The Global Nonhydrostatic Atmospheric Model MPAS:

Preliminary results from uniform and variable-resolution mesh tests

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MPAS
Model for Prediction Across Scales

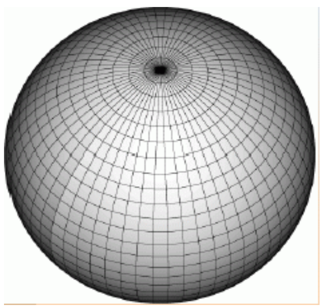
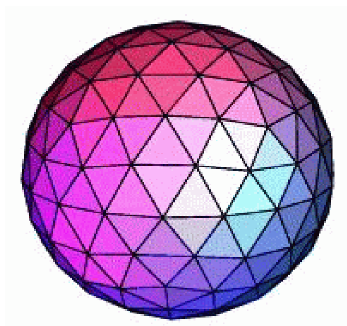
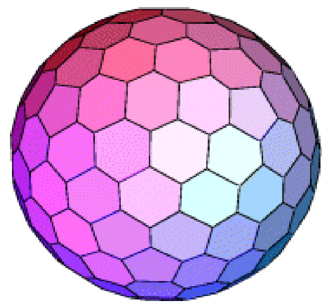
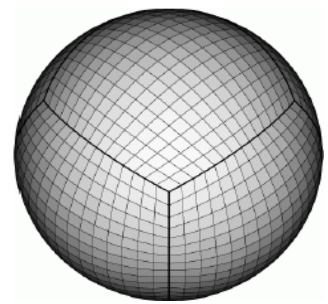
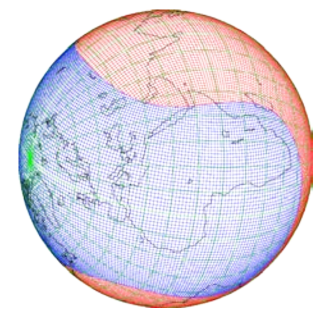
Based on unstructured centroidal Voronoi (hexagonal) meshes using C-grid staggering and selective grid refinement.

Jointly developed, primarily by NCAR and LANL/DOE, for weather, regional climate, and climate applications

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

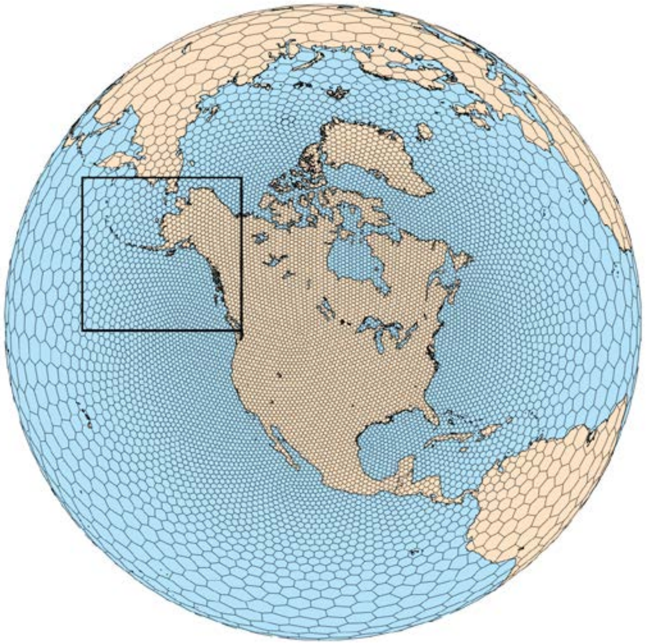
Primary drivers for global dynamical core development

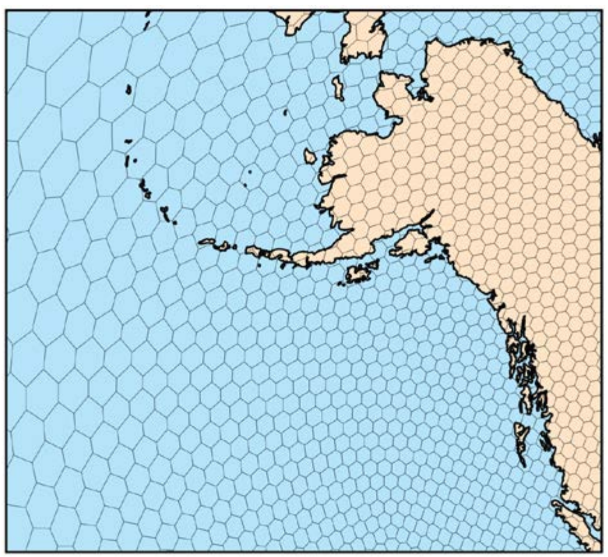
(1) Scalable solvers needed for the new computer architectures.
(2) Nonhydrostatic global atmospheric models needed for cloud-permitting simulations ($\Delta x \sim$ kms).

Newton Institute, PDEs on the sphere, major core development efforts:
(1) FV methods on icosahedral (hexagonal) meshes.
(2) FV, SE, and DG methods on the cubed sphere.
Most of these models are using horizontally-explicit integration techniques to facilitate scaling to 10^5-10^6 processors or application to accelerators.

MPAS: C-Grid Spherical Centroidal Voronoi Meshes





Unstructured mesh

Mesh generation uses a density function.
Uniform resolution – traditional icosahedral mesh.

Centroidal Voronoi

Mostly *hexagons*, some pentagons and 7-sided cells.
Cell centers are at cell center-of-mass.
Lines connecting cell centers intersect cell edges at right angles.
Lines connecting cell centers are bisected by cell edge.

C-grid

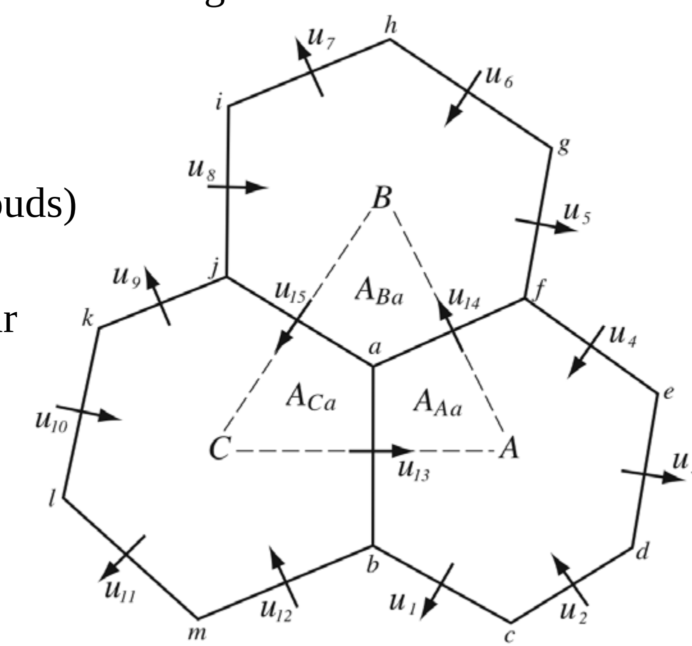
Solve for normal velocities on cell edges.

Equations

Fully compressible
nonhydrostatic equations
(*explicit* simulation of clouds)

Solver Technology

Integration scheme similar
to WRF.
WRF-NRCM physics



MPAS Nonhydrostatic Atmospheric Solver

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 scheme

As in Advanced Research WRF -
Split horizontally-explicit
vertically-implicit Runge-Kutta (3rd order)

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:

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

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

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

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

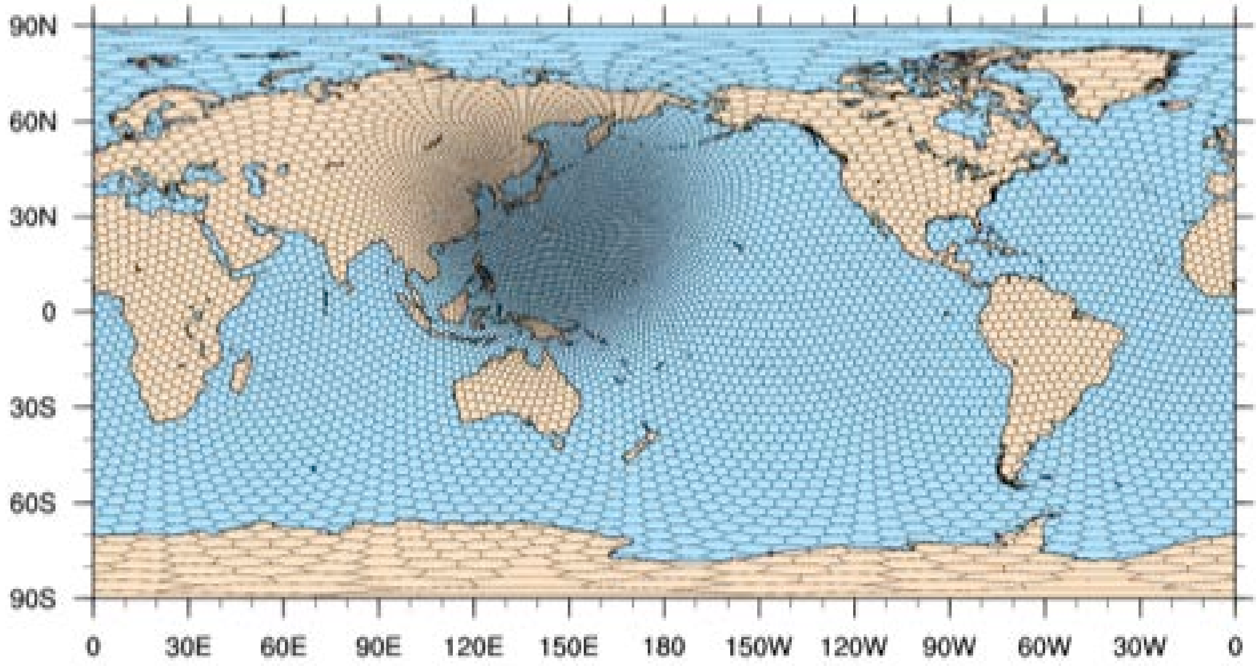
$$\frac{\partial Q_j}{\partial t} = -(\boldsymbol{\nabla} \cdot \boldsymbol{V}\, q_j)_\zeta + \rho_d S_j + F_{Q_j},$$

Diagnostics and definitions:

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

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

Variable Resolution Meshes

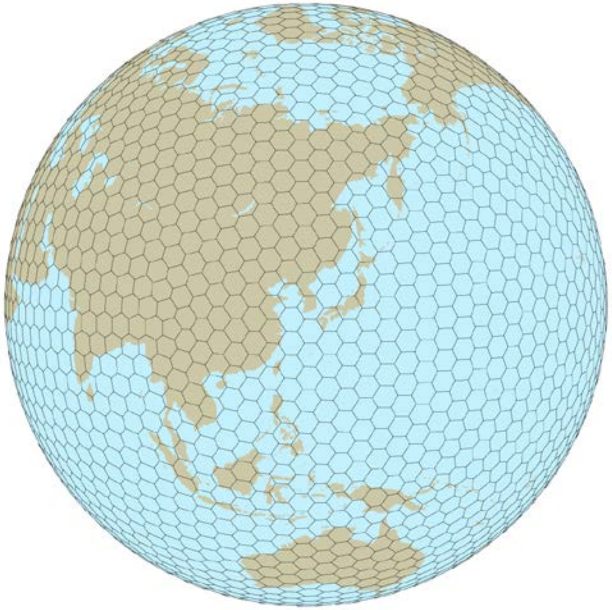


Applications: Regional climate, weather prediction
(address problems with one-way nesting)

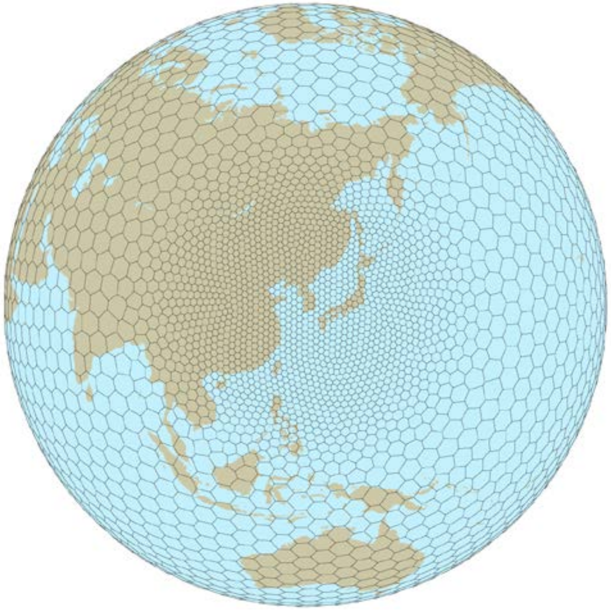
Static refinement: Obvious next step for applications

Smooth conforming meshes: Motivations
(i) unstructured mesh looks the same everywhere
(ii) preserve the accuracy of the numerics
(iii) minimize wave-reflection problems
at mesh density transitions

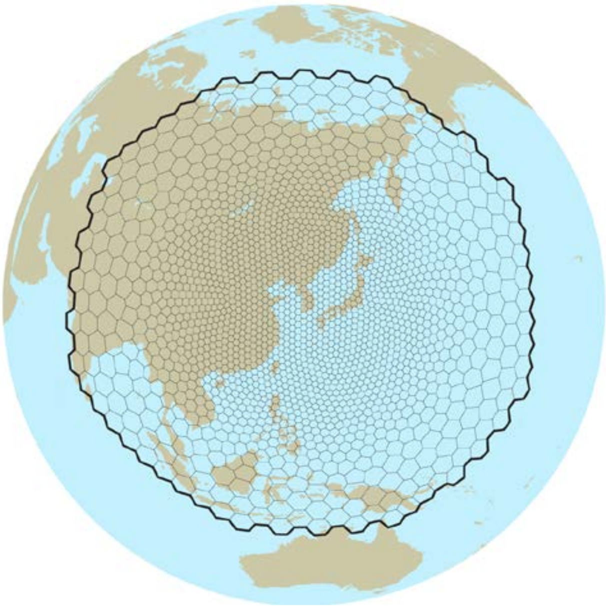
MPAS Global Mesh and Integration Options



Global Uniform Mesh



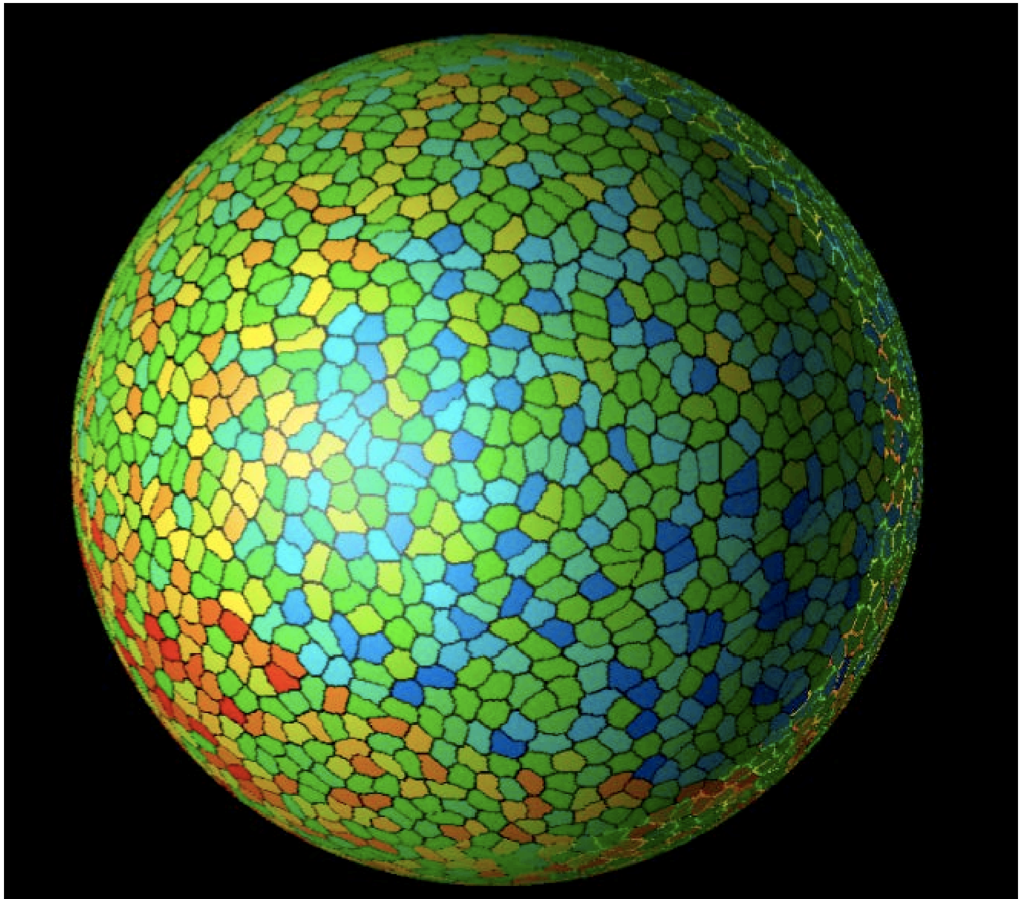
Global Variable Resolution Mesh



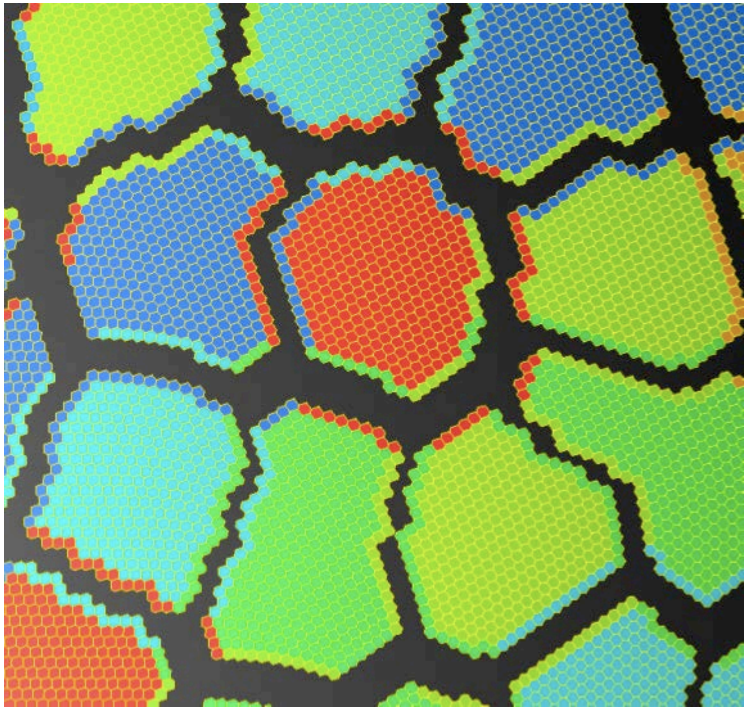
Regional Mesh - driven by
(1) previous global MPAS run
(no spatial interpolation needed!)
(2) other global model run
(3) analyses

Voronoi meshes will allow us to cleanly incorporate both downscaling and upscaling effects (avoiding the problems in traditional grid nesting) and to assess the accuracy of the traditional downscaling approaches used in regional climate and NWP applications.

Domain Decomposition for Parallel Processing



A global 30 km mesh broken into 2562 blocks



Close-up of block decomposition showing ghost cell data that indicates interblock communication

(from Todd Ringler)

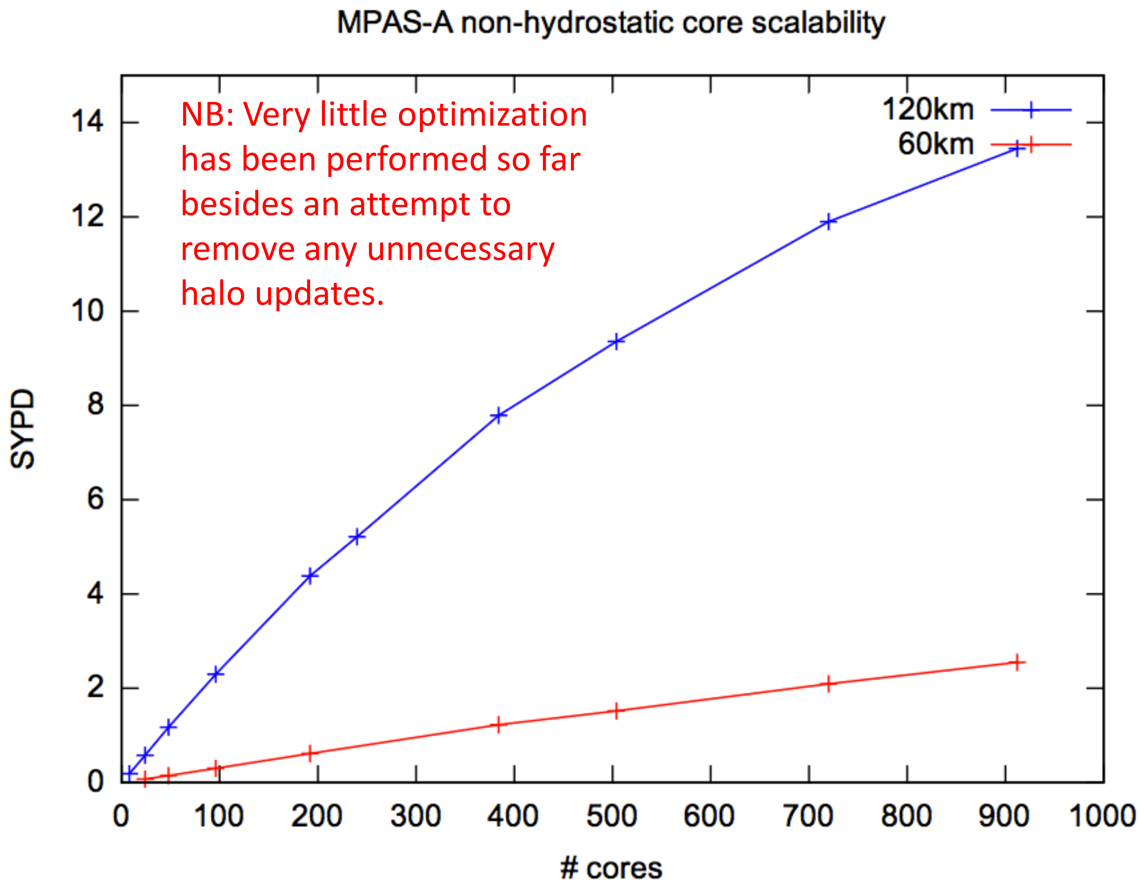
Preliminary MPAS-ANH Scaling Results

<u>120-km simulations:</u>
- 40962 grid cells
- 93% efficiency on 240 cores (relative to 8 cores)
- 79% efficiency on 504 cores
- 63% efficiency on 912 cores

<u>60-km simulations:</u>
- 163842 grid cells
- 98% efficiency on 504 cores (relative to 24 cores)
- 91% efficiency on 912 cores

<u>Weak-scaling extrapolation:</u>

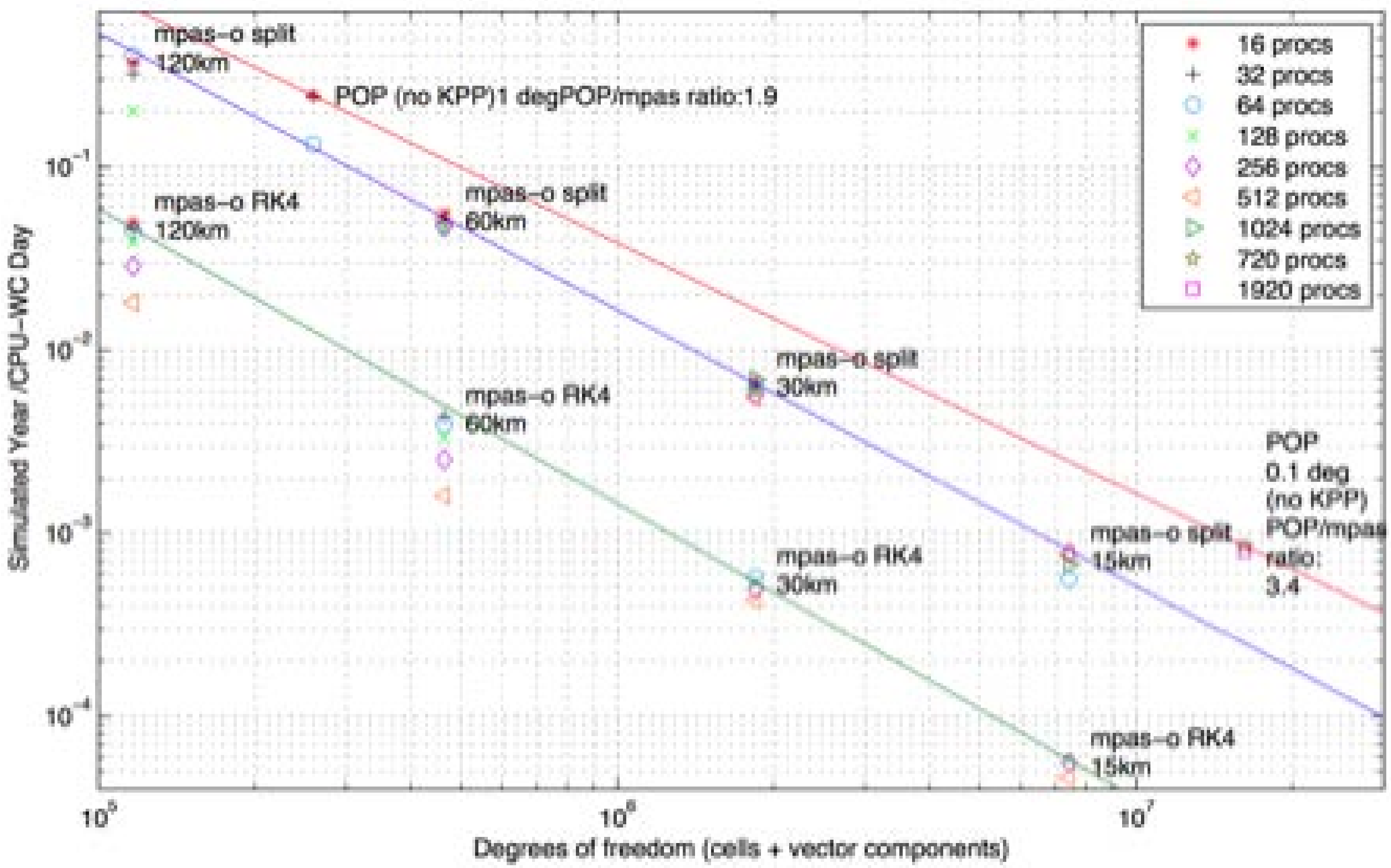
60 km – 912 cores (91%)
30 km – 3,648 cores
15 km – 14,592 cores
7.7 km – 58,368 cores
3.8 km – 233,472 cores
1.9 km – 933,888 cores



Simulation rate given for the dynamical core only
- 8 scalars w/positive-definite advection
- 41 vertical levels
- All runs on a Cray XT5m (lynx)
- MPI parallelism only; no OpenMP yet

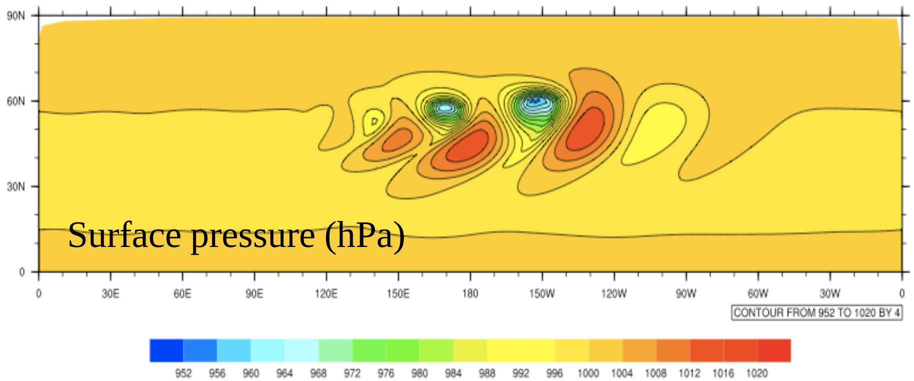
Preliminary MPAS-Ocean Scaling Results

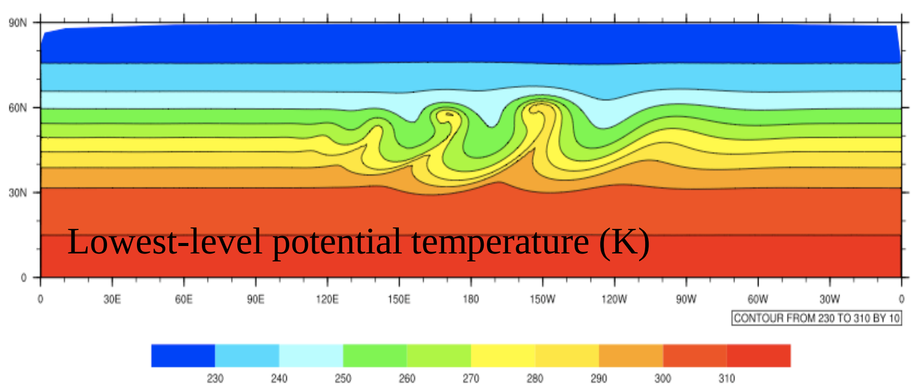
Hydrostatic ocean model
(1) Explicit RK4 integration
(2) Timesplit



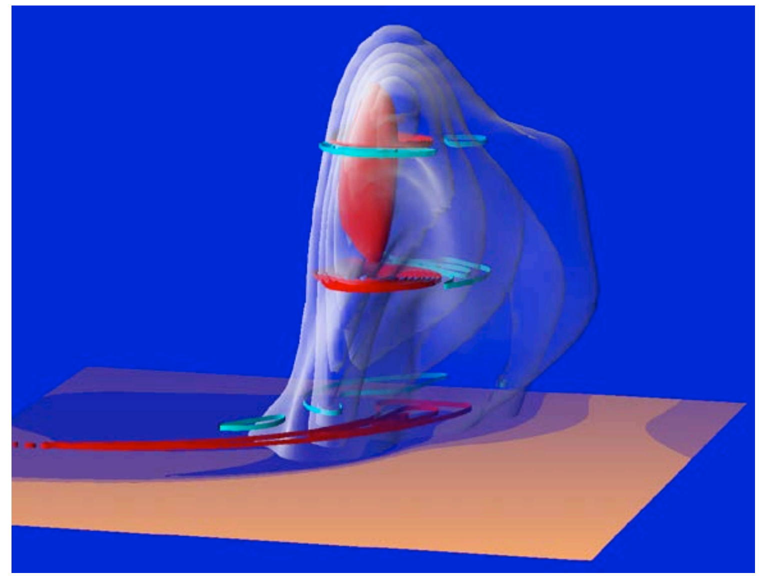
Model for Prediction Across Scales: MPAS

Global simulation tests
Baroclinic waves





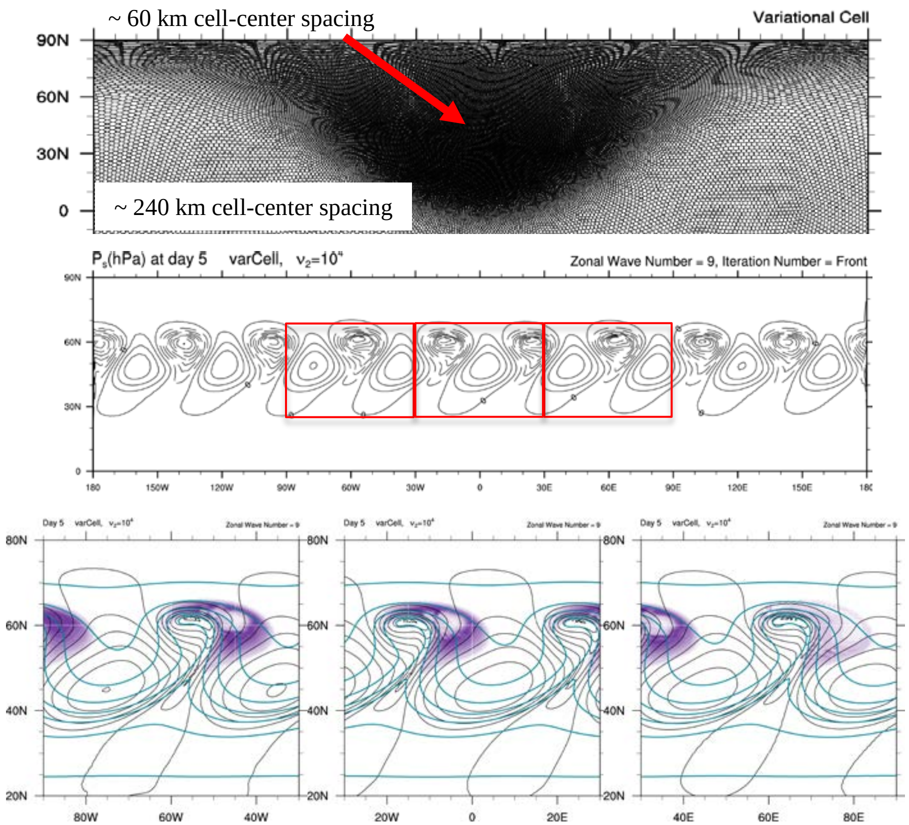
Convection on a Cartesian plane
Supercell thunderstorms



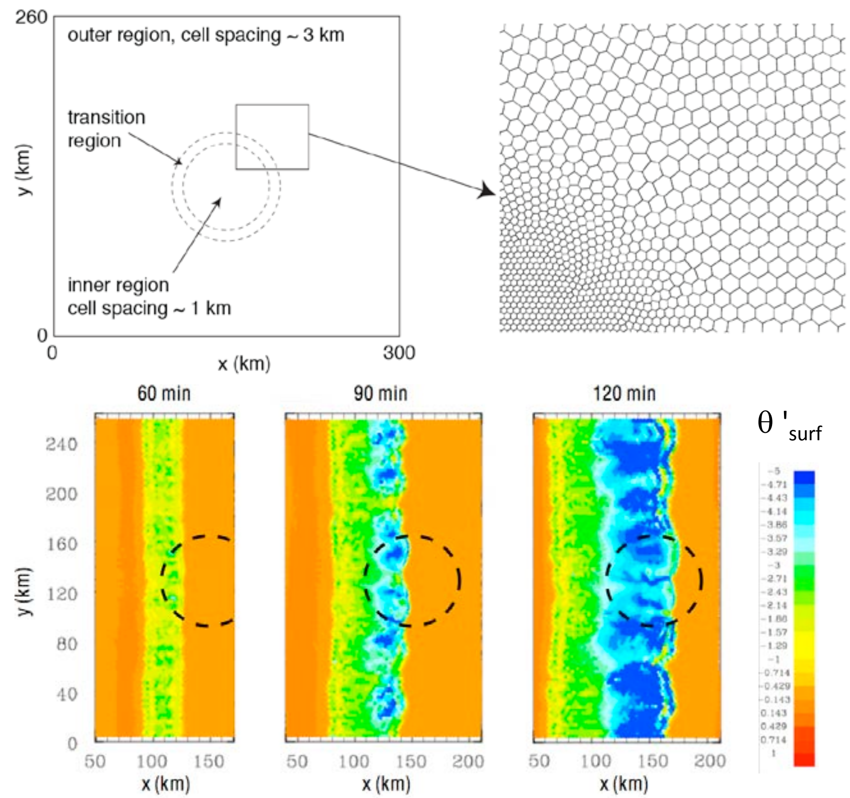
W contours at 1, 5, and 10 km (c.i. = 3 m/s)
30 m/s W surface shaded in red
Rainwater surfaces - transparent shells
Surface temperature shaded on baseplane
500 meter mesh

Model for Prediction Across Scales: MPAS

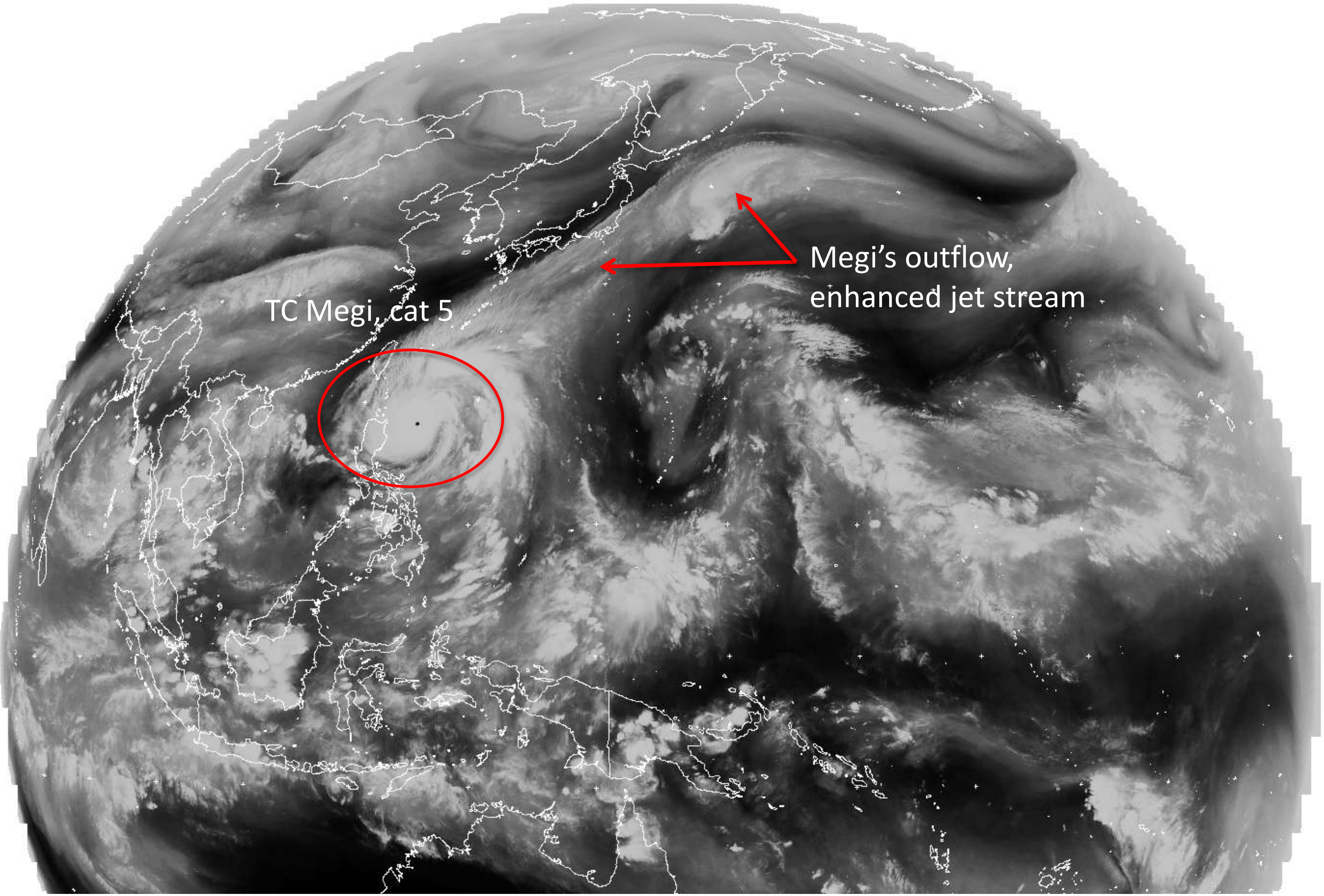
Global variable-resolution moist baroclinic waves



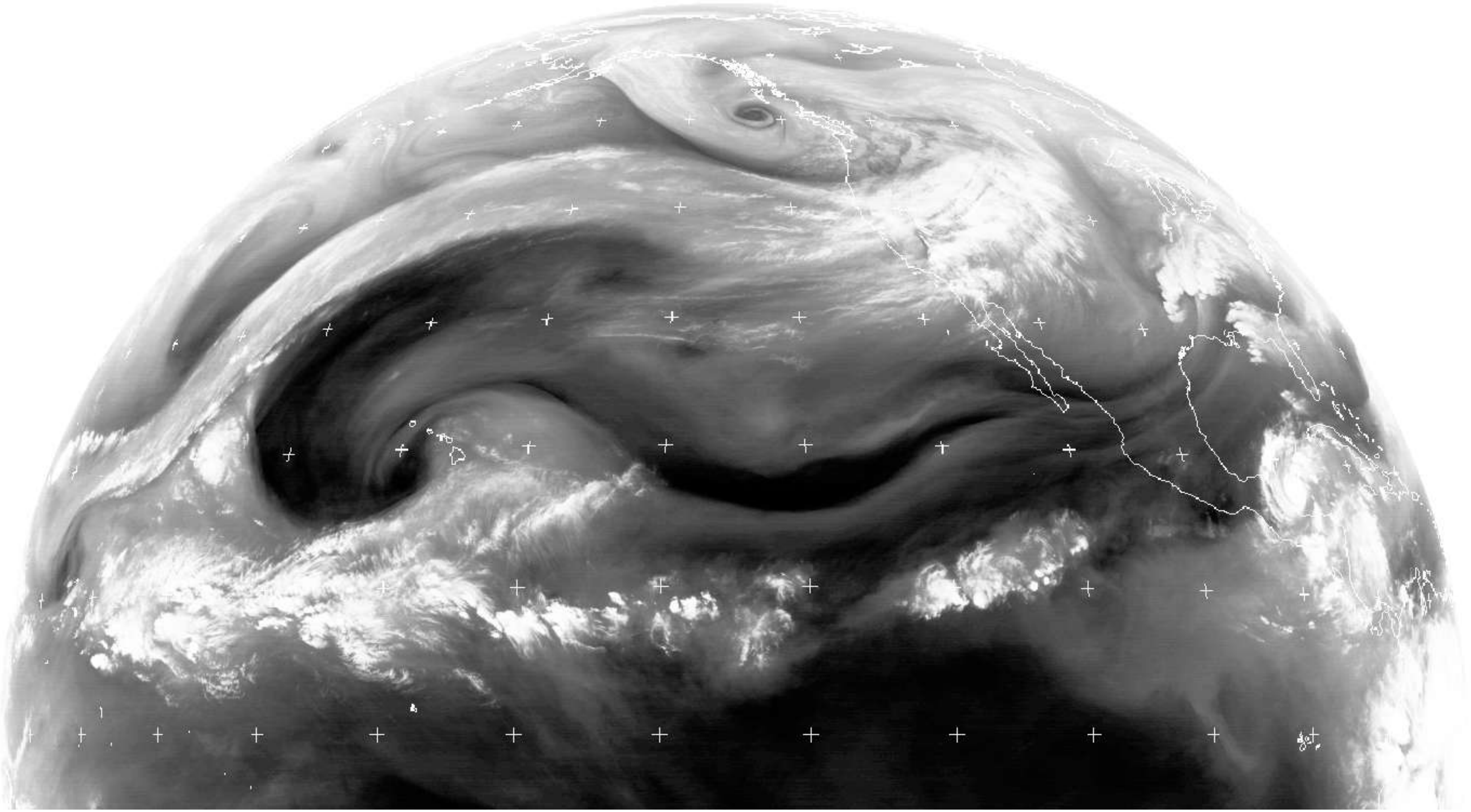
Squall-lines on a Cartesian plane using a variable-resolution mesh



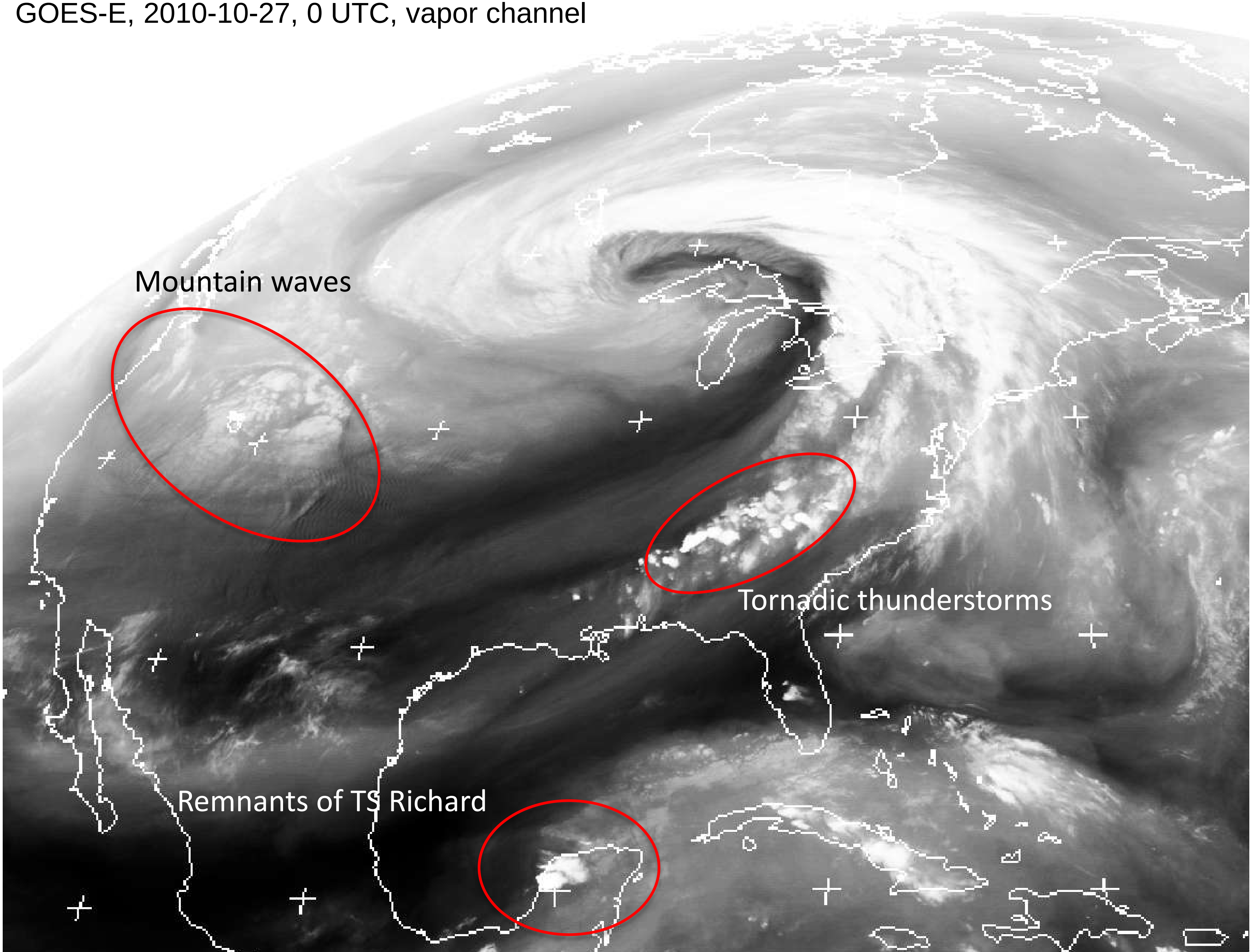
mtsat, 2010-10-17, 12 UTC, vapor channel



GOES-W, 2010-10-25, 0 UTC, vapor channel



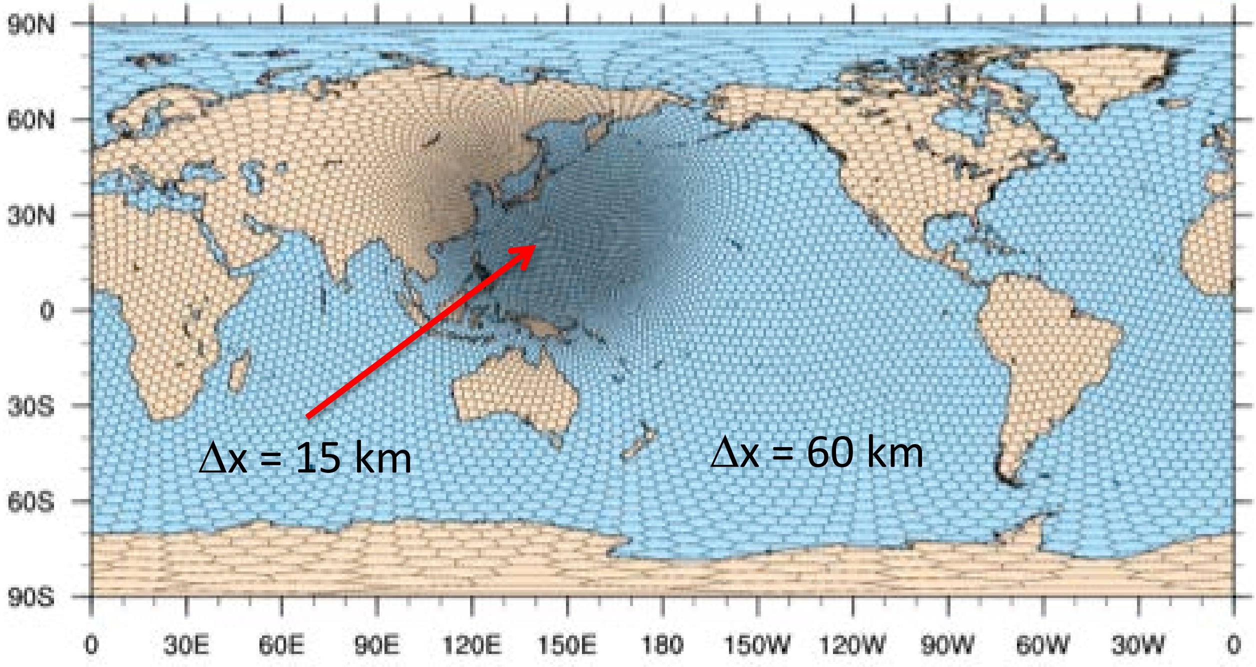
GOES-E, 2010-10-27, 0 UTC, vapor channel



MPAS Forecast Tests

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

MPAS mesh (4x finer than below), 41 levels



Western Pacific refinement

MPAS Forecast Tests

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

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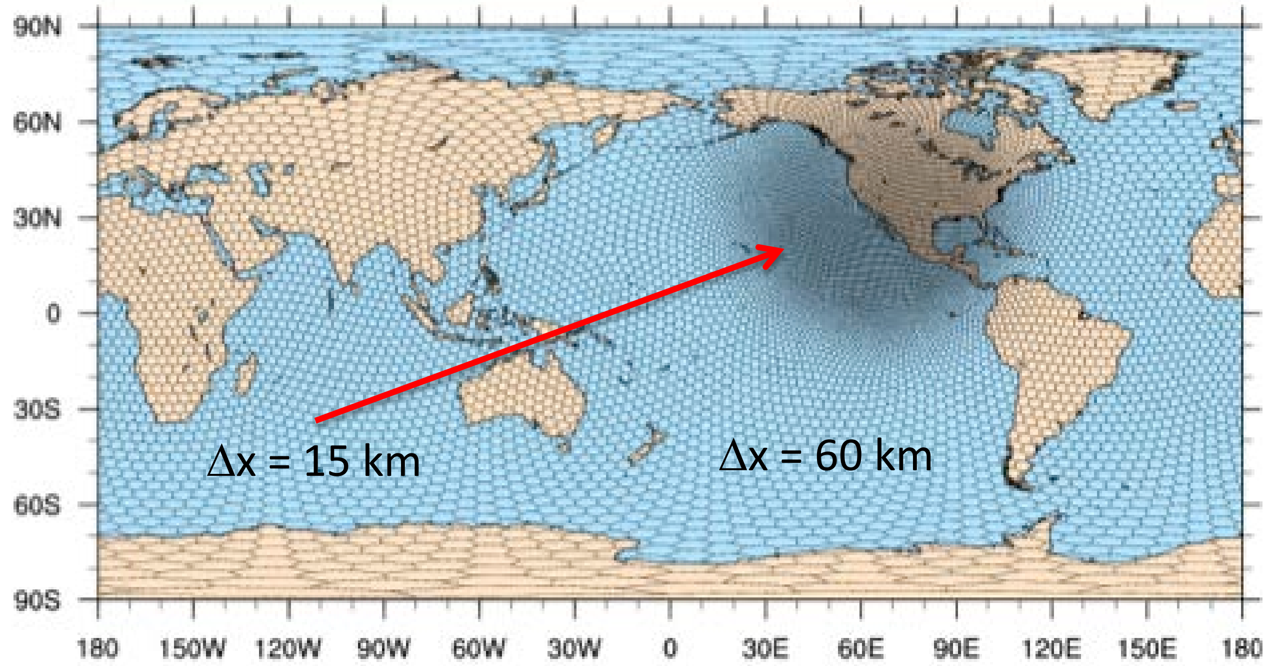


Eastern Pacific refinement

Variable Resolution Mesh Tests

Δt is constant on the variable-resolution mesh.

Smagorinsky: $K_h = c_s^2 l^2 |Def|$

l^2 scales with Δx^2

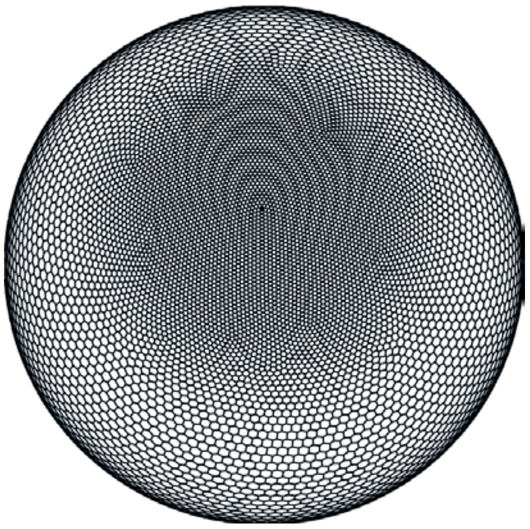
Viscosity and hyper-viscosity formulations:

$K_2 \nabla_\zeta^2 \phi$ — K_2 scales with Δx^2

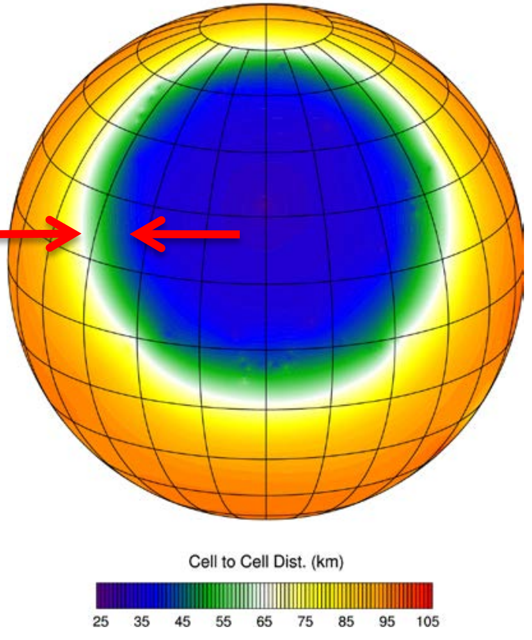
$K_4 \nabla_\zeta^2 \left(\nabla_\zeta^2 \phi \right)$ — K_4 scales with Δx^4

Locally 2Δ waves are damped at same rate.

MPAS TR-10 mesh



Transition-zone width

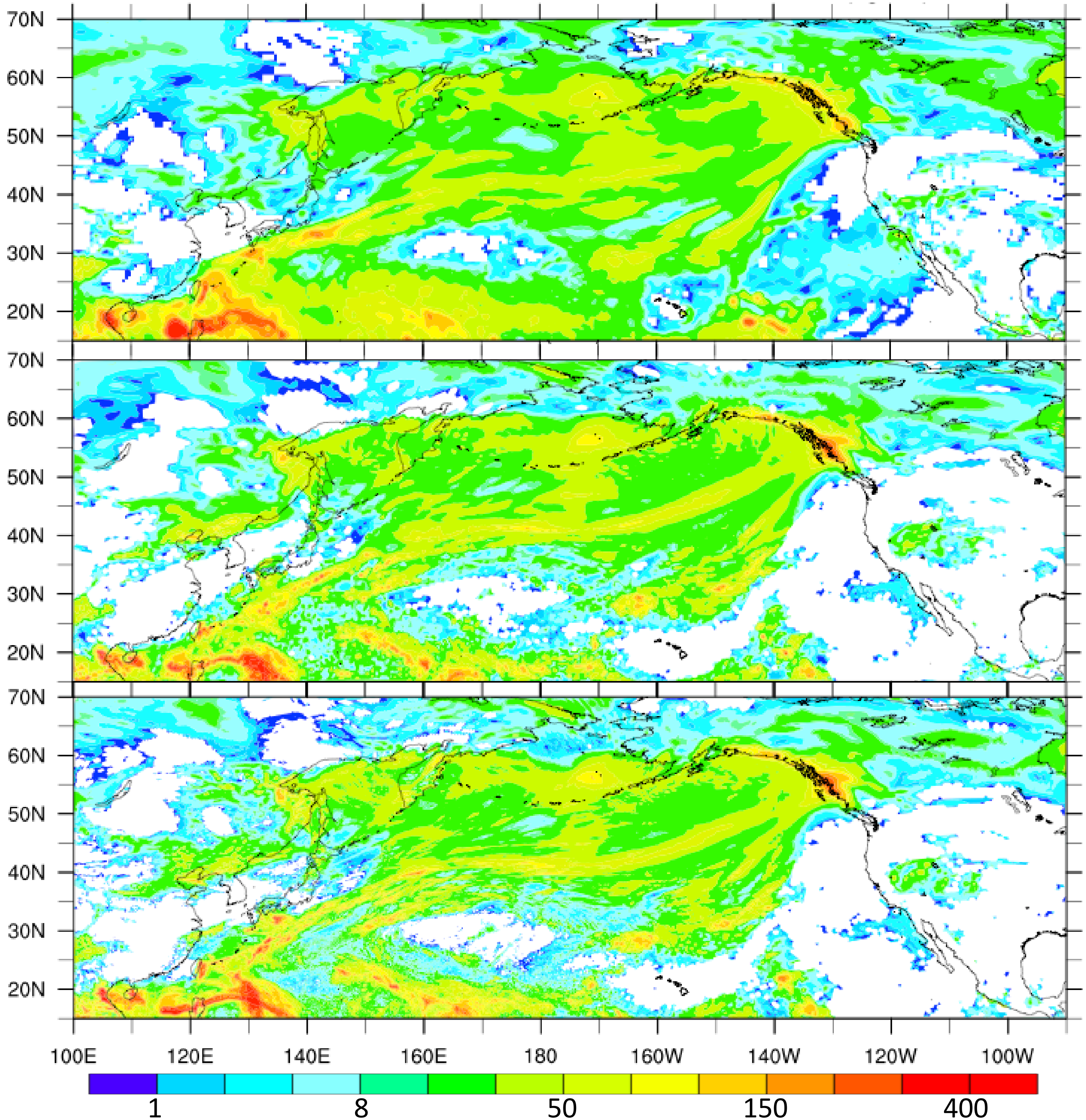


20 October 2010
5 day accumulated precipitation (mm)

CFSR (~ 40 km)

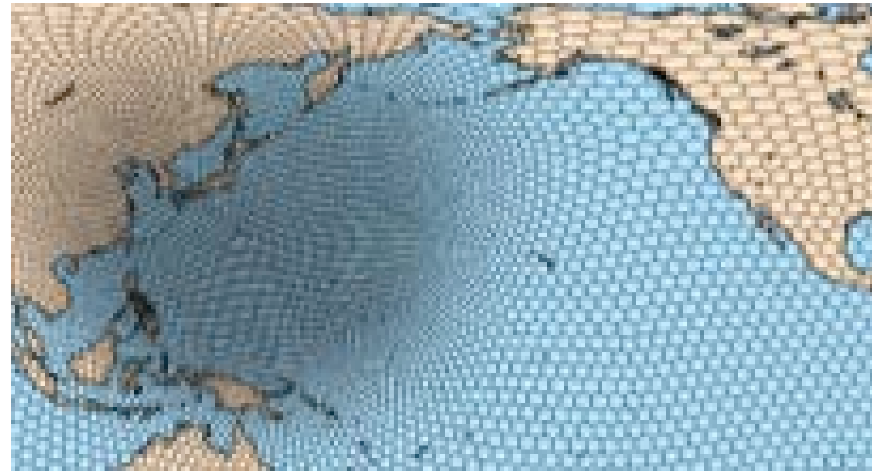
MPAS (60 km)
uniform resolution
Smagorinsky

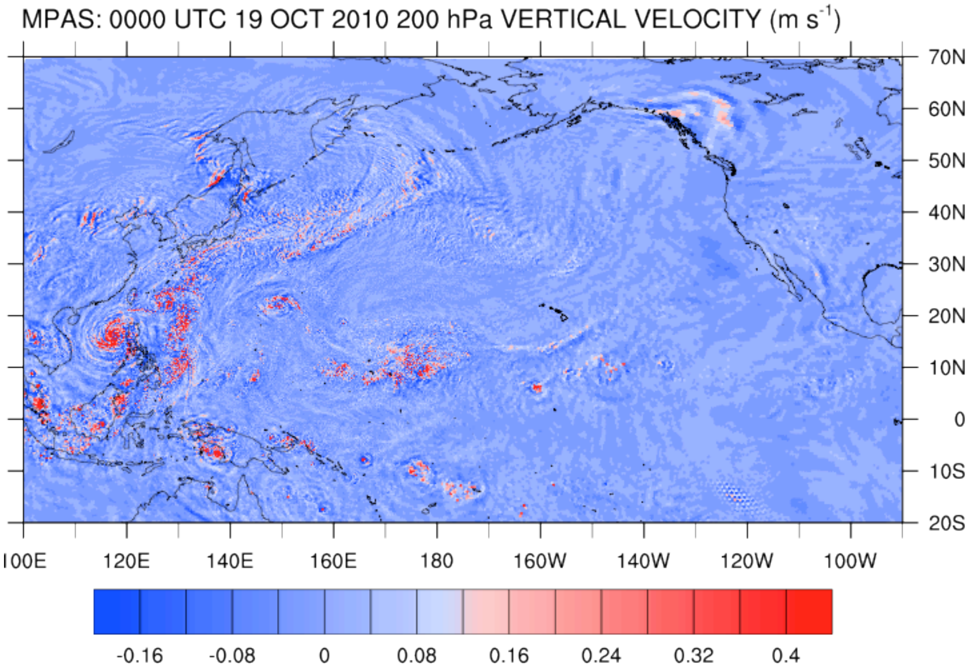
MPAS (60-15 km)
variable resolution
Western Pacific ref.
Smagorinsky,
(Δx^2 scaling)

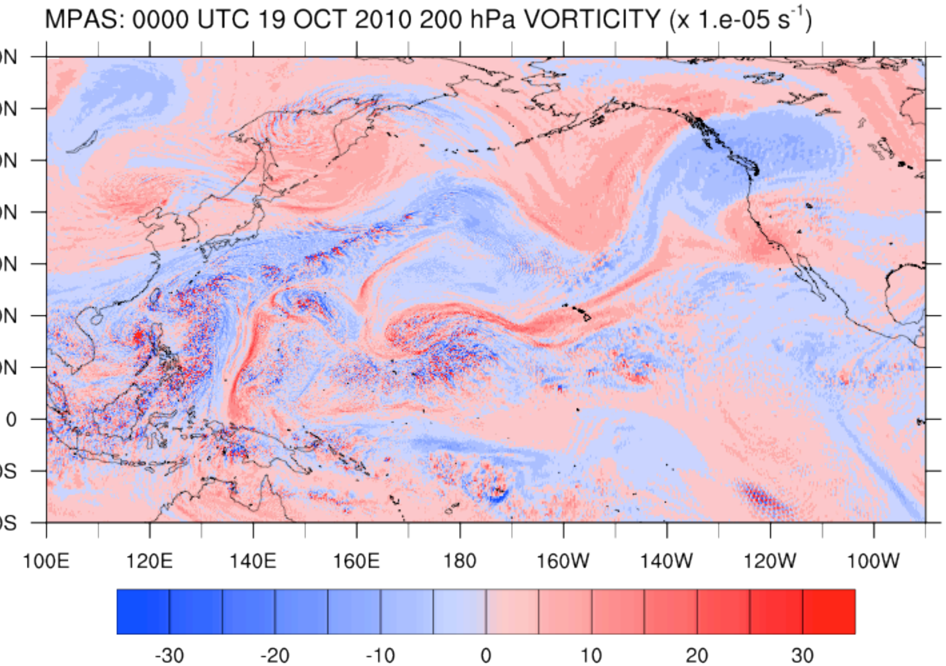


MPAS (60 – 15 km mesh)
Western Pacific refinement
15 October initialization

Smagorinsky, Δx^2 scaling

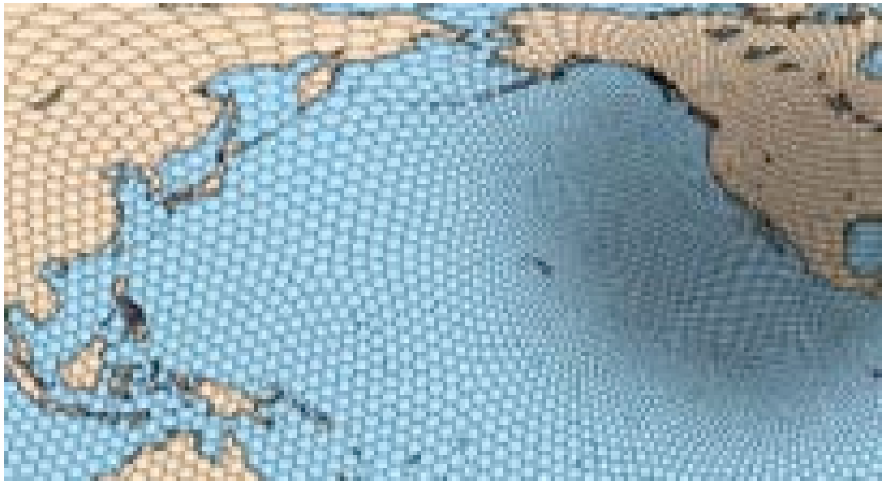


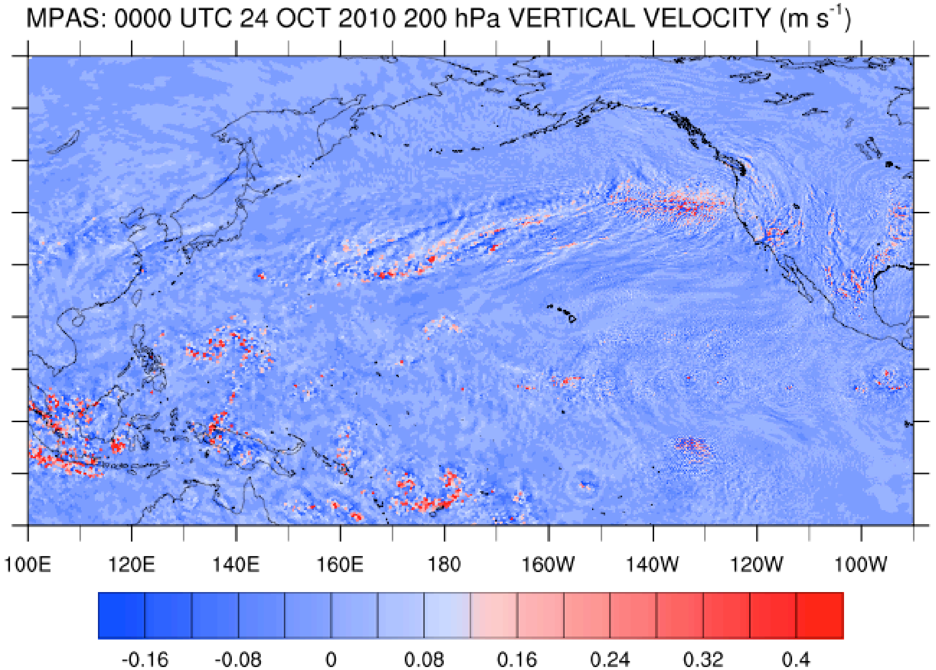


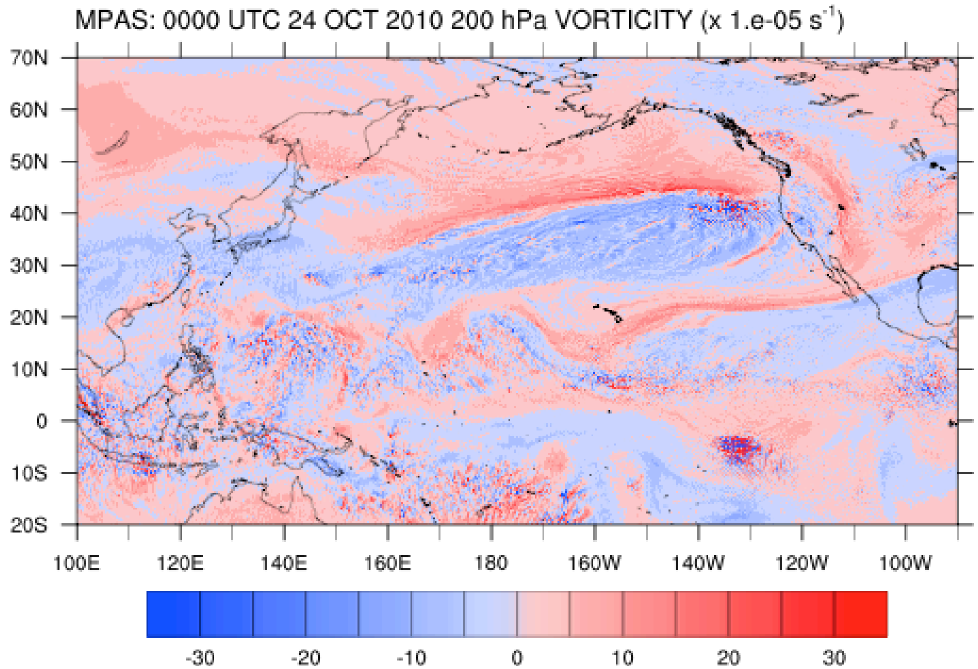


MPAS (60 – 15 km mesh)
Eastern Pacific refinement
21 October initialization

Smagorinsky, Δx^2 scaling

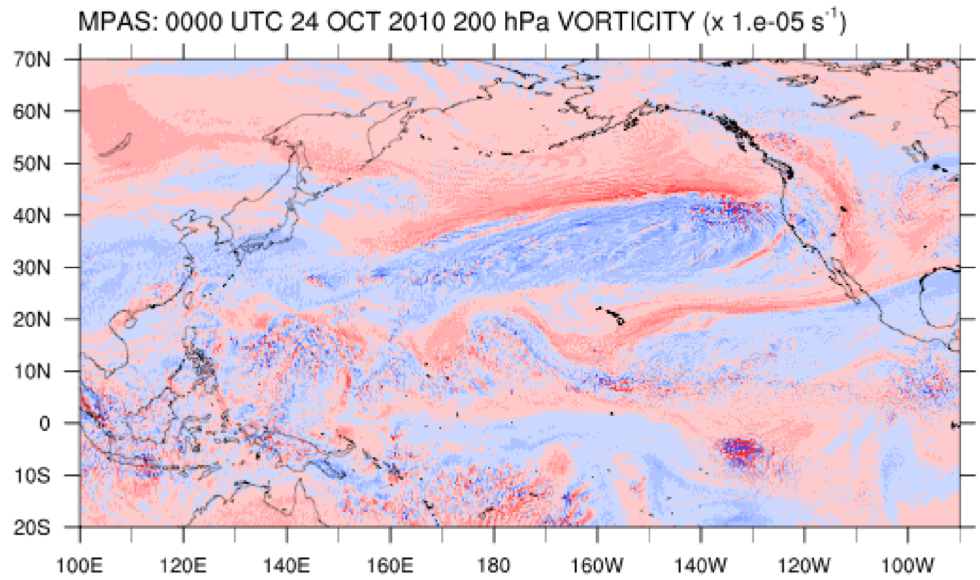




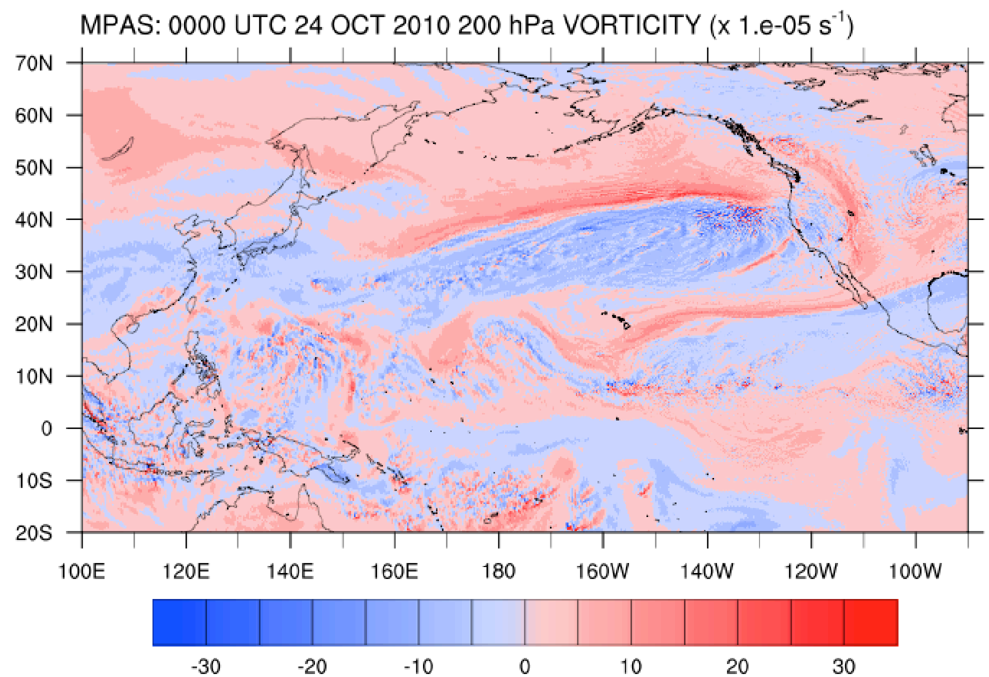


MPAS (60 – 15 km mesh) Eastern Pacific refinement 21 October initialization

East-Pac mesh (Δx = 60-15 km)
Smagorinsky, Δx^2 scaling



East-Pac mesh (Δx = 60-15 km)
Smagorinsky, Δx^2 scaling;
background $K_4 = 2 \times 10^{10}$ m^{4}s^{-1}
(15 km mesh value, Δx^4 scaling)



Summary

Preliminary results show adequate scaling for both ocean and atmospheric cores. (MPI-only configuration)

Variable-resolution mesh simulations in both idealized and full-physics NWP configurations suggest that the smooth mesh transitions are viable for applications.

The model filters, appropriately scaled by the mesh density, appear to be behaving properly.

Current and future work:

- Further optimization (MPI, OpenMP implementation).
- I/O (PIO) testing and development.
- Parameterizations (physics) need attention (scale-aware physics).
- Continued testing, hydrostatic – nonhydrostatic regime mesh transition.
- Applications.