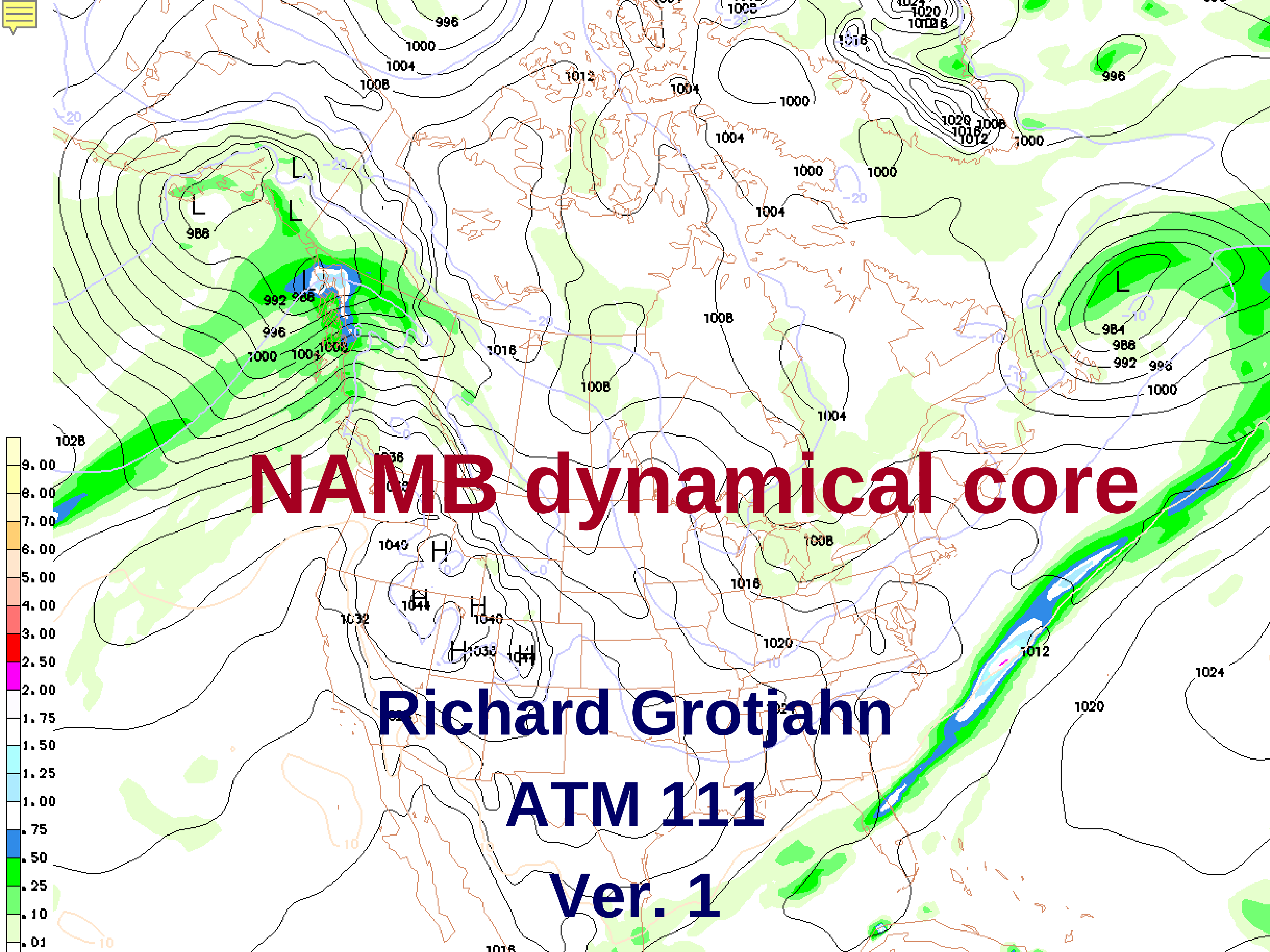


NAMB dynamical core

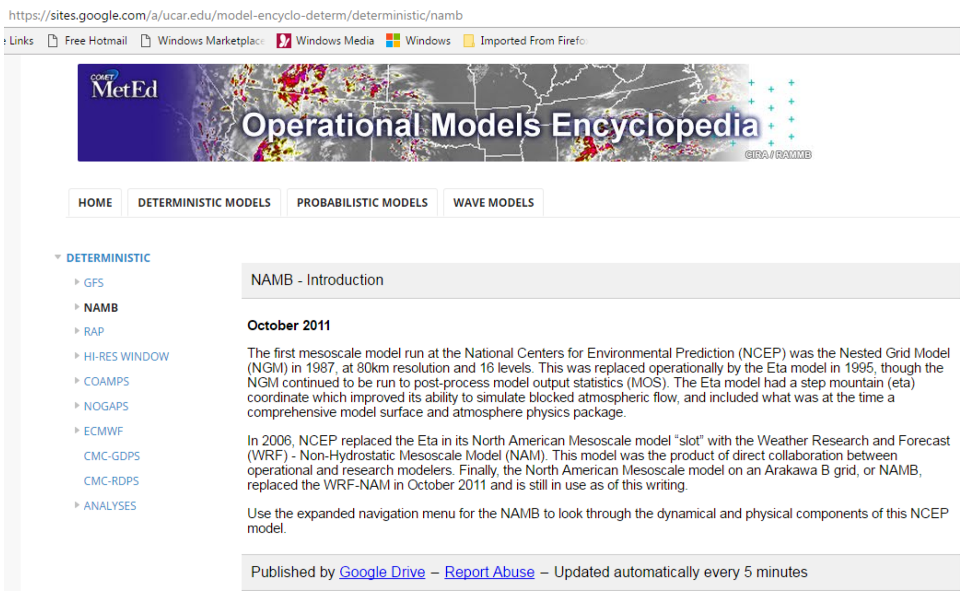
Richard Grotjahn

ATM 111

Ver. 1

Sources:

- Borrowed heavily from these NCEP documents.
- http://www.mmm.ucar.edu/wrf/users/tutorial/200807/NMM_Dynamics_jul2008_FINAL.pdf
- http://www.mmm.ucar.edu/wrf/users/tutorial/200807/tut_dyn_arw_200807.pdf
- Meted ‘Operational Models Encyclopedia’ google doc on NAMB (2017)



https://sites.google.com/a/ucar.edu/model-encyclo-determ/deterministic/namb

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MetEd Operational Models Encyclopedia

HOME | DETERMINISTIC MODELS | PROBABILISTIC MODELS | WAVE MODELS

DETERMINISTIC
- GFS
- NAMB
- RAP
- HI-RES WINDOW
- COAMPS
- NOGAPS
- ECMWF
- CMC-GDPS
- CMC-RDPS
- ANALYSES

NAMB - Introduction

October 2011

The first mesoscale model run at the National Centers for Environmental Prediction (NCEP) was the Nested Grid Model (NGM) in 1987, at 80km resolution and 16 levels. This was replaced operationally by the Eta model in 1995, though the NGM continued to be run to post-process model output statistics (MOS). The Eta model had a step mountain (eta) coordinate which improved its ability to simulate blocked atmospheric flow, and included what was at the time a comprehensive model surface and atmosphere physics package.

In 2006, NCEP replaced the Eta in its North American Mesoscale model “slot” with the Weather Research and Forecast (WRF) - Non-Hydrostatic Mesoscale Model (NAM). This model was the product of direct collaboration between operational and research modelers. Finally, the North American Mesoscale model on an Arakawa B grid, or NAMB, replaced the WRF-NAM in October 2011 and is still in use as of this writing.

Use the expanded navigation menu for the NAMB to look through the dynamical and physical components of this NCEP model.

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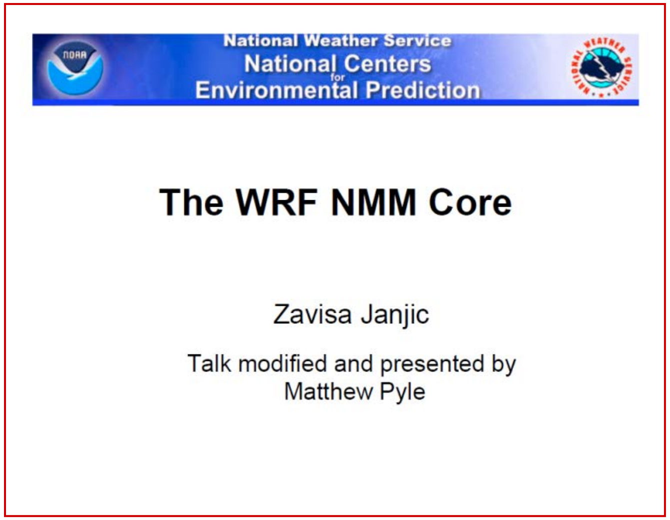
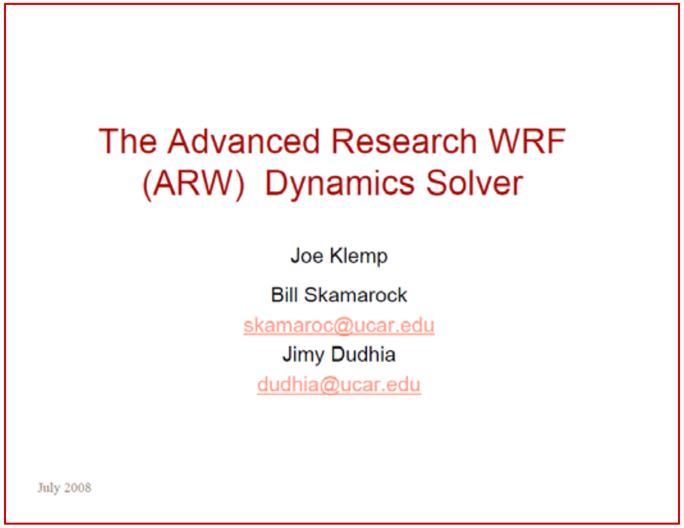


National Weather Service
National Centers for Environmental Prediction

The WRF NMM Core

Zavisa Janjic

Talk modified and presented by Matthew Pyle



The Advanced Research WRF (ARW) Dynamics Solver

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July 2008

Outline

- Basic principles
- Hybrid vertical coordinates σ & P
- Equations in terrain-following σ coordinates
- Boundary conditions
- Numerics
- Staggered grid
- Integration sequence
- Map projection
- NAM domain
- Resolution & topography
- Summary

Basic Principles

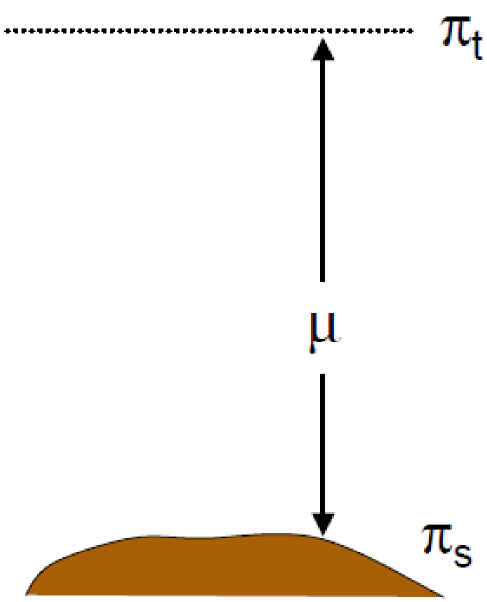
• > • Use full compressible equations split into hydrostatic and nonhydrostatic contributions
    - Easy comparison of hydro and nonhydro solutions
    - Reduced computational effort at lower resolutions
- Use modeling principles proven in NWP and regional climate applications
- Use methods that minimize the generation of small-scale noise
- Robust, computationally efficient

Vertical Coordinates

- >

Mass Based Vertical Coordinate

For simplicity, consider the sigma coordinate as representative of a vertical coordinate based on hydrostatic pressure (π):



$$\sigma = \frac{\pi - \pi_t}{\mu}$$

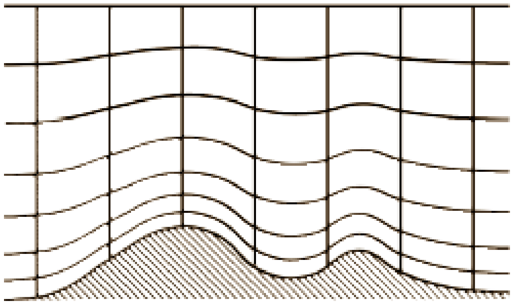
$$\mu = \pi_s - \pi_t$$

π_t = model top π
π_s = surface π

Hybrid Vertical Coordinate

Pressure-sigma hybrid (Arakawa and Lamb, 1977)

Has the desirable properties of a terrain-following, pressure coordinate:



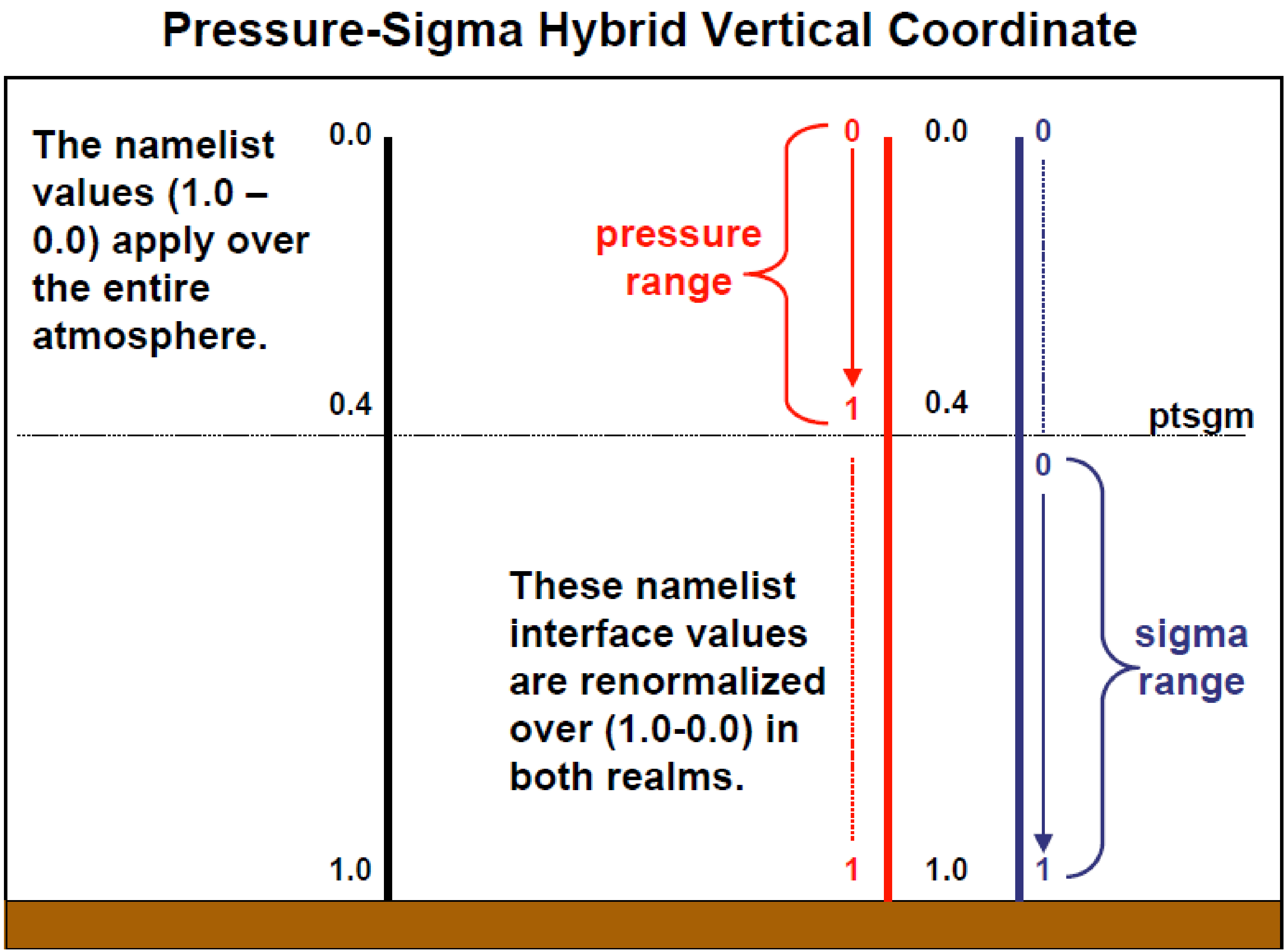
- Exact mass (etc.) conservation
- Nondivergent flow on pressure surfaces
- No problems with weak static stability
- No discontinuities or internal boundary conditions

And an additional benefit from the hybrid:

- Flat coordinate surfaces at high altitudes where sigma problems worst (e.g., Simmons and Burridge, 1981)

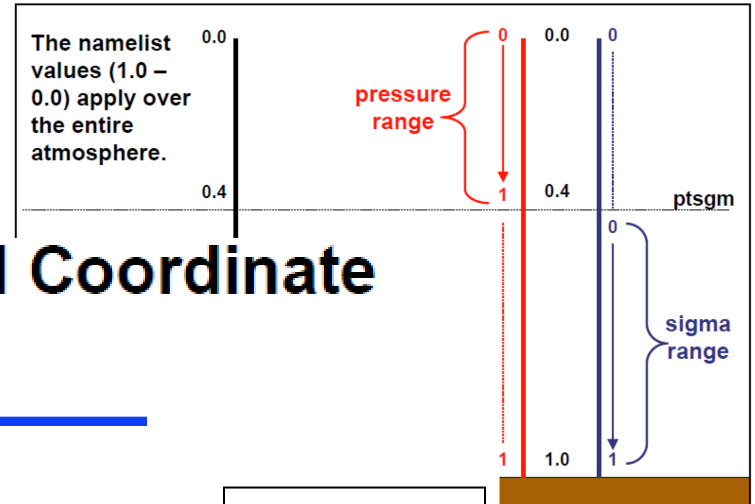
Vertical Coordinate

- NAMB has ptsgm at 300 hPa

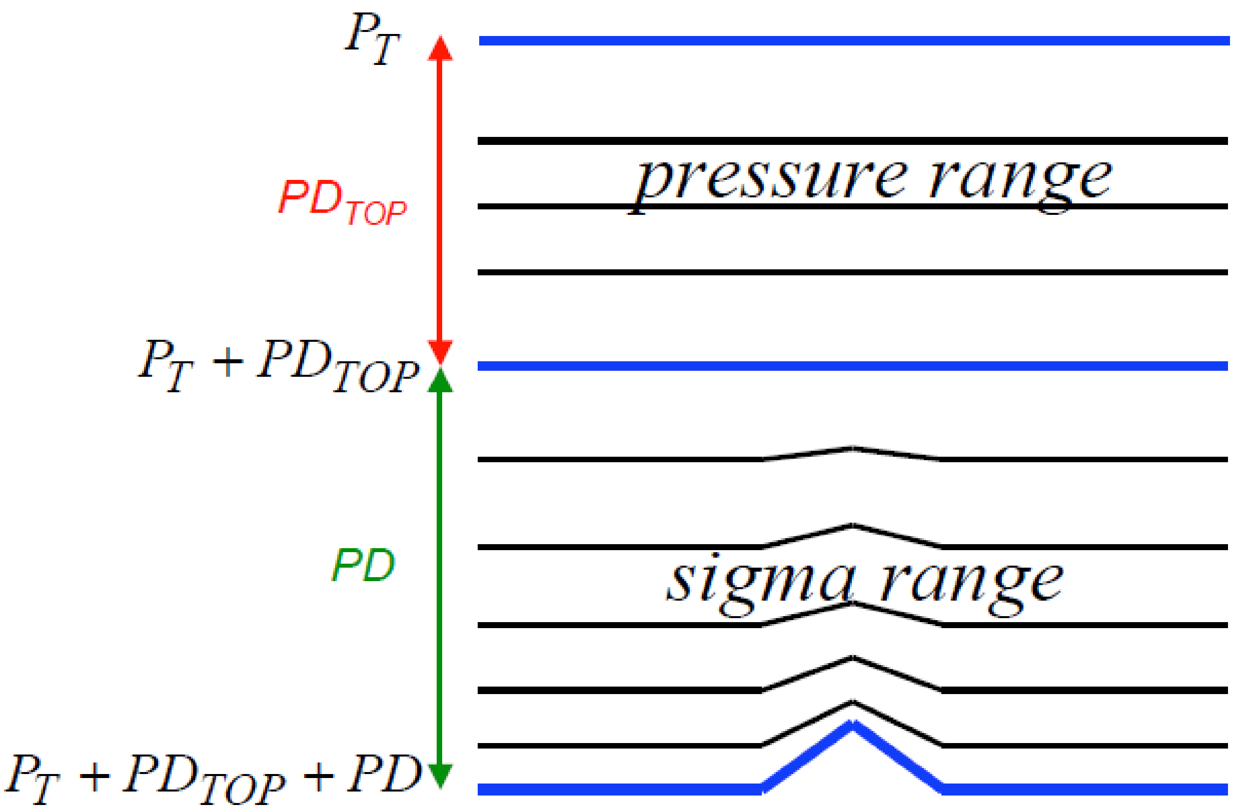


Vertical Coordinate

Pressure-Sigma Hybrid Vertical Coordinate



Pressure-Sigma Hybrid Vertical Coordinate



$eta_2 = 0$

$0 < eta_1 < 1$

$eta_1 = 1$

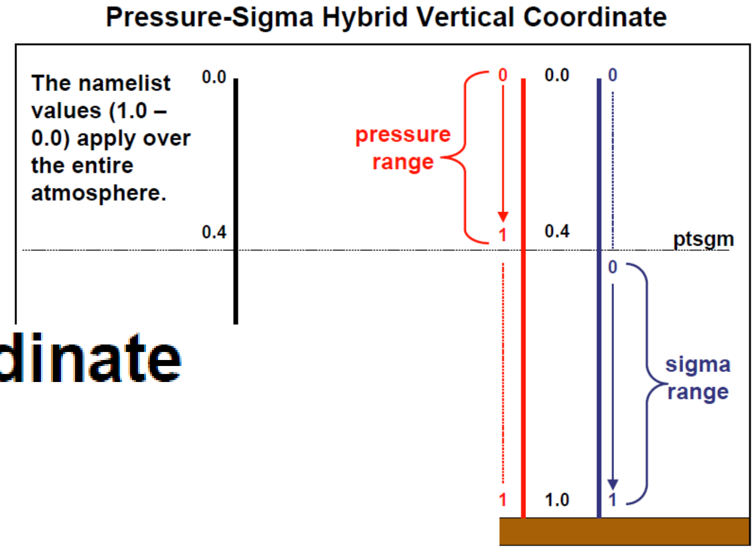
$0 < eta_2 < 1$

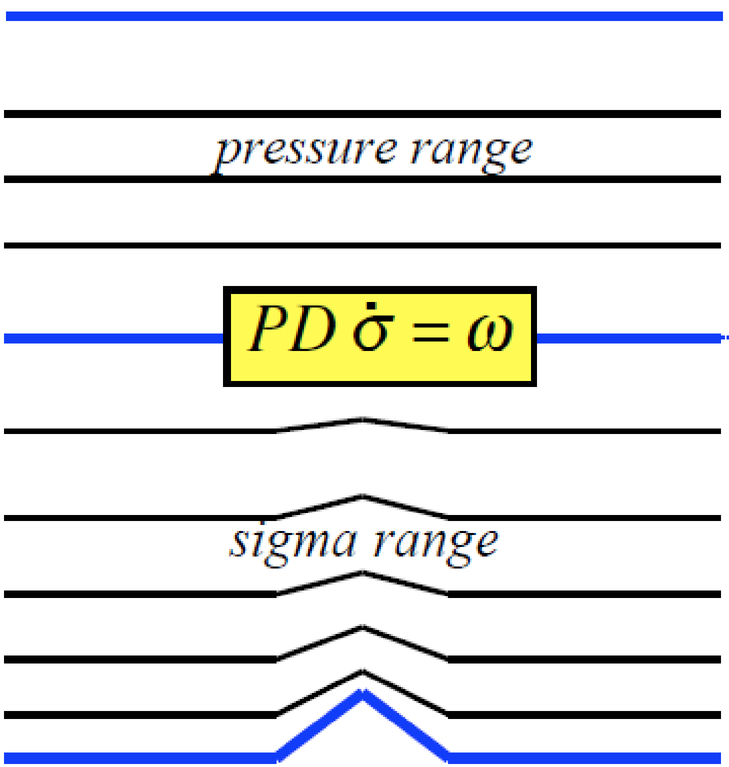
$$p = eta_1 * PD_{TOP} + eta_2 * PD + P_T$$

Vertical Coordinate

- Continuity Eqn:

Equations in Hybrid Coordinate





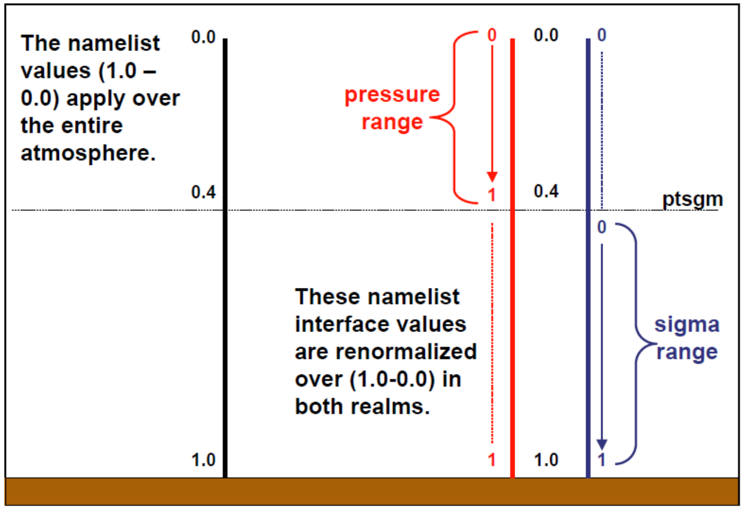
$$\nabla_p \bullet (\mathbf{v}) + \frac{\partial \omega}{\partial p} = 0$$

$$\frac{\partial PD}{\partial t} + \nabla_\sigma \cdot (PD\ \mathbf{v}) + \frac{\partial (PD\dot{\sigma})}{\partial \sigma} = 0$$

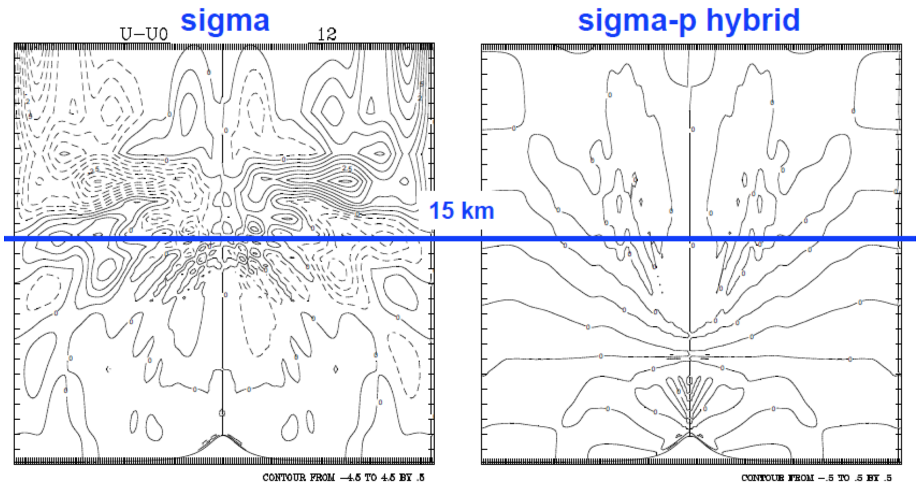
Vertical Coordinate

- Pressure gradient can cause large accelerations near topography in terrain following coordinates, especially at high elevations.
- Hybrid with boundary at about 400mb (~7km) can reduce that spurious acceleration. (Notice smaller winds (left figs) and smoother potential temps. (right figs)

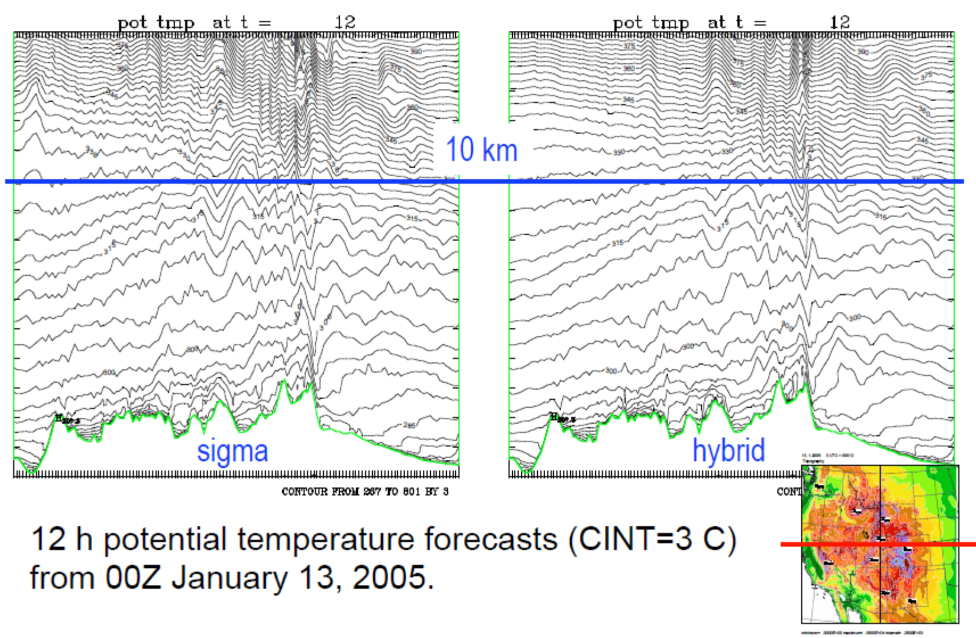
Pressure-Sigma Hybrid Vertical Coordinate



Example of nonphysical small scale energy source



Wind component developing due to the spurious pressure gradient force in an idealized integration. The hybrid coordinate boundary between the pressure and sigma domains is at at about 400 hPa.



12 h potential temperature forecasts (CINT=3 C) from 00Z January 13, 2005.

Terrain-following Eqns

- >

Inviscid, adiabatic, sigma (Janjic et al., 2001, MWR)

Analogous to a hydrostatic system, except for p and ε

p is the total (nonhydrostatic) pressure
π is the hydrostatic pressure

Momentum eqn.

$$\frac{\partial \mathbf{v}}{\partial t} = -\mathbf{v}\cdot\nabla_\sigma \mathbf{v} - \dot{\sigma}\frac{\partial \mathbf{v}}{\partial \sigma} - (1+\varepsilon)\nabla_\sigma \Phi - \alpha\nabla_\sigma p + f\mathbf{k}\times\mathbf{v}$$

Thermodynamic eqn.

$$\frac{\partial T}{\partial t} = -\mathbf{v}\cdot\nabla_\sigma T - \dot{\sigma}\frac{\partial T}{\partial \sigma} + \frac{\alpha}{c_p}[\frac{\partial p}{\partial t} + \mathbf{v}\cdot\nabla_\sigma p + \dot{\sigma}\frac{\partial p}{\partial \sigma}]$$

Continuity eqn.

$$\frac{\partial \mu}{\partial t} + \nabla_\sigma\cdot(\mu\mathbf{v}) + \frac{\partial(\mu\dot{\sigma})}{\partial \sigma} = 0$$

$$\boxed{\alpha = RT/p}$$

$$\boxed{\varepsilon \equiv \frac{1}{g}\frac{dw}{dt}}$$

3rd eqn of motion

$$\frac{\partial p}{\partial \pi} = 1 + \varepsilon$$

Hypsometric eqn.

$$\frac{\partial \Phi}{\partial \sigma} = -\mu\frac{RT}{p}$$

Nonhydrostatic continuity eqn.

$$w = \frac{1}{g}\frac{d\Phi}{dt} = \frac{1}{g}(\frac{\partial \Phi}{\partial t} + \mathbf{v}\cdot\nabla_\sigma \Phi + \dot{\sigma}\frac{\partial \Phi}{\partial \sigma})$$

Terrain-following Eqns

- >

Thermodynamic eqn. $$\frac{\partial T}{\partial t} = -\mathbf{v}\,.\,\nabla_\sigma T - \dot{\sigma}\frac{\partial T}{\partial \sigma} + \frac{\alpha}{c_p}[\frac{\partial p}{\partial t} + \mathbf{v}\,.\,\nabla_\sigma p + \dot{\sigma}\frac{\partial p}{\partial \sigma}]$$

Side note: separation of the thermodynamic equation into two parts

$$\frac{\partial T}{\partial t} = -\mathbf{v}\,.\,\nabla_\sigma T - \dot{\sigma}\frac{\partial T}{\partial \sigma} + \frac{\alpha}{c_p}[\omega_1 + \omega_2]$$

$$\left(\frac{\partial T}{\partial t}\right)_1 = -\mathbf{v}\cdot\nabla_\sigma T - \dot{\sigma}\frac{\partial T}{\partial \sigma} + \frac{1}{c_p}\alpha\omega_1$$
$$\omega_1 = (1+\varepsilon)\frac{\partial \pi}{\partial t} + \mathbf{v}\cdot\nabla_\sigma p + (1+\varepsilon)\dot{\sigma}\frac{\partial \pi}{\partial \sigma}$$

Reduces to hydrostatic equation for ε=0

$$\left(\frac{\partial T}{\partial t}\right)_2 = \frac{1}{c_p}\alpha\omega_2$$
$$\omega_2 = \frac{\partial p}{\partial t} - (1+\varepsilon)\frac{\partial \pi}{\partial t}$$

Vanishes for purely hydrostatic flow

- Φ, w, ε are not independent, no independent prognostic equation for w!
- ε<<1 in meso and large scale atmospheric flows
- Impact of nonhydrostatic dynamics becomes detectable at resolutions <10km, important at 1km.

Flux Form

- Express advective terms with implicit use of continuity eqn. for better numerical treatment.

Hydrostatic pressure coordinate:

hydrostatic pressure π

$$\eta = \frac{(\pi - \pi_t)}{\mu}, \qquad \mu = \pi_s - \pi_t \qquad \mu(x)\Delta\eta = \Delta\pi = -g\rho\Delta z$$

Conserved state variables:

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

Non-conserved state variable: $\phi = gz$

Inviscid, 2-D equations without rotation:

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

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

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

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

$$\frac{d\phi}{dt} = gw$$

Diagnostic relations:

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

Moist Equations:

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

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

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

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

Diagnostic relations:

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

Boundary Conditions

- Vertical motion (in the σ coordinate frame) vanishes at top and bottom of atmosphere
- Non-hydrostatic difference disappears at the top, is constant with σ at the bottom.

Vertical boundaries:

Top: $\dot{\sigma} = 0$, $p - \pi = 0$

Surface: $\dot{\sigma} = 0$, $\dfrac{\partial(p-\pi)}{\partial\sigma} = 0$

p is the total (nonhydrostatic) pressure

π is the hydrostatic pressure

Model Variables

WRF-NMM predictive variables

- Mass variables:
  - PD – hydrostatic pressure depth (time and space varying component) (Pa)
  - PINT – nonhydrostatic pressure (Pa)
  - T – sensible temperature (K)
  - Q – specific humidity (kg/kg)
  - CWM – total cloud water condensate (kg/kg)
  - Q2 – 2 * turbulent kinetic energy (m^2/s^2)
- Wind variables:
  - U, V – wind components (m/s)

Numerics (semi-implicit)

General Philosophy

• >

- Explicit time differencing preferred where possible, as allows for better phase speeds and more transparent coding:
  - horizontal advection of u, v, T
  - passive substance advection of q, cloud water, TKE
- Implicit time differencing for very fast processes that would require a restrictively short time step for numerical stability:
  - vertical advection of u, v, T and vertically propagating sound waves

Numerics

- >

Vertical advection of u, v, & T

Crank-Nicolson:

$$\frac{y^{\tau+1} - y^{\tau}}{\Delta t} = \frac{1}{2}[f(y^{\tau+1}) + f(y^{\tau})]$$

Stability:

An implicit method, it is absolutely stable numerically.

Horizontal advection of u, v, T

2nd order Adams-Bashforth:

$$\frac{y^{\tau+1} - y^{\tau}}{\Delta t} = \frac{3}{2} f(y^{\tau}) - \frac{1}{2} f(y^{\tau-1})$$

Stability/Amplification:

A-B has a weak linear instability (amplification) which can be tolerated in practice or stabilized by a slight off-centering as is done in the WRF-NMM.

$$\frac{y^{\tau+1} - y^{\tau}}{\Delta t} = 1.533 f(y^{\tau}) - 0.533 f(y^{\tau-1})$$

Numerics

- .

Advection of TKE (Q2) and moisture (Q, CWM)

- Similar to Janjic (1997) scheme used in Eta model:
  - Starts with an initial upstream advection step
  - anti-diffusion/anti-filtering step to reduce dispersiveness
  - conservation enforced after each anti-filtering step – maintain global sum of advected quantity, and prevent generation of new extrema.

Fast adjustment processes

Forward-Backward (Ames, 1968; Janjic and Wiin-Nielsen, 1977; Janjic 1979): Mass field computed from a forward time difference, while the velocity field comes from a backward time difference.

In a shallow water equation sense:

$$\frac{\partial u}{\partial t} = -g\frac{\partial h}{\partial x}, \frac{\partial h}{\partial t} = -H\frac{\partial u}{\partial x}$$

$$h^{\tau+1} = h^{\tau} - \Delta t\, H\frac{\partial u^{\tau}}{\partial x}$$

$$u^{\tau+1} = u^{\tau} - \Delta t\, g\frac{\partial h^{\tau+1}}{\partial x}$$

Mass field forcing to update wind from τ+1 time

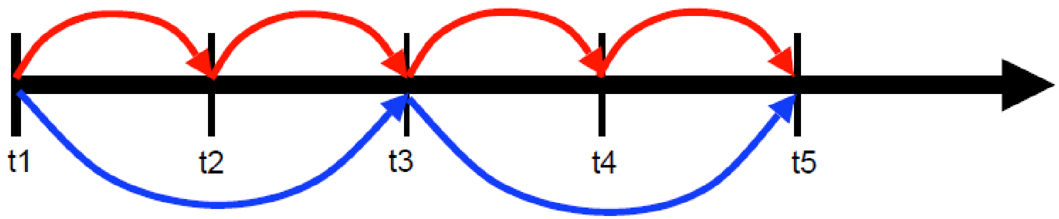
Numerics

- **Time step (dt) proportional to time that fastest mode treated *explicitly* can traverse the grid interval (dx)**

- **So, acoustic waves or certain gravity waves can limit the dt**

- **dt ~ 30-50s for 12km dx**

All dynamical processes every fundamental time step, except….



…passive substance advection, every other time step

Model time step “dt” specified in model namelist.input is for the fundamental time step.

Generally about 2.25X the horizontal grid spacing (km), or 350X the namelist.input “dy” value (degrees lat).

Guidelines for time step

Δt in seconds should be about $6*\Delta x$ (grid size in kilometers). Larger Δt can be used in smaller-scale dry situations, but *time_step_sound* (default = 4) should increase proportionately if larger Δt is used.

Numerics

- (ARW is a variation on WRF)

Time Integration in ARW

3rd Order Runge-Kutta time integration

advance $\phi^{t} \rightarrow \phi^{t+\Delta t}$

$$\phi^{*} = \phi^{t} + \frac{\Delta t}{3} R\left(\phi^{t}\right)$$

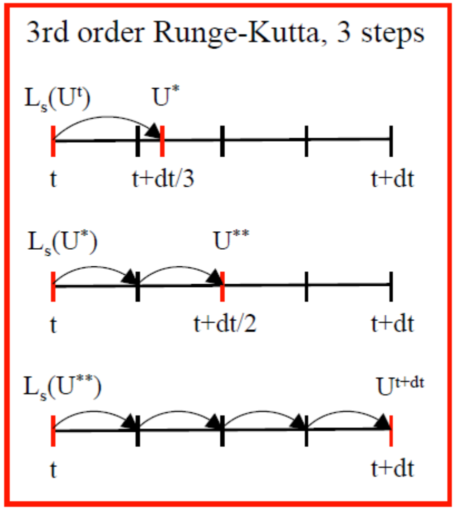
$$\phi^{**} = \phi^{t} + \frac{\Delta t}{2} R\left(\phi^{*}\right)$$

$$\phi^{t+\Delta t} = \phi^{t} + \Delta t \, R\left(\phi^{**}\right)$$

Amplification factor $\phi_t = i k \phi; \quad \phi^{n+1} = A \phi^{n}; \quad |A| = 1 - \frac{(k\Delta t)^4}{24}$

Time-Split Runge-Kutta Integration Scheme

$$U_t = L_{fast}(U) + L_{slow}(U)$$



- RK3 is 3rd order accurate for linear eqns, 2nd order accurate for nonlinear eqns.
- Stable for centered and upwind advection schemes.
- Stable for Courant number $Udt/dx < 1.73$
- Three $L_{slow}(U)$ evaluations per timestep.

Numerics

- (ARW is a variation on WRF)
- Various filters are used to control high frequency and unrealistic oscillations.
- 4 of examples shown (there are other numerical filters)

ARW Filters: Vertical Velocity Damping

Purpose: damp anomalously-large vertical velocities
(usually associated with anomalous physics tendencies)

Additional term:

$$\partial_t W = \ldots \underline{- \mu_d \,\mathrm{sign}(W) \gamma_w (Cr - Cr_\beta)}$$

$$Cr = \left| \frac{\Omega dt}{\mu d\eta} \right|$$

$Cr_\beta = 1.0$ typical value (default)
$\gamma_w = 0.3$ m/s² recommended (default)

ARW Filters: Upper Level Gravity-Wave Absorbers

(2) Traditional Rayleigh Damping - idealized cases only!

$$\begin{aligned}
\frac{\partial u}{\partial t} &= -\tau(z)\,(u - \overline{u}) \\
\frac{\partial v}{\partial t} &= -\tau(z)\,(v - \overline{v}) \\
\frac{\partial w}{\partial t} &= -\tau(z) w, \\
\frac{\partial \theta}{\partial t} &= -\tau(z)\,(\theta - \overline{\theta})
\end{aligned}$$

$$\tau(z) = \begin{cases} \gamma_r \sin^2\left[\frac{\pi}{2}\left(1 - \frac{z_{top} - z}{z_d}\right)\right] & \text{for } z \ge (z_{top} - z_d); \\ 0 & \text{otherwise,} \end{cases}$$

$\tau(z)$ - damping rate (t^{-1})
z_d - depth of the damping layer
γ_r - dimensionless damping coefficient

ARW Filters: Divergence Damping

Purpose: filter acoustic modes

$$p^{*\tau} = p^\tau + \gamma_d \left(p^\tau - p^{\tau - \Delta\tau}\right) \quad \text{since} \quad p_t \sim c^2 \nabla \cdot \rho \mathbf{V}$$

$$\delta_\tau U'' + \mu^{t^*} \alpha^{t^*} \partial_x p''^\tau + (\mu^{t^*} \partial_x \bar{p}) \alpha''^\tau + (\alpha/\alpha_d)[\mu^{t^*} \partial_x \phi''^\tau + (\partial_x \phi^{t^*})(\partial_\eta p'' - \mu'')^\tau] = R_U{}^{t^*}$$

$$\delta_\tau V'' + \mu^{t^*} \alpha^{t^*} \partial_y p''^\tau + (\mu^{t^*} \partial_y \bar{p}) \alpha''^\tau + (\alpha/\alpha_d)[\mu^{t^*} \partial_y \phi''^\tau + (\partial_y \phi^{t^*})(\partial_\eta p'' - \mu'')^\tau] = R_V{}^{t^*}$$

$\gamma_d = 0.1$ recommended (default)

ARW Filters: 2nd-Order Horizontal Mixing, Horizontal-Deformation-Based K_h

Purpose: mixing on horizontal coordinate surfaces
(real-data applications)

$$K_h = C_s^2\, l^2 \left[0.25(D_{11} - D_{22})^2 + \overline{D_{12}^2}^{xy}\right]^{\frac{1}{2}}$$

where $l = (\Delta x \Delta y)^{1/2}$

$$\begin{aligned}
D_{11} &= 2\, m^2 [\partial_x(m^{-1}u) - z_x \partial_z(m^{-1}u)] \\
D_{22} &= 2\, m^2 [\partial_y(m^{-1}v) - z_y \partial_z(m^{-1}v)] \\
D_{12} &= m^2 [\partial_y(m^{-1}u) - z_y \partial_z(m^{-1}u) \\
&\quad + \partial_x(m^{-1}v) - z_x \partial_z(m^{-1}v)]
\end{aligned}$$

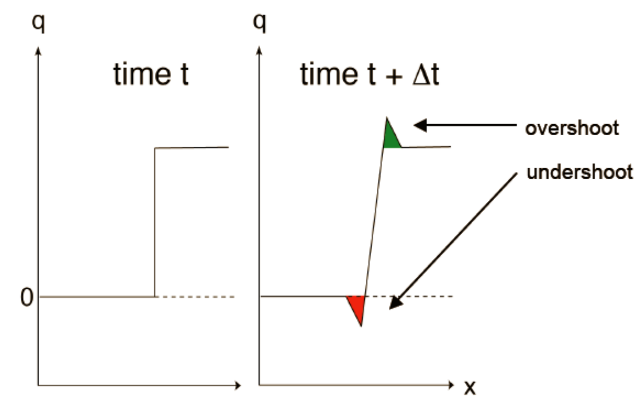
$C_s = 0.25$ (Smagorinsky coefficient, default value)

Numerics

- (ARW is a variation on WRF)
- Numerical advection is not perfect. Some variables (like moisture) can develop unrealistic negative values.
- Renormalization tries to remove those spurious values

Moisture Transport in ARW

1D advection



ARW scheme is conservative,
but not positive definite nor monotonic.
Removal of negative q
results in spurious source of q .

Positive-Definite Flux Renormalization

Scalar update, last RK3 step

$$(\mu\phi)^{t+\Delta t} = (\mu\phi)^{t} - \Delta t \sum_{i=1}^{n} \delta_{x_i}[f_i] \qquad (1)$$

(1) Decompose flux: $f_i = f_i^{upwind} + f_i^{c}$

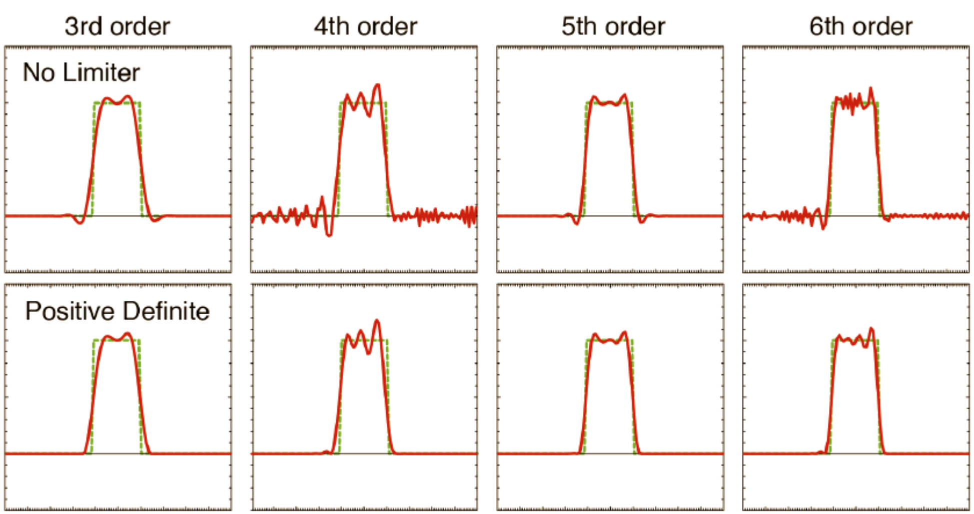
(2) Renormalize high-order correction fluxes f_i^{c} such that solution is positive definite: $f_i^{c} = R(f_i^{c})$

(3) Update scalar eqn. (1) using $f_i = f_i^{upwind} + R(f_i^{c})$

Skamarock, MWR 2006, 2241-2250

PD Limiter in ARW - 1D Example Top-Hat Advection

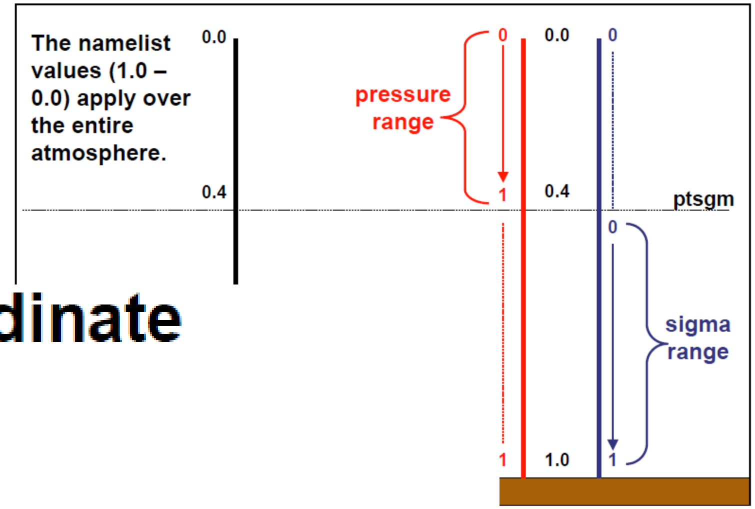
Cr = 0.5, 1 revolution (200 steps)



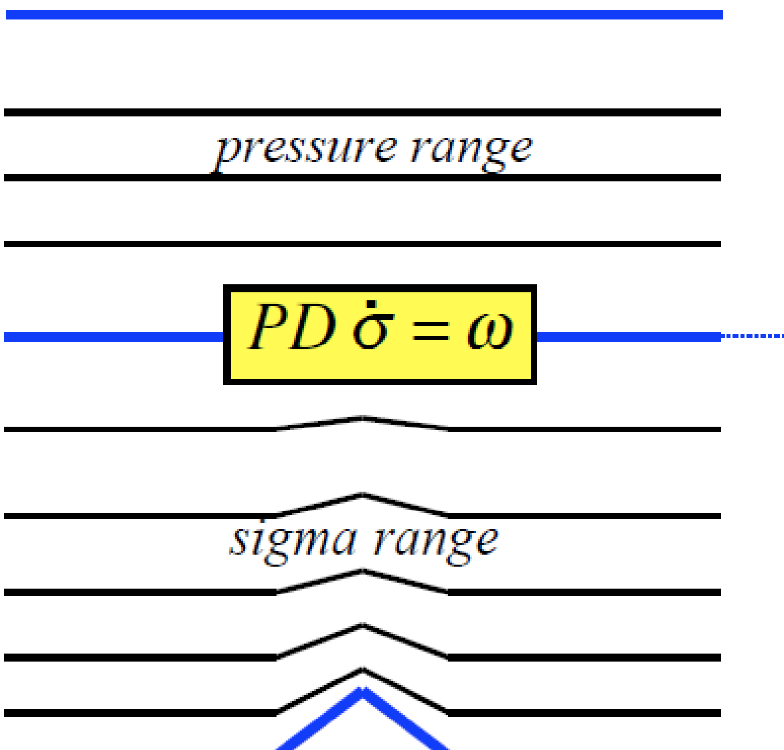
Vertical Coordinate

- Continuity Eqn:

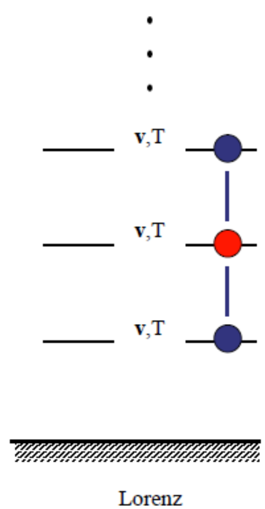
Pressure-Sigma Hybrid Vertical Coordinate



Equations in Hybrid Coordinate



Vertical discretization

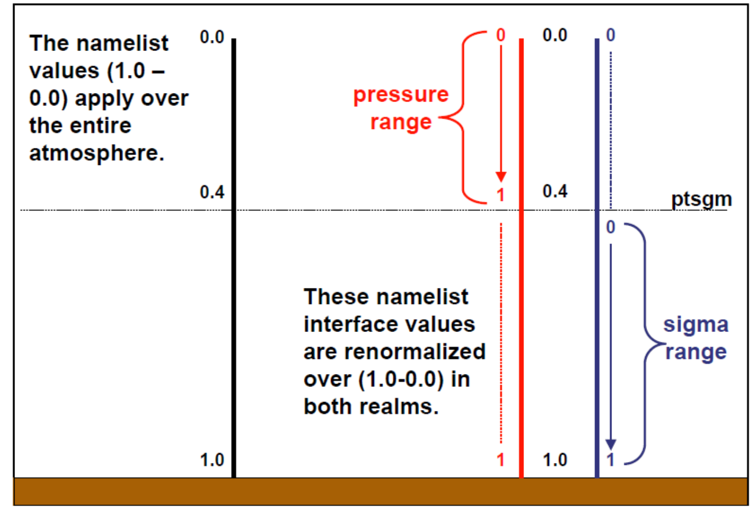


Vertical advection combines the advective fluxes computed above and below the layer of interest.

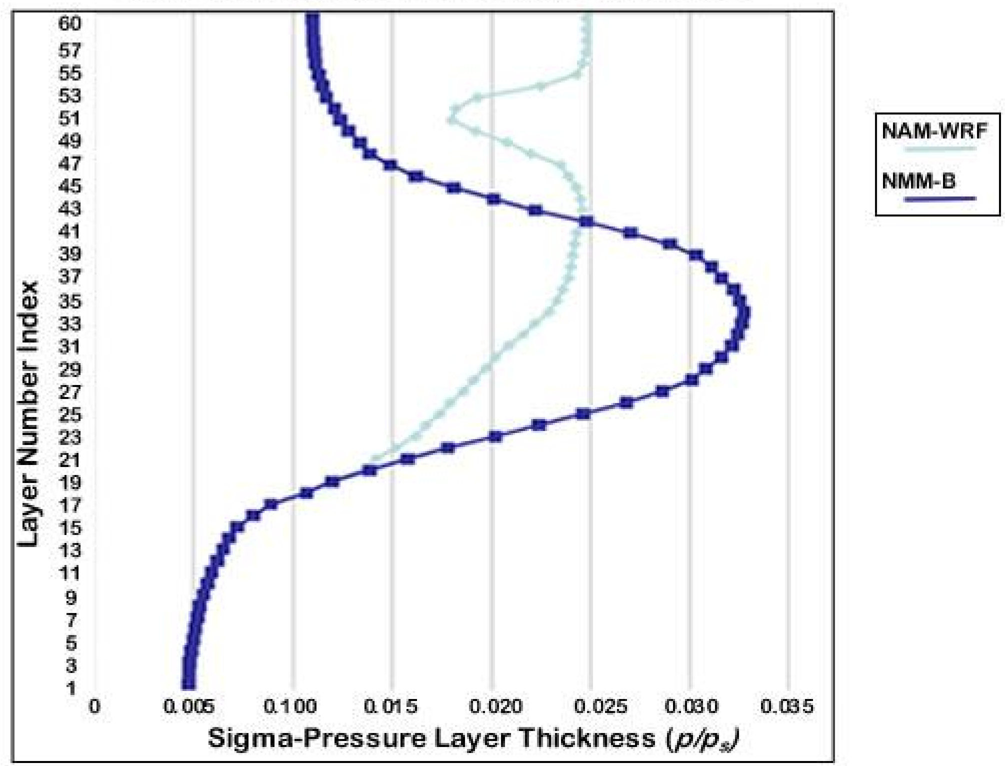
Vertical Coordinate

- NAMB vs NMM:
- Still 60 layers, but spacing changed
- Thinner layers in:
  - Stratosphere
- Thicker in mid-upper troposphere
- Pressure alone above 300 hPa

Pressure-Sigma Hybrid Vertical Coordinate



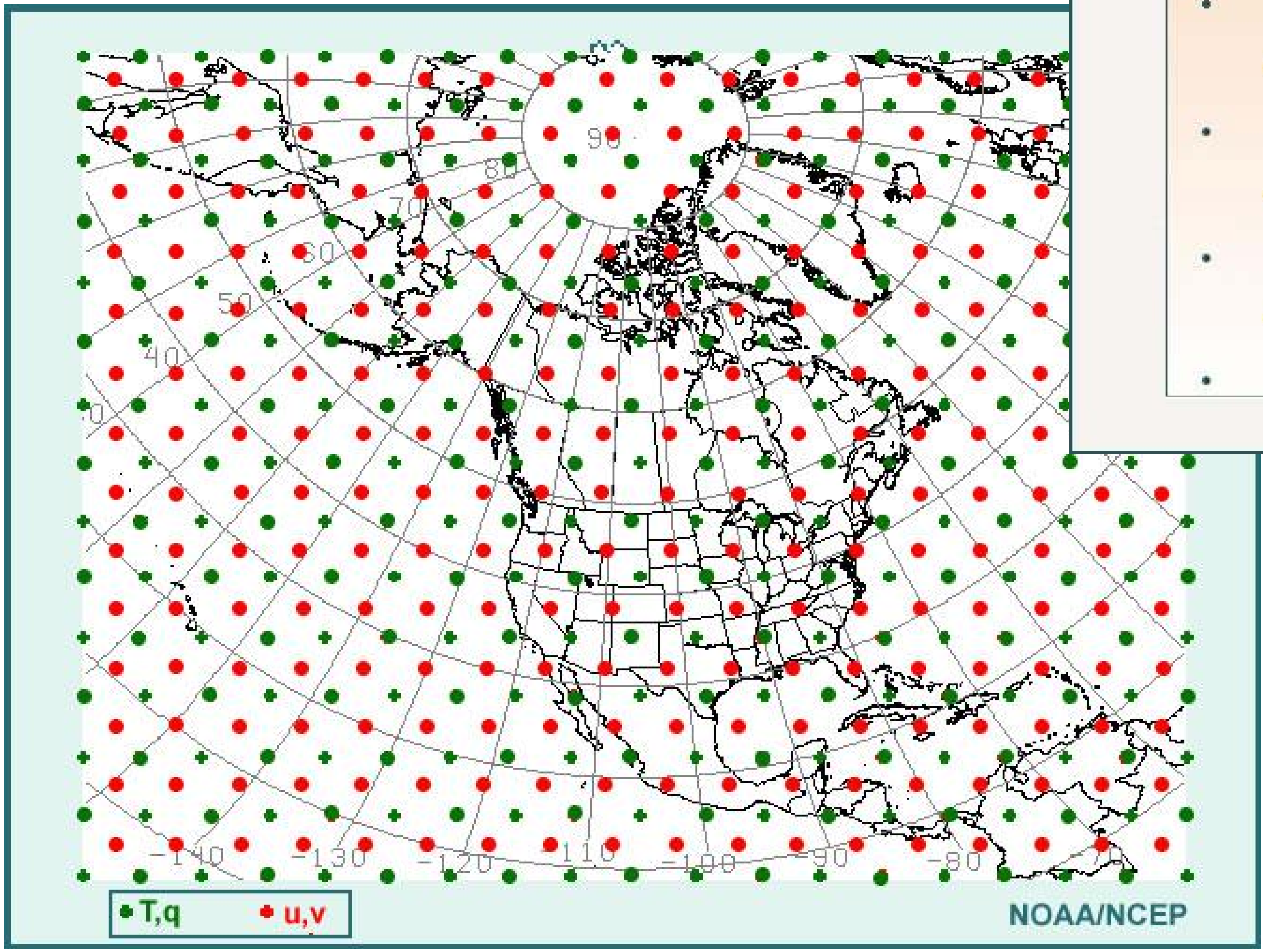
NAM-WRF versus NMM-B Layer Thickness

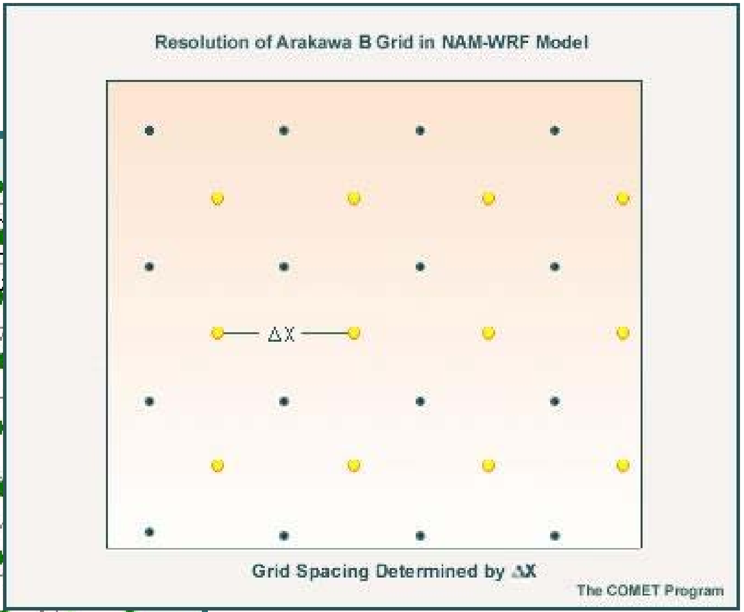


NOAA/NCEP

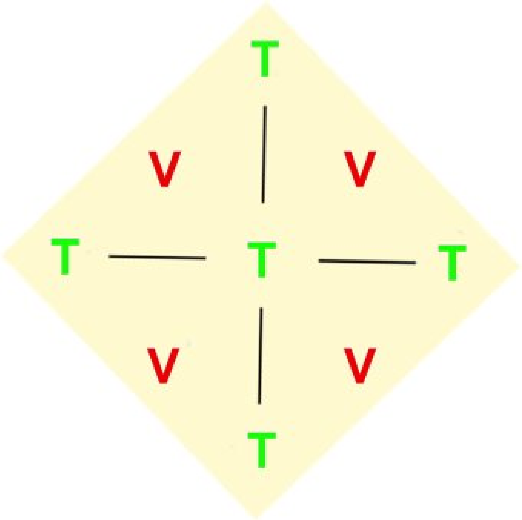
Horizontal Staggered Grid

- NAMB: Arakawa 'B' grid





Staggered Grid



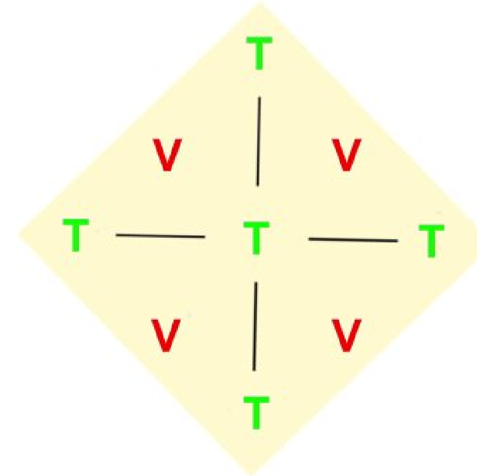
Arakawa ‘B’ grid

- .

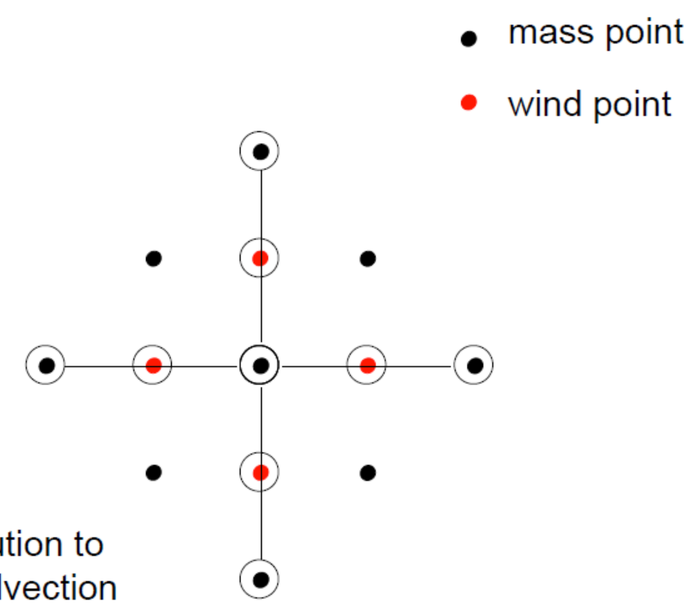
General Philosophy

- Conserve energy and enstrophy in order to control nonlinear energy cascade; eliminate the need for numerical filtering to the extent possible.
- Conserve a number of first order and quadratic quantities (mass, momentum, energy, …).
- Use consistent order of accuracy for advection and divergence operators and the omega-alpha term; consistent transformations between KE and PE.
- Preserve properties of differential operators.

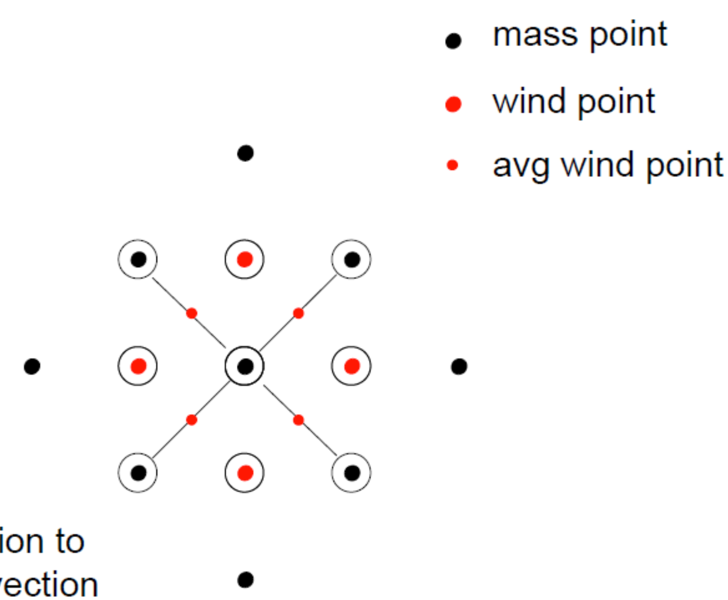
Staggered Grid



- Derivative in advection and divergence operator is average of several combinations of differencing options.
- Averaging operators can result in scheme that conserves things that should be conserved

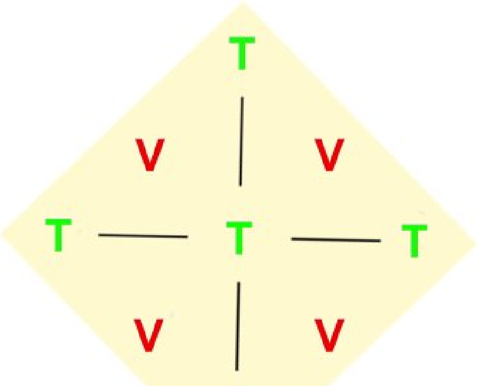


1/3 of contribution to divergence/advection comes from these N/S and E/W fluxes.

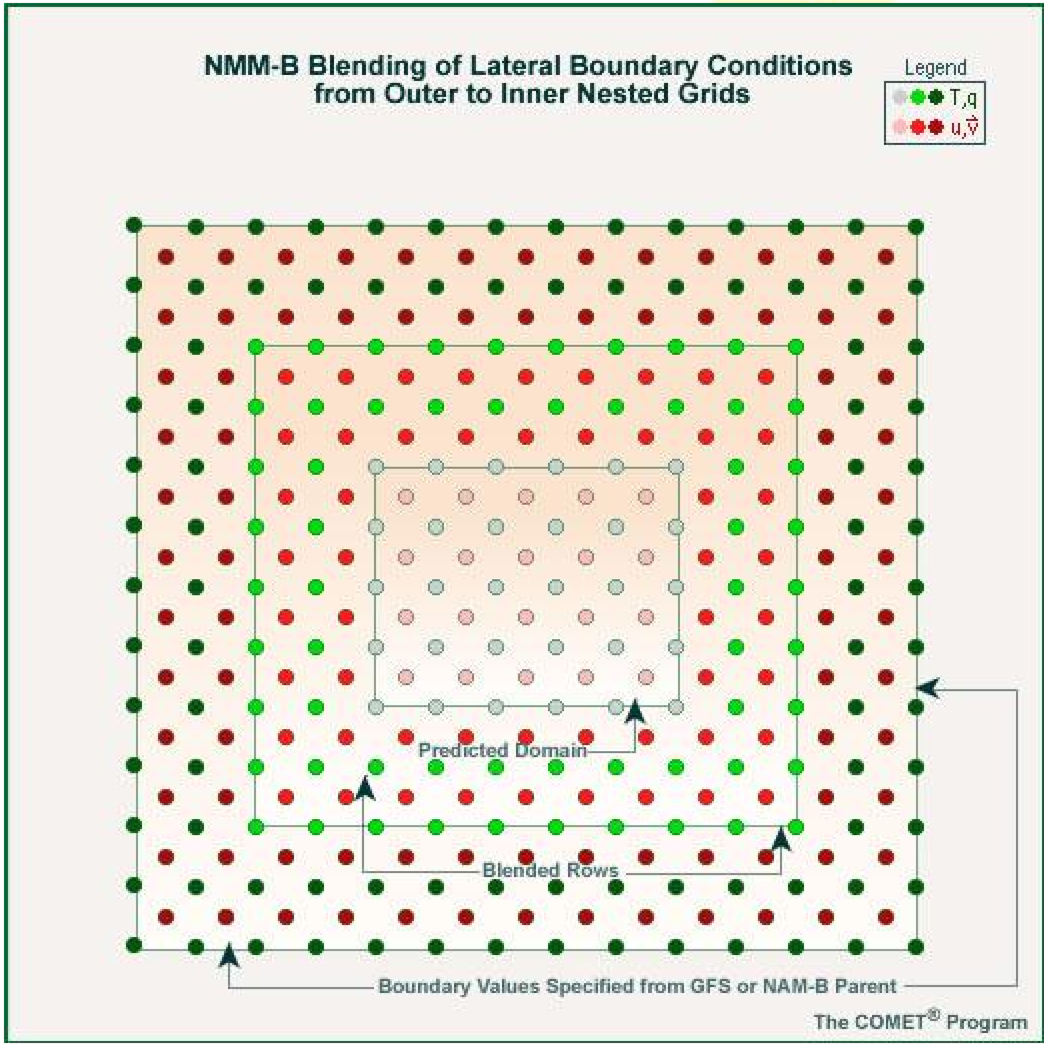


2/3 of contribution to divergence/advection comes from these diagonal fluxes.

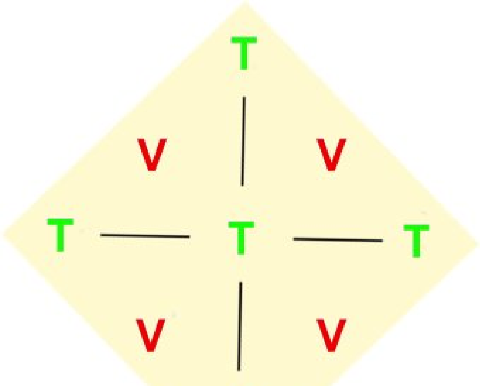
Boundary Conditions (BCs)



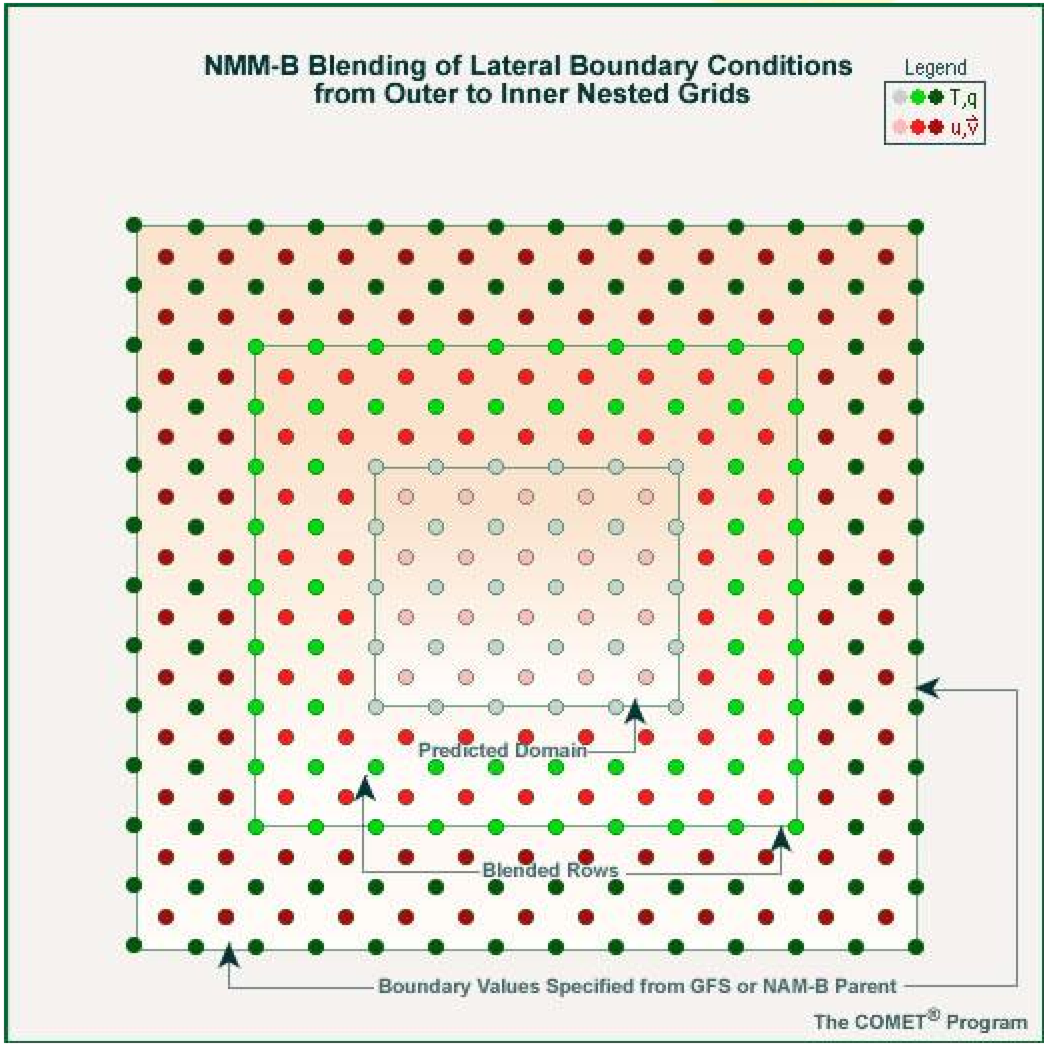
- GFS forecast (starting 6 hrs prior) provides boundary conditions for this limited area model.
- Linear in time and bi-linear in space transition from specified GFS outermost and NAMB predicted innermost grid values
- Additional nesting to inner layers in NAM use the NAM values but is one-way: inner affected by outer, but outer not affected by inner grid.
- Grid interval change by factor of 3 is typical.



Vertical BCs



- Top of atmosphere is rigid lid.
- Surface BCs are dynamical and based on time-varying processes largely handled in parameterization schemes (covered in another presentation)



Integration Sequence

- Fourier filtering (to remove small scales and high frequencies) also done at each stage of the acoustic loop and once again.

Begin time step

Runge-Kutta loop (steps 1, 2, and 3)

(i) advection, p-grad, buoyancy using $\left(\phi^{t}, \phi^{*}, \phi^{**}\right)$

(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 μ, Θ, then w, ϕ

(ii) time-average U,V, Ω

End acoustic loop

Advance scalars using time-averaged U,V, Ω

End Runge-Kutta loop

Adjustment physics (currently microphysics)

End time step

Integration Sequence

- >

$$\frac{\partial \mathbf{v}}{\partial t} = -\mathbf{v}\cdot\nabla_\sigma \mathbf{v} - \dot{\sigma}\frac{\partial \mathbf{v}}{\partial \sigma} - (1+\varepsilon)\nabla_\sigma \Phi - \alpha\nabla_\sigma p + f\mathbf{k}\times\mathbf{v}$$

$$\frac{\partial T}{\partial t} = -\mathbf{v}\cdot\nabla_\sigma T - \dot{\sigma}\frac{\partial T}{\partial \sigma} + \frac{\alpha}{c_p}\left[\frac{\partial p}{\partial t} + \mathbf{v}\cdot\nabla_\sigma p + \dot{\sigma}\frac{\partial p}{\partial \sigma}\right]$$

$$\frac{\partial \mu}{\partial t} + \nabla_\sigma\cdot(\mu\mathbf{v}) + \frac{\partial(\mu\dot{\sigma})}{\partial \sigma} = 0$$

$$\boxed{\alpha = RT/p}$$

$$\boxed{\varepsilon \equiv \frac{1}{g}\frac{dw}{dt}}$$

$$\frac{\partial p}{\partial \pi} = 1+\varepsilon$$

$$\frac{\partial \Phi}{\partial \sigma} = -\mu\frac{RT}{p}$$

$$w = \frac{1}{g}\frac{d\Phi}{dt} = \frac{1}{g}\left(\frac{\partial \Phi}{\partial t} + \mathbf{v}\cdot\nabla_\sigma\Phi + \dot{\sigma}\frac{\partial \Phi}{\partial \sigma}\right)$$

- Sequence of events within a solve_nmm loop (ignoring physics):
  - (0.6%) PDTE – integrates mass flux divergence, computes vertical velocity and updates hydrostatic pressure.
  - (26.4%) ADVE – horizontal and vertical advection of T, u, v, Coriolis and curvature terms applied.
  - (1.2%) VTOA – updates nonhydrostatic pressure, applies $\omega\alpha$ term to thermodynamic equation
  - (8.6%) VADZ/HADZ – vertical/horizontal advection of height. w=dz/dt updated.
  - (10.6%) EPS – vertical and horizontal advection of dz/dt, vertical sound wave treatment.

(relative % of dynamics time spent in these subroutines)

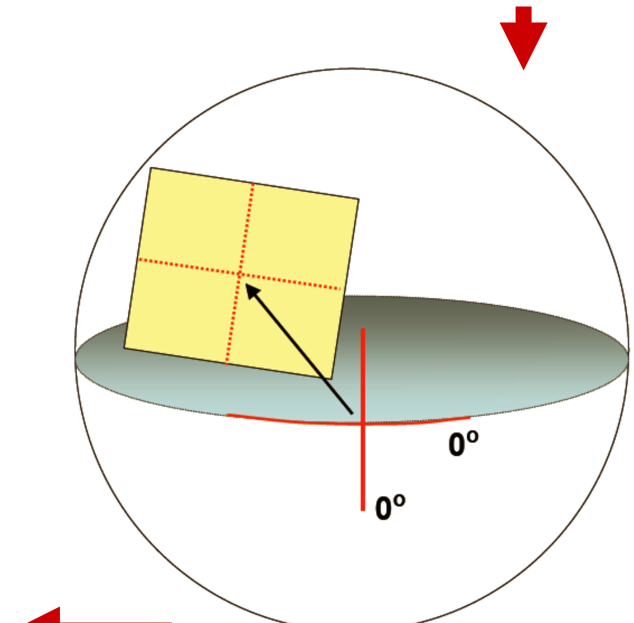
  - (19.5%) VAD2/HAD2 (every other step) – vertical/horizontal advection of q, CWM, TKE
  - (11.8%) HDIFF – horizontal diffusion
  - (1.2%) BOCOH – boundary update at mass points
  - (17.5%) PFDHT – calculates PGF, updates winds due to PGF, computes divergence.
  - (2.3%) DDAMP – divergence damping
  - (0.3%) BOCOV – boundary update at wind points

Map Projection

- Rotate lat. & long.

- Rotates the earth's latitude/longitude grid such that the intersection of the equator and prime meridian is at the center of the model domain.

- The rotation minimizes the convergence of meridians over the domain, and maintains a more uniform earth-relative grid spacing than exists for a regular lat-lon grid.



For a domain spanning 10N to 70N:

$$\Delta x \propto \cos(lat)$$

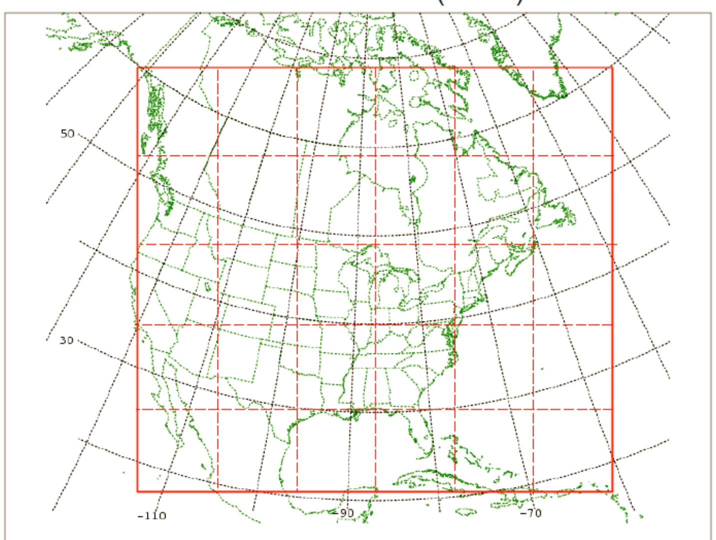
Regular lat-lon grid

$$\cos(70^0)/\cos(10^0) = 0.347$$

Rotated lat-lon grid

$$\cos(30^0)/\cos(0^0) = 0.866$$

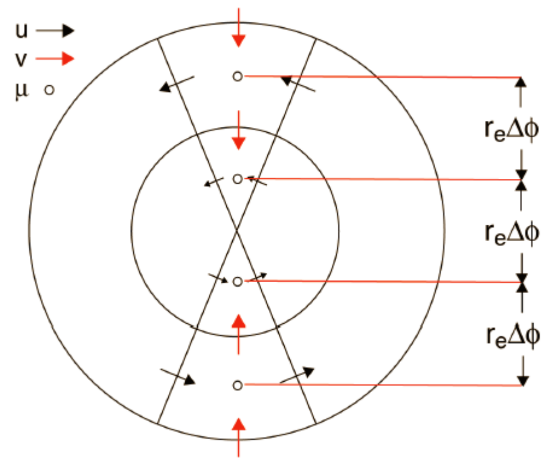
Sample rotated lat-lon domain (red), with earth lat-lon lines (black)



Map Projection

- Map factors (m_x, m_y) map spherical earth to model's rectangular grid
- All eqns. have these factors in them
- (Pole needs special care)

Polar boundary condition (pole point).



Meridional velocity (v) is undefined at the poles.

Zero meriodional flux at the poles (cell-face area is zero).

v (poles) only needed for meridional derivative of v near the poles (some approximation needed).

All other meriodional derivatives are well-defined near/at poles.

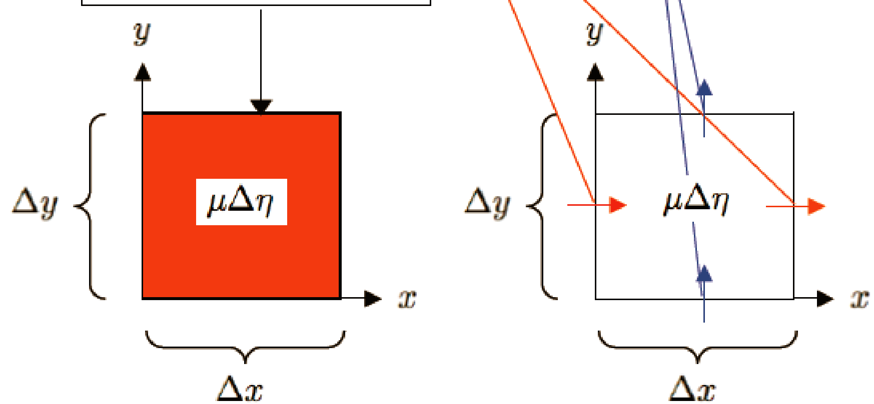
Map-scale factor: $m_x = \dfrac{\Delta x}{\text{distance on the earth}}, \quad m_y = \dfrac{\Delta y}{\text{distance on the earth}}$

Continuity equation:

$$\frac{\partial \mu}{\partial t} + m_x m_y \left[\frac{\partial}{\partial x}\left(\frac{\mu u}{m_y}\right) + \frac{\partial}{\partial y}\left(\frac{\mu v}{m_x}\right)\right] + \frac{\partial}{\partial \eta}(\mu\omega) = 0$$

$$\boxed{\propto \frac{1}{\text{control volume area}}}$$

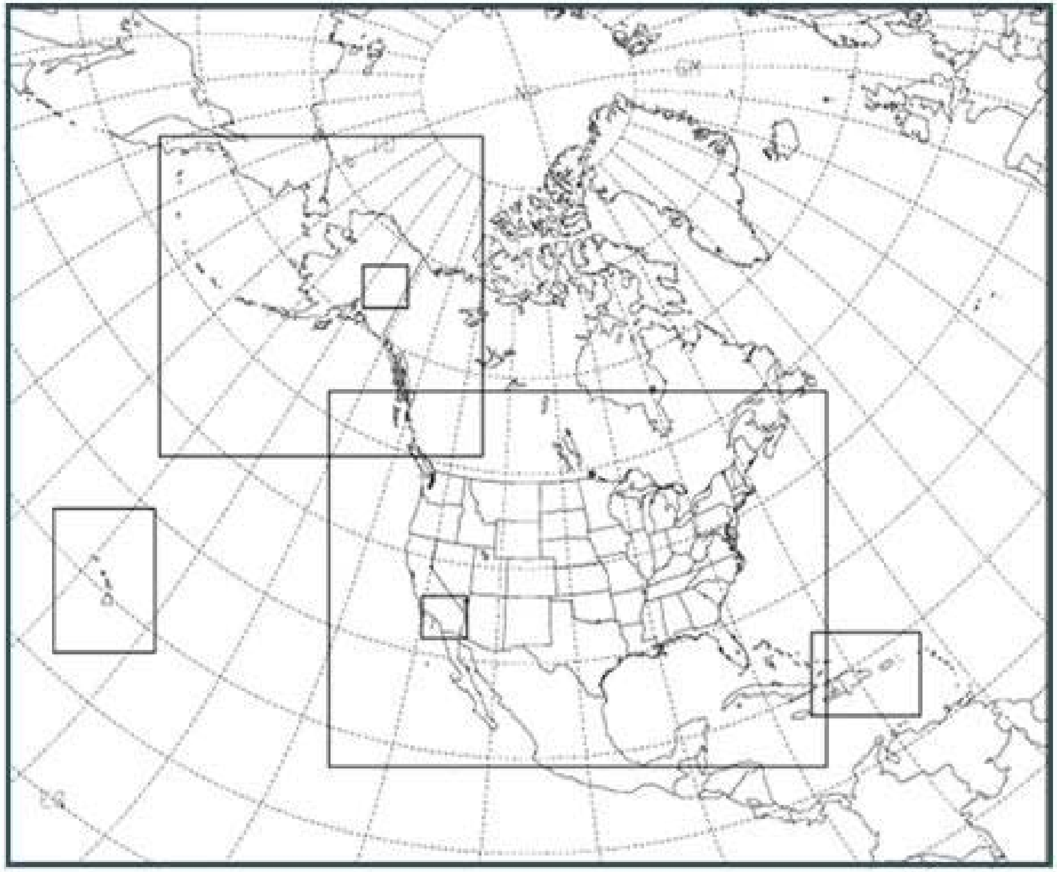
Control volume:



NAM Domains

- Extended domains include Alaska, Hawaii, Puerto Rico.
- Typical plots just over CONUS
- Higher resolution for special cases

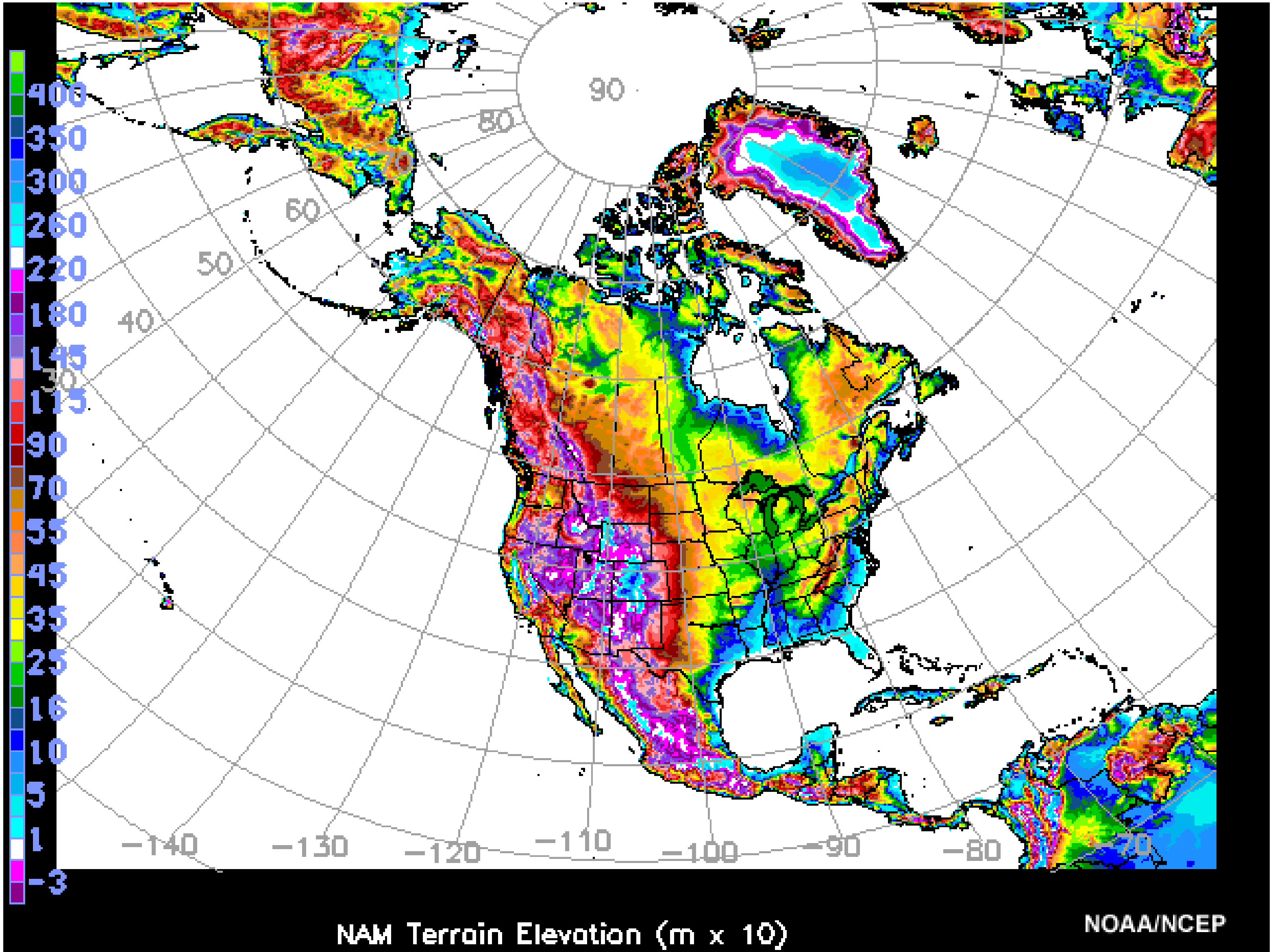
NAM-B Parent and CONUS, Alaska, Hawaii, Puerto Rico, and Example Fire Weather Nest Domains



NOAA/NCEP

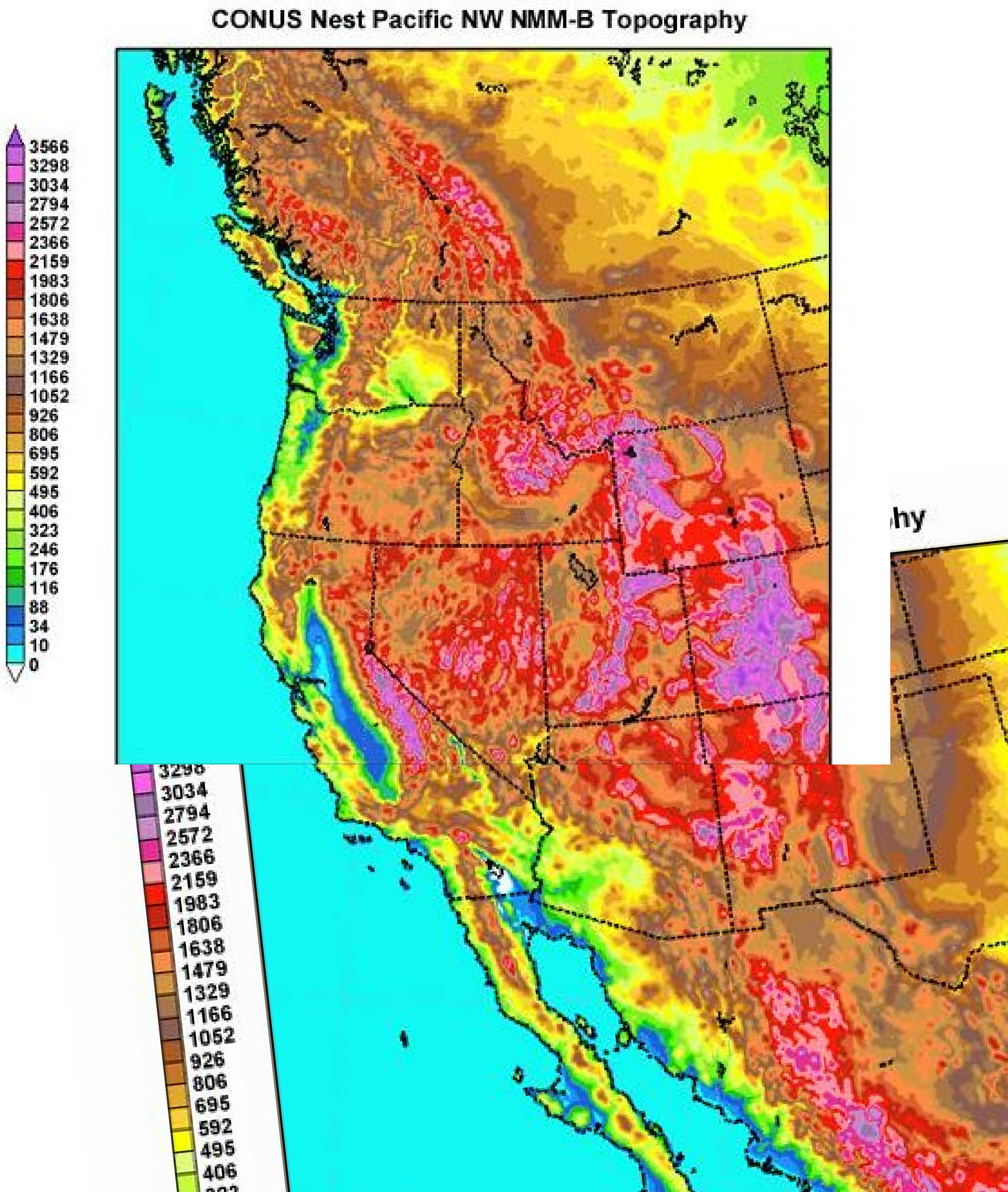
NAM topography

- Elevations in m for grid interval of 12 km (Eta topography)



NAMB topography

- Elevations in m
- 12 km grid interval
- Resolves 75 to 100 km in scale (6-8 grid pts)
- Cannot resolve:
  - Individual convective cells or clusters of cells
  - Lake breeze circulations
  - Mountain valley circulations
  - Sea breezes
  - Outflow boundaries



NAMB Dynamics Summary

- Robust, reliable, fast
- NWP on near-cloud scales successful more frequently and with stronger signal than if only by chance
- Replaced the Eta as NAM at NCEP on June 20, 2006

  Updated again: NMM → NAMB in 2011
- Near-cloud-scale runs (~4 km grid spacing) operational at NCEP for severe weather forecasting
- Operational as Hurricane WRF in 2007
- Operational and quasi-operational elsewhere.

- Nothing said yet about physics parameterization schemes!