# Global Nonhydrostatic Atmospheric Simulation with MPAS

MPAS
Model for Prediction Across Scales

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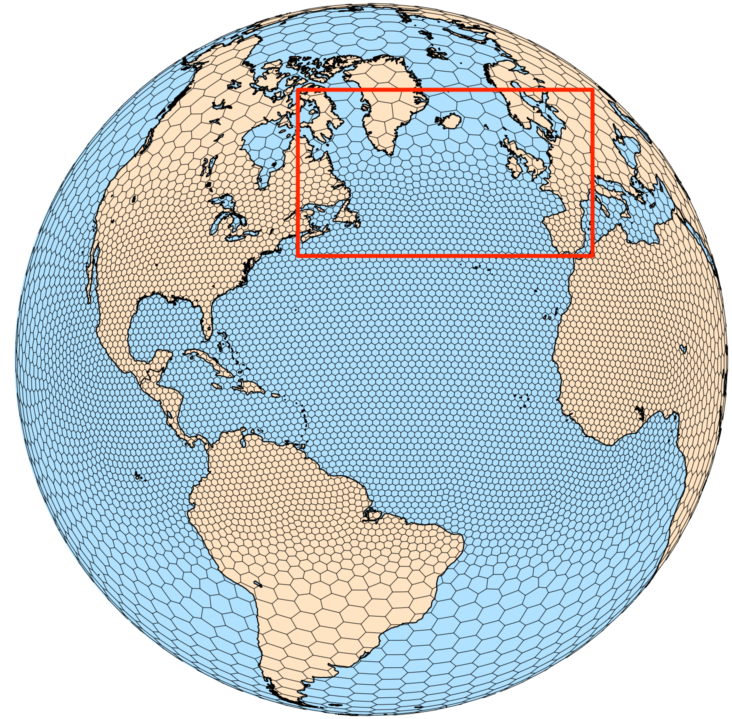
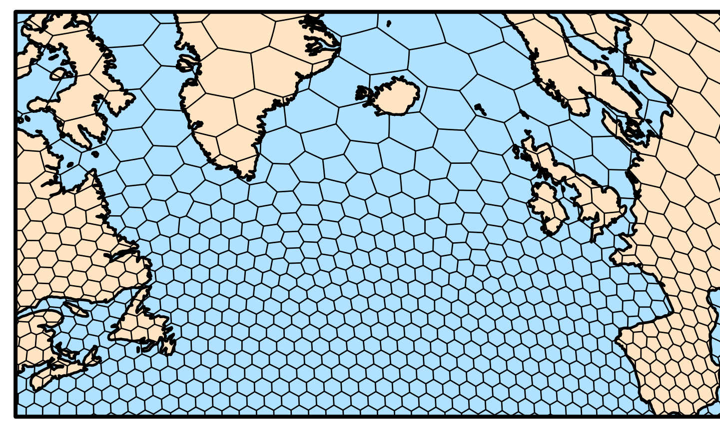
*Based on unstructured centroidal Voronoi (hexagonal) meshes using C-grid staggering and selective grid refinement.*

Collaboratively developed, primarily by NCAR and LANL/DOE

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





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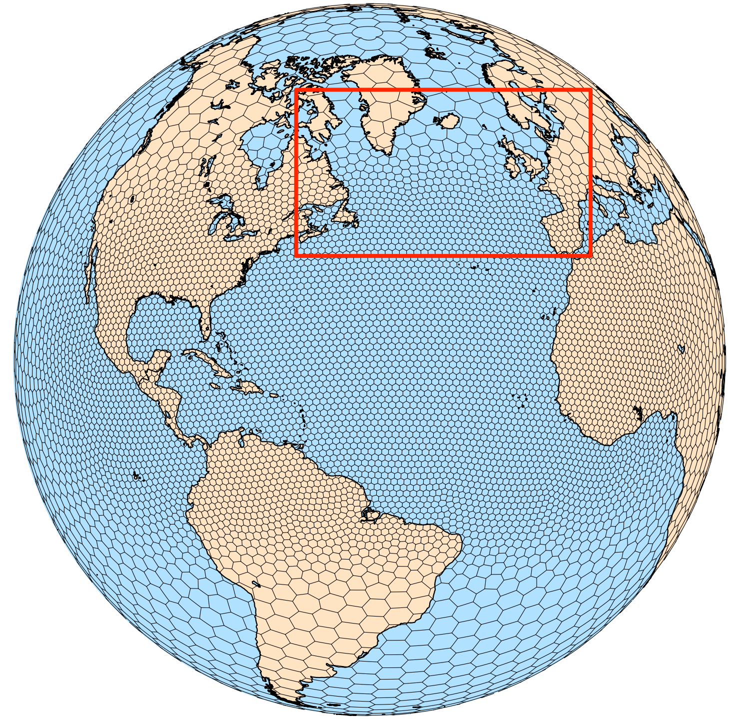
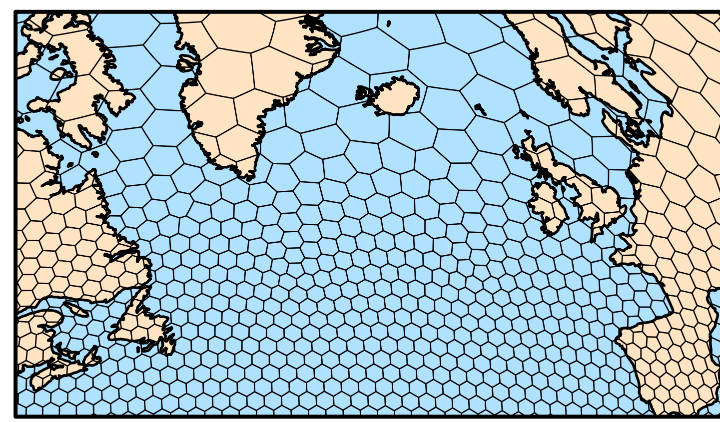
# Global Nonhydrostatic Atmospheric Simulation with MPAS

(1) What is it and why build it?
(2) Critical numerics
(3) Does it work?
(4) Early science:
Atmospheric KE spectra
(5) Where are we, and
where are we going?





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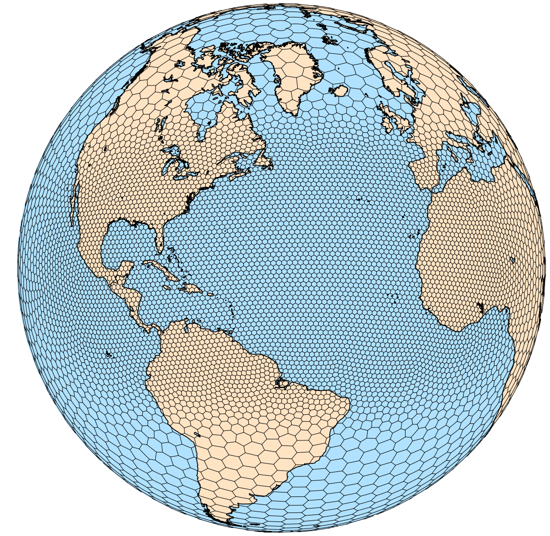
# *What is MPAS?*



*MPAS consists of geophysical fluid-flow solvers based on unstructured centroidal Voronoi (hexagonal) meshes using C-grid staggering and selective grid refinement.*

MPAS Version 2.1:

MPAS infrastructure - NCAR, LANL, others.

Infrastructure for the Voronoi mesh and solvers (data structures; mesh generation, manipulation; operators on the mesh).

MPAS - Atmosphere (NCAR)

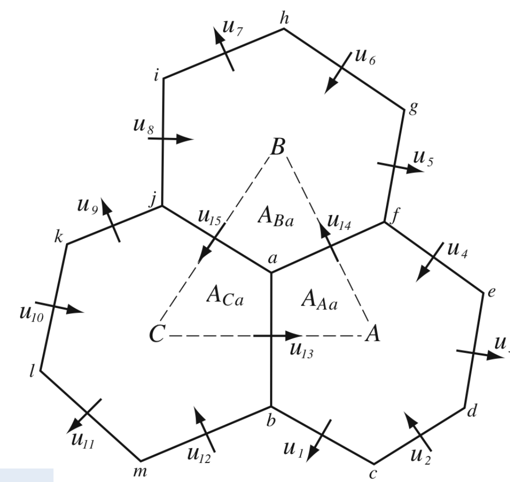
Nonhydrostatic atmospheric solver; pre- and post-processors

MPAS - Ocean (LANL)

Hydrostatic ocean solver, pre- and post-processors

MPAS - Ice, etc. (LANL and others)

Land-ice model, pre- and post-processors




*These are all stand-alone models – there is no coupler in MPAS*

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# *What is MPAS?*

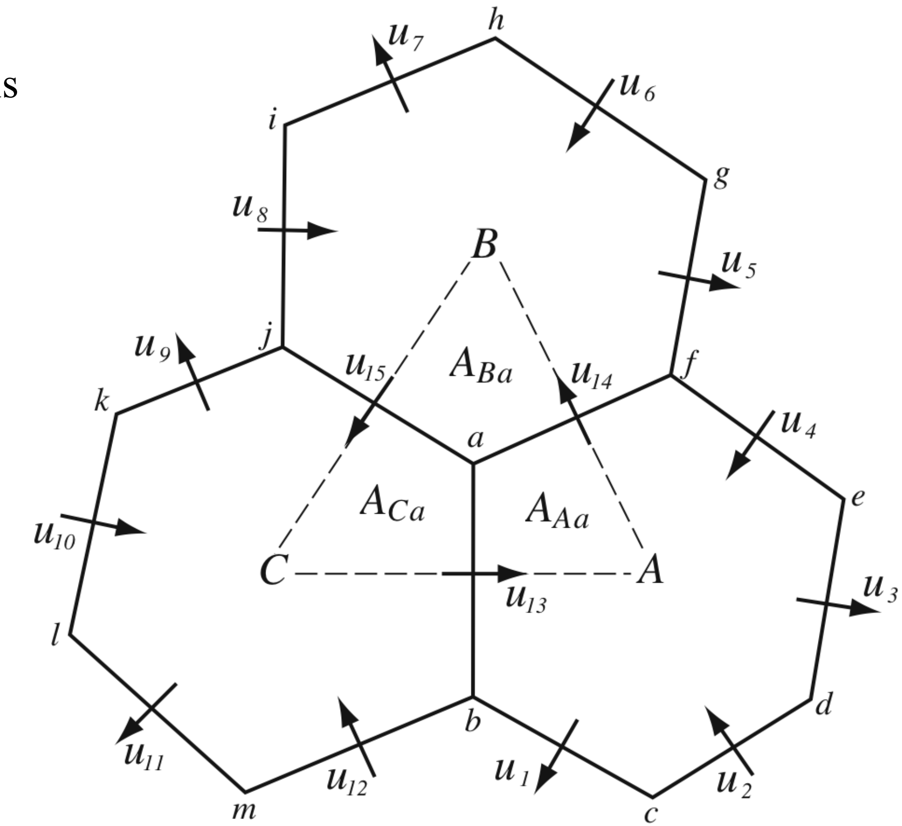
## Centroidal Voronoi Meshes

<u>Unstructured spherical centroidal Voronoi meshes</u>

- Mostly *hexagons*, some pentagons and 7-sided cells
- Cell centers are at cell center-of-mass (centroidal).
- Cell edges bisect and are orthogonal to the lines connecting cell centers.
- Uniform resolution – traditional icosahedral mesh.

<u>C-grid</u>

- Solve for normal velocities on cell edges.
- Gradient operators in the horizontal momentum equations are 2nd-order accurate.
- Velocity divergence is 2nd-order accurate for edge-centered velocities.
- Reconstruction of full velocity requires care.



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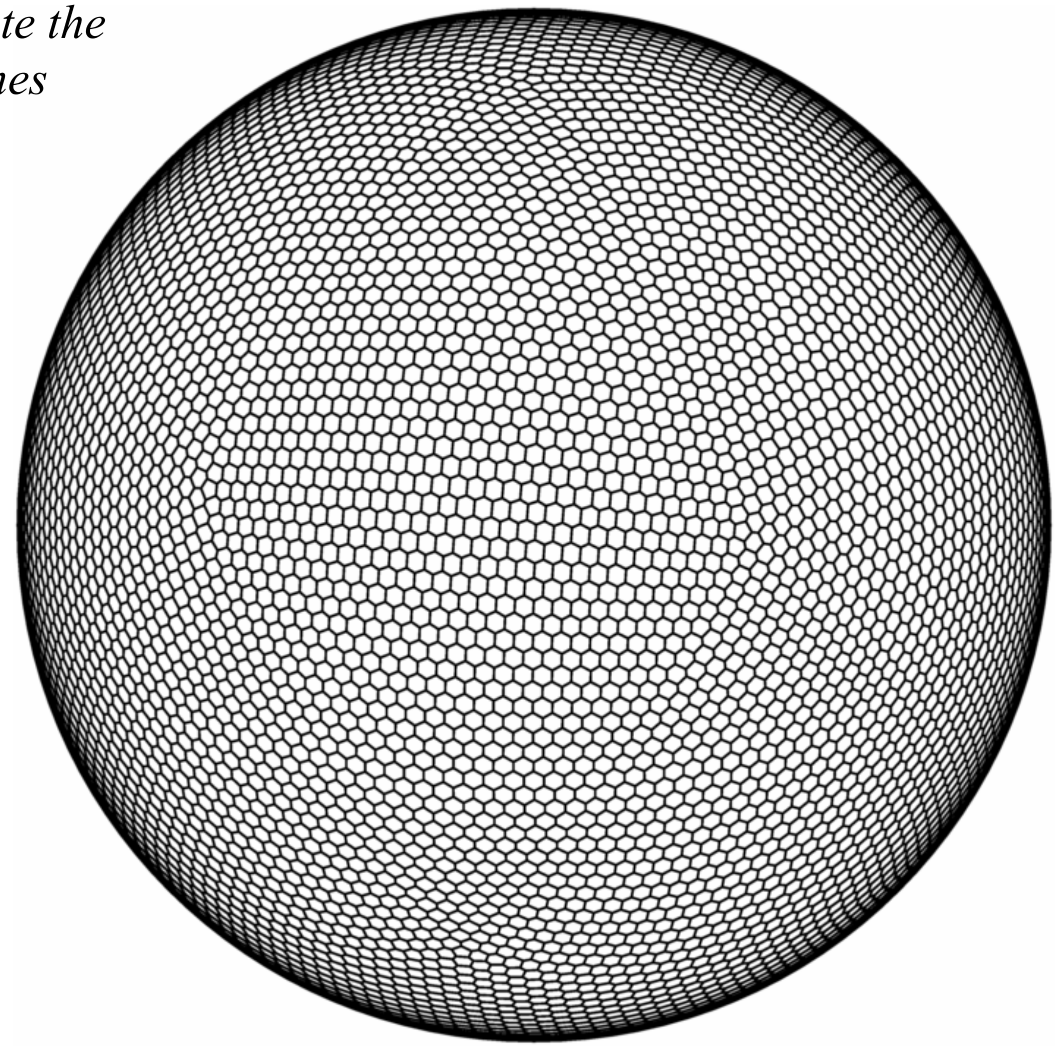
# Centroidal Voronoi Meshes: Mesh Generation

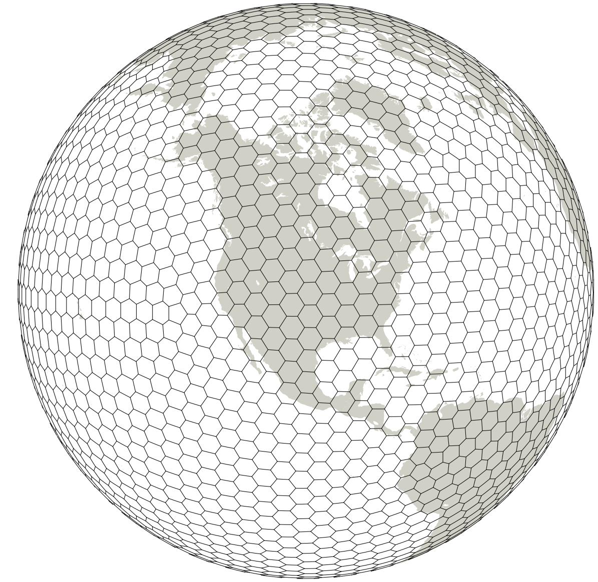
*We use Lloyd's method to generate the MPAS spherical Voronoi meshes*

An example of mesh generation beginning from an icosahedral mesh.

No points are fixed.



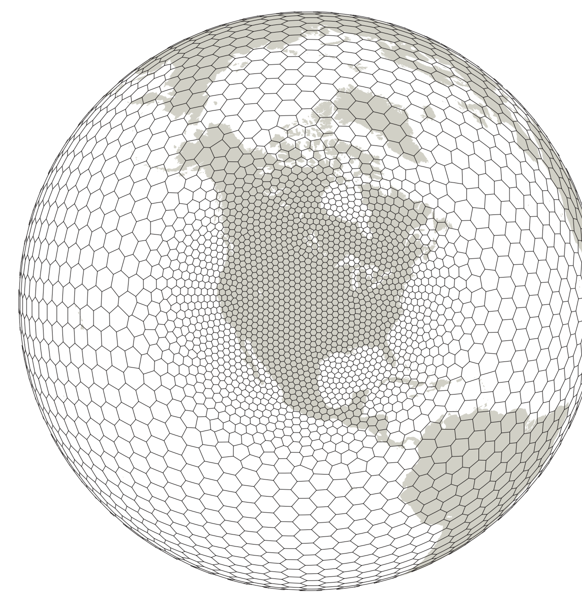
# *Why MPAS?*



*Uniform resolution applications:*

Convection-permitting (Δx ~ few km) global simulations of weeks to months are now feasible on present-day computers.

Global operational NWP models are now *mesoscale* models.
Examples: ECMWF, UKMO, even the GFS ~15 km mesh spacing.
- Nonhydrostatic (5 km) – factor of 30: 7+ years
- Convection permitting (3 km) – factor of 125: 10+ years



*Applications using regional meshes:*

Traditional (nested) regional NWP applications are limited by boundary-induced errors to short time integrations. Variable-resolution global MPAS removes this limitation.

Traditional (nested) regional climate applications have issues with its the downscaling philosophy and the nested BCs. Variable-resolution MPAS allows for upscaling, and has no lateral boundaries.

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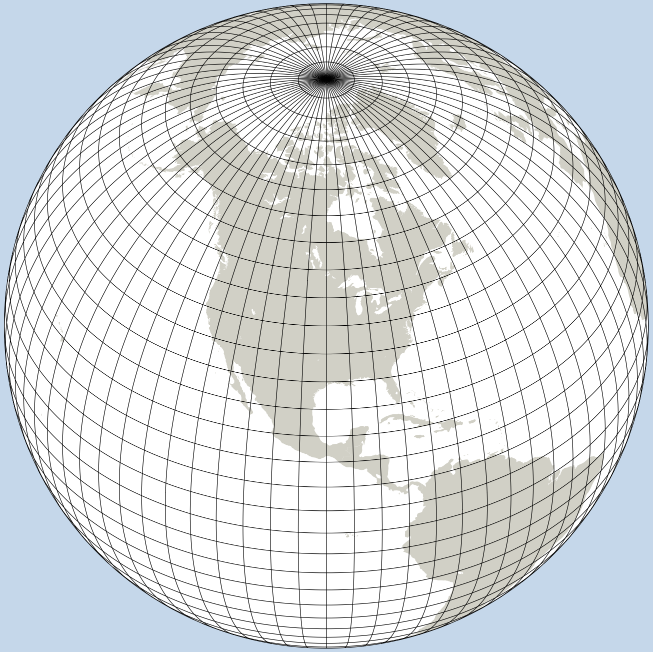
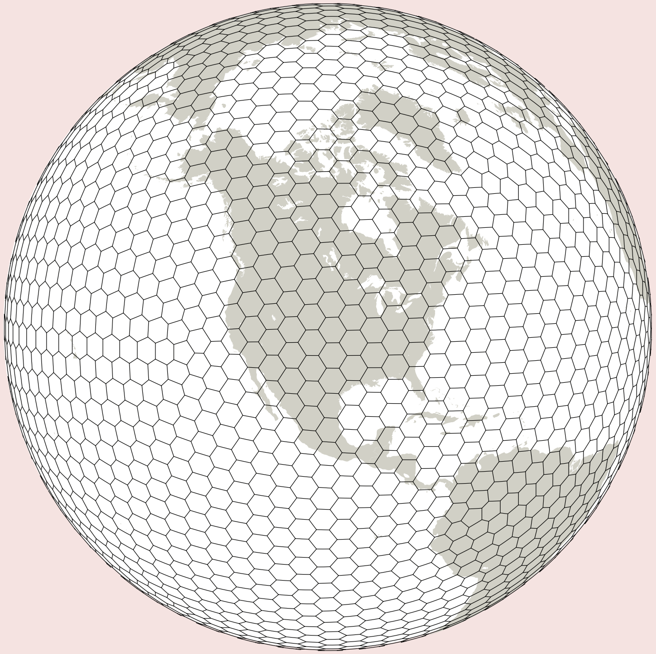
# *Why MPAS?*

## Significant differences between WRF and MPAS



### WRF
### Lat-Lon global grid

- Anisotropic grid cells
- Polar filtering required
- Poor scaling on massively parallel computers



### MPAS
### Unstructured Voronoi (hexagonal) grid

- Good scaling on massively parallel computers
- No pole problems

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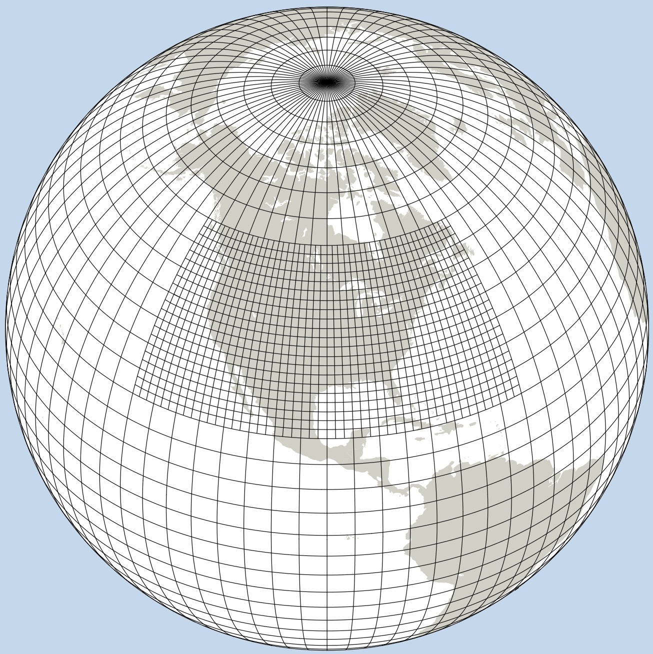
# *Why MPAS?*

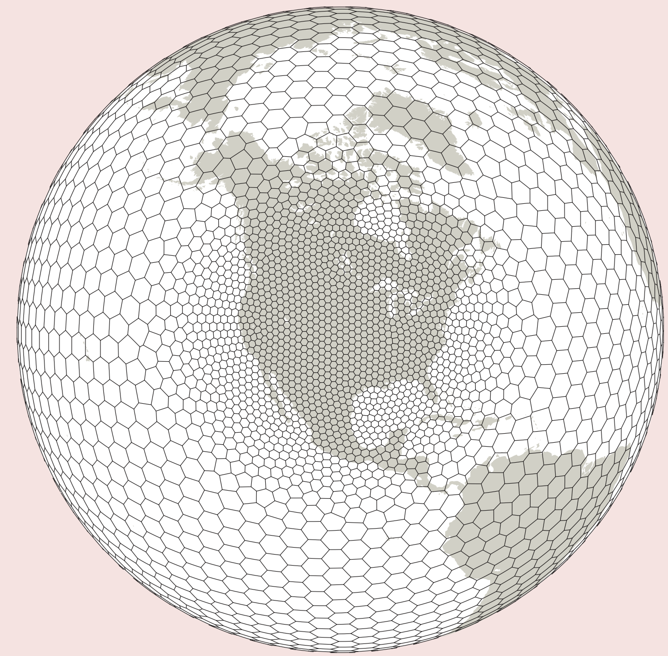
## Significant differences between WRF and MPAS



### WRF

Grid refinement through domain nesting

- Flow distortions at nest boundaries



### MPAS

Smooth grid refinement on a conformal mesh

- Increased accuracy and flexibility for variable resolution applications
- No abrupt mesh transitions.

# MPAS Nonhydrostatic Atmospheric Solver

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## Nonhydrostatic formulation

*Equations*

- Prognostic equations for coupled variables.
- Generalized height coordinate.
- Horizontally vector invariant eqn set.
- Continuity equation for dry air mass.
- Thermodynamic equation for coupled potential temperature.

*Time integration*

Split-explicit Runge-Kutta (3rd order), as in Advanced Research WRF

*Spatial discretization*

Similar to Advanced Research WRF except for a few critical terms.

Variables:

$$(U,V,\Omega,\Theta,Q_j) = \tilde{\rho}_d \cdot (u,v,\dot{\eta},\theta,q_j)$$

Vertical coordinate:

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

Prognostic equations:

$$\frac{\partial \mathbf{V}_H}{\partial t} = -\frac{\rho_d}{\rho_m}\left[\nabla_\zeta\left(\frac{p}{\zeta_z}\right) - \frac{\partial \mathbf{z}_H p}{\partial \zeta}\right] - \eta \mathbf{k} \times \mathbf{V}_H - \mathbf{v}_H \nabla_\zeta \cdot \mathbf{V} - \frac{\partial \Omega \mathbf{v}_H}{\partial \zeta} - \rho_d \nabla_\zeta K - eW\cos\alpha_r - \frac{uW}{r_e} + \mathbf{F}_{V_H},$$

$$\frac{\partial W}{\partial t} = -\frac{\rho_d}{\rho_m}\left[\frac{\partial p}{\partial \zeta} + g\tilde{\rho}_m\right] - (\nabla \cdot \mathbf{v}W)_\zeta + \frac{uU+vV}{r_e} + e(U\cos\alpha_r - V\sin\alpha_r) + F_W,$$

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

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

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

Diagnostics and definitions:

$$\theta_m = \theta[1 + (R_v/R_d)q_v] \qquad p = p_0\left(\frac{R_d \zeta_z \Theta_m}{p_0}\right)^\gamma$$

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

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# Operators on the Voronoi Mesh
## *'Nonlinear' Coriolis force*

$$\frac{\partial \boldsymbol{V}_H}{\partial t} = -\frac{\rho_d}{\rho_m}\left[\boldsymbol{\nabla}_\zeta\left(\frac{p}{\zeta_z}\right) - \frac{\partial \boldsymbol{z}_H p}{\partial \zeta}\right] - \eta\, \boldsymbol{k} \times \boldsymbol{V}_H$$
$$- \boldsymbol{v}_H \boldsymbol{\nabla}_\zeta \cdot \boldsymbol{V} - \frac{\partial \Omega \boldsymbol{v}_H}{\partial \zeta} - \rho_d \boldsymbol{\nabla}_\zeta K - eW\cos\alpha_r - \frac{uW}{r_e} + \boldsymbol{F}_{V_H},$$

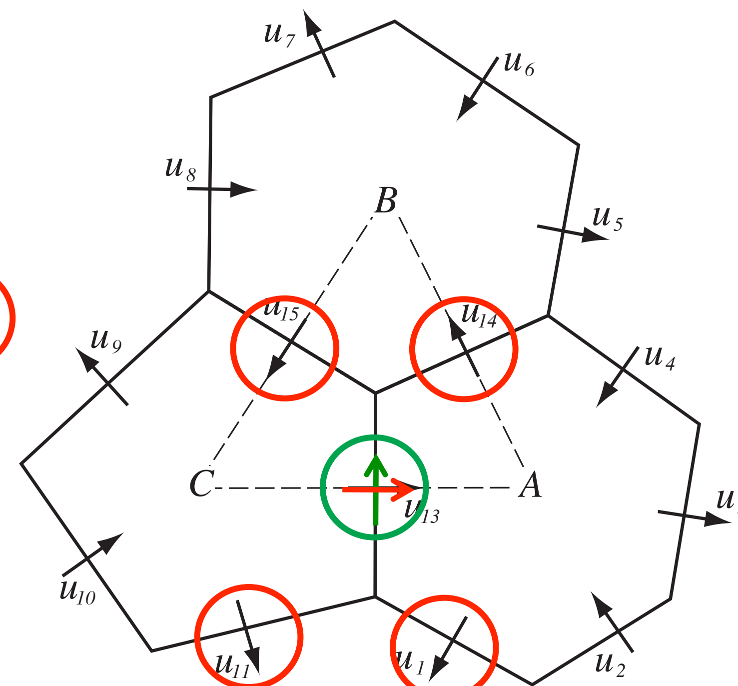
Linear piece $f\ \boldsymbol{k}\ x\ \boldsymbol{V_H}$, consider $u_{13}$ →

We need to reconstruct the tangential velocity

Simplest approach: Construct tangential velocities from weighted sum of the four nearest neighbors.

Result: Physically stationary geostrophic modes (geostrophically-balanced flow) will not be stationary in the discrete system; the solver is unusable.

(Nickovic et al, MWR 2002)



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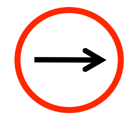
# Operators on the Voronoi Mesh
## *'Nonlinear' Coriolis force*

Linear piece: $f\ \mathbf{k} \times \mathbf{V}_H$

We construct tangential velocities from a weighted sum of normal velocities on edges of the adjacent cells.

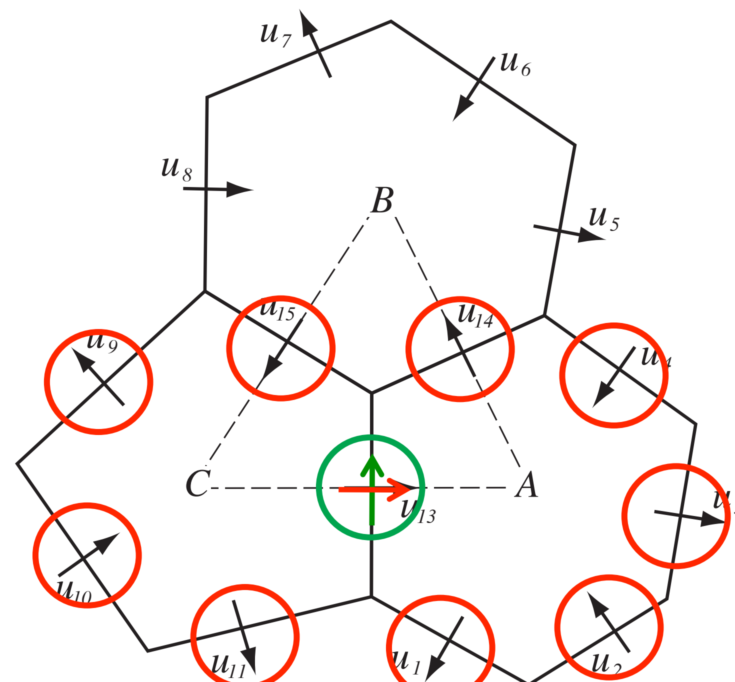


$$d_e\, u_e^{\perp} = \sum_j w_e^j\, l_j\, u_j$$

*We choose the weights such that the divergence in the triangle is the area-weighted sum of the divergence in the Voronoi cells sharing the vertex.*

Result: geostrophic modes are stationary; local and global mass and PV conservation is satisfied on the dual (triangular) mesh (for the SW equations).

*The general tangential velocity reconstruction also allows for PV, enstrophy and energy* conservation in the nonlinear SW solver.*




Thuburn et al (2009 JCP)
Ringler et at (2010, JCP)

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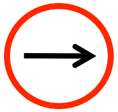
# Operators on the Voronoi Mesh
## *'Nonlinear' Coriolis force*

Linear piece: $f\ \boldsymbol{k} \times \boldsymbol{V_H}$

We construct tangential velocities from a weighted sum of normal velocities on edges of adjacent hexagons.



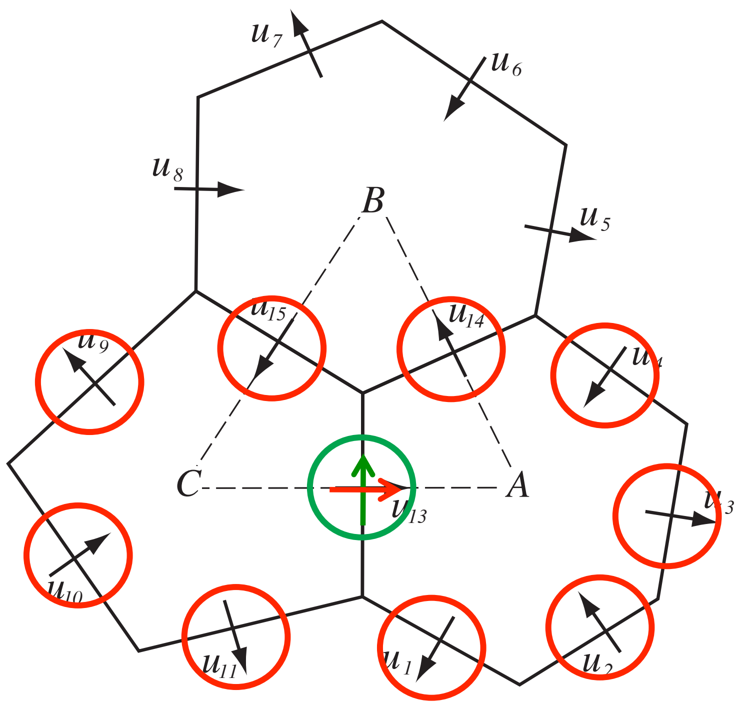
$$d_e\, u_e^{\perp} = \sum_j w_e^j\, l_j\, u_j$$

*We choose the weights such that the divergence in the triangle is the area-weighted sum of the divergence in the hexagons.*

*Why does this work?*
Consider the linearized SW equations

$$h_t = H\, \nabla \cdot \mathbf{V}$$
$$\zeta_t = -f\, \nabla \cdot \mathbf{V}$$

*Divergences on primary and dual meshes must be consistent to maintain stationarity*




Thuburn et al (2009 JCP)
Ringler et at (2010, JCP)

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# Uniform mesh MPAS-A simulations on Yellowstone

Global, uniform resolution.

6 simulations using average cell-center spacings:

60, 30, 15, 7.5 (2 - with and without convective param) and 3 km.

Cells in a horizontal plane: 163,842 (60 km), 655,362 (30 km), 2,621,442 (15 km), 10,485,762 (7.5 km) and 65,536,002 (3 km).

41 vertical levels, WRF-NRCM physics, prescribed SSTs.

*Hindcast periods:*
23 October – 2 November 2010
27 August – 1 September 2010, active TC period
15 January – 4 February 2009, MJO event

MPAS Physics:
WSM6 cloud microphysics
Tiedtke convection
Monin-Obukhov surface layer
YSU pbl, Noah land-surface
RRTMG lw and sw.

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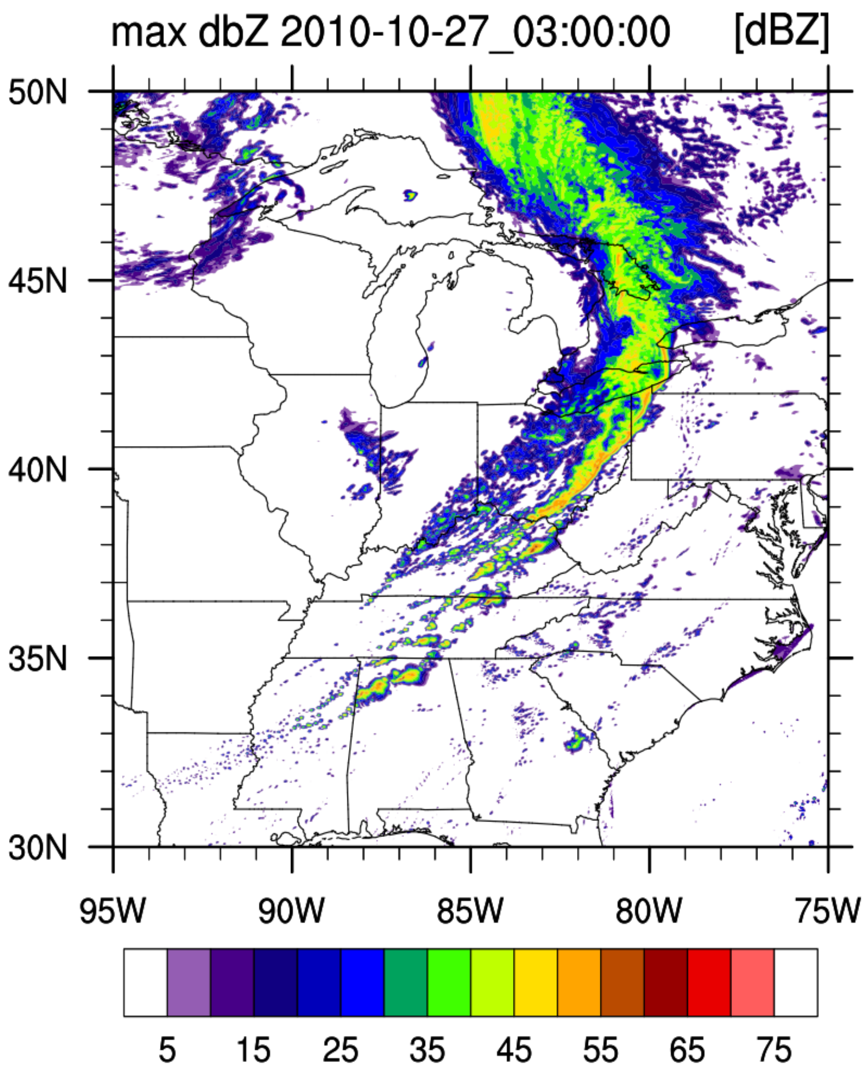
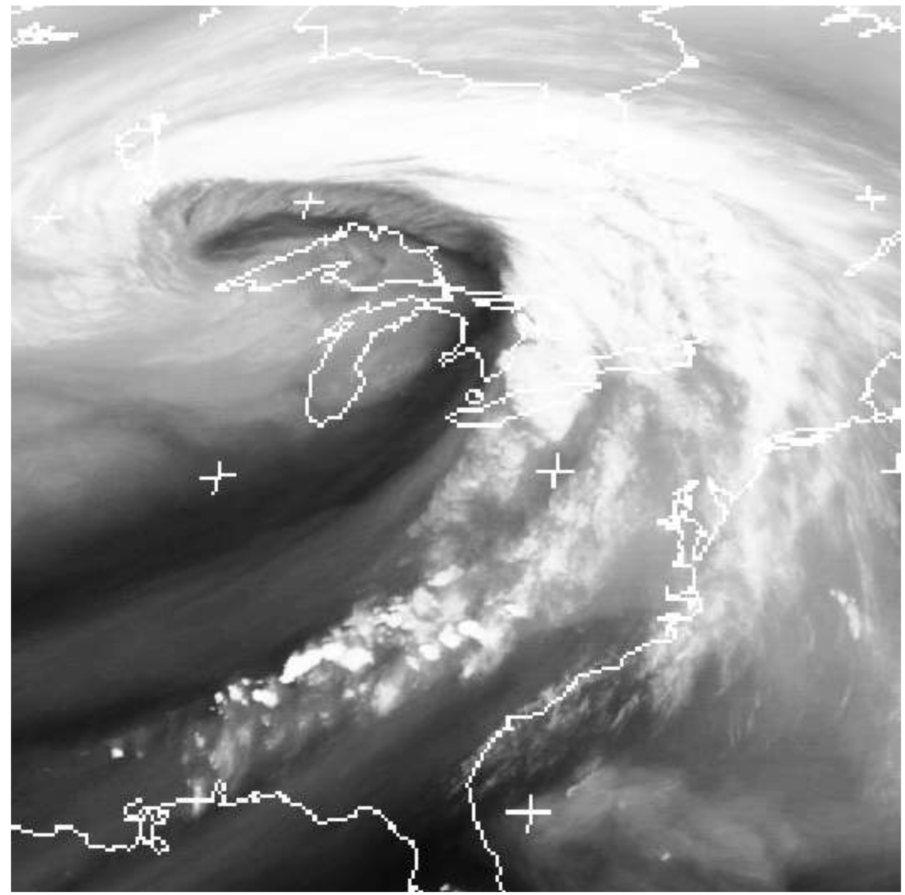
# 3 km global MPAS-A simulation 2010-10-23 init




GOES East, 2010-10-27 0 UTC
IR - vapor channel



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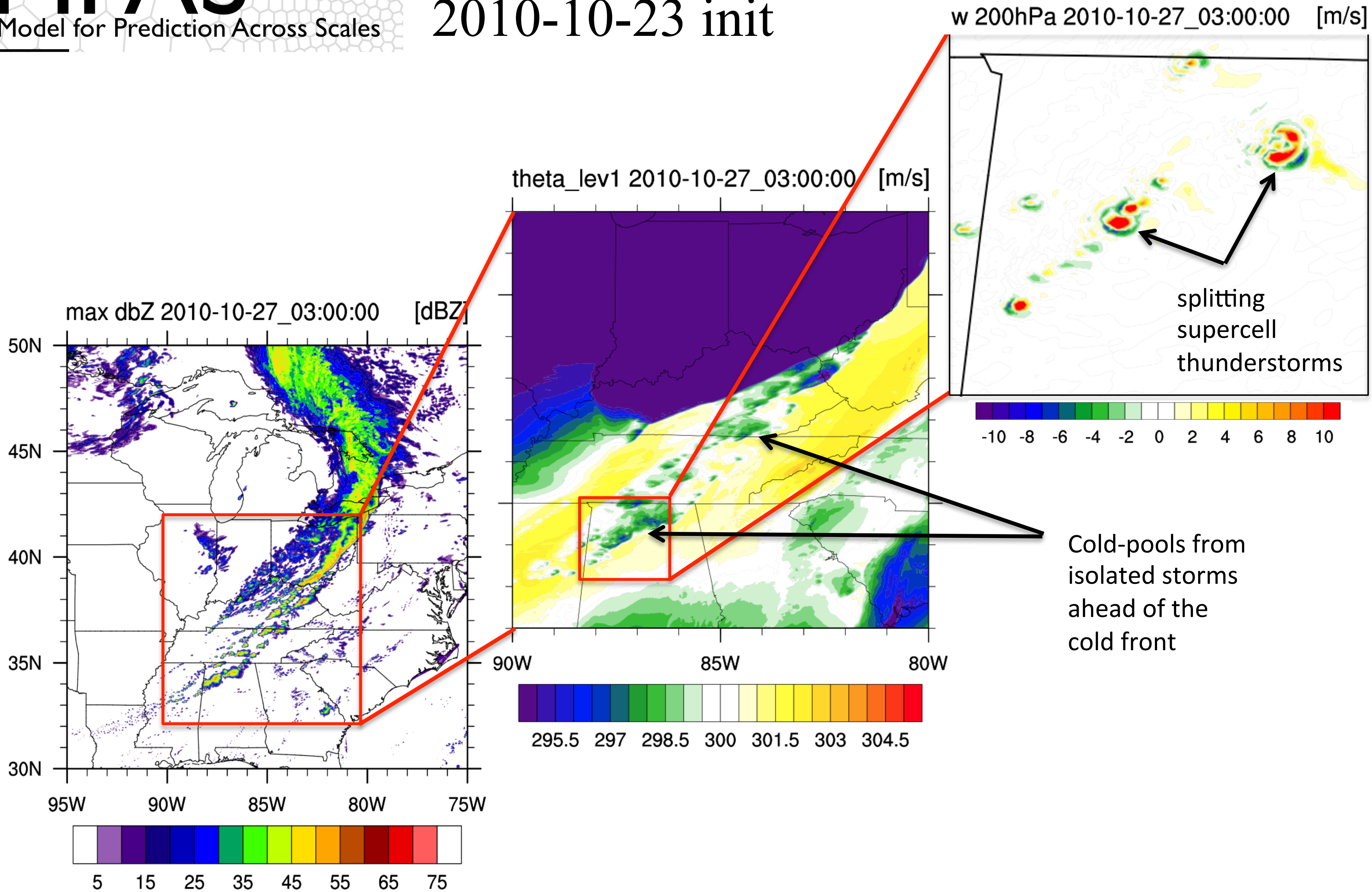
# 3 km global MPAS-A simulation 2010-10-23 init



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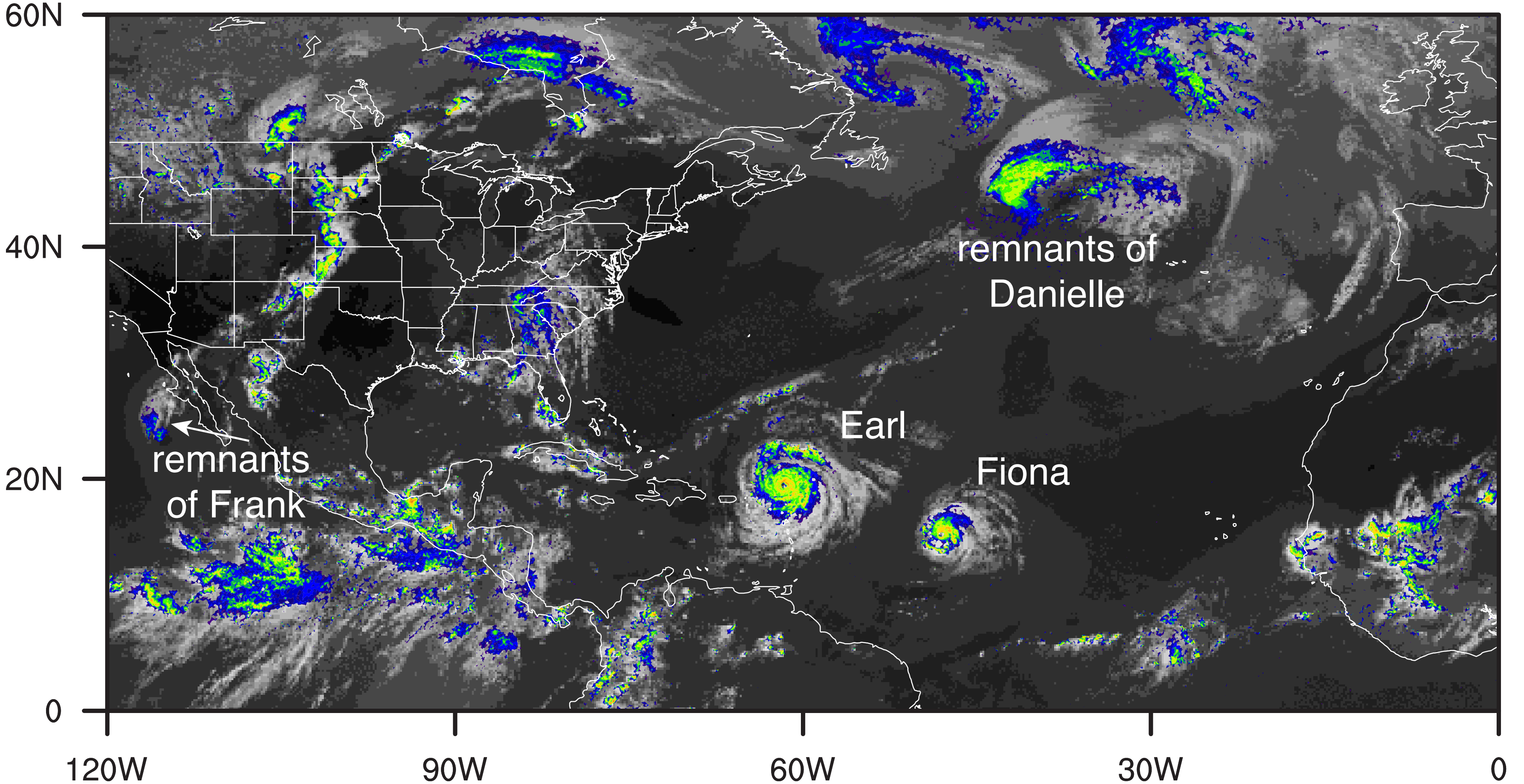
# MPAS 3 km global simulations

Outgoing Longwave Radiation and Column-Maximum Reflectivity
3 km global MPAS 4-day forecast, valid 0 UTC 31 August 2010



# MPAS 3km global simulations
# 27 Aug– 2 Sept 2010

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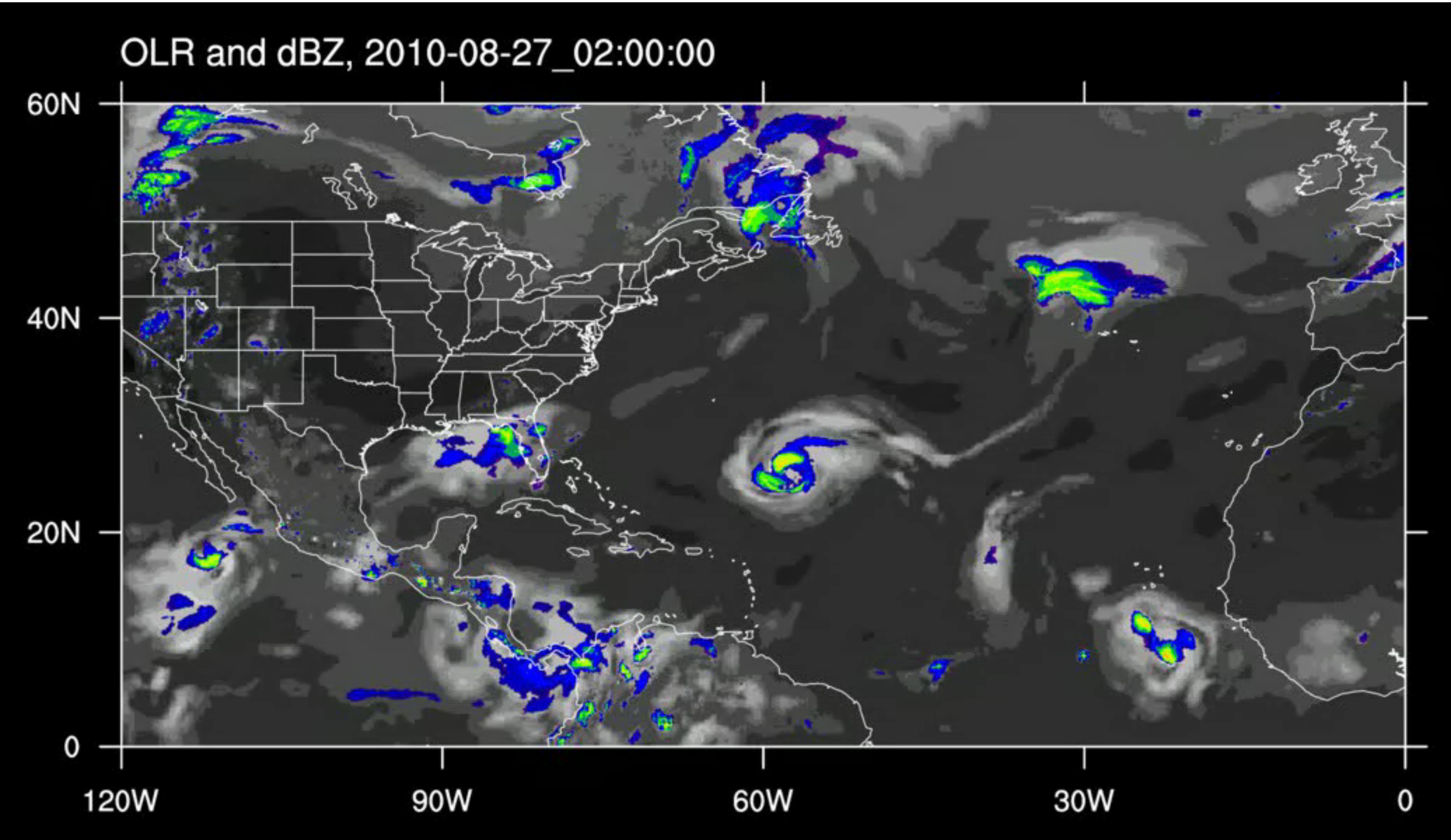
Outgoing longwave radiation and column maximum reflectivity



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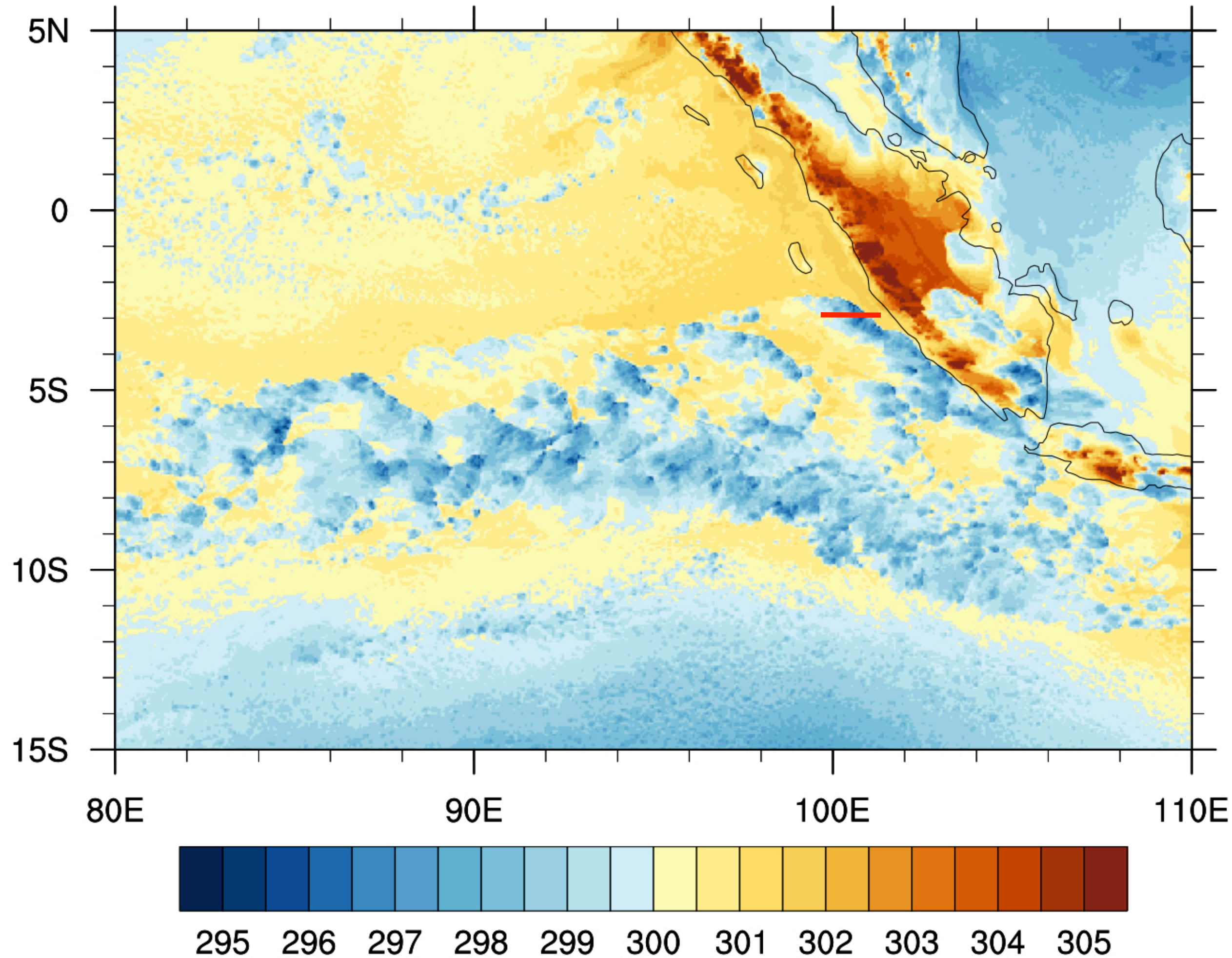
# Global nonhydrostatic simulations using MPAS
# 0 UTC 15 January – 0 UTC 4 February 2009

12 UTC 29 January 2009, MPAS global 3 km simulation
Lowest-model-level potential temperature (K)



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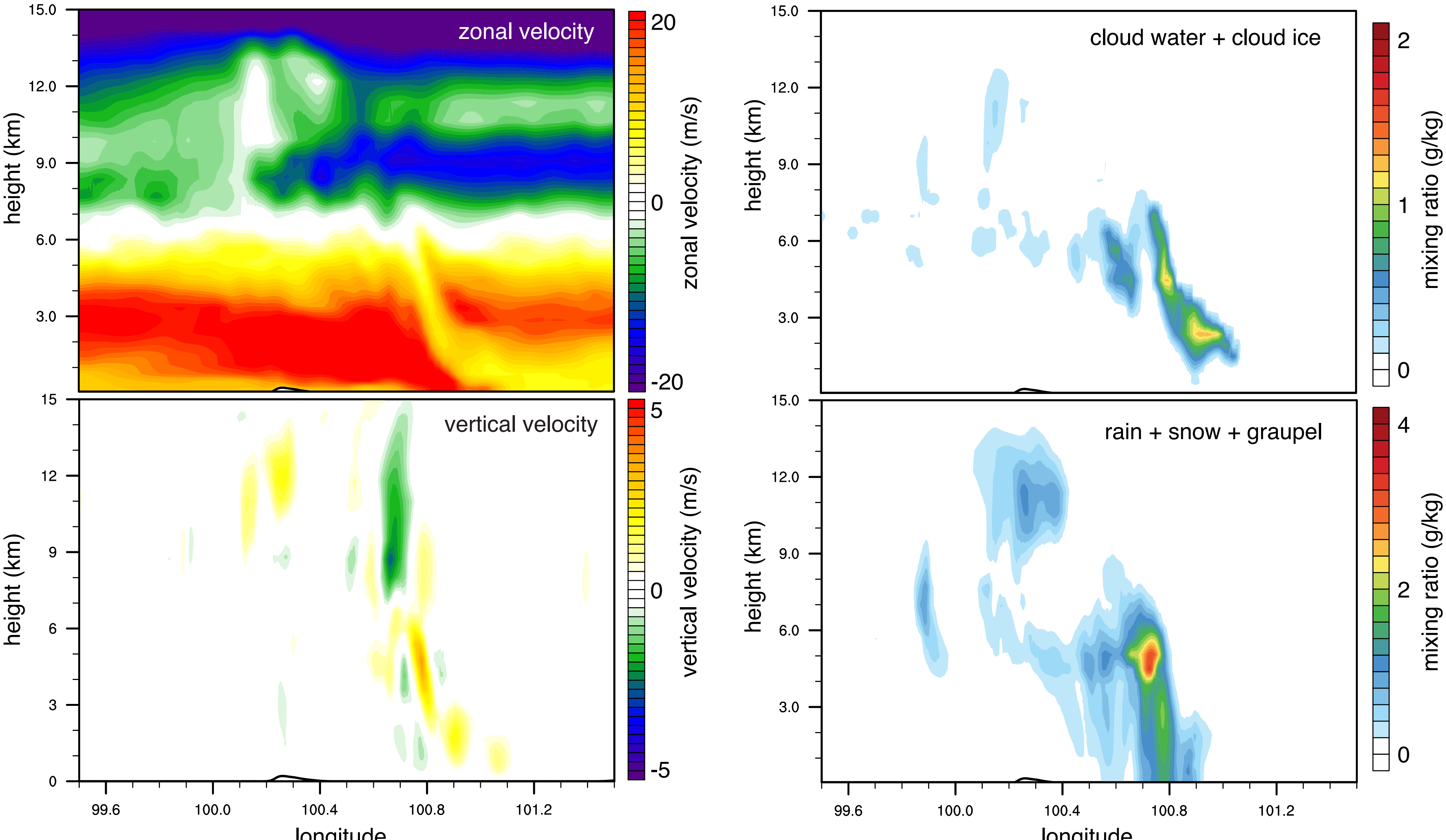
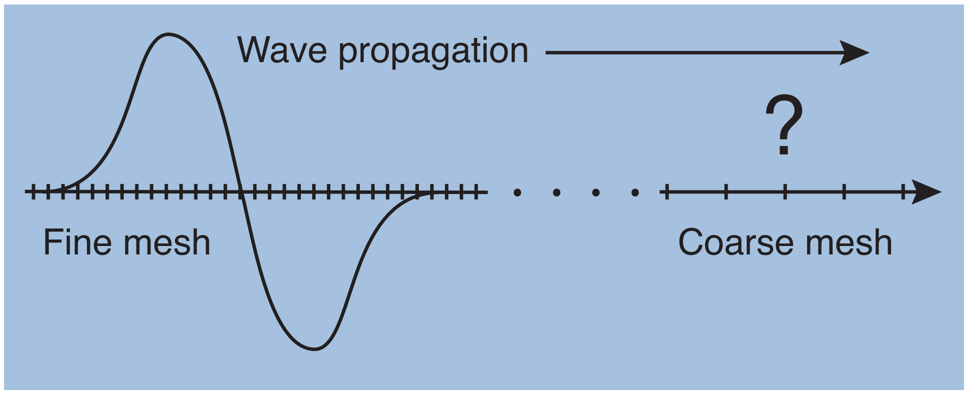
# Global nonhydrostatic simulations using MPAS
# 0 UTC 15 January – 0 UTC 4 February 2009

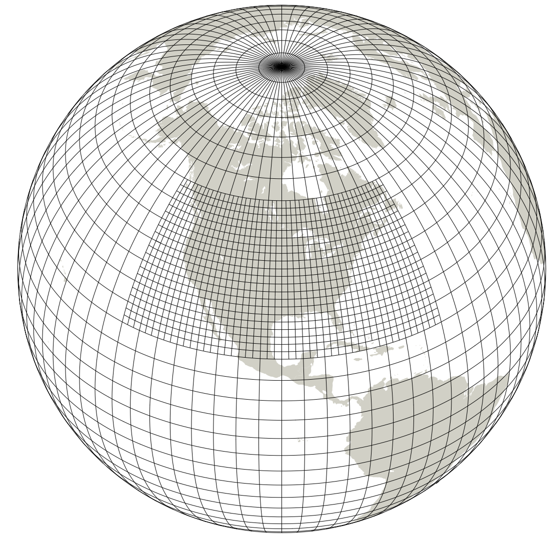
## 29 January 2009, Vertical Cross Section, (3S, 99.5:101.5E), 3 km MPAS

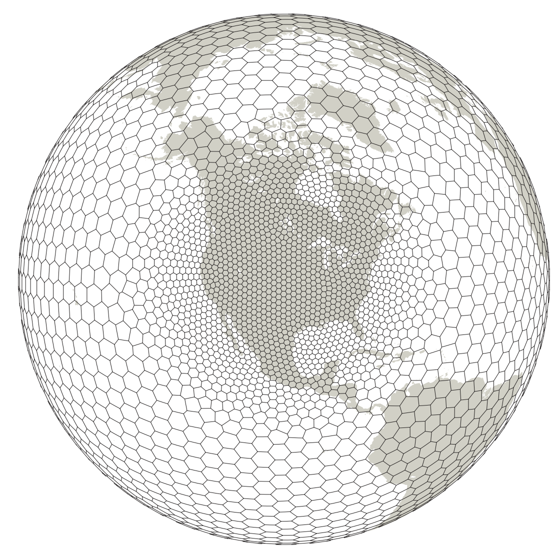


# Variable Resolution Meshes

## Reflections at mesh transitions?



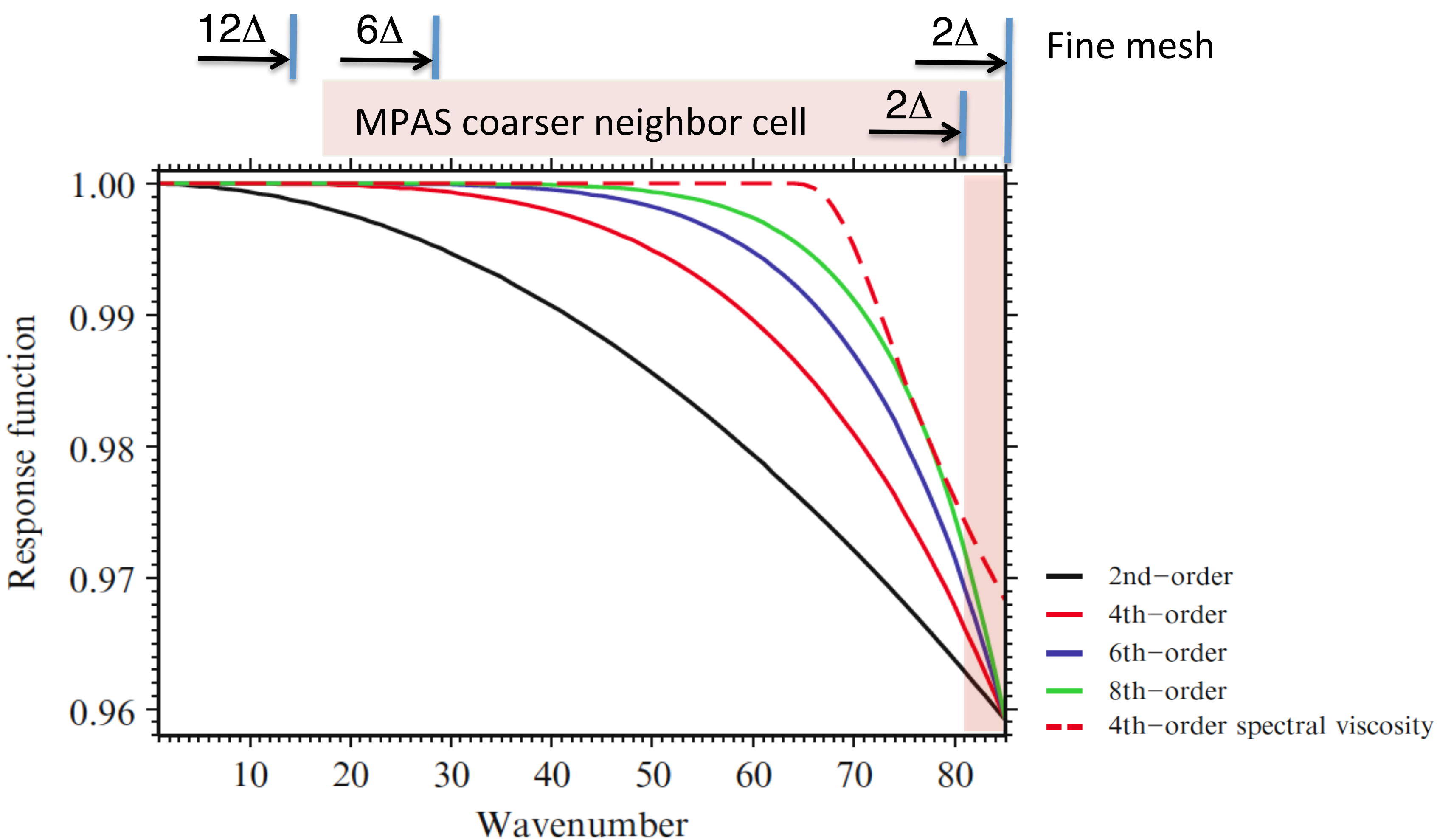





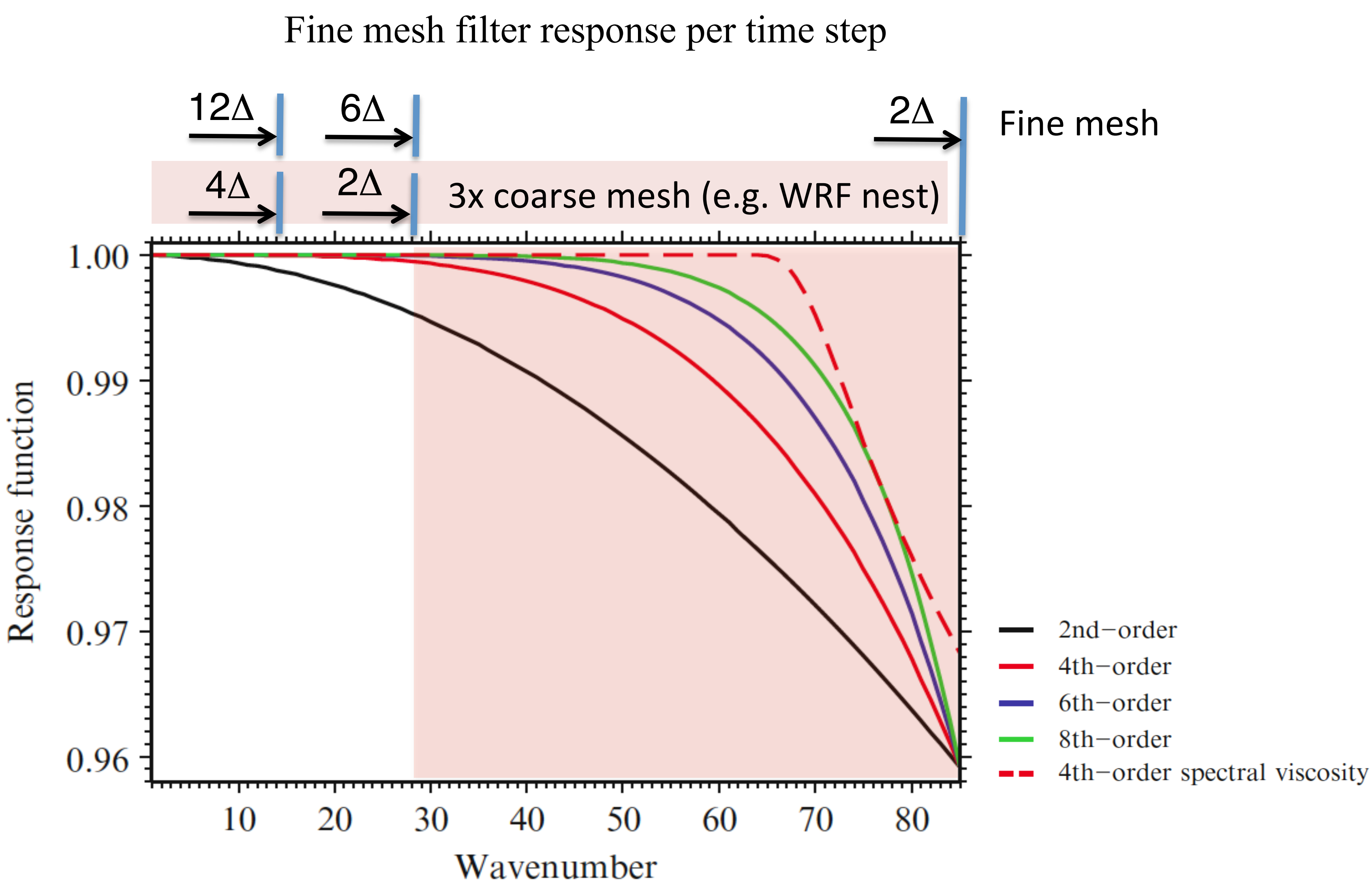
- Short-wavelength modes will be reflected in a fine-coarse mesh transition *unless they are filtered.*
- Abrupt transitions typically produce some reflection due to filter inadequacies.
- Smooth transitions minimize reflection of the short wavelength modes (locally) because only the very-shortest wavelengths are subject to reflection, and filters efficiently remove these modes.

# Variable Resolution Meshes

Fine mesh filter response per time step



# Variable Resolution Meshes



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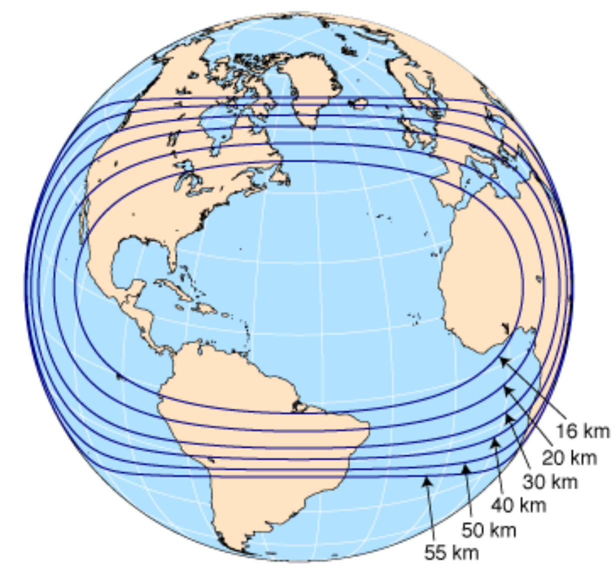
# MPAS-Atmosphere Testing

## Variable resolution tests

- 120 km – 25 km, 1 year simulations, regional climate configuration.
- *60 – 15 km 10 day forecasts during the 2013 and 2014 tropical cyclone seasons (Aug-Oct).*
- 50 – 3 km 3 day forecasts of selected cases (US convective outbreaks, tropical and extratropical cyclones, MJO events, etc).

### MPAS-Atmosphere
2013-2014 Tropical Cyclone Forecast Experiments

Aug-Oct 2013 & 2014
daily 10-day forecasts
(1) uniform 15 km mesh
(2) var-res 60-15 km meshes



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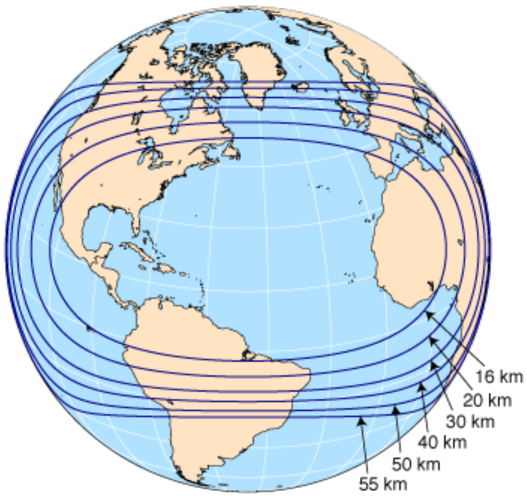
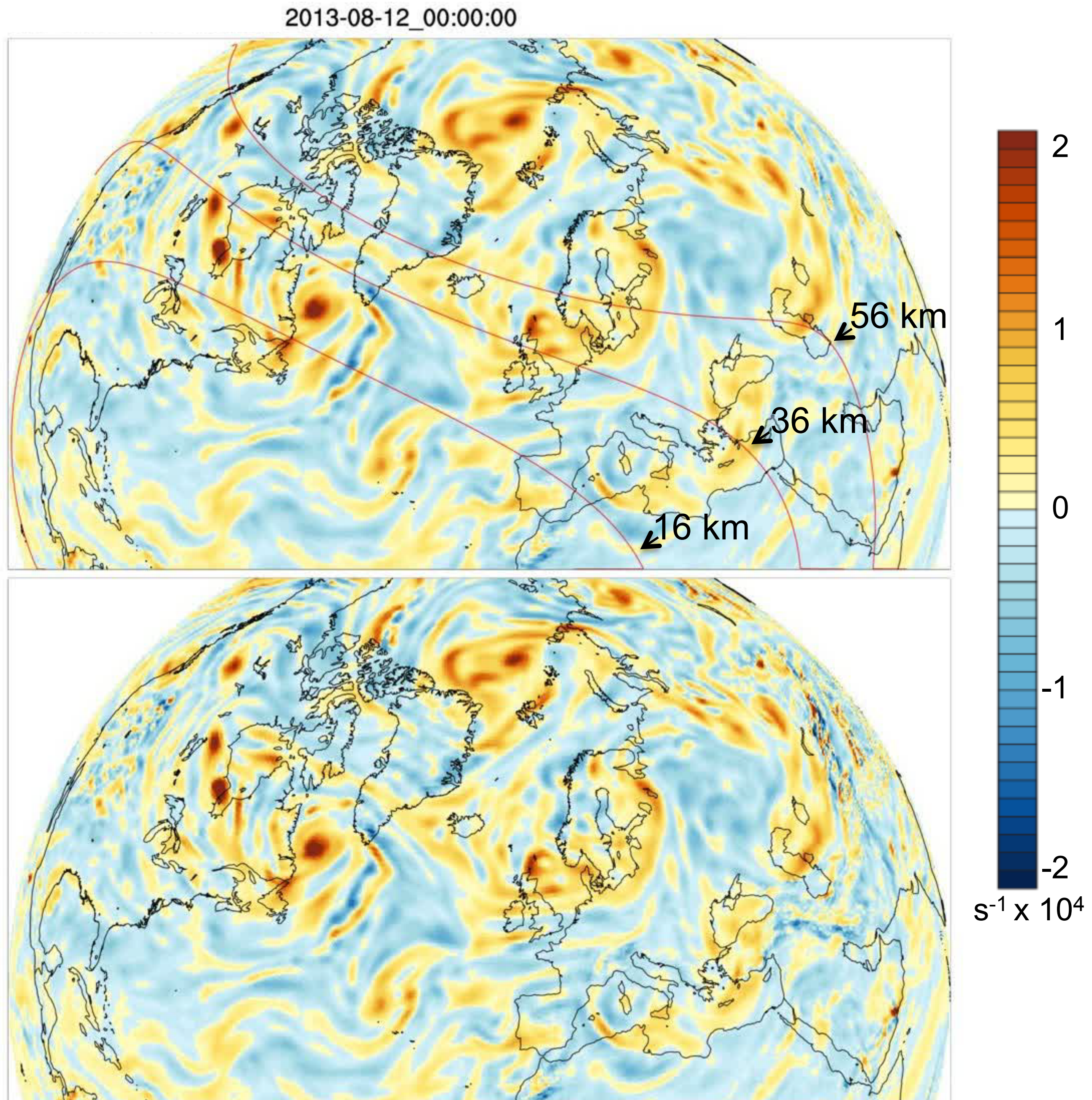
# 10-day 500 hPa Relative Vorticity Forecast

15-60 km variable resolution mesh




15 km uniform resolution mesh

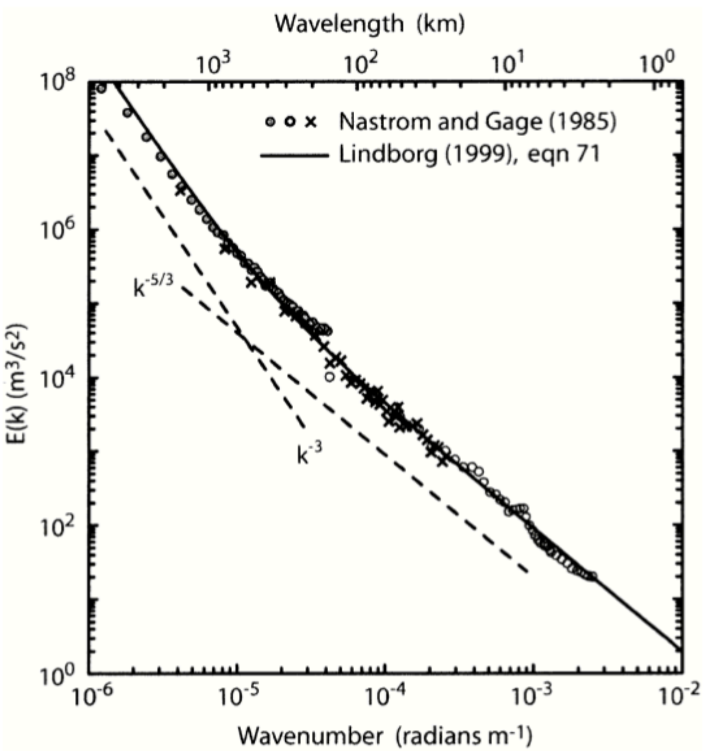



MPAS Physics:

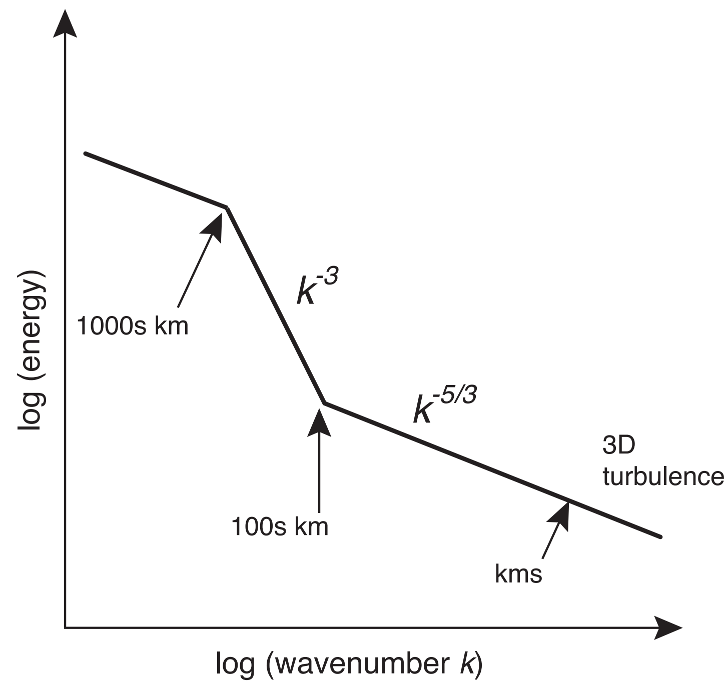
- WSM6 cloud microphysics
- Tiedtke convection scheme
- Monin-Obukhov surface layer
- YSU PBL
- Noah land-surface
- RRTMG lw and sw.

# Kinetic Energy (KE) Spectra

## Observations




## *Canonical* spectrum




Questions concerning: (1) Observational analyses
(2) KE spectra from simulations
(3) Dynamics

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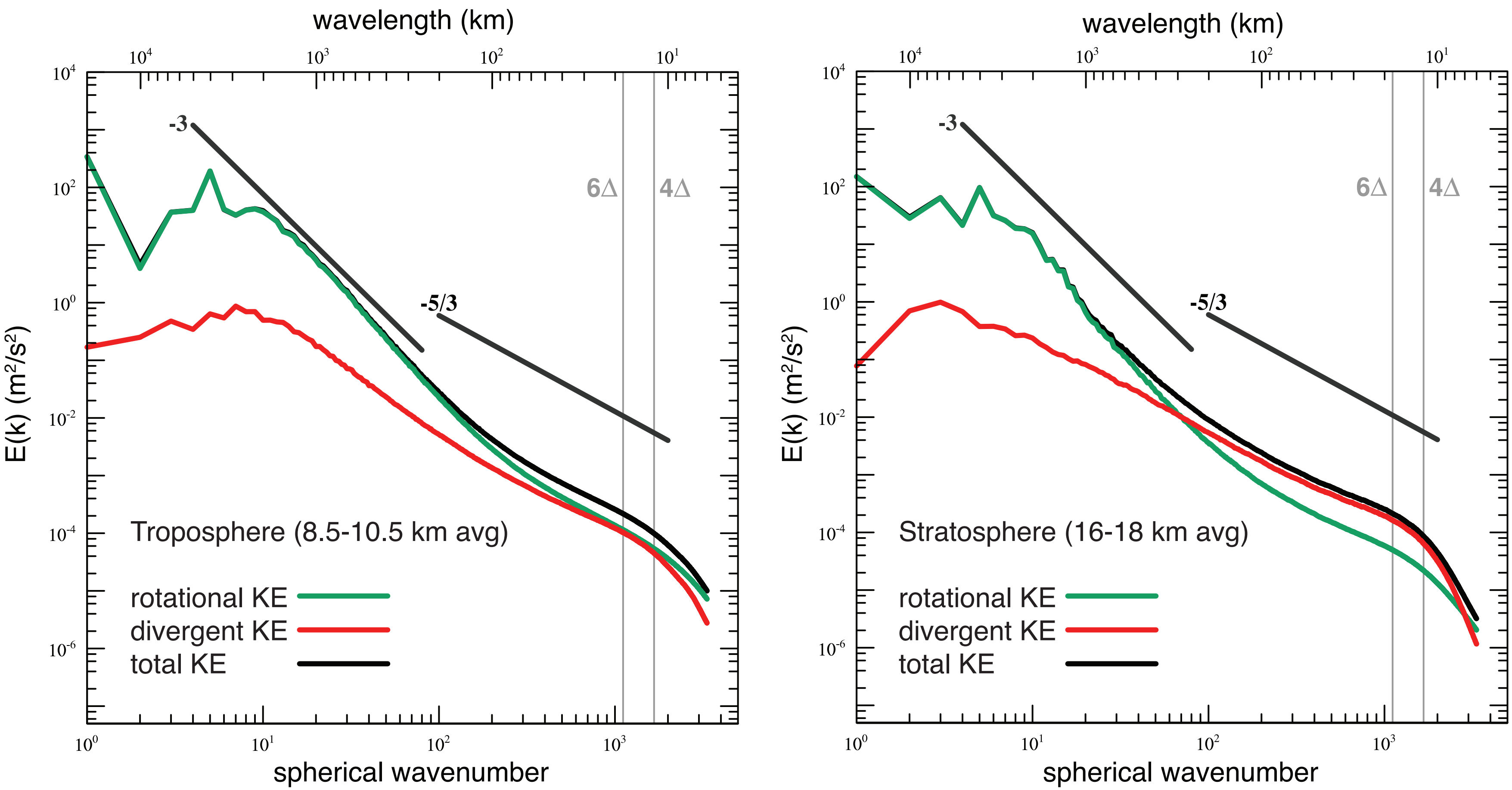
# 3 km global MPAS simulation

## 2009-01-15 init, 20 day simulation

## KE spectra averaged over 2009-01-20 to 01-30



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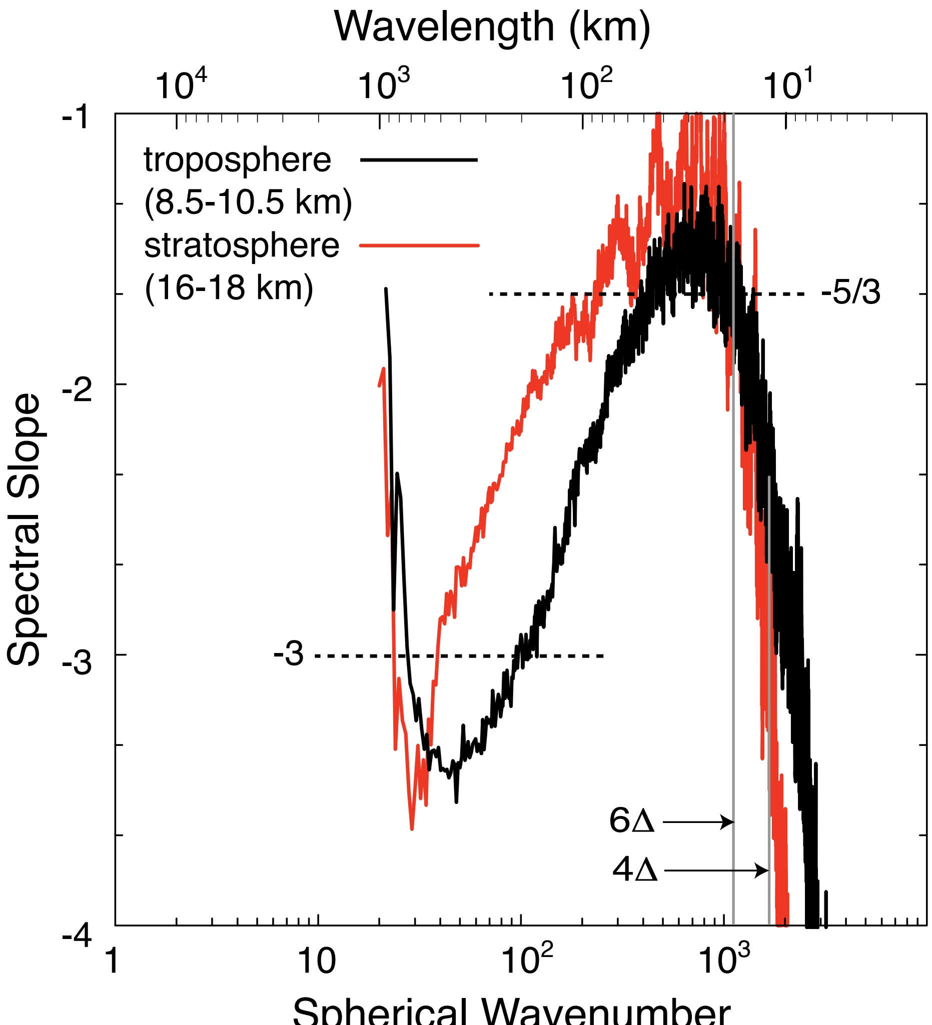


# Kinetic Energy (KE) Spectra

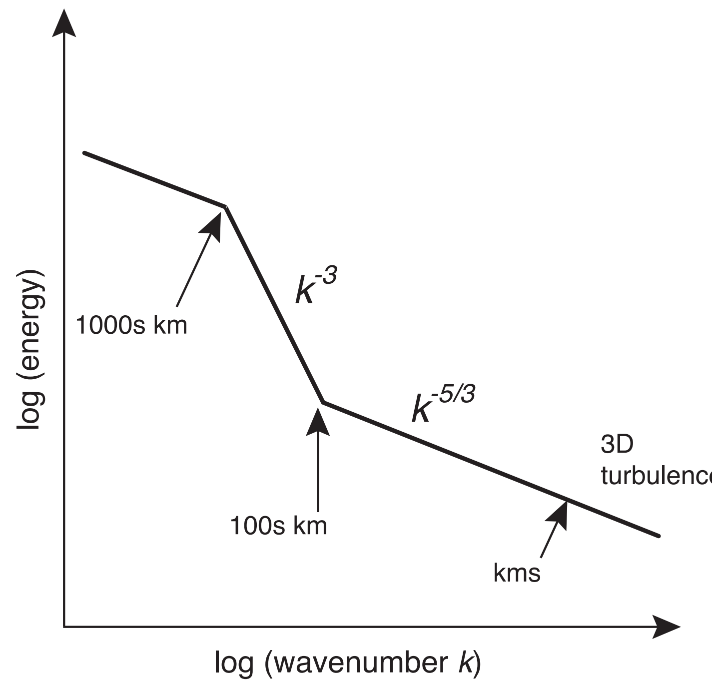
*What are the dynamics responsible for the $k^{-5/3}$ mesoscale portion of the KE spectrum?*

*Current theories include aspects of*

- rotating, stratified turbulence
- inertia gravity waves
- quasi-2D balanced dynamics

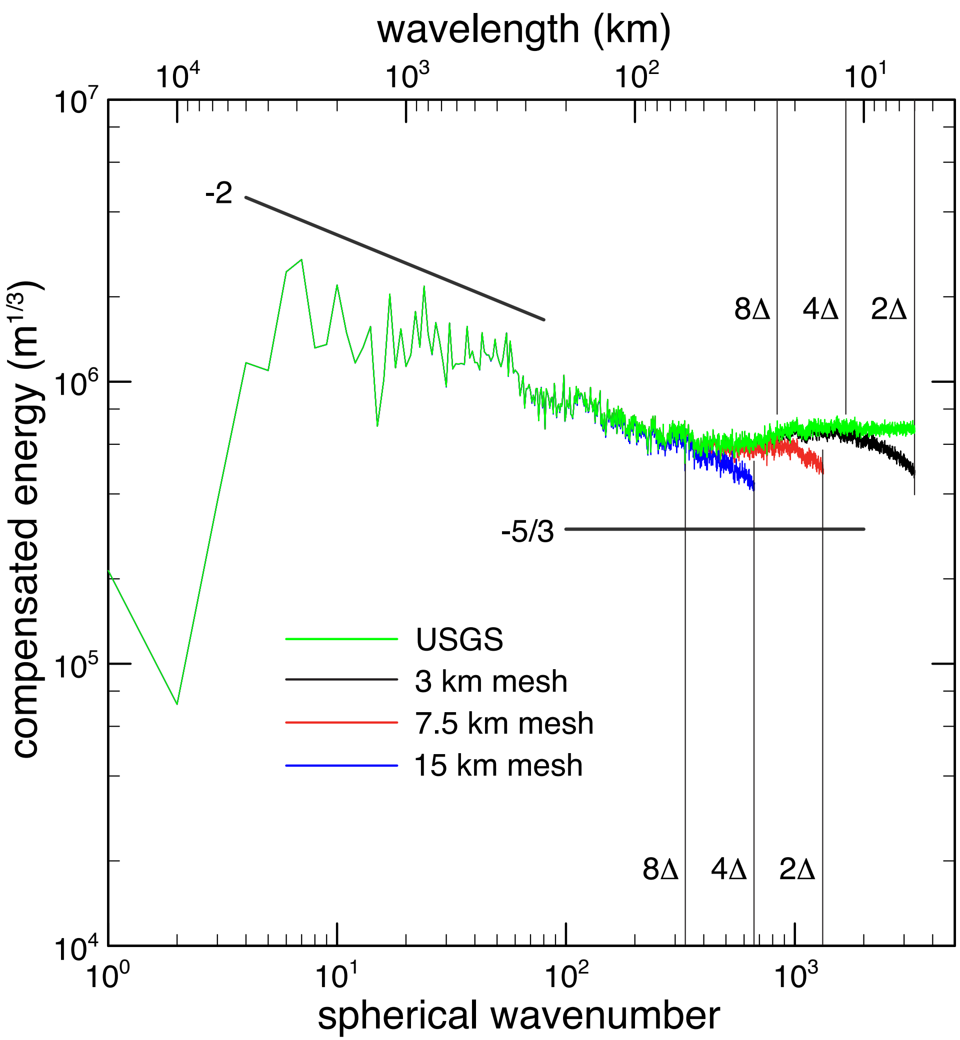
*Question: What are the roles played by external/internal forcings?*

- Topography
- Diabatic heating (moist processes).



# Kinetic Energy (KE) Spectra

## Topography Spectrum



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# Kinetic Energy (KE) Spectra Held-Suarez Test

*Held & Suarez (1994)*

$$\frac{\partial \vec{V}}{\partial t} = \ldots - k_v(\sigma)\vec{V}$$

$$\frac{\partial T}{\partial t} = \ldots - k_T(\phi,\sigma)\left[T - T_{eq}(\phi, p)\right]$$

$$T_{eq} = \max\left\{200K, \left[315 - (\Delta T)_y \sin^2\phi - (\Delta\theta)_z \log\left(\frac{p}{p_0}\right)\cos^2\phi\right]\left(\frac{p}{p_0}\right)^{\kappa}\right\}$$

$$k_T = k_a + (k_s - k_a)\max\left(0, \frac{\sigma - \sigma_b}{1 - \sigma_b}\right)\cos^4\phi$$

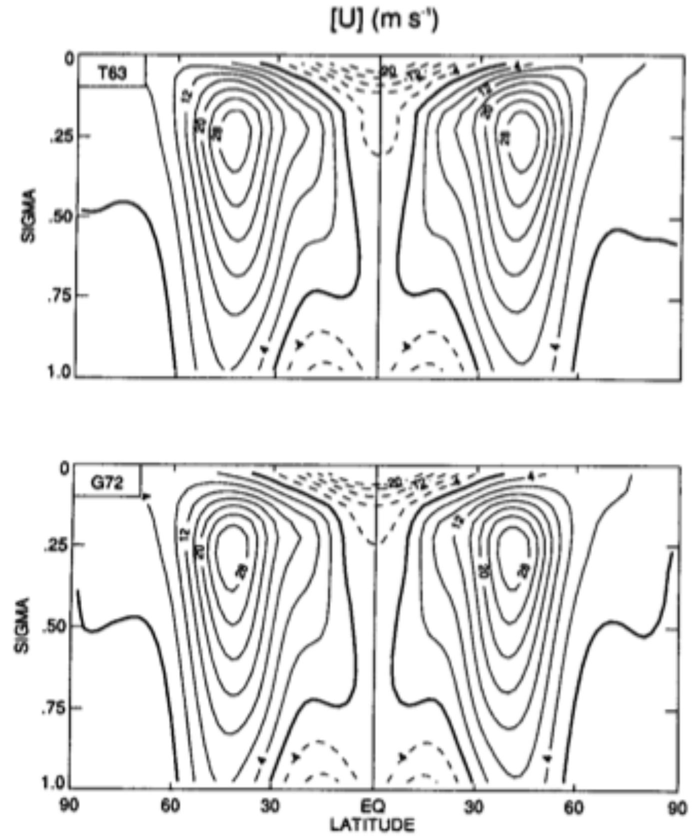
$$k_v = k_f \max\left(0, \frac{\sigma - \sigma_b}{1 - \sigma_b}\right)$$

$k_f = 1 \ day^{-1}$ $\qquad \sigma_b = 0.7$

$k_a = 1/40 \ day^{-1}$ $\qquad (\Delta T)_y = 60K$

$k_s = 1/4 \ day^{-1}$ $\qquad (\Delta\theta)_z = 10K$

$$\kappa = \frac{R}{C_p} = \frac{2}{7}$$



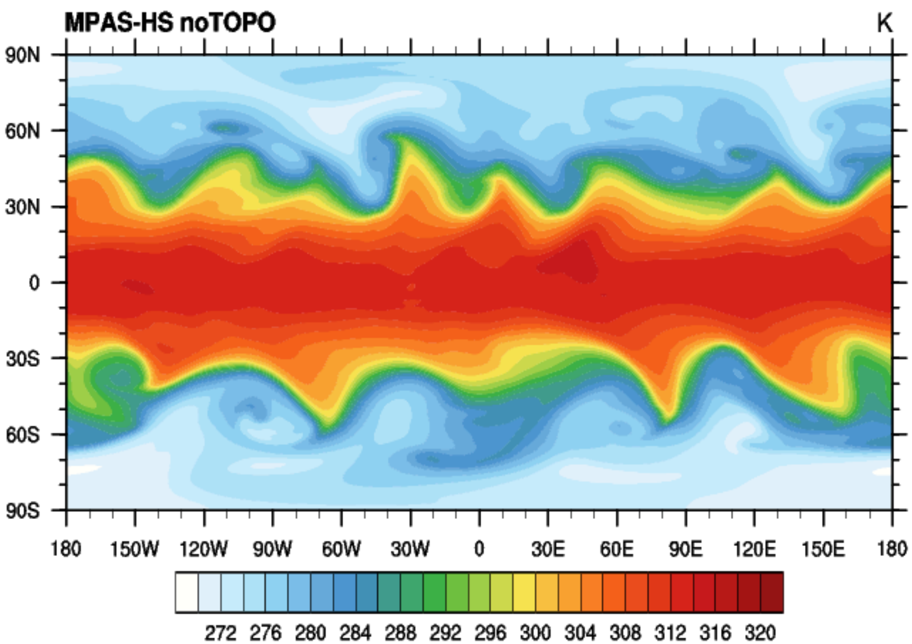

MPAS is run as a dynamical core in CESM/CAM
(SangHun Park, Peter Lauritzen, Chris Snyder)

MPAS
Model for Prediction Across Scales

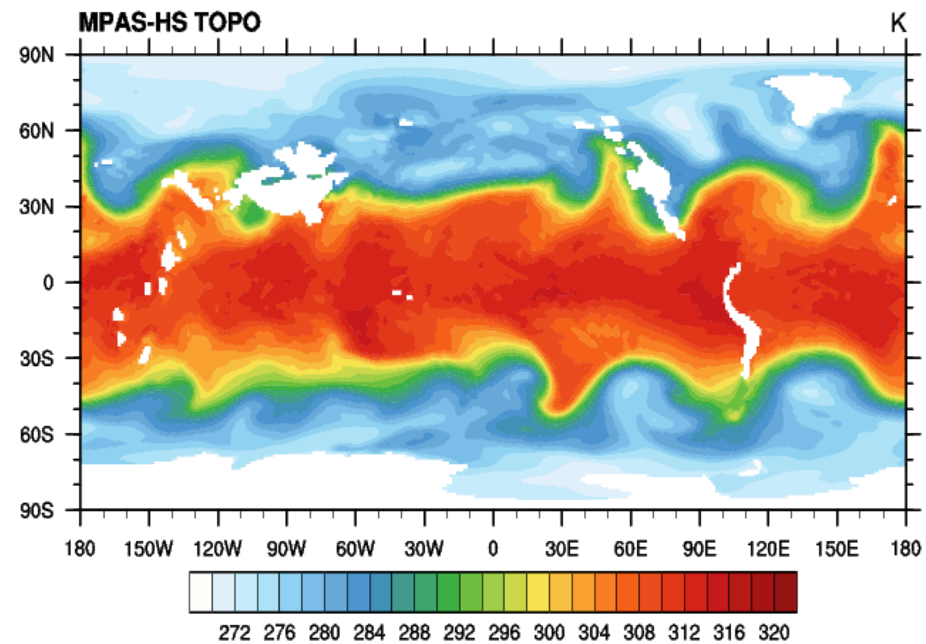
# Kinetic Energy (KE) Spectra
# Held-Suarez Test

1500 days run, 120km resolution, L30
model top ~ 40km

Day 1500: no topography




Day 1500: earth topography



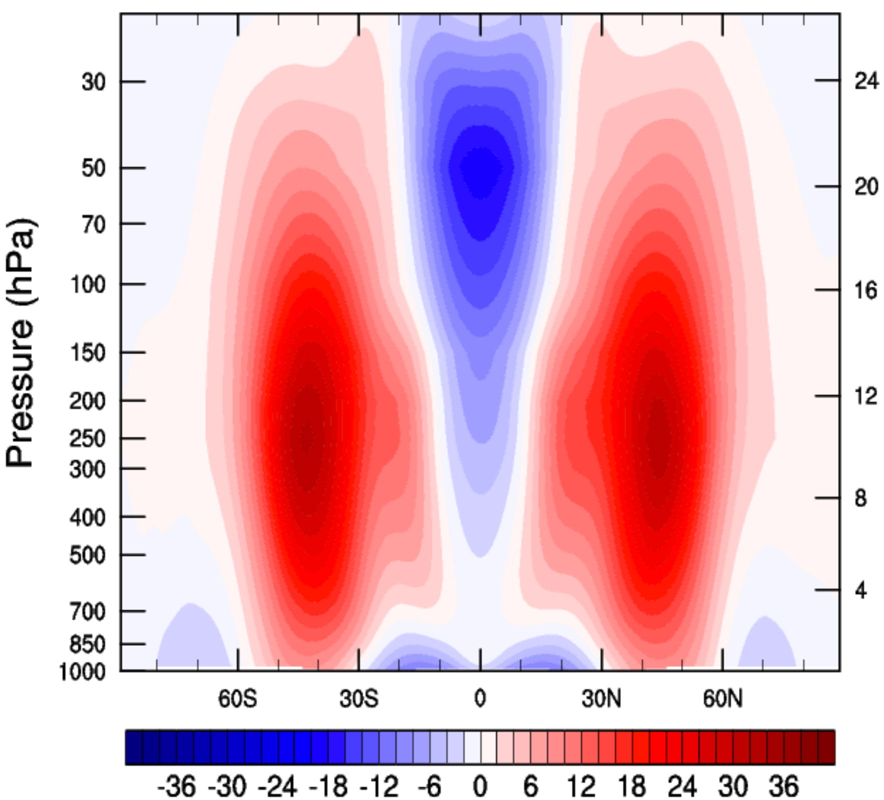

850hPa temperature (K)

MPAS
Model for Prediction Across Scales

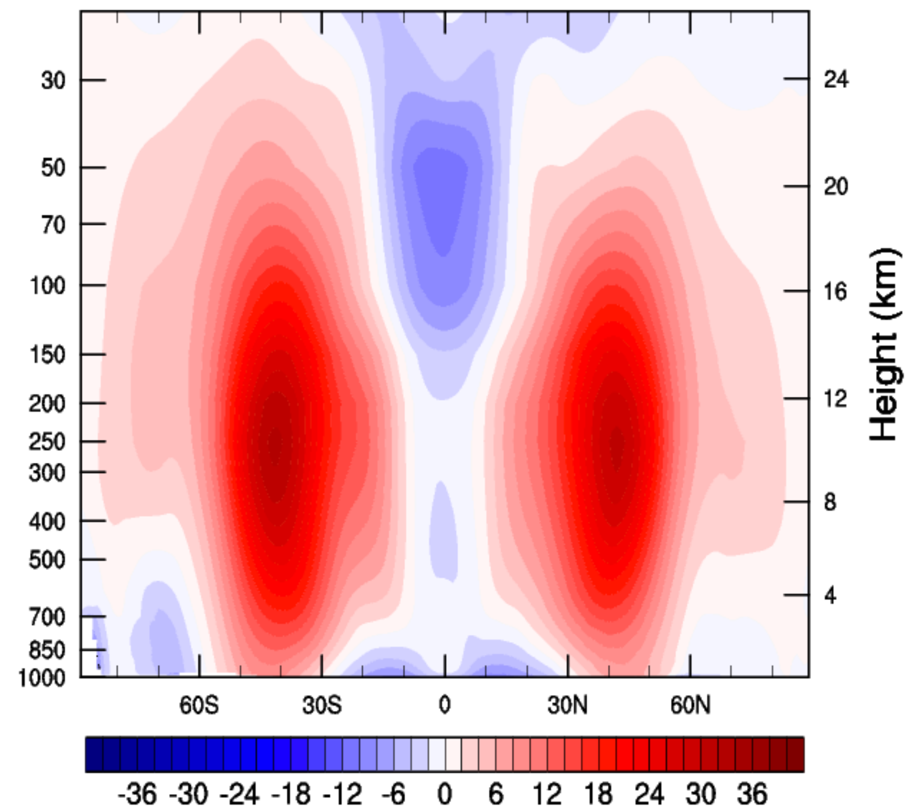
# Kinetic Energy (KE) Spectra Held-Suarez Test

1500 days run, 120km resolution, L30
model top ~ 40km

300-day average: no topography



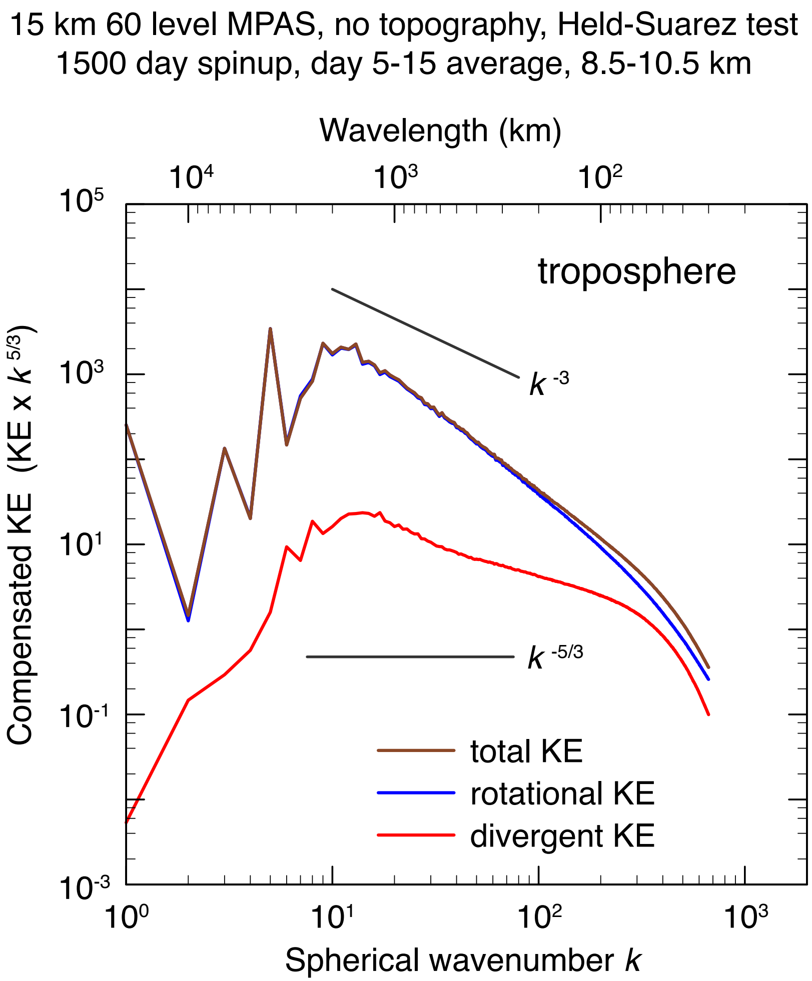

300-day average: earth topography

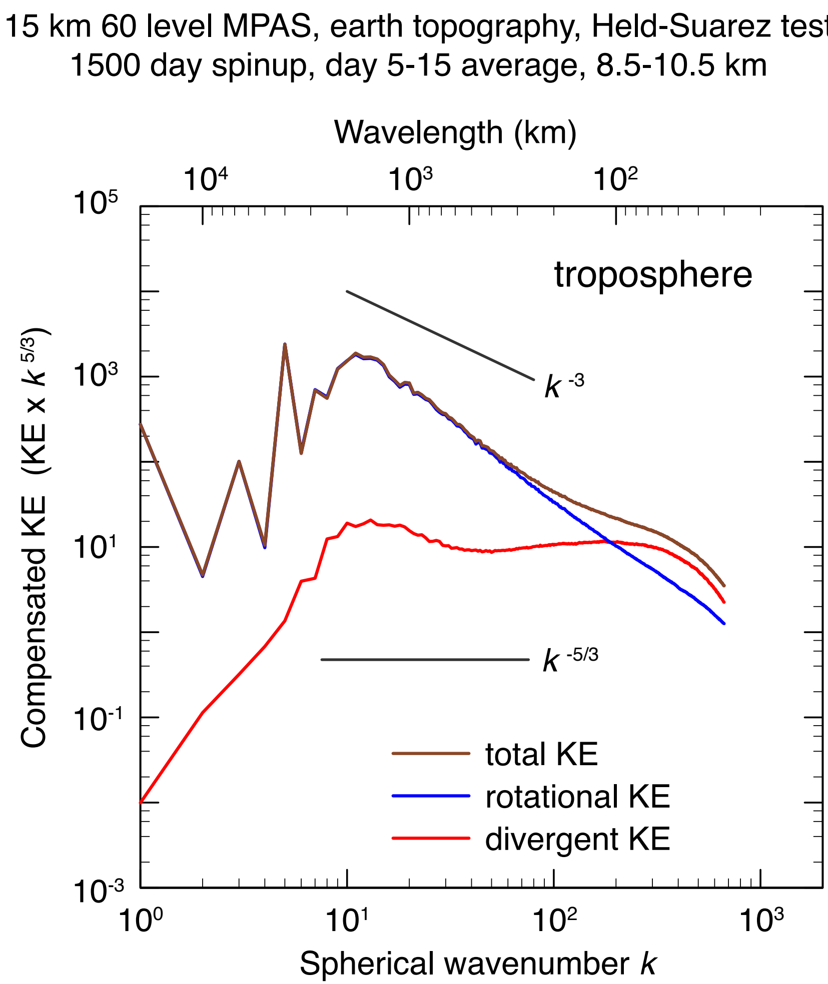



zonal velocity (zonal average; m/s)

MPAS
Model for Prediction Across Scales

# Kinetic Energy (KE) Spectra
# Held-Suarez Test

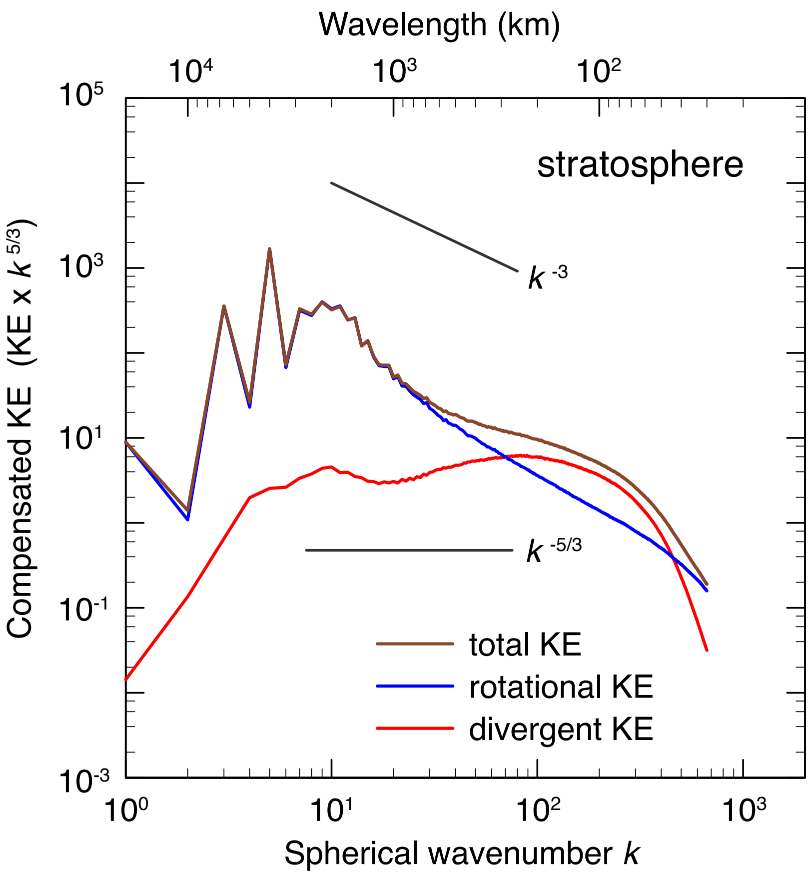


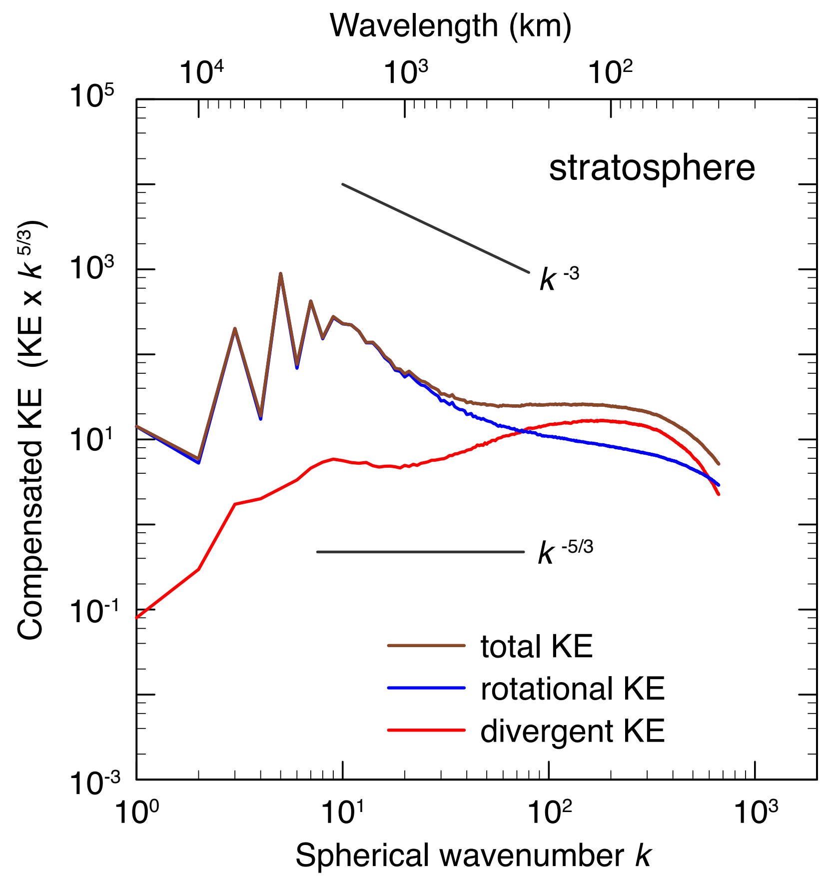
MPAS
Model for Prediction Across Scales

# Kinetic Energy (KE) Spectra
# Held-Suarez Test

15 km 60 level MPAS, no topography, Held-Suarez test
1500 day spinup, day 5-15 average, 16-18 km

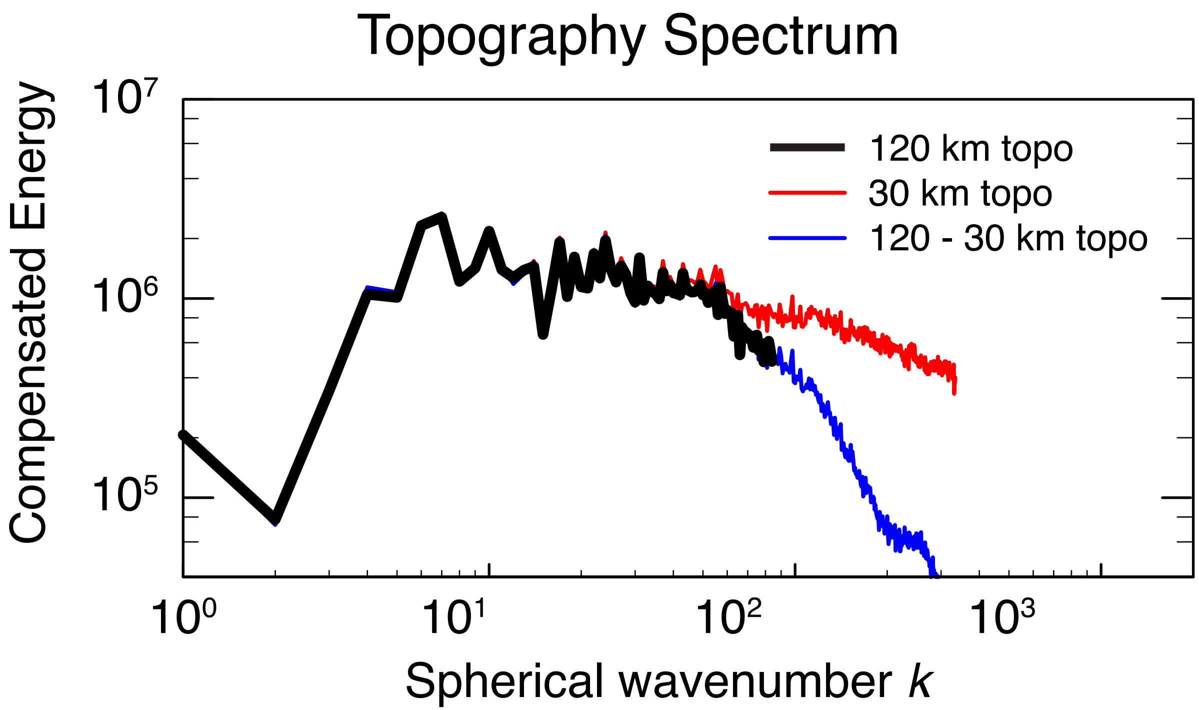



15 km 60 level MPAS, earth topography, Held-Suarez test
1500 day spinup, day 5-15 average, 16-18 km



MPAS
Model for Prediction Across Scales

# Kinetic Energy (KE) Spectra
# Held-Suarez Test

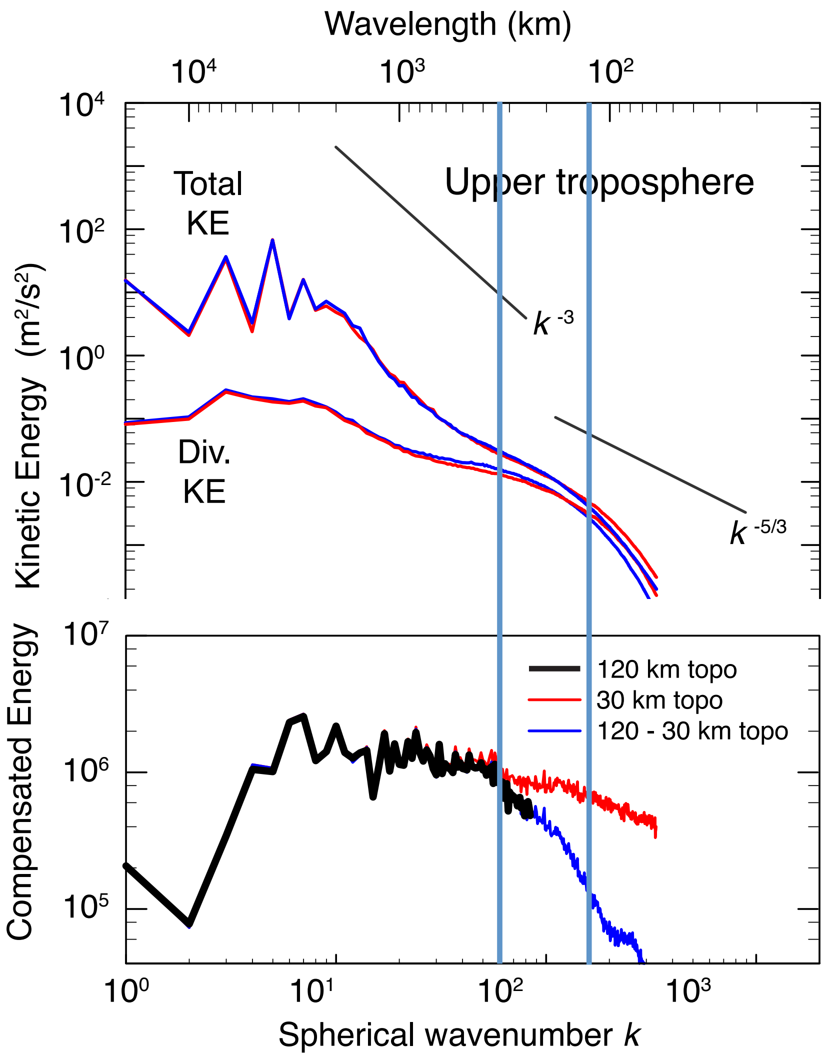


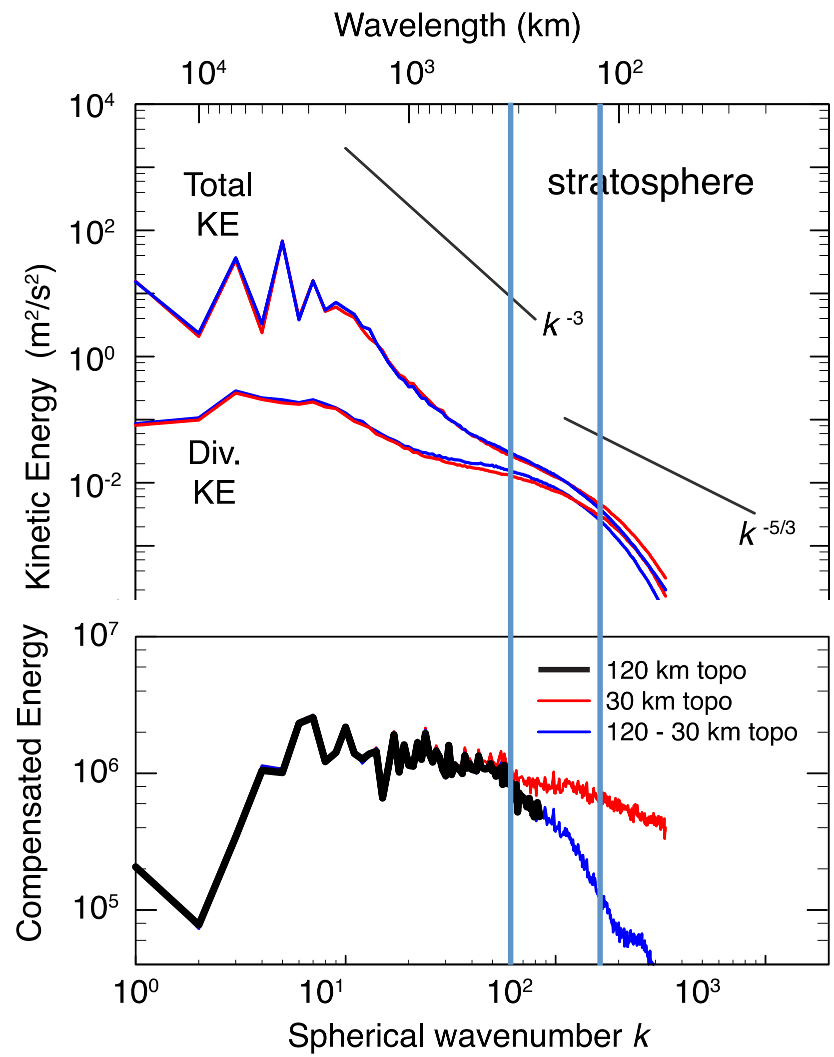

Two simulations:

(1) 30 km topography, 30 km mesh

(2) 120 km mesh topography interpolated to the 30 km mesh

# Kinetic Energy (KE) Spectra
# Held-Suarez Test

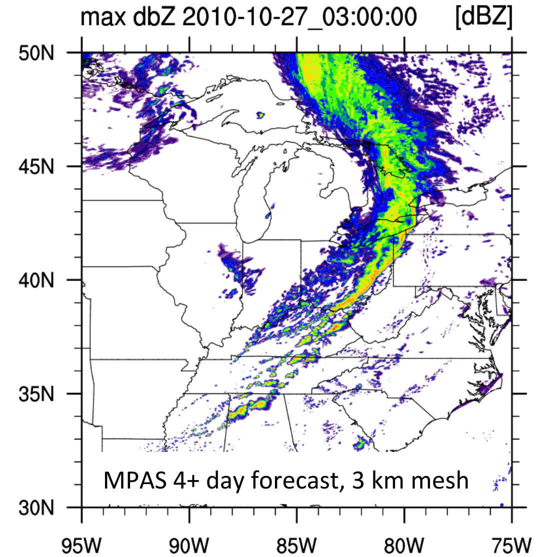


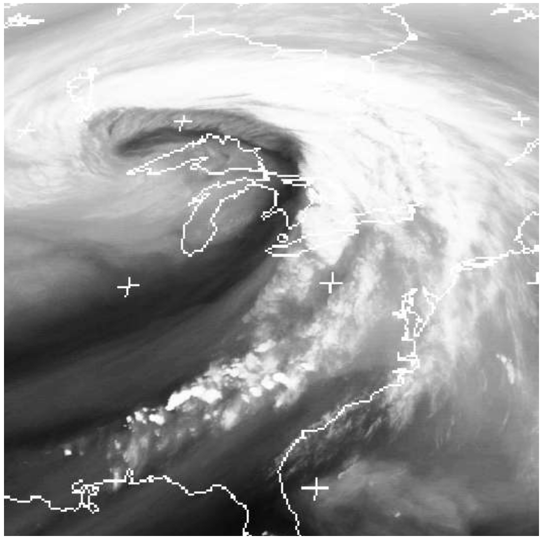



# MPAS
Model for Prediction Across Scales

# Where are we?

- MPAS-Atmosphere has the flexibility to run globally on uniform and variable-resolution meshes.
- MPAS-Atmosphere produces forecast similar to the Advanced Research WRF (ARW) at large scales and at cloud scales.
- Preliminary tests on variable-resolution meshes show promise. *Scale-aware* physics are needed.
- Data assimilation systems are being tested using MPAS, including variational (GSI), hybrid (hybrid GSI) and EnKF (DART) approaches.
- MPAS-A is a stand-alone model. Applications requiring coupling are being pursued in CESM where MPAS is a CAM core.



GOES East, 2010-10-27 0 UTC
IR - vapor channel

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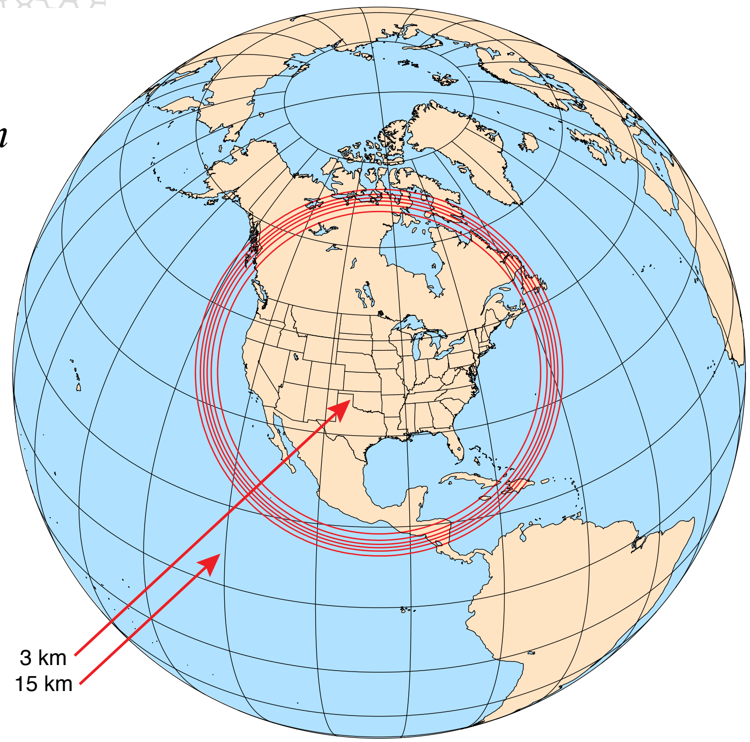
MPAS
Model for Prediction Across Scales

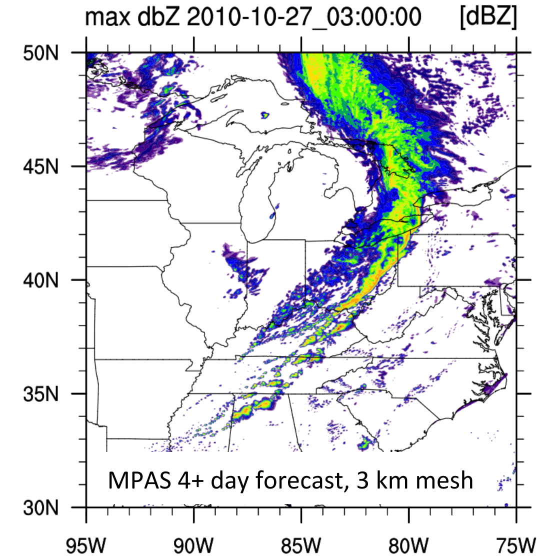
# Where are we going?

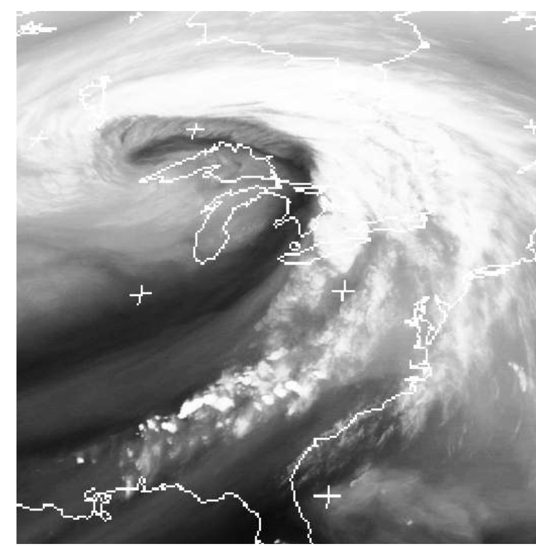
*A future high-resolution CONUS/global model?*

*<u>Challenges:</u>*
Scale-aware physics.
Data assimilation on variable meshes.
Efficiency on evolving computer architectures.




3-15 km mesh, Δx contours 4 - 14 by 2 km.
approximately 5.9 million cells
60% in the 3 km region; 40% in the 15 km region



GOES East, 2010-10-27 0 UTC
IR - vapor channel

*Further information and to access MPAS Version 2.0:*
http://mpas-dev.github.io/

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