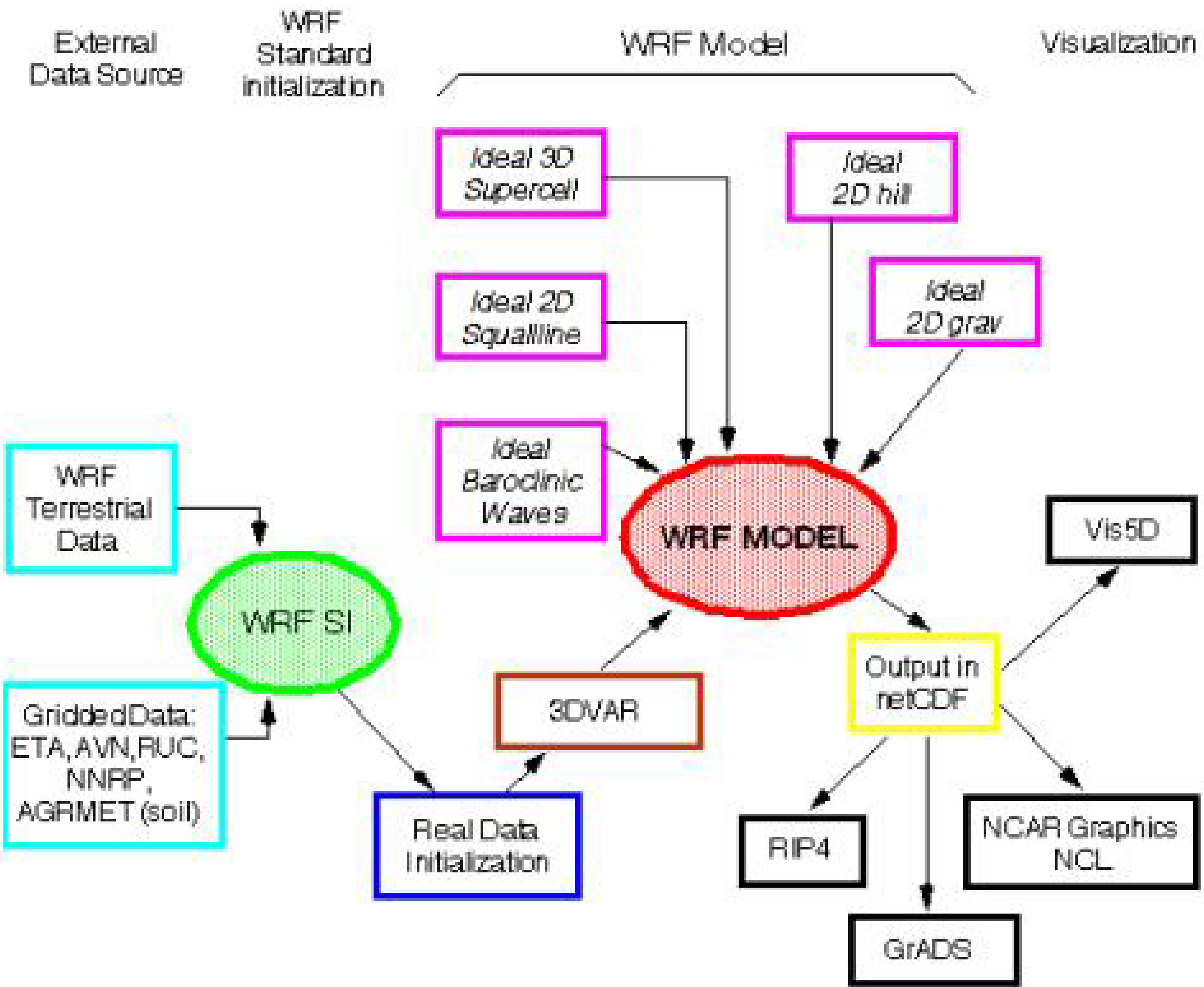
What does WRF model do?

- Developed by:

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

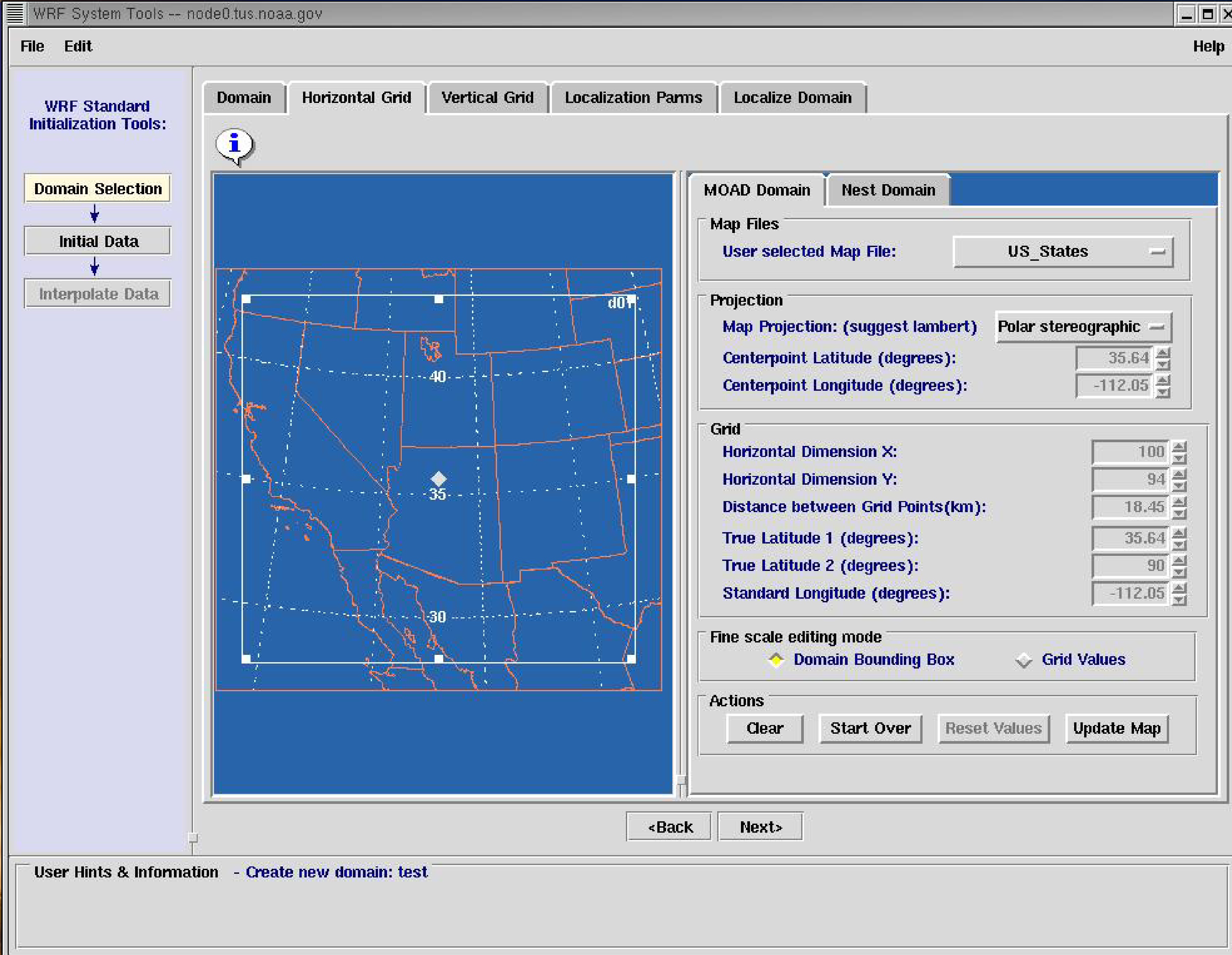
- Latest version: WRF version 2.0
- Developed for:
  - Idealized simulations (convection, baroclinic waves, large eddy simulations)
  - Parameterization research
  - Data assimilation research
  - Forecast research
  - Real-time NWP
  - Coupled-model applications

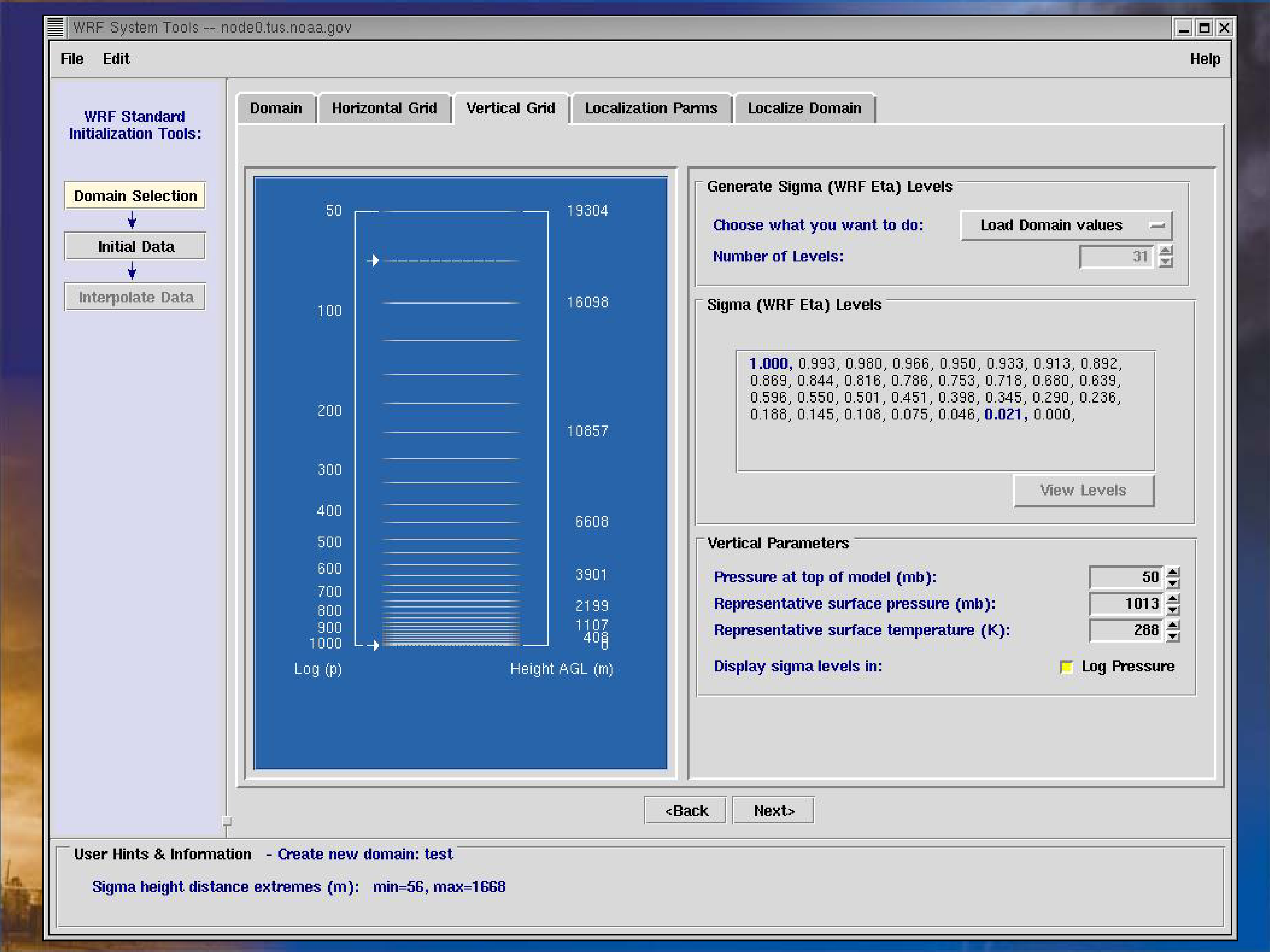
WRF Modeling System Flow Chart (*for WRFV2*)

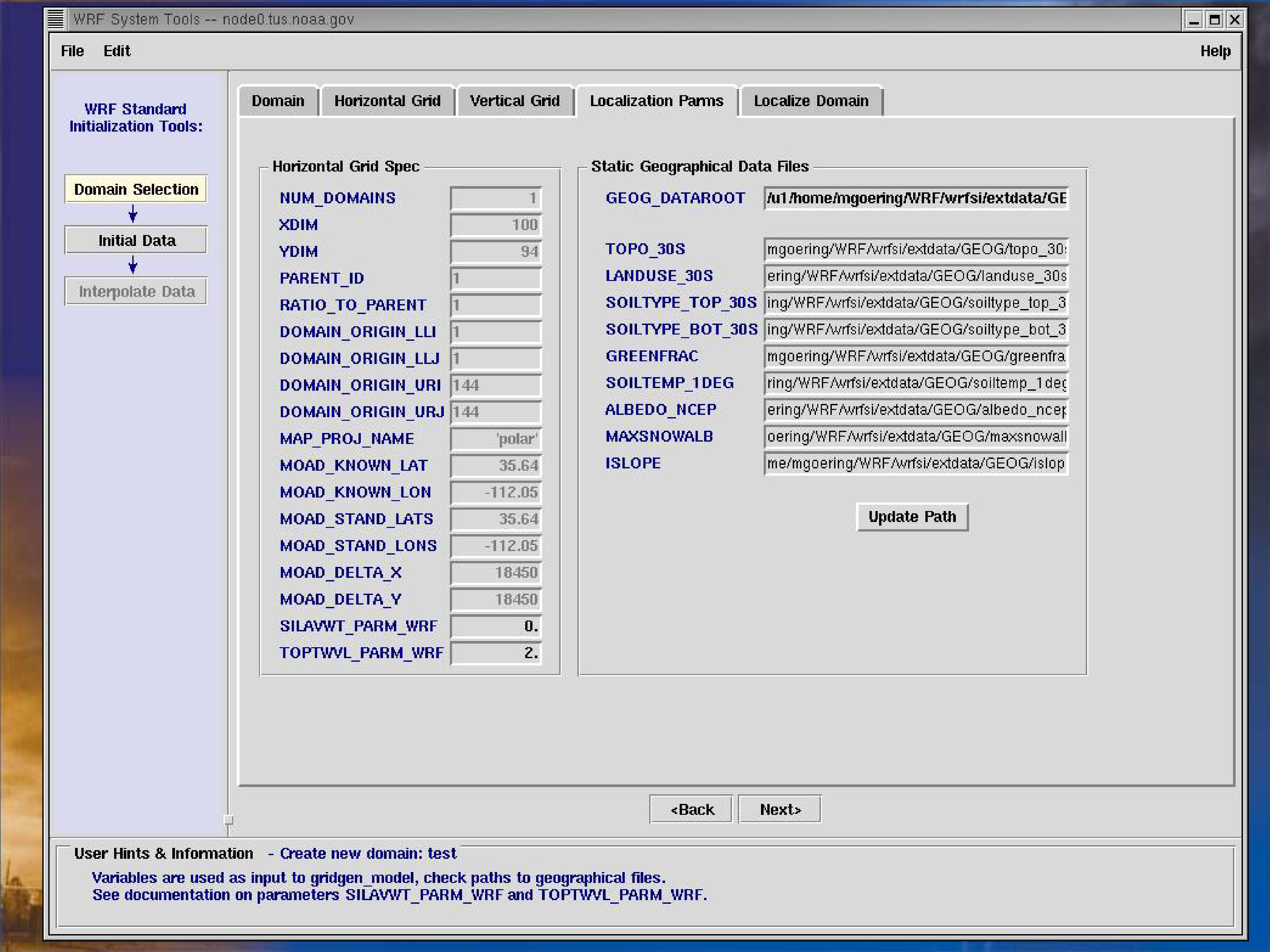


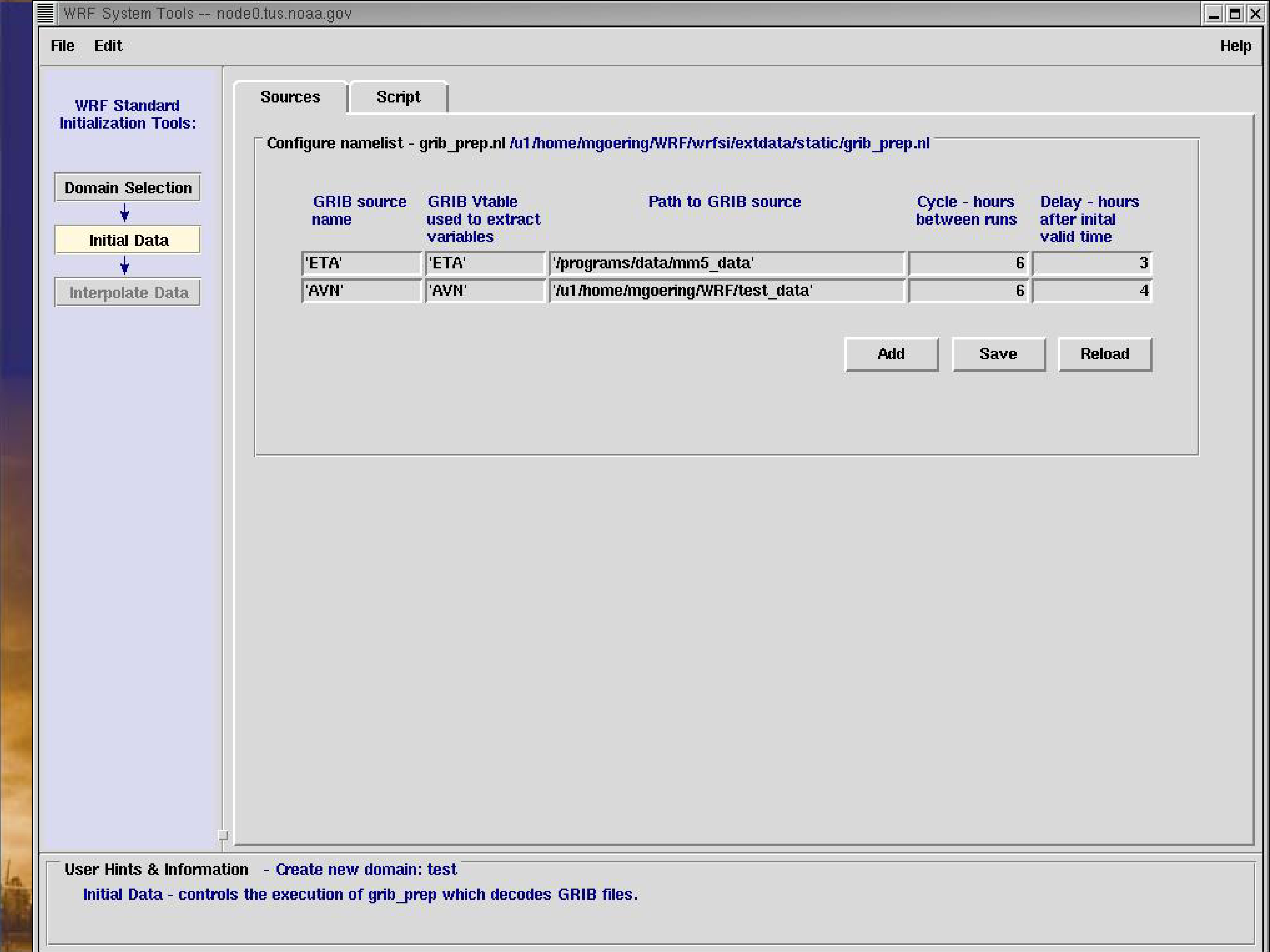
WRF Standard Initialization

- 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


WRF System Tools -- node0.tus.noaa.gov
File
Edit
Help
WRF Standard Initialization Tools:
Domain Selection
Initial Data
Interpolate Data
Domain
Horizontal Grid
Vertical Grid
Localization Parms
Localize Domain
d01
40
35
30
MOAD Domain
Nest Domain
Map Files
User selected Map File:
US_States
Projection
Map Projection: (suggest lambert)
Polar stereographic
Centerpoint Latitude (degrees):
35.64
Centerpoint Longitude (degrees):
-112.05
Grid
Horizontal Dimension X:
100
Horizontal Dimension Y:
94
Distance between Grid Points(km):
18.45
True Latitude 1 (degrees):
35.64
True Latitude 2 (degrees):
90
Standard Longitude (degrees):
-112.05
Fine scale editing mode
Domain Bounding Box
Grid Values
Actions
Clear
Start Over
Reset Values
Update Map
<Back
Next>
User Hints & Information
- Create new domain: test


WRF System Tools -- node0.tus.noaa.gov
File
Edit
Help
WRF Standard Initialization Tools:
Domain Selection
Initial Data
Interpolate Data
Domain
Horizontal Grid
Vertical Grid
Localization Parms
Localize Domain
50
100
200
300
400
500
600
700
800
900
1000
19304
16098
10857
6608
3901
2199
1107
408
0
Log (p)
Height AGL (m)
Generate Sigma (WRF Eta) Levels
Choose what you want to do:
Load Domain values
Number of Levels:
31
Sigma (WRF Eta) Levels
1.000, 0.993, 0.980, 0.966, 0.950, 0.933, 0.913, 0.892,
0.869, 0.844, 0.816, 0.786, 0.753, 0.718, 0.680, 0.639,
0.596, 0.550, 0.501, 0.451, 0.398, 0.345, 0.290, 0.236,
0.188, 0.145, 0.108, 0.075, 0.046, 0.021, 0.000,
View Levels
Vertical Parameters
Pressure at top of model (mb):
50
Representative surface pressure (mb):
1013
Representative surface temperature (K):
288
Display sigma levels in:
Log Pressure
<Back
Next>
User Hints & Information - Create new domain: test
Sigma height distance extremes (m): min=56, max=1668


WRF System Tools -- node0.tus.noaa.gov
File
Edit
Help
WRF Standard Initialization Tools:
Domain Selection
Initial Data
Interpolate Data
Domain
Horizontal Grid
Vertical Grid
Localization Parms
Localize Domain
Horizontal Grid Spec
NUM_DOMAINS 1
XDIM 100
YDIM 94
PARENT_ID 1
RATIO_TO_PARENT 1
DOMAIN_ORIGIN_LLI 1
DOMAIN_ORIGIN_LLJ 1
DOMAIN_ORIGIN_URI 144
DOMAIN_ORIGIN_URJ 144
MAP_PROJ_NAME 'polar'
MOAD_KNOWN_LAT 35.64
MOAD_KNOWN_LON -112.05
MOAD_STAND_LATS 35.64
MOAD_STAND_LONS -112.05
MOAD_DELTA_X 18450
MOAD_DELTA_Y 18450
SILAVWT_PARM_WRF 0.
TOPTWVL_PARM_WRF 2.
Static Geographical Data Files
GEOG_DATAROOT /u1/home/mgoering/WRF/wrfsi/extdata/GE
TOPO_30S mgoering/WRF/wrfsi/extdata/GEOG/topo_30
LANDUSE_30S ering/WRF/wrfsi/extdata/GEOG/landuse_30s
SOILTYPE_TOP_30S ing/WRF/wrfsi/extdata/GEOG/soiltype_top_3
SOILTYPE_BOT_30S ing/WRF/wrfsi/extdata/GEOG/soiltype_bot_3
GREENFRAC mgoering/WRF/wrfsi/extdata/GEOG/greenfra
SOILTEMP_1DEG ring/WRF/wrfsi/extdata/GEOG/soiltemp_1deg
ALBEDO_NCEP ering/WRF/wrfsi/extdata/GEOG/albedo_ncep
MAXSNOWALB oering/WRF/wrfsi/extdata/GEOG/maxsnowall
ISLOPE me/mgoering/WRF/wrfsi/extdata/GEOG/islop
Update Path
<Back
Next>
User Hints & Information - Create new domain: test
Variables are used as input to gridgen_model, check paths to geographical files.
See documentation on parameters SILAVWT_PARM_WRF and TOPTWVL_PARM_WRF.


WRF System Tools -- node0.tus.noaa.gov
File
Edit
Help
WRF Standard Initialization Tools:
Domain Selection
Initial Data
Interpolate Data
Sources
Script
Configure namelist - grib_prep.nl /u1/home/mgoering/WRF/wrfsi/extdata/static/grib_prep.nl
GRIB source name
GRIB Vtable used to extract variables
Path to GRIB source
Cycle - hours between runs
Delay - hours after inital valid time
'ETA'
'ETA'
'/programs/data/mm5_data'
6
3
'AVN'
'AVN'
'/u1/home/mgoering/WRF/test_data'
6
4
Add
Save
Reload
User Hints & Information - Create new domain: test
Initial Data - controls the execution of grib_prep which decodes GRIB files.

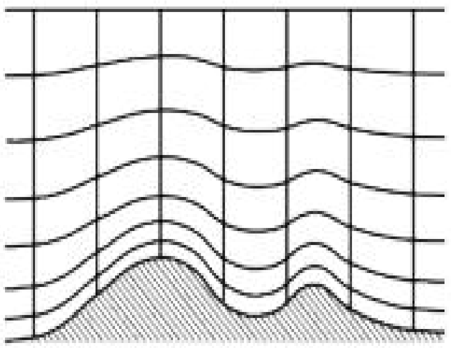
WRF Dynamics

- 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

$$\frac{\partial \phi}{\partial t} + u\frac{\partial \phi}{\partial x} + v\frac{\partial \phi}{\partial y} + \omega\frac{\partial \phi}{\partial \eta} = gw$$



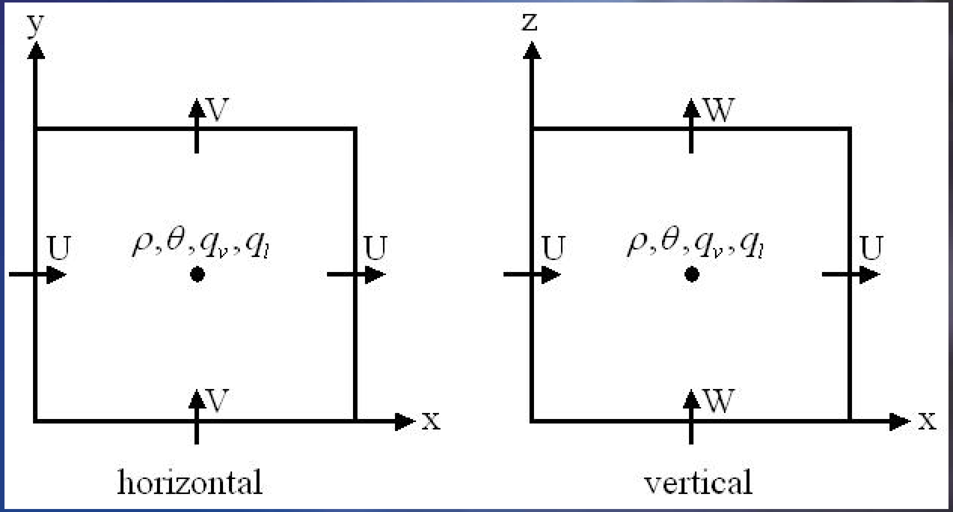
Vertical Coordinate

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

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

Grid Staggering

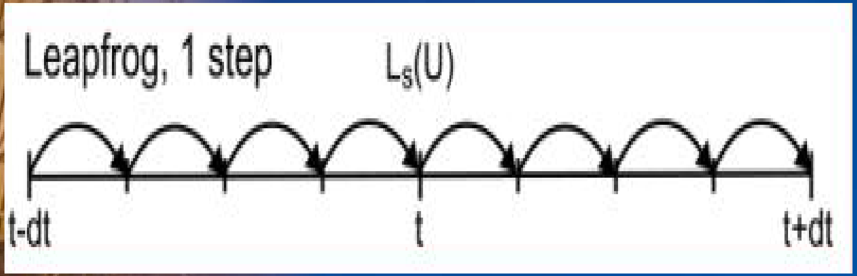
- C grid spacing

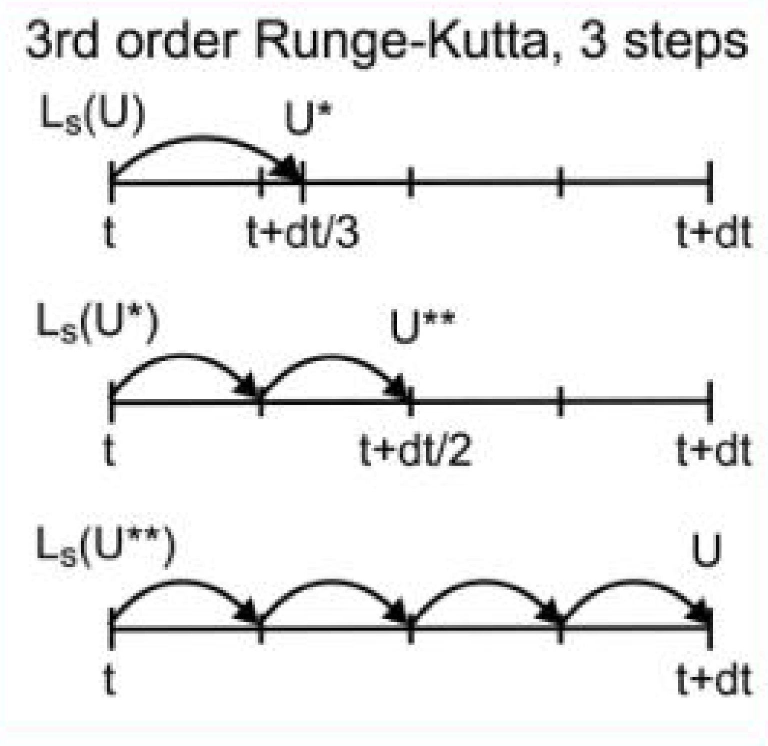


Time-split Leap Frog and Runge-Kutta scheme

- 3rd order RK generally stable using timestep twice as large in leapfrog model
- Courant number limited to

$$C_r = U\Delta t / \Delta x < 1.73$$





Wicker and Skamarock, 2002 MWR

- RK3 method excellent scheme for integrating the compressible equations and is ideal candidate for NWP
- RK3 best combination of accuracy and simplicity

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

	Spatial order			
Time scheme	3rd	4th	5th	6th
Leapfrog	U	0.72	U	0.62
RK2	0.88	U	0.30	U
RK3	1.61	1.26	1.42	1.08

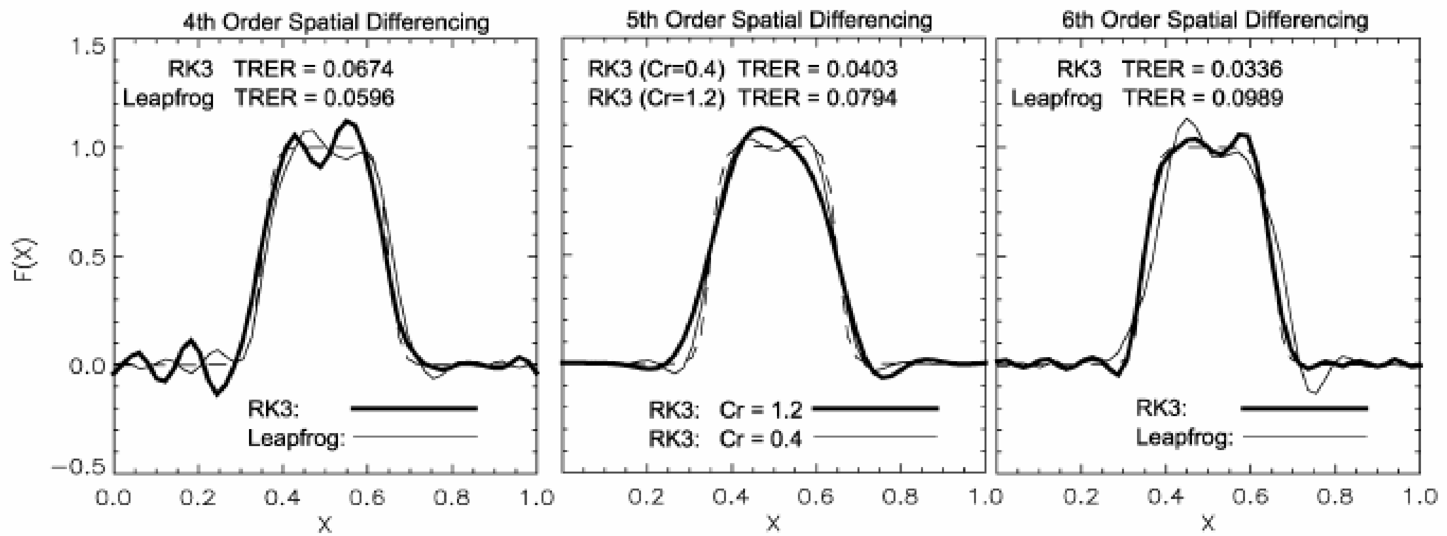


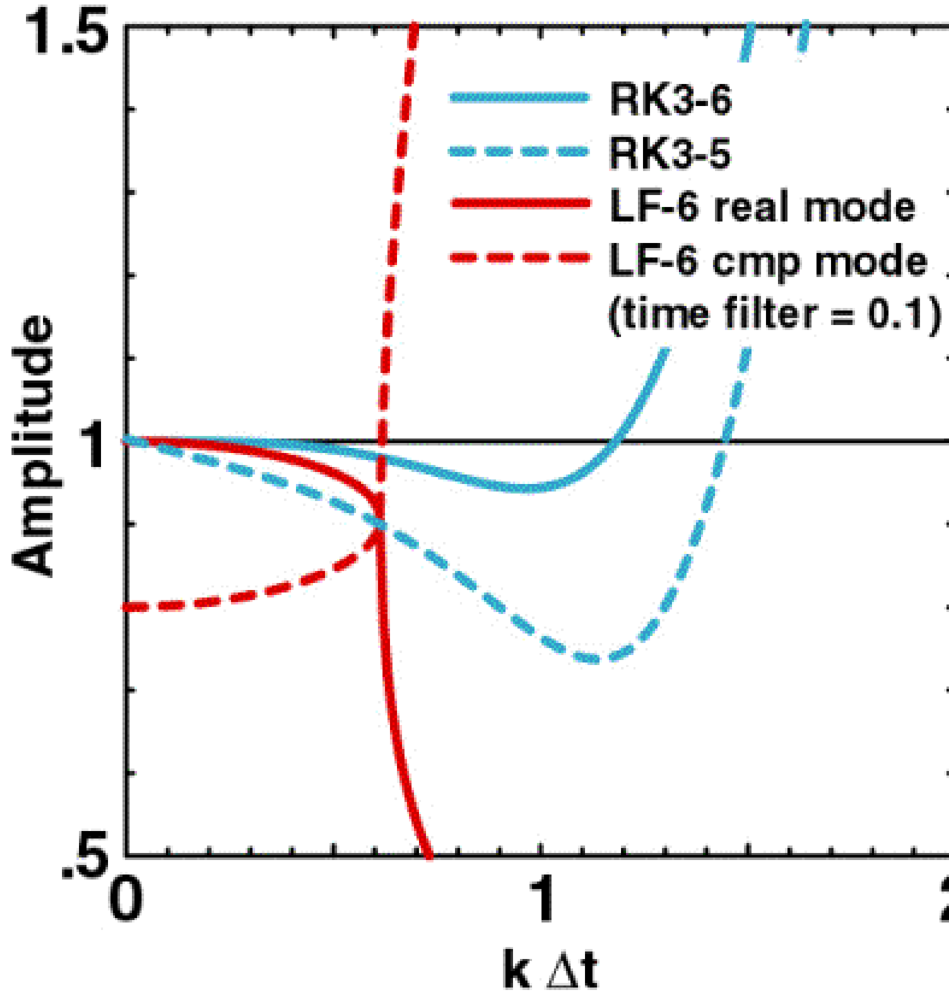
FIG. 1. One-dimensional advection tests for RK3 and leapfrog integration schemes using (a) 4th, (b) 5th, and (c) 6th order spatial discretization schemes. TRER errors for each solution are listed at the top of each box. Unless otherwise noted, the Courant number equals 0.4.

Phase and Amplitude errors for LF and RK3

Advection equation analysis

$$\phi_t = U\phi_x$$

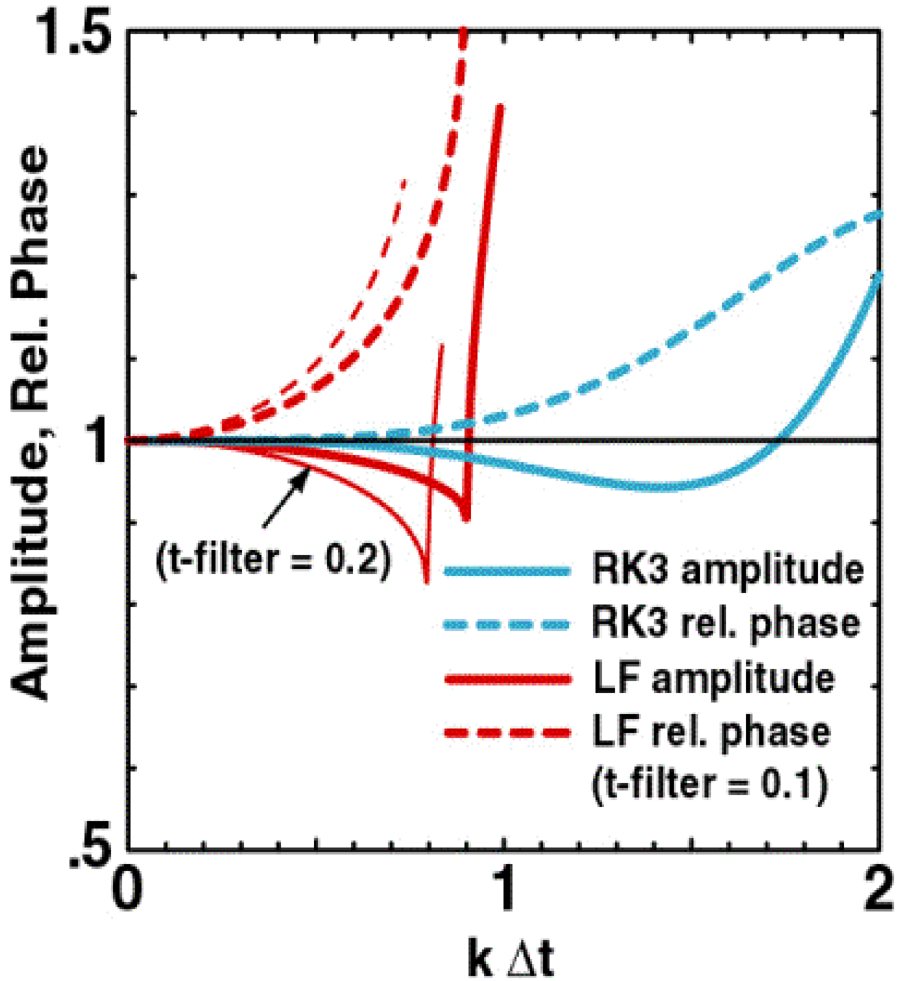
5^{th} and 6^{th} order upwind-biased and centered schemes. Analysis for $4\Delta x$ wave.



Phase and Amplitude errors for LF and RK3

Oscillation equation analysis

$$\phi_t = ik\phi$$



Conservation Equations Mass Coordinate (Flux)

Momentum

$$\frac{\partial U}{\partial t} + \mu\alpha \frac{\partial p}{\partial x} + \frac{\partial p}{\partial \eta}\frac{\partial \phi}{\partial x} = -\frac{\partial Uu}{\partial x} - \frac{\partial \Omega u}{\partial \eta}$$

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

Heat

$$\frac{\partial \Theta}{\partial t} + \frac{\partial U\theta}{\partial x} + \frac{\partial \Omega\theta}{\partial \eta} = \mu Q$$

Continuity

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

geopotential ($\phi = gz$) $\quad \frac{d\phi}{dt} = gw$

Diagnostic Relations

Hydrostatic pressure

$$\frac{\partial \phi}{\partial \eta} = -\mu\alpha,$$

Ideal Gas Law

$$p = \left(\frac{R\theta}{p_0\alpha}\right)^{\gamma}, \quad \Omega = \mu\dot{\eta}$$

Conservation Equation Height Coordinates (Flux)

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

Conservative Variables

$$\frac{\partial U}{\partial t} + \gamma R \pi \frac{\partial \Theta}{\partial x} - fV = -\frac{\partial Uu}{\partial x} - \frac{\partial Wu}{\partial z}$$

$$\frac{\partial W}{\partial t} + \gamma R \pi \frac{\partial \Theta}{\partial z} + g\rho = -\frac{\partial Uw}{\partial x} - \frac{\partial Ww}{\partial z}$$

Momentum

$$\frac{\partial \Theta}{\partial t} + \frac{\partial U\theta}{\partial x} + \frac{\partial W\theta}{\partial z} = \rho Q$$

Heat

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

Continuity

$$\gamma R \pi \nabla \Theta = c_p \Theta \nabla \pi = \nabla p$$

Pressure terms related to Θ

Moist Equations

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

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

Momentum

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

Continuity

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

Heat

Hydrostatic Pressure **Ideal Gas Law**

$$\frac{\partial \phi}{\partial \eta} = -\alpha_d \mu_d, \qquad p = \left(\frac{R\Theta}{p_o \mu_d \alpha_v}\right)^{\gamma}$$

Diagnostic Relations

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

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

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

$$\Delta t\frac{\delta(U\phi)}{\Delta x}\bigg|_{5th} = \Delta t\frac{\delta(U\phi)}{\Delta x}\bigg|_{6th} - \underbrace{\left|\frac{U\Delta t}{\Delta x}\right|\frac{1}{60}\left(-\phi_{i-3} + 6\phi_{i-2} - 15\phi_{i-1} + 20\phi_i - 15\phi_{i+1} + 6\phi_{i+2} - \phi_{i+3}\right)}_{\frac{Cr}{60}\frac{\partial^6\phi}{\partial x^6} + H.O.T}$$

For constant U

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

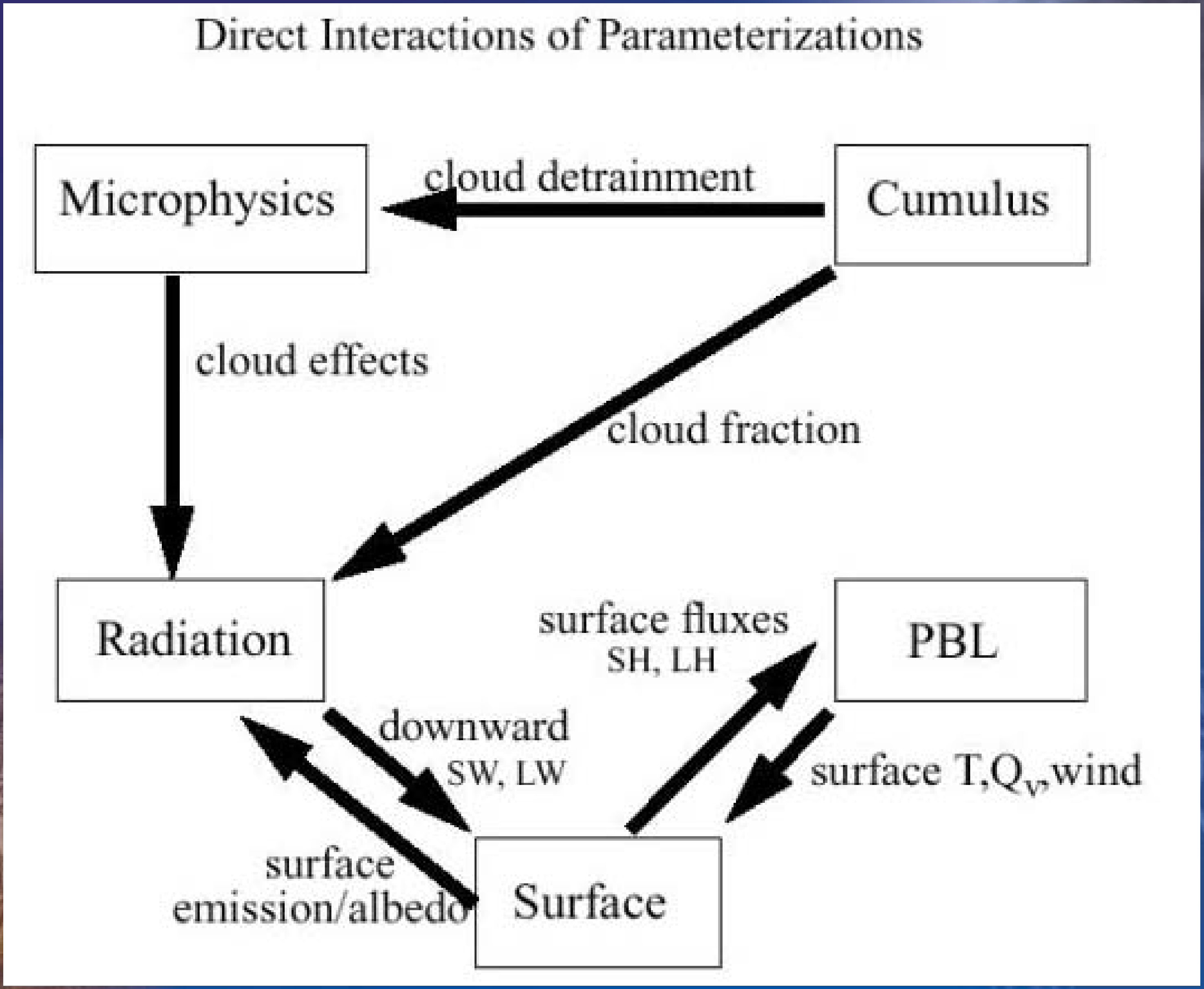
Lateral

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

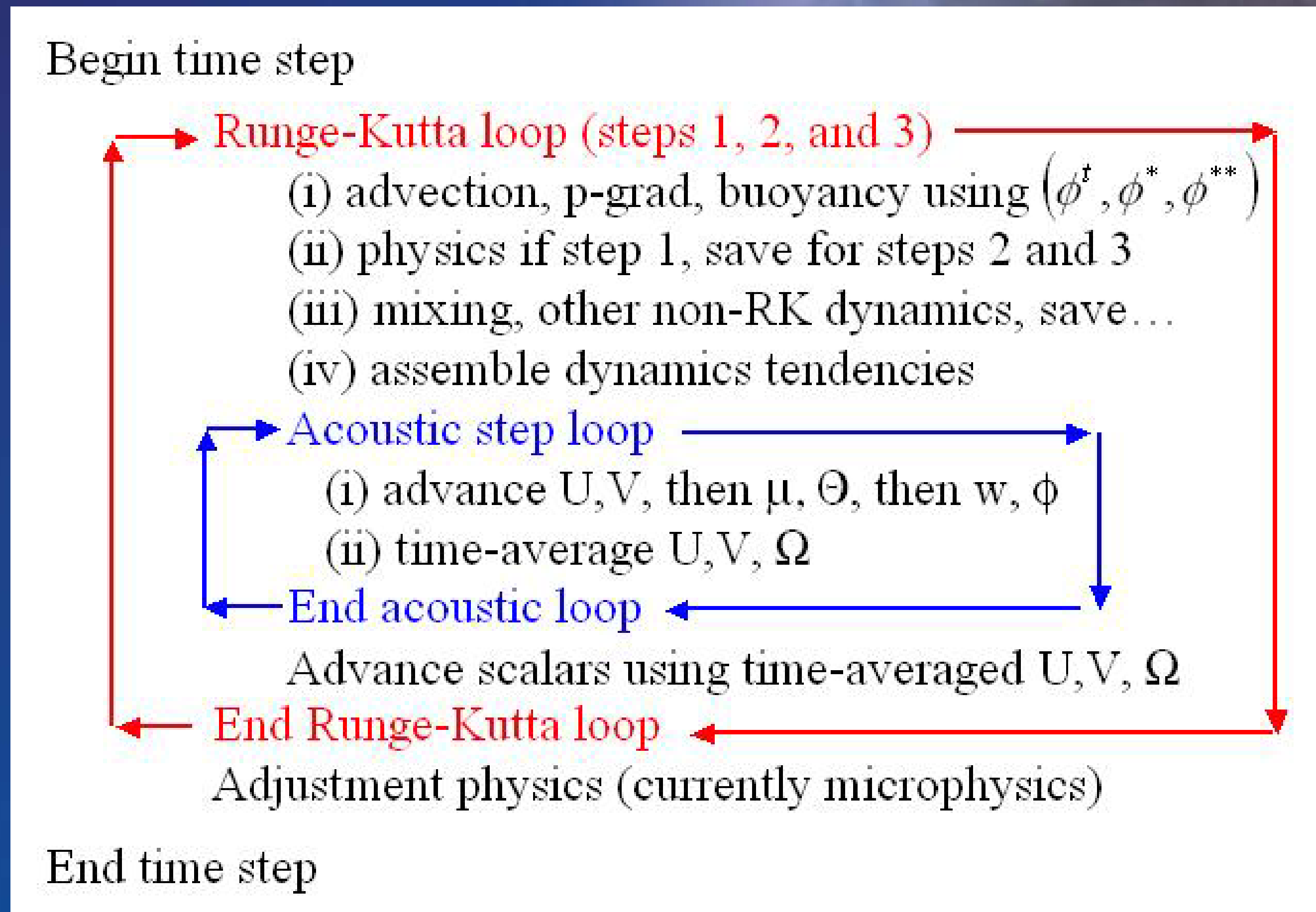
- Subgrid Eddy diffusion
- PBL
- Cumulus parameterization
- Radiation
- Microphysics
- Surface

Parameterizations Interactions



Parameterizations Interactions

- It appears that the physic options are done within each RK loop EXCEPT the microphysics
- Microphysics:
  - Heat/moisture tendencies
  - Microphysics rates
  - Surface rainfall

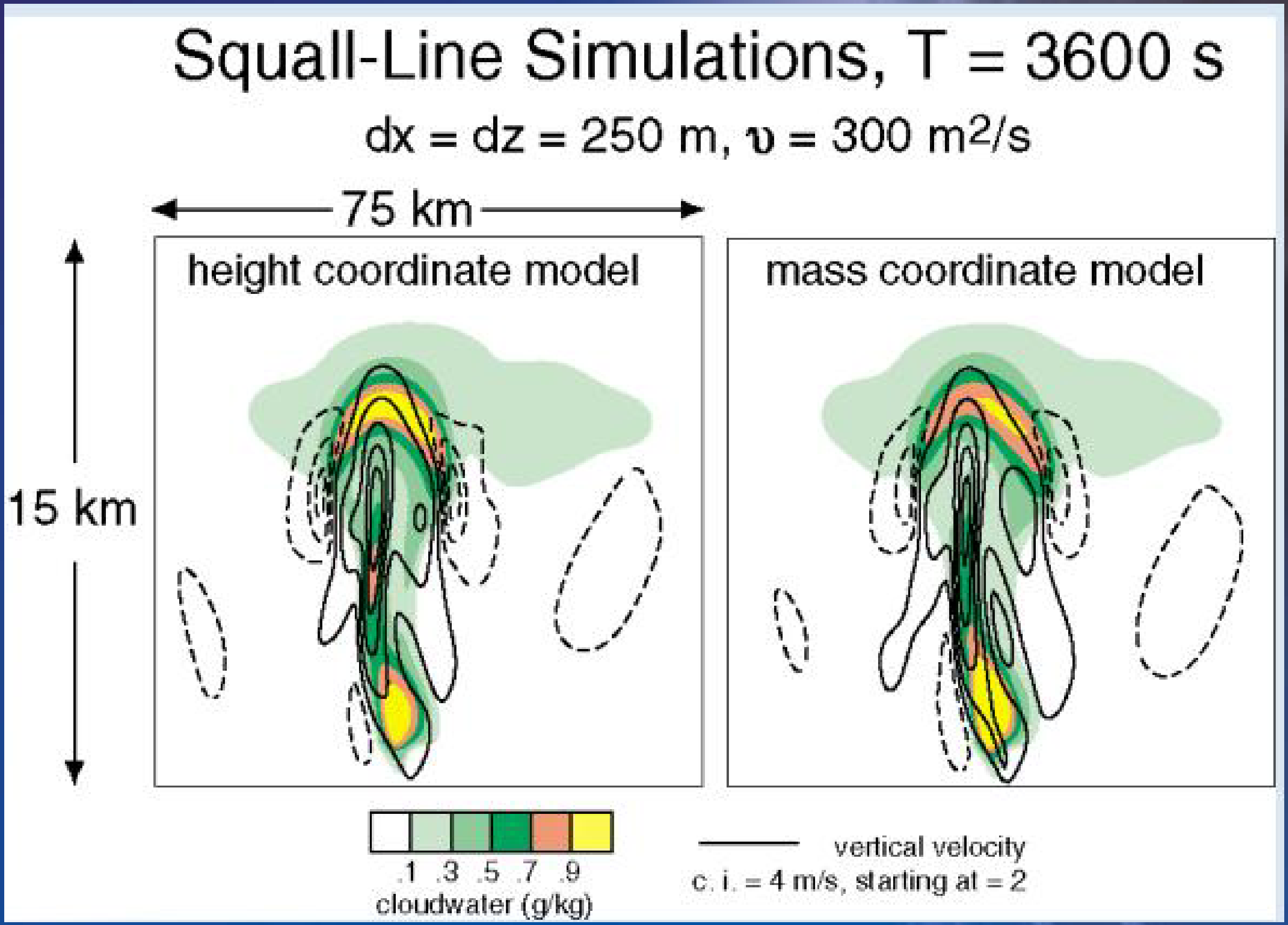


Physics	Options	Comments
Subgrid eddy diffusion	• Constant diffusion • Level 2.5 TKE • Stress/deformation Smagorinsky • 2D Horizontal Smagorinsky	• Const khdif and kvdif • Based on K • Based on horiz wind for horiz diffusion only
Boundary Layer* * Includes surface similarity theory	• YSU • MRF • Mellor-Yamada-Janjic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

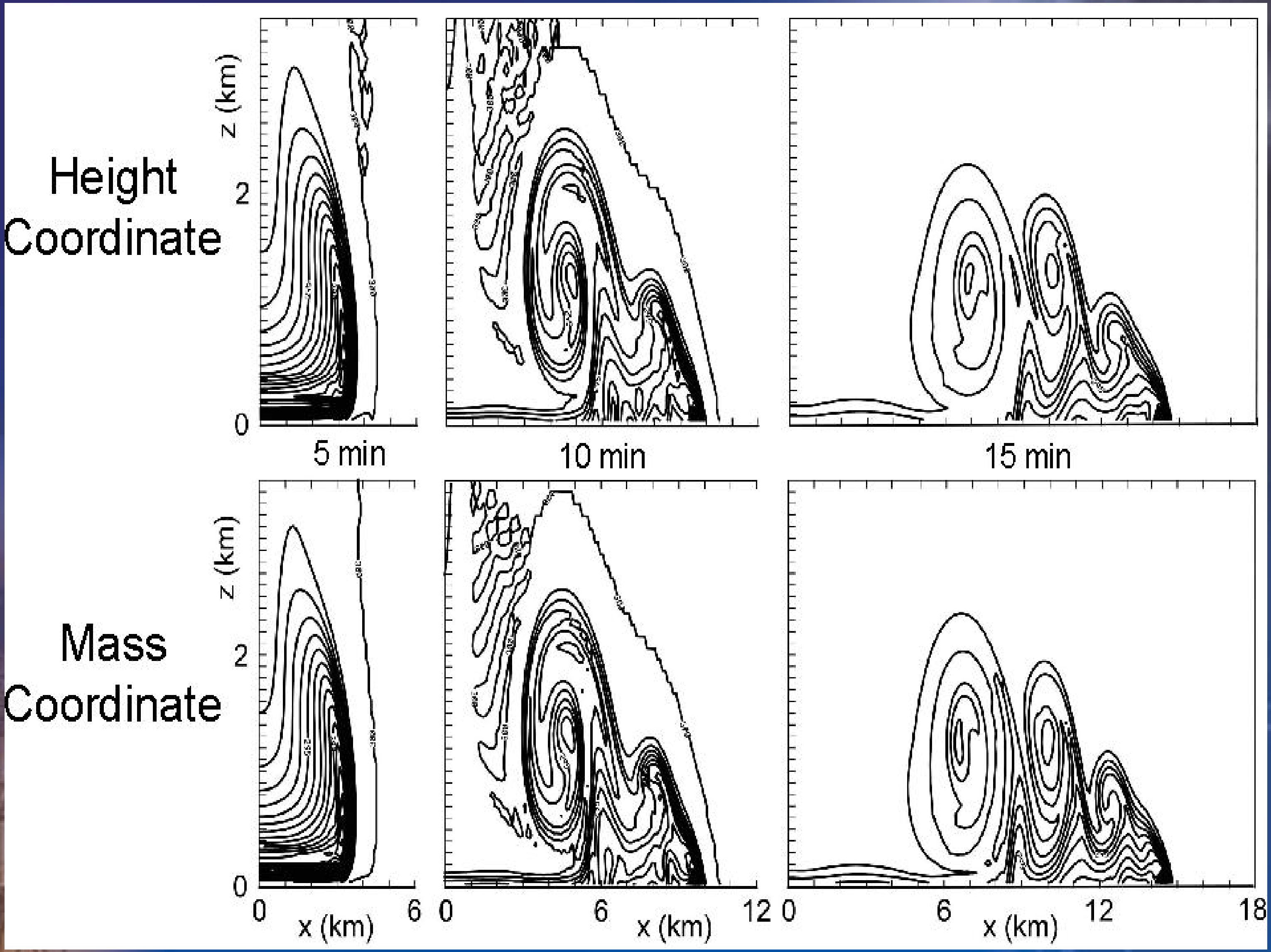
Physics	Options	Comments
Longwave Radiation	• RRTM (MM5) • Eta (GFDL)	• Spectral scheme with K distribution and a look up table • Spectral scheme from global model used in Eta
Shortwave Radiation	• Dudhia (MM5) • Goddard • Eta (GFDL)	• Simple downward calculation, clear scattering •Spectral method • Used in Eta, ozone effects and interacts with clouds
Land-Surface	• 5 layer thermal diffusion • NOAH Land Surface • RUC Land Surface	• layers 1,2,4,8,and 16 cm thick • soil temp and moisture 4 layers • soil temp and moisture 6 layers
Micro-physics	• Kessler • Lin et al. • WSM3 • WSM5 • Eta (Ferrier) • WSM6	• warm rain, no ice, idealized • 5 class including graupel • 3 class with ice, ice processes • 5 class with ice, supercooled H_20 • one prognostic total condensate • 6 class with graupel

Testing and Verification

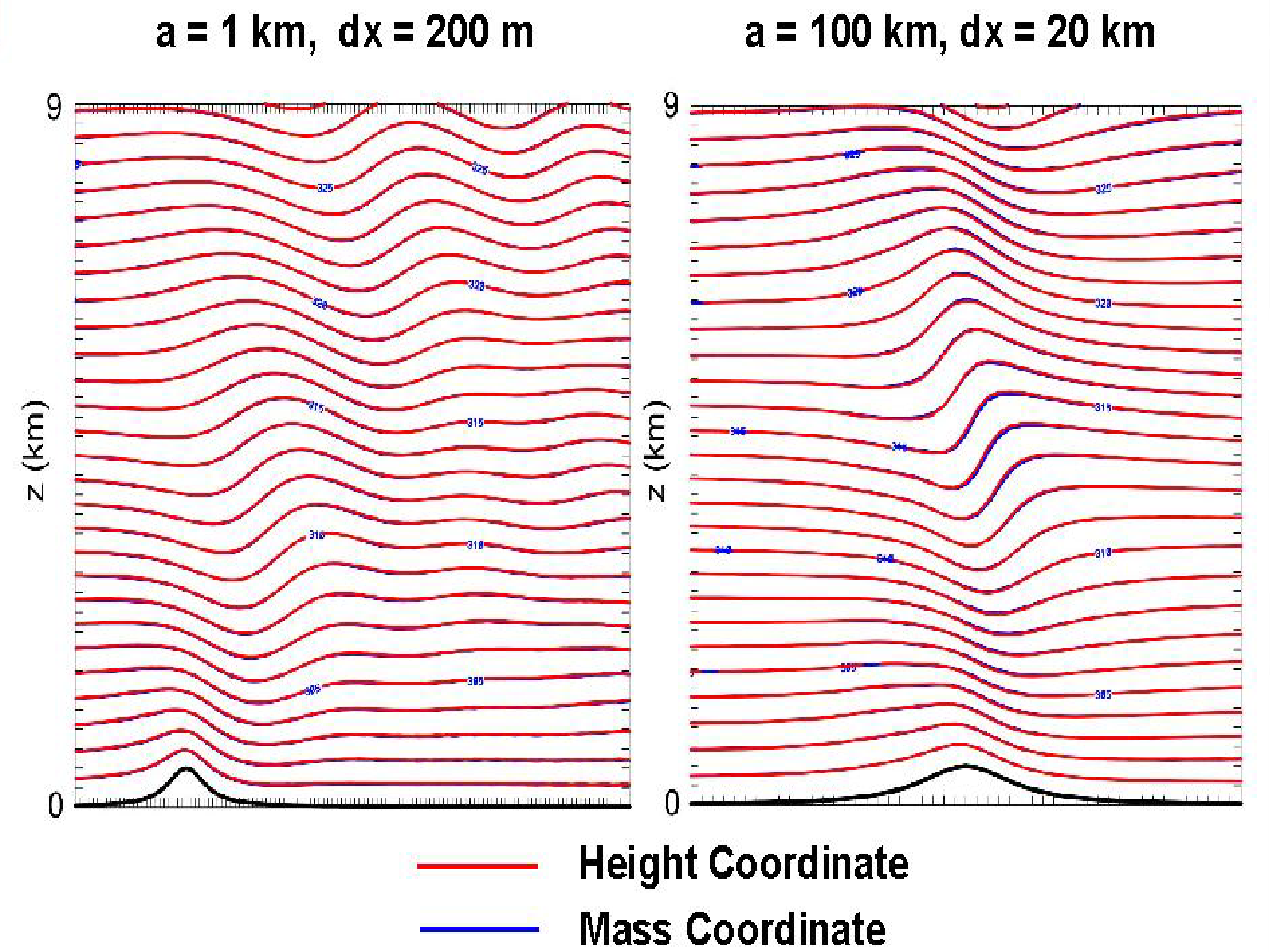
- Simulations run to target specific facets of research or forecasting.



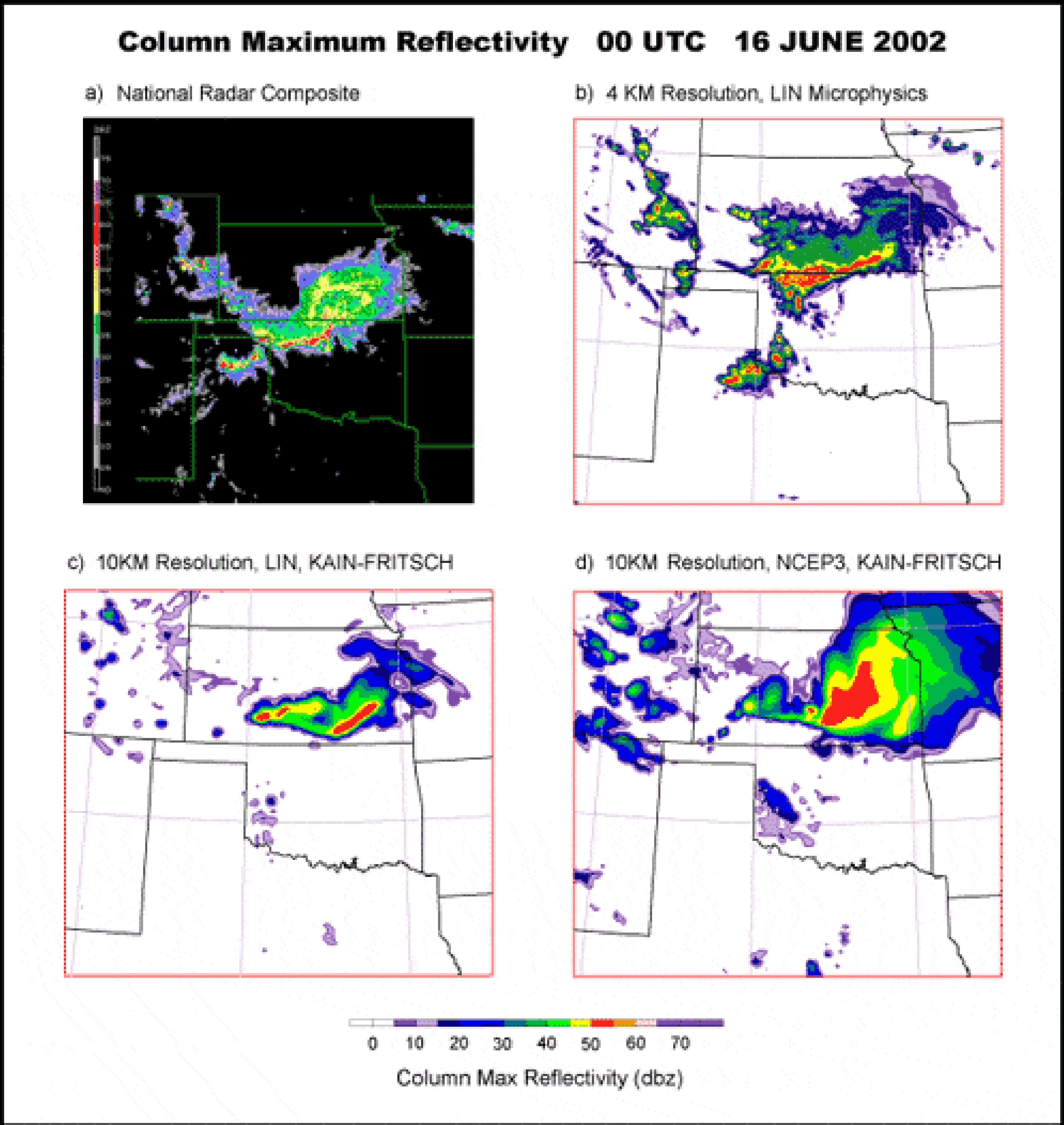
Testing and Verification



Testing and Verification



Verification



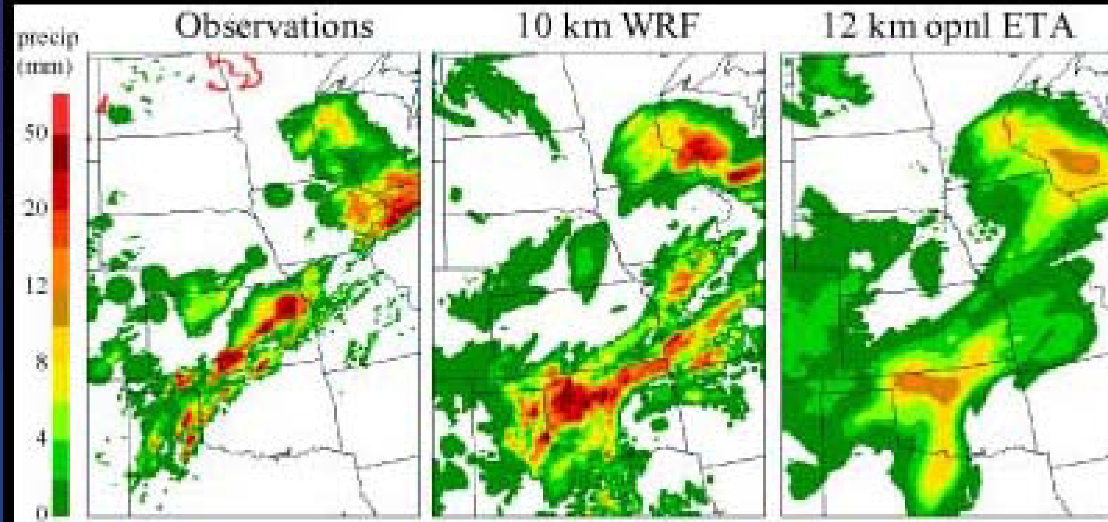
Weisman et al.

- 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 H_20 project (IHOP)

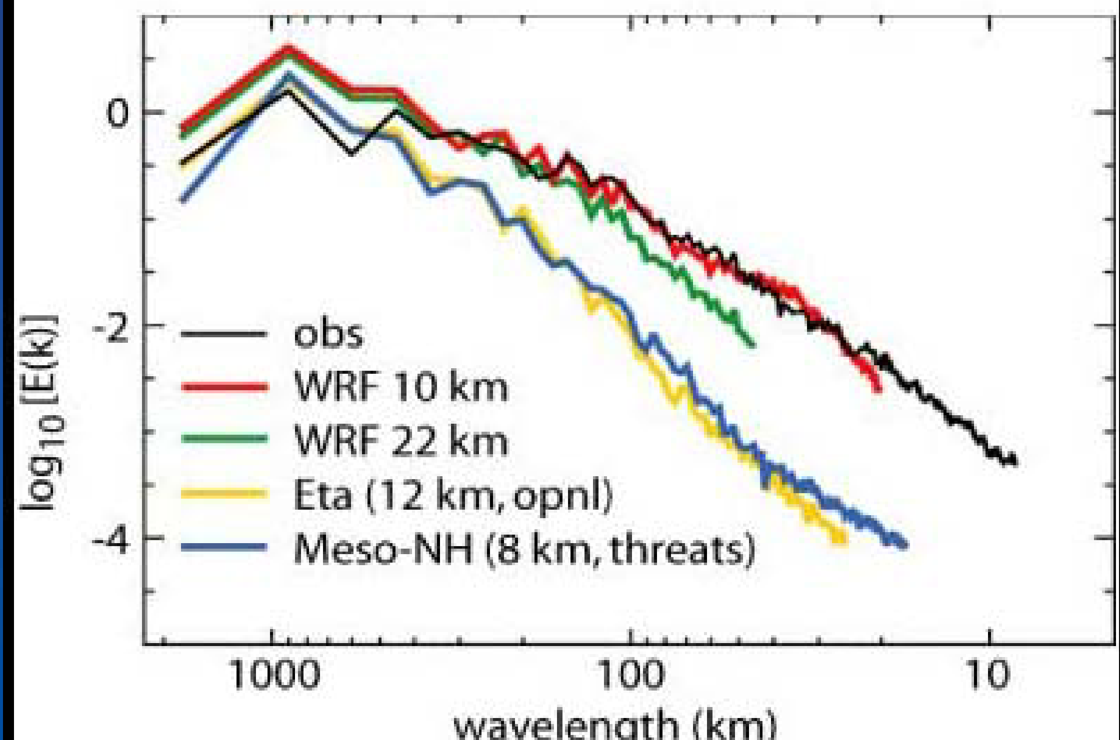
Verification

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



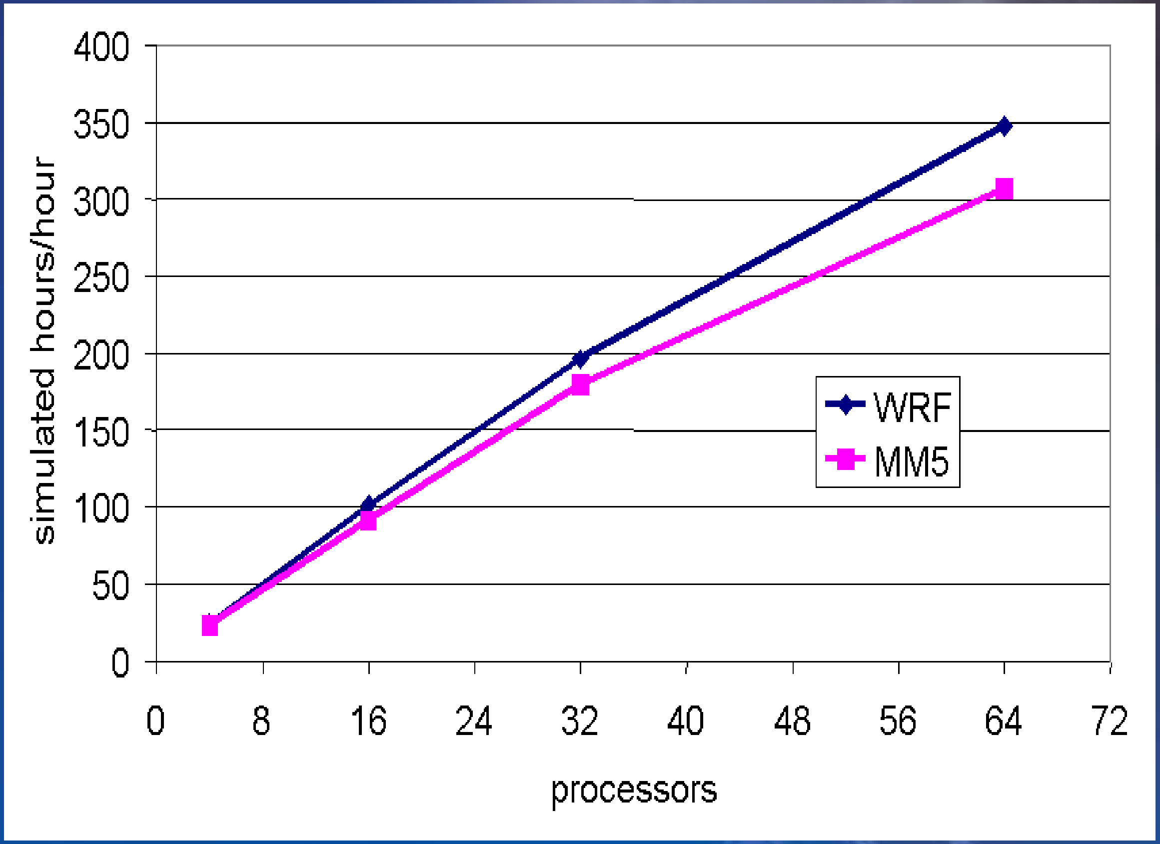
3 hr accumulated precipitation valid at 18Z from 12Z 4 June 2002 model run.



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 x112 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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ATMO 595E

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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
http://www.mmm.ucar.edu/individual/skamarock/meso2001pp_wcs.pdf

Weisman et al. 2002, : Preliminary Results from 4km Explicit Convective Forecasts Using the WRF Model. (Preprint) AMS 19th Conf. on Weather Analysis and Forecasting and 15th Conf. on Numerical Weather Prediction. Aug. 12th.

Wicker L.J. and W. Shamarock, 2002: Time-Splitting Methods for Elastic Models Using Forward Time Schemes. *Mon. Wea. Rev.*, Vol. 130, pg. 2088-2097.

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