Numerical Weather Prediction in the Next Decade - Convective Forecasts with a Global Atmospheric Model?

Bill Skamarock

National Center for Atmospheric Research

Mesoscale and Microscale Meteorology Laboratory

Convective Forecasts with a Global Atmospheric Model?

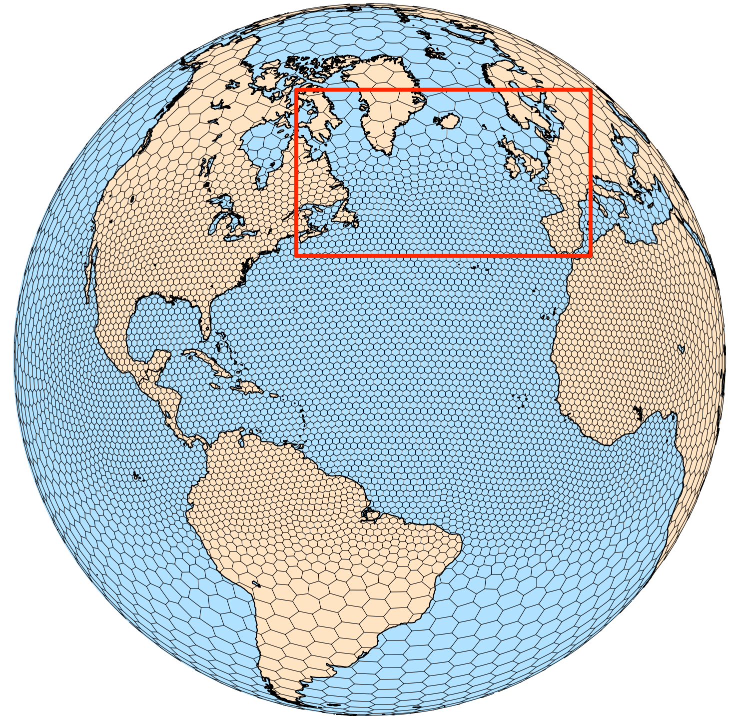
Why *should* we pursue global convective-scale NWP?

- To better resolve topography.
- To better resolve land use.
- Explicitly simulate deep convection, i.e. remove major uncertainties associated with deep-convection parameterization.

Why *shouldn't* we pursue global convective-scale NWP?

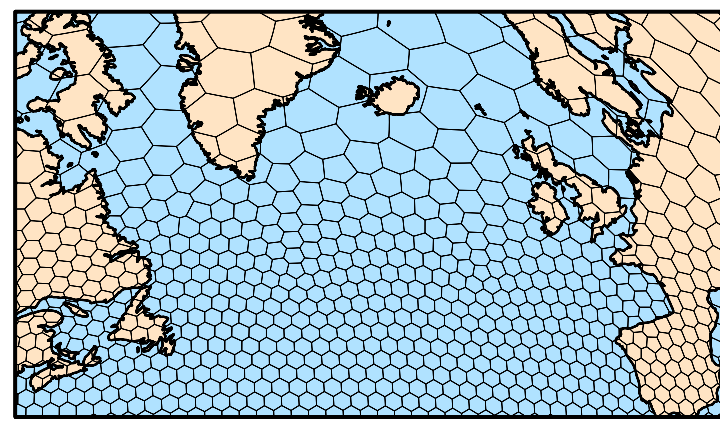
- Newly resolved scale have short predictability timescales.
- Regional models (downscaling) are sufficient for convective-scale forecasts.
- Limited observations at these scales.
- Convective-scale DA approaches are immature.
- Cost-benefit analyses suggest ensembles at mesoscale resolutions are a more efficient use of resources.

Variable-Resolution Global Atmospheric Simulations Bridging the Hydrostatic and Nonhydrostatic Regimes



MPAS
Model for Prediction Across Scales

Bill Skamarock, Joe Klemp, Michael Duda,
Laura Fowler, Sang-Hun Park
National Center for Atmospheric Research



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

Los Alamos NATIONAL LABORATORY EST. 1943

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NSF

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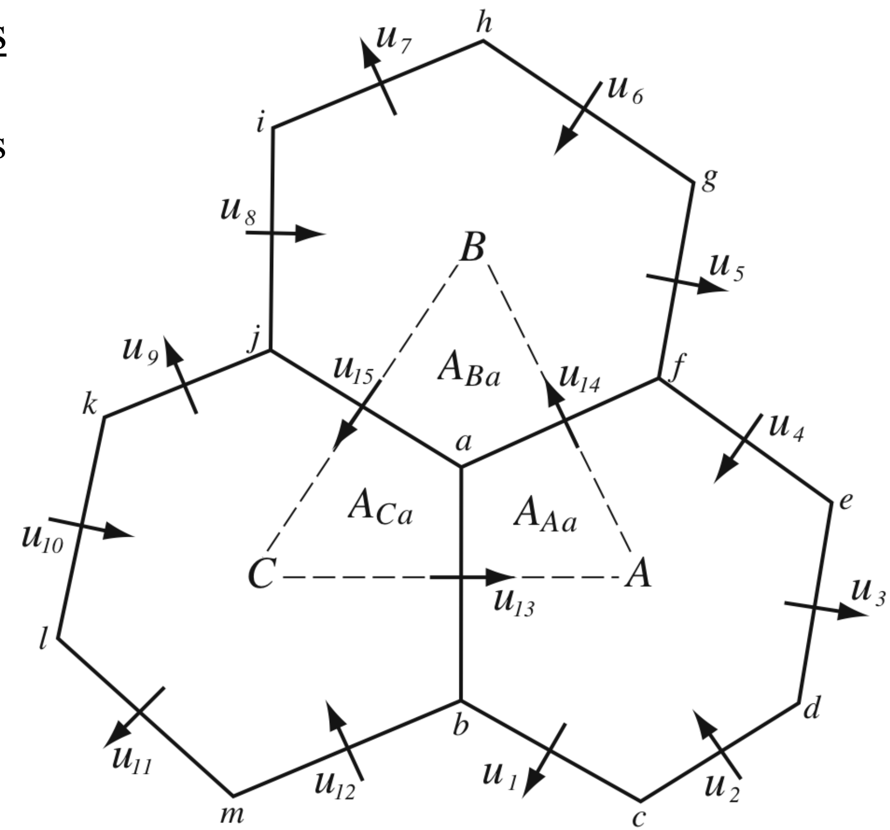
Centroidal Voronoi Meshes

<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.



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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

- Split-explicit Runge-Kutta (3rd order), as in Advanced Research WRF.
- Single time-step for the global mesh, CFL limited by highest resolution.

Spatial discretization

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

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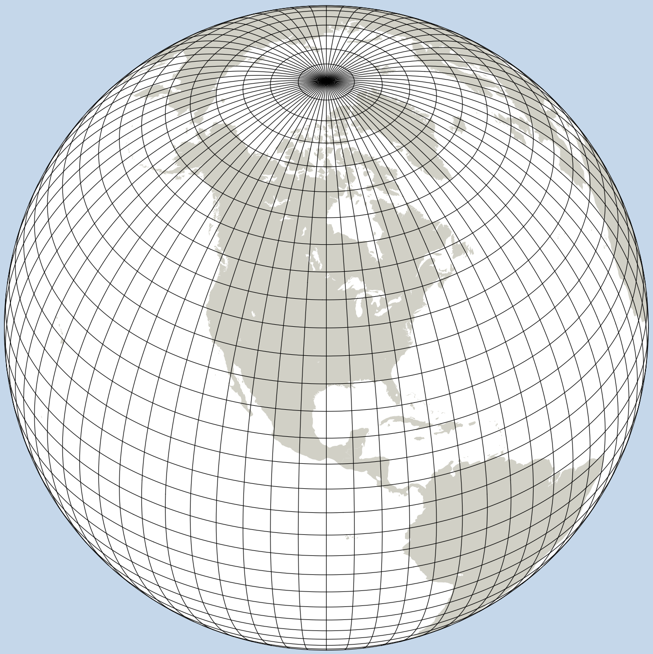
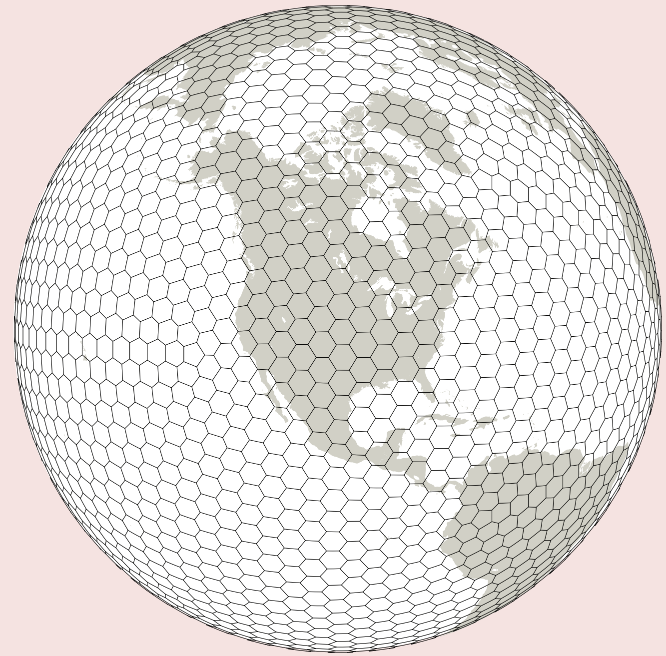
Why MPAS?

Significant differences between WRF and MPAS



WRF
Lat-Lon global grid

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

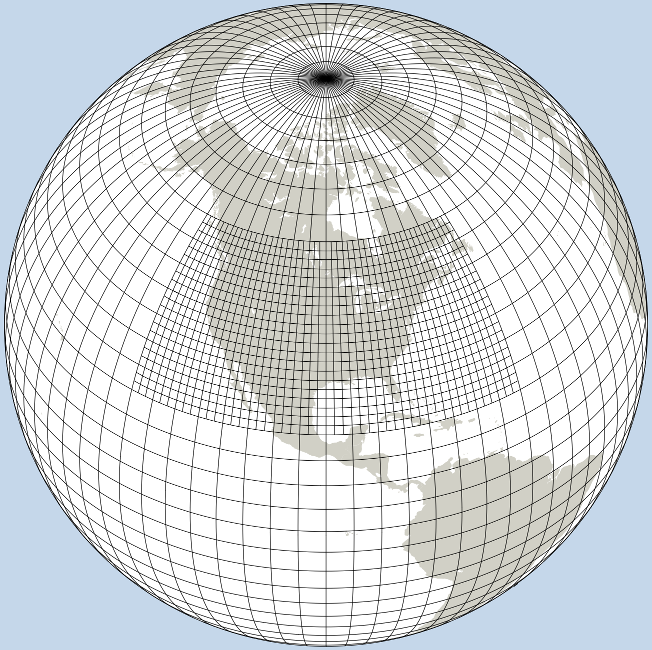


MPAS
Unstructured Voronoi (hexagonal) grid

- Good scaling on massively parallel computers
- No pole problems

Why MPAS?

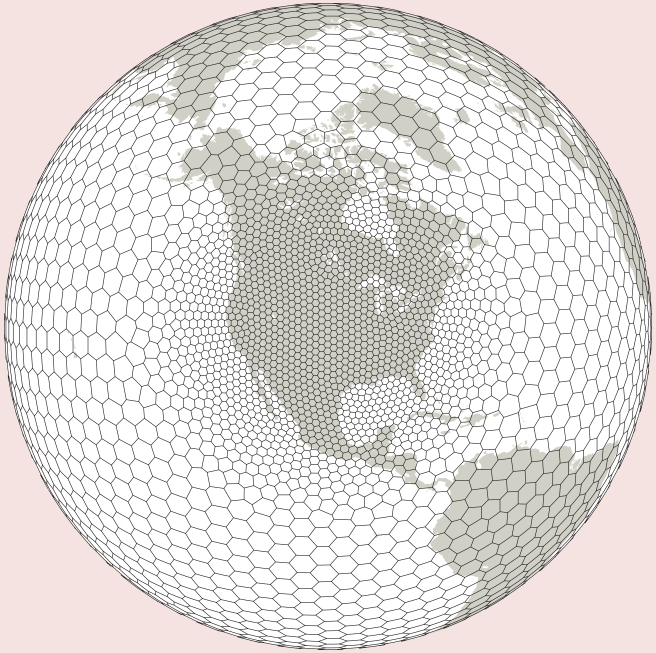
Significant differences between WRF and MPAS



WRF

Grid refinement through domain nesting

- Flow distortions at nest boundaries



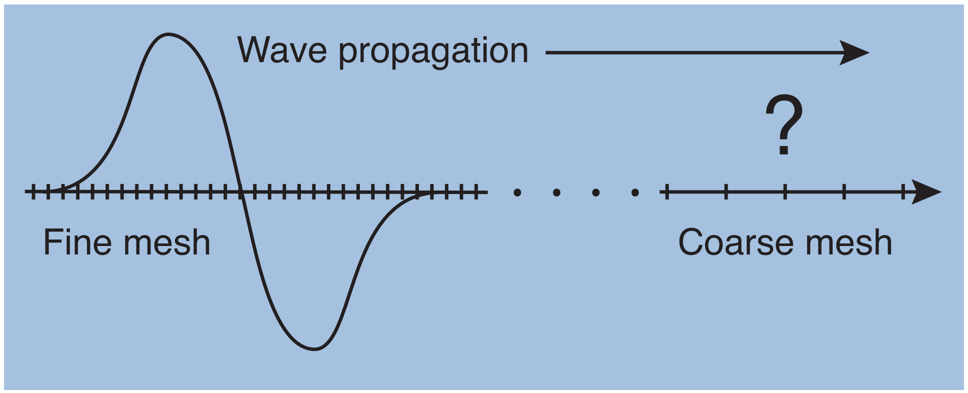
MPAS

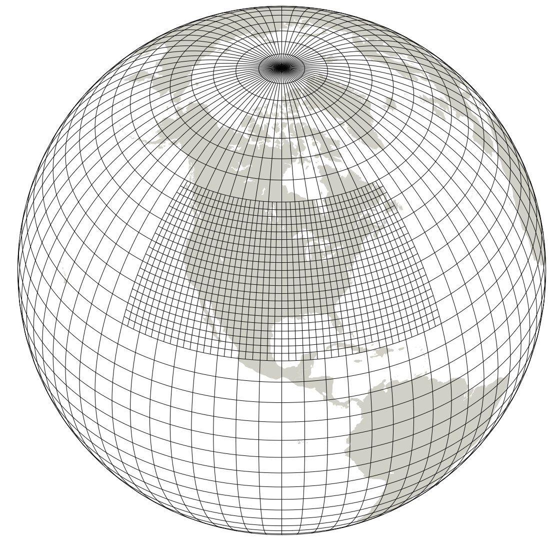
Smooth grid refinement on a conformal mesh

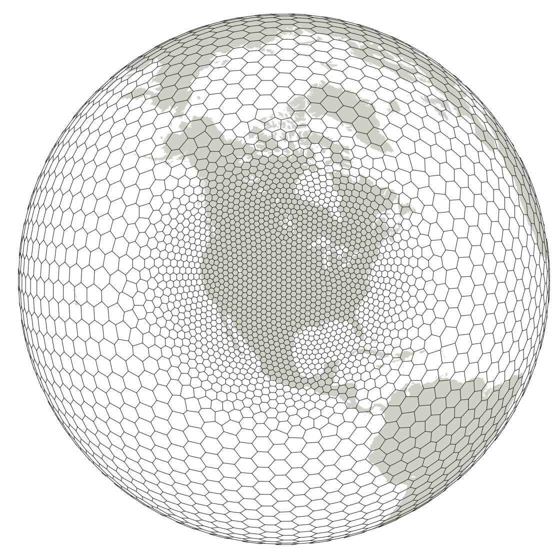
- Increased accuracy and flexibility for variable resolution applications
- No abrupt mesh transitions.

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.

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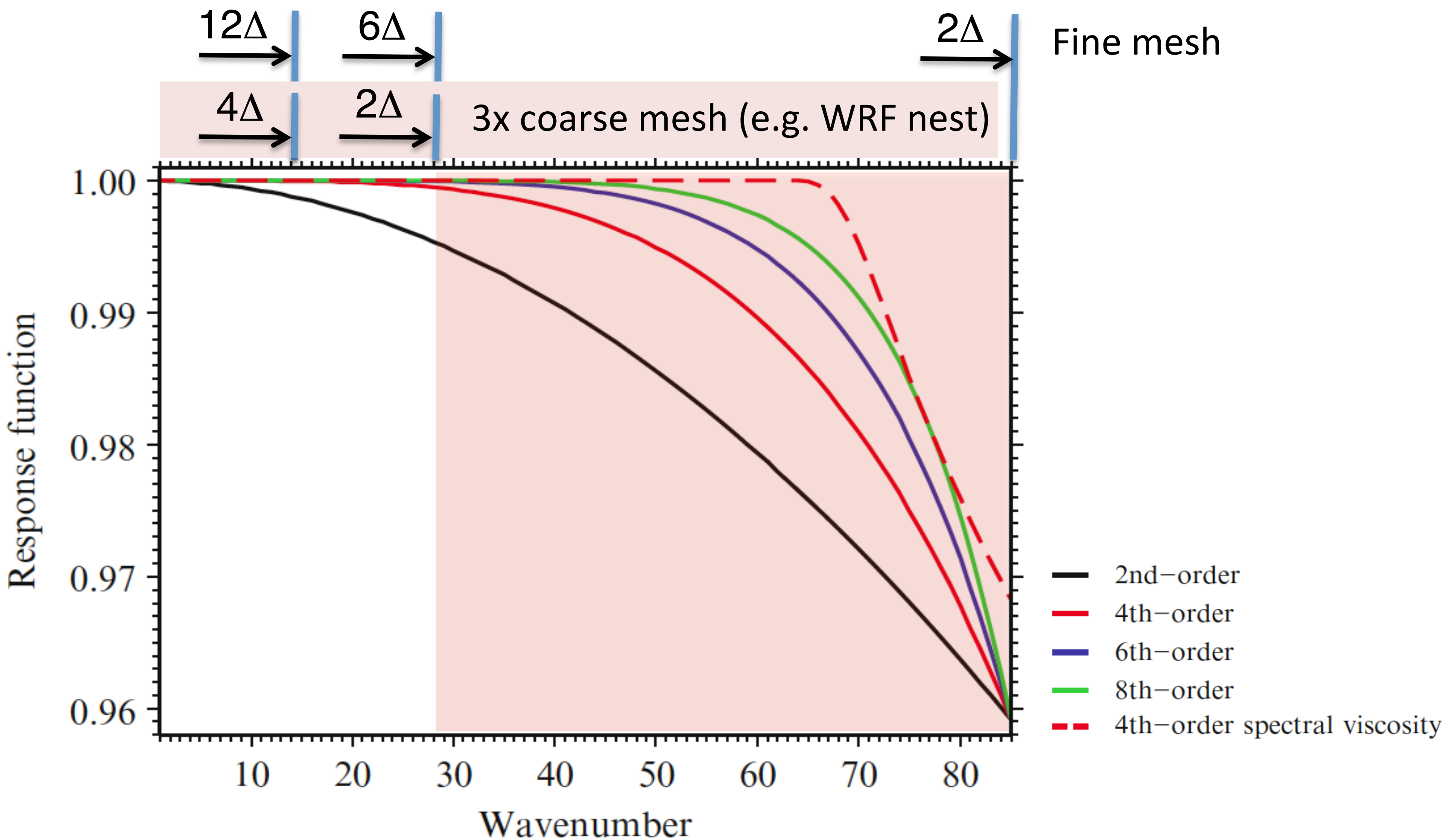
Model for Prediction Across Scales

Variable Resolution Meshes

Fine mesh filter response per time step



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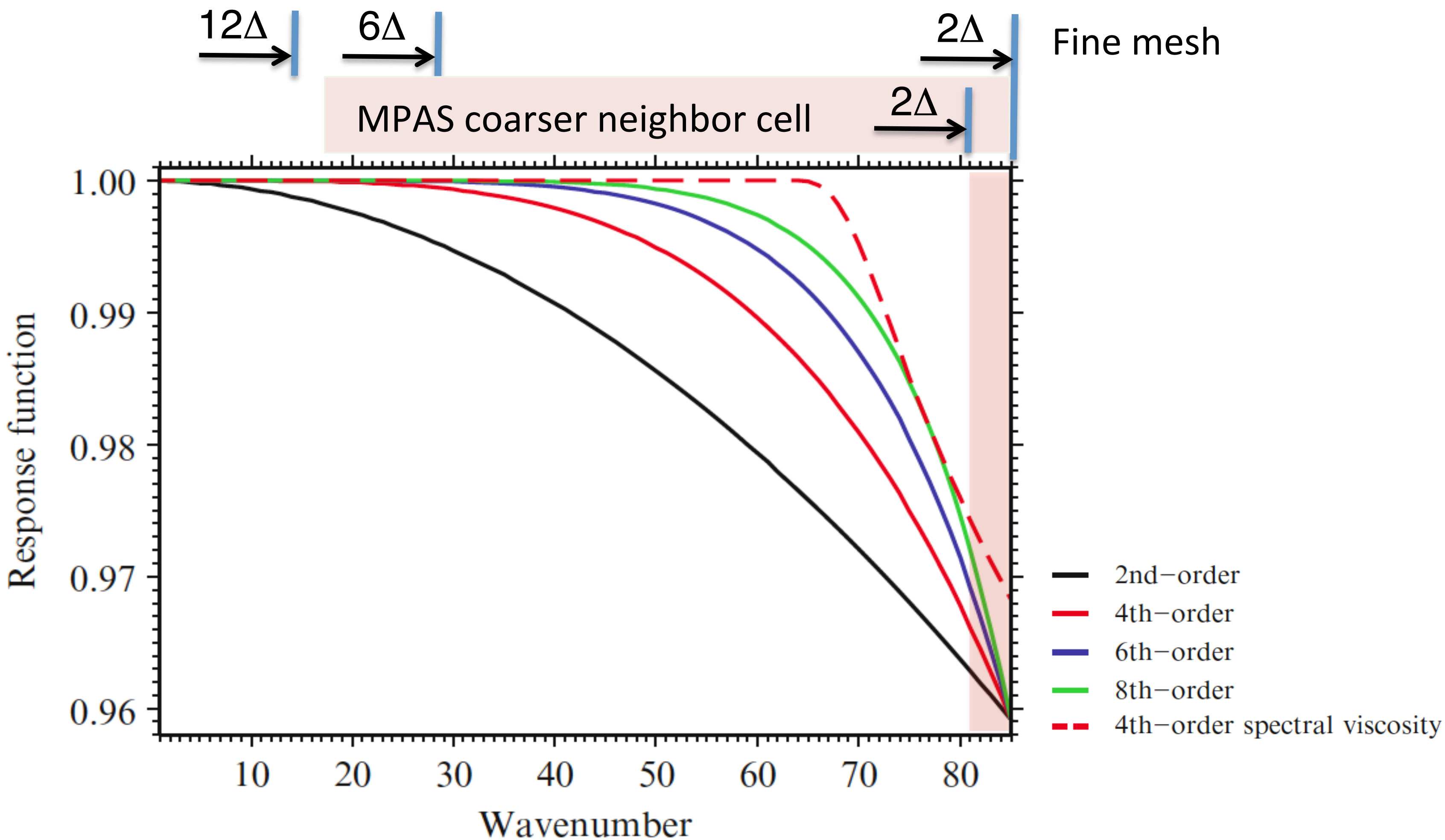
Variable Resolution Meshes

Fine mesh filter response per time step



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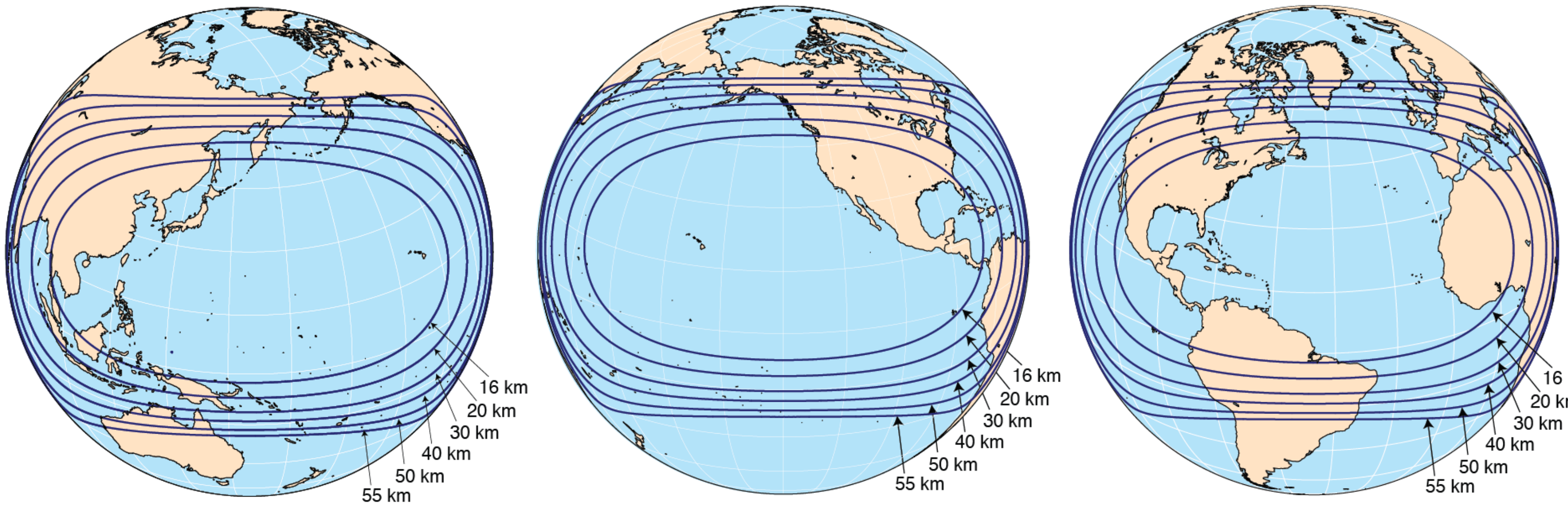
Model for Prediction Across Scales

Variable Resolution Tests
Hydrostatic Scale, TC forecasts

MPAS-Atmosphere
2013-2015 Tropical Cyclone Forecast Experiments
60-15 km variable-resolution meshes

Aug-Oct 2013, 2014, 2015
daily 10-day forecasts, GFS analysis initialization

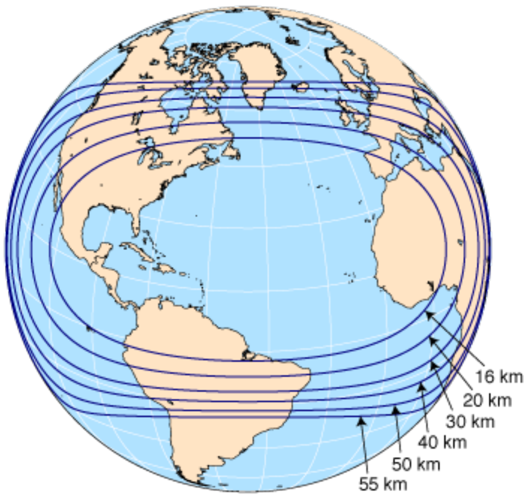


MPAS

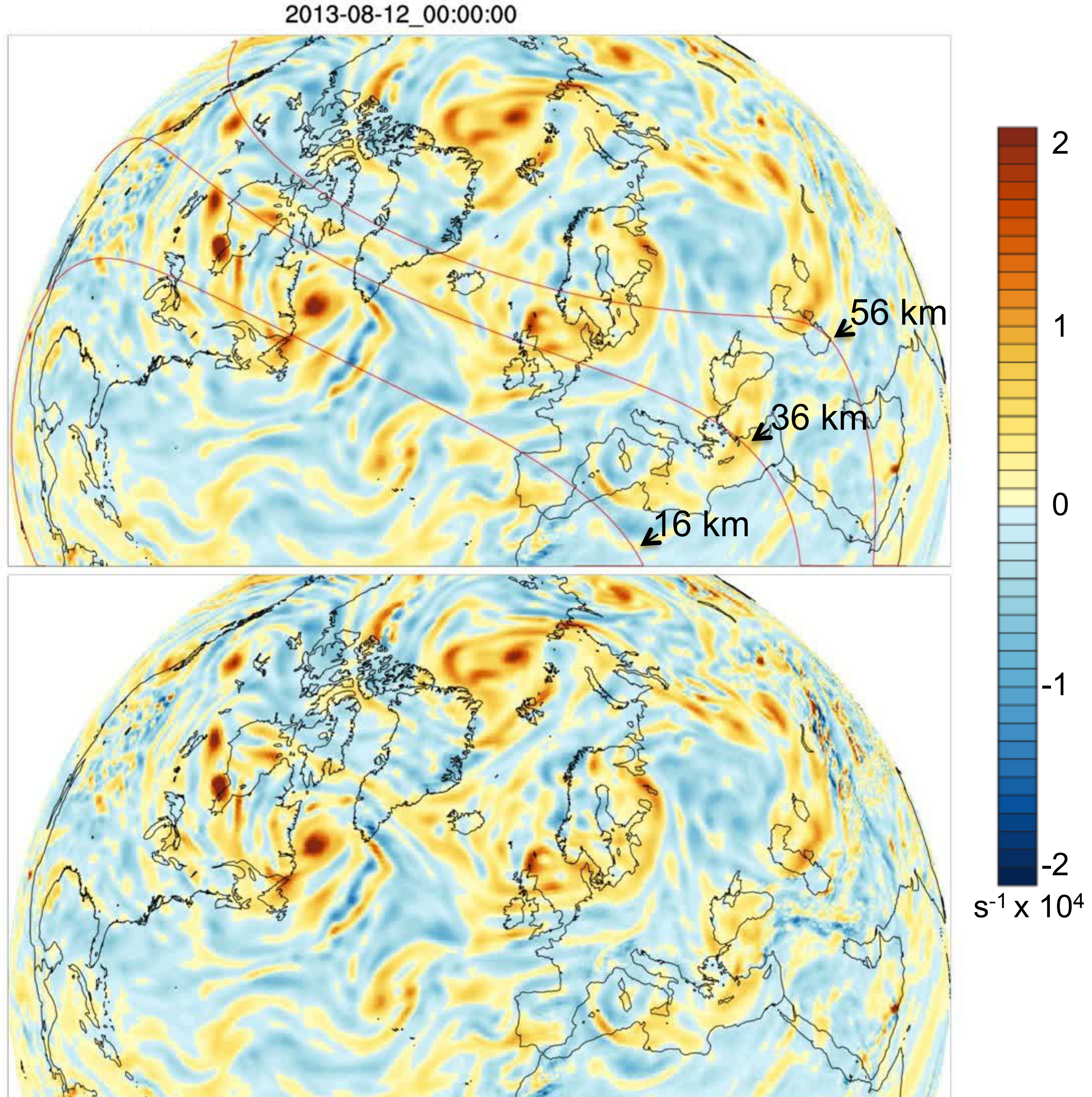
Model for Prediction Across Scales

10-day 500 hPa Relative Vorticity Forecast

15-60 km variable resolution mesh



15 km uniform resolution mesh

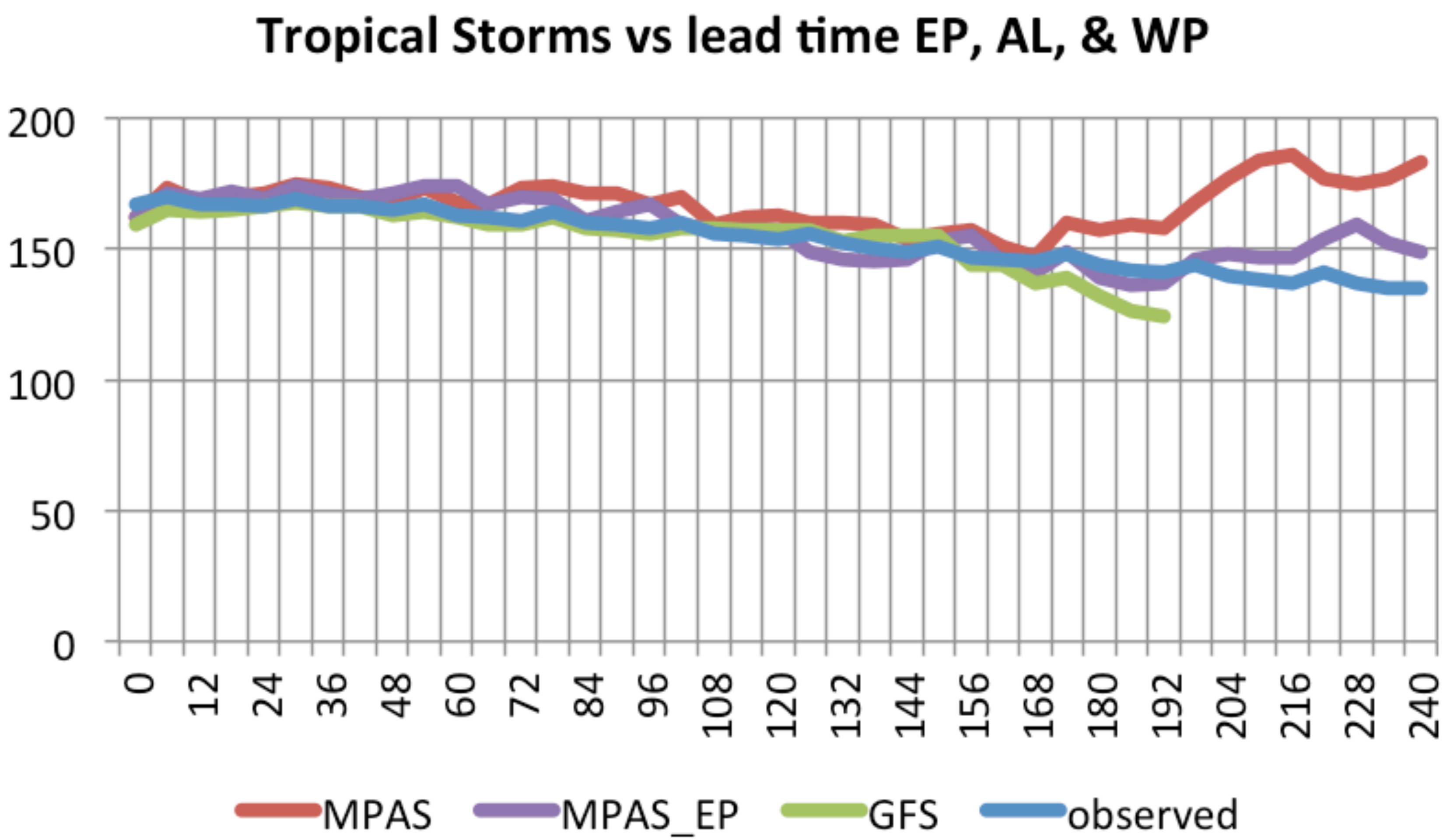


MPAS Physics:

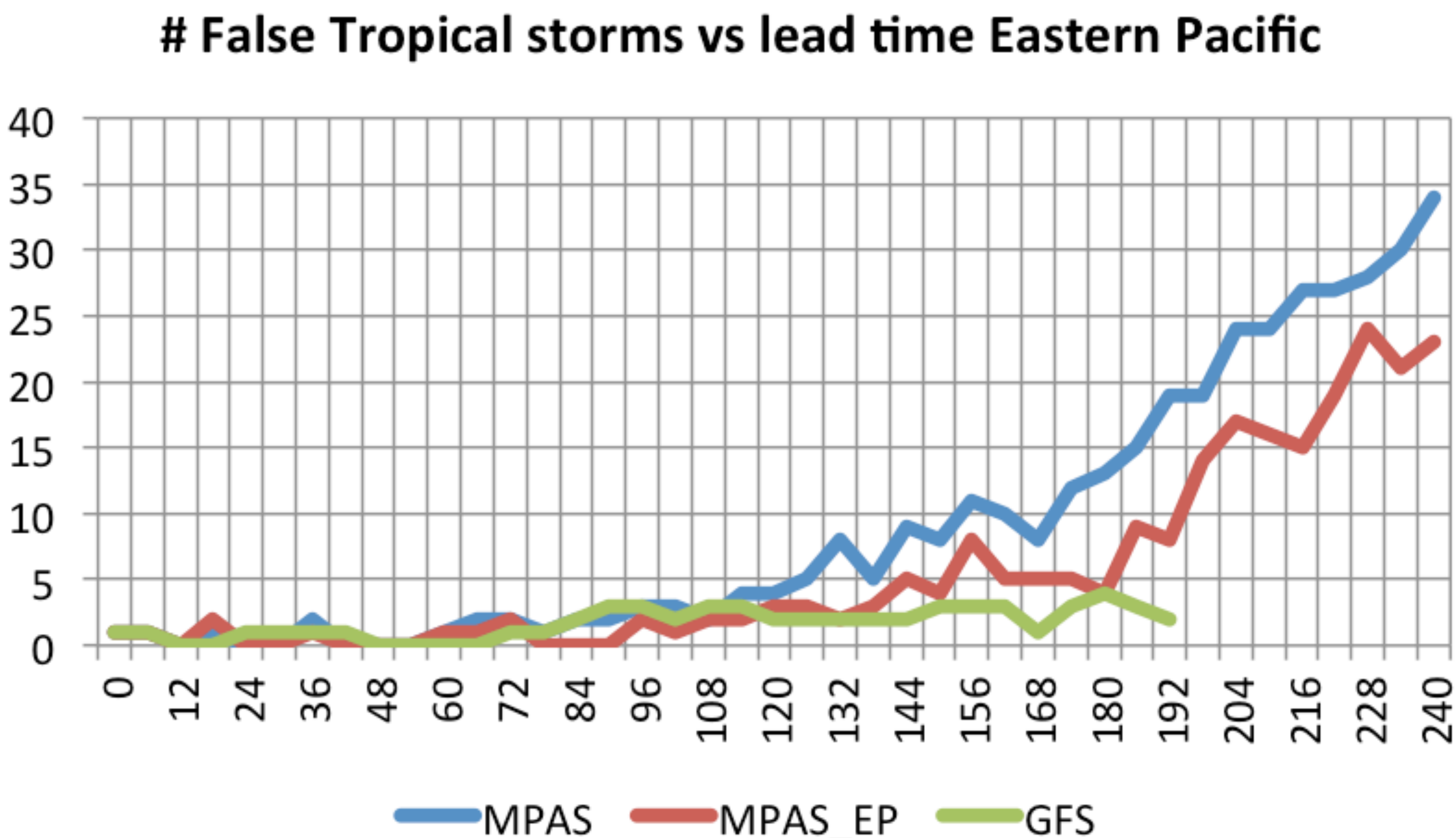
- WSM6 cloud microphysics
- Tiedtke convection scheme
- Monin-Obukhov surface layer
- YSU PBL
- Noah land-surface
- RRTMG lw and sw.

MPAS
Model for Prediction Across Scales

Variable Resolution Tests
Hydrostatic Scale, TC forecasts



Variable Resolution Tests
Hydrostatic Scale, TC forecasts



MPAS
Model for Prediction Across Scales

Variable Resolution Tests Spanning Hydrostatic to Nonhydrostatic Scales

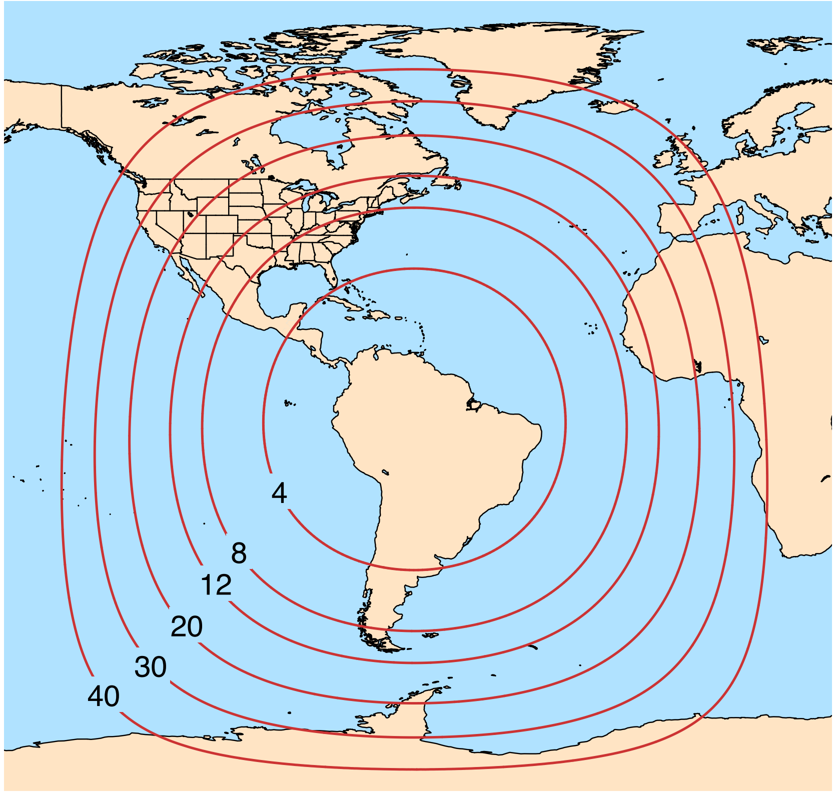
MPAS mesh:

50 – 3 km variable resolution.
Very smooth transition.

MPAS Physics:

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

MPAS mesh mean cell spacing (km)



3-50 km mesh, Δx contours 4, 8, 12, 20, 30 40 km
approximately 6.85 million cells
68% have < 4 km spacing
(158 pentagons, 146 septagons)

MPAS
Model for Prediction Across Scales

Grell-Freitas Convection Scheme in MPAS

<u>Scale-aware/aerosol-aware (Grell and Freitas, 2014, ACP)</u>

- Stochastic scheme (Grell and Devenyi, 2002).
- Scale aware by adapting the Arakawa et al approach (2011).
  - Relates vertical convective eddy transport to convective updraft/downdraft fraction σ:

$$\rho\overline{w\psi} = (1-\sigma)^2 M_c(\psi_c - \bar{\psi})_{adj} \quad \text{with} \quad M_c \equiv \rho\sigma w_c$$

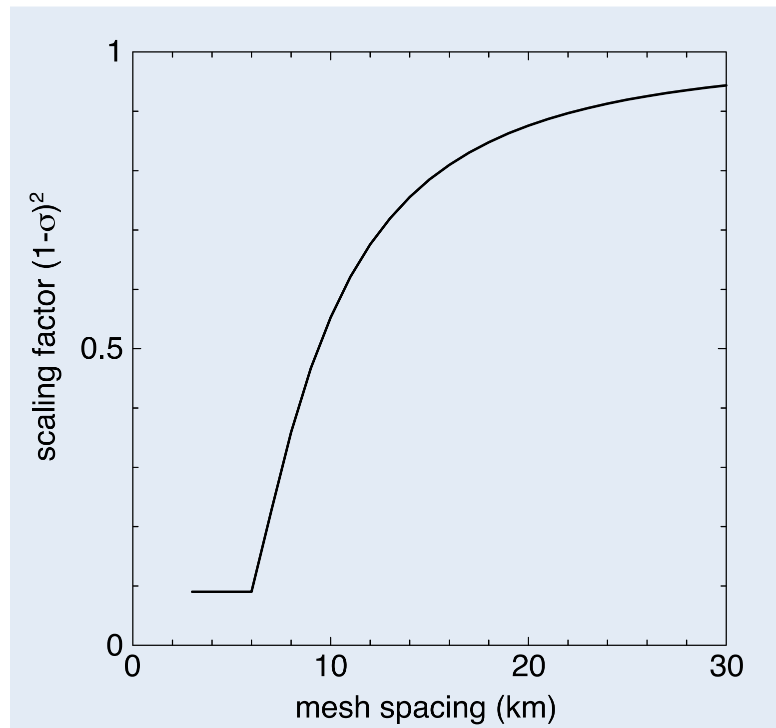
  - GF: σ is the fractional area covered by active updraft and downdraft plume.

$$\sigma = \frac{\pi R^2}{A_{grid\,cell}},\ R_{conv} = \frac{0.2}{\varepsilon},\ \varepsilon = 7\times10^{-5}$$

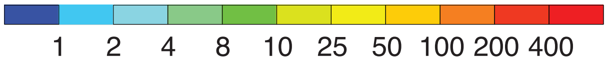
entrainment rate (fixed)

$$\sigma_{max} = 0.7$$

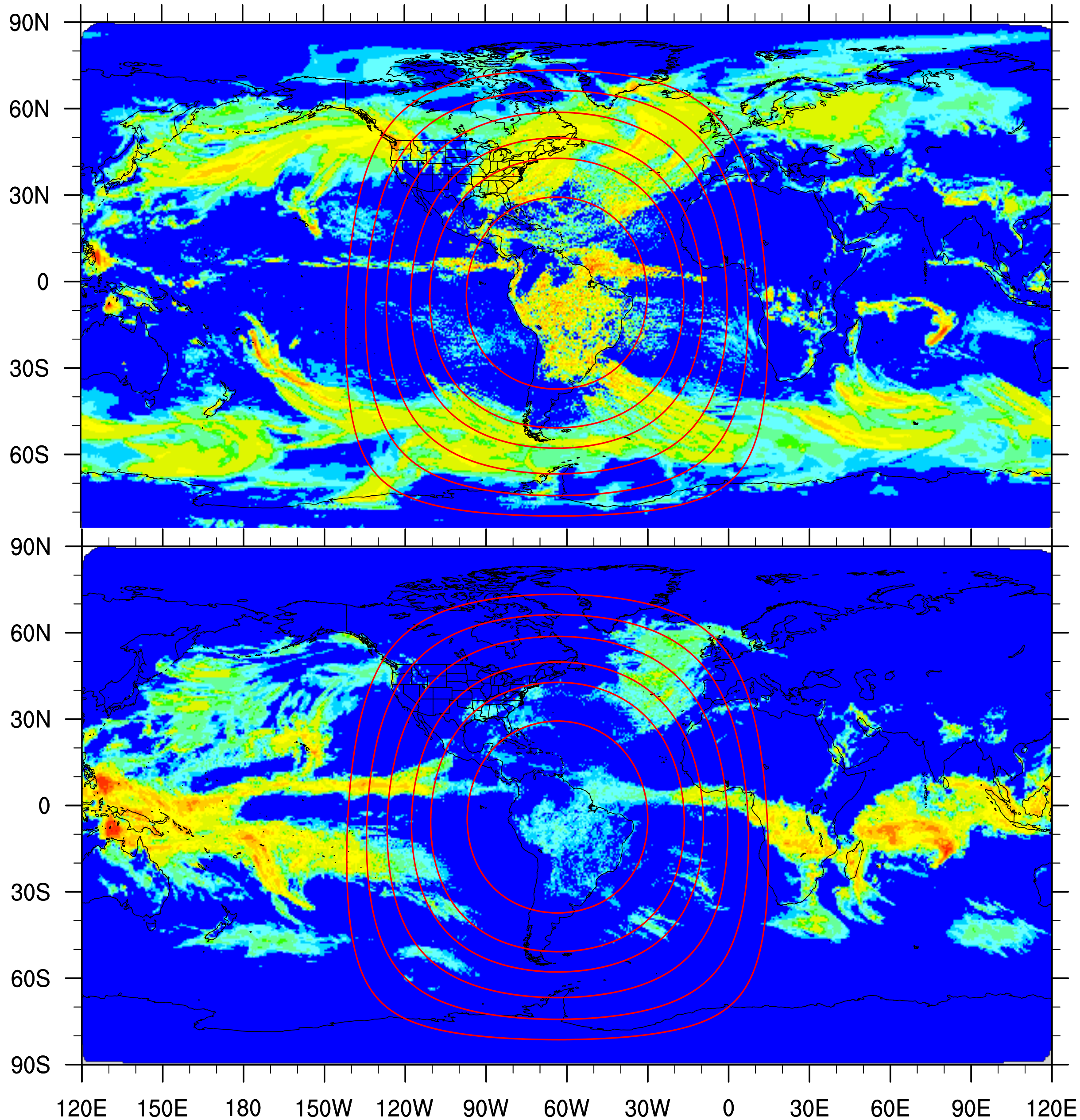
  - At convection-permitting resolution, parameterized convection becomes much shallower – cloud tops near 800 mb (down from 200-300 mb).
  - Temperature & moisture tendencies decrease as resolution increases.



MPAS 50-3 km mesh,
Grell-Freitas convection scheme
3 day forecast valid at
2014-01-13_00:00
Explicit precipitation



Accumulated precipitation (mm)

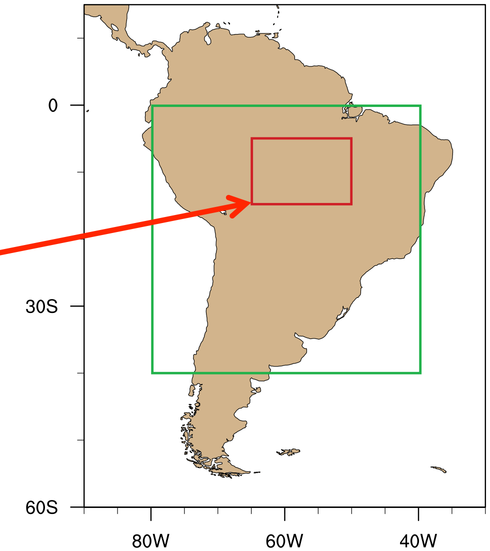


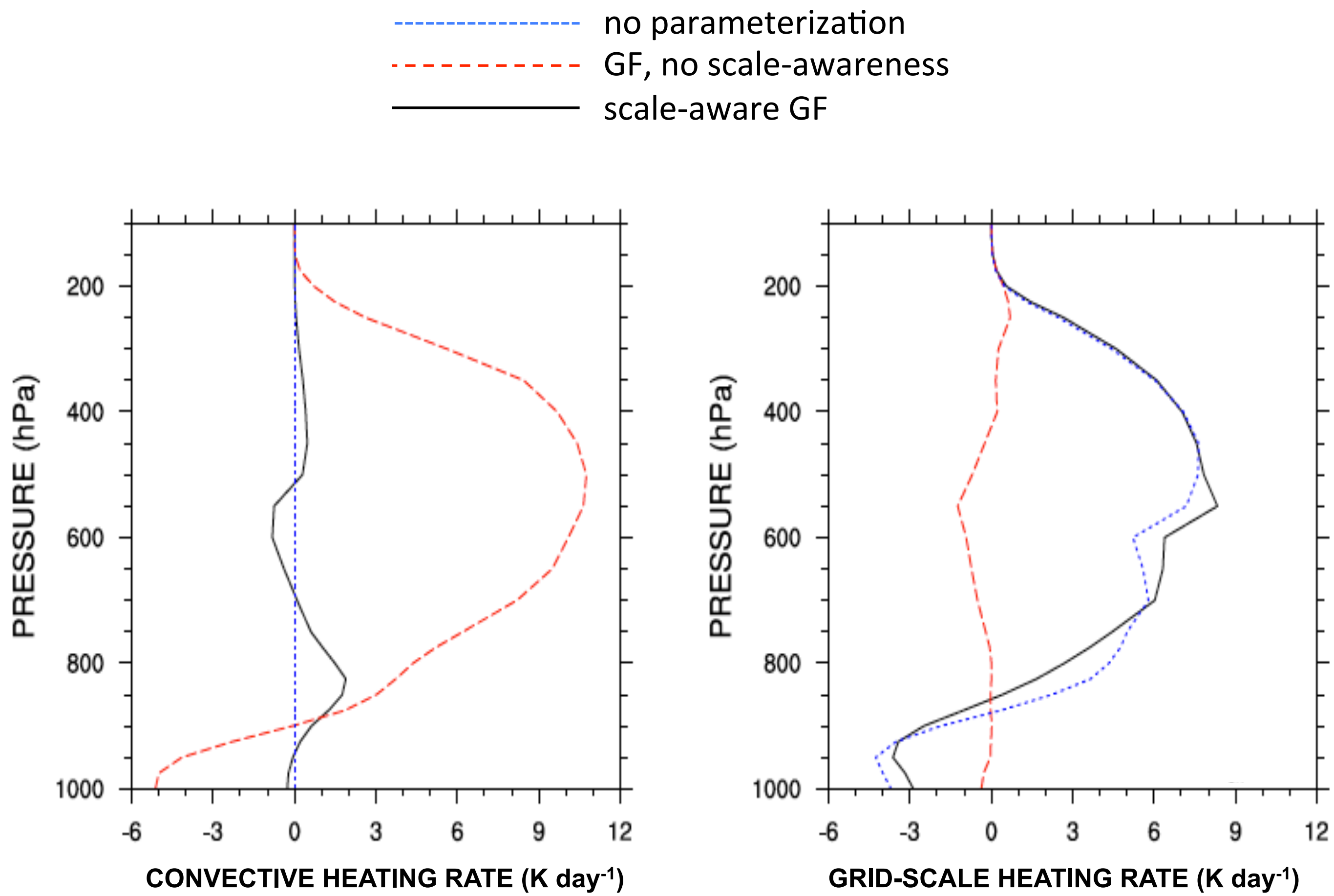
MPAS 50-3 km mesh,
Grell-Freitas convection scheme
3 day forecast valid at
2014-01-13_00:00
Convective precipitation

Mesh spacing
(4, 8, 12, 20, 30 40 km)

Variable Resolution Tests with the Grell-Freitas Convection Scheme

MPAS 50-3 km mesh, Grell-Freitas convection scheme
10-13 January 2014 forecasts, 3-day average heating rates



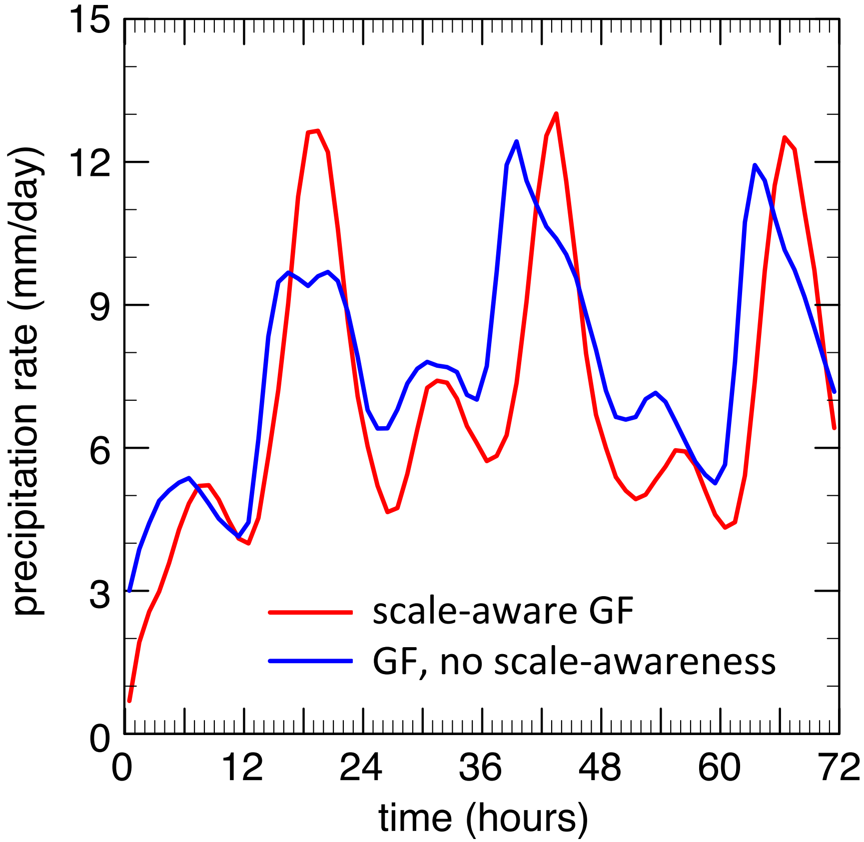


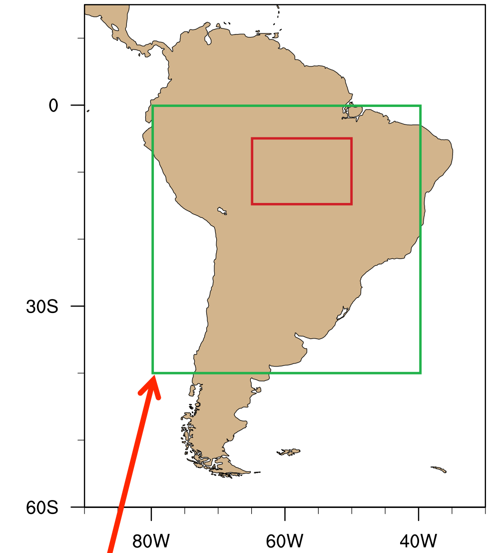
(from the GF scheme)

(explicit, from the microphysics)

Variable Resolution Tests
with the Grell-Freitas Convection Scheme

0 UTC 10 January 2014 - 0 UTC 13 January 2014
270 - 310 E, -40 - 0 N (South America)





MPAS 50-3 km mesh,
Grell-Freitas convection scheme
10-13 January 2014 forecasts
Precipitation rates

MPAS
Model for Prediction Across Scales

Variable Resolution Tests Spanning Hydrostatic to Nonhydrostatic Scales

MPAS mesh:

50 – 3 km variable resolution.
CONUS is the 3 km region.
Very smooth transition.

MPAS Physics:

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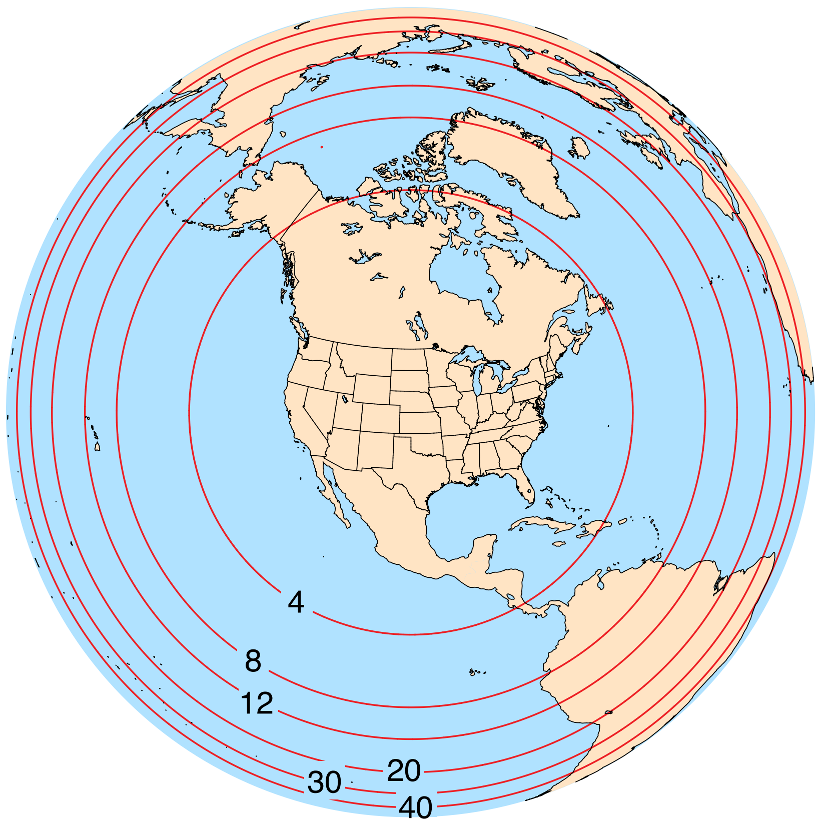

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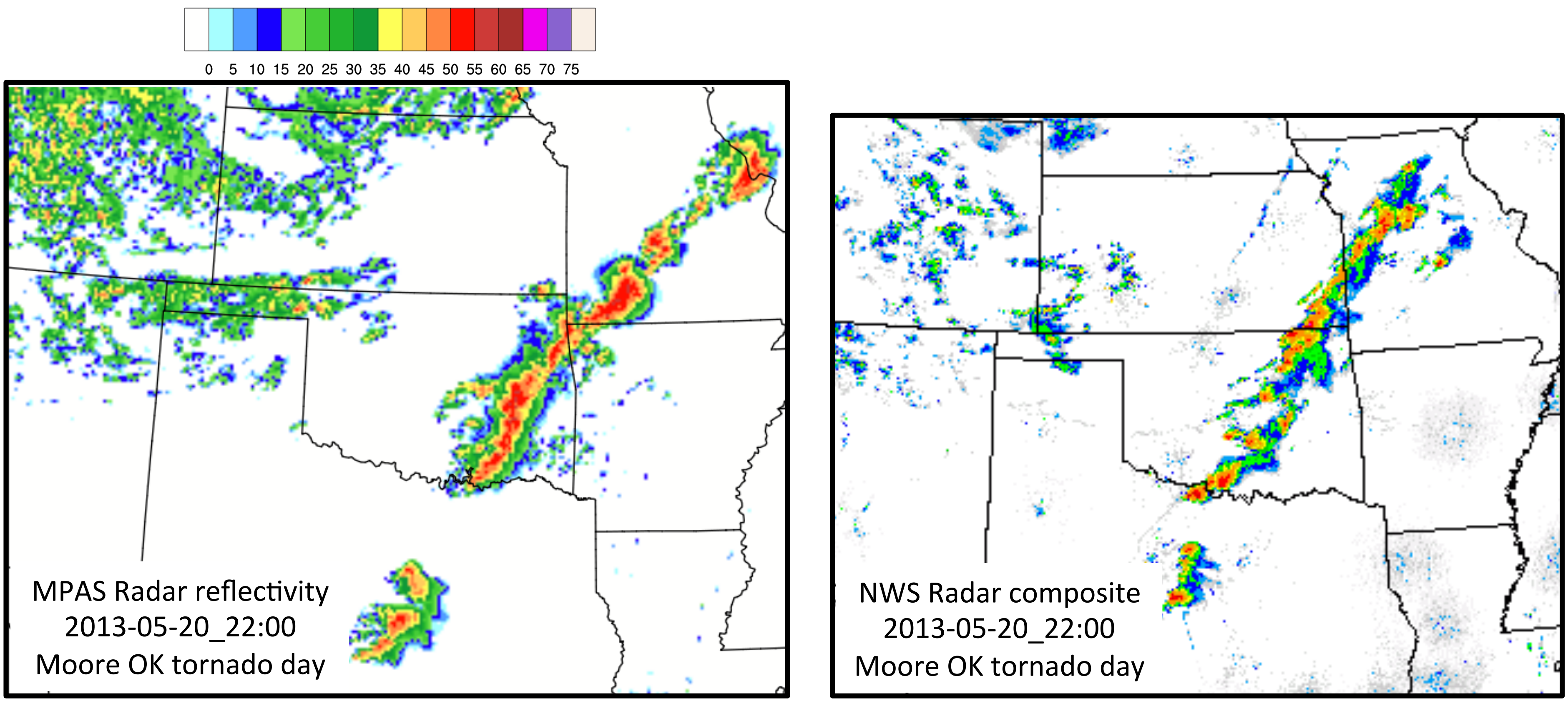
Variable Resolution Tests Forecast

0 UTC 18 May – 12 UTC 21 May 2013

- 3.5 day forecast
- Significant convective activity in the late afternoon/early evening in the central plains. Tornadoes reported on all three days.
- Moore OK tornado on the third day
  (19 UTC 20 May; 24 fatalities, $2B damages).

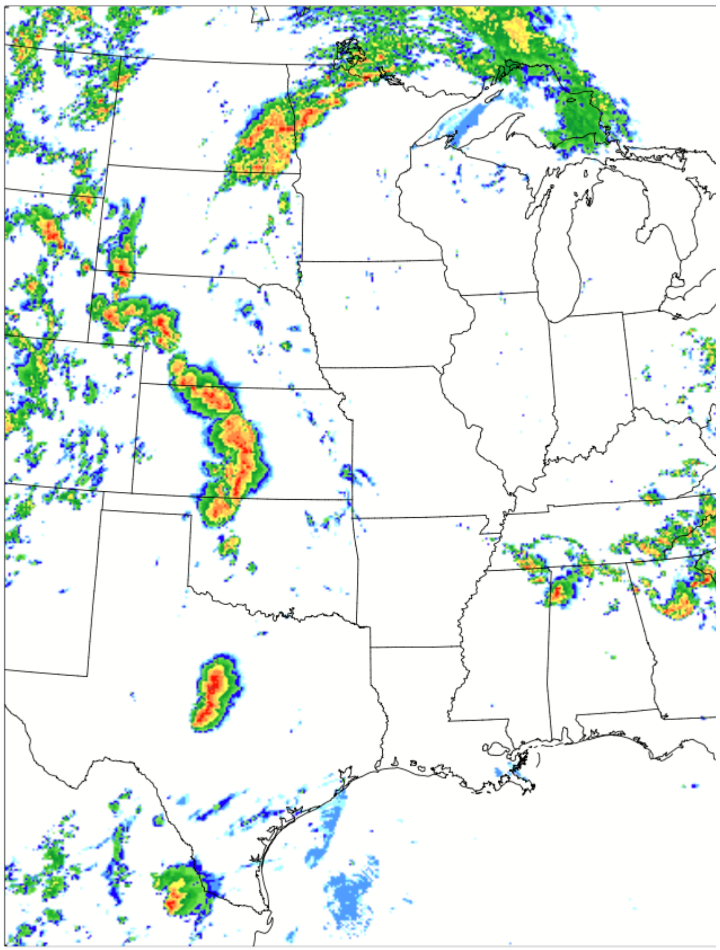


MPAS
Model for Prediction Across Scales

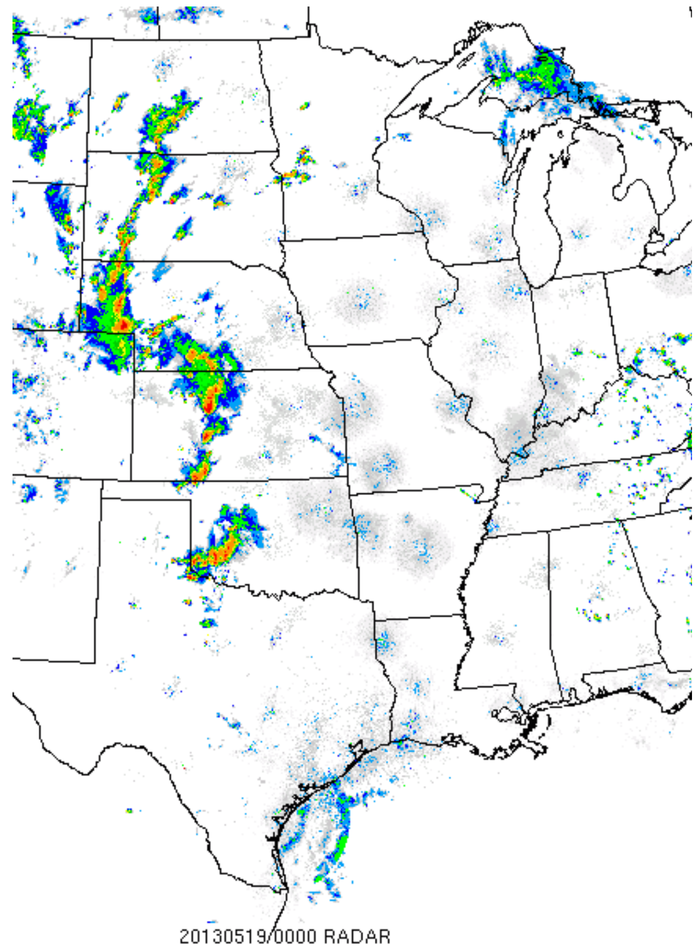
Variable Resolution Tests Forecast

0 UTC 18 May – 12 UTC 21 May 2013
Central plains convection in MPAS, day 1

column max dBZ, 2013-05-19_00:00:00



MPAS, 24 h forecast

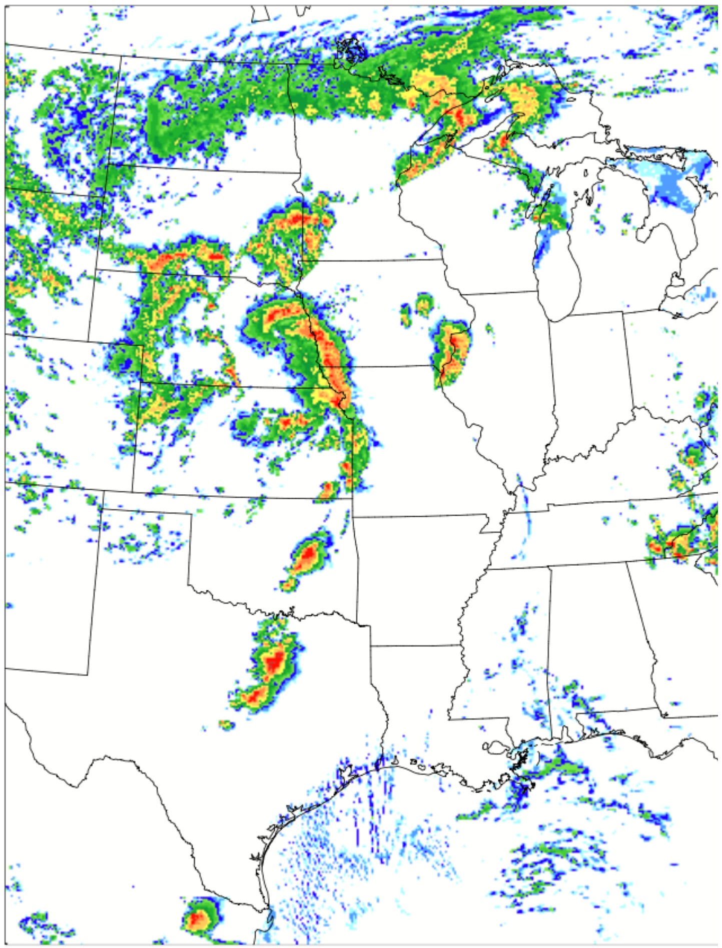


NWS radar composite

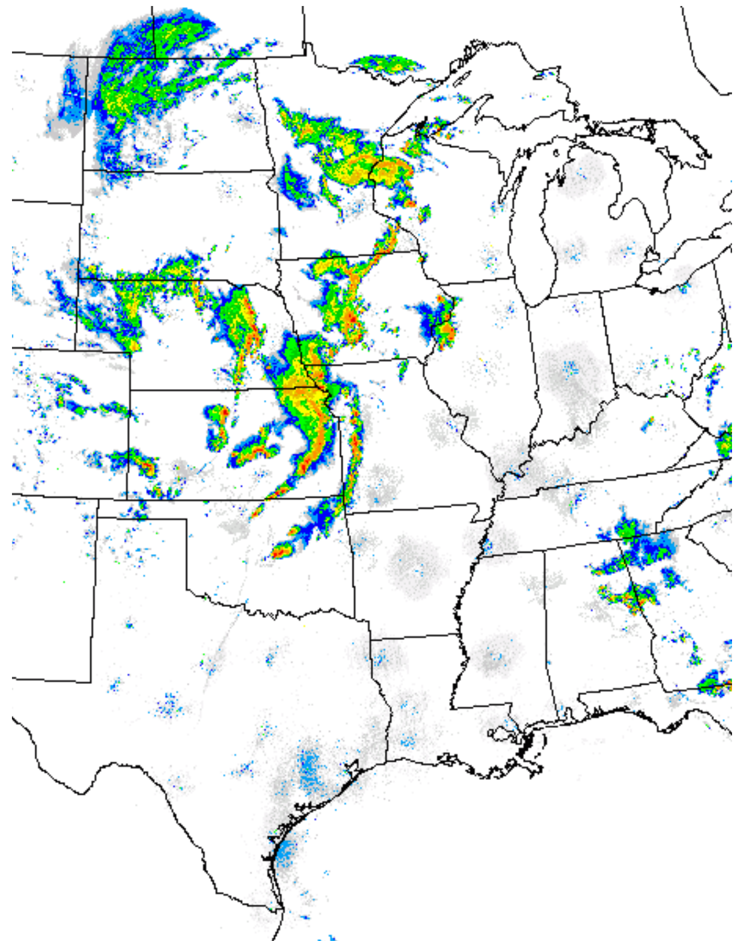
MPAS
Model for Prediction Across Scales

Variable Resolution Tests Forecast
0 UTC 18 May – 12 UTC 21 May 2013
Central plains convection in MPAS, day 2

column max dBZ, 2013-05-20_00:00:00



MPAS, 48 h forecast



NWS radar composite

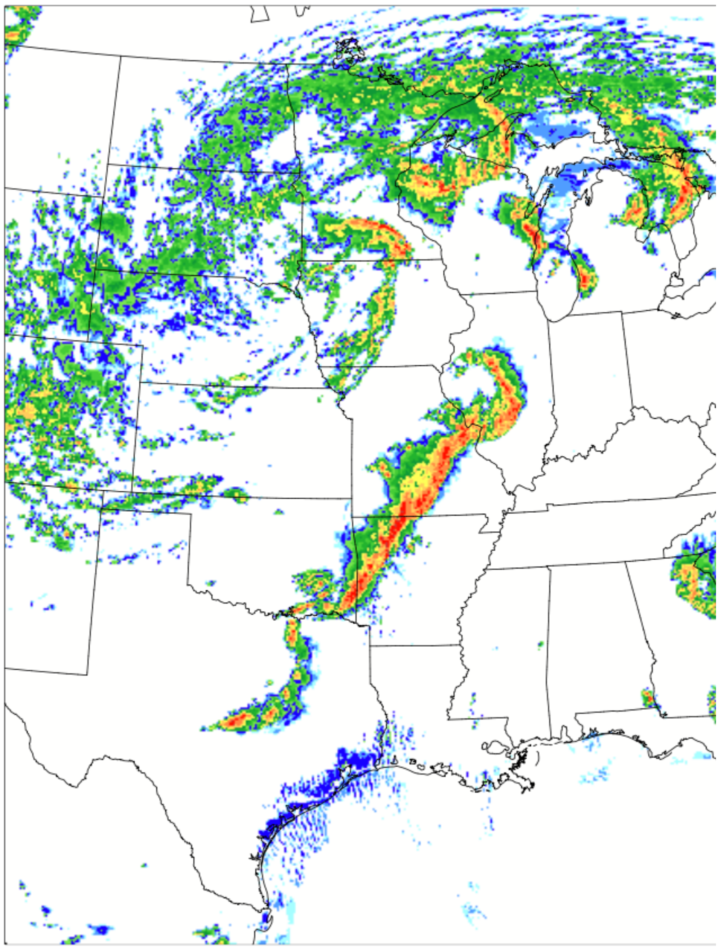
MPAS
Model for Prediction Across Scales

Variable Resolution Tests Forecast

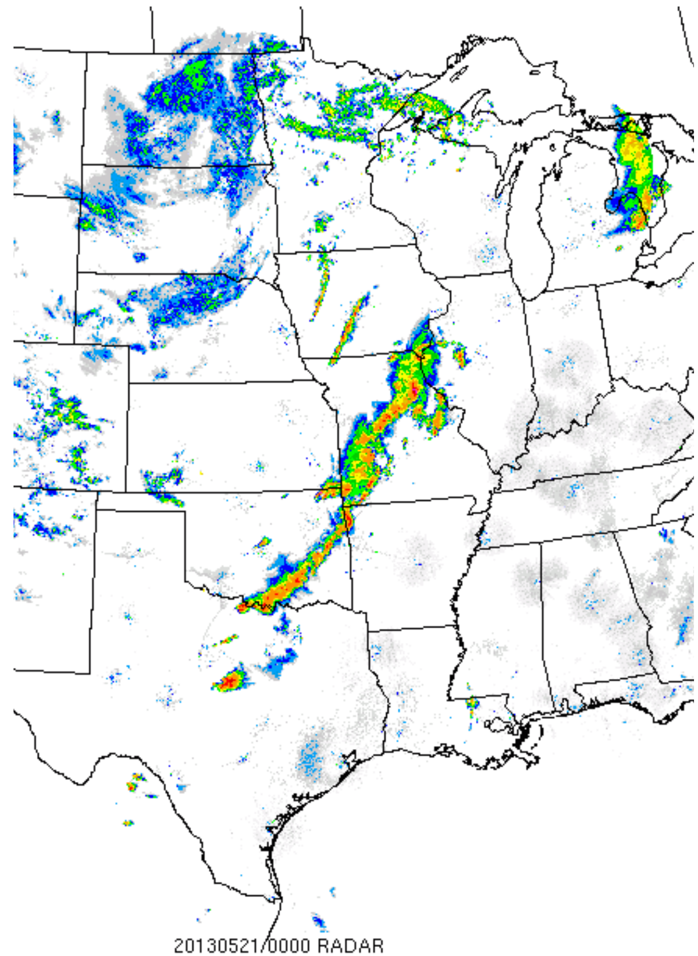
0 UTC 18 May – 12 UTC 21 May 2013

Central plains convection in MPAS, day 3

column max dBZ, 2013-05-21_00:00:00



MPAS, 72 h forecast



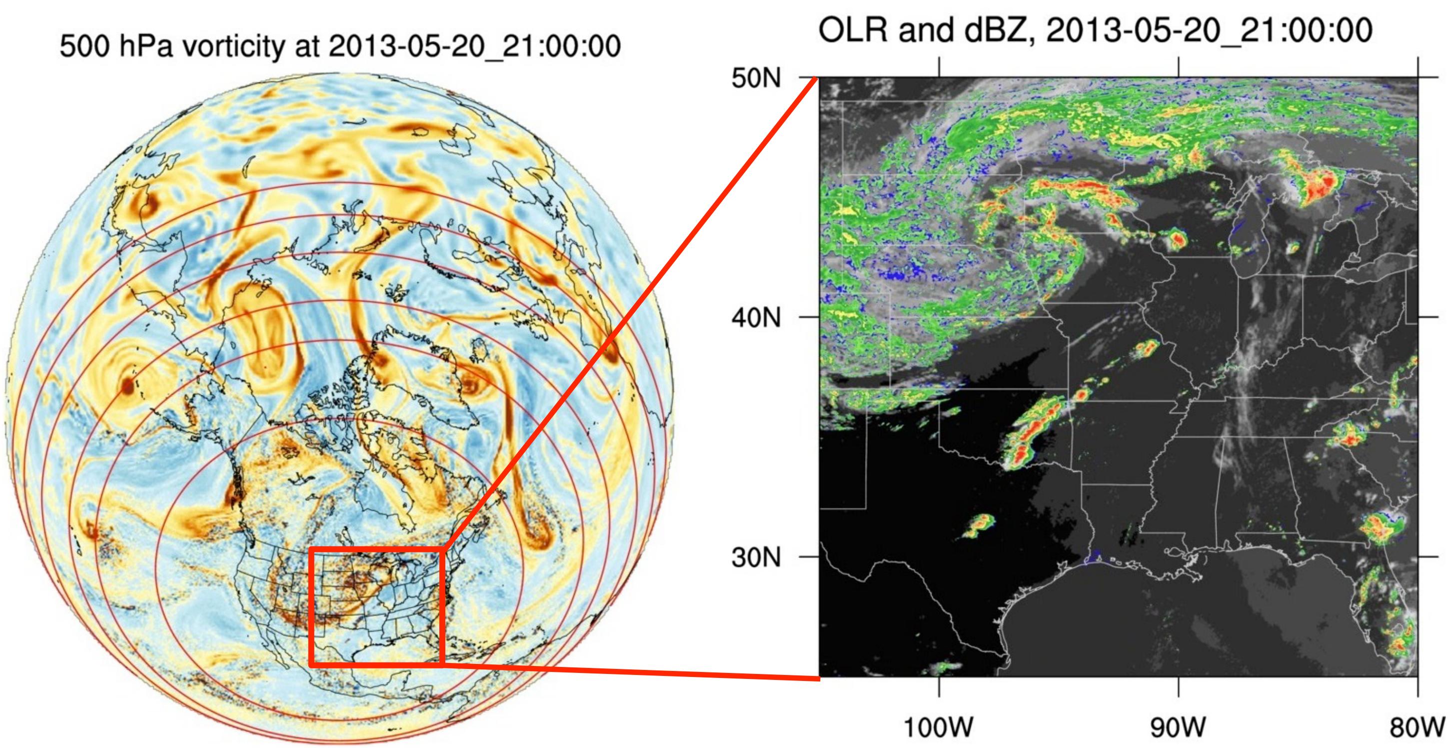
NWS radar composite

Variable Resolution Tests Forecast

0 UTC 18 May – 12 UTC 21 May 2013

Animation (next slide): What to observe

- Spin-up of small scales is relatively short, 6 to 12 hours.
- Relative vorticity: Smoothly evolving, most importantly in the mesh transition region. Evolving jet structure in central US, associated with tornadic storms, is evident.
- OLR and radar reflectivity: 3 convective episodes, severe storms in the warm sector ahead of the cold front. Upper-level low develops to the N-NW. Some hint of dry-line in the OLR.



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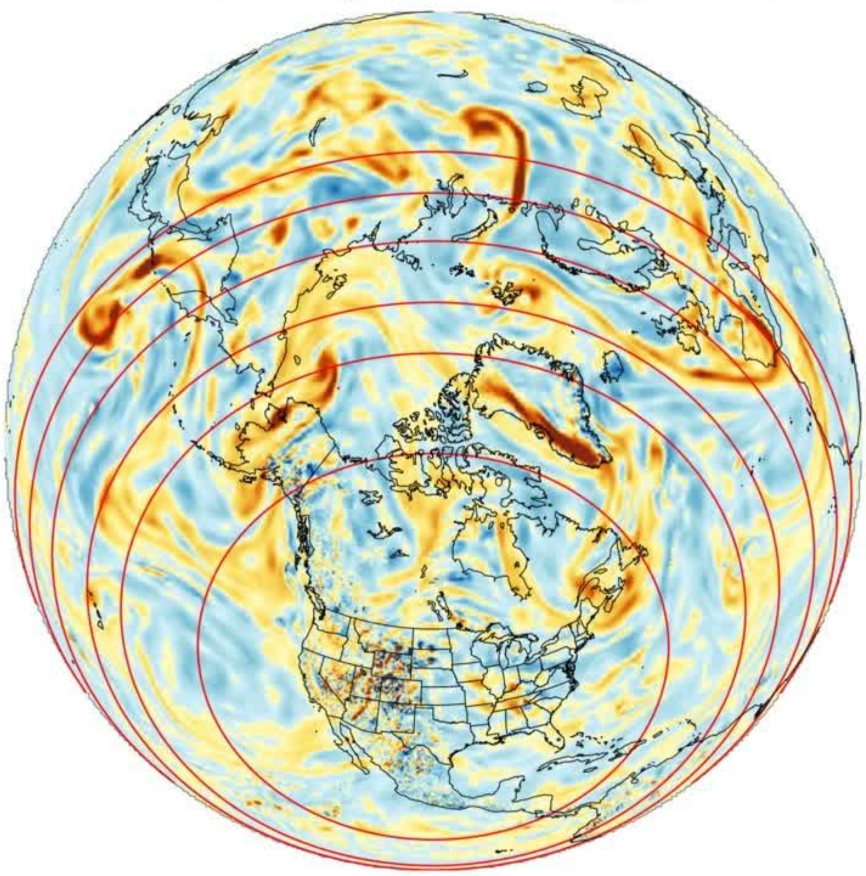
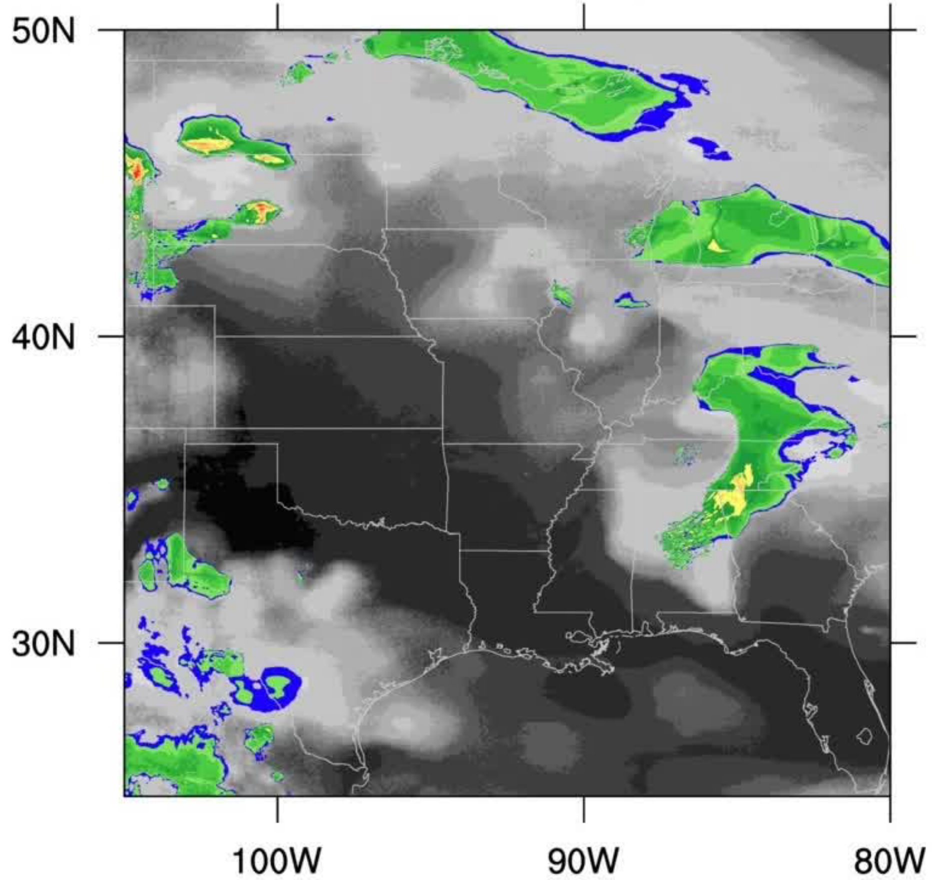




MPAS
Model for Prediction Across Scales

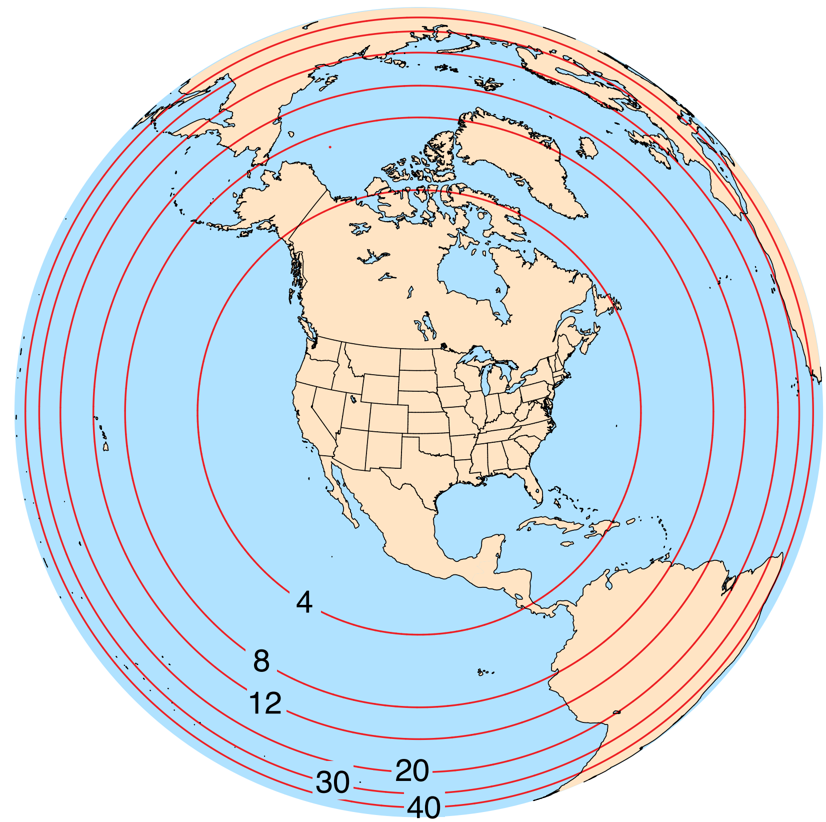
Hazardous Weather Testbed Spring Experiment 2015
Forecasts Results from MPAS

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

Application question:
Can a global variable-resolution convection permitting model provide extended range severe weather guidance?

Modeling question:
Will the MPAS parameterizations (convection, microphysics) result in appropriate behavior of the modeled precipitation processes in the mesh transition region?

MPAS mesh mean cell spacing (km)



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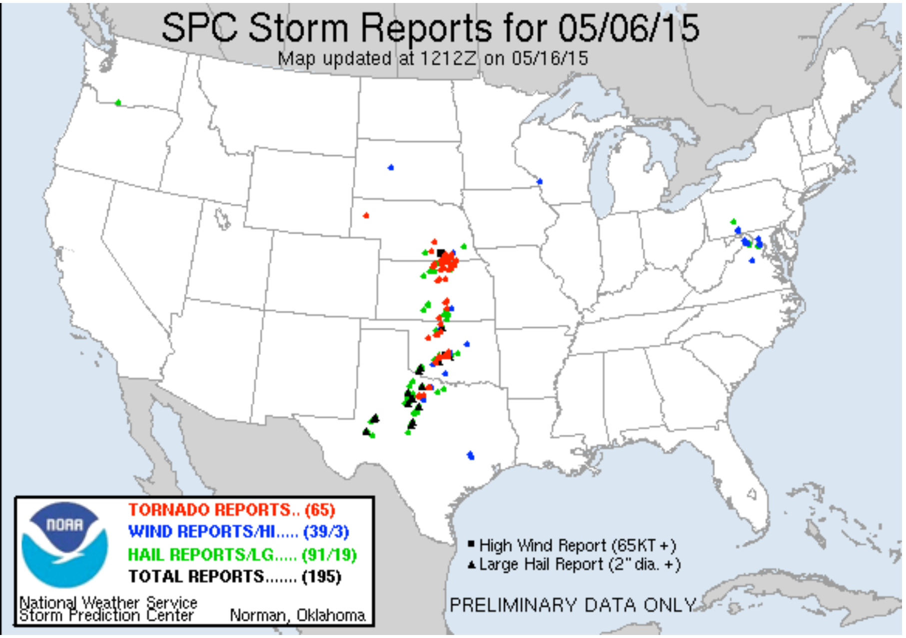
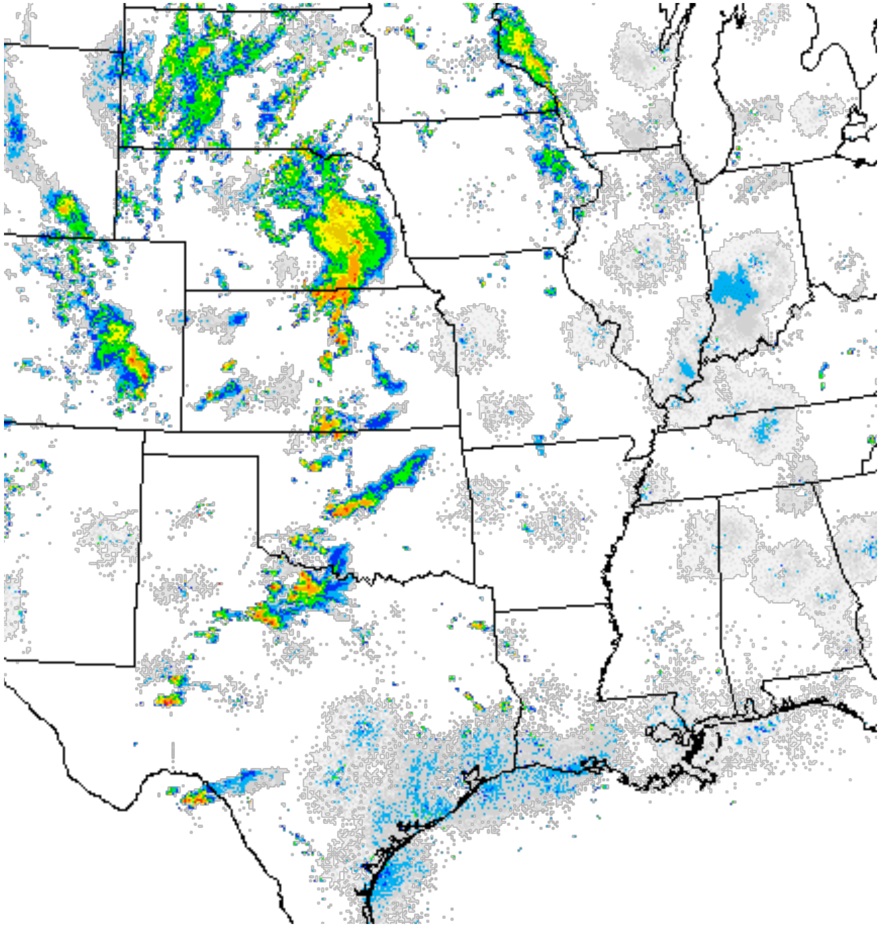


Reflectivity, NOAA SPC archive
valid 2015-05-07 00 UTC



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Hazardous Weather Testbed Spring Experiment 2015

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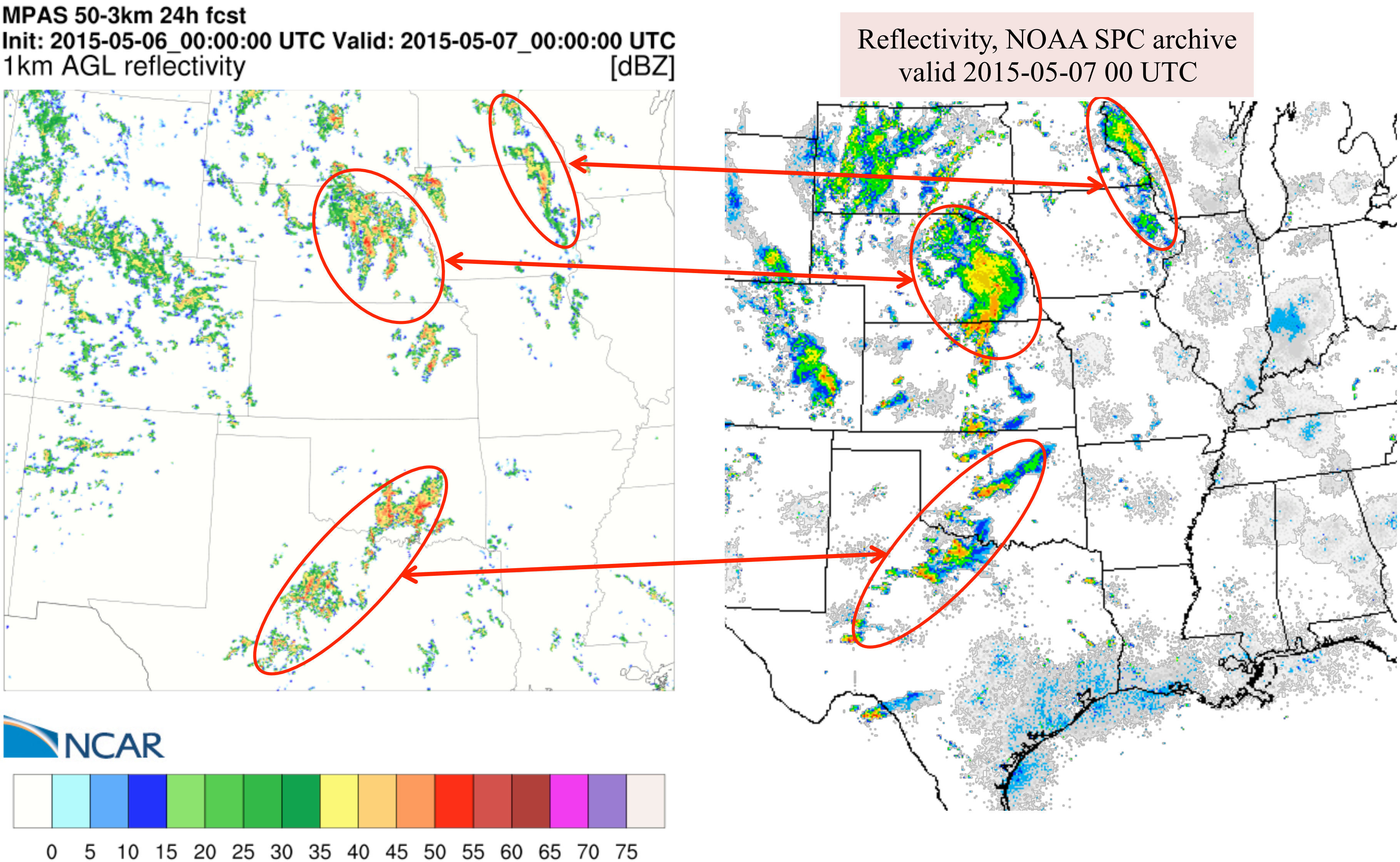

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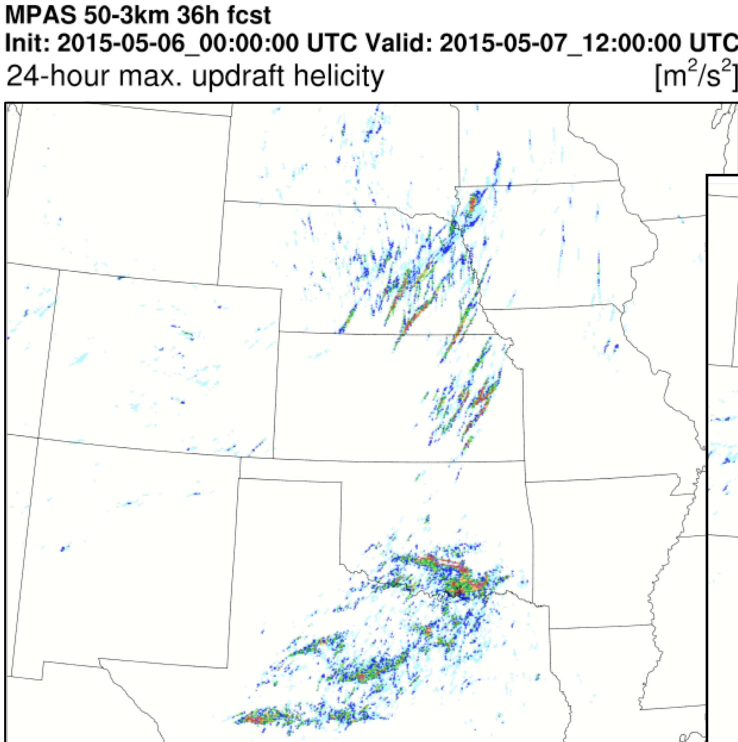
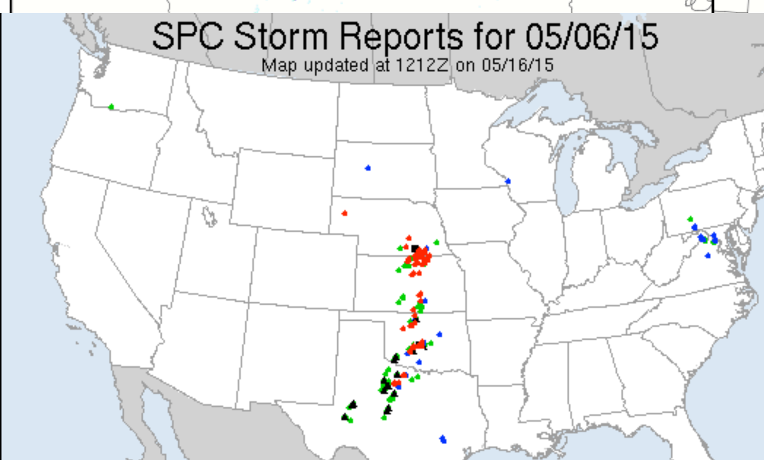
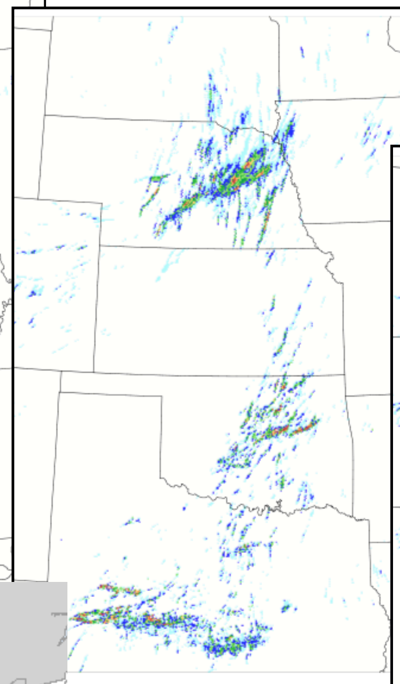
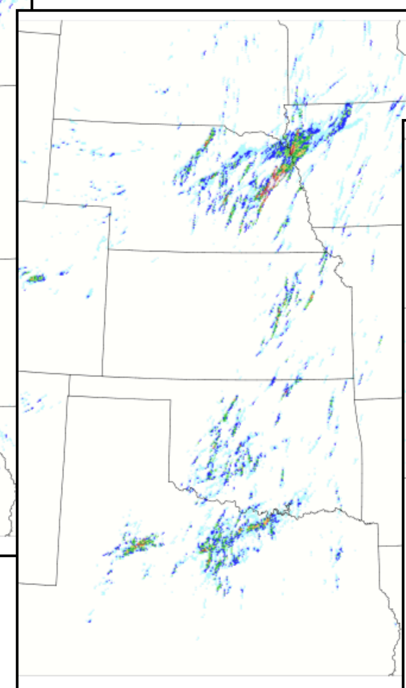




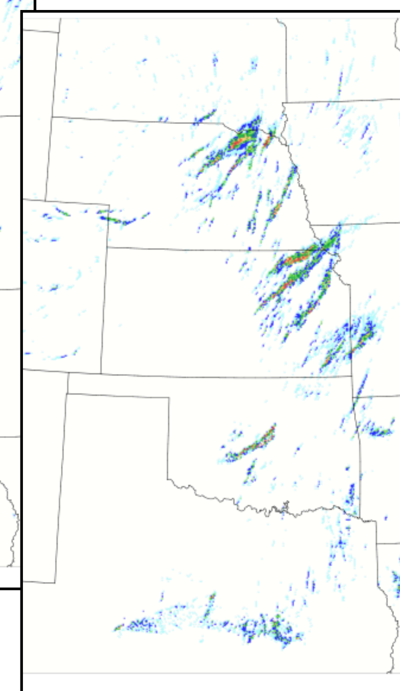
60h forecast



84h forecast



108h forecast



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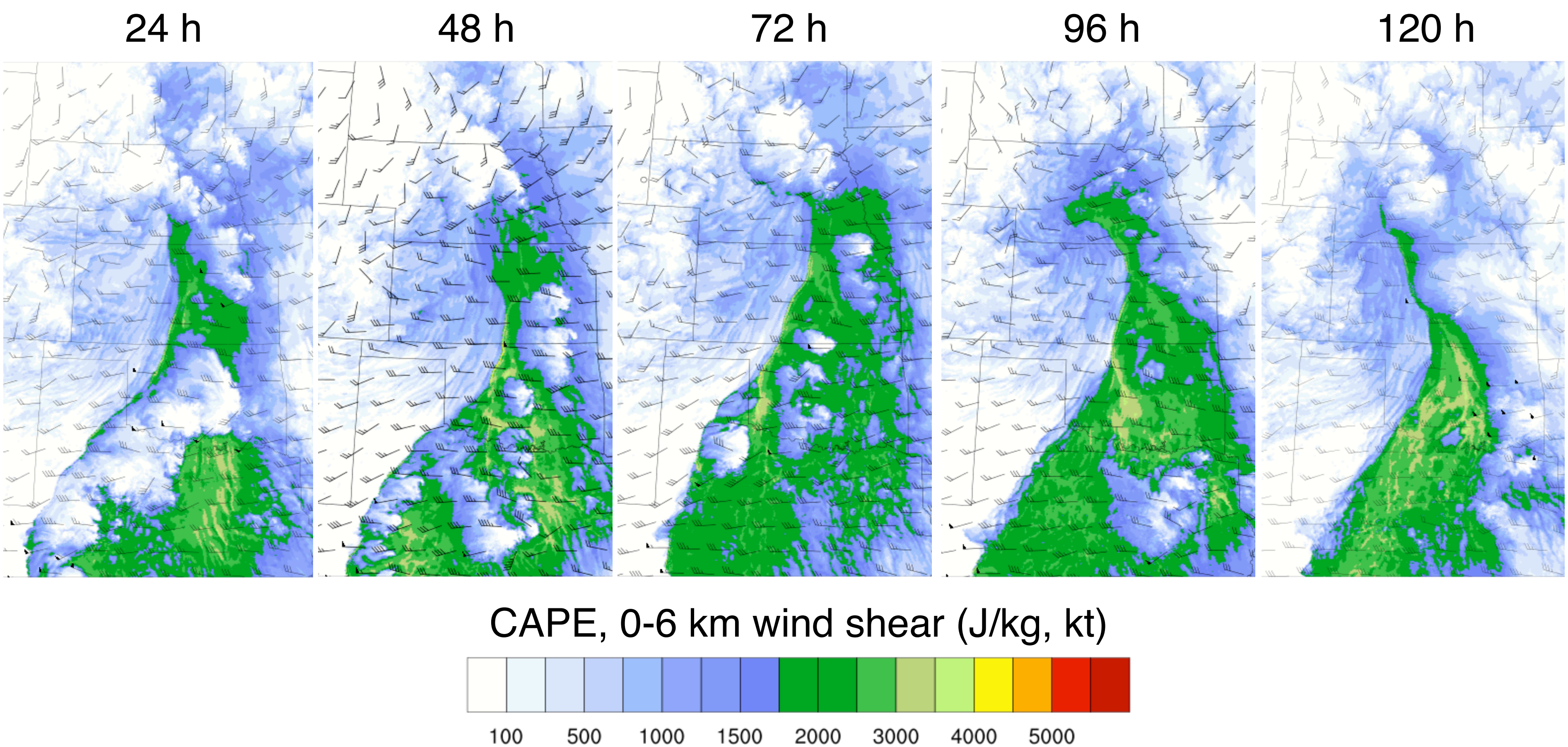
Hazardous Weather Testbed
Spring Experiment 2015
Forecasts Results from MPAS

Forecasts valid 2015-05-7 00 UTC



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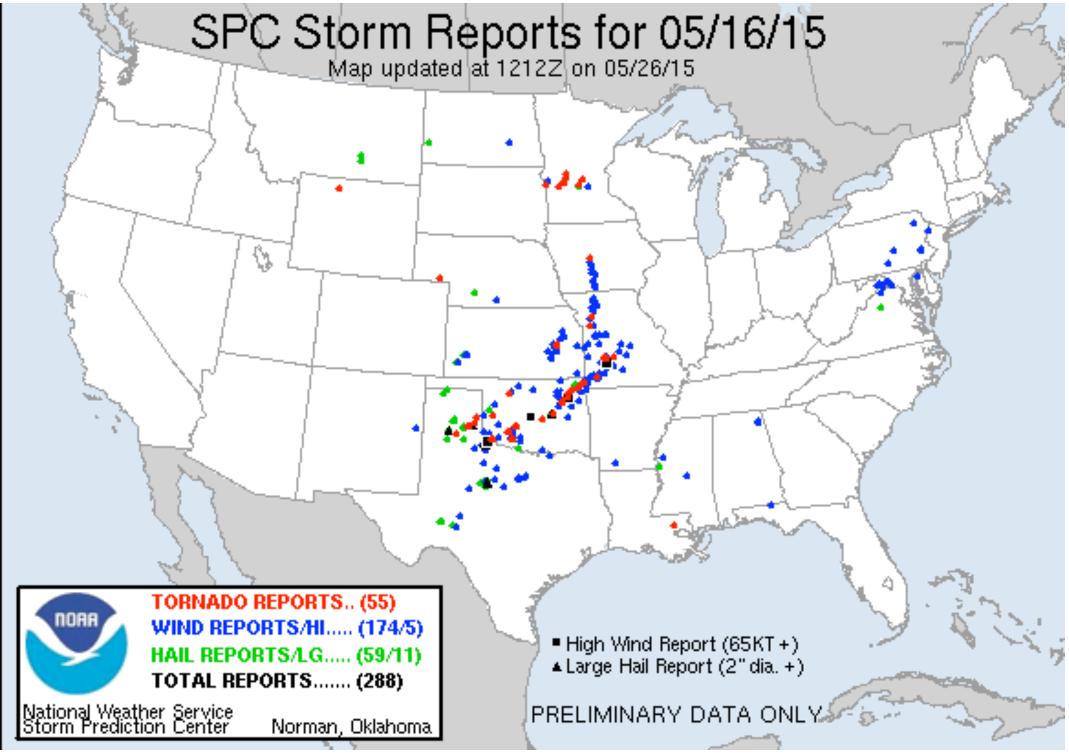
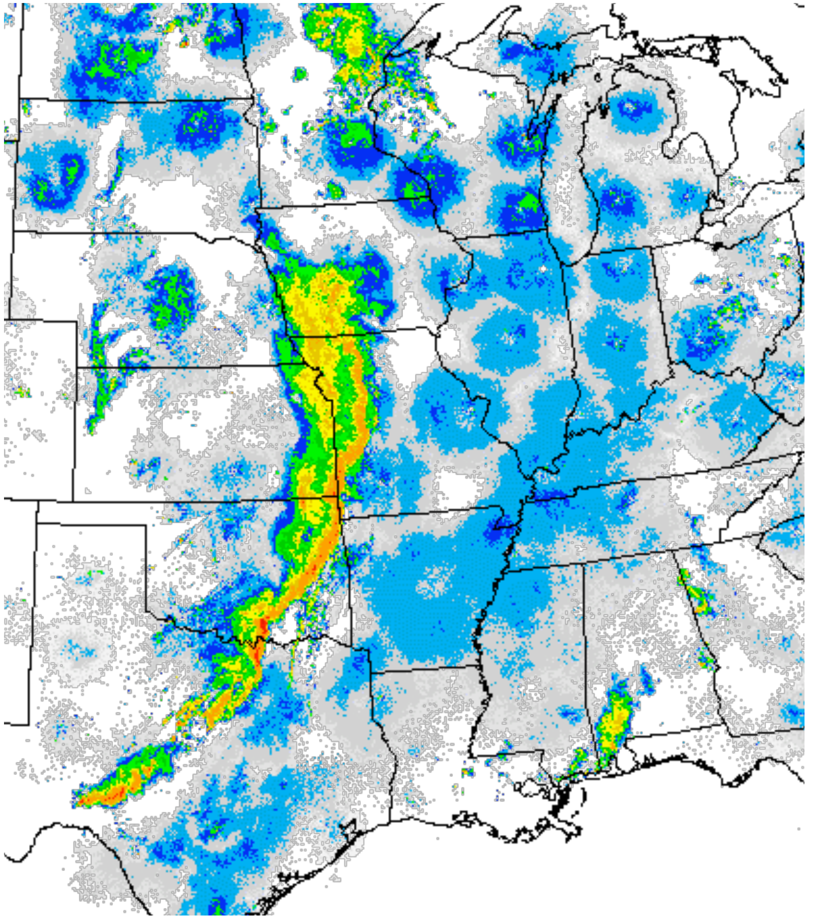
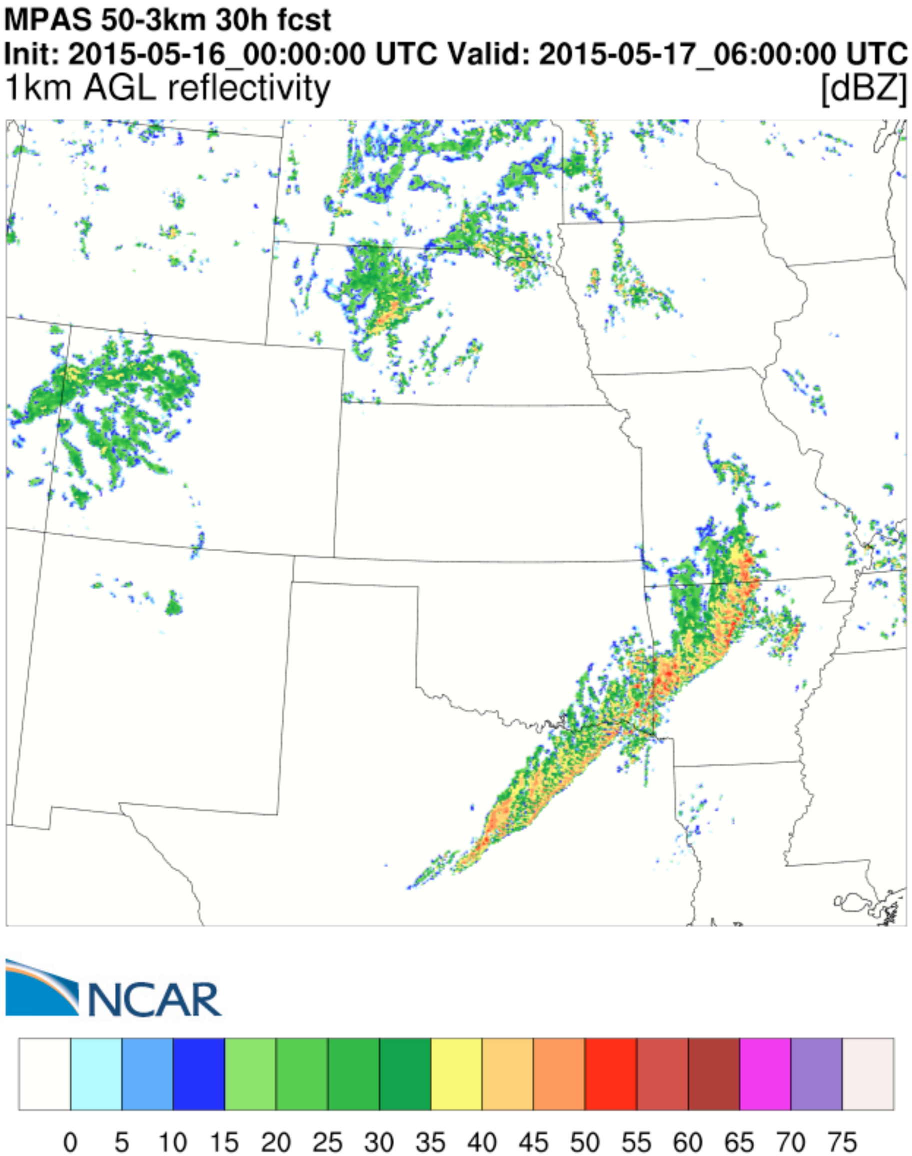


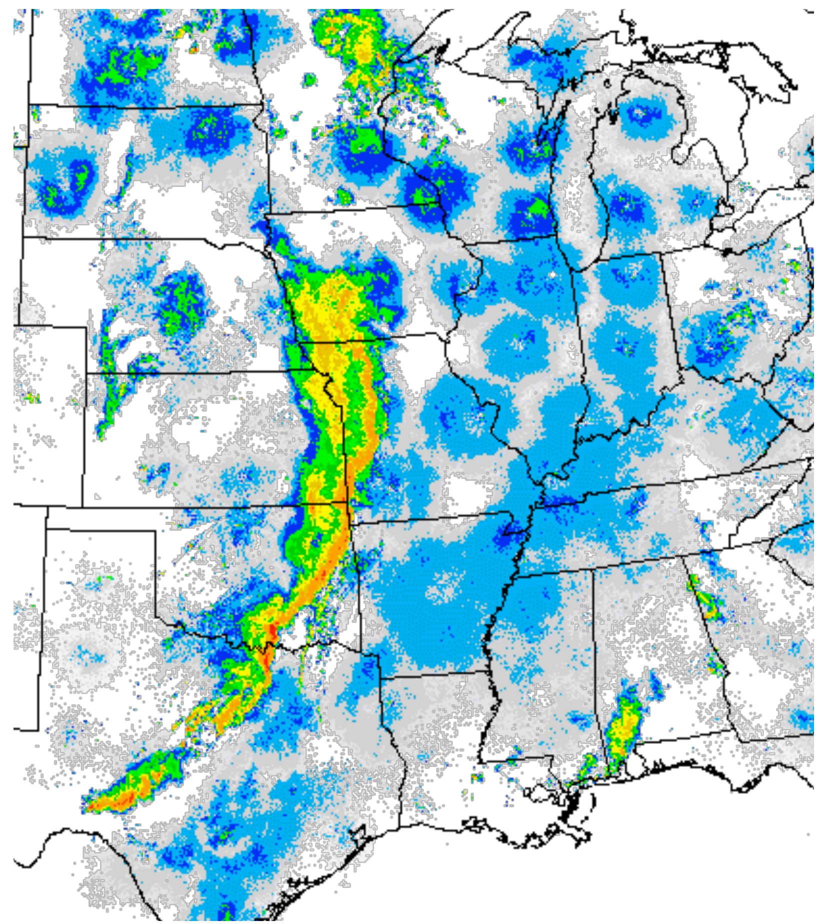
Reflectivity, NOAA SPC archive
valid 2015-05-17 06 UTC



Hazardous Weather Testbed
Spring Experiment 2015
Forecasts Results from MPAS



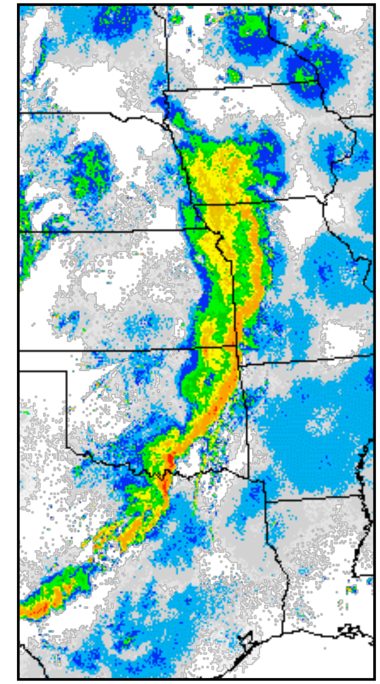
Reflectivity, NOAA SPC archive
valid 2015-05-17 06 UTC

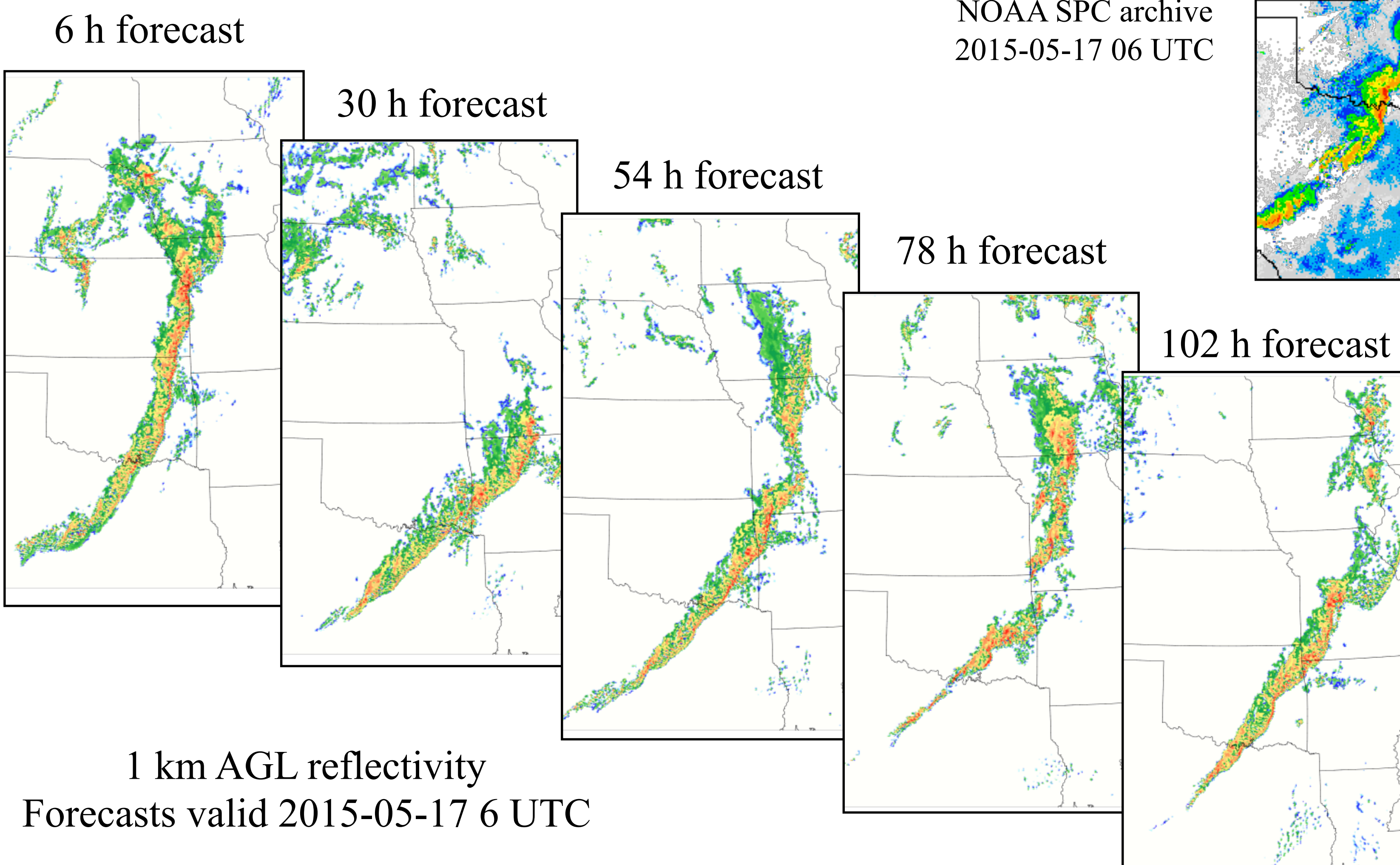


MPAS
Model for Prediction Across Scales

Hazardous Weather Testbed
Spring Experiment 2015
Forecasts Results from MPAS

Reflectivity
NOAA SPC archive
2015-05-17 06 UTC





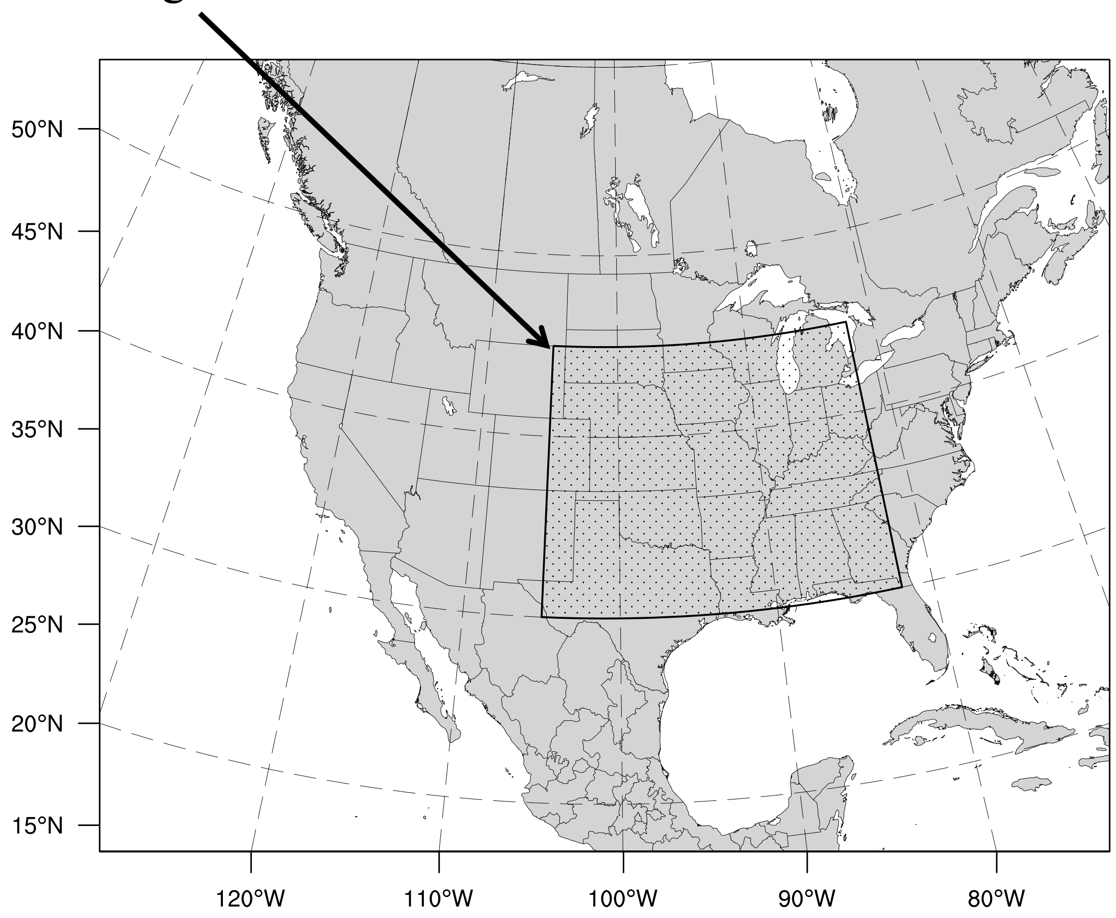
1 km AGL reflectivity
Forecasts valid 2015-05-17 6 UTC

MPAS
Model for Prediction Across Scales

Hazardous Weather Testbed Spring Experiment 2015

Verification against ST4 precipitation analyses

Verification region



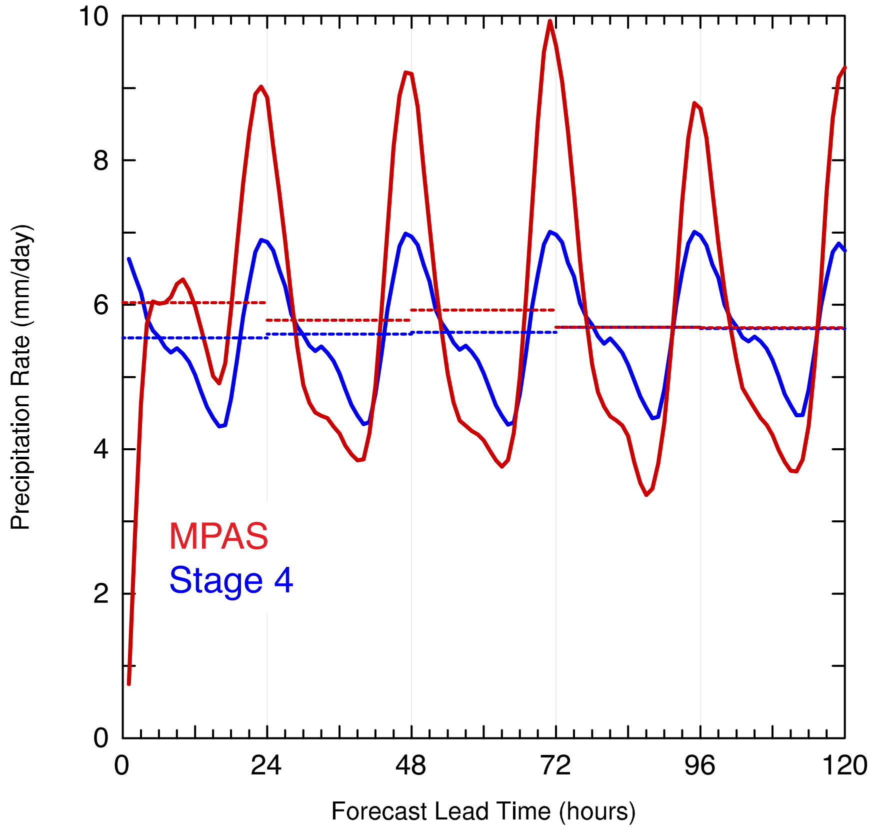
Hazardous Weather Testbed Spring Experiment 2015

Verification against ST4 precipitation analyses

- Timing of diurnal precipitation maxima and minima is very good.
- Significant over-estimation of diurnal precipitation maxima.
- Significant underestimation of diurnal precipitation minima.
- Over (under) estimation does not improve over time.

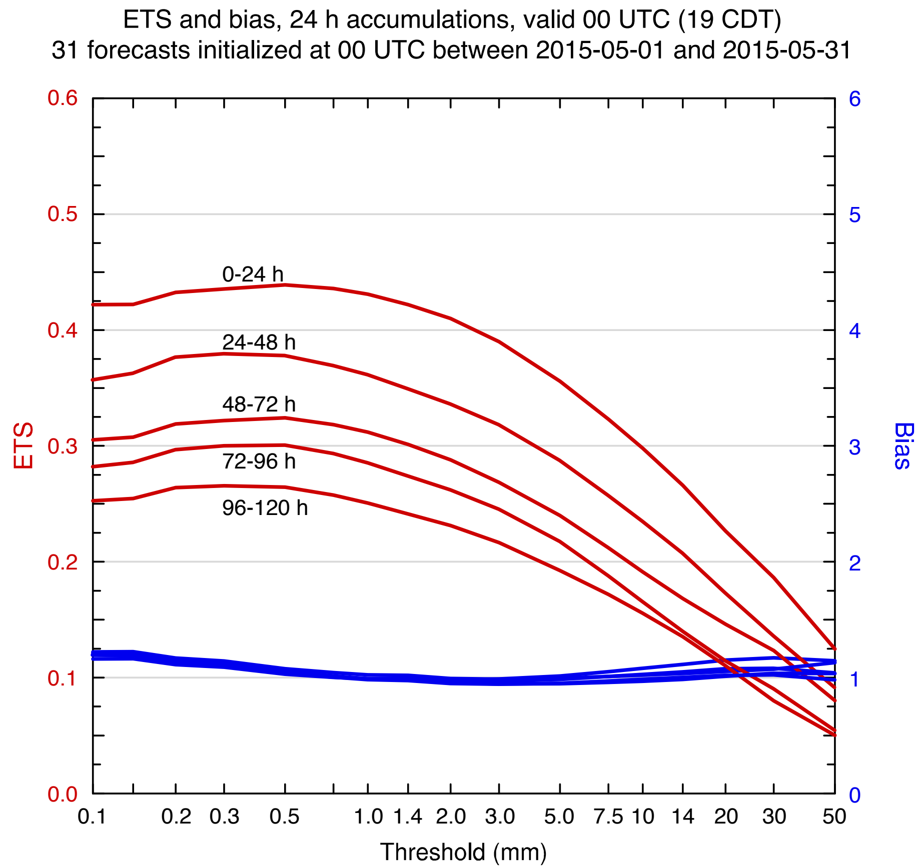
- Daily average precipitation (dashed lines) shows a small positive bias early, decreasing over time.

Average Precipitation Rate
1-31 May MPAS Forecasts,
NCEP Stage 4 Analyses



Hazardous Weather Testbed
Spring Experiment 2015
Verification against ST4 precipitation analyses

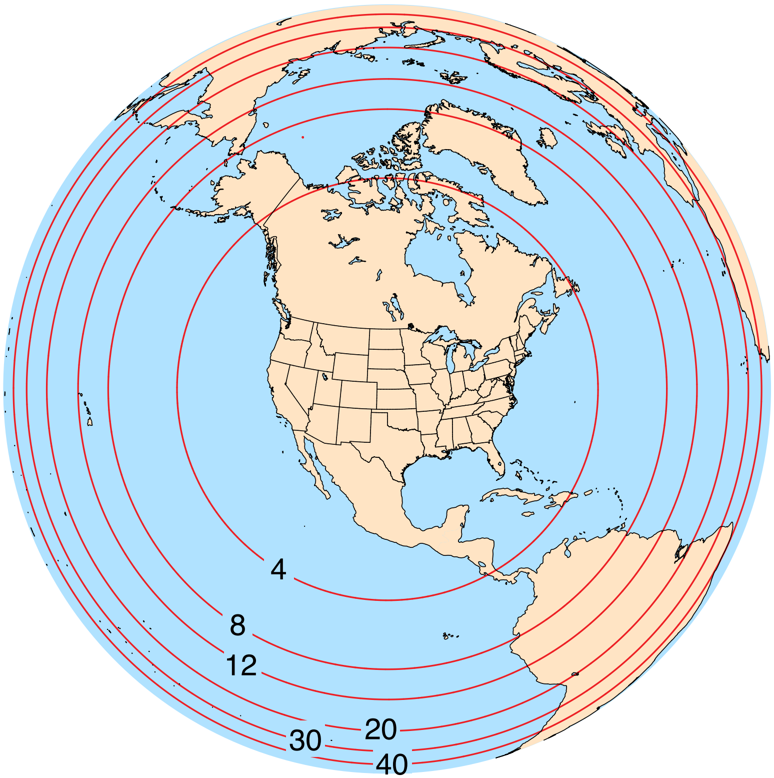
MPAS Model for Prediction Across Scales



24 h accumulations

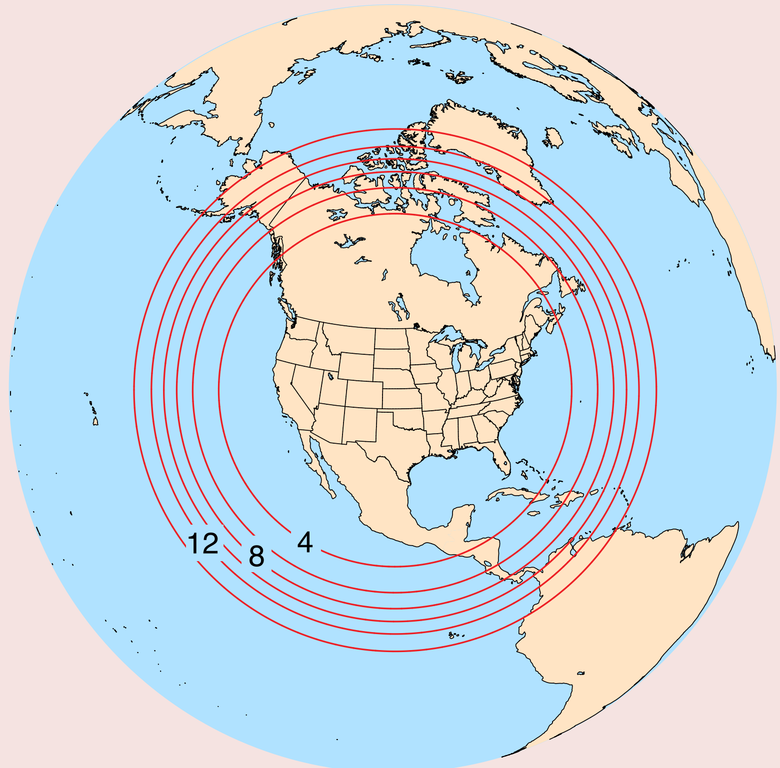
MPAS
Model for Prediction Across Scales

HWT Spring Experiment
5-day forecasts, 50 – 3 km mesh
1-31 May 2015



3-50 km mesh, Δx contours 4, 8, 12, 20, 30, 40
approximately 6.85 million cells
68% have < 4 km spacing

PECAN field campaign
3-day forecasts, 15 – 3 km mesh
7 June – 15 July 2015



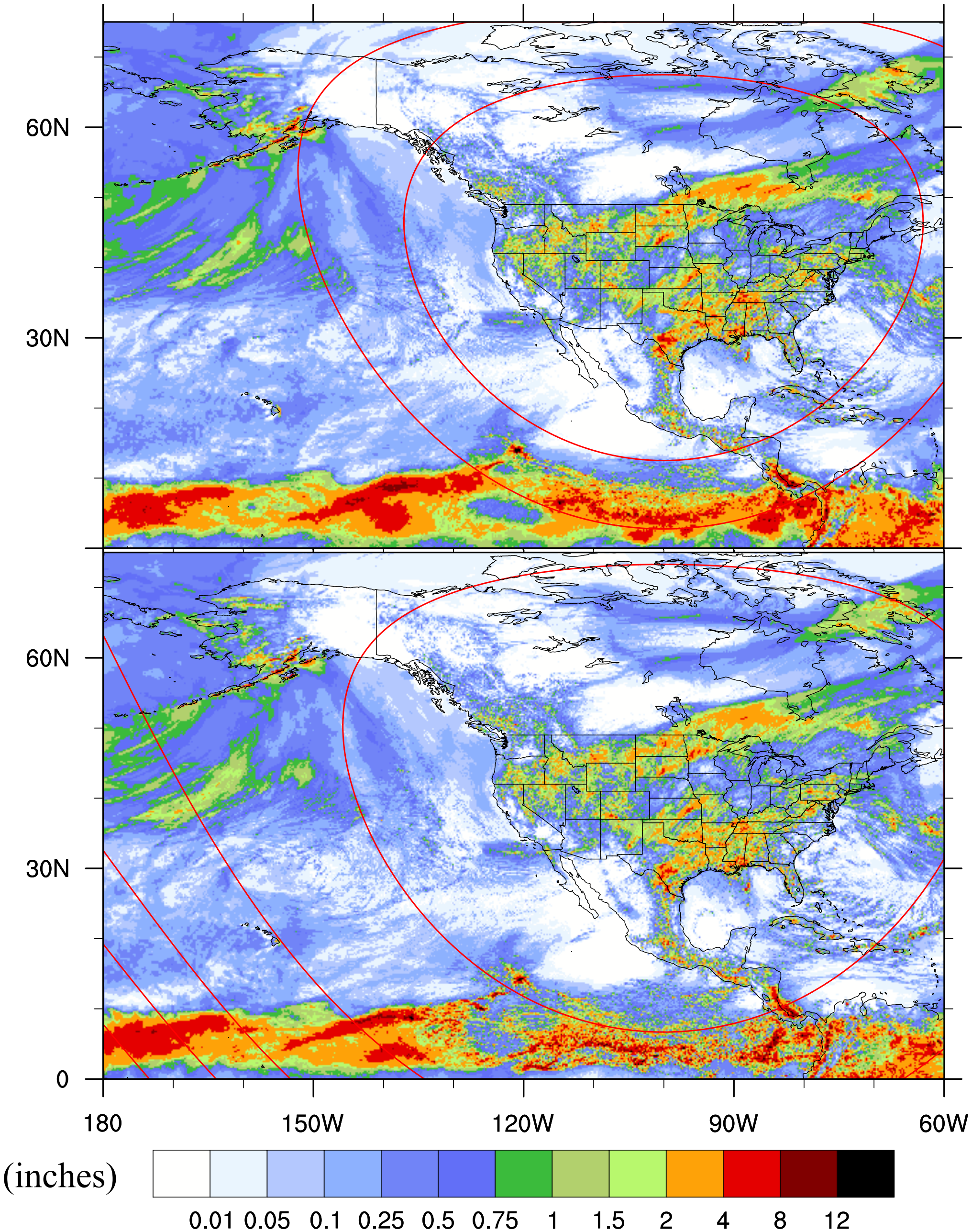
3-15 km mesh, Δx contours
approximately 6.5 million cells
50% have < 4 km spacing

15 May test forecasts comparing the response on the two meshes

2015-05-15 00 UTC
Initialization

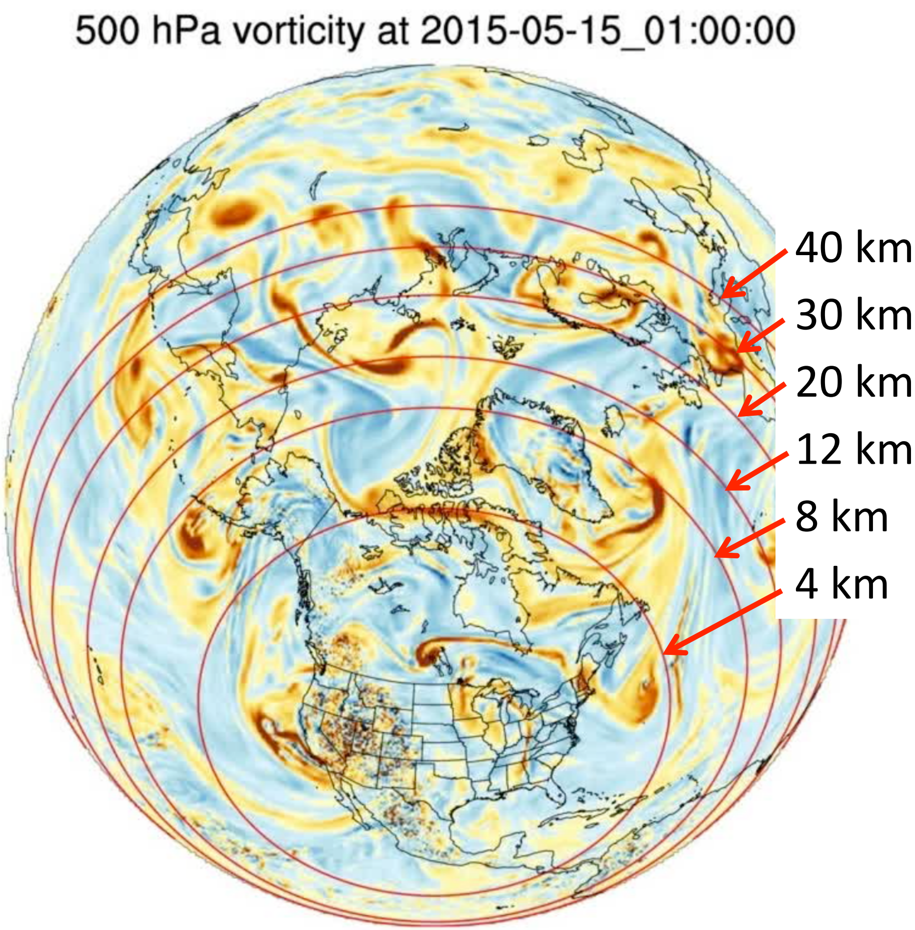
120 hour forecasts
accumulated precipitation

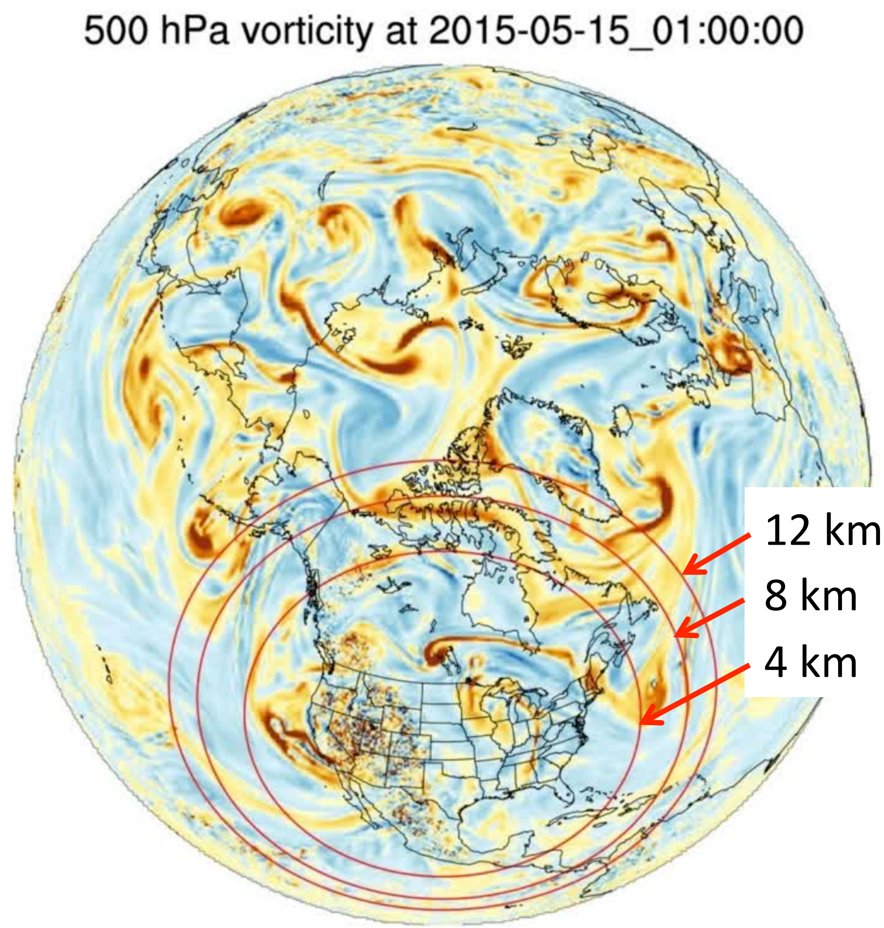
Mesh spacing contours
4, 10, 20, 30, 40 km



Variable Resolution Tests Forecast

0 UTC 15 May – 0 UTC 20 May 2015

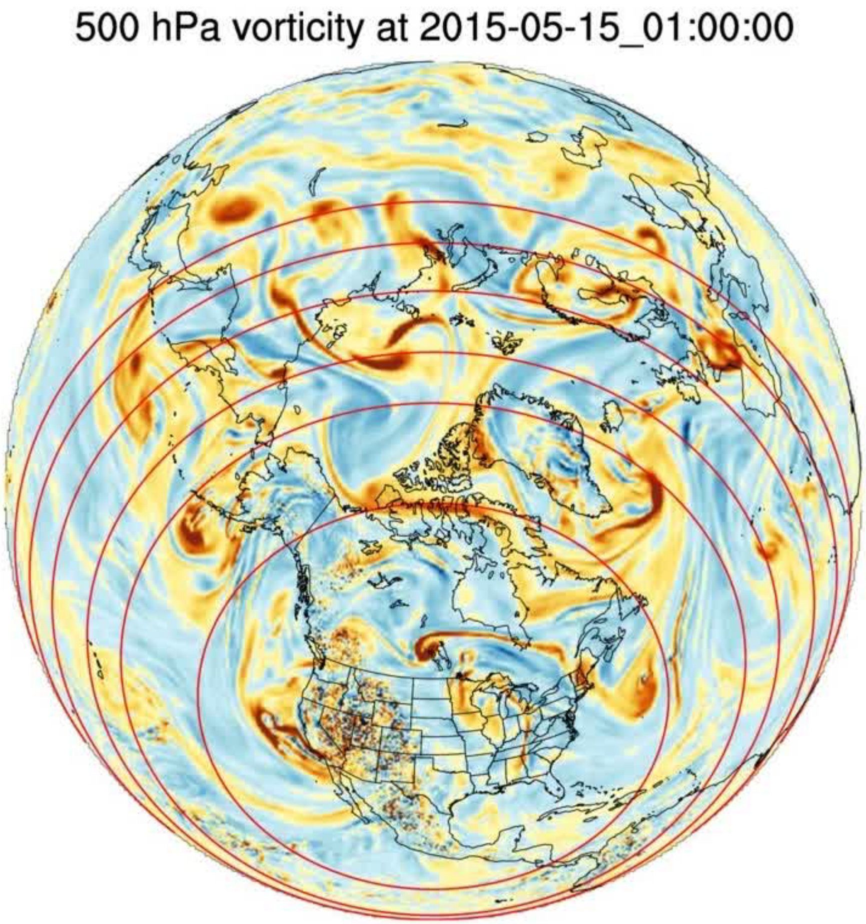


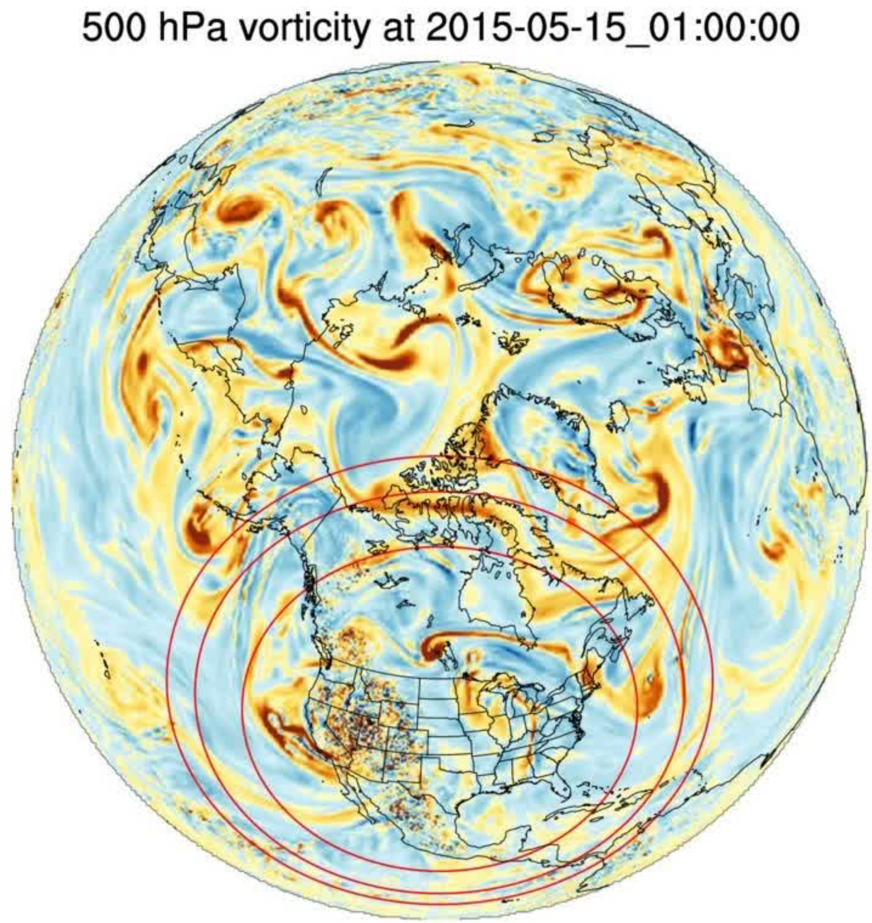


MPAS
Model for Prediction Across Scales

Variable Resolution Tests Forecast

0 UTC 15 May – 0 UTC 20 May 2015





Variable Resolution Tests Forecast

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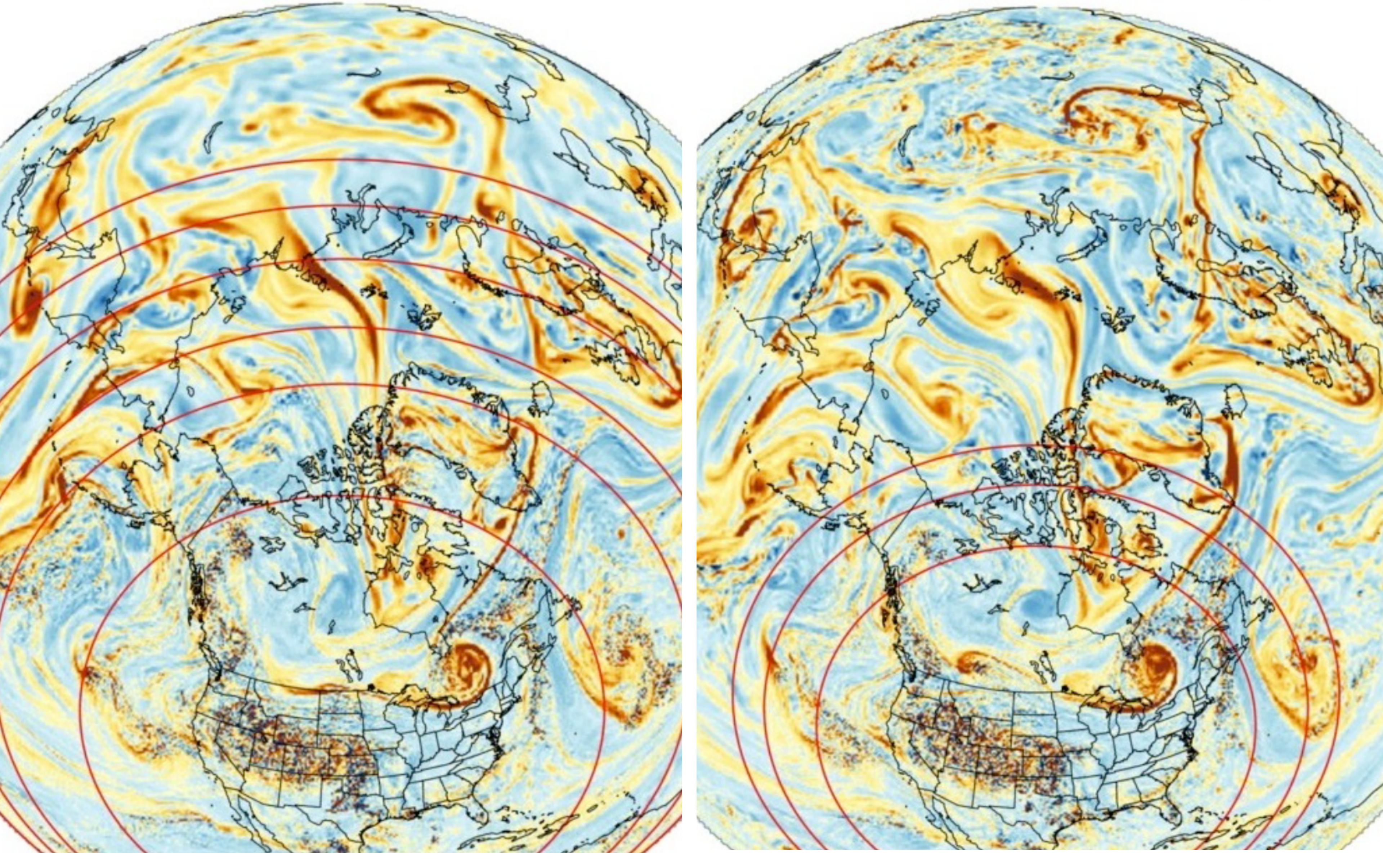


MPAS
Model for Prediction Across Scales

Convective Forecasts with a Global Atmospheric Model

Summary

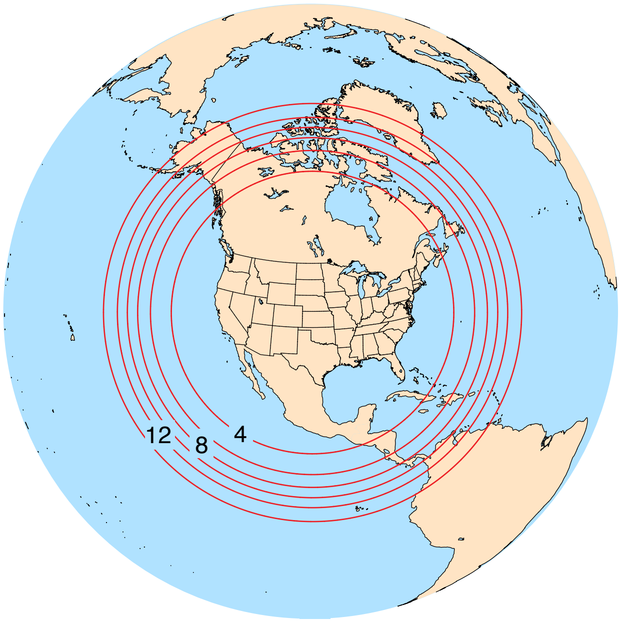
Variable-resolution, nonhydrostatic-scale atmospheric simulations are viable

- Fidelity of convection similar to that in ARW.
- MPAS variable-resolution forecasts may contain some extended-range convective guidance.
- Simulation rates >100 days/day are attainable.
- GF convection scheme appears to be viable for hydrostatic-nonhydrostatic scale-aware applications.

Challenges

Scale-aware physics:
- *Convection*
- Microphysics
- Boundary layer

Data assimilation on variable meshes



3-15 km mesh, Δx contours
approximately 6.5 million cells
50% have < 4 km spacing

Forecasts available at
http://wrf-model.org/plots/realtime_main.php

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