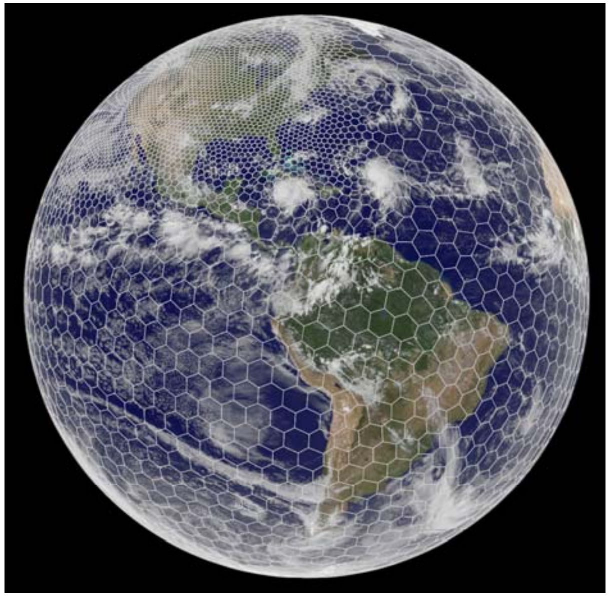
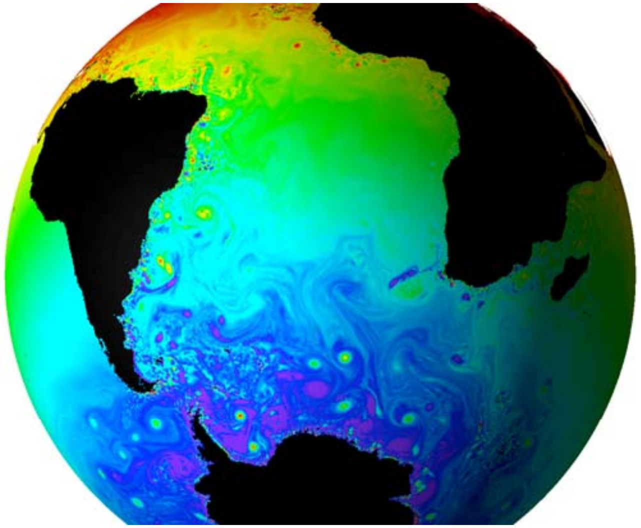
MPAS
Model for Prediction Across Scales

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



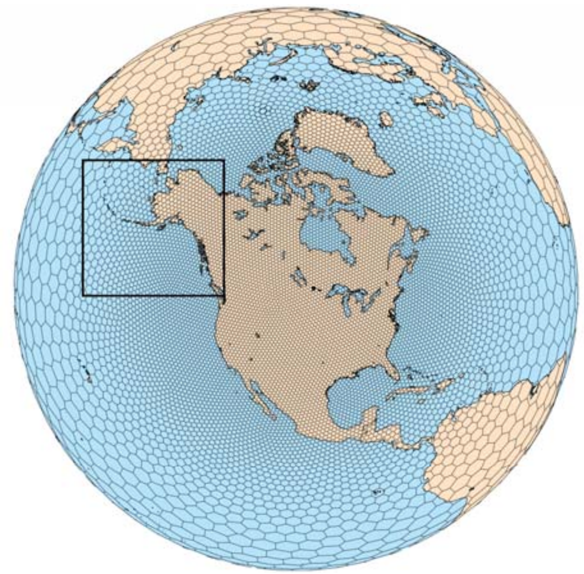
Jointly developed, primarily by NCAR and LANL/DOE

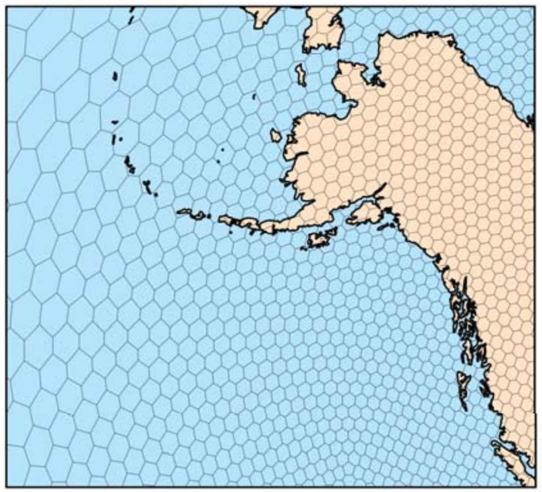
MPAS infrastructure - NCAR, LANL, others.
MPAS - Atmosphere (NCAR)
MPAS - Ocean (LANL)
MPAS - Ice, etc. (LANL and others)



Project leads: Todd Ringler (LANL)
Bill Skamarock (NCAR)

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.

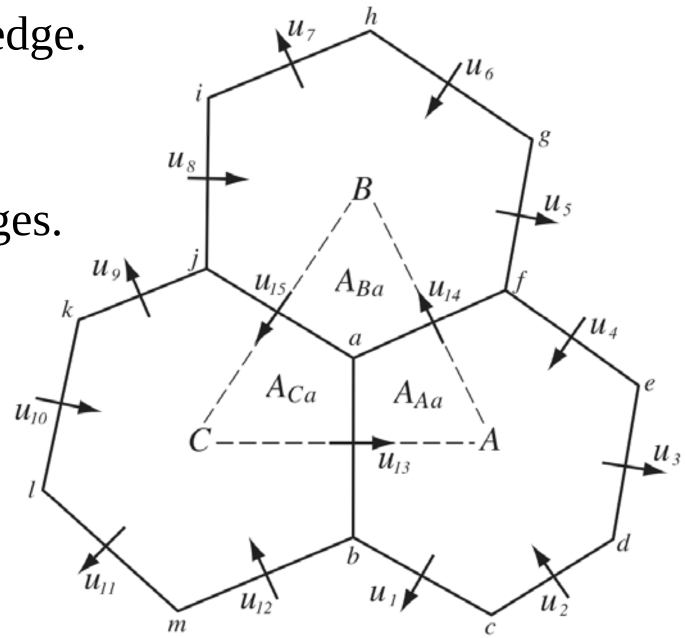
Cell centers are at cell center-of-mass.

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.



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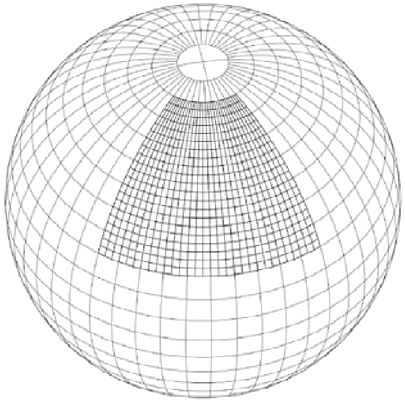
Why Voronoi Meshes (hexagons)?

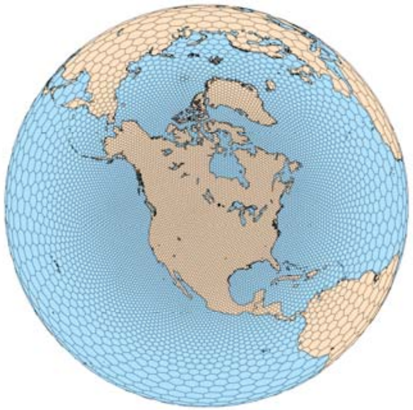


lat-long grid

Lat-long grid issues:

Poor scaling on computers with $O(10^4 – 10^5)$ processors because of polar filters.

Local refinement limited to nesting or problematic coordinate transformations.



Voronoi grid (MPAS)

Advantages over lat-long grid:

Scales well on MPP architectures (no poles).

Flexible local refinement using variable-resolution grids.

MPAS: Current Status

Ocean (MPAS-O)

<u>Hydrostatic solver (MPAS-O):</u>

Being implemented in a CESM/CAM branch (2013).
Testing uniform and variable meshes.
Parallelization - MPI only at present.

Atmosphere (MPAS-A)

<u>Hydrostatic solver (MPAS-AH):</u>

Implemented in a CESM/CAM branch (2010).
Testing uniform and variable meshes with APE and AMIP simulations.

<u>Nonhydrostatic solver (MPAS-ANH):</u>

NWP testing on uniform and variable-resolution meshes is underway.
Testing within cycling DA system (DART) has begun.
Year-long free forecasts are being produced for comparison with WRF-NRCM.
Will replace MPAS-AH in CESM/CAM in early 2013, then APE and AMIP testing.
Physics - WRF-NRCM, NCEP GFS/CFS (port in progress), CESM/CAM.
Parallelization - MPI only at present.

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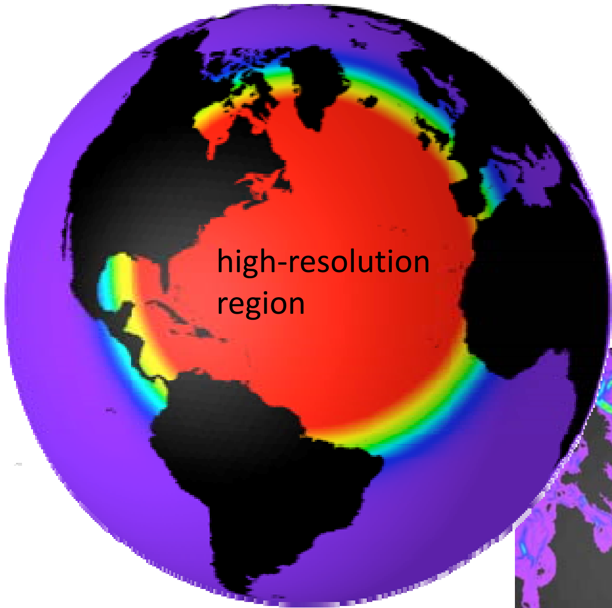
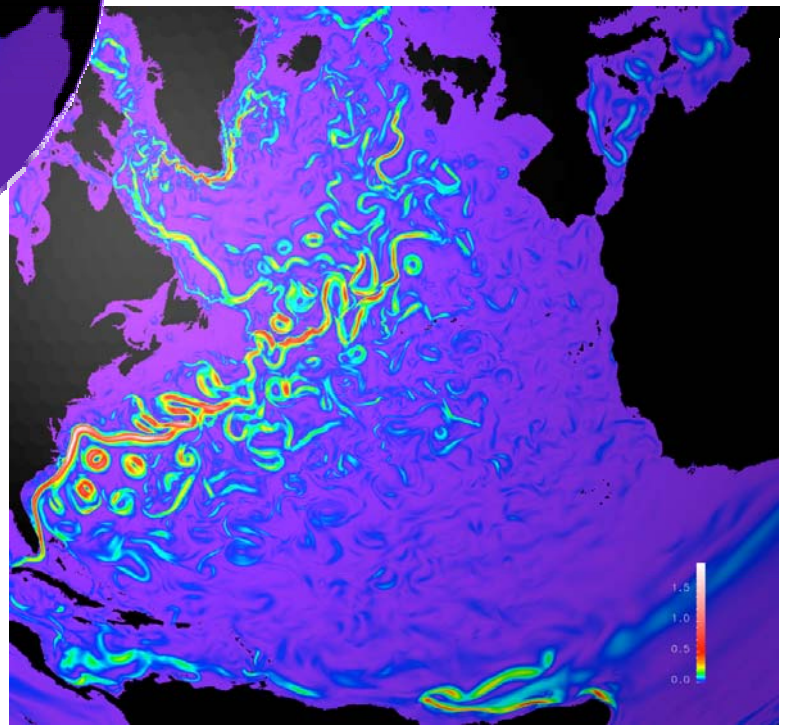
MPAS-O: A Global, Multi-Scale Ocean Model

MPAS-O: hydrostatic PE solver, explicit time-split integration. Supports both quasi-uniform and variable resolution meshing of the sphere.

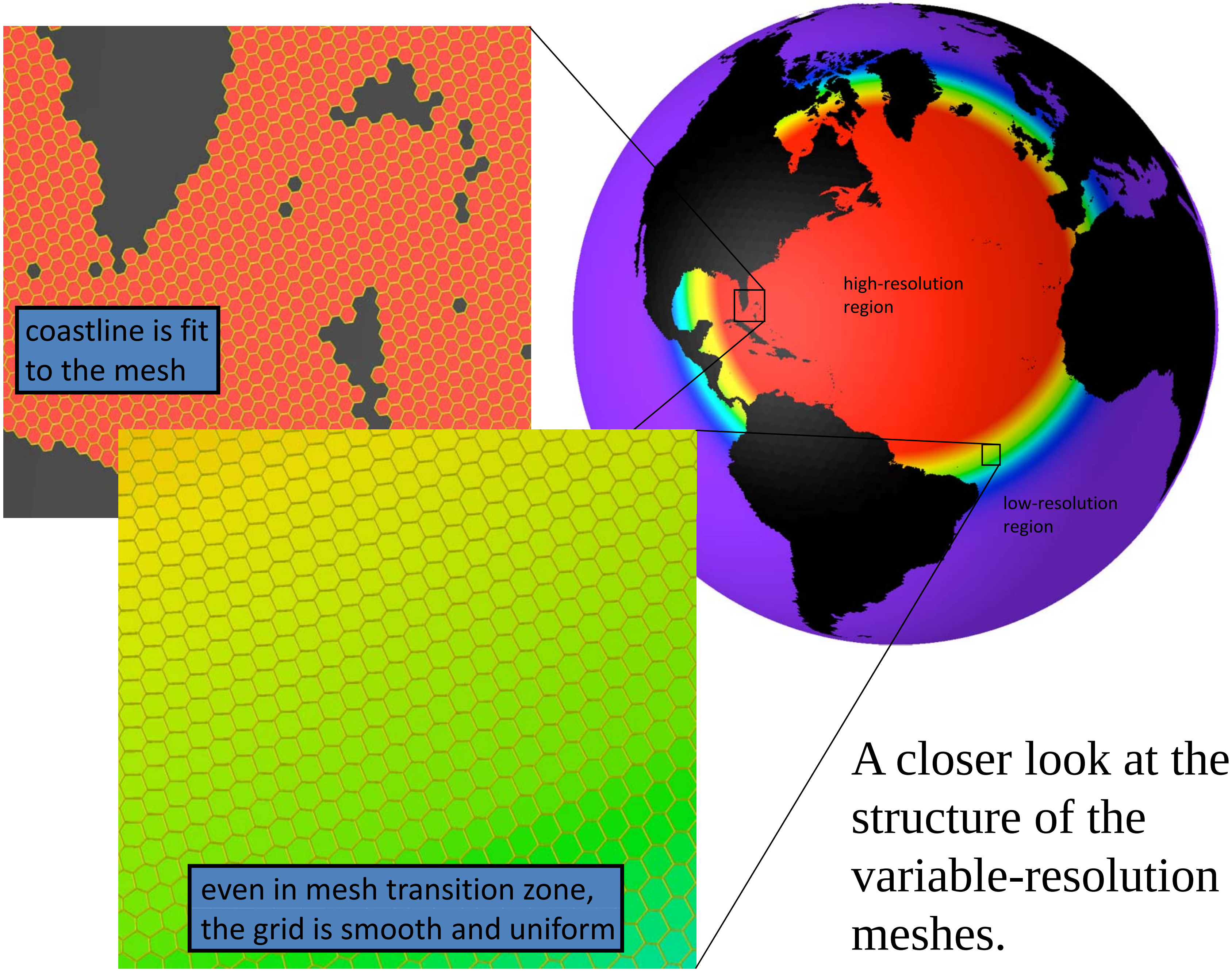


Below: Snapshot of kinetic energy from a global ocean simulation with 7.5 km resolution in the North Atlantic. The rest of the global ocean is resolved with a 38 km mesh.



MPAS-O: Questions

1. Is it viable as a global, quasi-uniform ocean model?
2. Is the multi-resolution configuration able to reproduce aspects of its quasi-uniform counterpart?
3. Can the multi-resolution configuration produce a better climate than its quasi-uniform counterpart at a fixed cost?



A closer look at the structure of the variable-resolution meshes.

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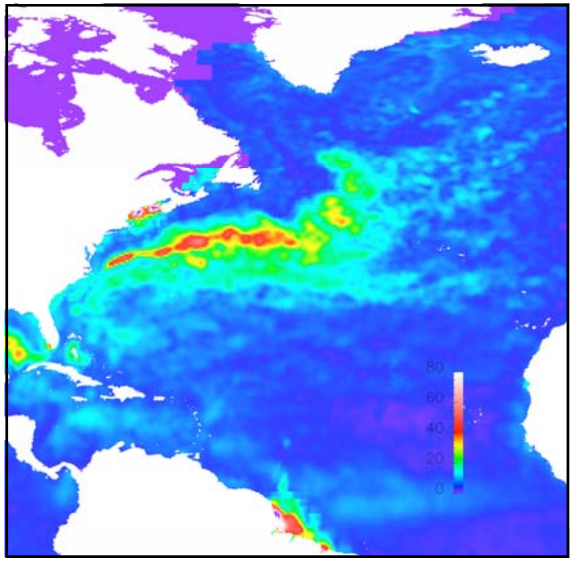
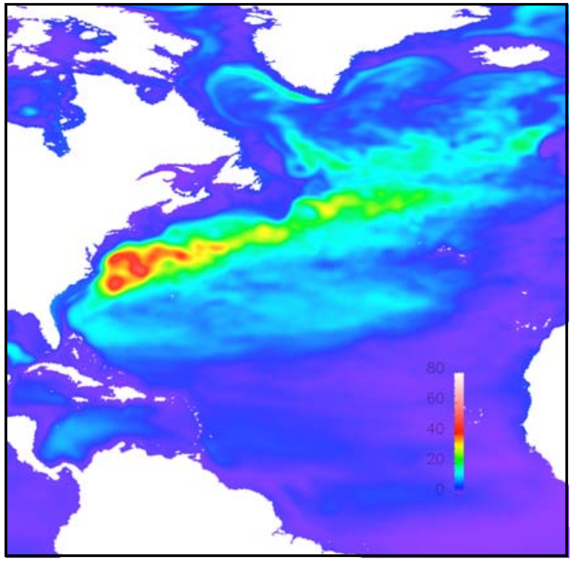
Model for Prediction Across Scales

Simulating Mesoscale Eddies on a Variable Resolution Mesh.

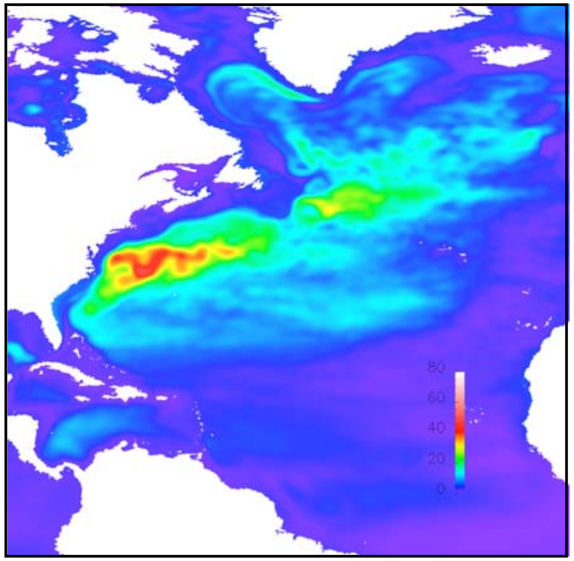
Observations: AVISO



Traditional Approach:
Global, quasi-uniform mesh
15 km resolution everywhere



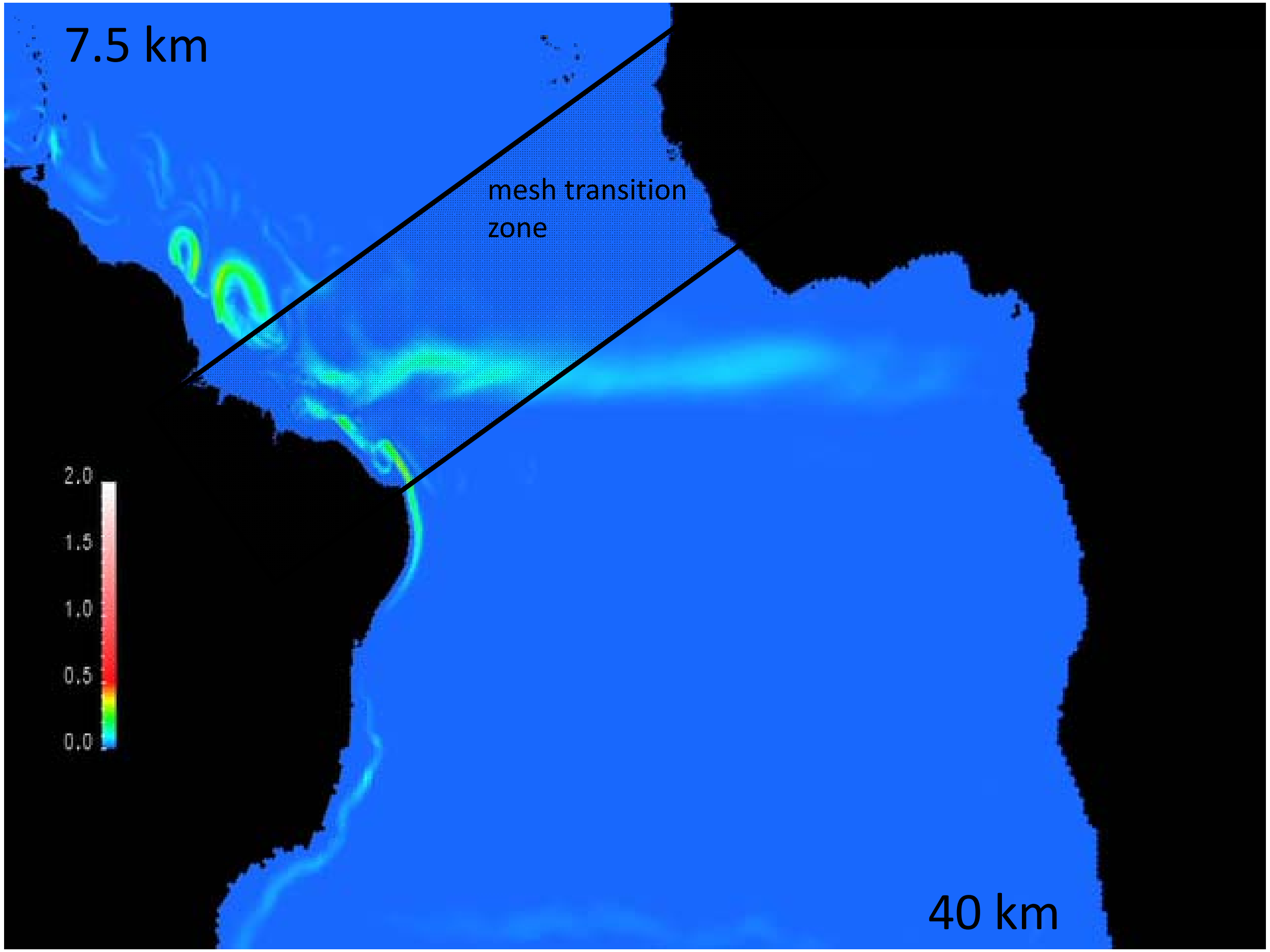
New Approach:
Global, variable-resolution mesh
15 km in North Atlantic, 75 km elsewhere



Figures show sea-surface height RMS which is a proxy for the amplitude of mesoscale ocean eddies.

The mesoscale eddies in the North Atlantic are simulated as well on the variable resolution mesh as on the uniform-resolution mesh, but at only 15% the cost.

Retroflection of north Brazil current
data: snapshots of KE @ 100 m depth
movie: one frame per month for 20 years



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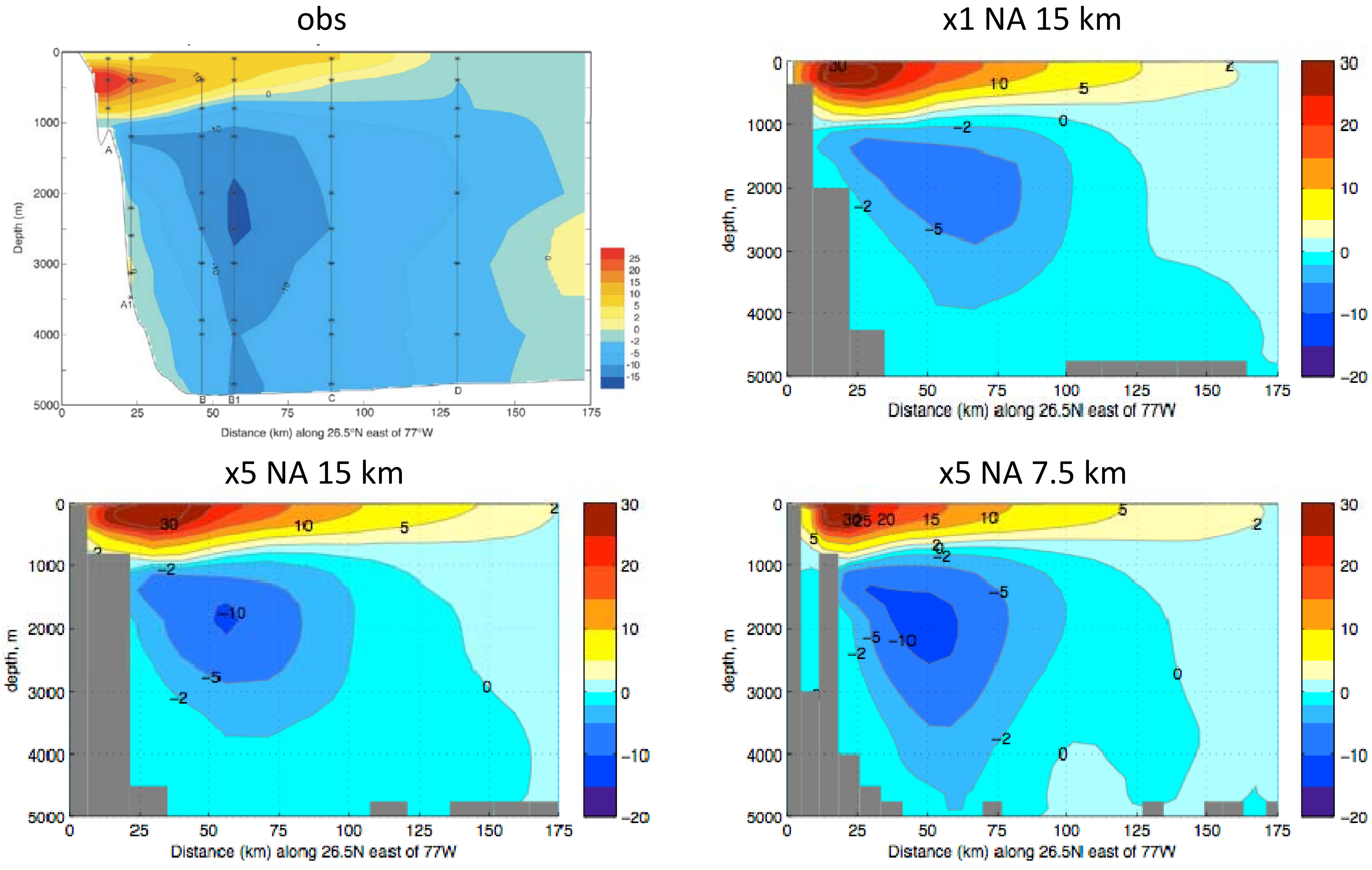
Deep Western Boundary Current



meridional velocity (cm/s)

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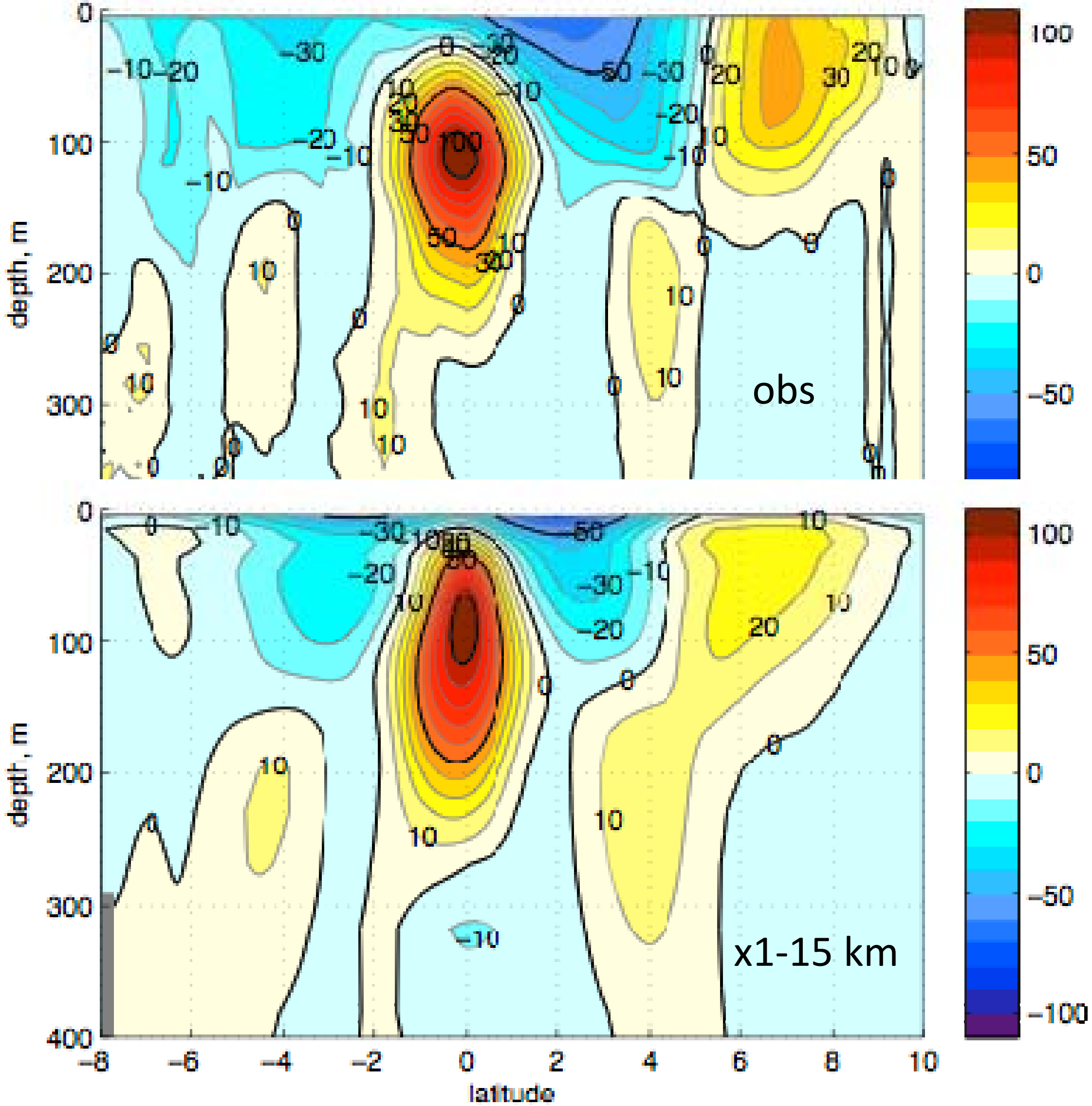
Model for Prediction Across Scales

The equatorial currents are surprisingly accurate.



zonal
velocity
(cm/s)

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Revisiting the three questions ....

Q: Is the quasi-uniform model viable?
(Compare x1.15km to observations.)
A: The model is competitive with its peers, e.g. the x1.15km simulation is simulating equatorial currents and mesoscale activity slightly better than the POP 1/10 degree model.

Is the multi-resolution viable at fixed resolution?
(Compare x5.NA.15km to x1.15km in North Atlantic region.)
A: Unequivocally, yes. For all practical purposes the x5.NA.15km the is an exact reproduction of the x1.15km in the North Atlantic.

Q: Is the multi-resolution viable at fixed computation cost?
(Compare x5.NA.7.5km to x1.15km in North Atlantic region.)
A: Maybe. Certainly nothing got worse. Some aspect of the climate improved marginally.

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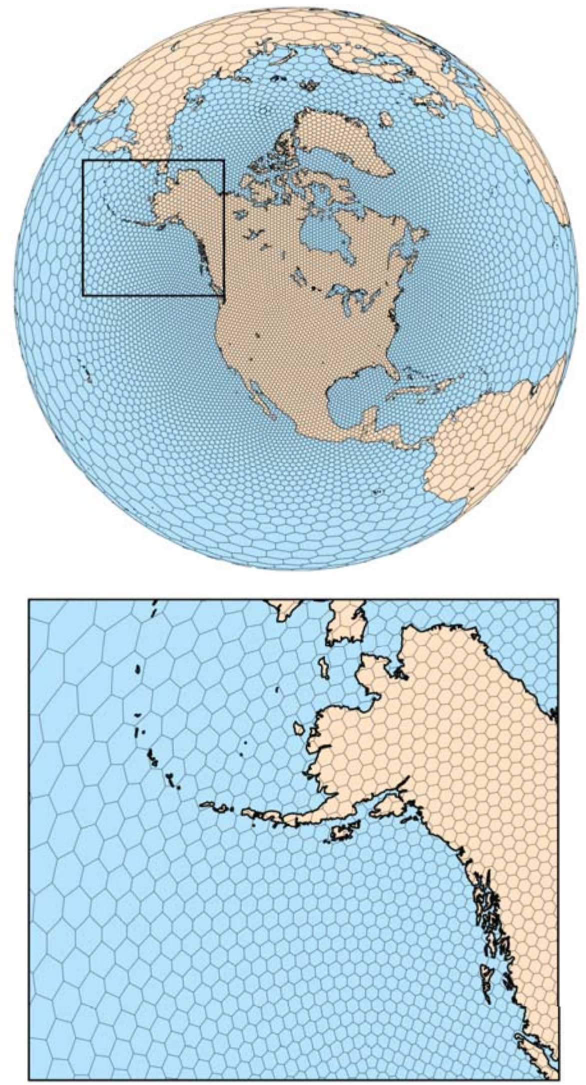
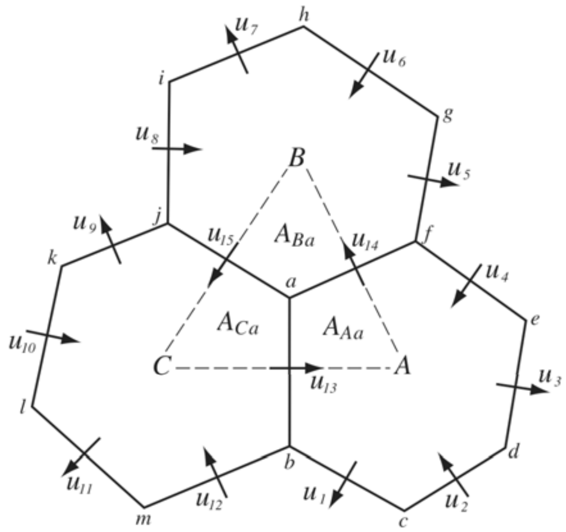
Model for Prediction Across Scales

MPAS-Atmosphere





Applications

- NWP, Regional Climate and Climate

Equations

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

Solver Technology

- Most of the techniques for integrating the nonhydrostatic equations come from WRF.
- C-grid centroidal Voronoi mesh.
- ARW physics (Nested Regional Climate model configuration).

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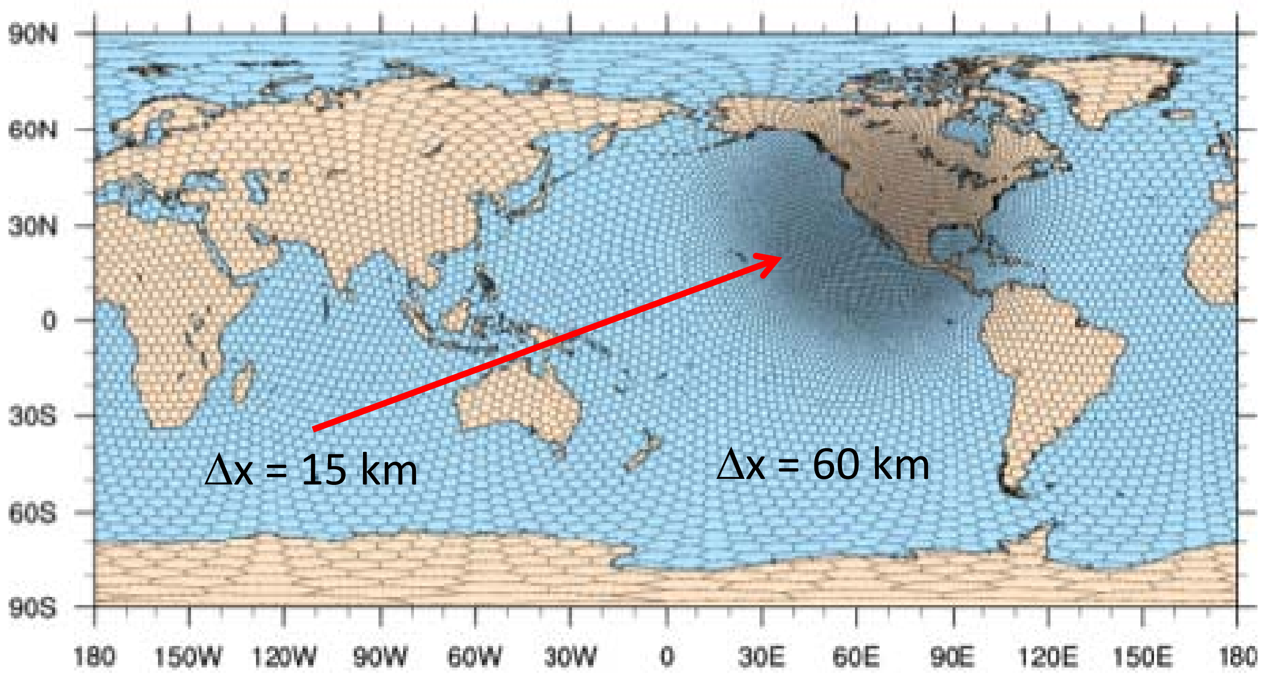
MPAS-A Forecast Tests

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



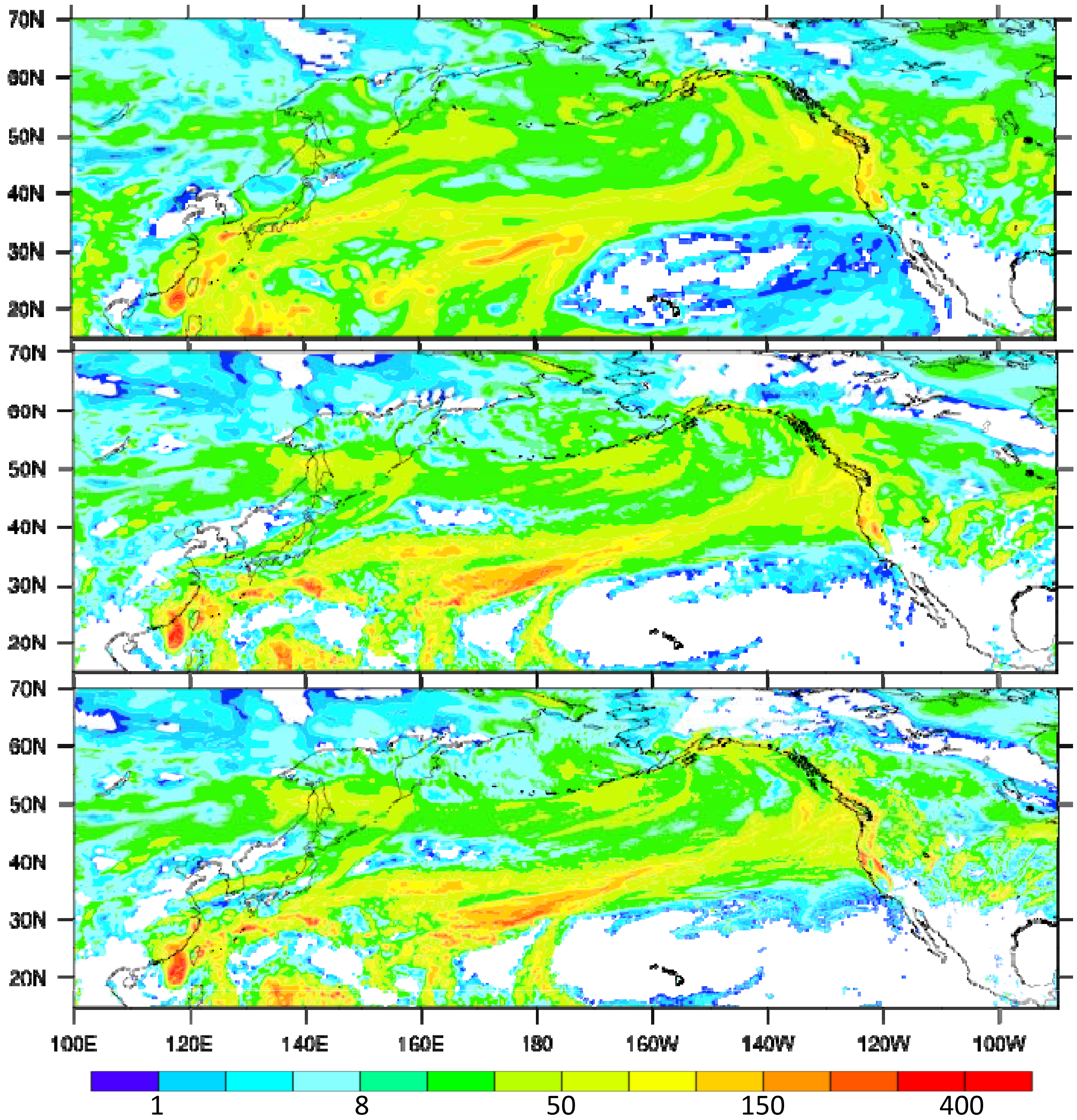
Eastern Pacific refinement

26 October 2010
5 day accumulated
precipitation (mm)

CFSR (~ 40 km)

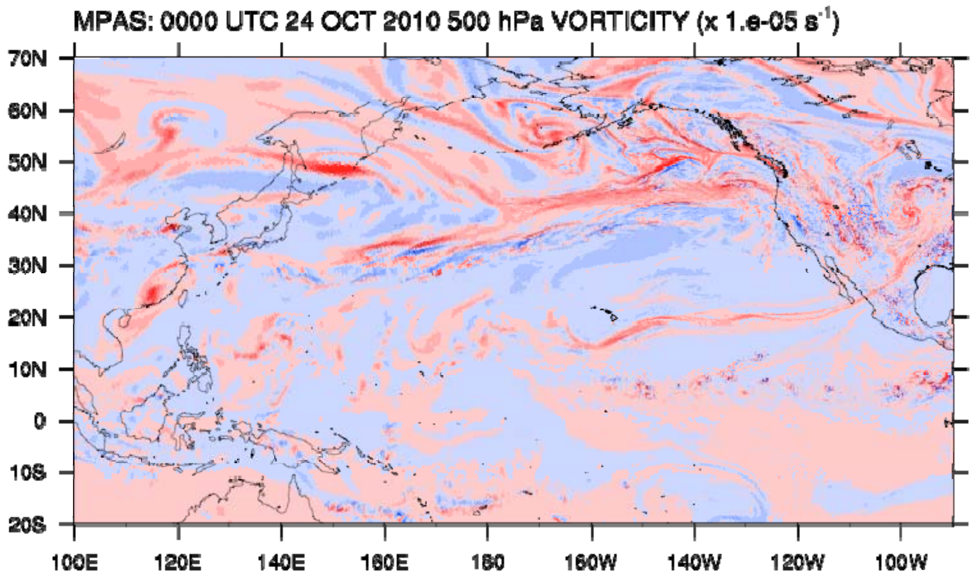
MPAS-A (60 km)
uniform resolution
Smagorinsky

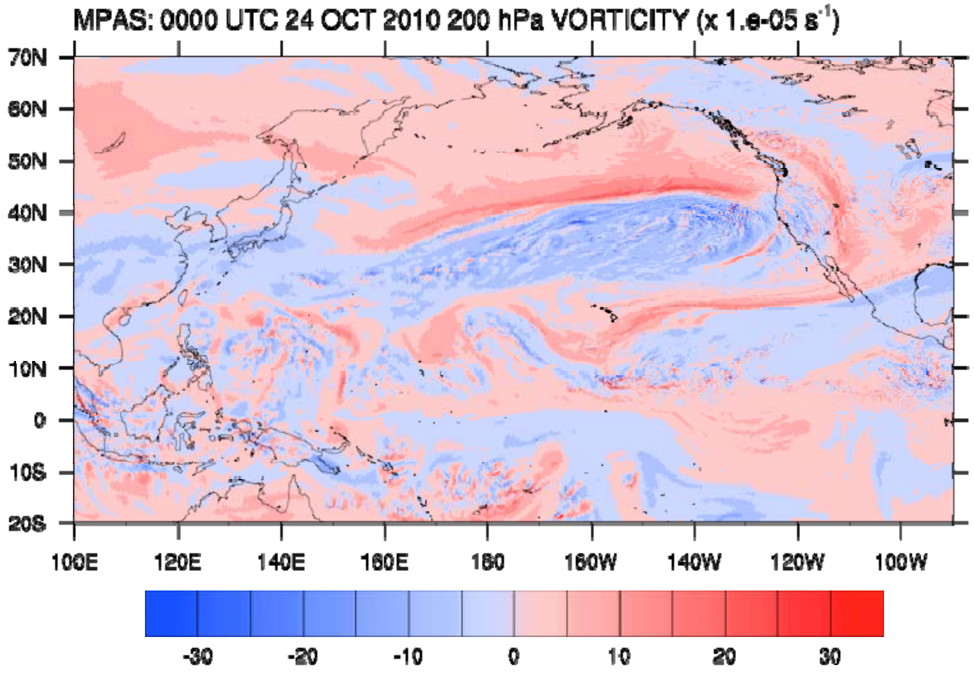
MPAS-A (60-15 km)
variable resolution
Eastern Pacific ref.
Smagorinsky,
(Δx^2 scaling)



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

East-Pac mesh (Δx = 60-15 km)
Smagorinsky, Δx^2 scaling;
background $K_4 = 1 \times 10^{11}\ m^4 s^{-1}$
(15 km mesh value, Δx^4 scaling)





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:

<u>Completed:</u>

23 October – 2 November 2010 (60, 30, 15 – (2 conv params))

23 October – 31 October (7.5 meshes, convective param on/off)

23 October – 29 October 2010 (3 km mesh)

<u>In progress:</u>

27 August – 6 September 2010

<u>Next up:</u>

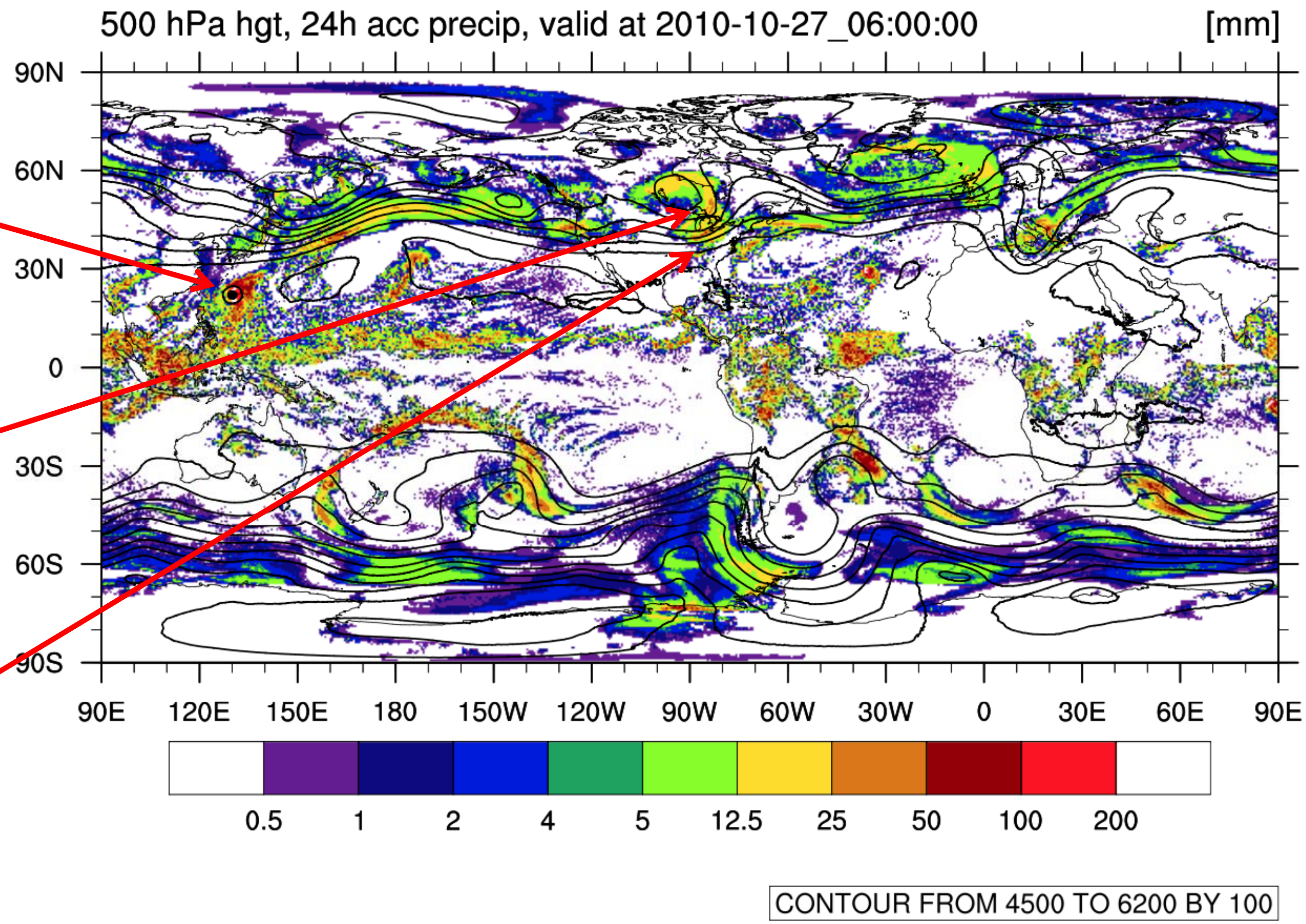
MJO event, period TBD (after 2010 simulations complete)

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

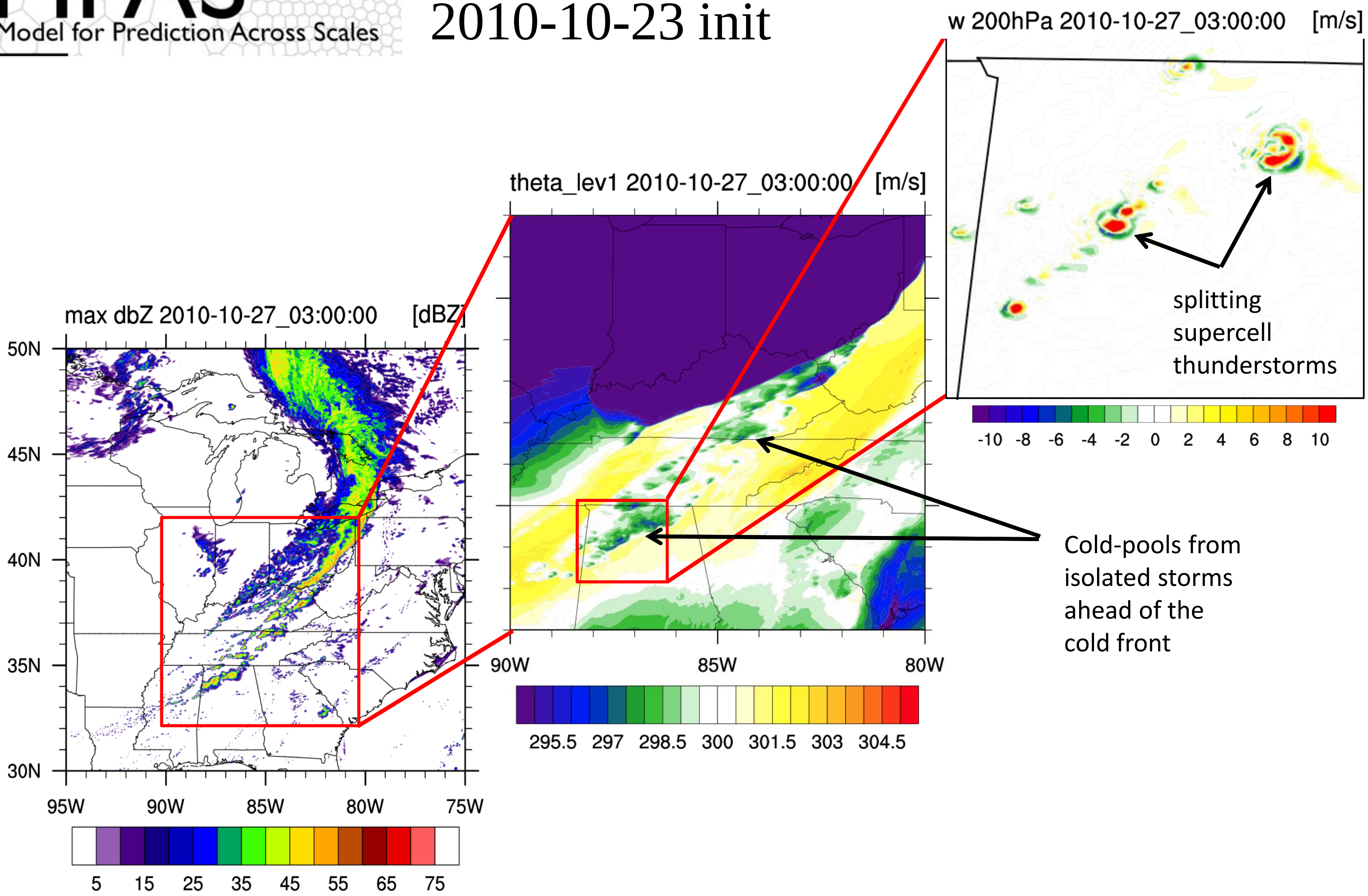
Tropical cyclone Chaba (cat 3)

Observed extratropical cyclone with the lowest recorded surface pressure in North America

Isolated tornadic storms observed in warm sector ahead of the cold front

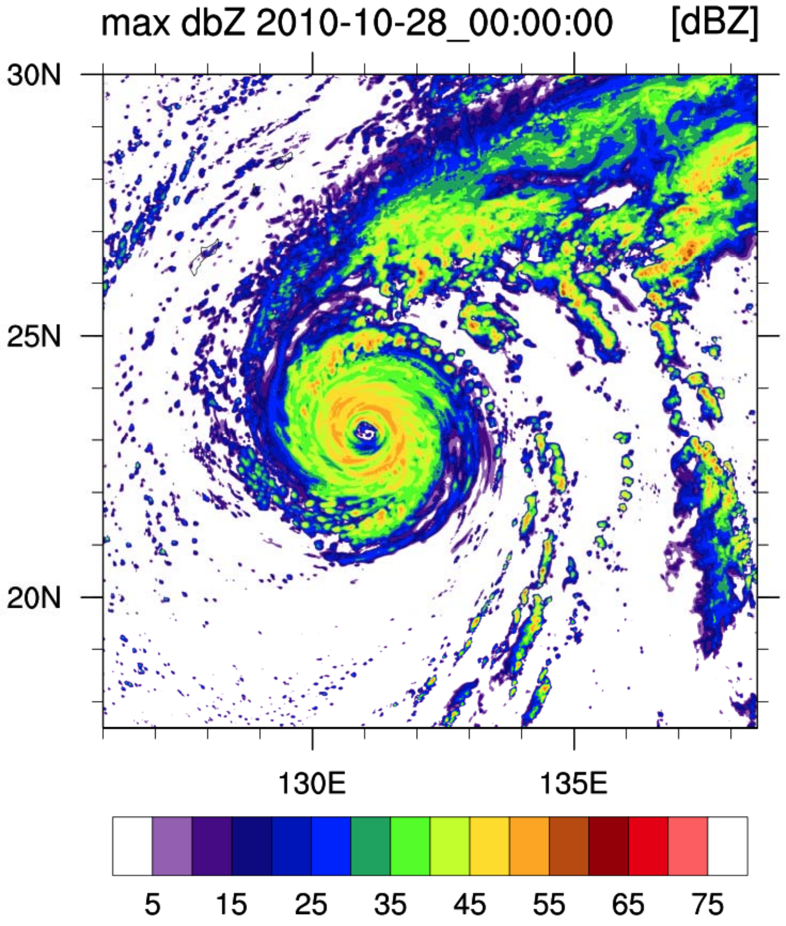


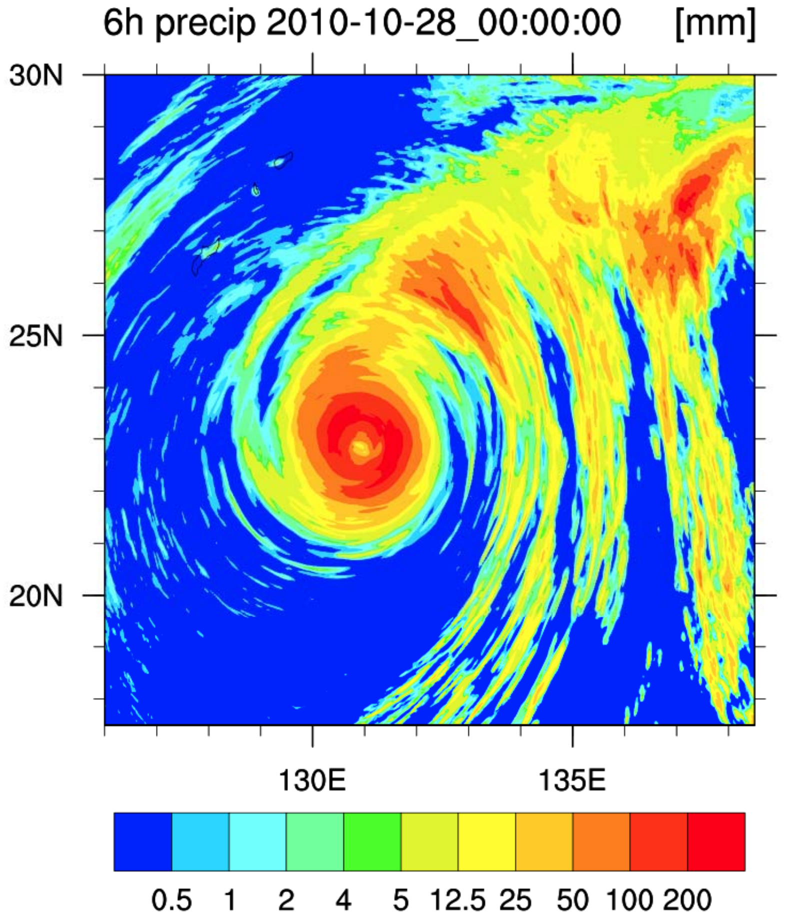
3 km global MPAS-A simulation
2010-10-23 init



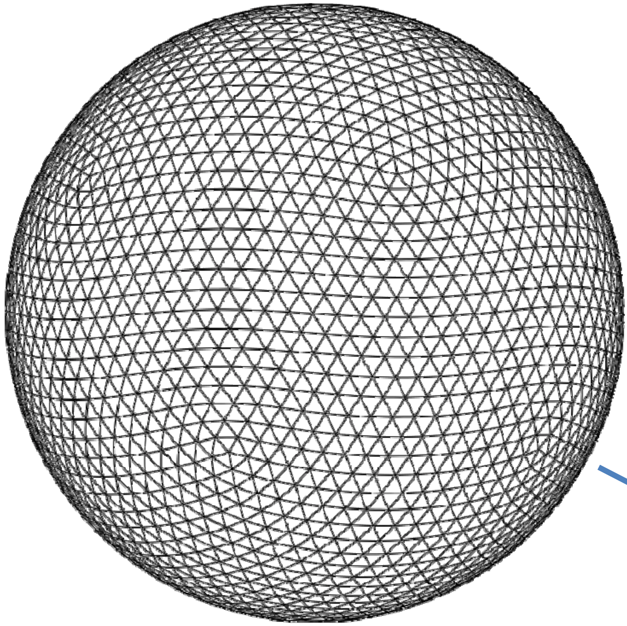
3 km global MPAS-A simulation 2010-10-23 init

Typhoon Chaba



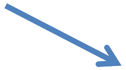


Parallel decomposition

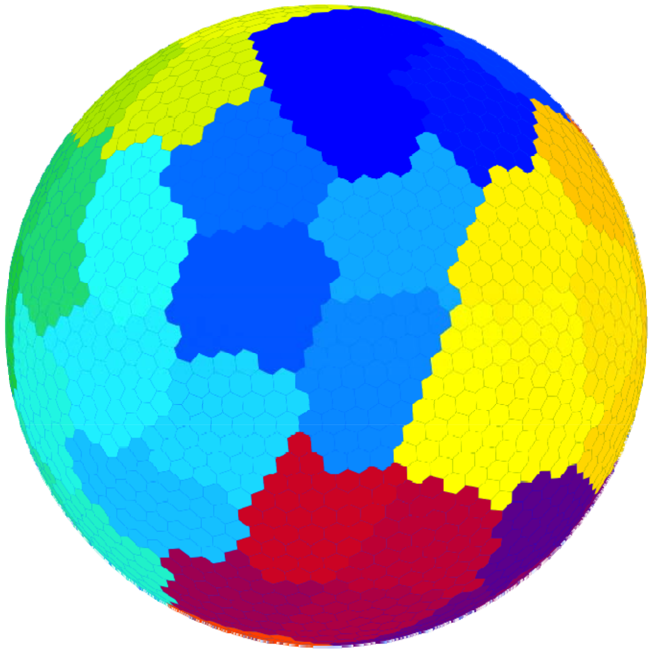


The *dual* mesh of a Voronoi tessellation is a Delaunay triangulation – essentially the connectivity graph of the cells

Parallel decomposition of an MPAS mesh then becomes a graph partitioning problem: ***equally distribute nodes among partitions (give each process equal work) while minimizing the edge cut (minimizing parallel communication)***



Graph partitioning



We use the Metis package for parallel graph decomposition

- Currently done as a pre-processing step, but could be done “on-line”

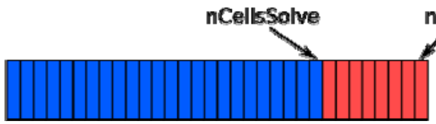
Metis also handles weighted graph partitioning

- Given *a priori* estimates for the computational costs of each grid cell, we can better balance the load among processes

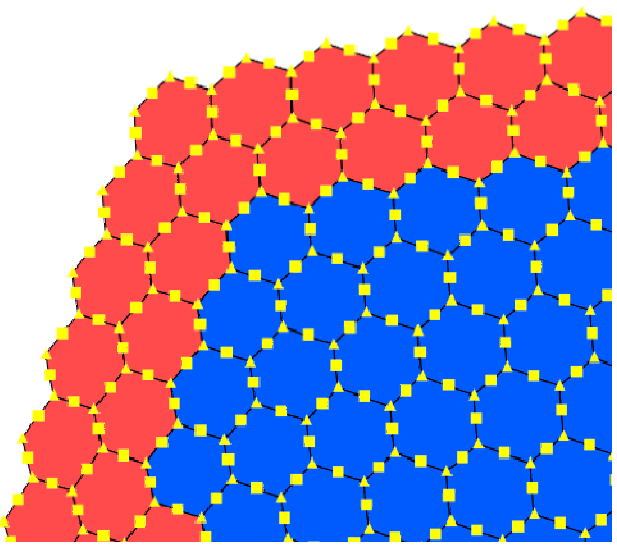
MPAS
Model for Prediction Across Scales

Parallel decomposition

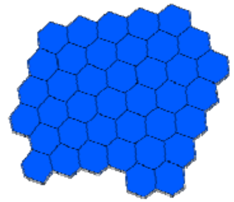
Given an assignment of cells to a process, any number of layers of halo (ghost) cells may be added



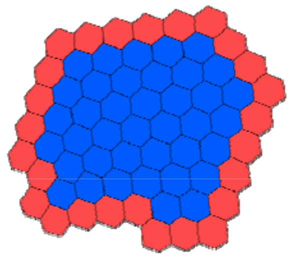
Cells are stored in a 1d array (2d with vertical dimension, etc.), with halo cells at the end of the array; the order of real cells may be updated to provide better cache re-use



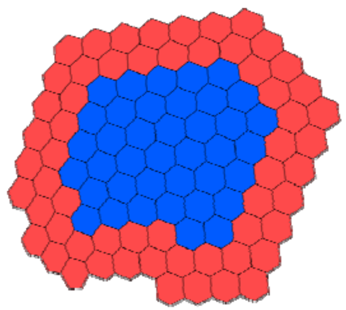
With a complete list of cells stored in a block, adjacent edge and vertex locations can be found; we apply a simple rule to determine ownership of edges and vertices adjacent to real cells in different blocks



Block of cells owned by a process



Block plus one layer of halo/ghost cells

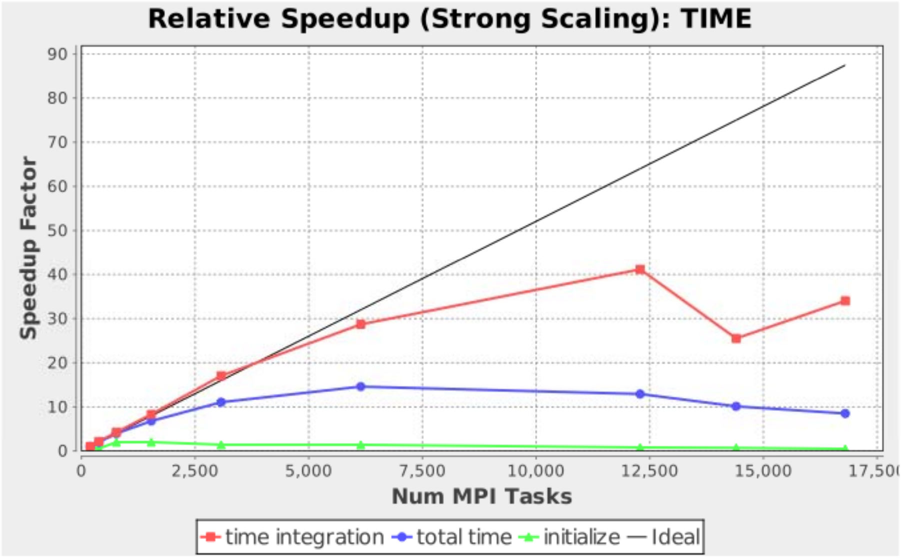


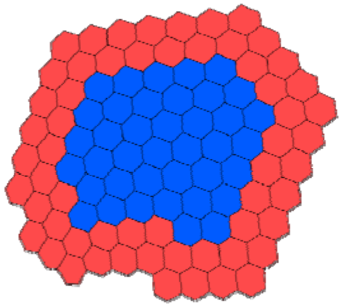
Block plus two layers of halo/ghost cells

MPAS-Ocean scaling

Model for Prediction Across Scales

15 km global mesh
(1.8M horizontal cells).
5 simulation days.
40 vertical levels.
3 scalars with FCT.





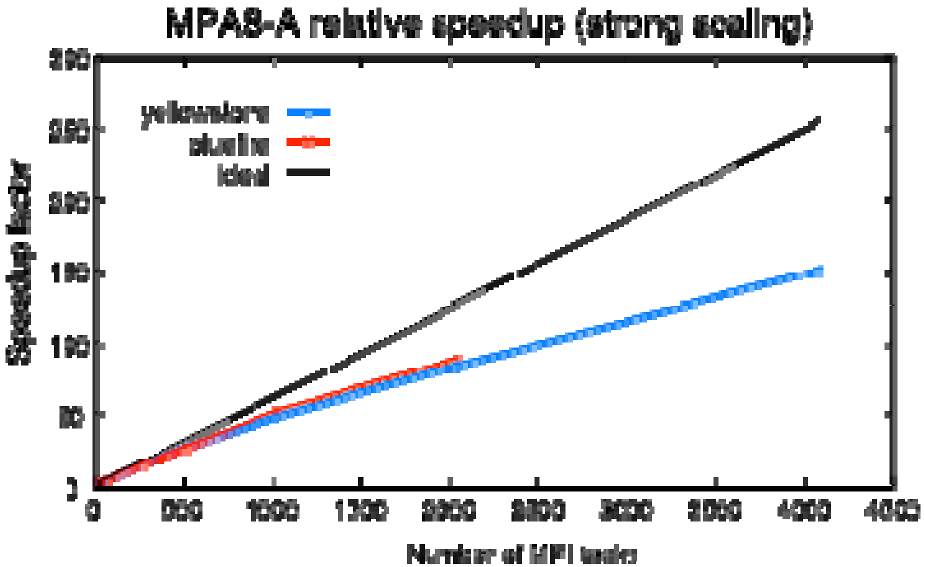
Block plus two layers of halo/ghost cells

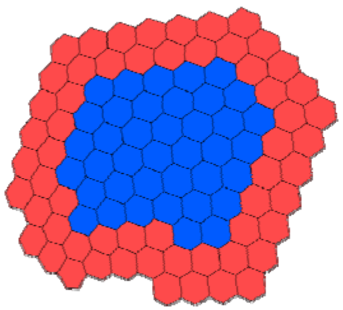
Processors	Cells Per Proc	Speed Up	Efficiency	SYPD
192	9626	1.00	100.00%	0.19
384	4813	2.19	109.58%	0.43
768	2406	4.32	107.94%	0.85
1536	1203	8.34	104.26%	1.64
3072	602	16.00	106.62%	3.35
6144	301	28.71	89.71%	5.63
12288	150	41.16	64.32%	8.11
14400	128	25.51	34.02%	5.02
16800	110	34.03	38.89%	6.70

MPAS
Model for Prediction Across Scales

MPAS-Atmosphere scaling

60 km global mesh
(163,842 horizontal cells).
6 hour simulation
40 vertical levels.
8 scalars with FCT.
Full physics





Block plus two layers of halo/ghost cells

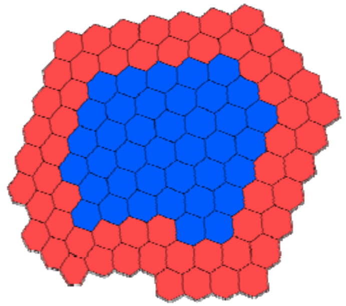
Yellowstone results

MPI tasks	Cells per task	Speedup	Efficiency
16	10240	1.00	100.00%
32	5120	1.97	98.40%
64	2560	3.90	97.49%
128	1280	7.67	95.88%
256	640	14.65	91.57%
512	320	27.56	86.12%
1024	160	48.49	75.77%
2048	80	85.21	66.57%
4096	40	151.43	59.15%

MPAS optimizations

Communication optimizations to be implemented:
- Aggregation of same-stencil halo communications
- Overlap computation and communication
- Switch to one-sided communication?

Computation optimizations to be implemented:
- Tighter loop bounds to minimize redundant computation

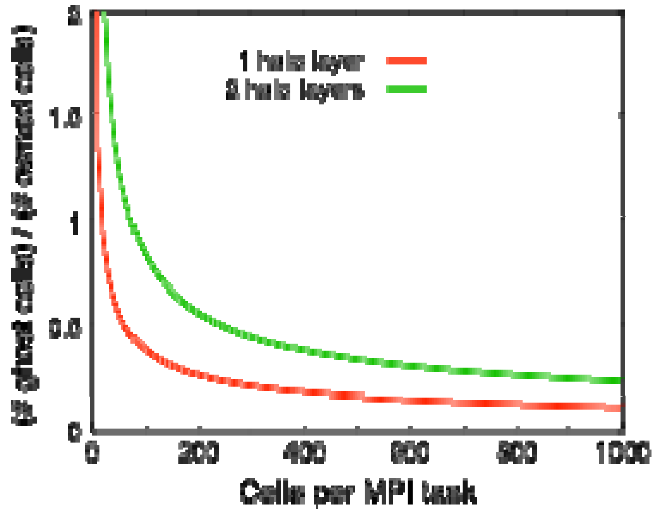


Block plus two layers of halo/ghost cells

SMP plans: (1) Multiple blocks per MPI task, (2) loop-level parallelism.

For 2 halo layers, the number of ghost (halo) cells, N_G, is approximately related to the number of owned cells, N_O, by

$$N_g = \pi \left(\sqrt{\frac{N_o}{\pi}} + 2 \right)^2 - N_o$$



Summary

- MPAS-Ocean and MPAS-Atmosphere (nonhydrostatic) are being tested using full-physics NWP and climate tests.
- Variable-resolution capabilities of the MPAS solvers shows some promise for NWP, regional climate and climate applications.
- Initial MPI implementations of MPAS-O/A are showing efficiencies and parallel scaling similar to other NWP and ocean models.
- Much optimization work remains; we are considering some solver design changes to accommodate accelerators.
- MPAS-A: Our use of variable-resolution meshes is leading us to consider scale-awareness issues in our physics.
- Release of MPAS-O and MPAS-A is scheduled for early June 2013.

Further information:
MPAS-O: http://public.lanl.gov/ringler/files/multiResolutionOceanR1.pdf
MPAS-A: http://www.mmm.ucar.edu/people/skamarock/mpas_mwr_2012_final.pdf
MPAS: http://mpas.sourceforge.net/ (to be updated soon)

MPAS
Model for Prediction Across Scales

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-explicit 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:

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

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