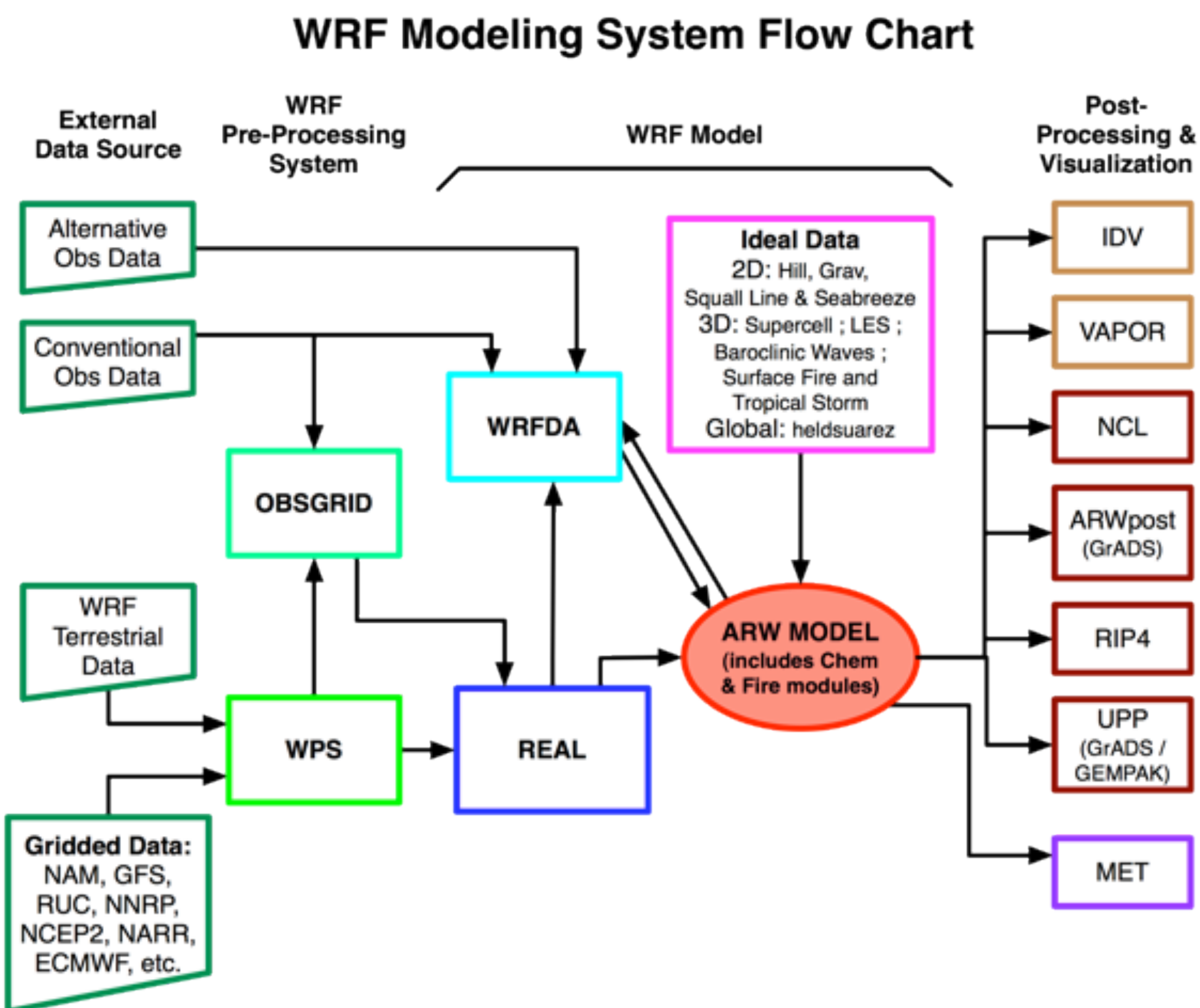
The Advanced Research WRF (ARW) Dynamics Solver

1. Terrain, vertical coordinate
2. Equations and variables
3. Time integration scheme
4. Grid staggering
5. Advection (transport) and conservation
6. Time step parameters
7. Filters
8. Map projections and global configuration

Bill Skamarock (skamaroc@ucar.edu)

Dynamics: Introduction



WRF ARW Tech Note

A Description of the Advanced Research WRF Version 3

http://www.mmm.ucar.edu/wrf/users/pub-doc.html

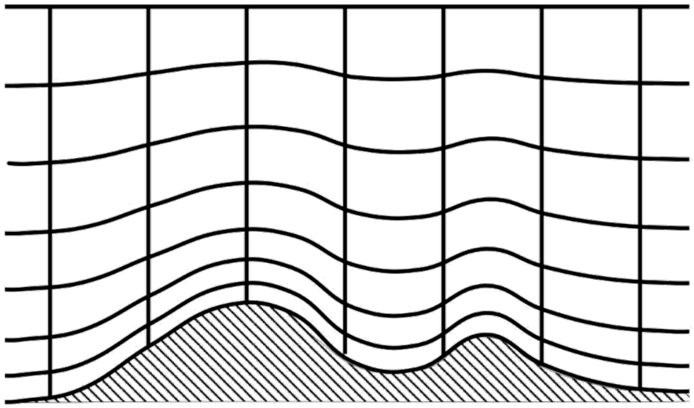
Dynamics: 1. Terrain, vertical coordinate

Hydrostatic pressure π

Column mass (per unit area) $\mu = \pi_s - \pi_t$

Vertical coordinate $\eta = \dfrac{(\pi - \pi_t)}{\mu}$

Layer mass (per unit area) $\mu \Delta\eta = \Delta\pi = g\rho\Delta z$



Conserved state (prognostic) variables:

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

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

Dynamics: 2. Equations and variables – moist equations

Moist Equations:

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

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

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

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

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

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

Diagnostic relations:

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

Dynamics: 2. Equations and variables – velocities

Vertical momentum eqn.

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

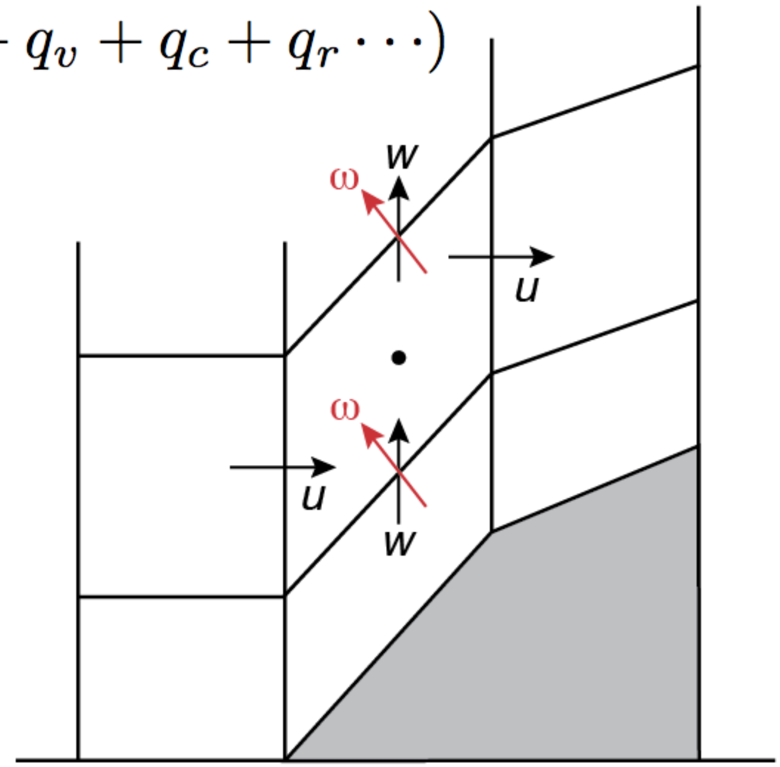
Subscript *d* denotes *dry*, and

$$\alpha_d = \frac{1}{\rho_d} \qquad \begin{aligned} \alpha &= \alpha_d\left(1 + q_v + q_c + q_r \cdots\right)^{-1} \\ \rho &= \rho_d\left(1 + q_v + q_c + q_r \cdots\right) \end{aligned}$$

covariant (u, ω) and
contravariant w velocities

$$u = \frac{dx}{dt}, \quad w = \frac{dz}{dt}, \quad \omega = \frac{d\eta}{dt}$$

$$U = \mu u, \quad W \mu w, \quad \Omega = \mu\omega$$



3rd Order Runge-Kutta time integration

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

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

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

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

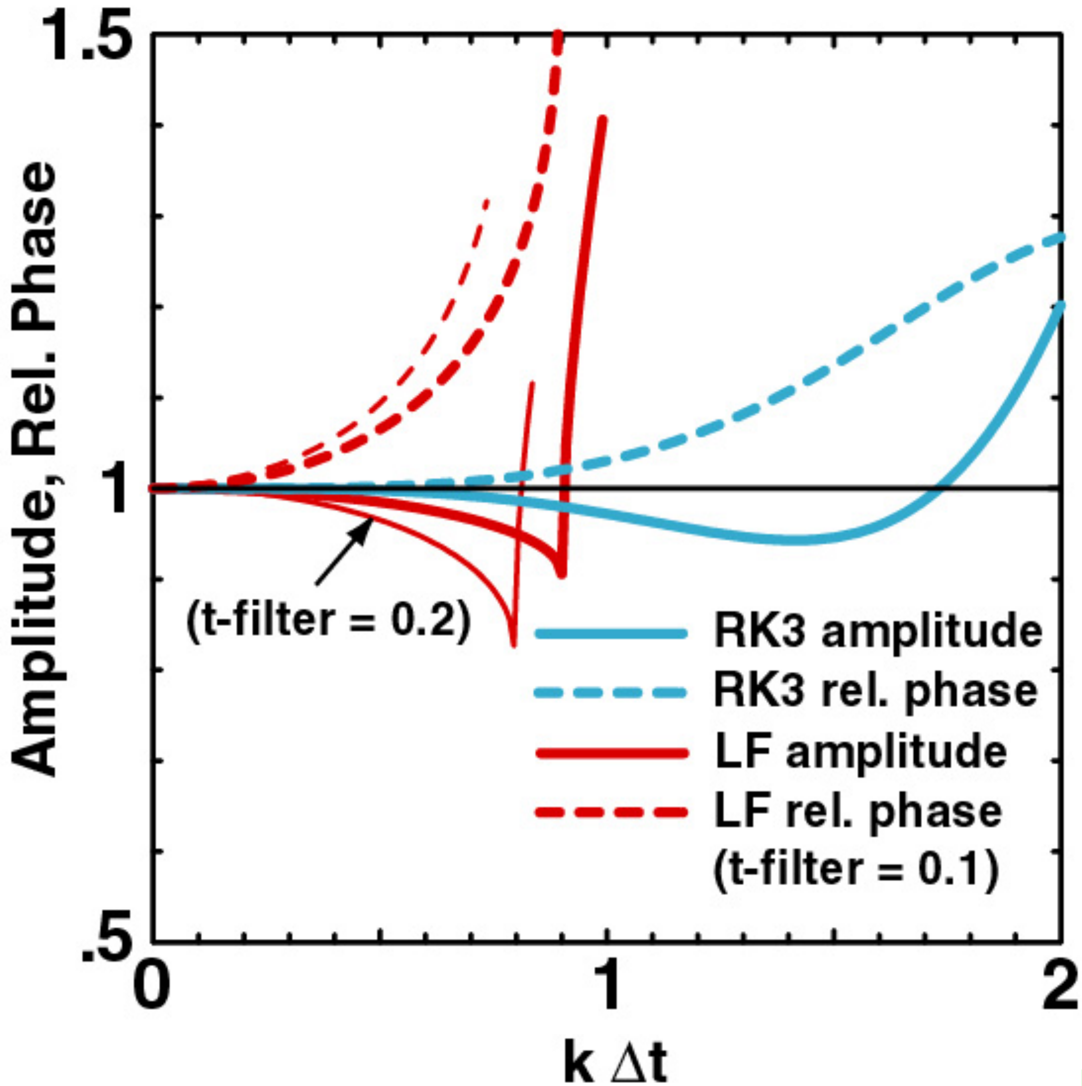
Amplification factor $\phi_{t} = i k \phi; \quad \phi^{n+1} = A \phi^{n}; \quad |A| = 1 - \frac{(k \Delta t)^{4}}{24}$

Bill Skamarock (skamaroc@ucar.edu)

Phase and amplitude errors for LF, RK3

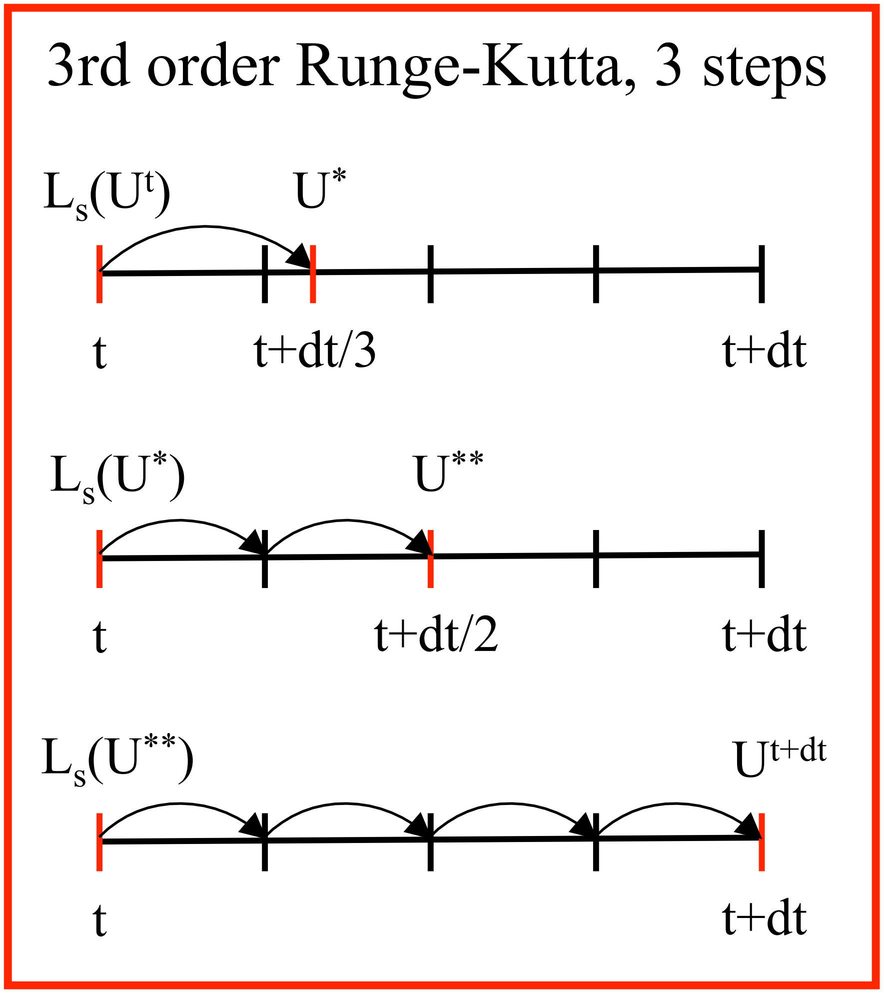
Oscillation equation analysis

$$\phi_t = ik\phi$$



Dynamics: 3. Time integration scheme – time splitting

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



- 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.

Bill Skamarock (skamaroc@ucar.edu)

Dynamics: 3. Time integration scheme - implementation

Begin time step

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

(i) advection, p-grad, buoyancy using (ϕ^t, ϕ^*, ϕ^{**})

(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

Bill Skamarock (skamaroc@ucar.edu)

Dynamics: 3. Time integration scheme – perturbation variables

Introduce the perturbation variables:

$$\phi = \overline{\phi}(\overline{z}) + \phi', \mu = \overline{\mu}(\overline{z}) + \mu';$$
$$p = \overline{p}(\overline{z}) + p', \alpha = \overline{\alpha}(\overline{z}) + \alpha'$$

Note – $\phi = \overline{\phi}(\overline{z}) = \overline{\phi}(x, y, \eta),$

likewise $\overline{p}(x, y, \eta), \overline{\alpha}(x, y, \eta)$

Reduces horizontal pressure-gradient errors.

For small time steps, recast variables as perturbations from time t

$$U' = U'^{t} + U'', \; V' = V'^{t} + V'', \; W' = W'^{t} + W'',$$
$$\Theta' = \Theta'^{t} + \Theta'', \; \mu' = \mu'^{t} + \mu'', \; \phi' = \phi'^{t} + \phi'';$$
$$p' = p'^{t} + p'', \; \alpha' = \alpha'^{t} + \alpha''$$

Allows vertical pressure gradient to be expressed in terms of φ''.

Dynamics: 3. Time integration scheme – acoustic step

(Without expanding variables into perturbation form)

$U^{\tau+\Delta\tau}$ $$\frac{\partial U}{\partial t} + \left(\mu_d \alpha \frac{\partial p}{\partial x} + \frac{\alpha}{\alpha_d}\frac{\partial p}{\partial \eta}\frac{\partial \phi}{\partial x}\right)^{\tau} = R_U^t$$

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

$\Theta^{\tau+\Delta\tau}$ $$\frac{\partial \Theta}{\partial t} + \left(\frac{\partial U \theta^t}{\partial x} + \frac{\partial \Omega \theta^t}{\partial \eta}\right)^{\tau+\Delta\tau} = R_\Theta^t$$

$W^{\tau+\Delta\tau}$, $\phi^{\tau+\Delta\tau}$

$$\left\{\begin{aligned} \frac{\partial W}{\partial t} + g\overline{\left(\mu_d - \frac{\alpha}{\alpha_d}\frac{\partial p}{\partial \eta}\right)}^{\tau} &= R_W^t \\ \mu_d^t \frac{\partial \phi}{\partial t} + U^{\tau+\Delta\tau}\frac{\partial \phi}{\partial x}^t + \Omega^{\tau+\Delta\tau}\frac{\partial \phi}{\partial \eta}^t - g\overline{W}^{\tau} &= R_\phi^t \end{aligned}\right.$$

- Forward-backward differencing on U, Θ, and μ equations
- Vertically implicit differencing on W and ϕ equations

Dynamics: 3. Time integration scheme – hydrostatic option

Instead of solving vertically implicit equations for W and ϕ

Integrate the hydrostatic equation to obtain p (π):

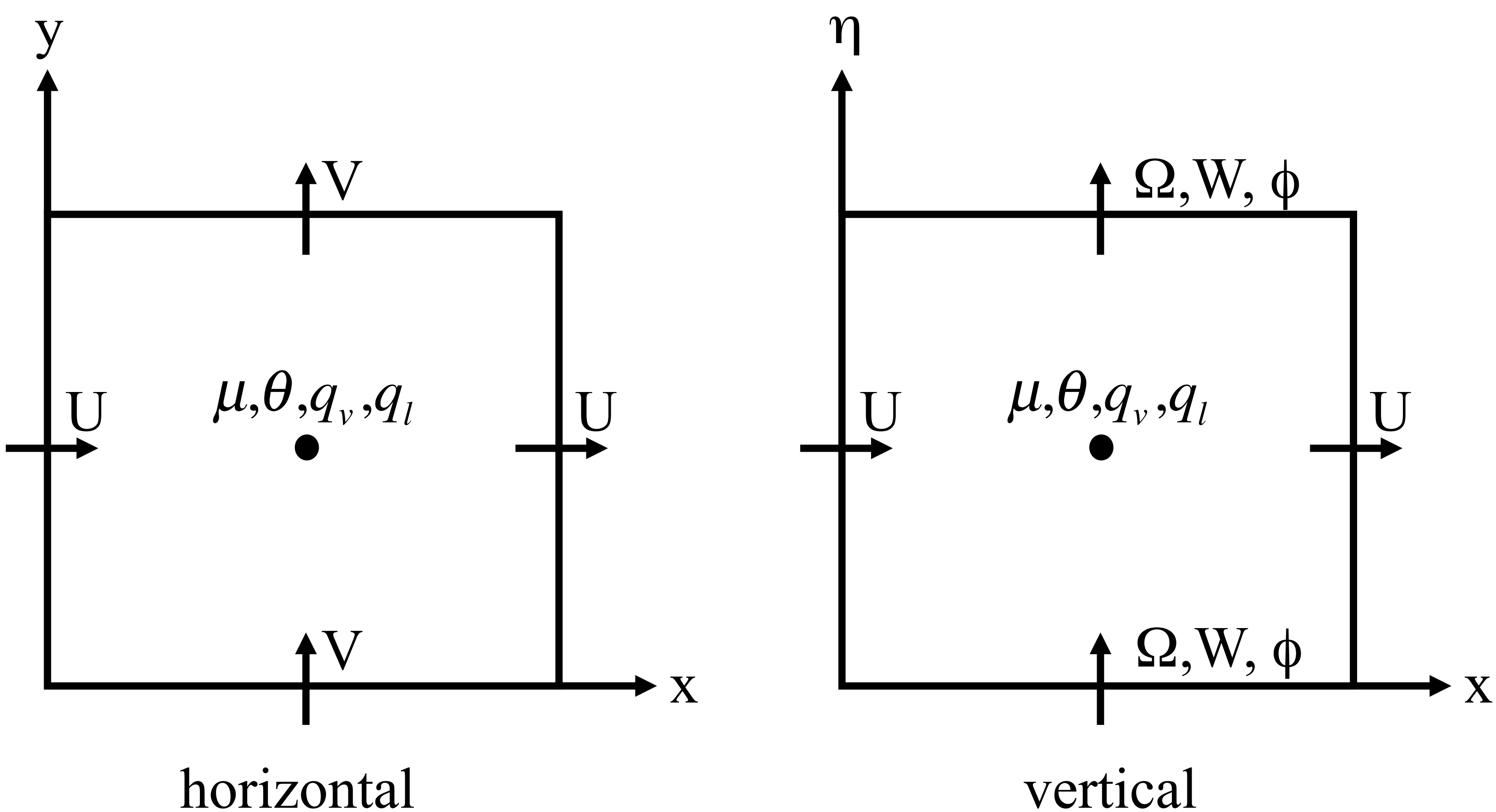
$$\frac{\partial p}{\partial \eta} = \left(\frac{\alpha_d}{\alpha}\right)^t \mu_d$$

Recover α and ϕ from: $p = p_0 \left(\frac{R\theta}{p_0 \alpha_v}\right)^\gamma$, and $\frac{\partial \phi}{\partial \eta} = -\mu_d \alpha_d$

W is no longer required during the integration.

Dynamics: 4. Grid staggering – horizontal and vertical

C-grid staggering



2nd, 3rd, 4th, 5th and 6th order centered and upwind-biased schemes are available in the ARW model.

Example: 5th order scheme

$$\frac{\partial(U\psi)}{\partial x} = \frac{1}{\Delta x}\left(F_{i+\frac{1}{2}}(U\psi) - F_{i-\frac{1}{2}}(U\psi) \right)$$

where

$$F_{i-\frac{1}{2}}(U\psi) = U_{i-\frac{1}{2}}\left\{ \frac{37}{60}(\psi_i + \psi_{i-1}) - \frac{2}{15}(\psi_{i+1} + \psi_{i-2}) + \frac{1}{60}(\psi_{i+2} + \psi_{i-3}) \right\}$$

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

For constant U, the 5th order flux divergence tendency becomes

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

The odd-ordered flux divergence schemes are equivalent to the next higher ordered (even) flux-divergence scheme plus a dissipation term of the higher even order with a coefficient proportional to the Courant number.

 Bill Skamarock (skamaroc@ucar.edu)

Maximum Courant Number for Advection

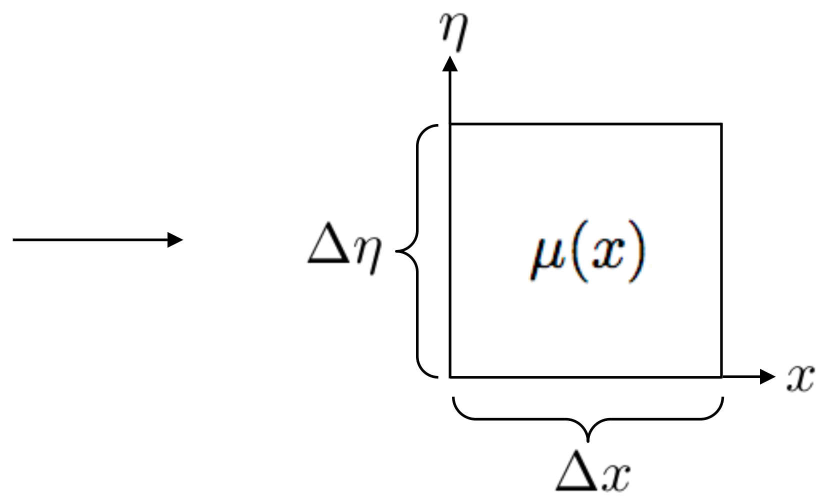
$$C_a = U\Delta t / \Delta x$$

Time Integration Scheme	*Advection Scheme*				
	2nd	*3rd*	*4th*	*5th*	*6th*
Leapfrog (γ=0.1)	0.91	U	0.66	U	0.57
RK2	U	0.90	U	0.39	U
RK3	1.73	1.63	1.26	1.43	1.09

U = unstable

(Wicker & Skamarock, 2002)

control volume
(2D example)



Mass in a control volume is proportional to

$$(\Delta x \Delta \eta)(\mu)^t$$

since $\mu(x)\Delta\eta = \Delta\pi = -g\rho\Delta z$

Dynamics: 5. Advection (transport) and conservation – dry-air mass

Mass in a control volume $(\Delta x \Delta \eta)(\mu)^t$

2D example

Mass conservation equation

$$\Delta t^{-1}(\Delta x \Delta \eta) \cdot \left[(\mu)^{t+\Delta t} - (\mu)^t)\right] = \left[(\mu u \Delta \eta)_{x-\Delta x/2,\eta} - (\mu u \Delta \eta)_{x+\Delta x/2,\eta})\right] + \left[(\mu \omega \Delta x)_{x,\eta-\Delta \eta/2} - (\mu \omega \Delta x)_{x,\eta+\Delta \eta/2})\right]$$

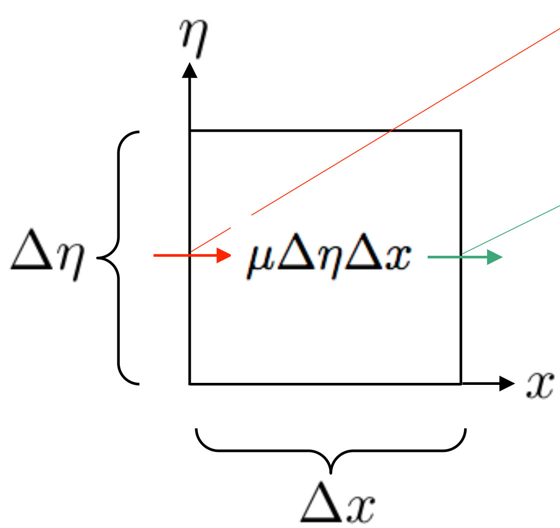
Change in mass over a time step

mass fluxes through control volume faces

Mass in a control volume $(\Delta x \Delta \eta)(\mu)^t$

Mass conservation equation

$$\Delta t^{-1}(\Delta x \Delta \eta) \cdot \left[(\mu)^{t+\Delta t} - (\mu)^t\right] = \left[(\mu u \Delta \eta)_{x-\Delta x/2,\eta} - (\mu u \Delta \eta)_{x+\Delta x/2,\eta}\right] + \left[(\mu \omega \Delta x)_{x,\eta-\Delta \eta/2} - (\mu \omega \Delta x)_{x,\eta+\Delta \eta/2}\right]$$



Horizontal fluxes through the vertical control-volume faces

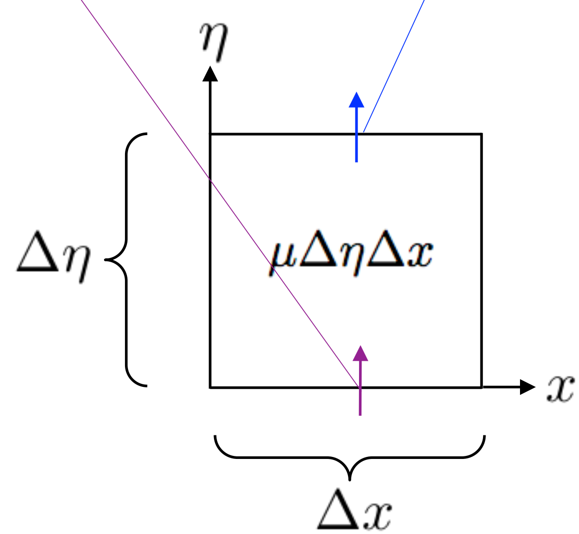
Dynamics: 5. Advection (transport) and conservation – dry-air mass

Mass in a control volume $(\Delta x \Delta \eta)(\mu)^t$

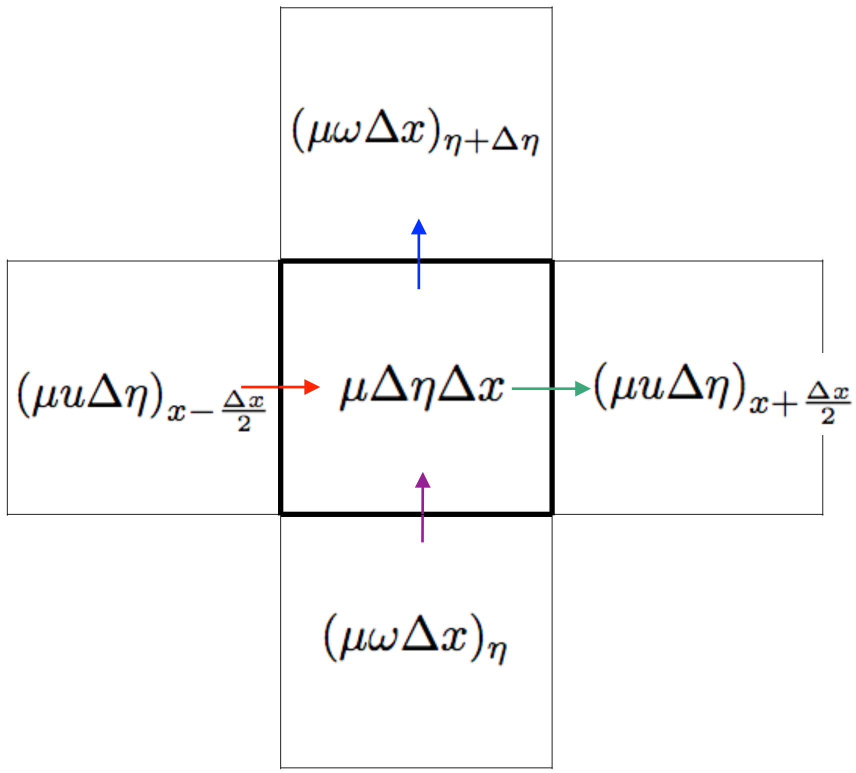
Mass conservation equation

$$\Delta t^{-1}(\Delta x \Delta \eta) \cdot \left[(\mu)^{t+\Delta t} - (\mu)^t\right] = \left[(\mu u \Delta \eta)_{x-\Delta x/2,\eta} - (\mu u \Delta \eta)_{x+\Delta x/2,\eta}\right] + \left[(\mu \omega \Delta x)_{x,\eta-\Delta \eta/2} - (\mu \omega \Delta x)_{x,\eta+\Delta \eta/2}\right]$$

Vertical fluxes through the horizontal control-volume faces



The same mass fluxes are used for neighboring grid cells - hence mass is conserved locally and globally.



Dynamics: 5. Advection (transport) and conservation – scalars

Mass in a control volume	$(\Delta x \Delta \eta)(\mu)^t$
Scalar mass	$(\Delta x \Delta \eta)(\mu\phi)^t$

Mass conservation equation:

$$\Delta t^{-1}(\Delta x \Delta \eta) \cdot \left[(\mu)^{t+\Delta t} - (\mu)^t)\right] = \left[(\mu u \Delta \eta)_{x-\Delta x/2,\eta} - (\mu u \Delta \eta)_{x+\Delta x/2,\eta})\right] + \left[(\mu \omega \Delta x)_{x,\eta-\Delta \eta/2} - (\mu \omega \Delta x)_{x,\eta+\Delta \eta/2})\right]$$

change in mass over a time step

mass fluxes through control volume faces

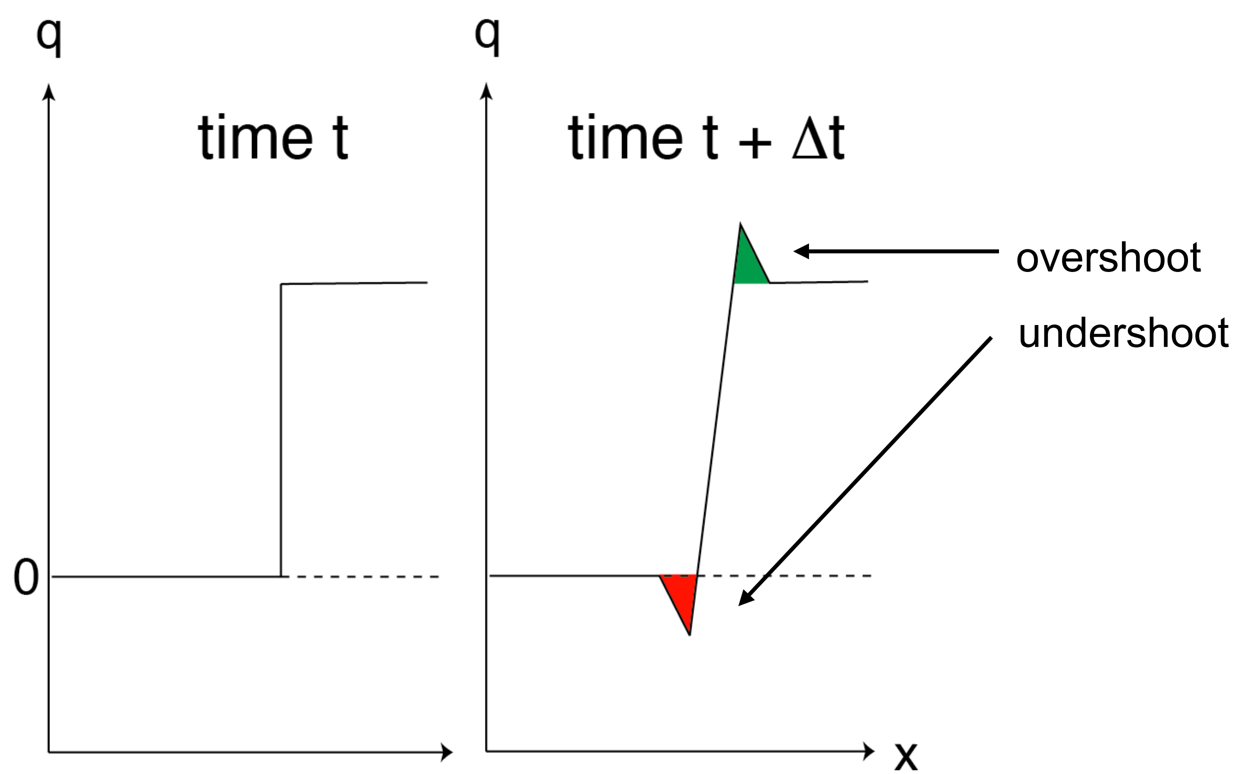
Scalar mass conservation equation:

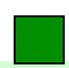
$$\Delta t^{-1}(\Delta x \Delta \eta) \cdot \left[(\mu\phi)^{t+\Delta t} - (\mu\phi)^t)\right] = \left[(\mu u \phi \Delta \eta)_{x-\Delta x/2,\eta} - (\mu u \phi \Delta \eta)_{x+\Delta x/2,\eta})\right] + \left[(\mu \omega \phi \Delta x)_{x,\eta-\Delta \eta/2} - (\mu \omega \phi \Delta x)_{x,\eta+\Delta \eta/2})\right]$$

change in tracer mass over a time step

tracer mass fluxes through control volume faces

1D advection



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

Dynamics: 5. Advection (transport) and conservation – shape preserving

Scalar update, last RK3 step

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

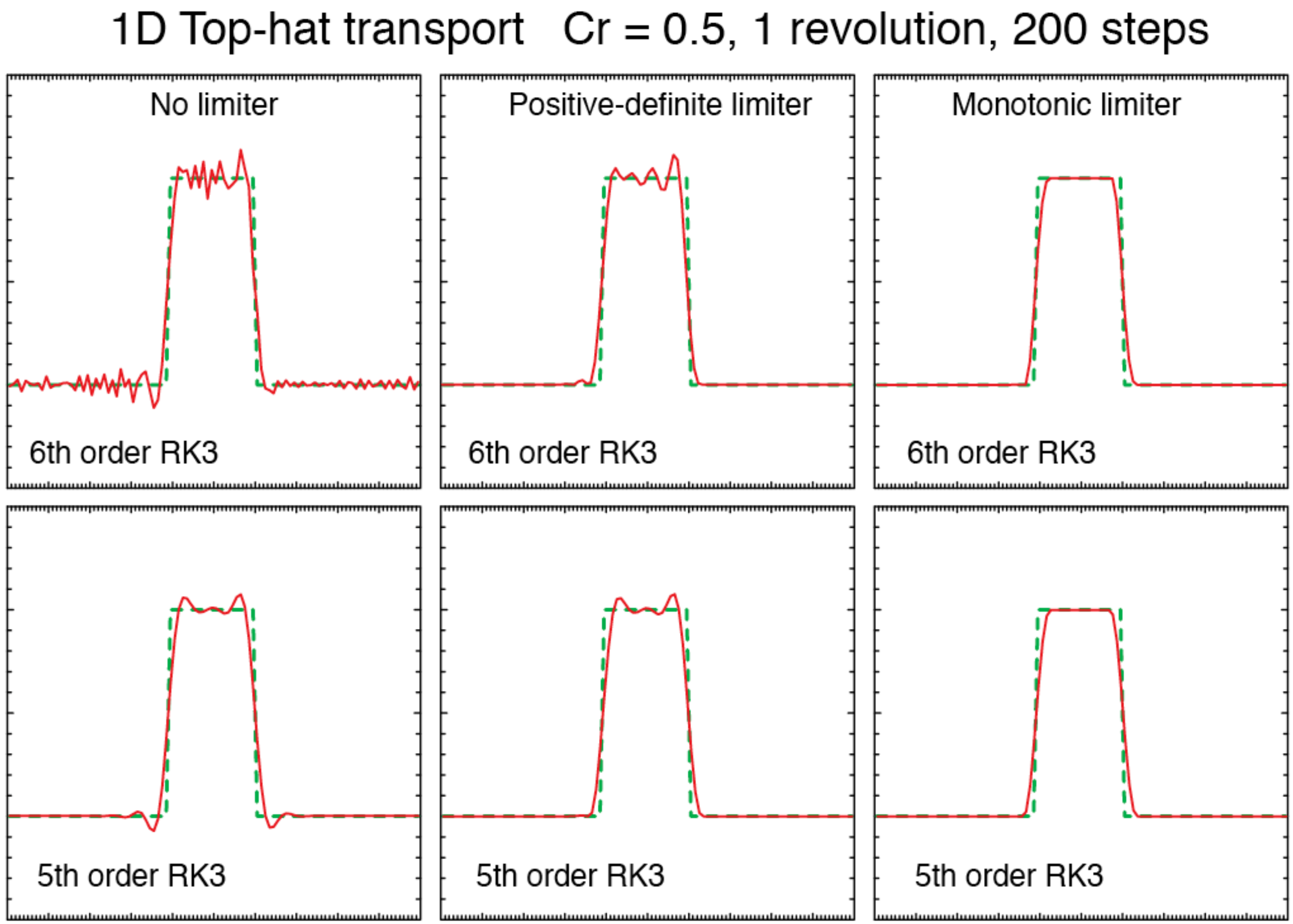
(1) Decompose flux: $f_i = f_i^{upwind} + f_i^c$

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

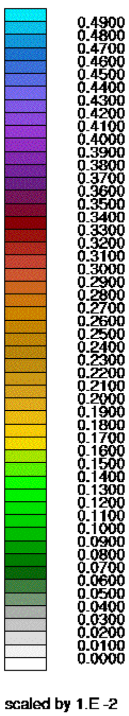
(3) Update scalar eqn. (1) using $f_i = f_i^{upwind} + R(f_i^c)$

Skamarock, MWR 2006, 2241-2250

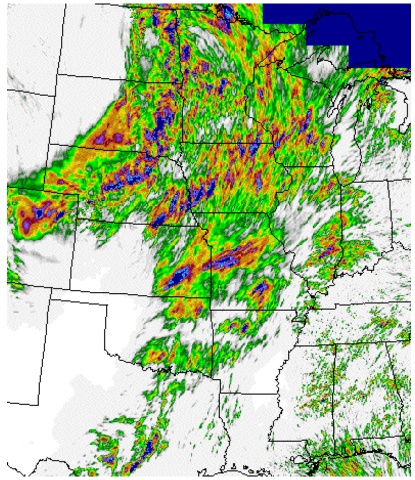
1D Example: Top-Hat Advection



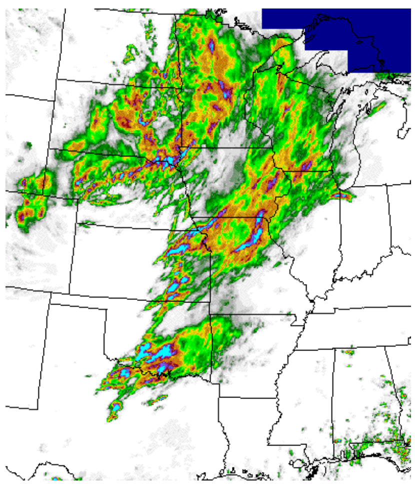
Dynamics: 5. Advection (transport) and conservation – examples



Initialized 00 UTC 04 June 2005

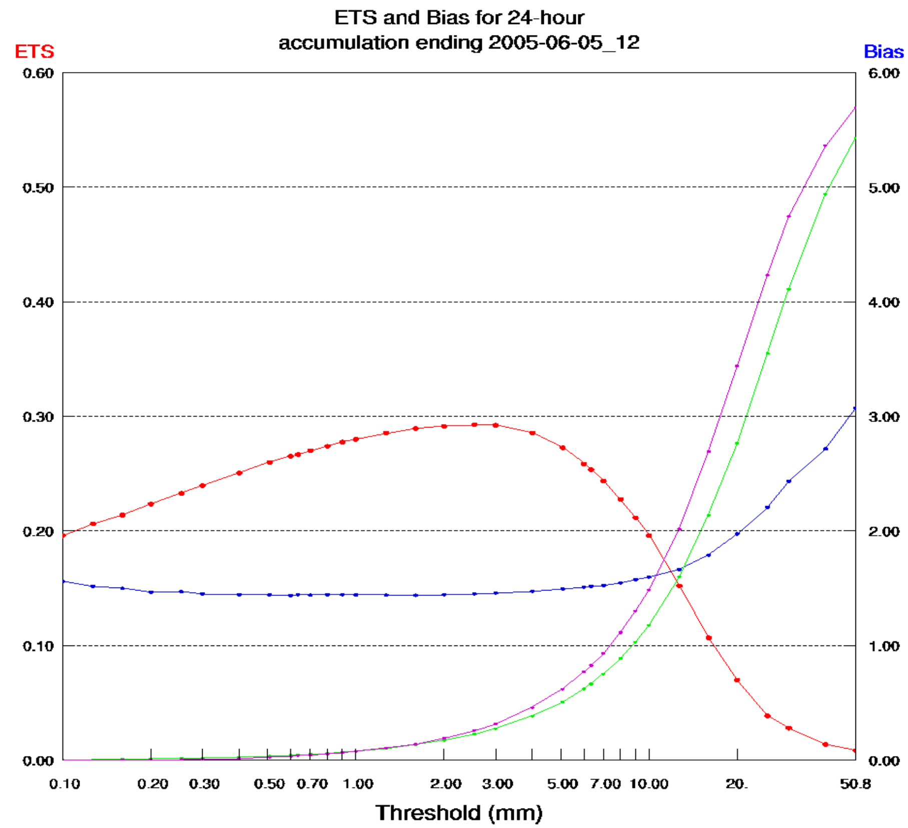


ARW 12-36 h Forecast Precip



24 h Observed (ST4) Precip

2005 ARW 4 km Forecasts:

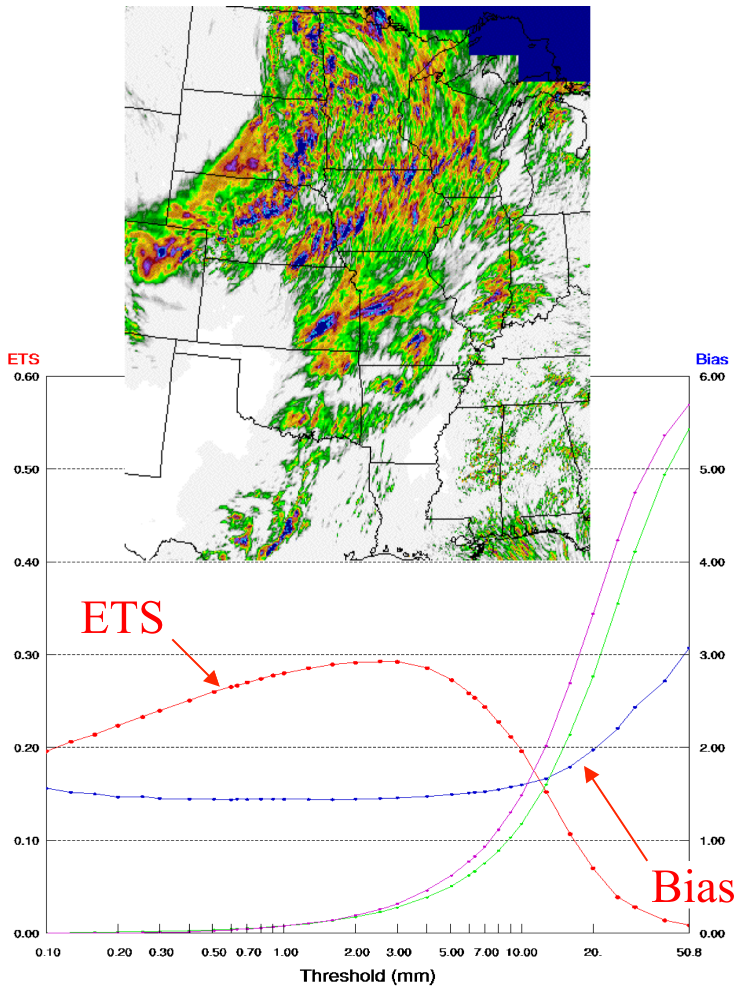


Bill Skamarock (skamaroc@ucar.edu)

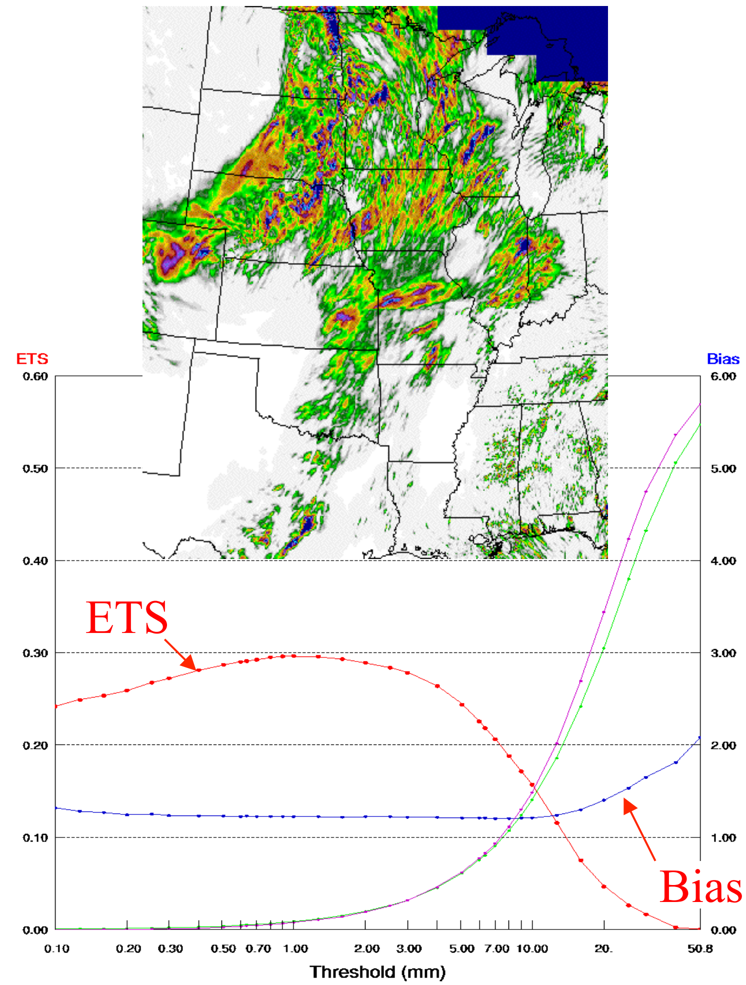
Dynamics: 5. Advection (transport) and conservation – examples

Initialized 00 UTC 04 June 2005

Standard advection



Positive-definite advection



Dynamics: 5. Advection (transport) and conservation

Where are the transport-scheme parameters?

The namelist.input file:

&dynamics

h_mom_adv_order
v_mom_adv_order
h_sca_adv_order
v_sca_adv_order

scheme order (2, 3, 4, or 5)
defaults:
horizontal (h_*) = 5
vertical (v_*) = 3

momentum_adv_opt →

= 1 standard scheme
= 3 5^{th} order WENO
default: 1

moist_adv_opt
scalar_adv_opt
chem_adv_opt
tracer_adv_opt
tke_adv_opt

options:
= 1, 2, 3 : no limiter,
positive definite (PD),
montonic
= 4 : 5^{th} order WENO
= 5 : 5^{th} order PD WENO

3rd order Runge-Kutta time step Δt_{RK}

Courant number limited, 1D: $C_r = \dfrac{U\Delta t}{\Delta x} < 1.43$

Generally stable using a timestep approximately twice as large as used in a leapfrog model.

Where?

The namelist.input file:

&domains

time_step (integer seconds)

time_step_fract_num

time_step_fract_den

Bill Skamarock (skamaroc@ucar.edu)

Dynamics: 6. Time step parameters

3rd order Runge-Kutta time step Δt_{RK} (&domains *time_step*)

Acoustic time step

2D horizontal Courant number limited: $C_r = \frac{C_s \Delta\tau}{\Delta h} < \frac{1}{\sqrt{2}}$

$$\Delta\tau_{sound} = \Delta t_{RK} / (\text{number of acoustic steps})$$

Where?

The namelist.input file:

&dynamics

time_step_sound (integer)

3rd order Runge-Kutta time step Δt_{RK} (&domains *time_step*)

Acoustic time step [&dynamics *time_step_sound* (integer)]

Guidelines for time step

Δt_{RK} 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.

If ARW blows up (aborts) quickly, try:

Decreasing Δt_{RK} (that also decreases Δt_{sound}),

or increasing time_step_sound (that decreases Δt_{sound} but does not change Δt_{RK})

Dynamics: 7. Filters – divergence damping

Purpose: filter acoustic modes (3-D divergence, $D = \nabla \cdot \rho\mathbf{V}$ *)*

$$\left\{ \frac{\partial \rho \mathbf{V}}{\partial t} + \nabla p + \ldots = \gamma_d' \nabla D \right\}$$

$$\nabla \cdot \left\{ \quad \right\} \quad \rightarrow \quad \frac{\partial D}{\partial t} + \nabla^2 p + \ldots = \gamma_d' \nabla^2 D$$

From the pressure equation: $p_t \simeq c^2 D$

$$\frac{\partial \rho \mathbf{V}}{\partial t} + \nabla [p_\tau + \gamma_d (p^\tau - p^{\tau - \Delta\tau})] + \ldots = 0$$

$\gamma_d = 0.1$ recommended (default) (&dynamics *smdiv*)

(Illustrated in height coordinates for simplicity)

Bill Skamarock (skamaroc@ucar.edu)

Dynamics: 7. Filters – time off-centering the vertical acoustic modes

Purpose: damp vertically-propagating acoustic modes

$$\frac{\partial W}{\partial t} + g\overline{\left(\mu_d - \frac{\alpha}{\alpha_d}\frac{\partial p}{\partial \eta}\right)}^{\tau} = \ldots$$

$$\frac{\partial \phi}{\partial t} - \frac{g}{\mu_d^t}\overline{W}^{\tau} = \ldots$$

$$\overline{(\quad)}^{\tau} = \frac{1+\beta}{2}\overline{(\quad)}^{\tau+\Delta\tau} + \frac{1-\beta}{2}\overline{(\quad)}^{\tau}$$

Slightly forward centering the vertical pressure gradient damps 3-D divergence as demonstrated for the divergence damper

$\beta = 0.1$ recommended (default) [&dynamics *epssm*]

Dynamics: 7. Filters – external mode filter

Purpose: filter the external mode

Vertically integrated horizontal divergence, $D_h = \int_1^0 (\nabla_\eta \cdot \mu \mathbf{V}_h) d\eta$

$$\left\{ \frac{\partial \mu \mathbf{V}_h}{\partial t} + \ldots = -\gamma_e \nabla_\eta D_h \right\}$$

$$\int_1^0 \nabla_\eta \cdot \left\{ \quad \right\} d\eta \quad \rightarrow \quad \frac{\partial D_h}{\partial t} + \ldots = \gamma_e \nabla^2 D_h$$

Continuity equation: $\frac{\partial \mu}{\partial t} = -\nabla_\eta \cdot \mu \mathbf{V}_h - \frac{\partial \mu \dot{\eta}}{\partial \eta} = D_h$

$$\boxed{\frac{\partial \mu \mathbf{V}_h}{\partial \tau} + \ldots = -\gamma_e \frac{\Delta x^2}{\Delta \tau^2} \nabla_\eta (\mu^\tau - \mu^{\tau - \Delta \tau})}$$

$\gamma_e = 0.01$ recommended (default) [&dynamics *emdiv*]

(Primarily for real-data applications)

Bill Skamarock (skamaroc@ucar.edu)

Purpose: damp anomalously-large vertical velocities

(usually associated with anomalous physics tendencies)

Additional term:

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

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

Cr_β = 1.0 typical value (default)

[share/module_model_constants.F *w_beta*]

γ_w = 0.3 m/s^2 recommended (default)

[share/module_model_constants.F *w_alpha*]

[&dynamics *w_damping* 0 (off; default) 1 (on)]

2nd-Order Horizontal Mixing, Horizontal-Deformation-Based K_h

Purpose: mixing on horizontal coordinate surfaces (real-data applications) [&dynamics *diff_opt=1, km_opt=4*]

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

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

$$D_{11} = 2\, m^2 \left[\partial_x (m^{-1} u) - z_x \partial_z (m^{-1} u) \right]$$
$$D_{22} = 2\, m^2 \left[\partial_y (m^{-1} v) - z_y \partial_z (m^{-1} v) \right]$$
$$D_{12} = m^2 \big[\partial_y (m^{-1} u) - z_y \partial_z (m^{-1} u) + \partial_x (m^{-1} v) - z_x \partial_z (m^{-1} v) \big]$$

$C_s = 0.25$ (Smagorinsky coefficient, default value) [&dynamics *c_s*]

Bill Skamarock (skamaroc@ucar.edu)

Implicit Rayleigh w Damping Layer for Split-Explicit Nonhydrostatic NWP Models (gravity-wave absorbing layer)

Modification to small time step:

- Step horizontal momentum, continuity, and potential temperature equations to new time level: $U^{\tau+\Delta\tau}$ $\mu^{\tau+\Delta\tau}$ $\Omega^{\tau+\Delta\tau}$ $\Theta^{\tau+\Delta\tau}$
- Step vertical momentum and geopotential equations (implicit in the vertical): $W^{*\tau+\Delta\tau}$ $\phi^{*\tau+\Delta\tau}$
- Apply implicit Rayleigh damping on *W* as an adjustment step: $W^{\tau+\Delta\tau} = W^{*\tau+\Delta\tau} - \Delta\tau R_w(\eta) W^{\tau+\Delta\tau}$
- Update final value of geopotential at new time level: $\phi^{\tau+\Delta\tau}$

Implicit Rayleigh w Damping Layer for Split-Explicit Nonhydrostatic NWP Models (gravity-wave absorbing layer)

$$W^{\tau+\Delta\tau} = W^{*\tau+\Delta\tau} - \Delta\tau R_w(\eta) W^{\tau+\Delta\tau}$$

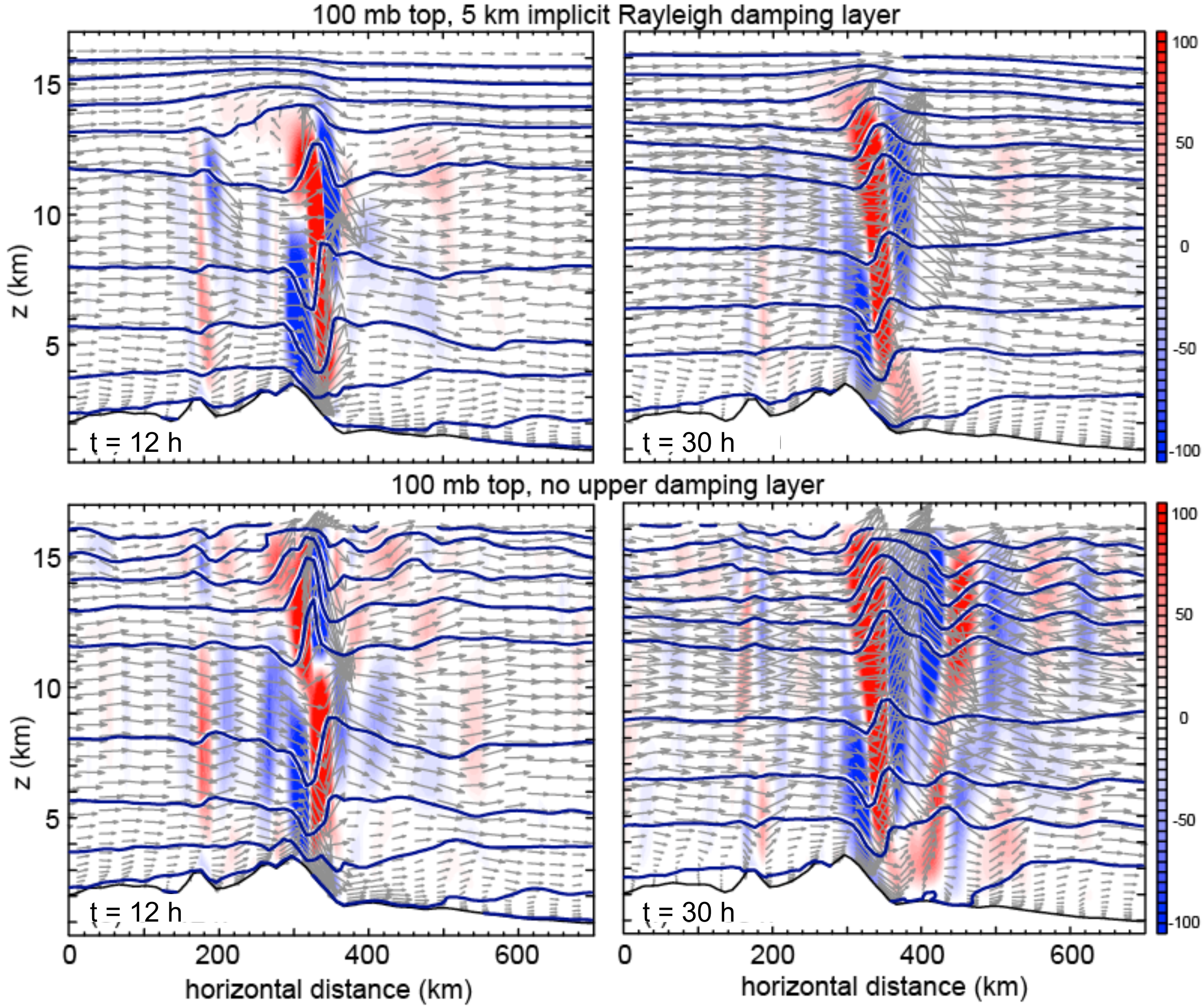
$$R_w(\eta) = \begin{cases} \gamma_r \sin^2\left[\frac{\pi}{2}\left(1 - \frac{z_{top}-z}{z_d}\right)\right] & \text{for } z \geq (z_{top} - z_d); \\ 0 & \text{otherwise,} \end{cases}$$

$R_w(\eta)$- damping rate (t^{-1})
z_d - depth of the damping layer
γ_r - damping coefficient

[&dynamics *damp_opt = 3* (default = 0)]
[&dynamics *damp_coef = 0.2* (recommended, = 0. default)]
[&dynamics *zdamp = 5.0* ($z_d(km)$; default); height below model top where damping begins]

Dynamics: 7. Filters – gravity-wave absorbing layer example

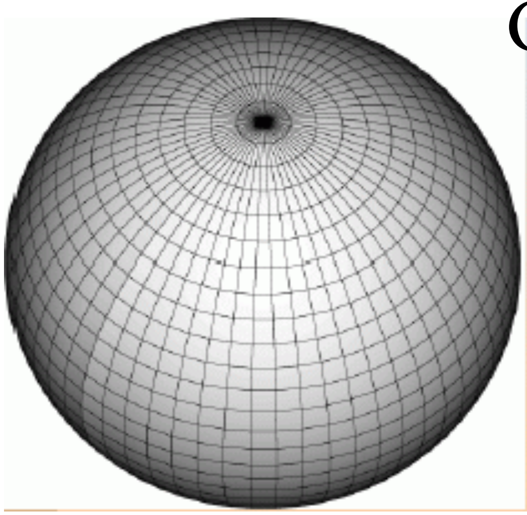
Model Initialized 04 Dec 2007 00 UTC



ARW Model: projection options

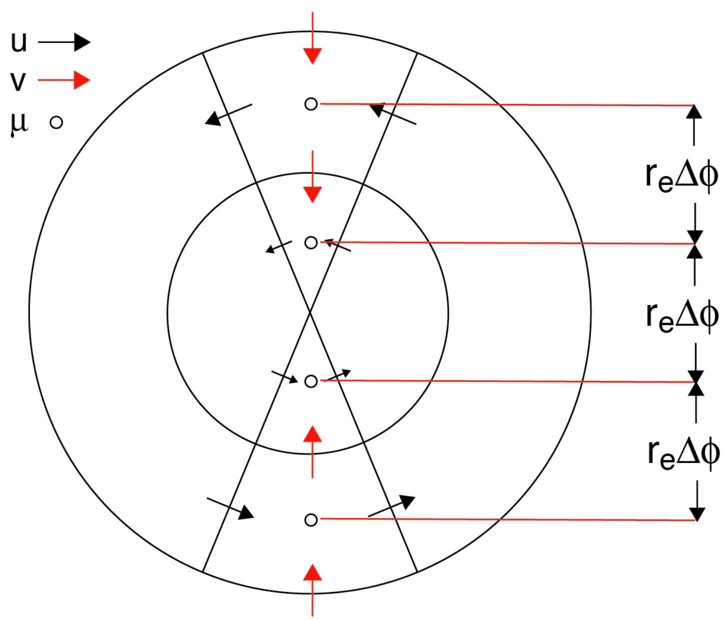
1. Cartesian geometry:
   idealized cases
2. Lambert Conformal:
   mid-latitude applications
3. Polar Stereographic:
   high-latitude applications
4. Mercator:
   low-latitude applications
5. Latitude-Longitude (new in ARW V3)
   global
   regional

Projections 1-4 are isotropic ($m_x = m_y$)
Latitude-Longitude projection is anistropic ($m_x \neq m_y$)



Global ARW - Latitude-Longitude Grid

- Map factors - m_x and m_y
  - Computational grid poles need not be geographic poles.
  - Limited area and nesting capable.
- Polar boundary conditions
- Polar filtering



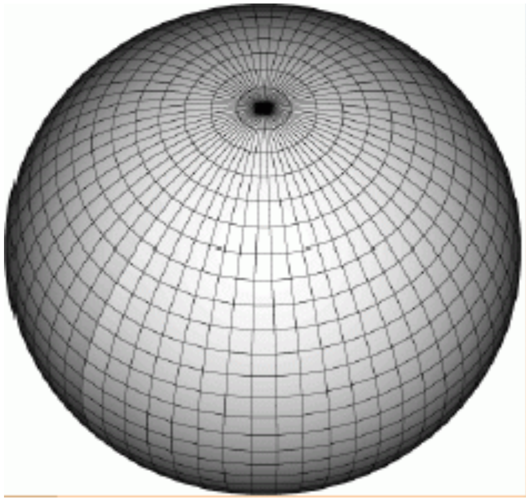
Zero meriodional flux at the poles (cell-face area is zero).

v (poles) only needed for meridional derivative of v near the poles (we interpolate).

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

Bill Skamarock (skamaroc@ucar.edu)

Global ARW – Polar filters

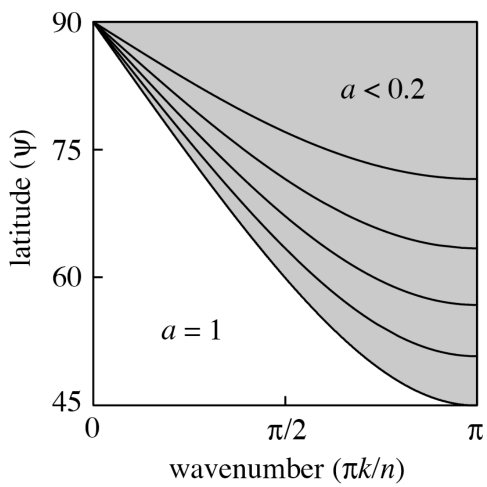


Converging gridlines severely limit timestep.
The polar filter removes this limitation.

Filter procedure - Along a grid latitude circle:

1. Fourier transform variable.
2. Filter Fourier coefficients.
3. Transform back to physical space.

Filter Coefficient $a(k)$, $\psi_o = 45^o$



$$\hat{\phi}(k)_{filtered} = a(k)\,\hat{\phi}(k), \quad \text{for all } k$$

$$a(k) = \min\left[1., \max\left(0., \left(\frac{\cos\psi}{\cos\psi_o}\right)^2 \frac{1}{\sin^2(\pi k/n)}\right)\right]$$

$k =$ dimensionless wavenumber
$\hat{\phi}(k) =$ Fourier coefficients from forward transform
$a(k) =$ filter coefficients
$\psi =$ latitude $\psi_o =$ polar filter latitude, filter when $|\psi| > \psi_o$

ARW integration

Begin time step

- Runge-Kutta loop (steps 1, 2, and 3)
    - (i) advection, p-grad, buoyancy, physics
    - Acoustic step loop
        - (i) advance U,V
        - (ii) advance μ, Θ
        - (iii) advance w, ϕ
    - End acoustic loop
    - Advance scalars
- End Runge-Kutta loop
- Adjustment physics (currently microphysics)

End time step

ARW integration with polar filtering

Begin time step

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

(i) advection, p-grad, buoyancy, physics

Acoustic step loop

(i) advance U,V (Fourier Filter U,V)

(ii) advance μ, Θ (Fourier Filter μ, Θ)

(iii) advance w, ϕ (Fourier Filter w, ϕ)

End acoustic loop

Advance scalars (Fourier Filter Sc)

End Runge-Kutta loop

Adjustment physics (currently microphysics) (Fourier Filter Sc)

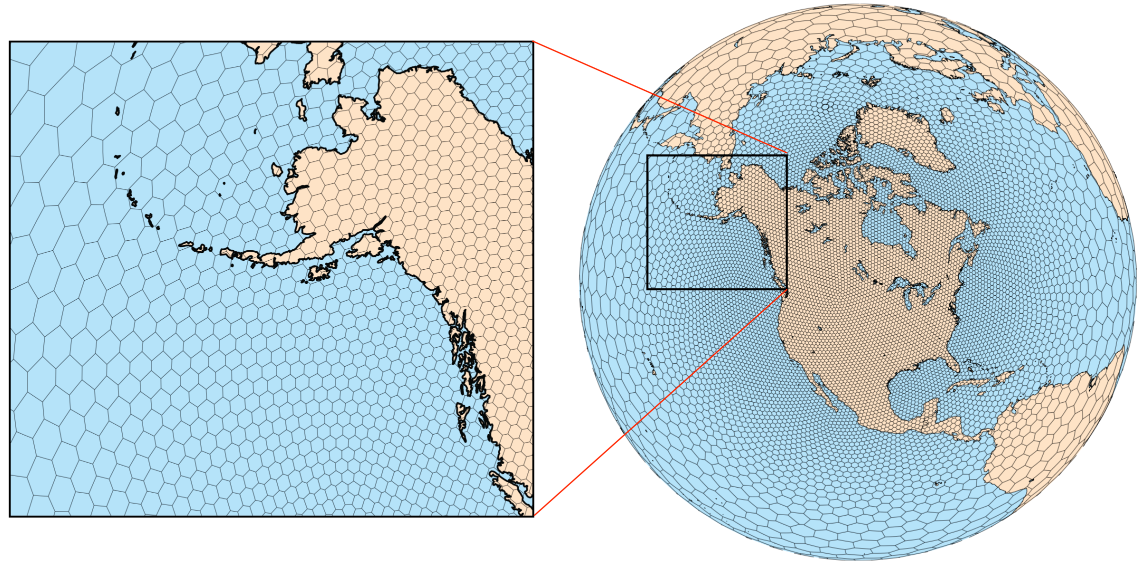
End time step

Timestep limited by minimum Δx outside of polar-filter region.
Monotonic and PD transport is not available for global model.

Dynamics: 8. Map projections and global configuration

An alternative to global ARW…

MPAS
Model for Prediction Across Scales



- Global, nonhydrostatic, C-grid Voronoi mesh
- Numerics similar to WRF; WRF-NRCM physics
- No pole problems
- Variable-resolution mesh – no nested BC problems

Available at: http://mpas-dev.github.io/

Bill Skamarock (skamaroc@ucar.edu)

ARW Model: Boundary Condition Options

Lateral boundary conditions

1. Specified (Coarse grid, real-data applications).
2. Open lateral boundaries (gravity-wave radiative).
3. Symmetric lateral boundary condition (free-slip wall).
4. Periodic lateral boundary conditions.
5. Nested boundary conditions (specified).

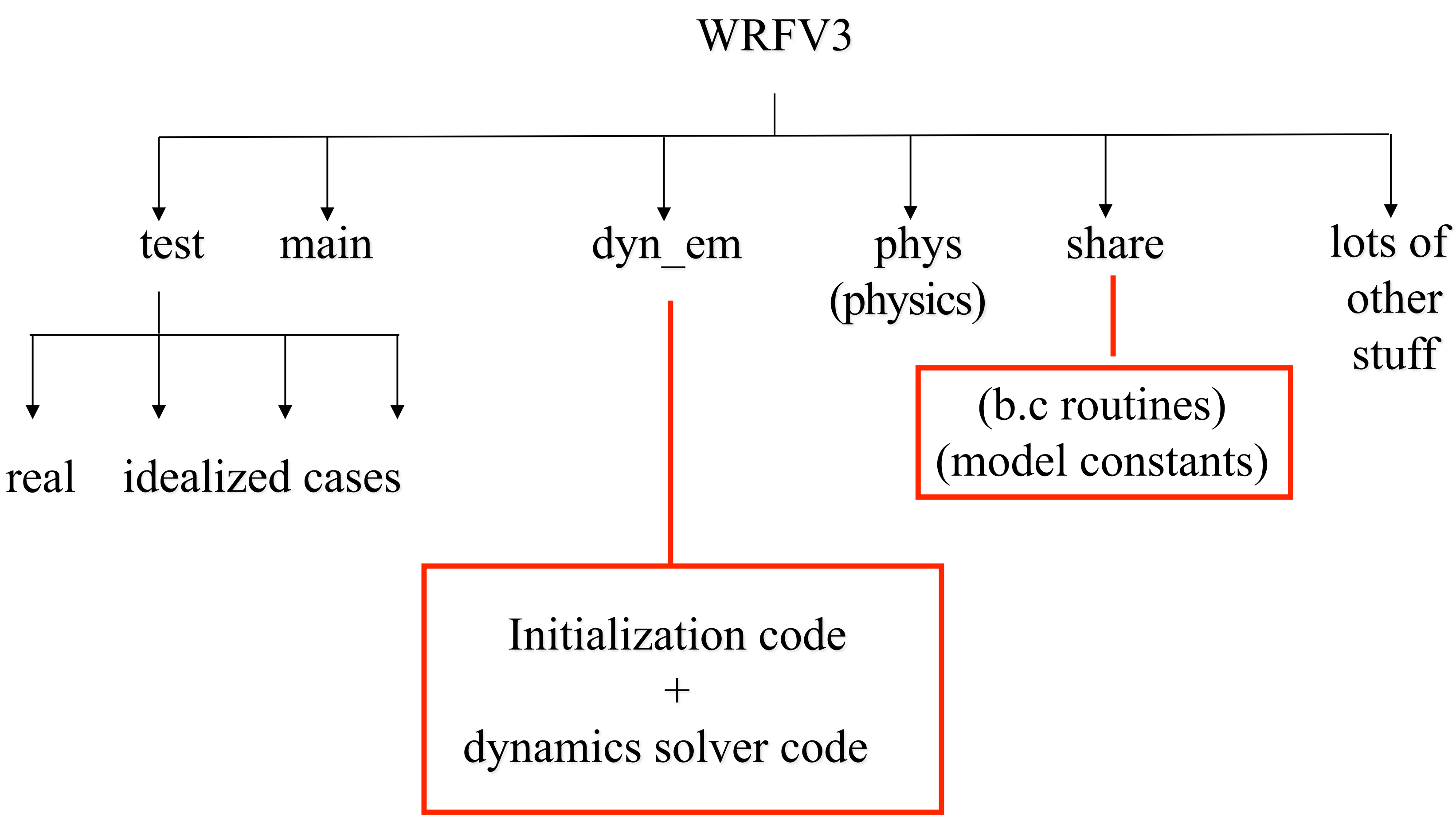
Top boundary conditions

1. Constant pressure.

Bottom boundary conditions

1. Free slip.
2. Various B.L. implementations of surface drag, fluxes.

Dynamics: Where are things?



WRF ARW Tech Note
A Description of the Advanced Research WRF Version 3 (June 2008, 2012 update)
http://www.mmm.ucar.edu/wrf/users/pub-doc.html