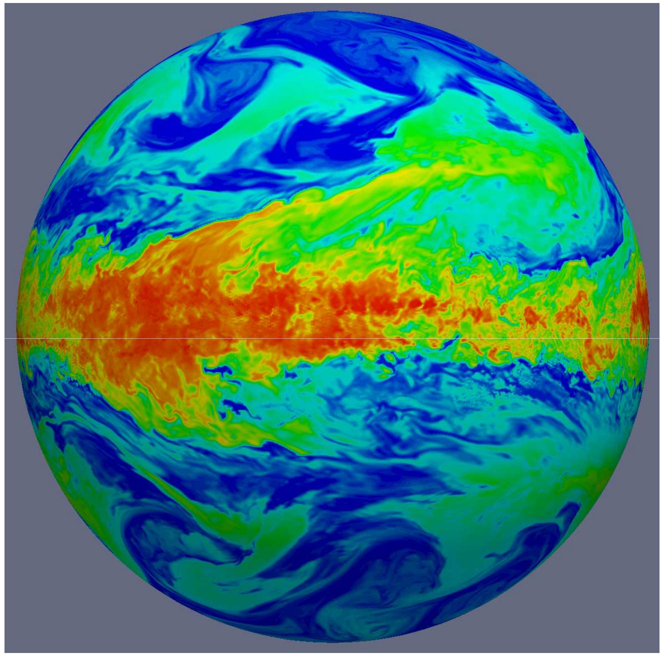
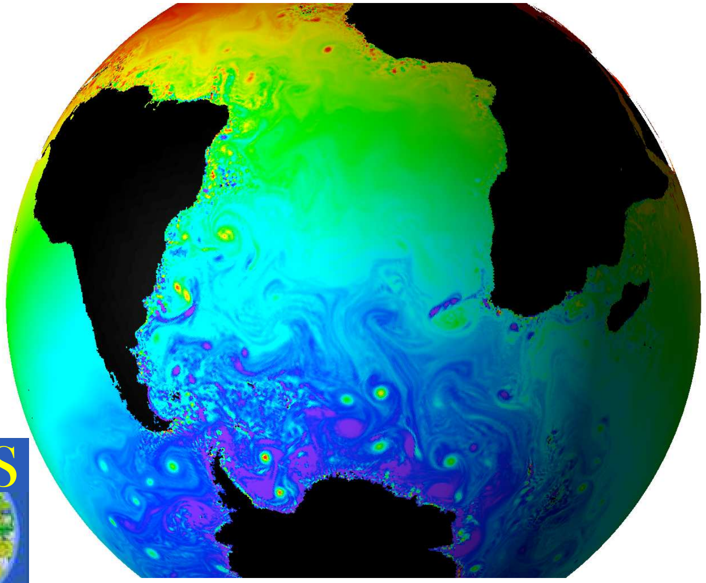
Model for Prediction Across Scales: MPAS



Atmosphere



Ocean

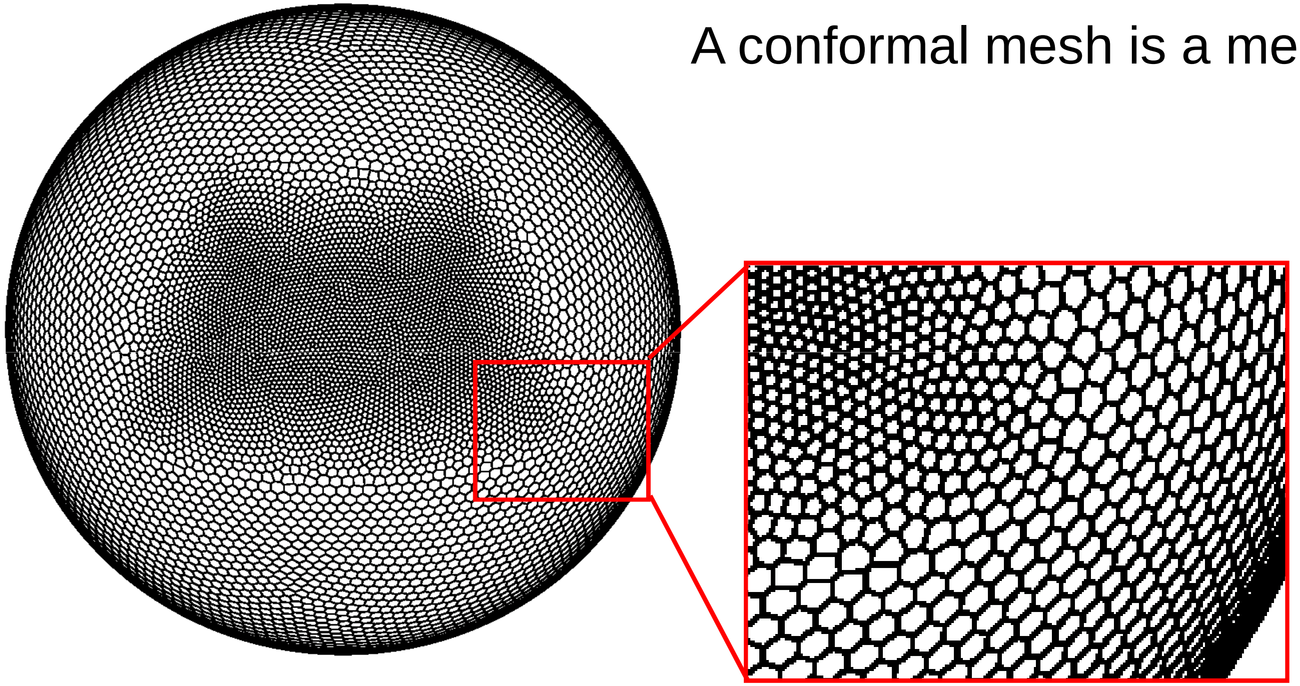
Global modeling system for unstructured centroidal Voronoi (hexagonal) meshes using C-grid staggering and selective grid refinement

Jointly developed, primarily by NCAR and Los Alamos National Laboratory (LANL), for weather, regional climate, and climate applications

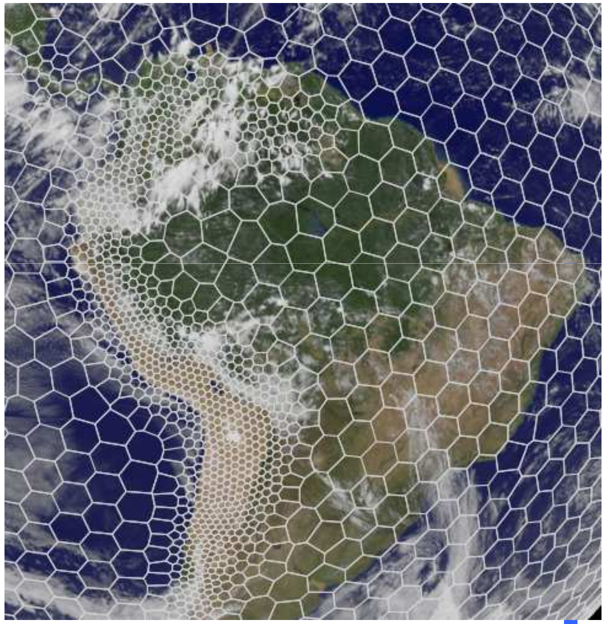
MPAS infrastructure - NCAR, LANL, others.
MPAS - Atmosphere (NCAR)
MPAS - Ocean (LANL)
MPAS - Ice, etc.

Bill Skamarock, Joe Klemp, Michael Duda, Sang-Hun Park, and Laura Fowler	NCAR
Todd Ringler	LANL
John Thuburn	Exeter University, UK

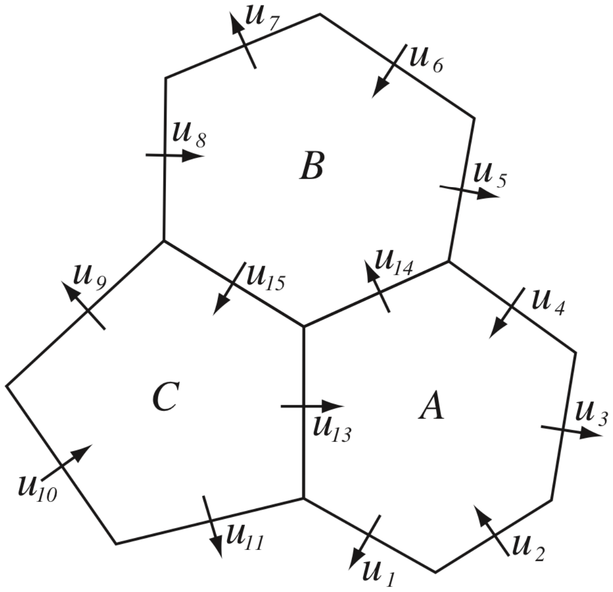
Conforming, Variable-Resolution Voronoi Meshes



A conformal mesh is a mesh with no hanging nodes.



Conjecture: Smooth refinement on conformal meshes should mitigate many refinement problems.



C-grid staggering

Why a C-grid staggering?

- Provides good accuracy for the fast (gravity-wave) modes
- Avoids the parasitic mode inherent in an A grid
- Proper reconstruction of tangential velocity ensures stationary geostrophic modes (Thuburn et al, JCP 2009)

Nonhydrostatic MPAS Formulation

Equations:

- Prognostic equations in conservative (flux) form: $(U, V, W, \Theta, Q_j) = \rho_d \cdot (u, v, w, \theta, q_j)$
- Continuity equation for dry air mass
- Terrain-following height-based coordinate ζ
- Horizontal momentum equation in vector-invariant form.

Integration Scheme:

- Finite-volume (conservative) spatial discretization.
- Split-explicit Runge-Kutta (3rd order), as in Advanced Research WRF
- Higher order WRF transport scheme extended to unstructured polygonal meshes (Skamarock and Gassmann, MWR 2011)

Prognostic Equations:

$$\frac{\partial \boldsymbol{V}_H}{\partial t} = -\frac{\rho_d}{\rho_m}\left[\boldsymbol{\nabla}_\zeta\left(\frac{p}{\zeta_z}\right) - \frac{\partial \boldsymbol{z}_H p}{\partial \zeta}\right] - \eta\,\boldsymbol{k} \times \boldsymbol{V}_H$$

$$- \boldsymbol{v}_H \boldsymbol{\nabla}_\zeta \cdot \boldsymbol{V} - \frac{\partial \Omega \boldsymbol{v}_H}{\partial \zeta} - \rho_d \boldsymbol{\nabla}_\zeta K - eW\cos\alpha_r - \frac{uW}{r_e} + \boldsymbol{F}_{V_H},$$

$$\frac{\partial W}{\partial t} = -\frac{\rho_d}{\rho_m}\left[\frac{\partial p}{\partial \zeta} + g\tilde{\rho}_m\right] - (\boldsymbol{\nabla} \cdot \boldsymbol{v} W)_\zeta$$

$$+ \frac{uU + vV}{r_e} + e(U\cos\alpha_r - V\sin\alpha_r) + F_W,$$

$$\frac{\partial \Theta_m}{\partial t} = -(\boldsymbol{\nabla} \cdot \boldsymbol{V}\,\theta_m)_\zeta + F_{\Theta_m},$$

$$\frac{\partial \tilde{\rho}_d}{\partial t} = -(\boldsymbol{\nabla} \cdot \boldsymbol{V})_\zeta,$$

$$\frac{\partial Q_j}{\partial t} = -(\boldsymbol{\nabla} \cdot \boldsymbol{V}\,q_j)_\zeta + \rho_d S_j + F_{Q_j},$$

Diagnostics and Definitions:

$$p = p_0\left(\frac{R_d \zeta_z \Theta_m}{p_0}\right)^\gamma$$

$$\theta_m = \theta[1 + (R_v/R_d)q_v]$$

$$\frac{\rho_m}{\rho_d} = 1 + q_v + q_c + q_r + \dots$$

MPAS

Smoothed Terrain-Following (STF) hybrid Coordinate

$$z(x,y,\zeta) = \zeta + A(\zeta)h_s(x,y,\zeta)$$

Progressively smooths coordinate surfaces while transitioning to a height coordinate

$A(\zeta) = 1 - \frac{\zeta}{z_t}, \quad h_s(x,y,\zeta) = h(x,y) \quad \Rightarrow$ BTF coordinate

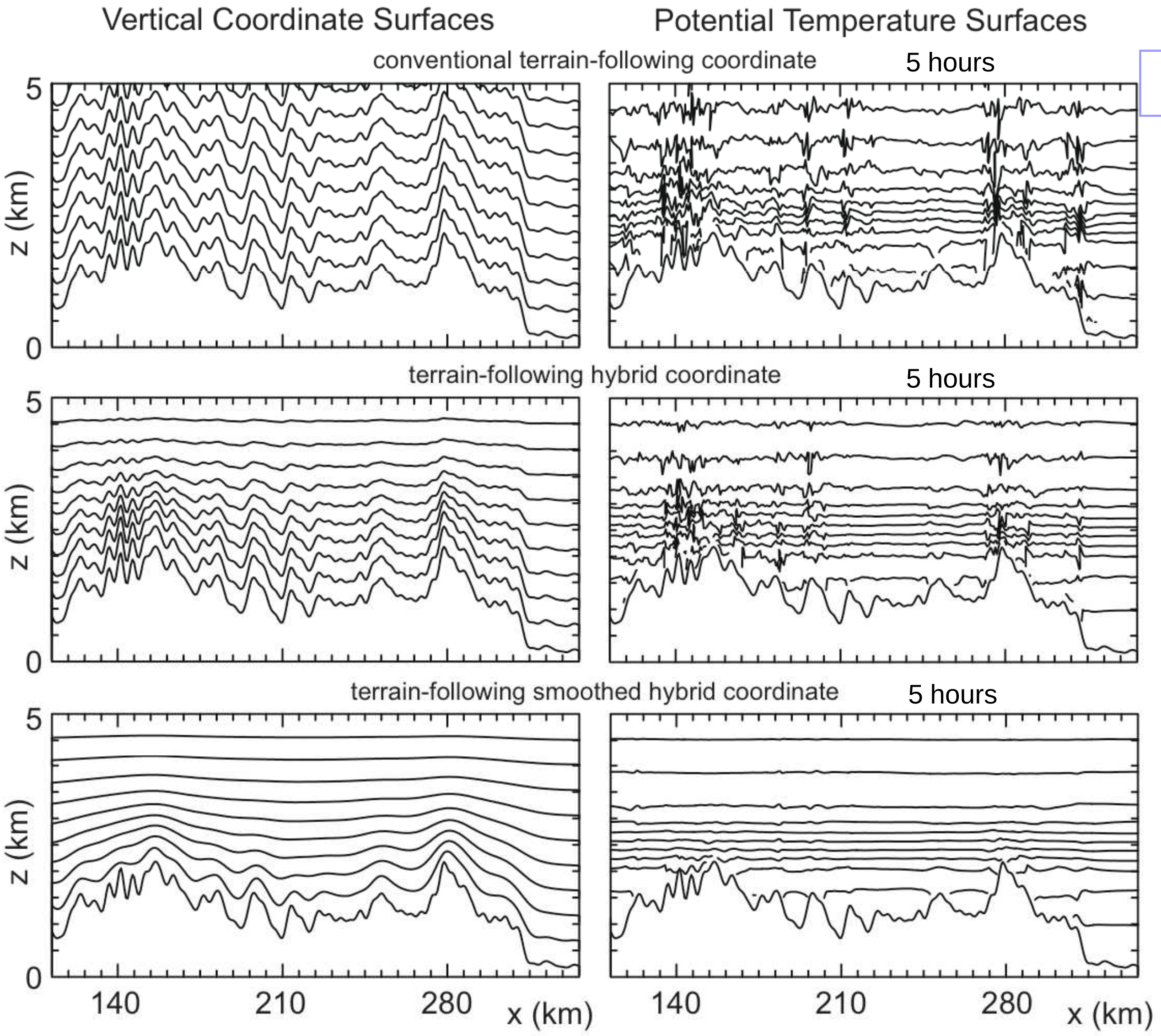
$h_s(x,y,\zeta) = h(x,y) \quad \Rightarrow$ HTF coordinate

$A(\zeta) = 0 \quad \Rightarrow$ Pure height coordinate

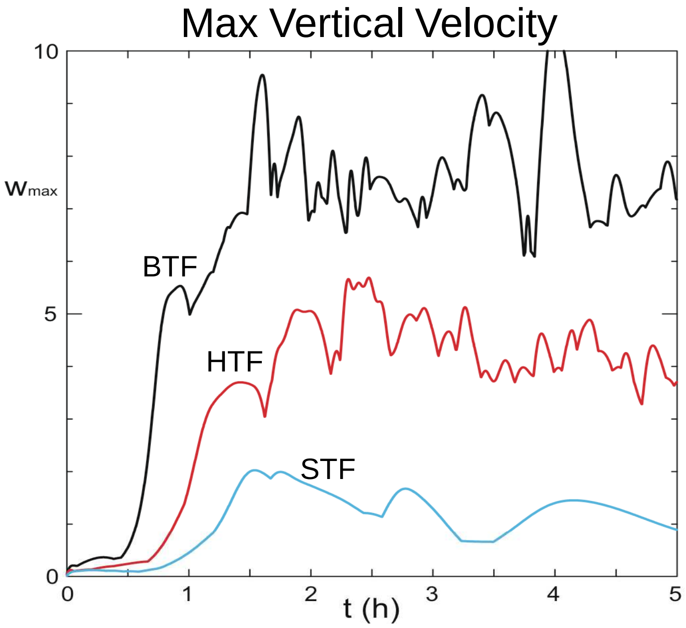
Multiple passes of simple Laplacian smoother at each ζ level:

$$h_s^{(n)} = h_s^{(n-1)} + \beta(\zeta) d^2 \boldsymbol{\nabla}_\zeta^2 h_s^{(n-1)}$$

Resting Atmosphere Simulation - Real Terrain

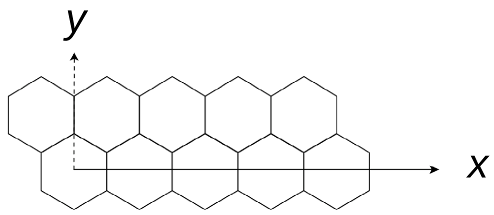


Model top at 20 km



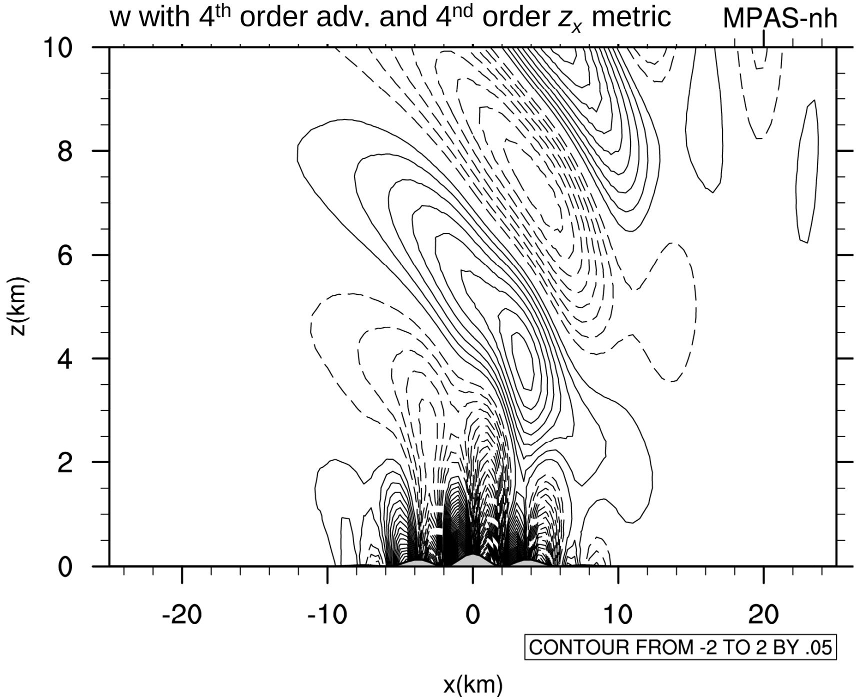
2-D Mountain Waves - Schar Test Case

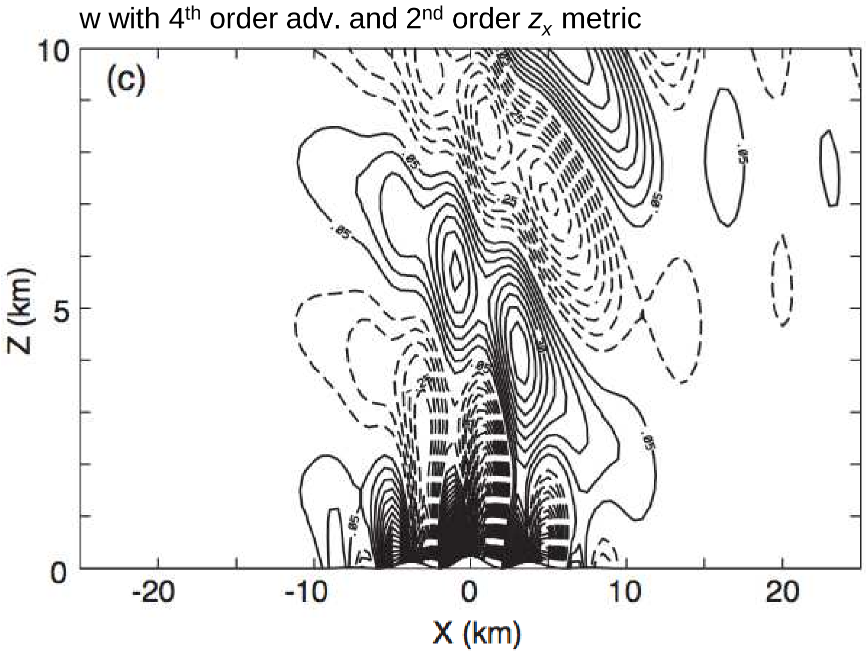
2D (y,z) simulations
Based on 3D doubly
periodic (x,y) config.



U = 10 ms^{-1} Δx = 500 m

N = .01 s^{-1} Δz = 300 m


w with 4th order adv. and 4nd order z_x metric MPAS-nh


w with 4th order adv. and 2nd order z_x metric

Confirms that numerical accuracy of terrain metric term is consistent with accuracy of advection

$$\frac{d\theta}{dt} = \frac{\partial\theta}{\partial t} + u\boxed{\frac{\partial\theta}{\partial x}} + \omega\frac{\partial\theta}{\partial\zeta} = 0$$

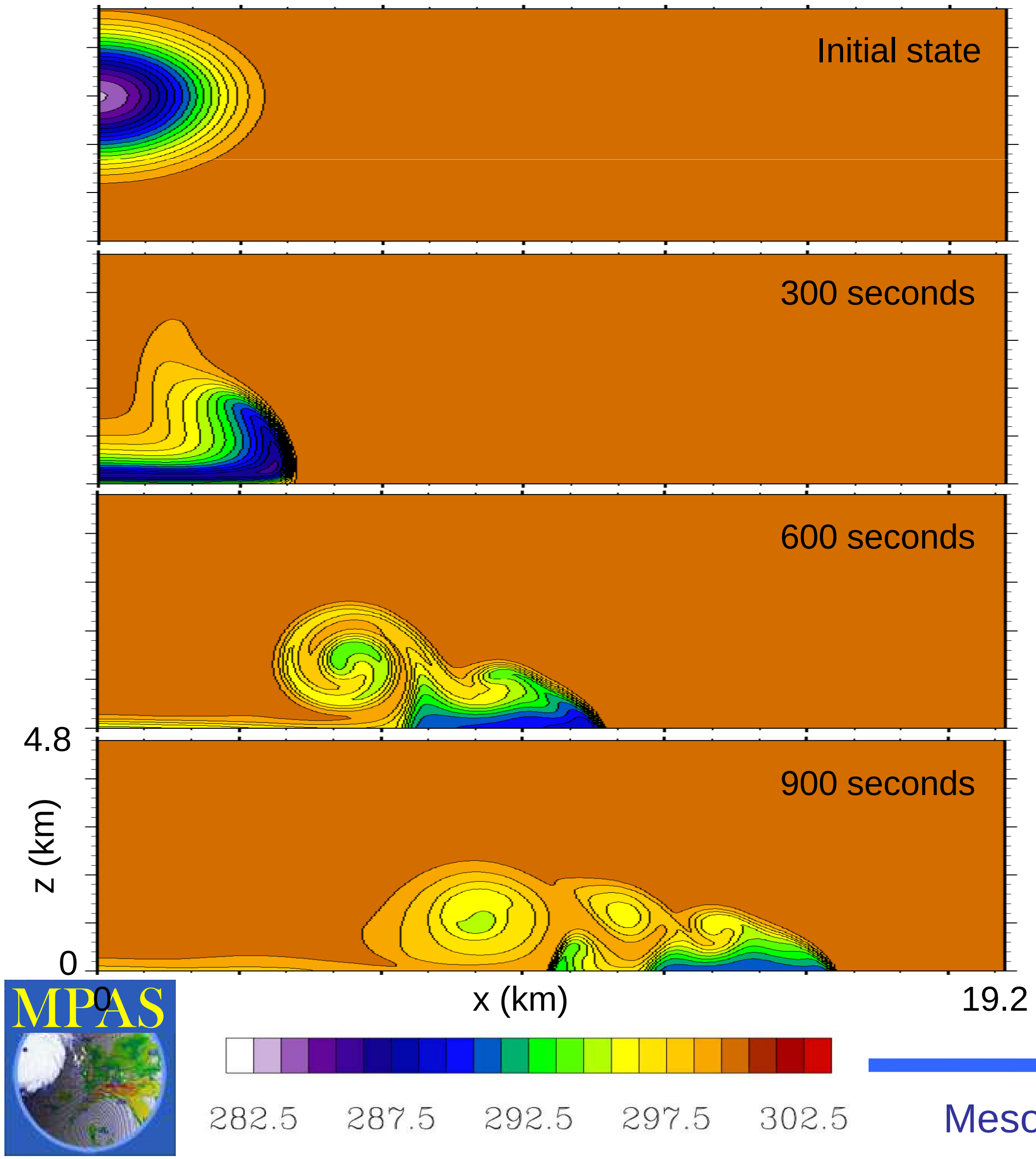
$$\omega \equiv \frac{d\zeta}{dt} = u\boxed{\frac{\partial\zeta}{\partial x}} + w\frac{\partial\zeta}{\partial z}$$

(Schar et al. MWR 2002, Klemp et al. MWR 2003)

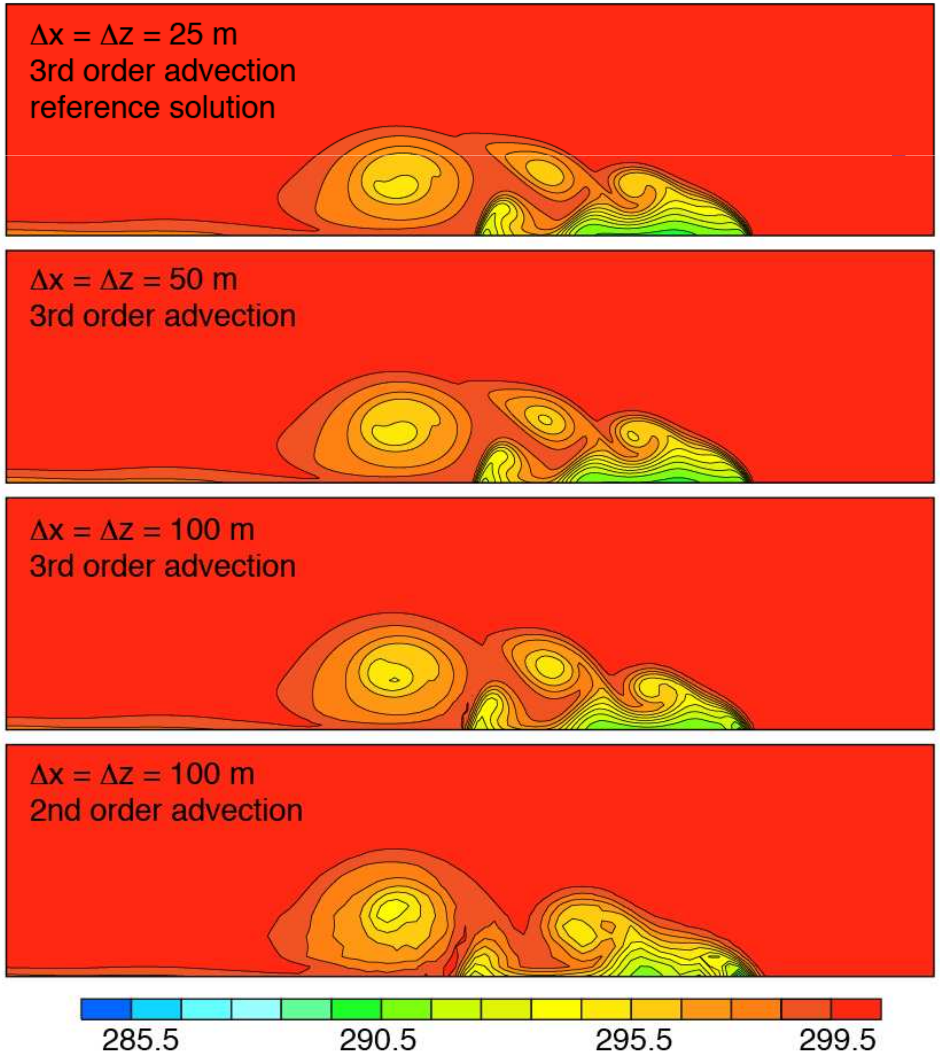
Density-Current Simulation

Potential Temperature, fixed physical viscosity = 75 m^2/s
Test case configuration: Straka et al (1993)

WRF simulation

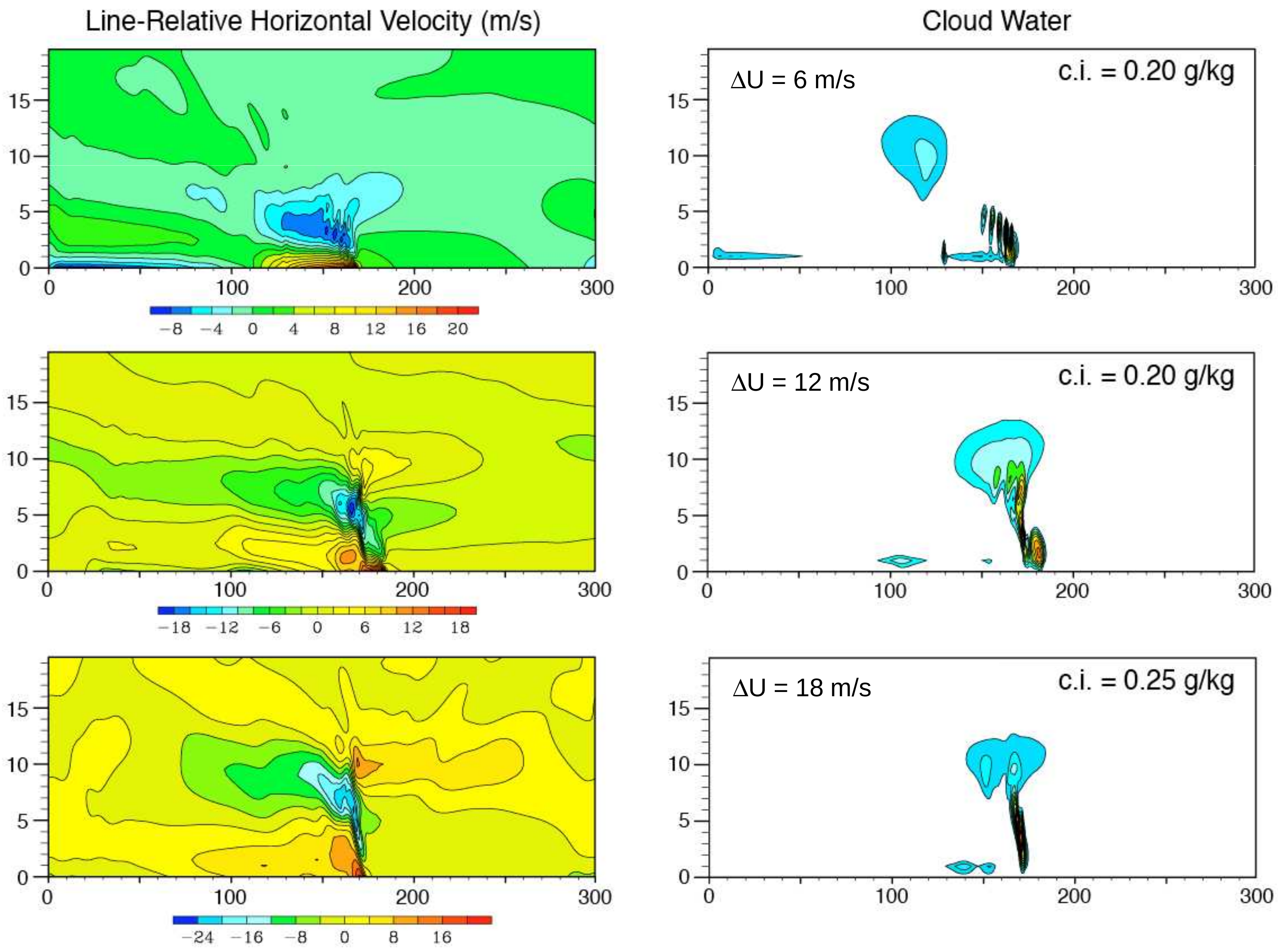


MPAS, t = 900 s

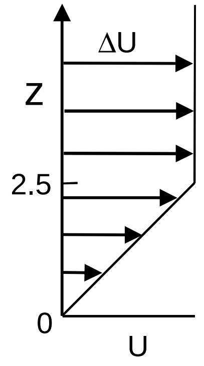


Nonhydrostatic Squall-Line Tests

Low-level shear (0-2.5 km), Weisman-Klemp sounding
Warm-bubble perturbation, results at 3 hours


Line-Relative Horizontal Velocity (m/s)

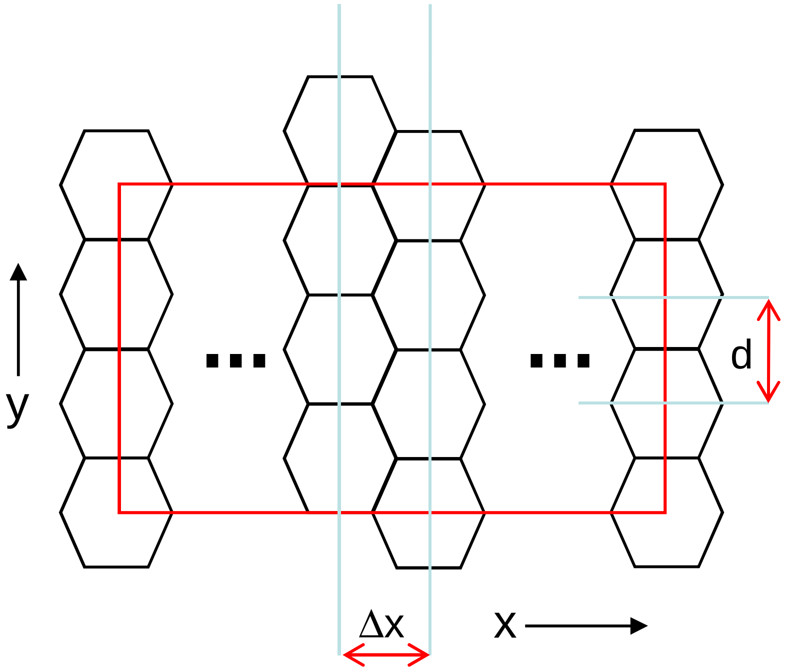
Cloud Water



(from Max Menchaca)

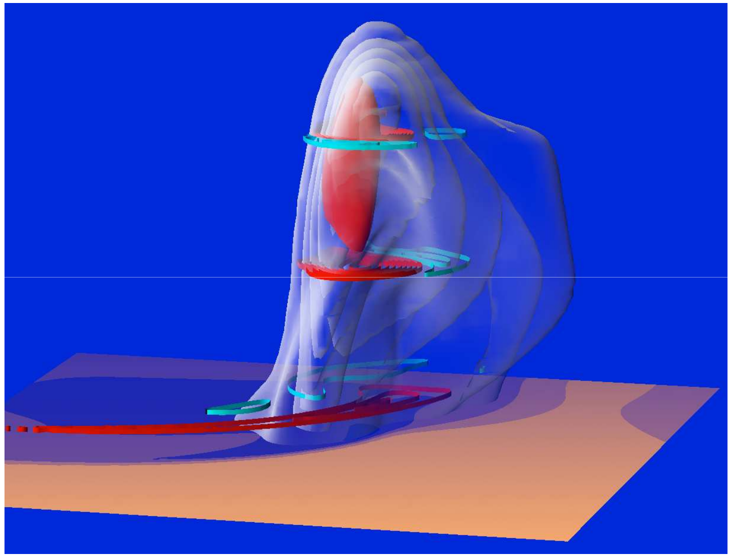
Supercell Simulations, MPAS & Reference Cloud Model

- Full MPAS model code used for idealized simulations
- Grid generated on flat plane with periodic boundaries

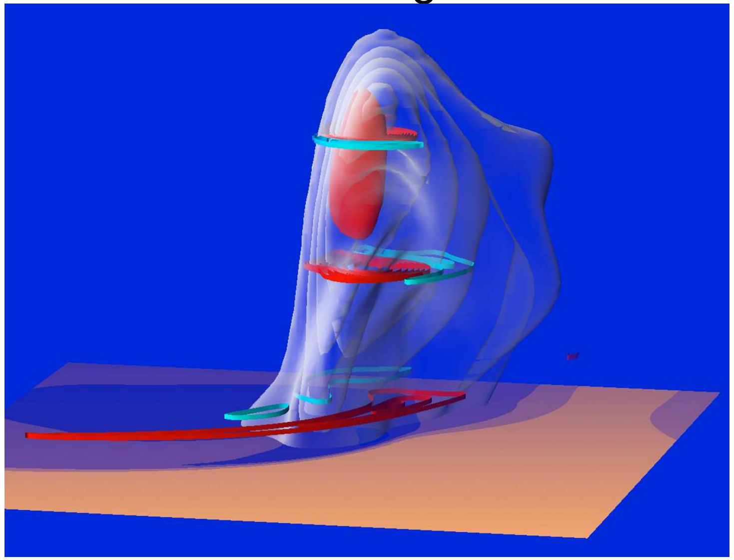


🟥 🟦 Vertical velocity contours at 1, 5, and 10 km (c.i. = 3 m/s)
30 m/s vertical velocity surface shaded in red
Rainwater surfaces shaded as transparent shells
Perturbation surface temperature shaded on baseplane

~500 m MPAS

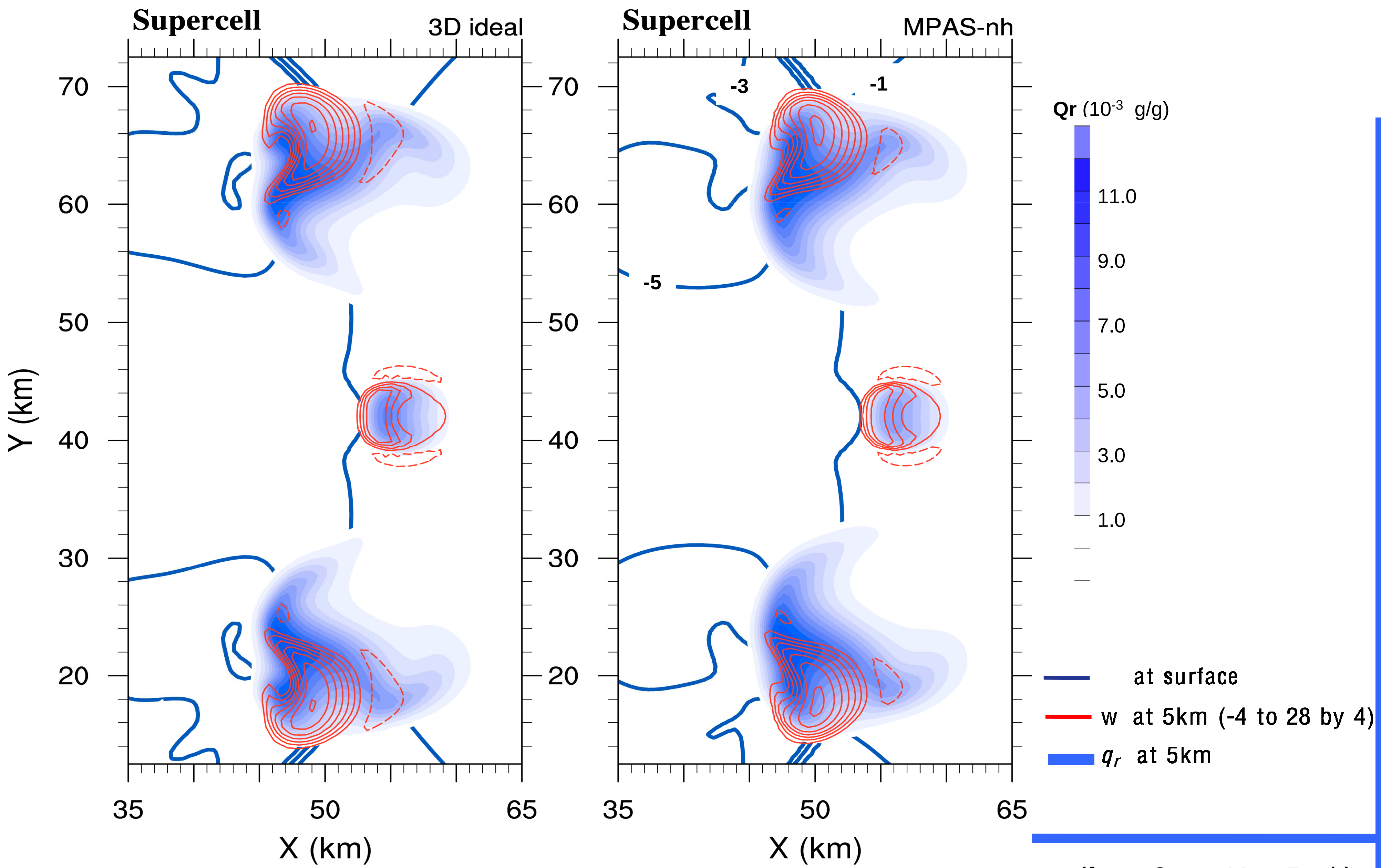


500 m Rectangular Grid



Supercell Simulations, MPAS & Reference Cloud Model

500 m grid, horizontal cross sections, t = 2 hours



(from Sang-Hun Park)

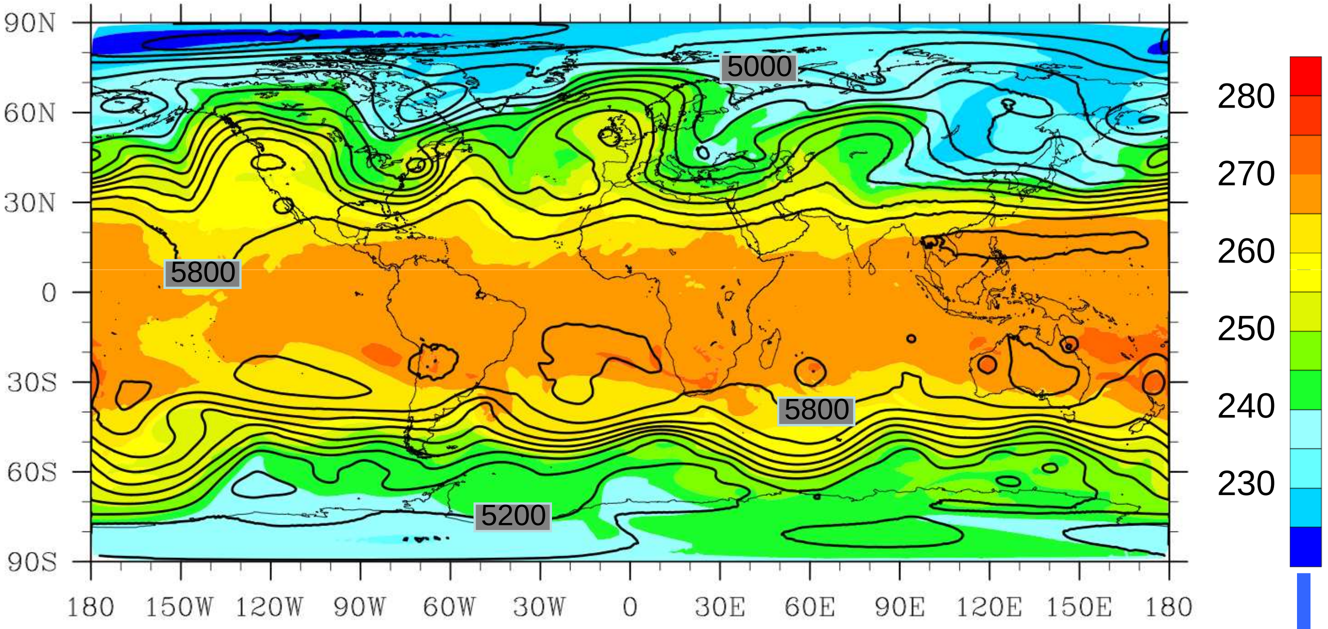
MPAS Nonhydrostatic NWP Testing

500 hPa temperature (K), heights (m), cinc = 100 m

5 day forecast

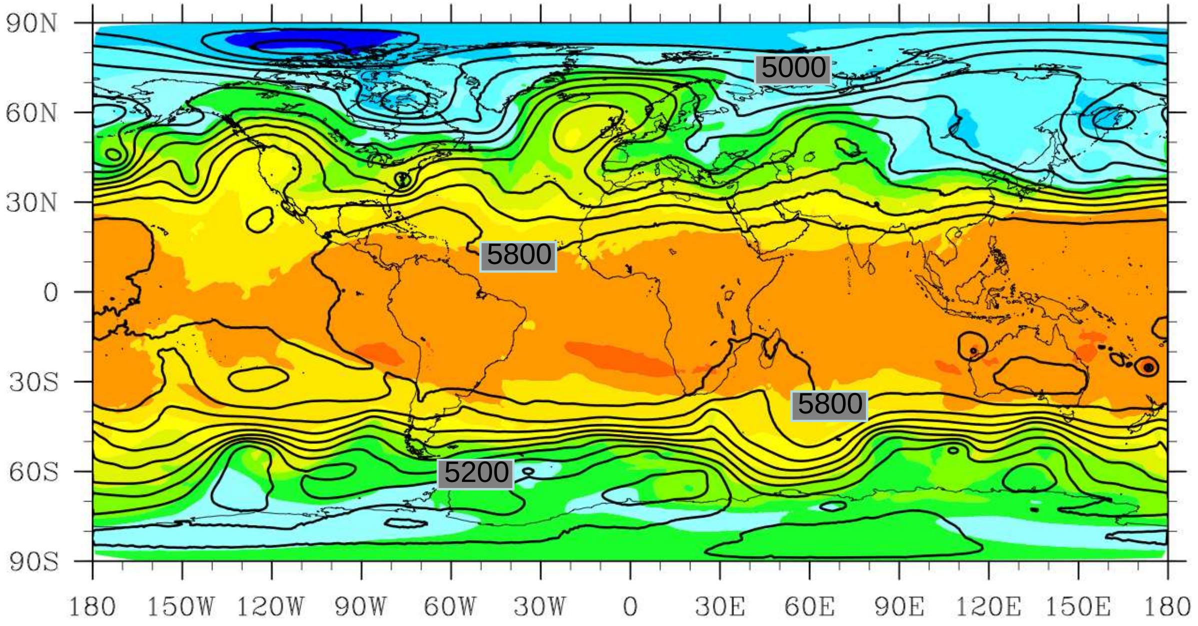
Valid 00Z 26 January 2011

60 km uniform mesh



GFS analysis

Valid 0Z 26 January 2011

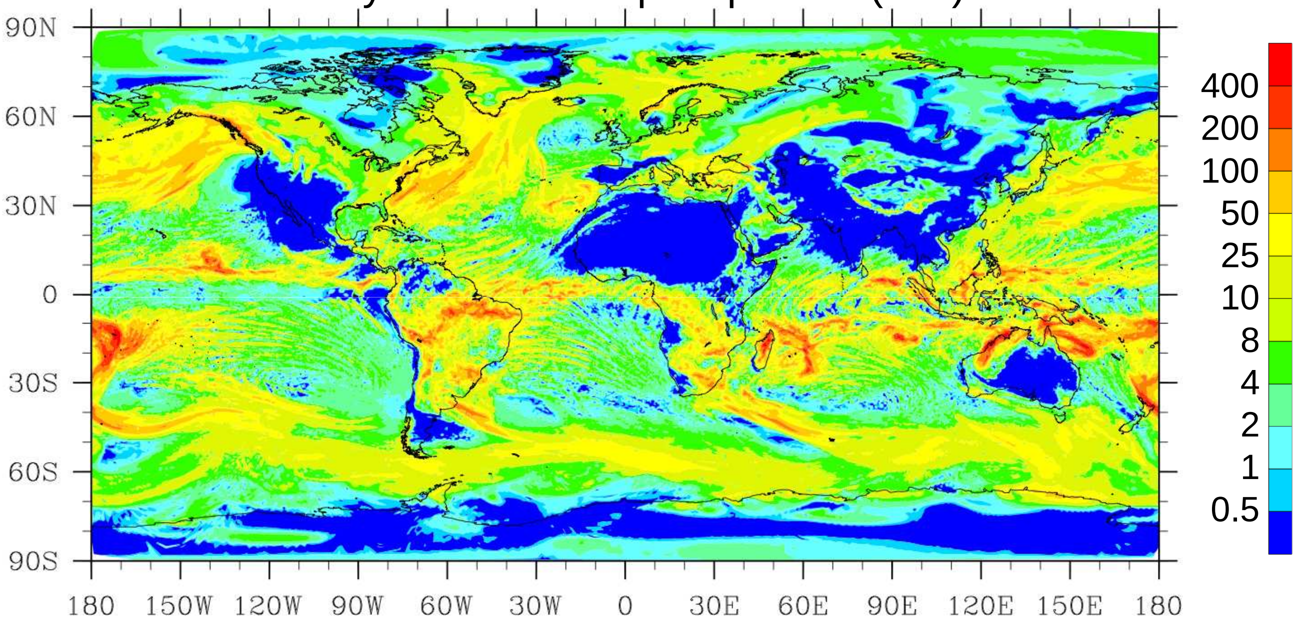


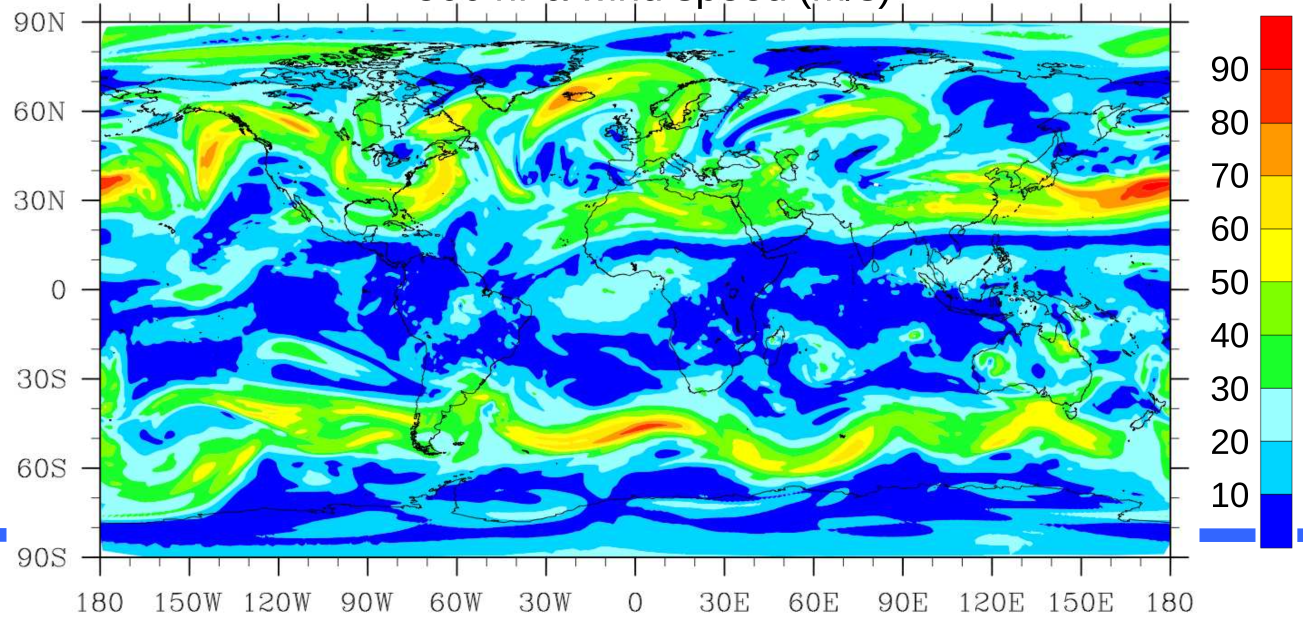
MPAS Nonhydrostatic NWP Testing

5 day forecast

Valid 00Z 26 January 2011

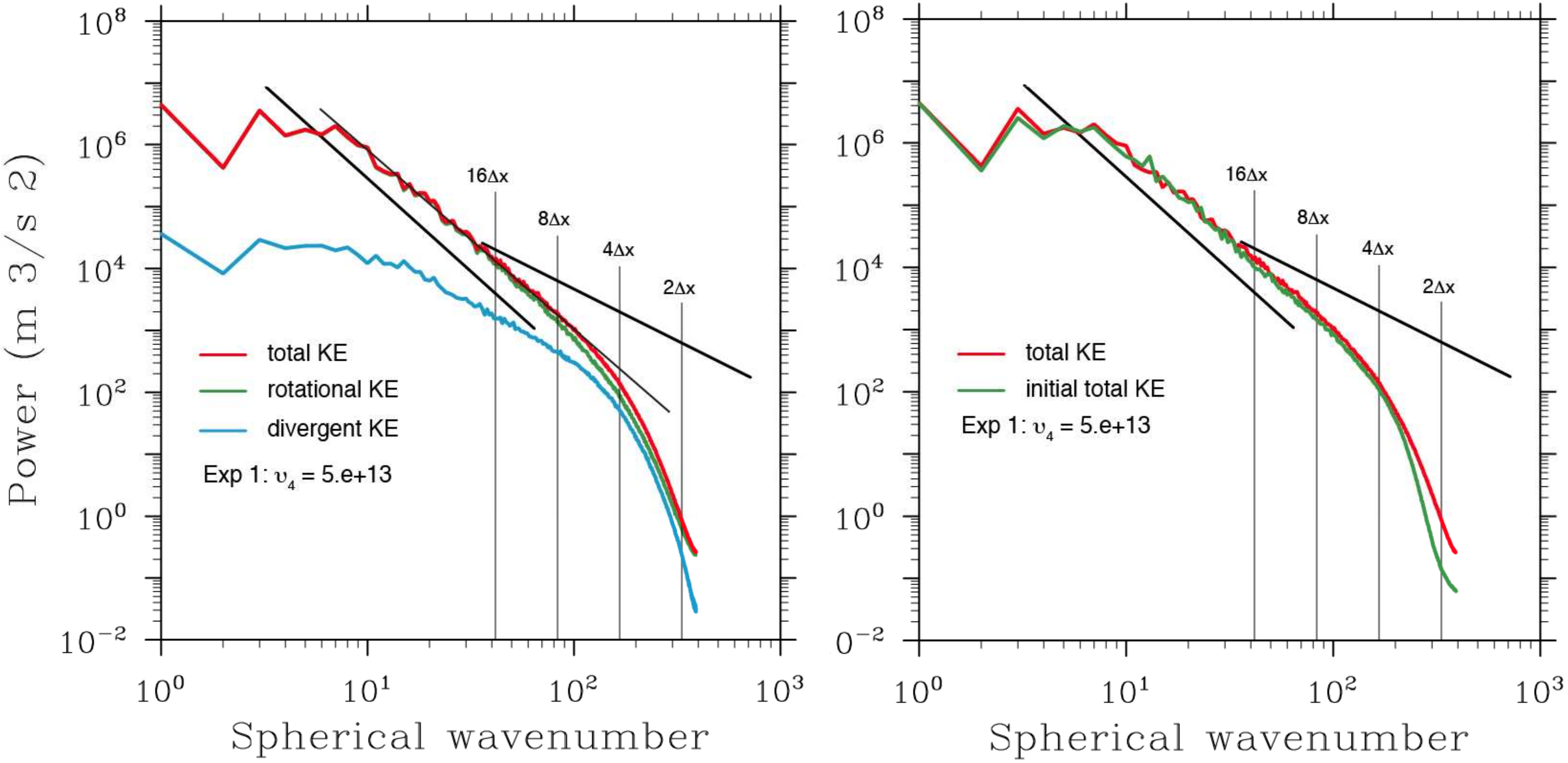
60 km uniform mesh


5-day accumulated precipitation (mm)


500 hPa wind speed (m/s)

MPAS Nonhydrostatic NWP Testing

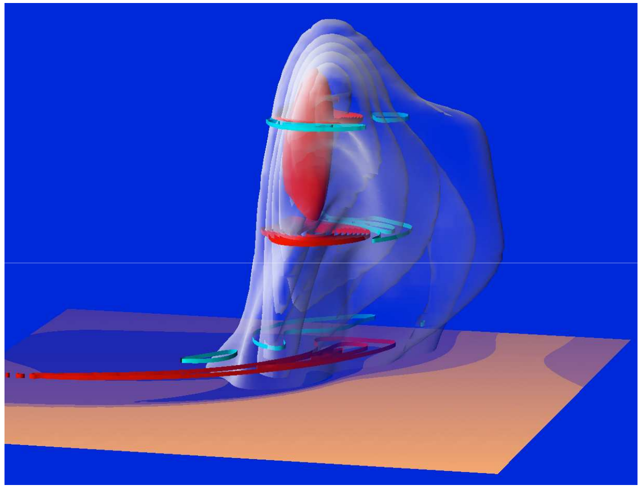
MPAS Kinetic Energy Spectra, 60 km mesh
5 day forecast valid 00z 26 January2011

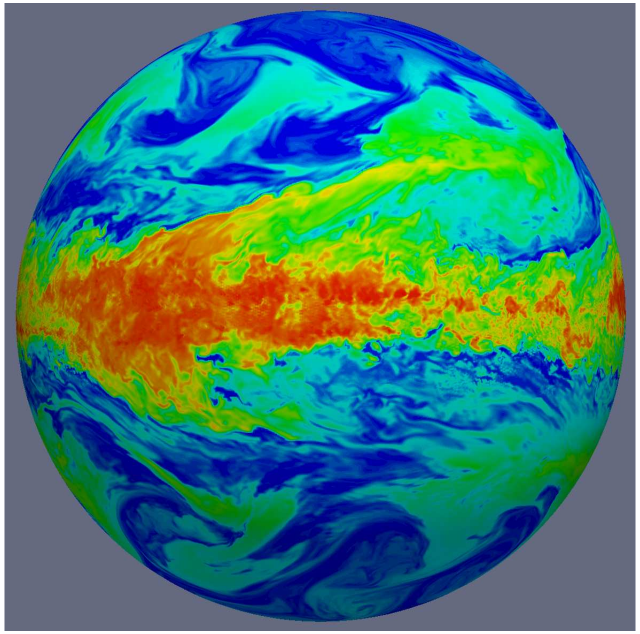


MPAS Development - Summary

Current Status

- Hydrostatic MPAS 3D SVCT solver
  - Implemented as CAM core in the CESM.
  - Aqua-planet simulations within CAM confirm robust behavior.
- Nonhydrostatic MPAS 3D SVCT solver
  - Configurable for the sphere and for 2D and 3D Cartesian domains.
  - Accurate results for idealized test nonhydrostatic test cases (including moisture).
  - Initial full-physics NWP simulations are encouraging.





Future Development

- Testing for NWP and regional climate applications on uniform and variable-resolution meshes.
- Scale-aware physics on variable resolution meshes.
- Nonhydrostatic core to be implemented as CAM core later this year.
- First MPAS release to friendly users anticipated about the first of next year.