Variable-Resolution Global Atmospheric Models: Where are the Applications?

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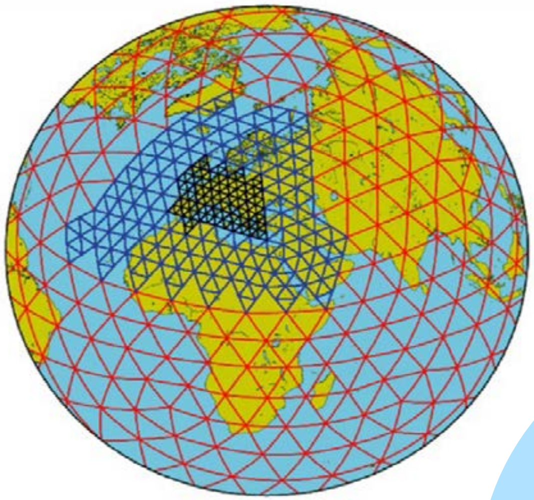
Mesoscale and Microscale Meteorology Laboratory

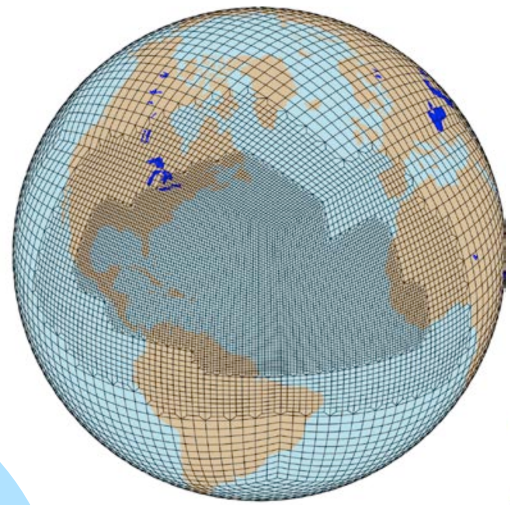
Examples of Variable-Resolution Models

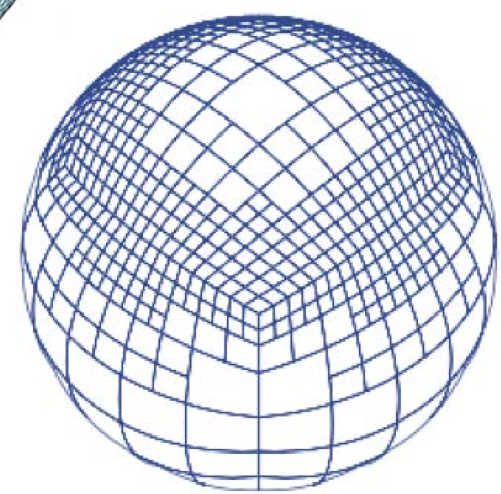
ICON
(ICOsahedral Non-hydrostatic)
Model



MPAS
Model for Prediction Across Scales

CESM/CAM (and ACME)
Spectral Element dynamical core.



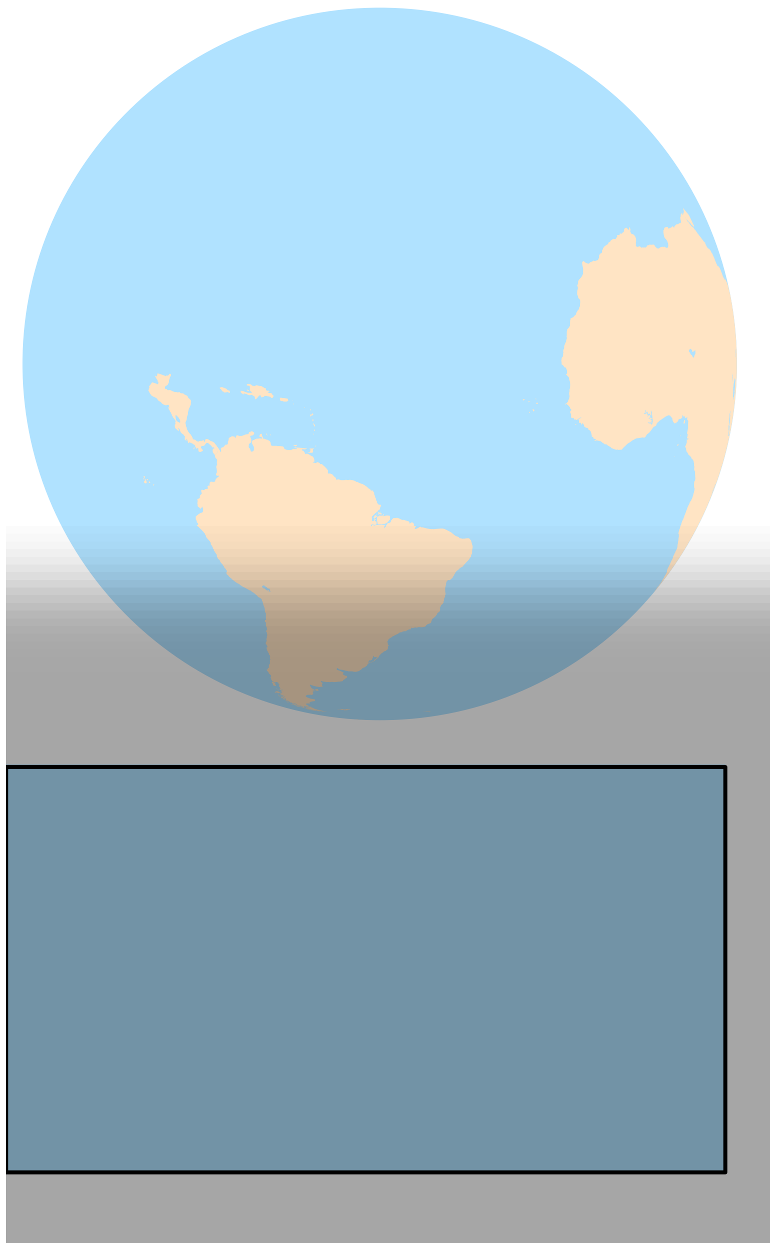


NUMA (Non-hydrostatic Unified
Model of the Atmosphere).
Basis of NEPTUNE.

MPAS
Model for Prediction Across Scales

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

MPAS-Atmosphere - nonhydrostatic



Variable-Resolution Models

What problems associated with traditional 1-way and 2-way nesting are the new variable-resolution solvers trying to address?

Wave reflection and refraction.

- Noise at nest boundaries.
- Solutions: sponge layers

Downscaling (1-way nesting issue).

- Divergence from driving analysis.
- Solutions: spectral nudging, etc.

Upscaling (1- and 2-way nesting issue).

- Upscaling is absent from 1-way nested solutions.
- Can we trust upscaled solutions from traditional 2-way nested models?

Small-scale spin-up question.

- Newly resolved small scales take time to spin-up in the flow.

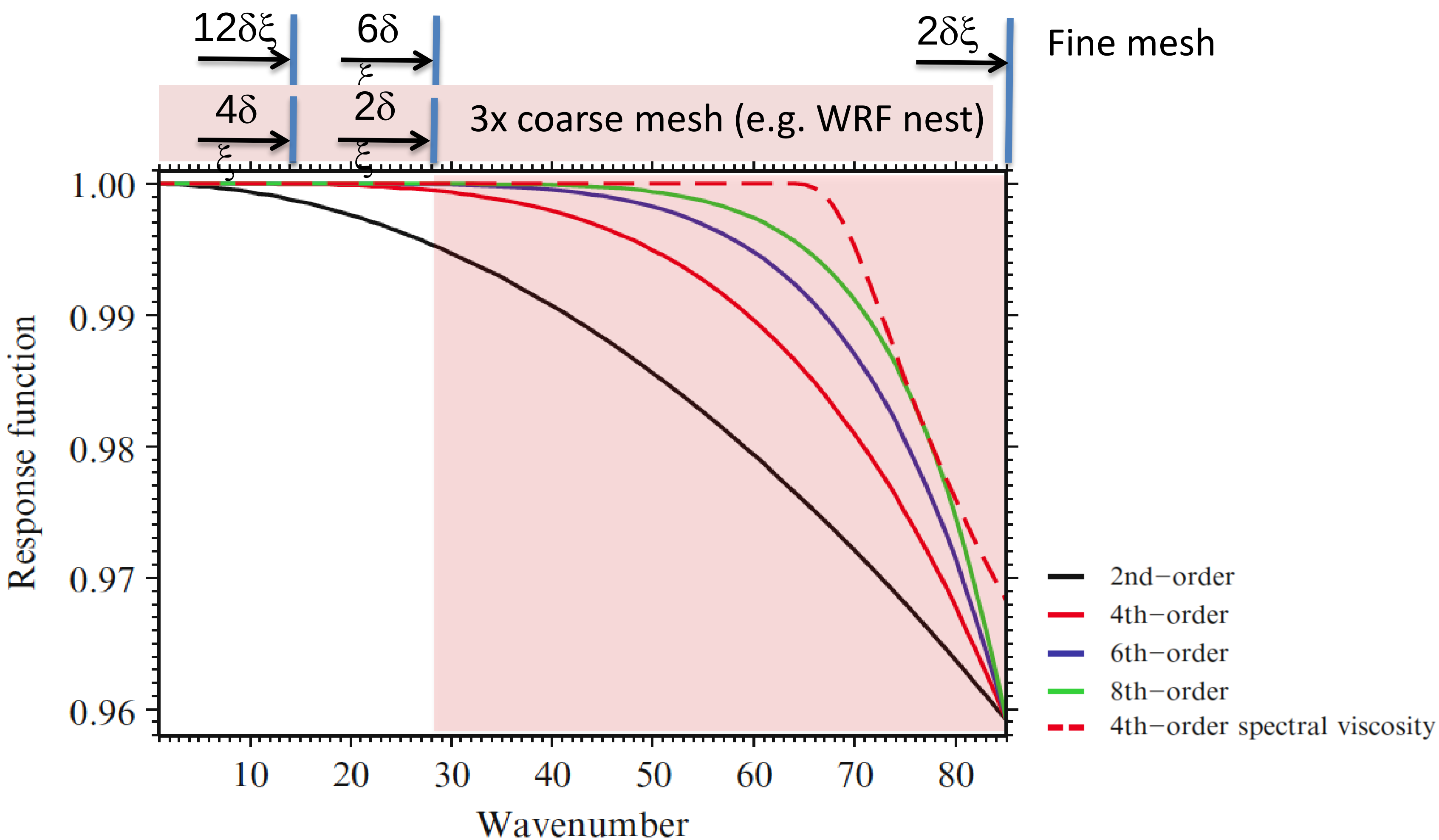
Sub-grid/filter-scale physics.

- Physics must work everywhere, even in the mesh transition regions.

Variable Resolution Meshes

Variable Resolution Meshes

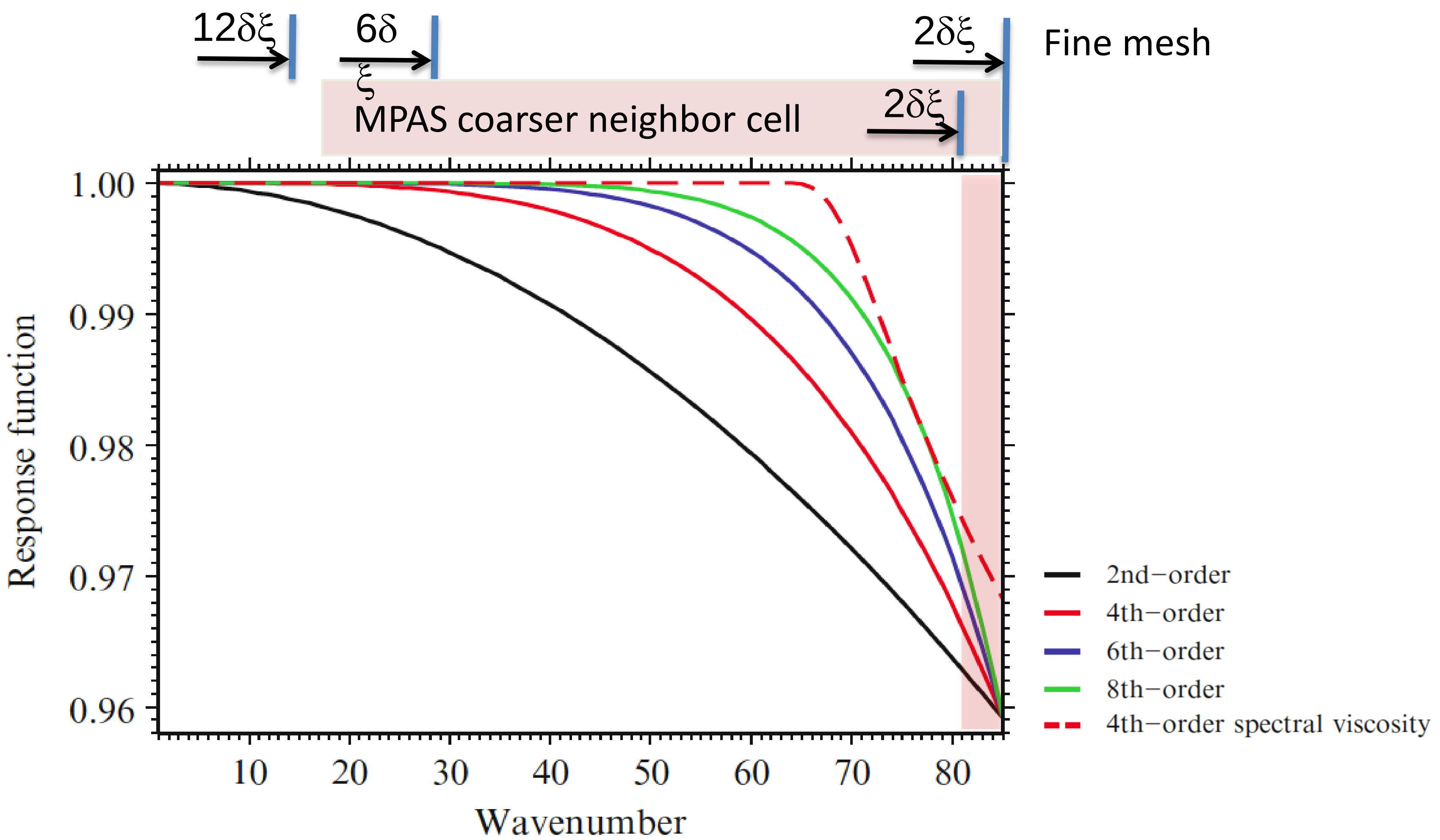
Fine mesh filter response per time step



Variable Resolution Meshes

MPAS
Model for Prediction Across Scales

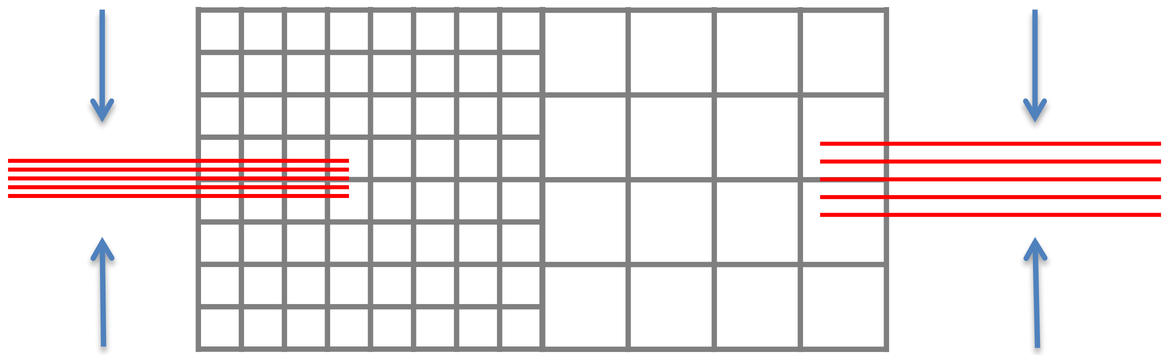
Fine mesh filter response per time step



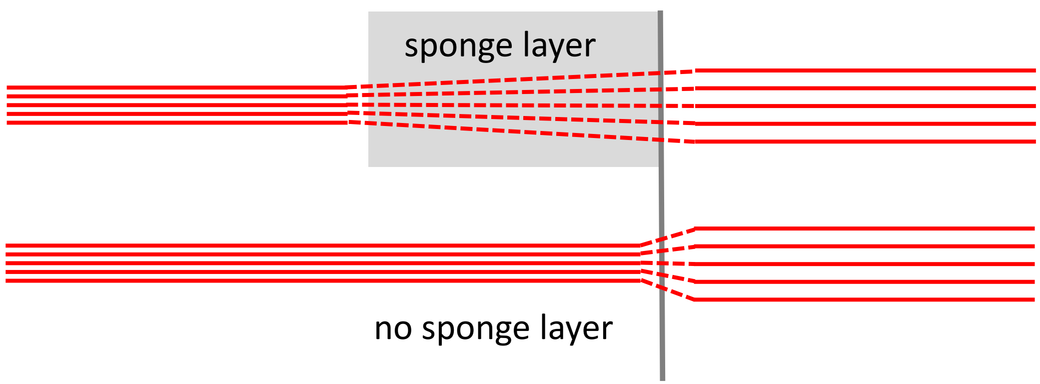
Variable-Resolution Models

What happens to grid-scale structures at mesh-refinement boundaries?

Consider a deformational flow creating a front collapsed to the grid scale



How does the front adjust to the change in grid spacing?



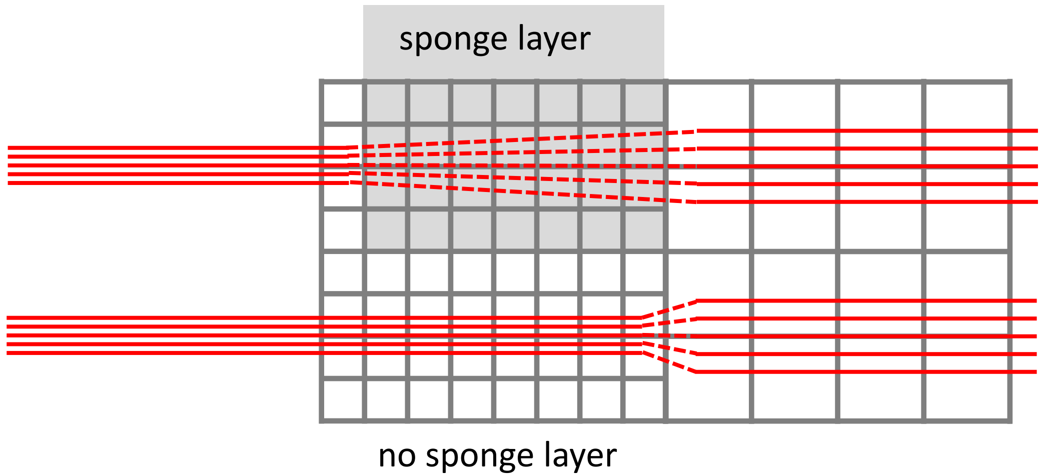
Is this a problem?

Variable-Resolution Models

What happens to grid-scale structures at mesh-refinement boundaries?

(1)

(2)



Is this a problem?

For fixed refinement – likely yes in the case of (2), perhaps problems we can live with in the case of (1).

Question: will sponge layers be needed in solver formulations that employ stepwise refinement (i.e. cell division) in static-refinement applications?

Variable-Resolution Models

How should model filters (stabilization) work on variable-resolution meshes?

$$\frac{\partial \phi}{\partial t} = \cdots + \nu_4 \nabla^4 \phi$$

$$\nu_4 = c_o (\Delta x)^q$$

q = 3.2 Boville (1991, JCli)
Takahashi et al (2006, Geophys. Res. Letters)
CAM-SE, uniform mesh

q = 3.322 CAM-SE, var-res: Zarzycki et al, several papers in 2014

"Diffusion is scaled such that the hyperviscosity coefficient in each region matches the default CAM-SE hyperviscosity for the uniform grid of that resolution (Levy et al. 2013 – DOE tech report)"

q = 3 MPAS, var-res, similar logic to *Levy et al (2013)*

None of these are based on theory

Variable-Resolution Models

How should model filters (stabilization) work on variable-resolution meshes?

$$\frac{\partial \phi}{\partial t} = \cdots + \nu_4 \nabla^4 \phi$$

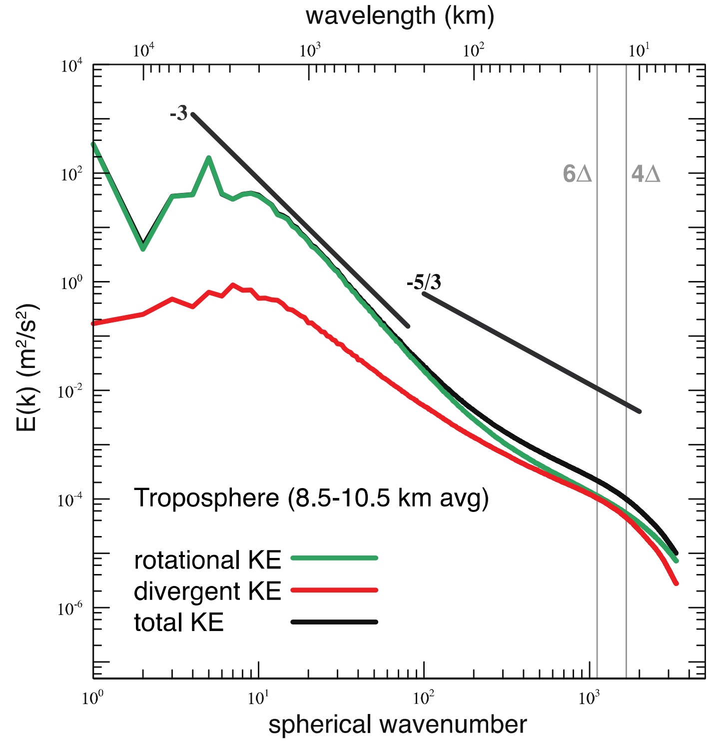
$$\nu_4 = c_o (\Delta x)^q$$

Why are there different values of *q*?

MPAS: if dt/dx = constant, then $q = 3$ gives the same damping rate for 2 dx waves per timestep.

$q = 3.2$ is tuned for large-scale flow regimes ($E(k) \sim k^{-3}$), MPAS is informed by meso- and cloud-scale regimes ($E(k) \sim k^{-5/3}$).

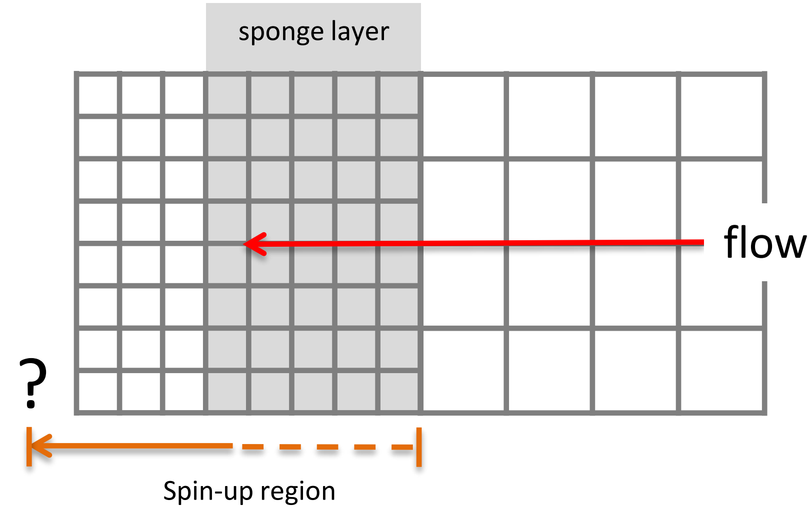
MPAS 3 km global spectrum



Variable-Resolution Models

<u>The spin-up problem – more than just resolved and SGS turbulence</u>

For example, how does a *scale-aware convective parameterization* know that it may need to handle deep convection in the sponge and spin-up regions? Can we even define or diagnose the spin-up region?



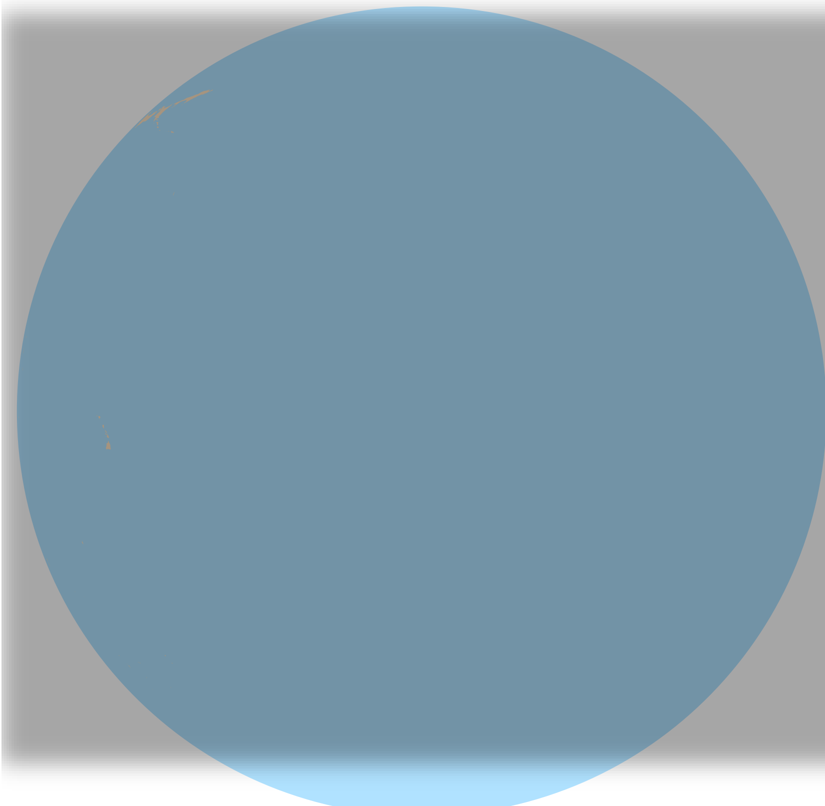
Mesoscale modeling experience with nesting, e.g. WRF:

(1) Ignore the parameterization questions.
(2) Sponge-layer width based on experience.
(3) The bigger the nest the better, i.e. put the nest boundaries as far as possible from region of interest.

MPAS experience and philosophy:

(1) Need scale-aware parameterizations, with scale defined by local cell spacing.
(2) Gradual mesh transition allows spin-up to happen naturally. *However, we have not developed a theory for mesh transition characteristics based on any model of the spin-up.*

Variable-Resolution Models

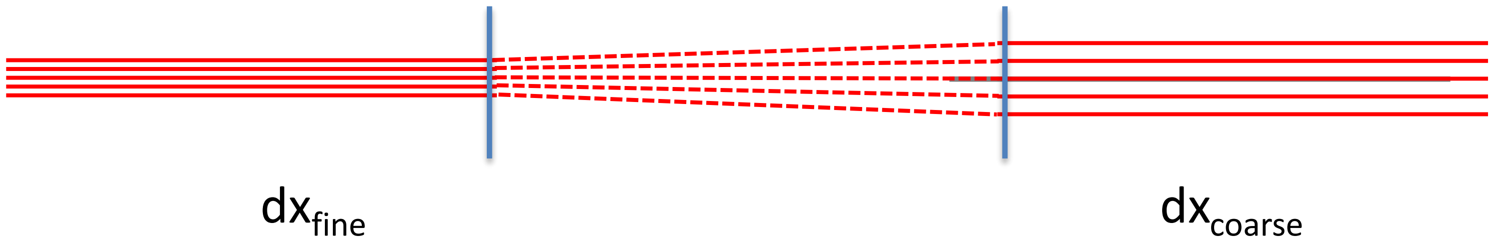


3-15 km mesh, δx contours 4, 6, 8, 10, 12, 14 km
approximately 6.49 million cells (horz.)
50% have < 4 km spacing
(194 pentagons, 182 septagons)

Mesh transition example:
How gradual is our gradual mesh transition in practice?

Variable-Resolution Models

MPAS?

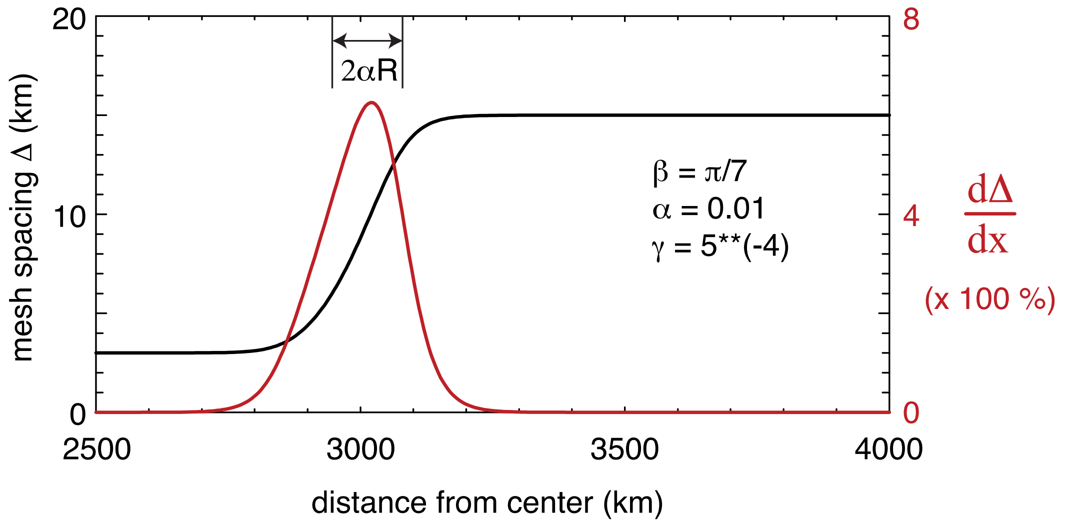


Voronoi mesh generated using Lloyd's method. One of our mesh generation density functions:

$$\rho = \frac{1-\gamma}{2}\left[\tanh\left(\frac{\beta - x}{\alpha}\right) + 1\right] + \gamma$$

$$\Delta(x) = \Delta_o\,\rho^{-1/4}$$

The MPAS mesh transition is typically very gradual.

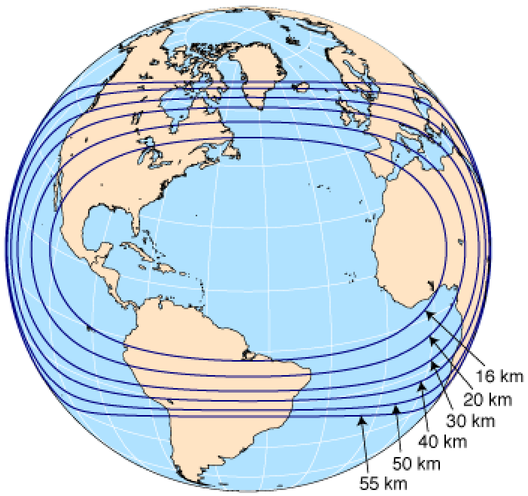


MPAS

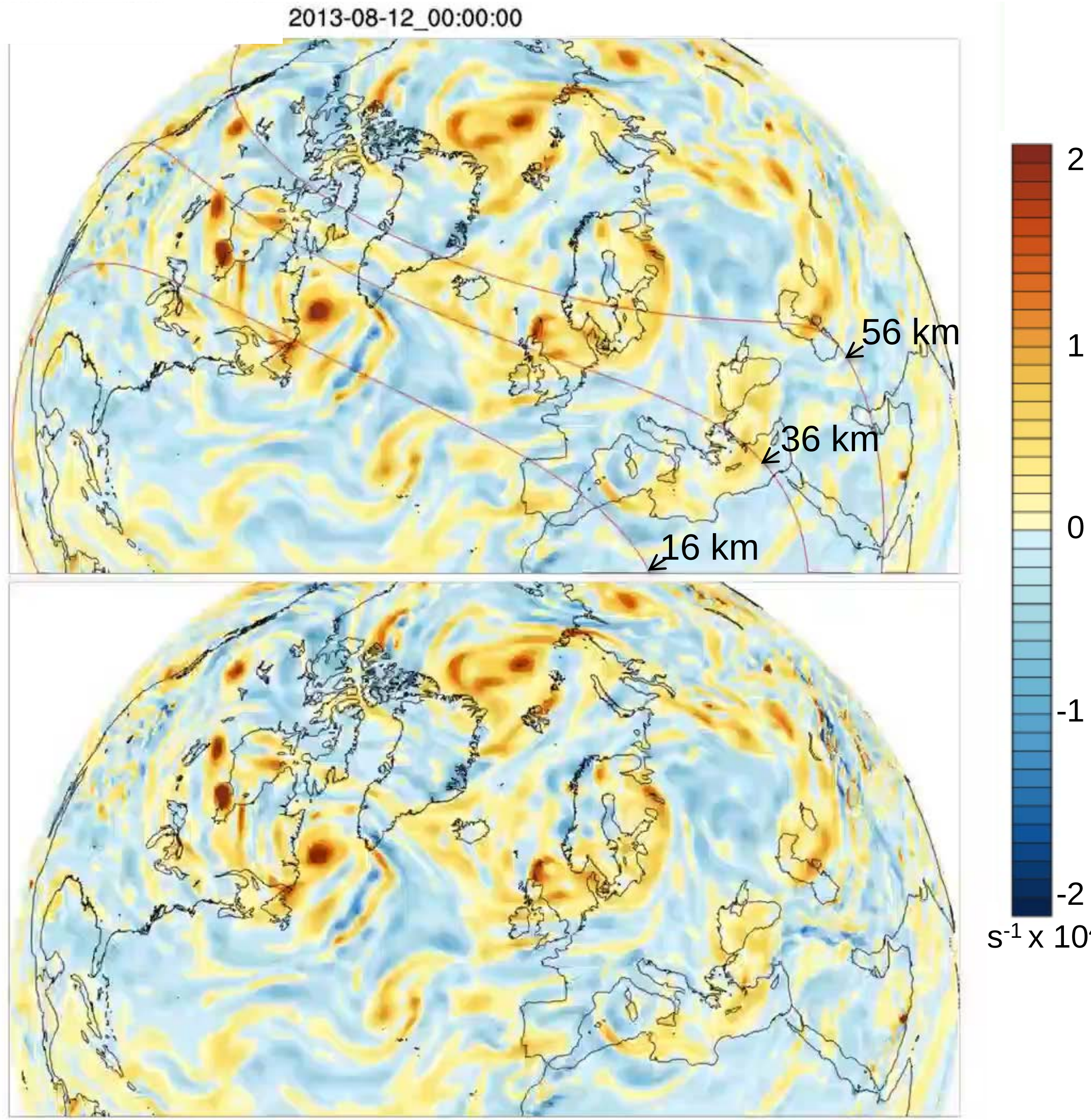
Model for Prediction Across Scales

10-day 500 hPa Relative Vorticity Forecast

15-60 km variable resolution mesh



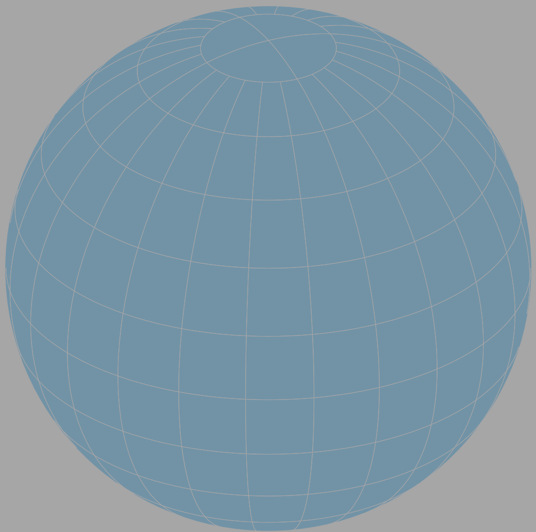
15 km uniform resolution mesh



MPAS Physics:

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

MPAS TC Forecasts for 2016 Western Pacific



MPAS
Model for Prediction Across Scales

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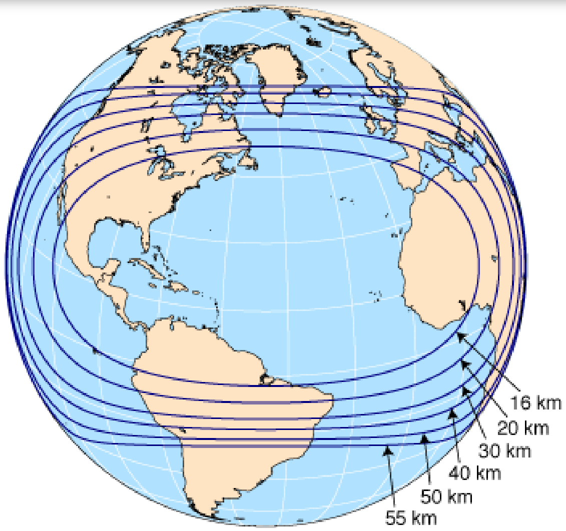


Numerics

- Model top ~ 30 km
- Model levels ~ 55 levels
- Mesh size ~ 535554 cells

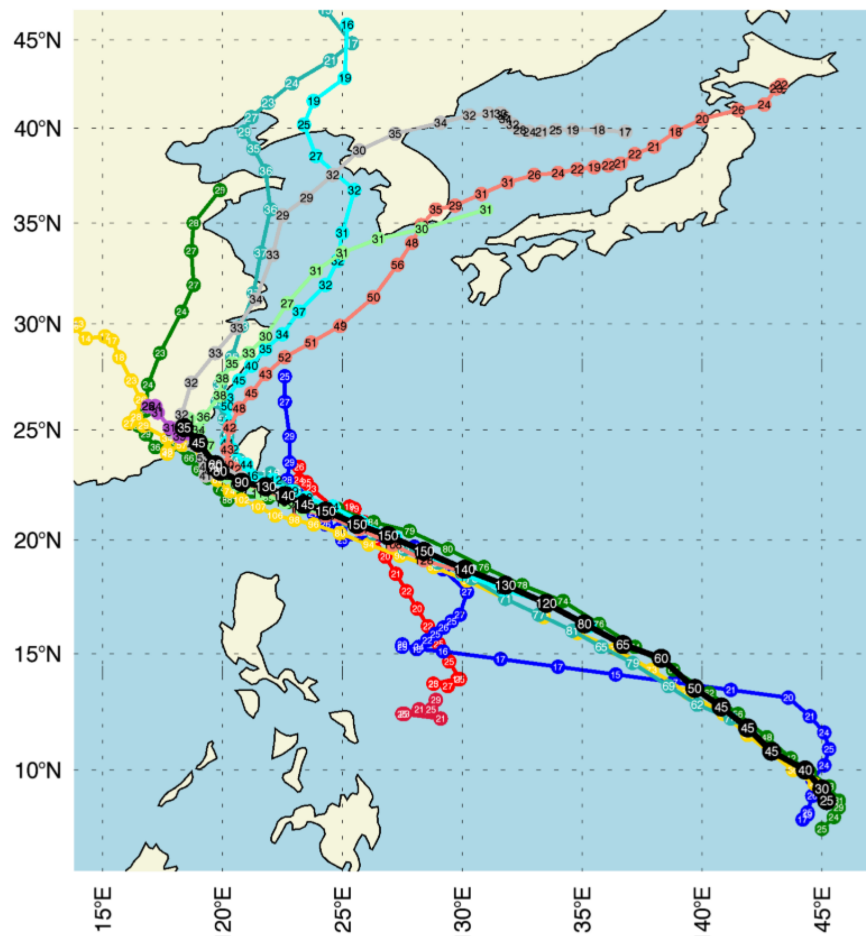
(NOTE :: uniform 15km mesh size ~ 2621442)

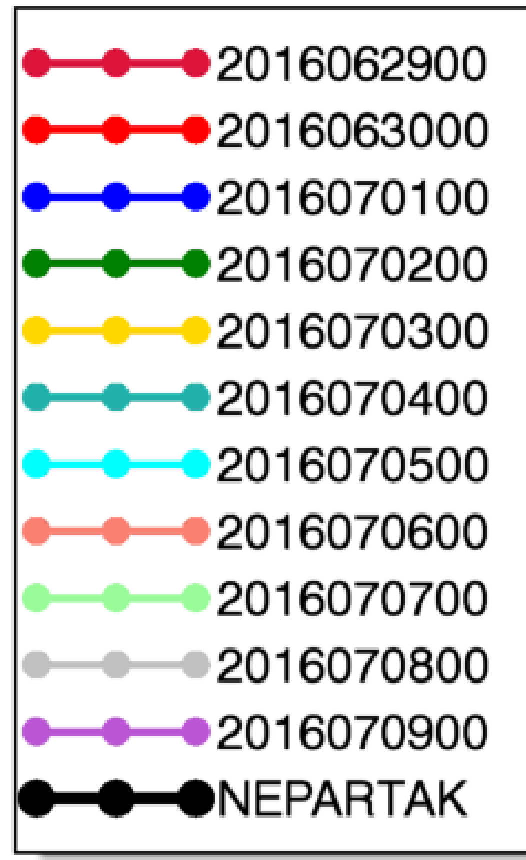
Physics

- Surface Layer : Monin-Obukov
- PBL : YSU
- Land Surface Model : NOAH 4-layers
- Gravity Wave Drag : *YSU GWD scheme*
- Convection : *nTiedtke*
- Microphysics : WSM6
- Radiation : RRTMG
- Ocean Mixed Layer (modified from WRFV3.6)

MPAS TC Forecasts for 2016 Western Pacific

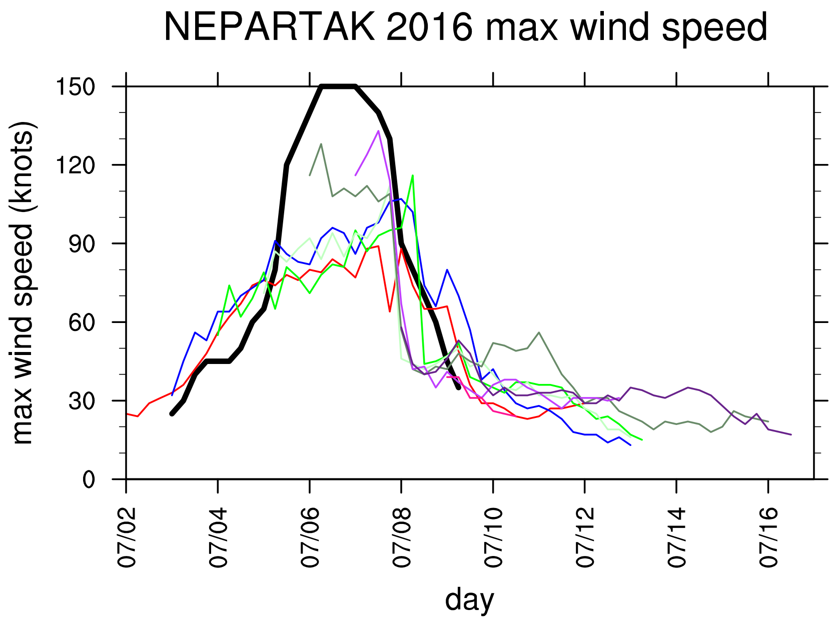
wp022016 NEPARTAK tracks from wp

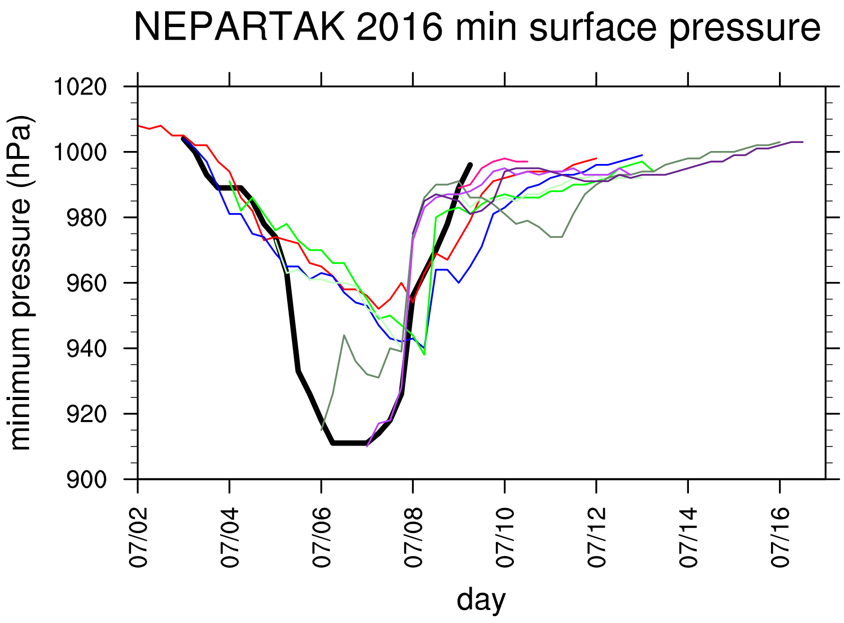




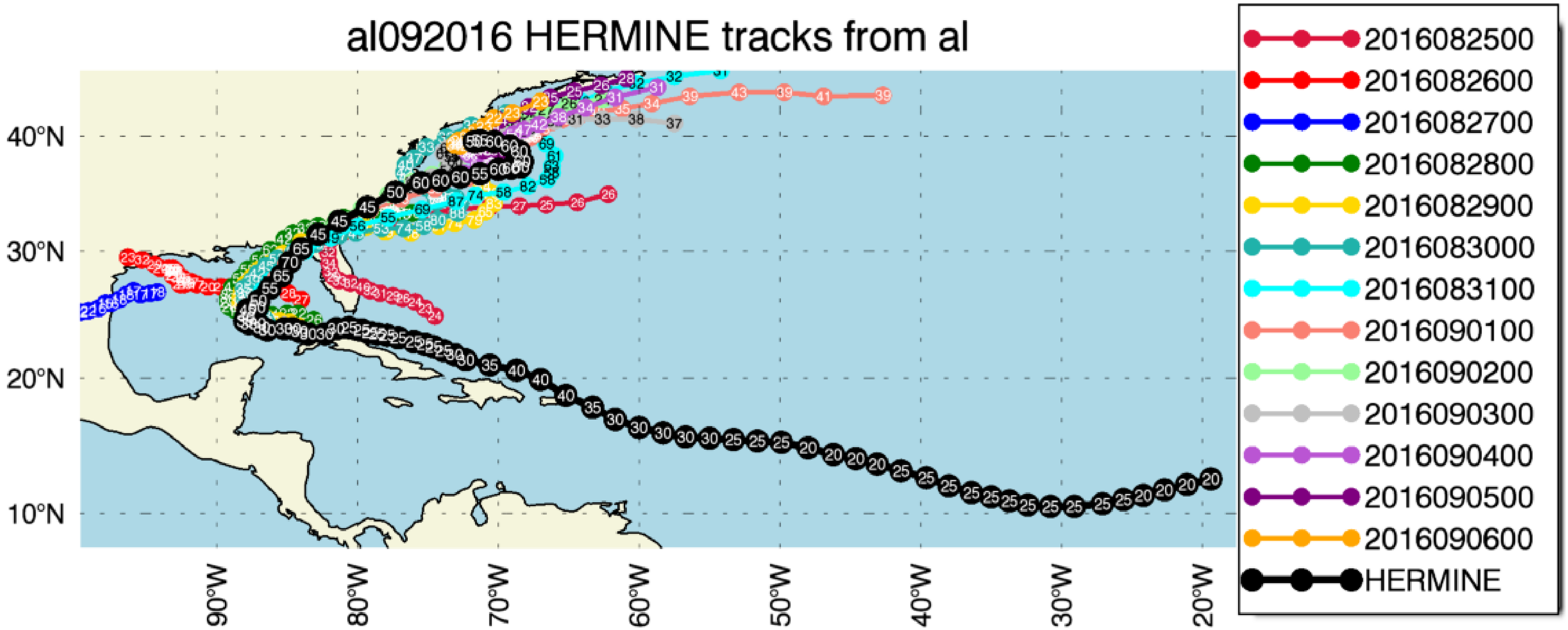
Landfall 2230 UTC 7 July

MPAS TC Forecasts for 2016 Western Pacific

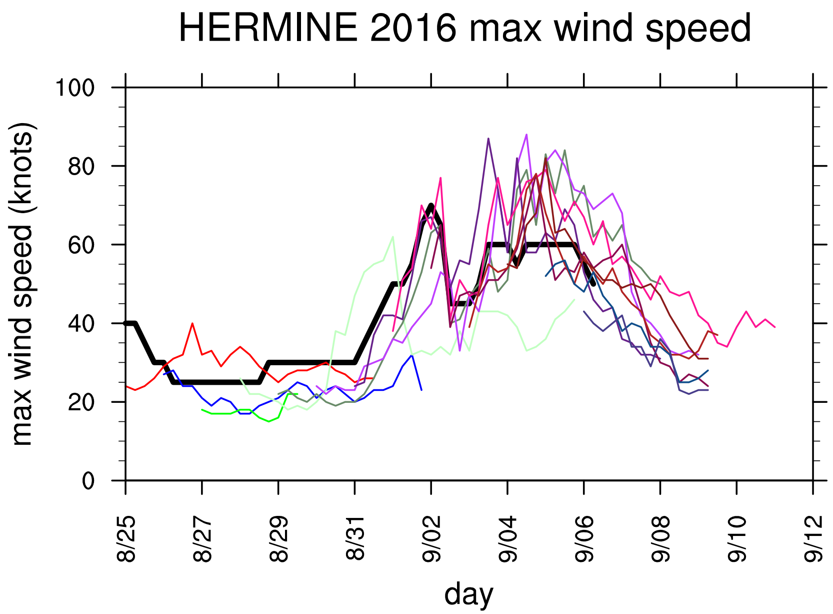


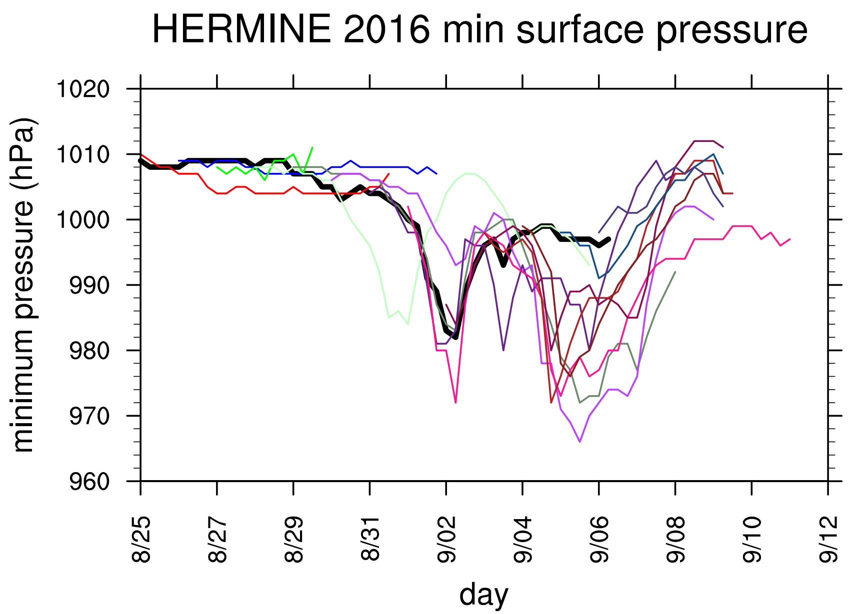


MPAS TC Forecasts for 2016 Atlantic

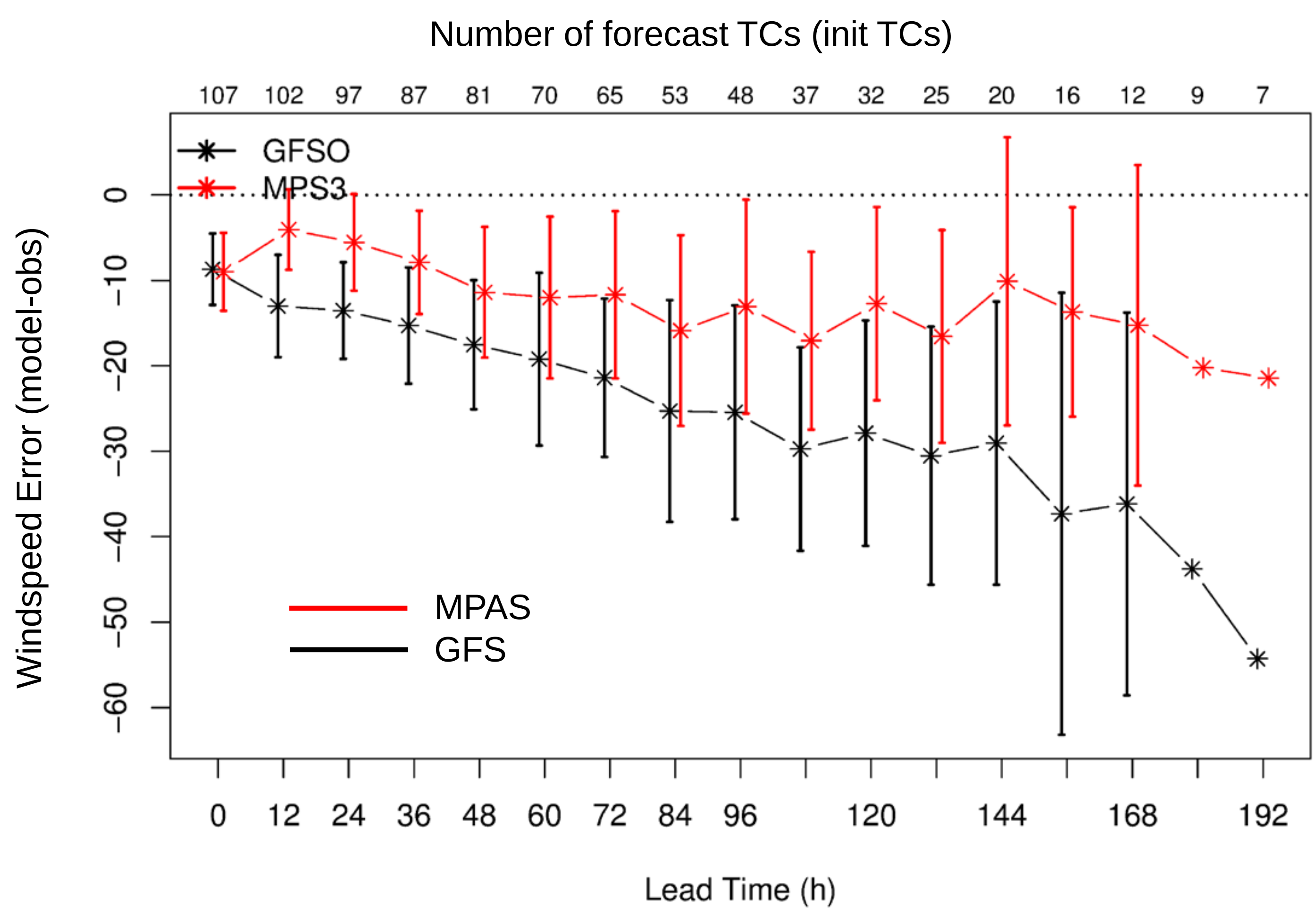


MPAS TC Forecasts for 2016 Atlantic





MPAS TC Forecasts for 2016 Western Pacific



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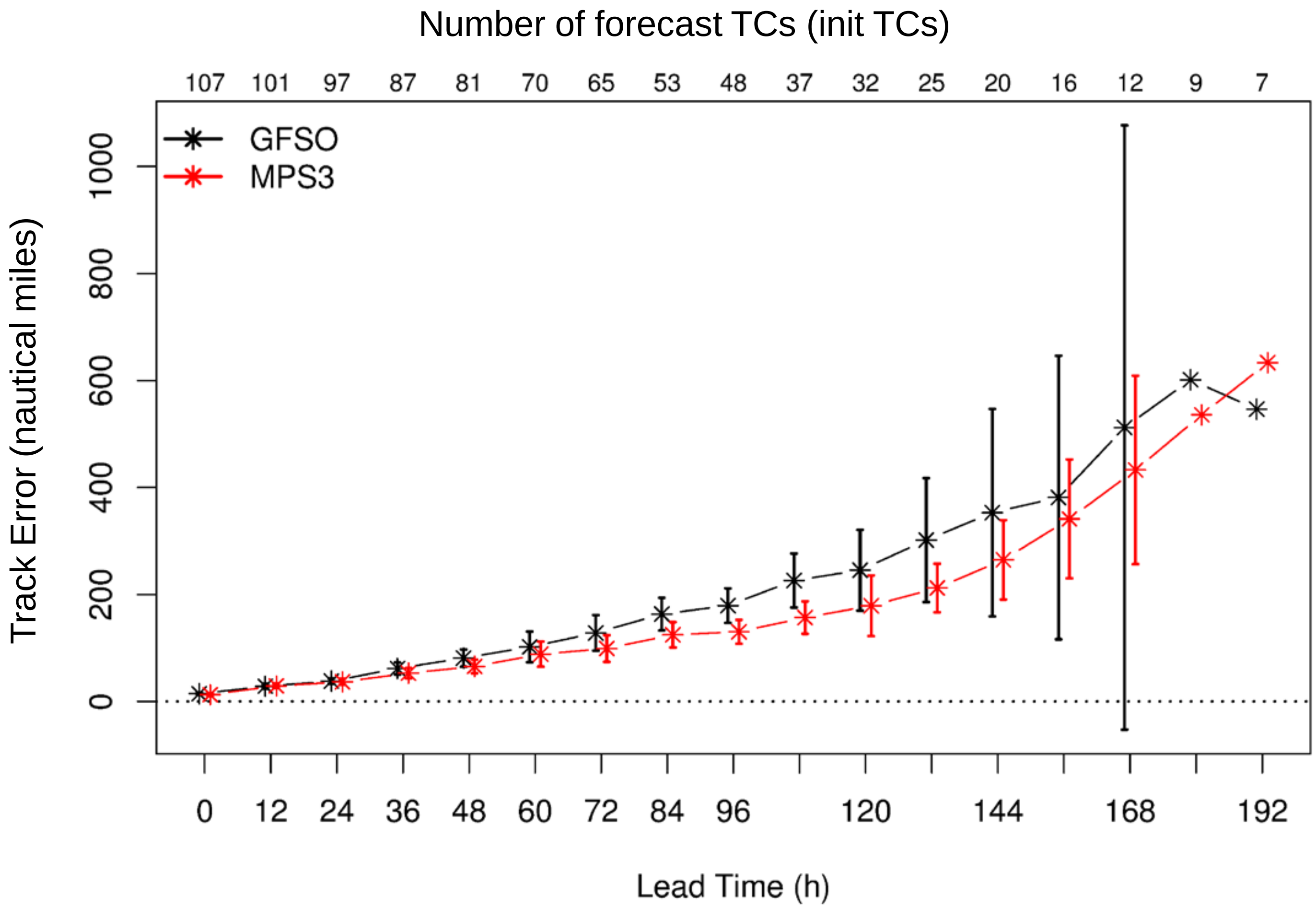
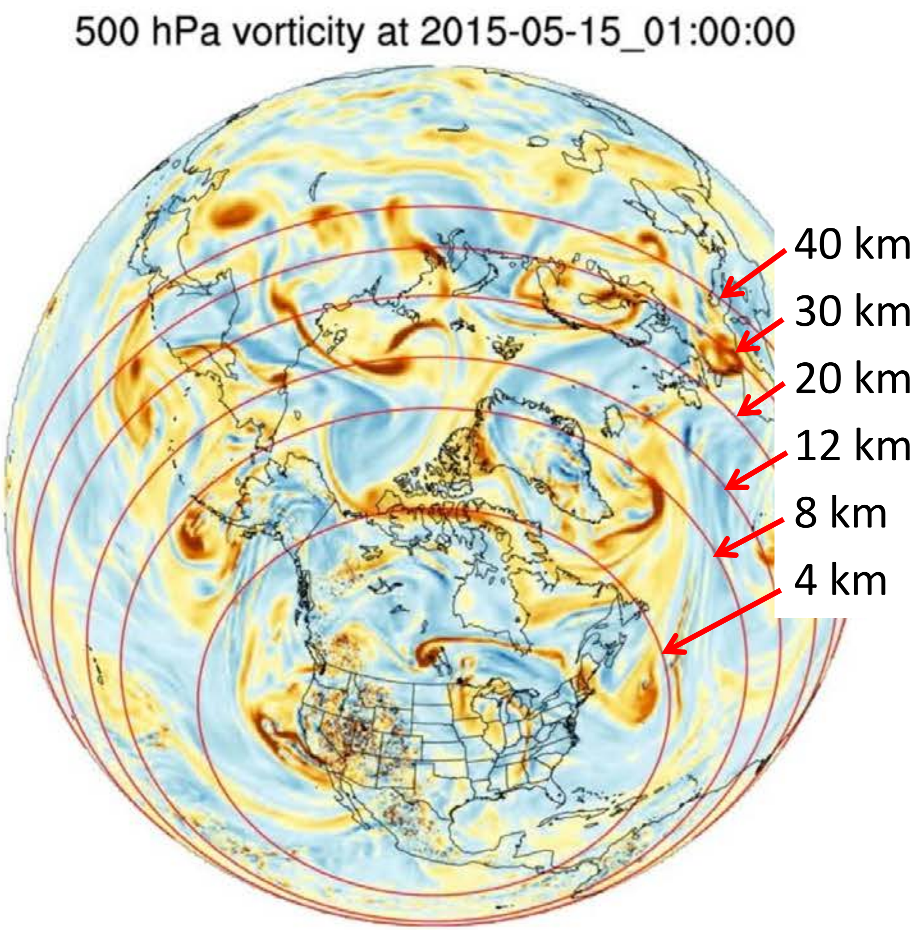
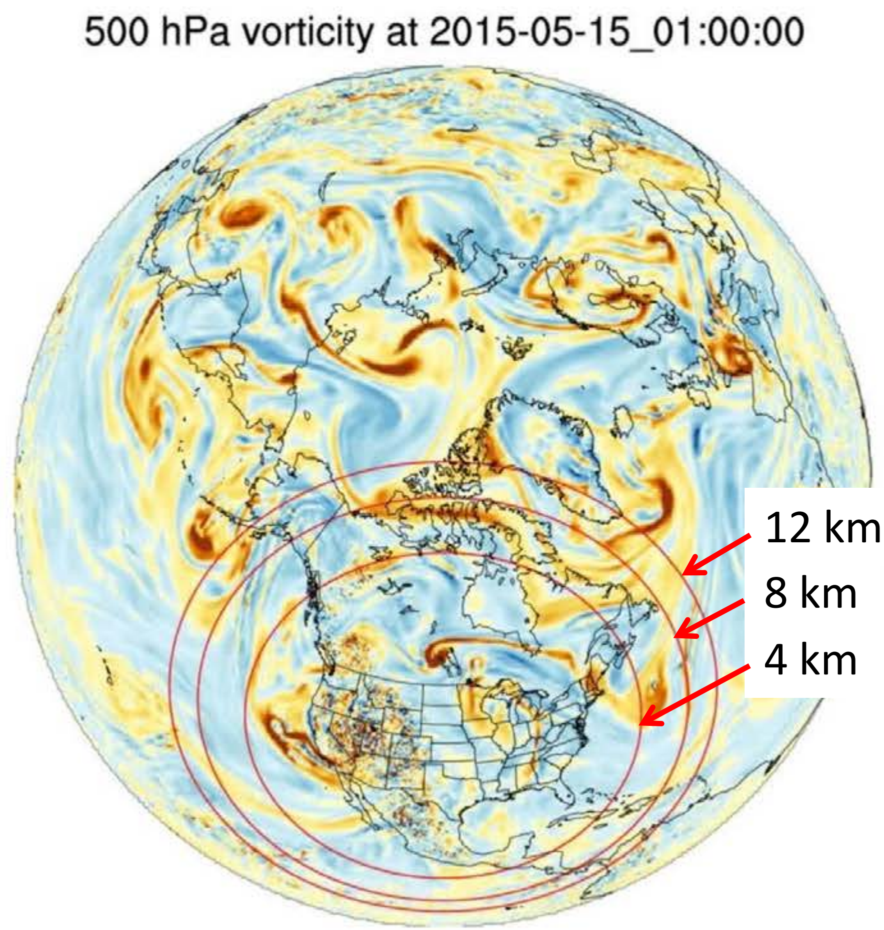


MPAS
Model for Prediction Across Scales

Variable Resolution Tests Forecast

0 UTC 15 May – 0 UTC 20 May 2015

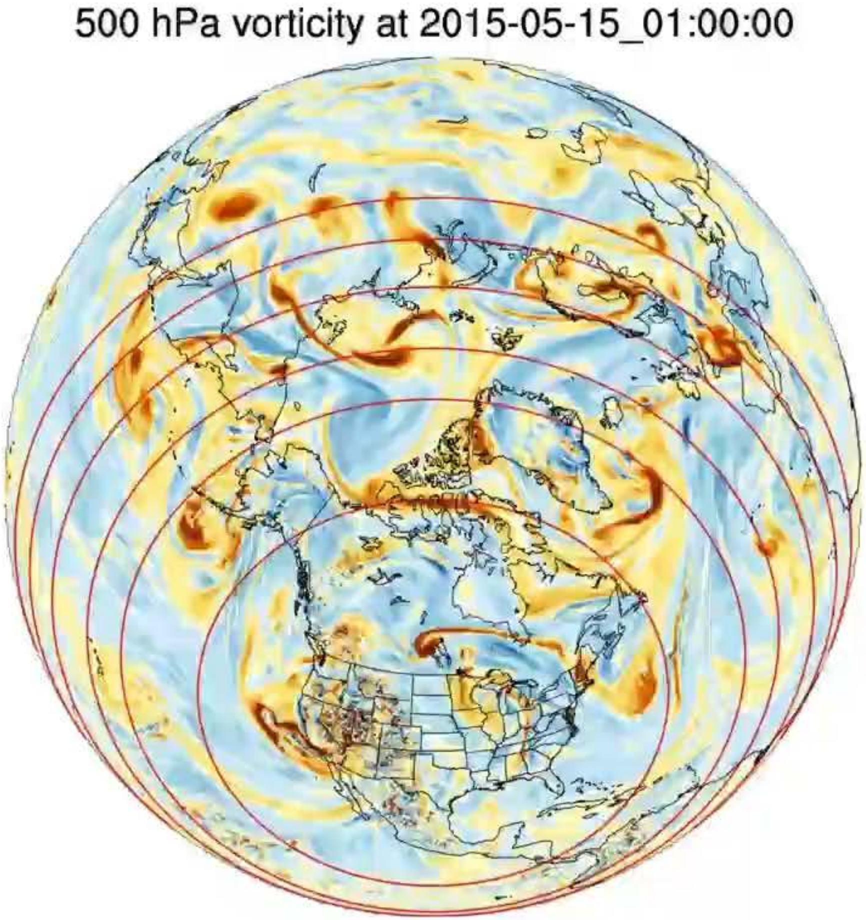


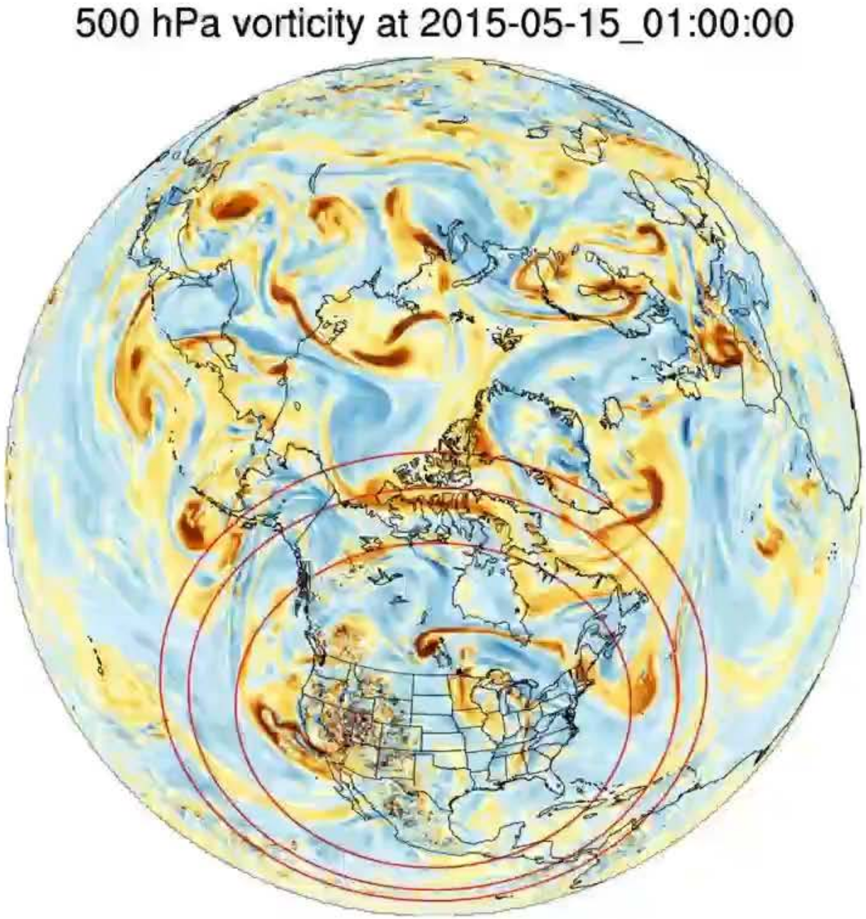


MPAS
Model for Prediction Across Scales

Variable Resolution Tests Forecast

5-day forecasts valid 0 UTC 20 May 2015





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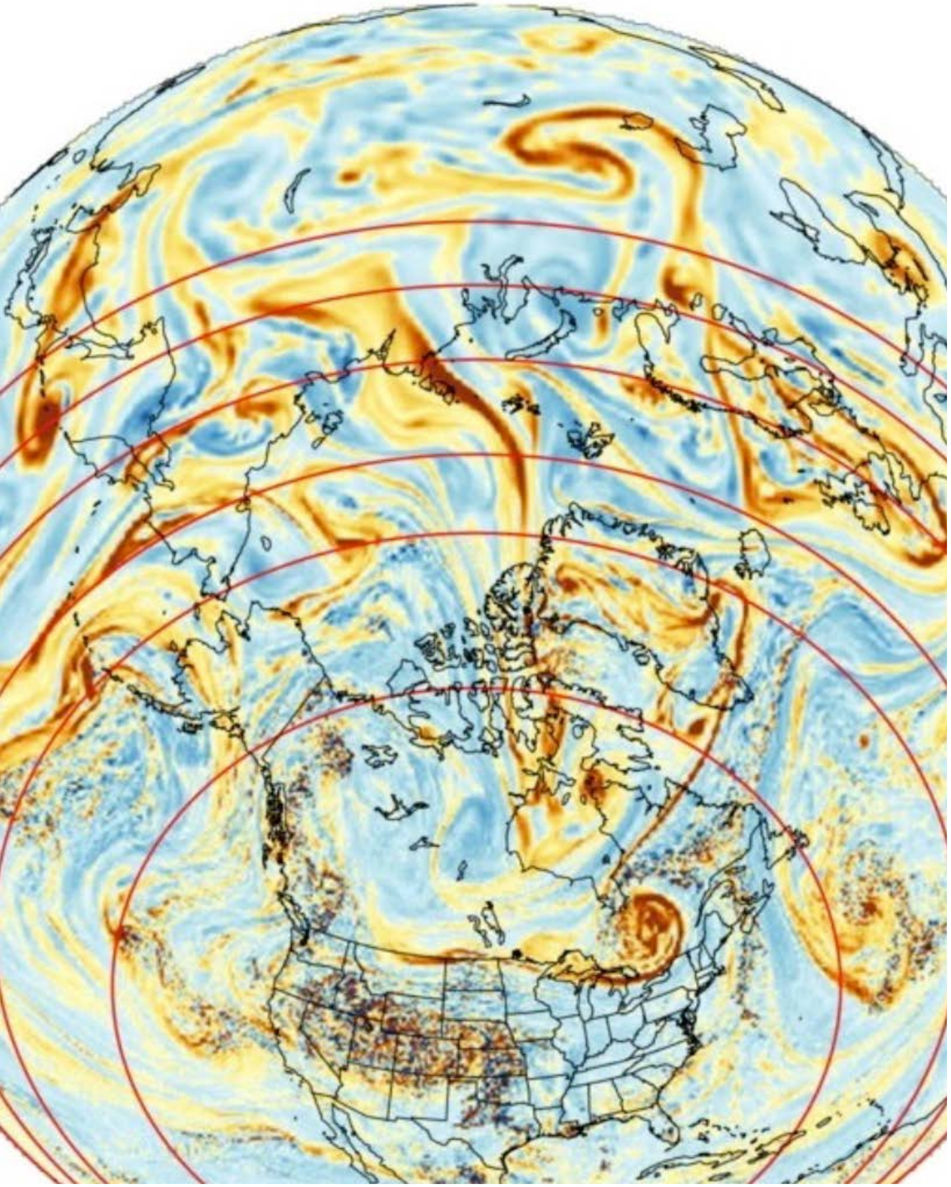
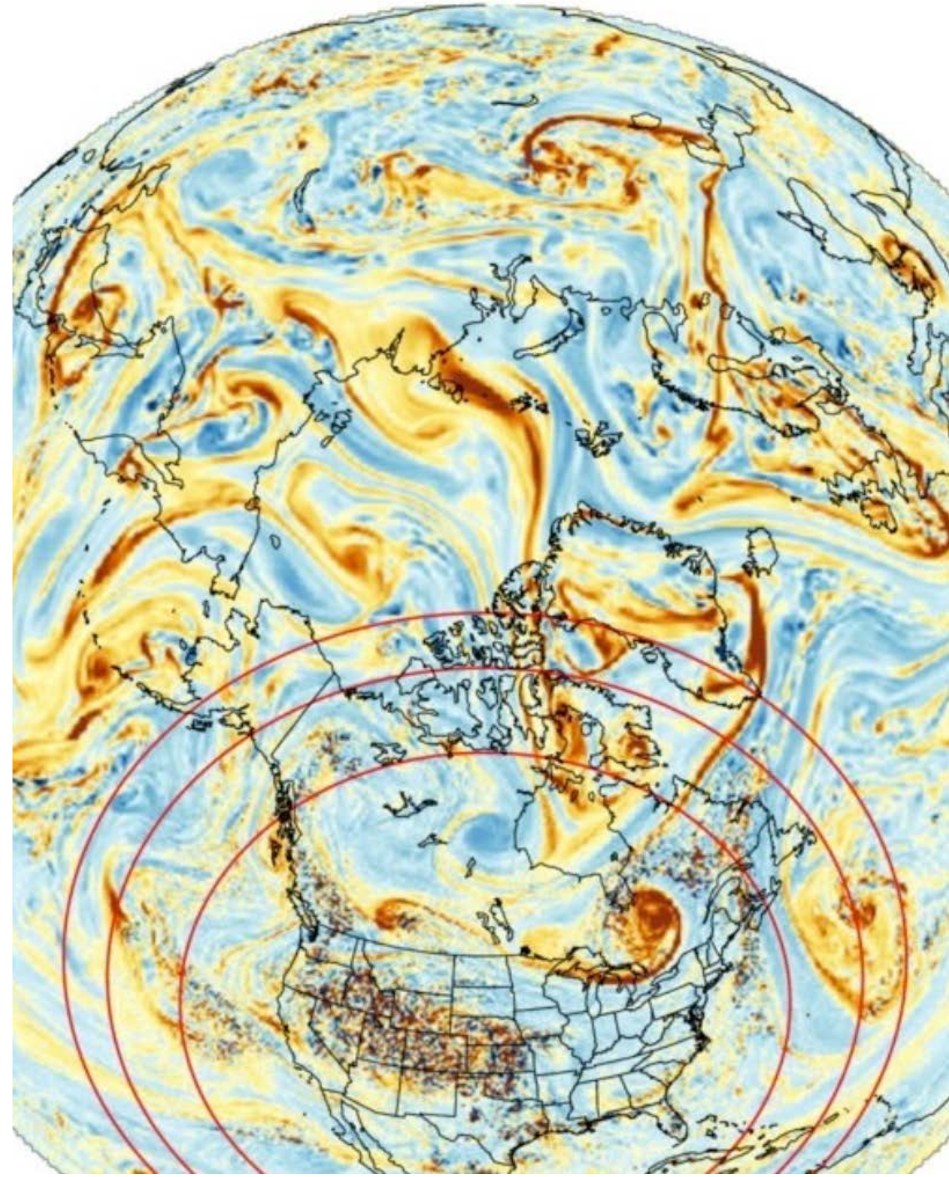
Model for Prediction Across Scales

Variable Resolution Tests Forecast

5-day forecasts valid 0 UTC 20 May 2015





MPAS
Model for Prediction Across Scales

Hazardous Weather Testbed
Spring Experiment 2015, 2016
Forecasts Results from MPAS

Application Test
NOAA SPC/NSSL HWT
May 2015, May 2016
Convective Forecast Experiment
Daily 5-day MPAS forecasts
00 UTC GFS analysis initialization

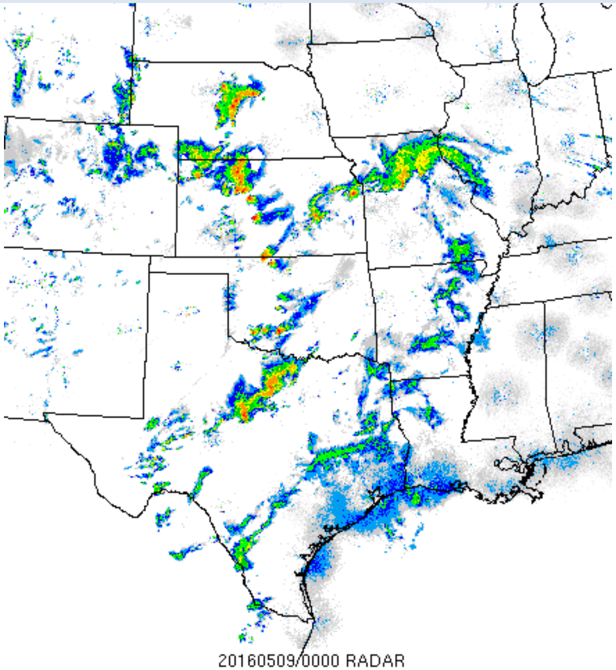
MPAS Physics:

- *WSM6 cloud microphysics (2015)*
- *Thompson microphysics (2016)*
- Grell-Freitas convection scheme (scale-aware)
- Monin-Obukhov surface layer
- MYNN PBL
- Noah land-surface
- RRTMG lw and sw.

MPAS 2016 mesh

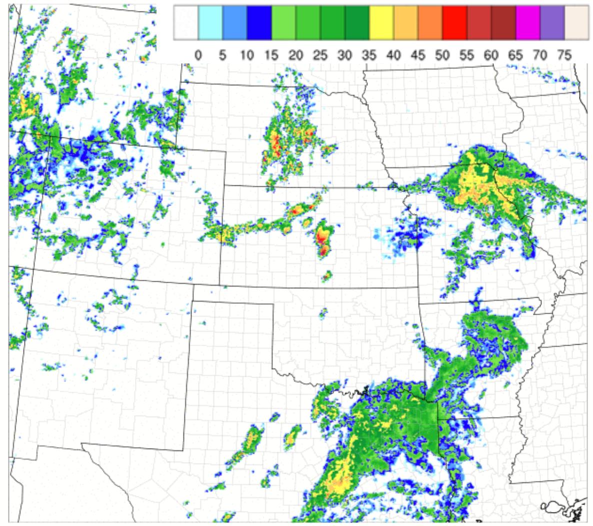
3-15 km mesh, δx contours 4, 6, 8, 10, 12, 14 km
approximately 6.49 million cells (horz.)
50% have < 4 km spacing
(194 pentagons, 182 septagons)

NOAA/SPC composite, 00 UTC 9 May 2016

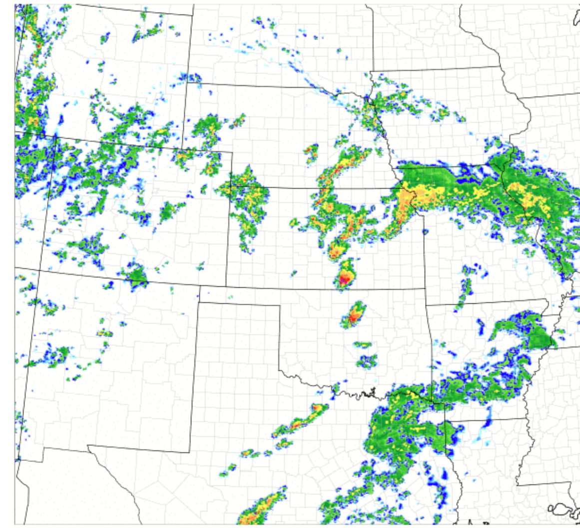


MPAS 1 km AGL Reflectivity

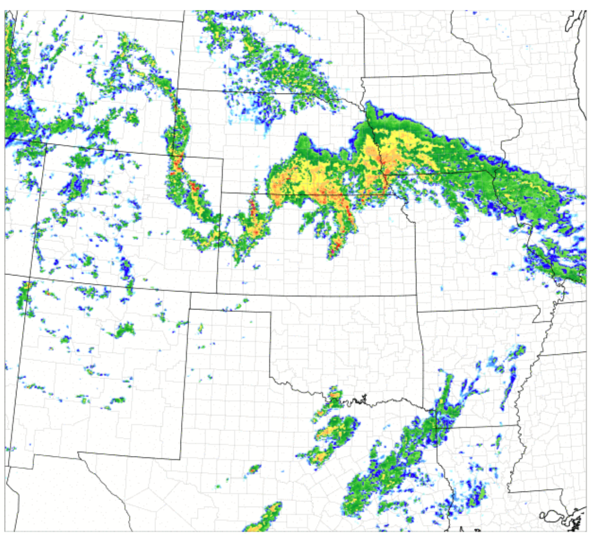
MPAS 24h forecast



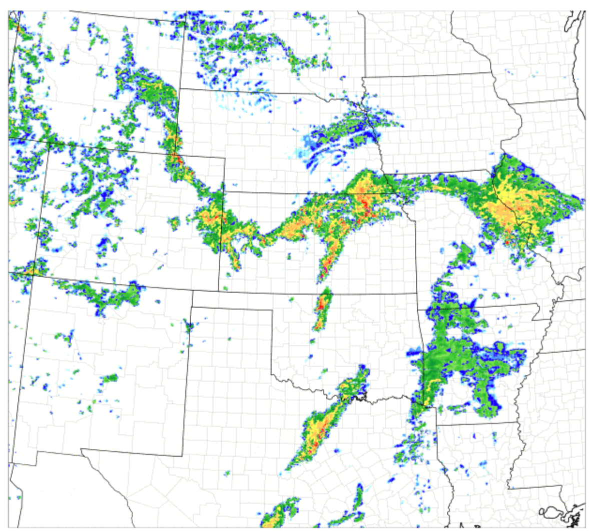
MPAS 48h forecast



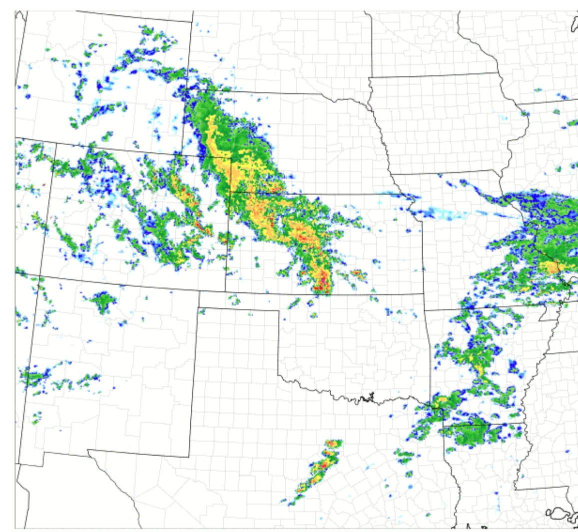
MPAS 72h forecast



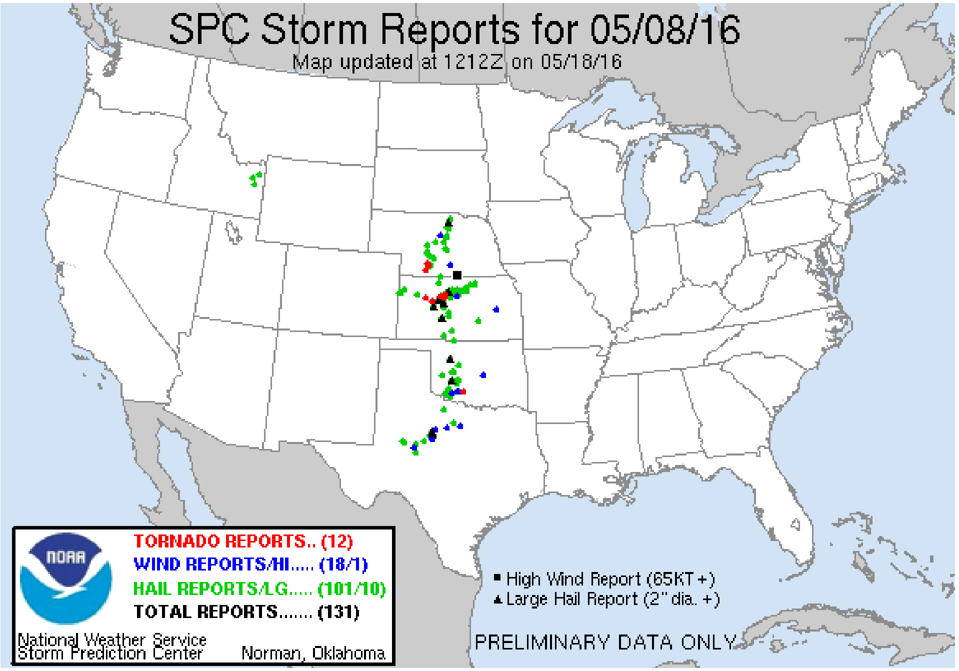
MPAS 96h forecast



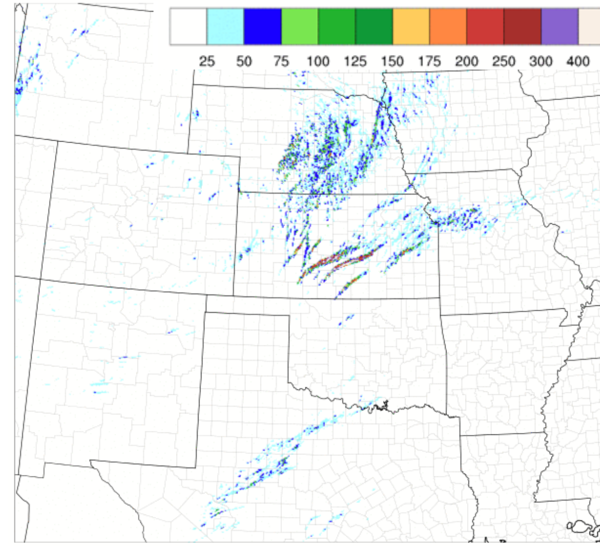
MPAS 120h forecast



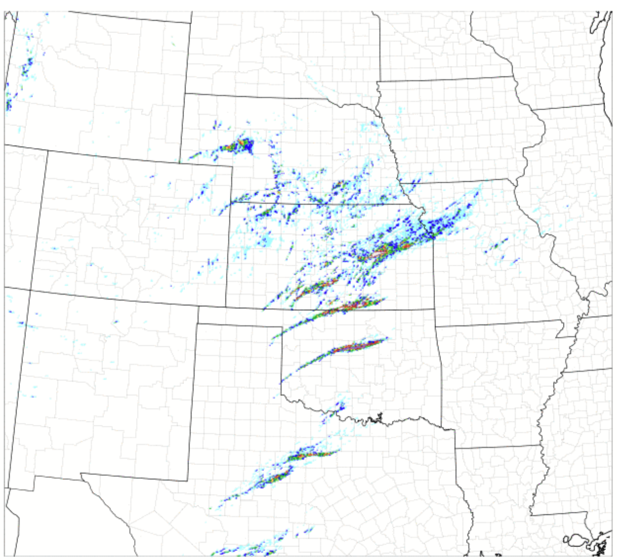
MPAS 24h Max Updraft Helicity (m^2/s^2)



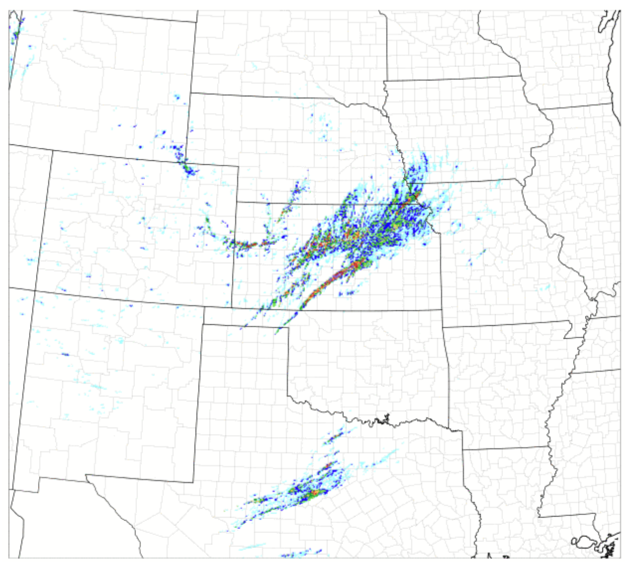
MPAS 36h forecast



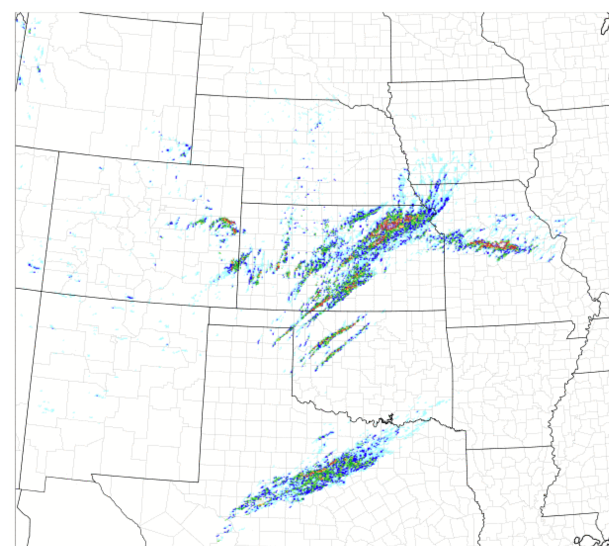
MPAS 60h forecast



MPAS 84h forecast



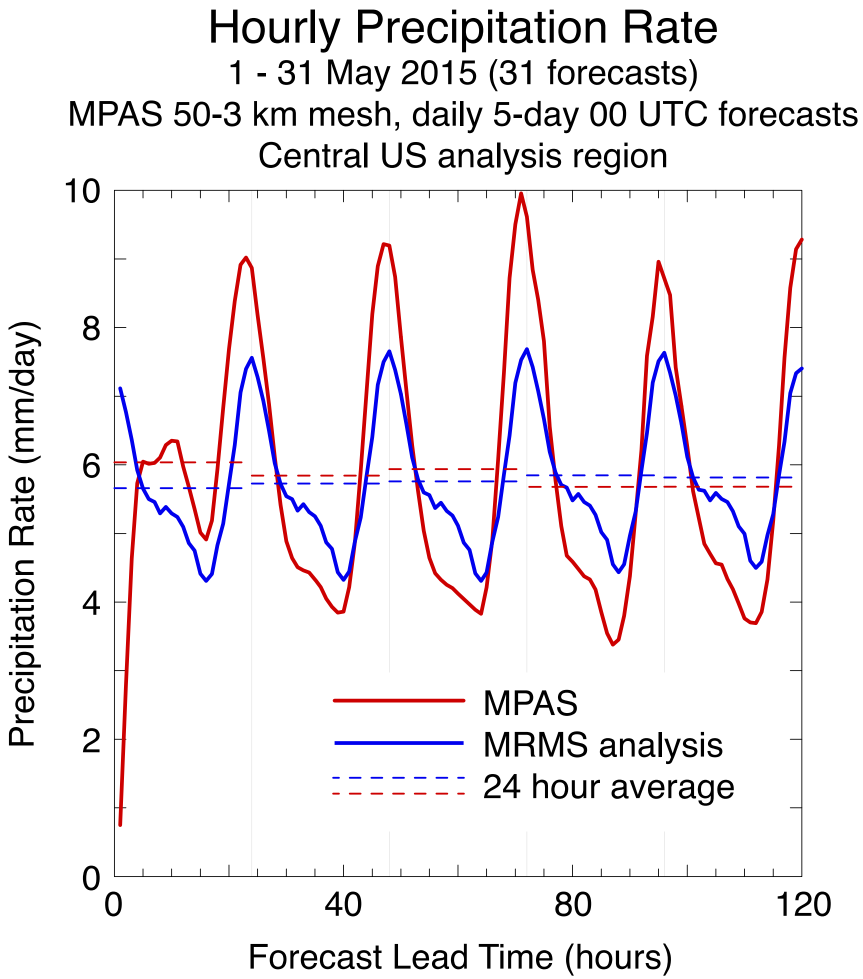
MPAS 108h forecast

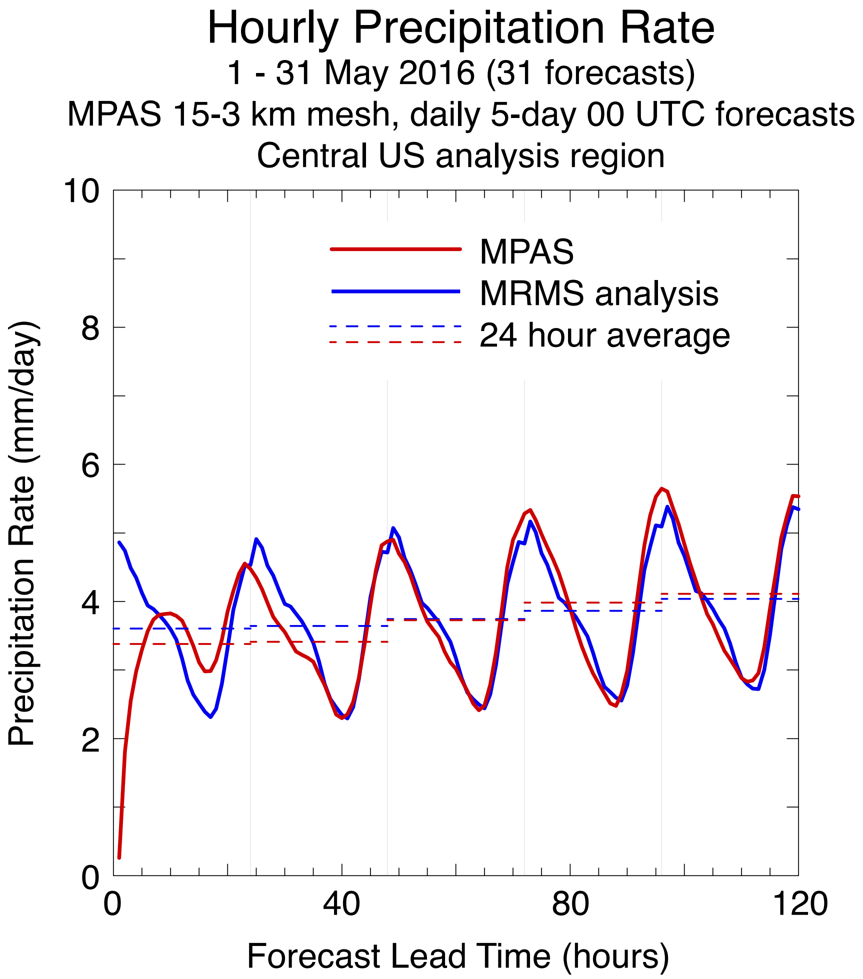


Hazardous Weather Testbed
Spring Experiment 2015, 2016
Forecasts Results from MPAS

Verification region

Hazardous Weather Testbed Spring Experiment 2015, 2016 *Forecasts Results from MPAS*

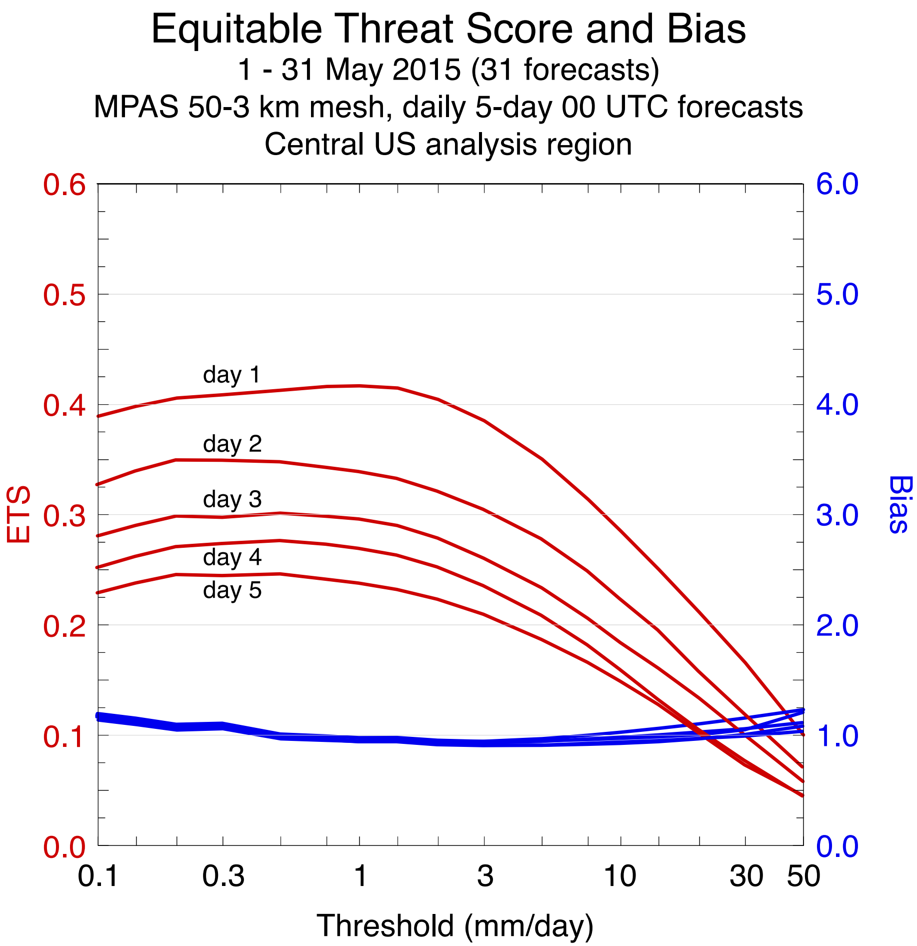


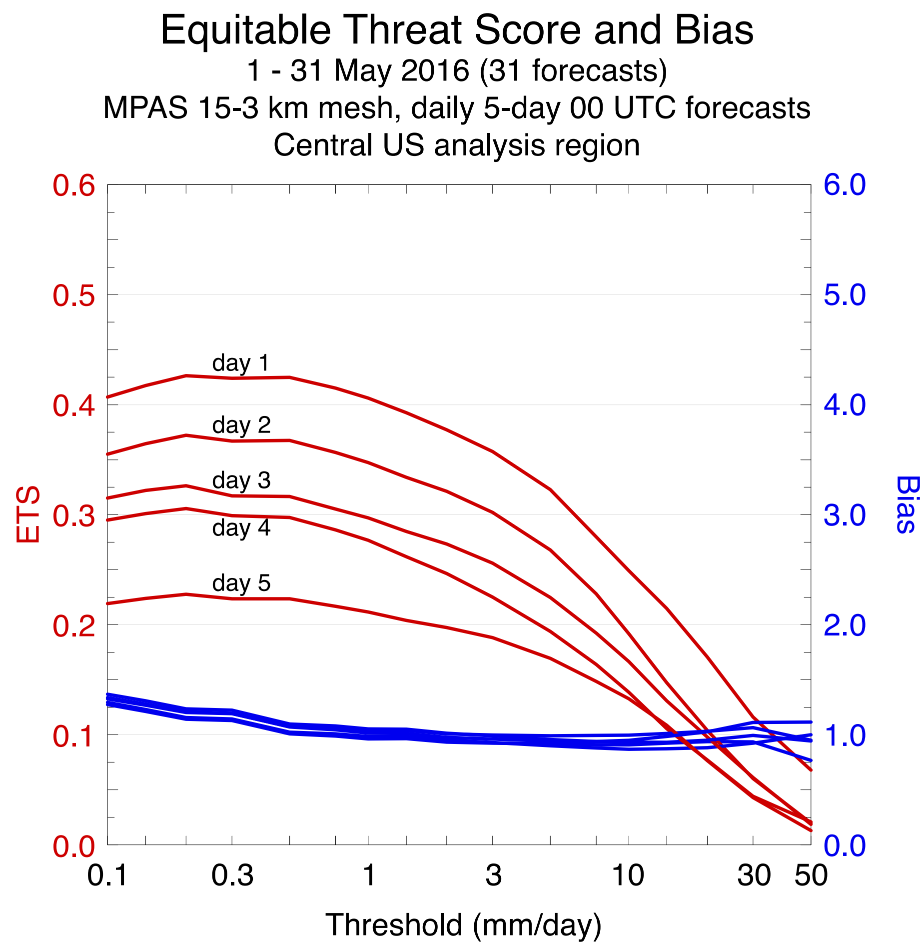


MPAS
Model for Prediction Across Scales

Hazardous Weather Testbed Spring Experiment 2015, 2016

Forecasts Results from MPAS





MPAS
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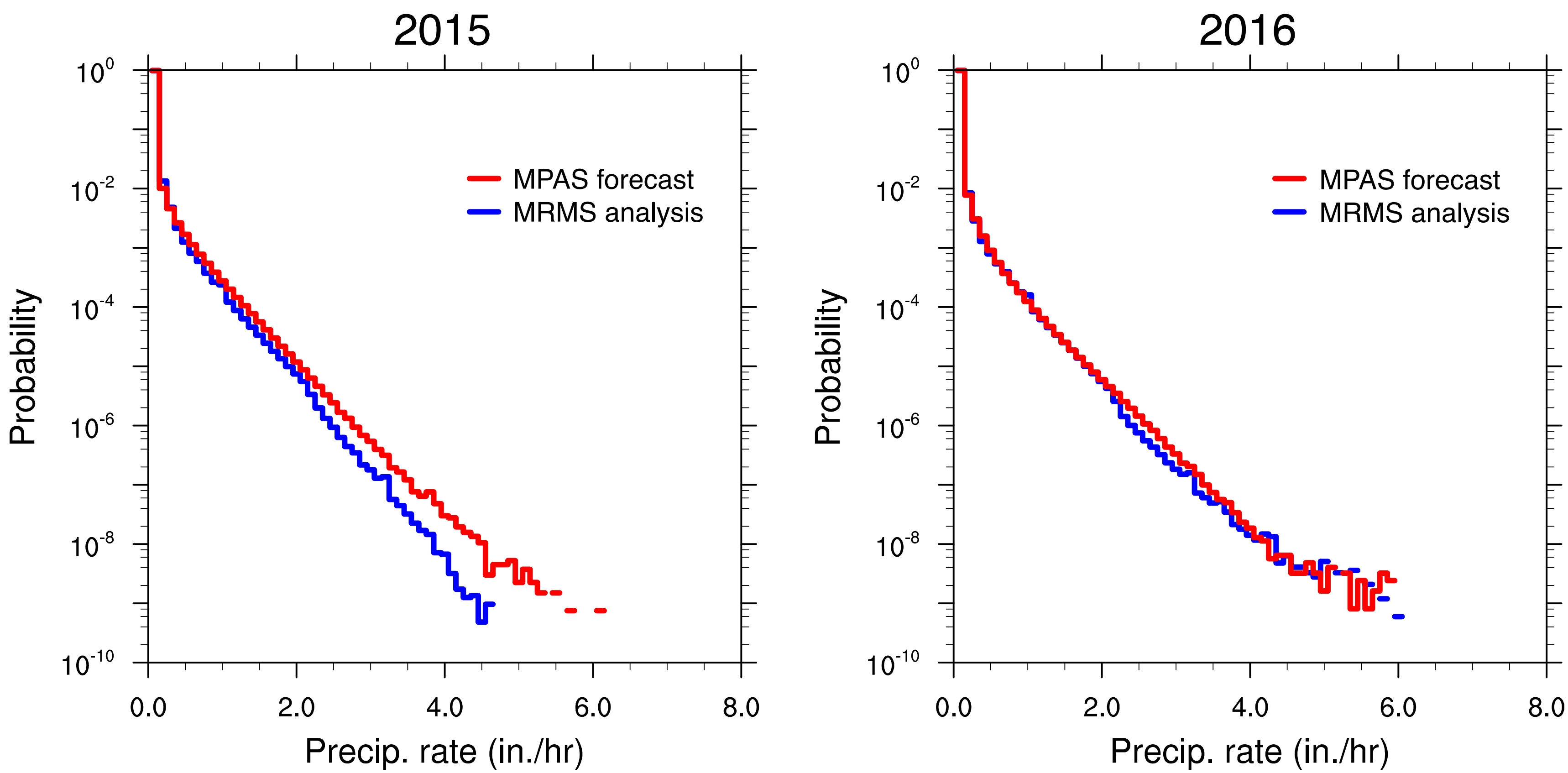
Precipitation Rate PDF
1 - 31 May 2015, 2016 (31 forecasts each year)
MPAS 50-3 and 15-3 km meshes, daily 5-day 00 UTC forecasts
Central US analysis region



Variable-Resolution Applications

Convection permitting variable-resolution global configurations are the obvious first applications. Why?: Cost (cpu and data), capability to test global convection-permitting configurations at high resolutions.

Should variable-resolution global models be used in place of existing regional NWP models?

- For forecasts of 1-2+ days at convection permitting resolutions, indications are one does not gain anything.
- The benefits of the cleaner downscaling and upscaling have yet to be demonstrated in longer-range NWP applications – more testing needed.

Should variable-resolution global models be used in place of existing models for regional climate and climate applications?

- Yes, but the variable-resolution configurations will need to be tuned.
- S2S applications are attractive applications for this technology.

Significant remaining issues with global variable-resolution models:

- Scale-aware physics
- Dissipation and step-wise change in resolution (reflection, spin-up, etc)