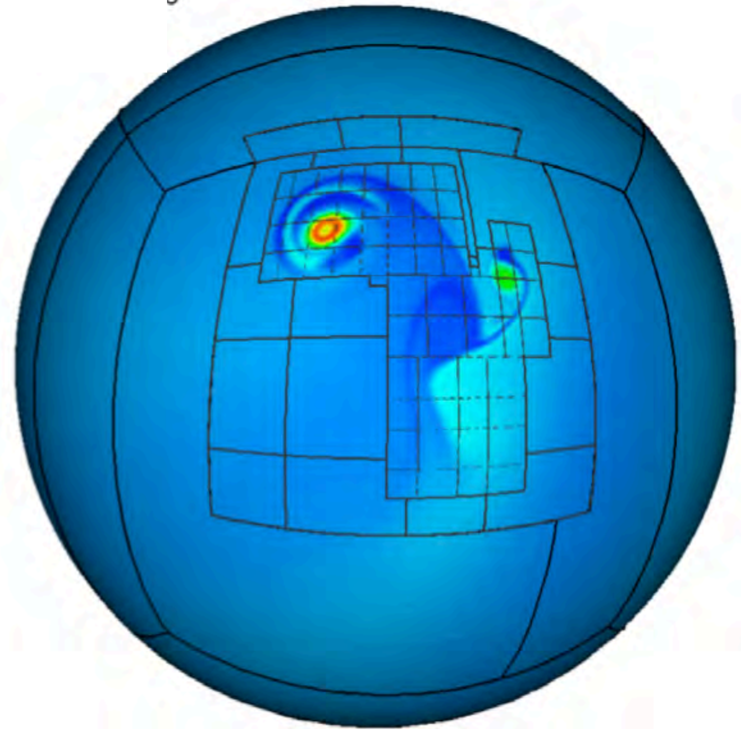
High-Resolution Climate Modeling via Variable-Resolution Approaches



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PRIMAVERA Meeting

KNMI, De Bilt, Netherlands, Nov/29-Dec/1, 2016

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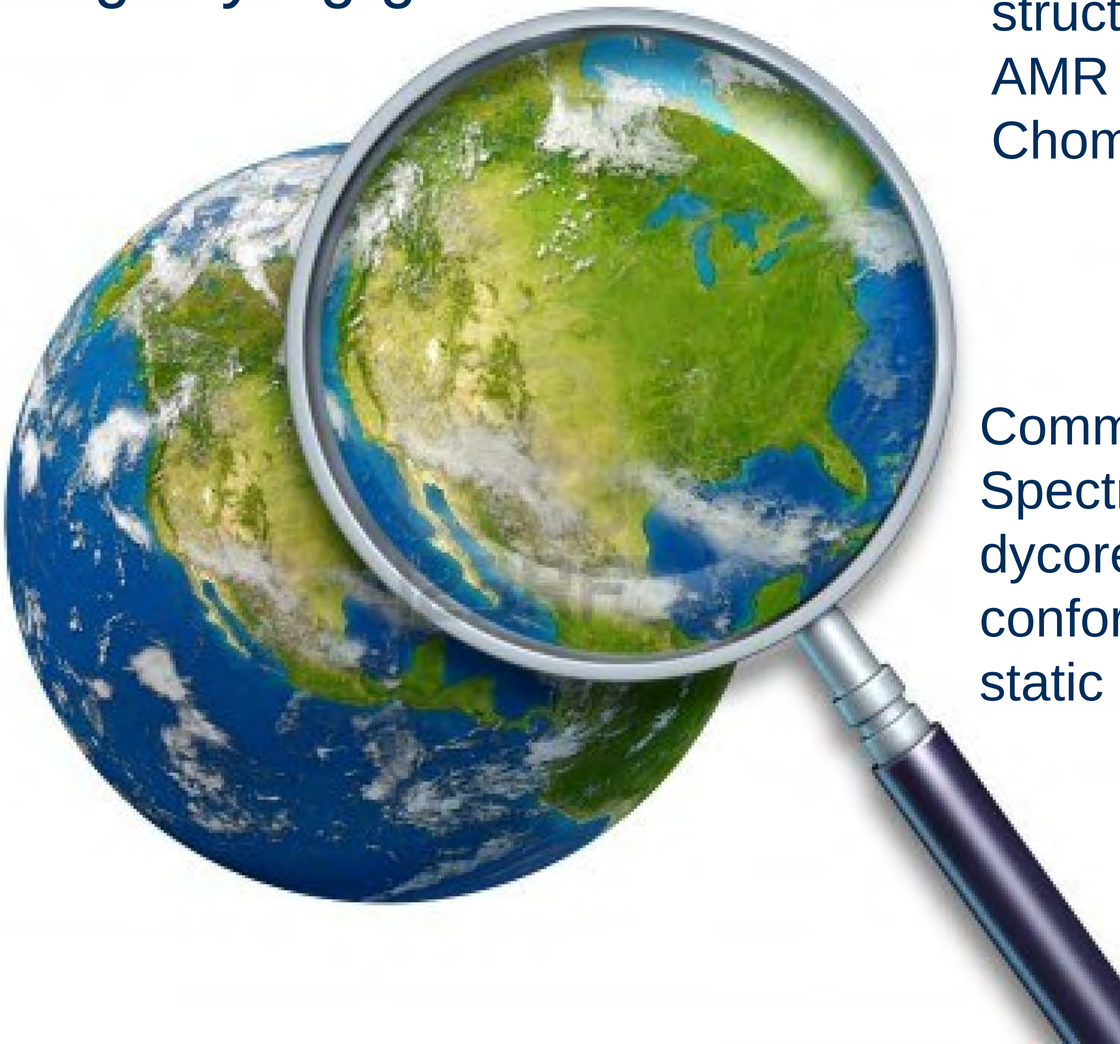
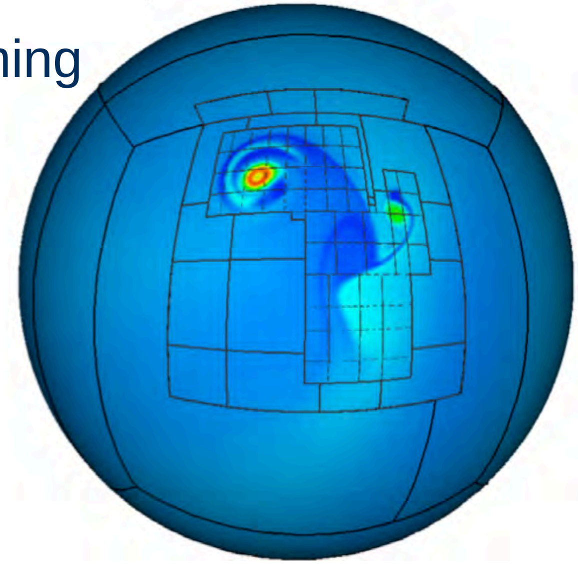
AMR and Variable-Resolution Modeling

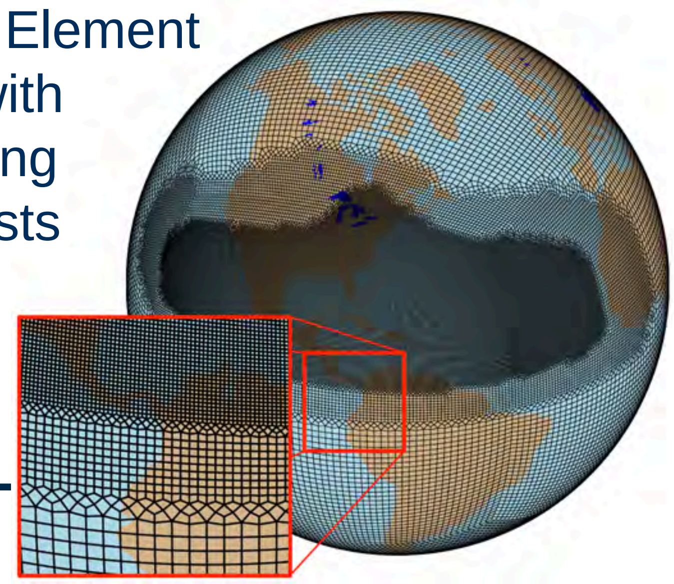
Variable resolution acts as a magnifying glass



Non-conforming block-structured AMR with Chombo



Community Atmosphere Model (CAM) Spectral Element dycore with conforming static nests



Overview of the talk

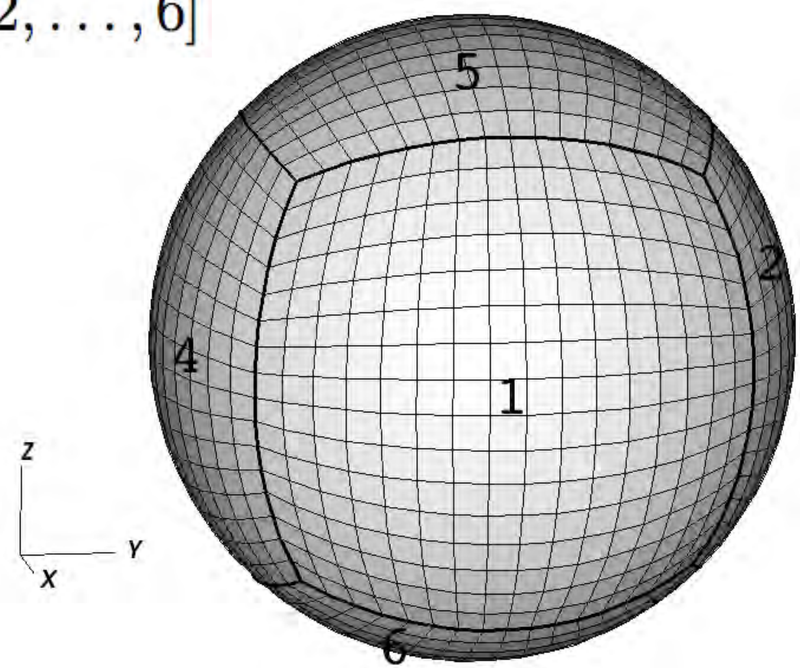
1. Adaptive Mesh Refinement (AMR) Modeling with the Chombo-AMR model
    - Focus of the AMR assessments in a 2D shallow water mode

2. Variable-Resolution Modeling with the Spectral Element dynamical core of the NCAR/Department of Energy (DoE) Community Atmosphere Model (CAM)
    - Full-physics model assessments (with prescribed sea surface temperatures) in long-term “climate mode” and short-term “weather prediction mode”

Chombo Model Description: Cubed Sphere

- AMR Library, developed at DoE's Lawrence Berkeley National Lab (LBNL)
- Gnomonic (equiangular) cubed-sphere grid with $\Delta\alpha = \Delta\beta$
- Coordinates are given in terms of (α, β, n_p) where $\alpha, \beta \in [-\frac{\pi}{4}, \frac{\pi}{4}]$ and $n_p \in [1, 2, \ldots, 6]$
- Resolution given in c{N_c}

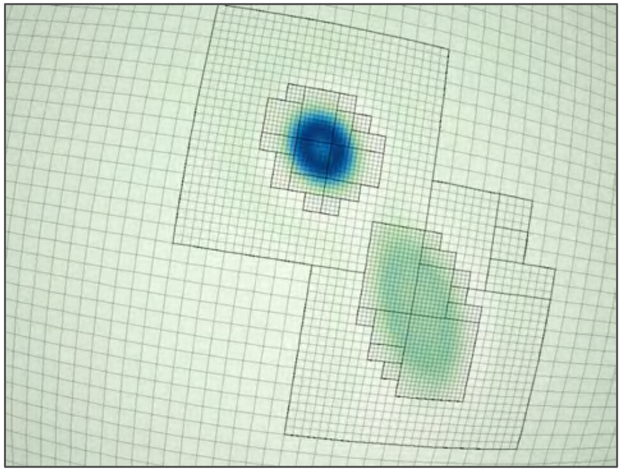
Resolution	Δ x	Δ degree	TXX equiv
c32	313 km	2.8°	T42
c64	156 km	1.4°	T85
c128	78 km	0.7°	T170
c256	39 km	0.35°	T340
c512	20 km	0.18°	T680



Chombo-AMR Dynamical Core

Multi-block Refinement

- Refinement grid levels are nested on coarse levels
- Arbitrary number of levels and refinement ratio (factors of 2: 2,4,8 tested)
- Intermediate levels must have sufficient number of cells between levels for ghost cell interpolation
- Refinement can be determined by various refinement criteria:
  - *Height gradient, Vorticity, Tracer values, Topography, combinations*



Resolution	Δx
c32	313 km
c64	156 km
c128	78.2 km
c256	39.1 km
c512	19.5 km

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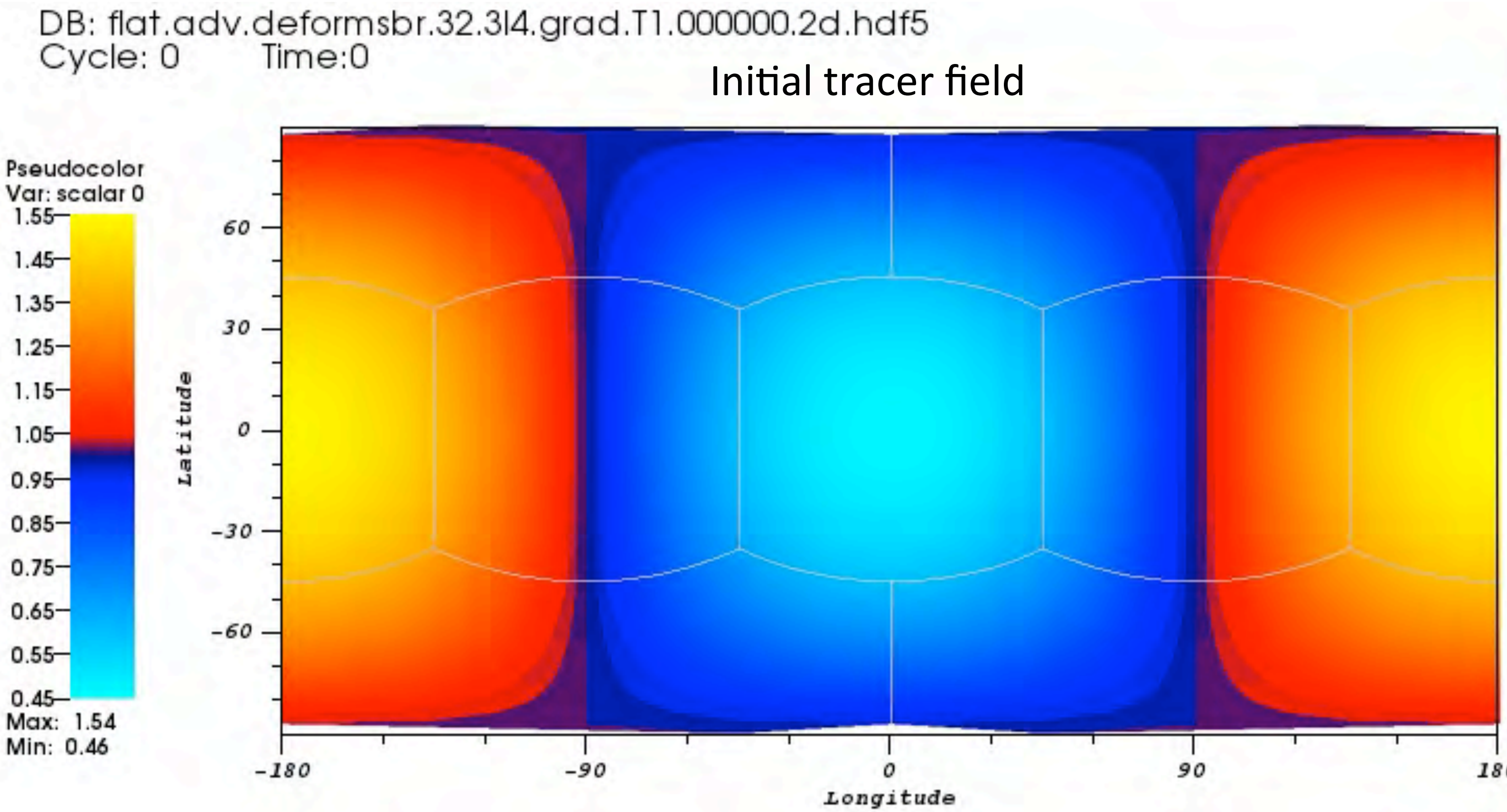
Chombo-AMR Test Cases

- AMR Advection Test
  – Moving Vortices (Nair and Jablonowski, 2008)
- Shallow Water Tests
  – Do No Harm Tests
    - Steady-state test case (test case 2 of Williamson et al., 1992)
  – AMR Tests
    - Symmetric Vortices

Ferguson, J. O., C. Jablonowski, H. Johansen, P. McCorquodale, P. Colella and P. A. Ullrich (2016), Analyzing the Adaptive Mesh Refinement (AMR) characteristics of a high-order 2D cubed-sphere shallow-water model, Mon. Wea. Rev., Vol. 144, 4641-4666

Advection Test: Moving Vortices

Advection test case in which an initially smooth passive tracer is rolled up into tight spiral bands over a 12 day period. (*Nair and Jablonowski, 2008*), has an **analytic solution**

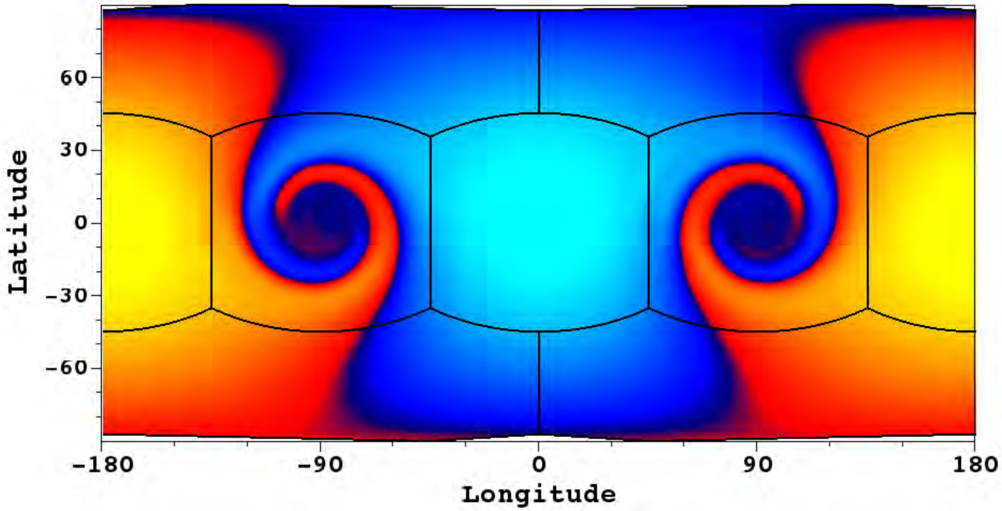


Initial tracer field

AMR c32/c128/c512 (from 310 km to 20 km)

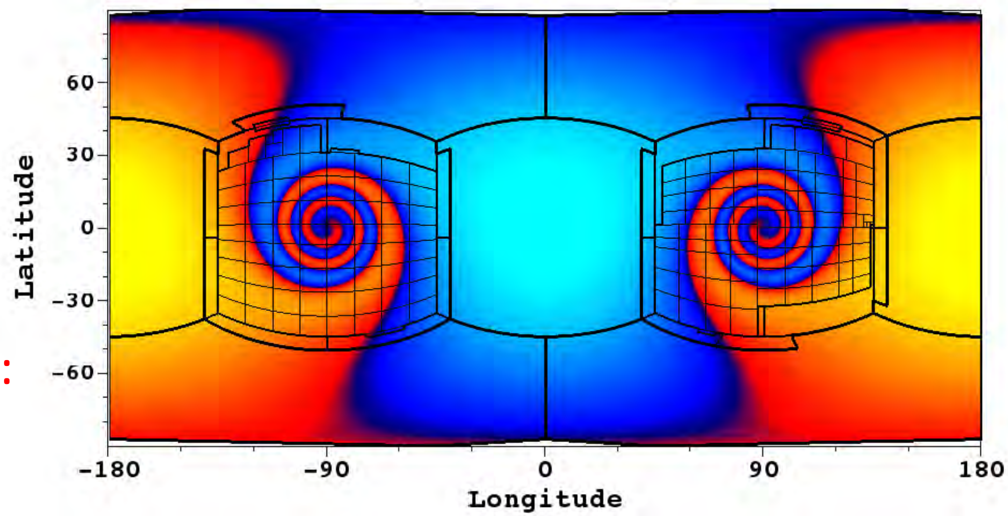
Advection Test: Tracer Field of the Moving Vortices Test at Day 12

Uniform c32
(313 km)



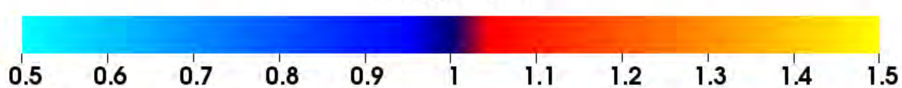
Vortices are diffused, resolution not sufficient to capture the strong gradients of the tracer

AMR
c32/c128/c512
(313/156/39 km)



AMR grid retains the accuracy of the spiraling tracers

Refinement ratio: factor of 4



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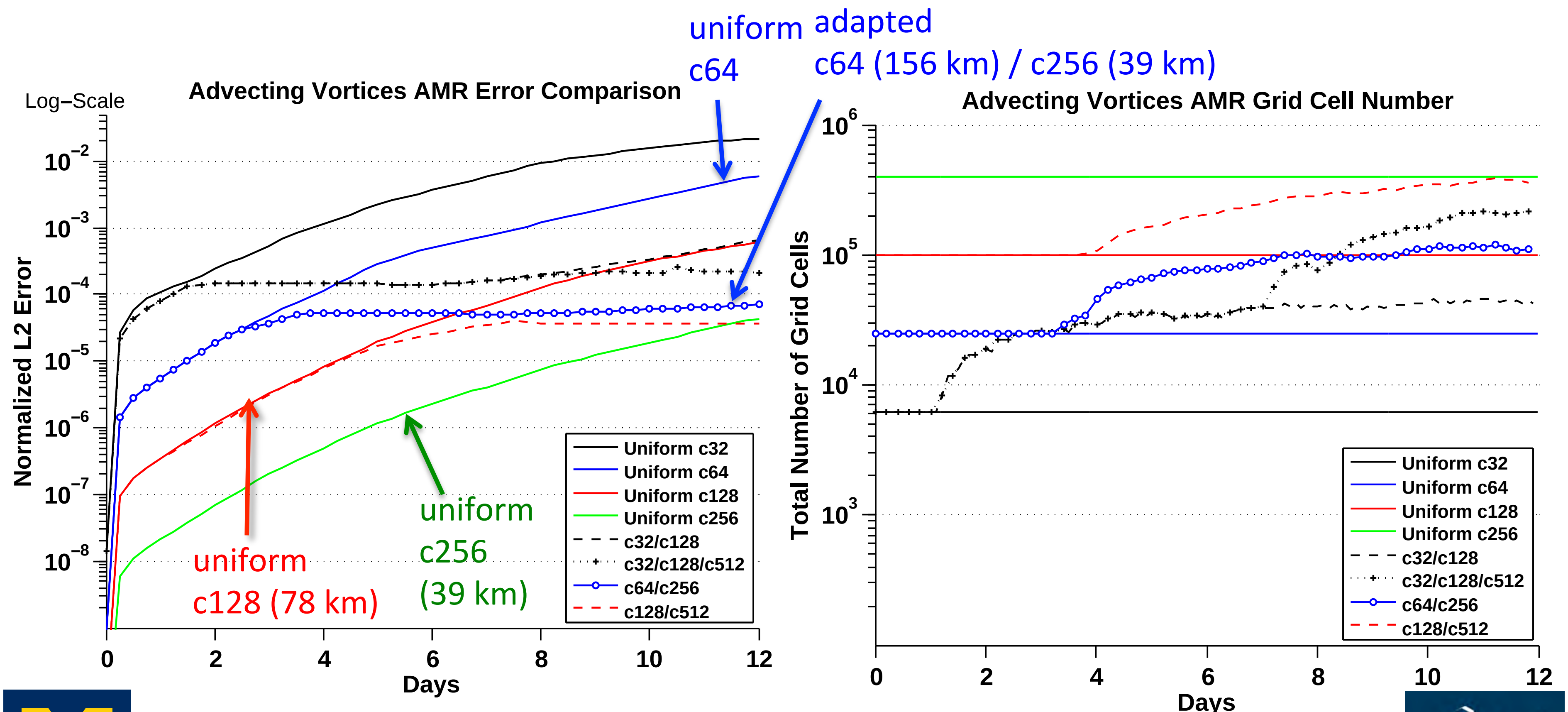
Advecting Vortices: Error norms

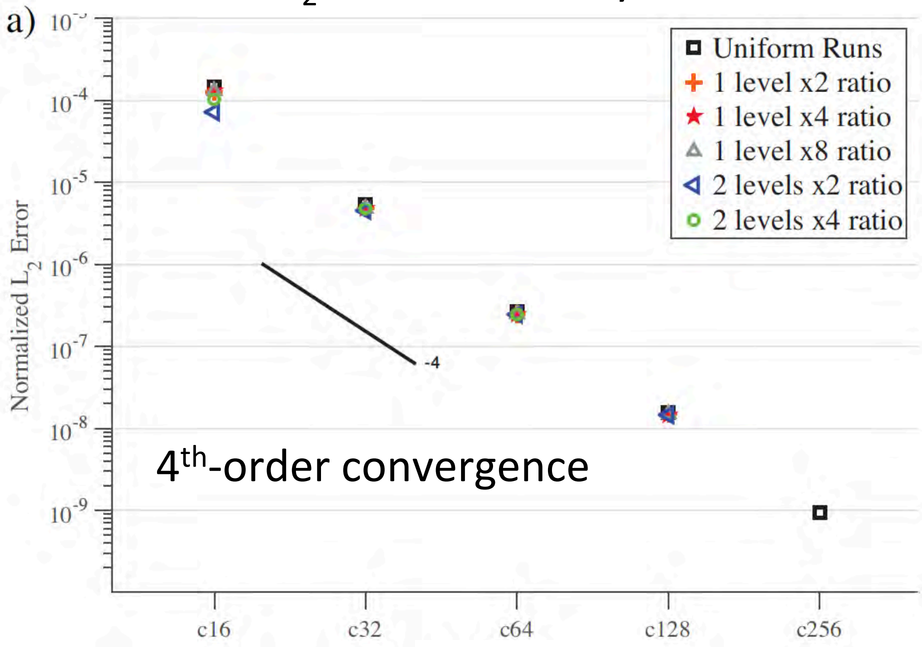
- Comparison of the normalized l_2 error and total number of grid cells for each simulation
- AMR almost matches high-resolution uniform runs after 12 days with reduced number of grid cells (e.g. see **blue** and **green (39 km)** lines)



Shallow Water Test: Test 2

- Zonal steady state flow (*Williamson et al. 1992*)
- "Do no harm" test: Refinement not needed (flow is resolved), insert non-moving patches
- AMR does not increase the global l_2 error in comparison to uniform resolution runs, very minor reductions in error

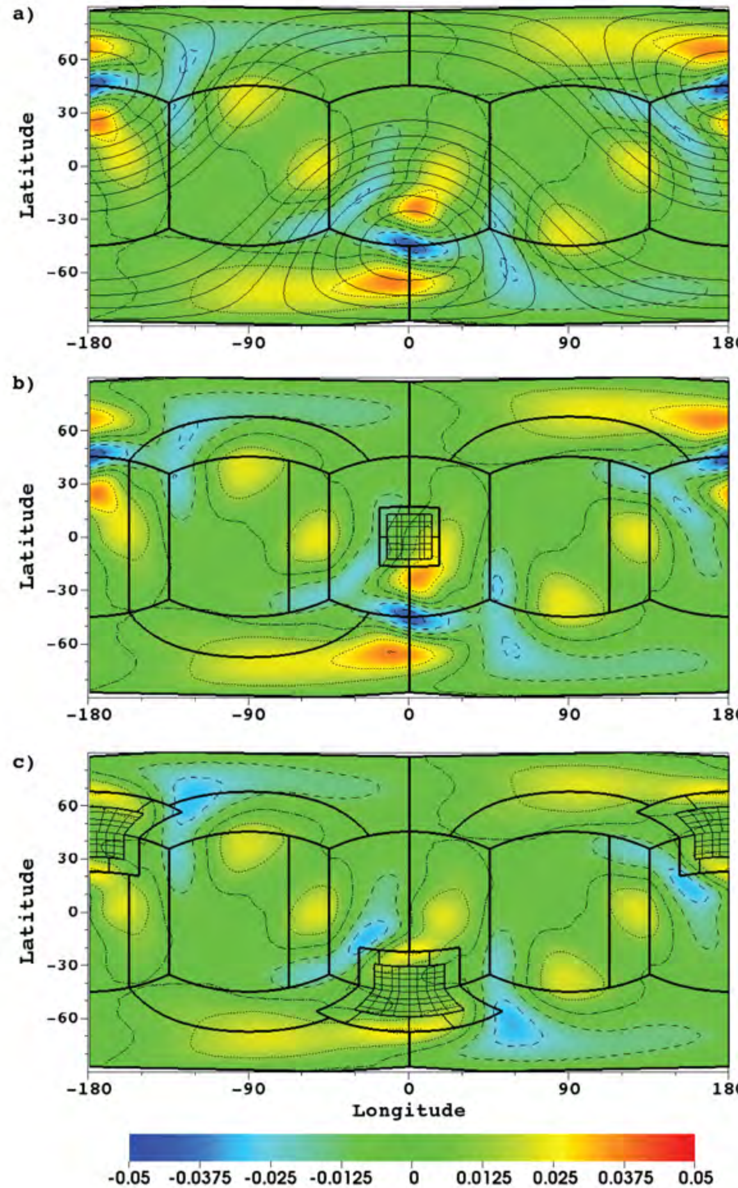
Normalized l_2 error for steady-state test at day 5



4th-order convergence

Resolution

Color: Height error at day 5 for c32 base



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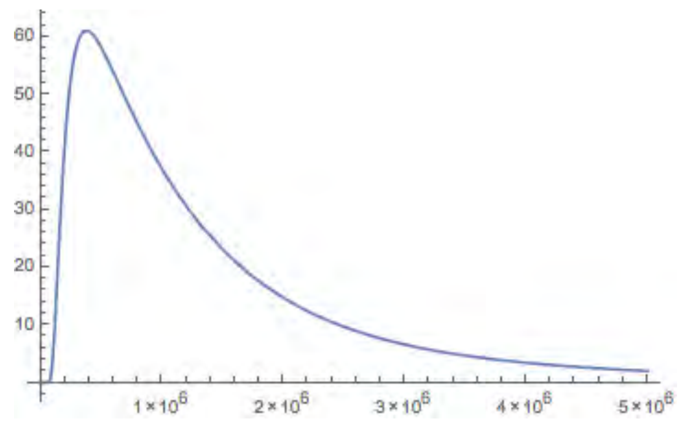
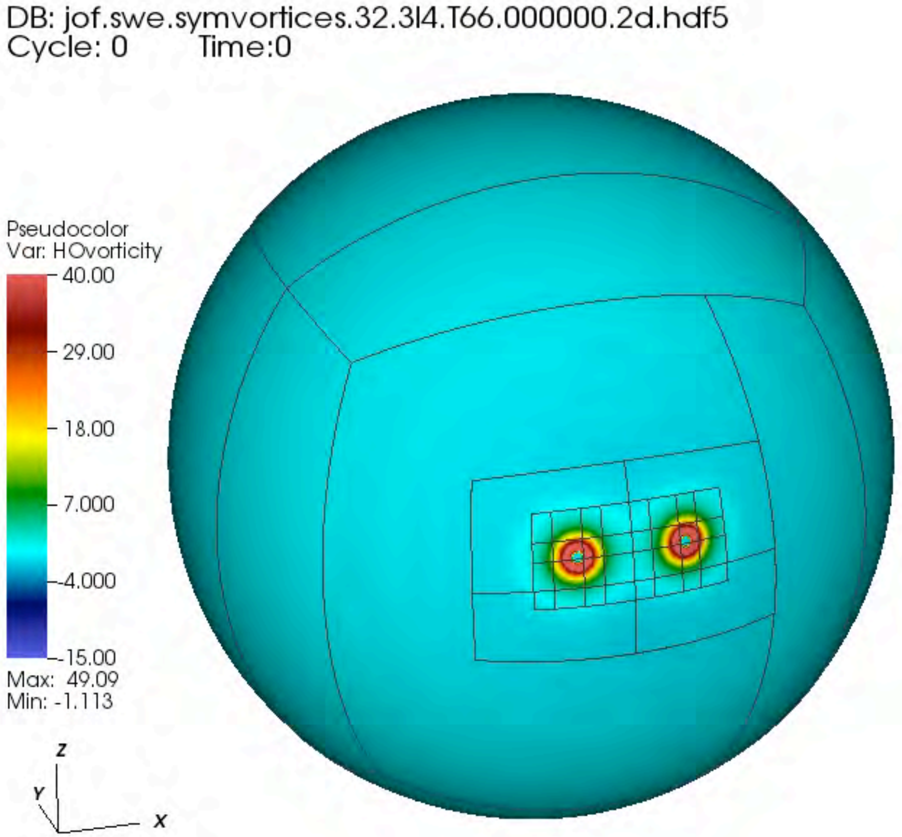
Shallow Water Test: Binary Vortices (Merger)

- An isolated pair of symmetric vortices interact
- Depending on their size, strength, and separation distance. they either merge together or repel each other.
- Judge AMR criteria's ability to capture key features



Initial tangential velocity (m/s) vs distance from center (m)

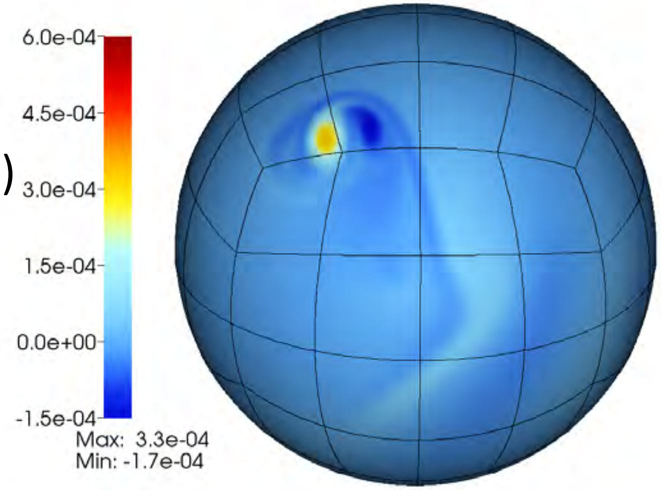
Evolution of the relative vorticity over 4 days



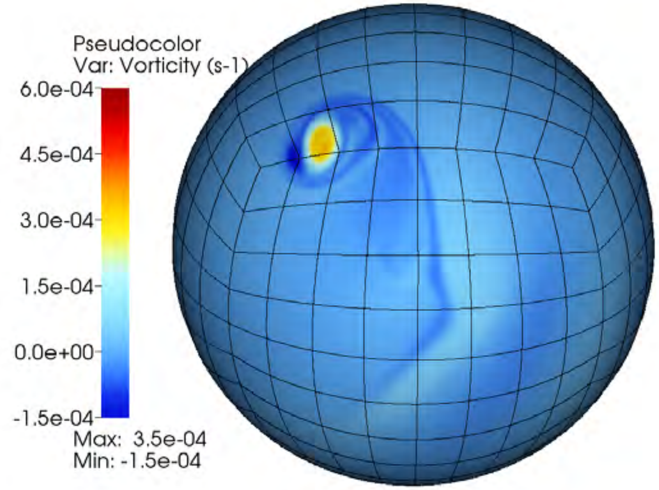
Binary Vortices: Merging Case

- Reference simulations: Day 4 vorticity comparison on uniform runs

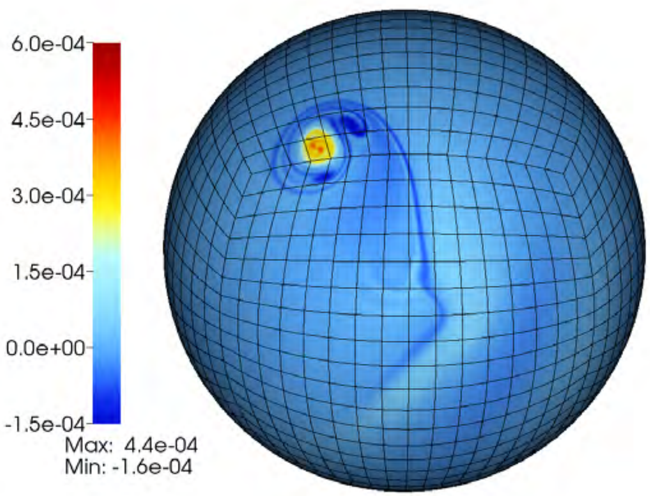
C128
(~78 km)



C256
(~39 km)

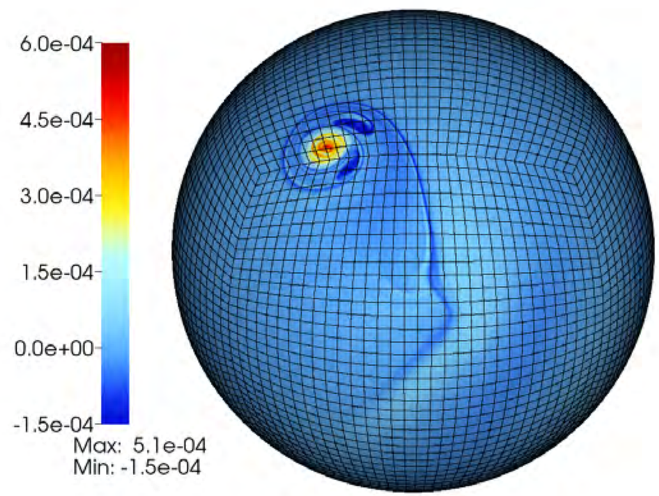


c512
(~19 km)



Reference solution:

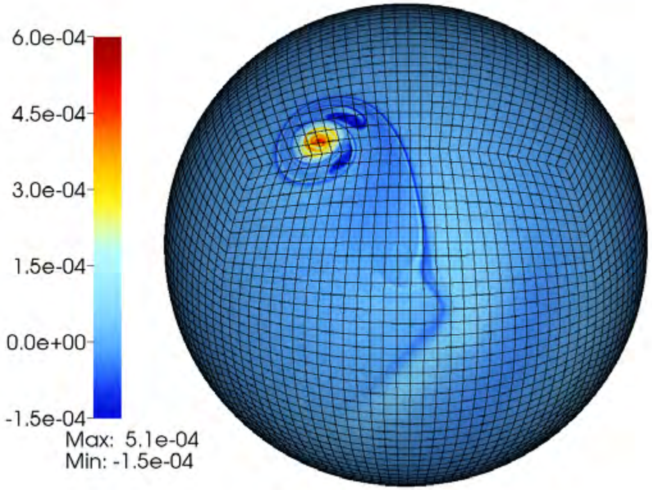
c1024
(~10 km)

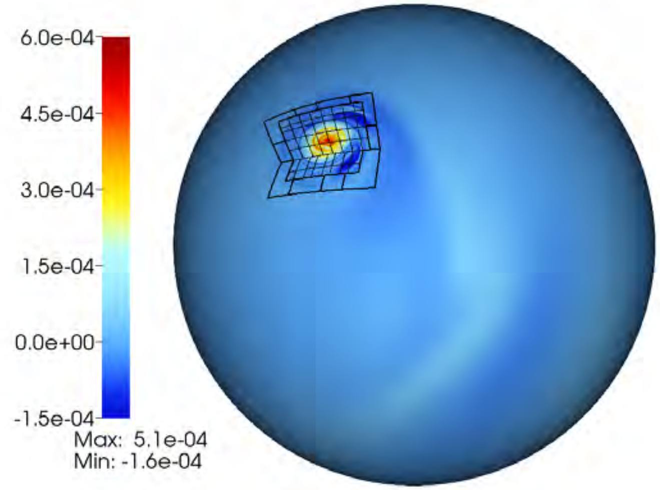


Comparison of Refinement Criteria: Binary Vortices (Merger)

- Day 4 vorticity comparison, c64 base grid (156 km), merger is captured well

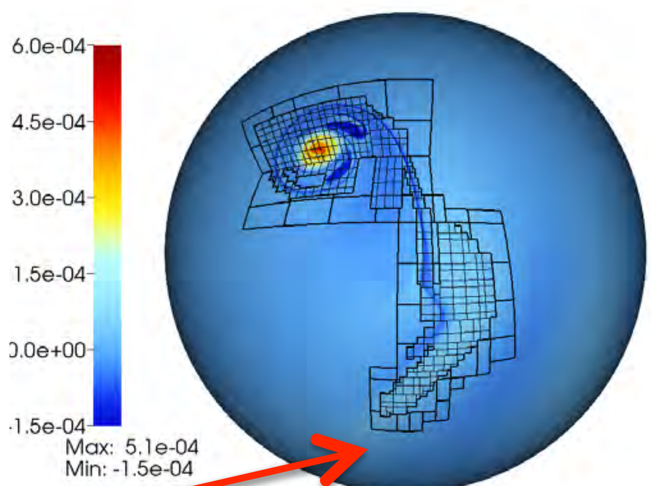
c1024 (~10km)

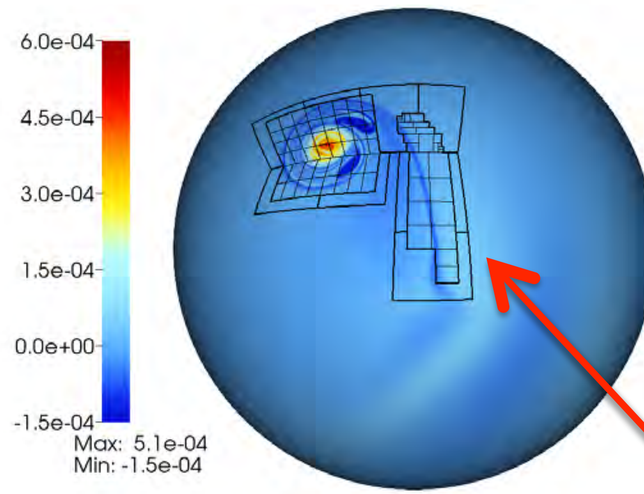




c64/c256/ c1024 AMR tagged on height grad. (high threshold): keeps AMR grid small

c64/c256/ c1024 AMR tagged on vorticity: captures wave in the lee of vortex

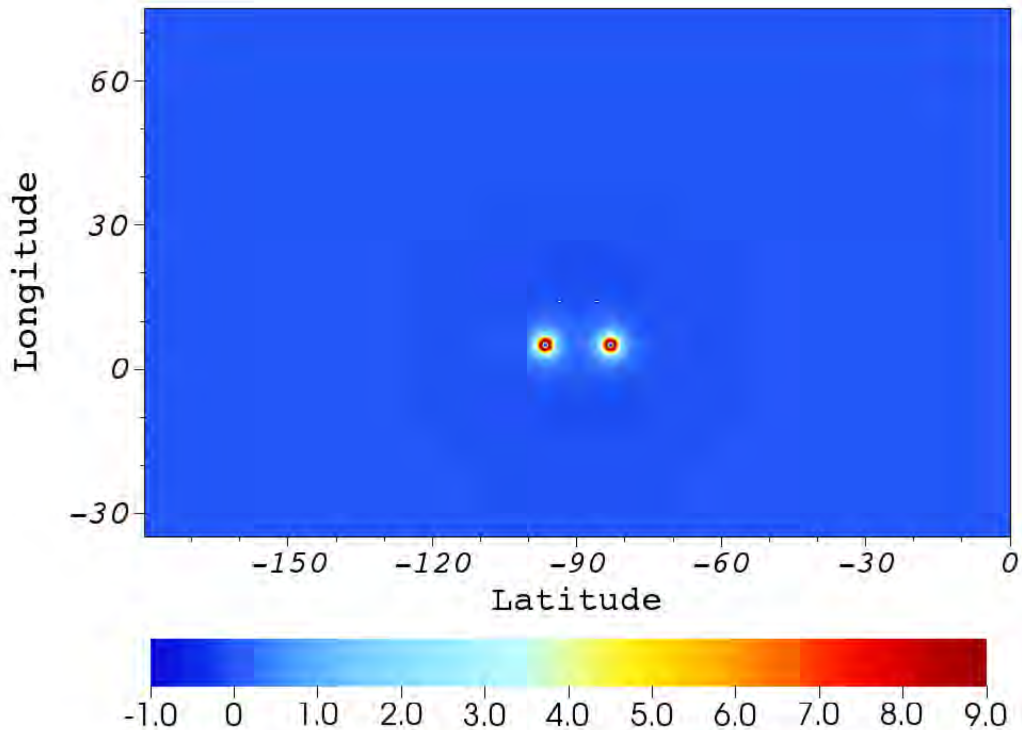




c64/c256/ c1024 AMR tagged on height grad. (lower threshold): lee wave partly captured

Binary Vortices: Separation Case

- Different initial conditions for size, intensity, and separation distance
- Rotate once around each other then separate
- Judge AMR effects on strength and positioning of vortices



Vorticity in units x10^{-4} s^{-1}

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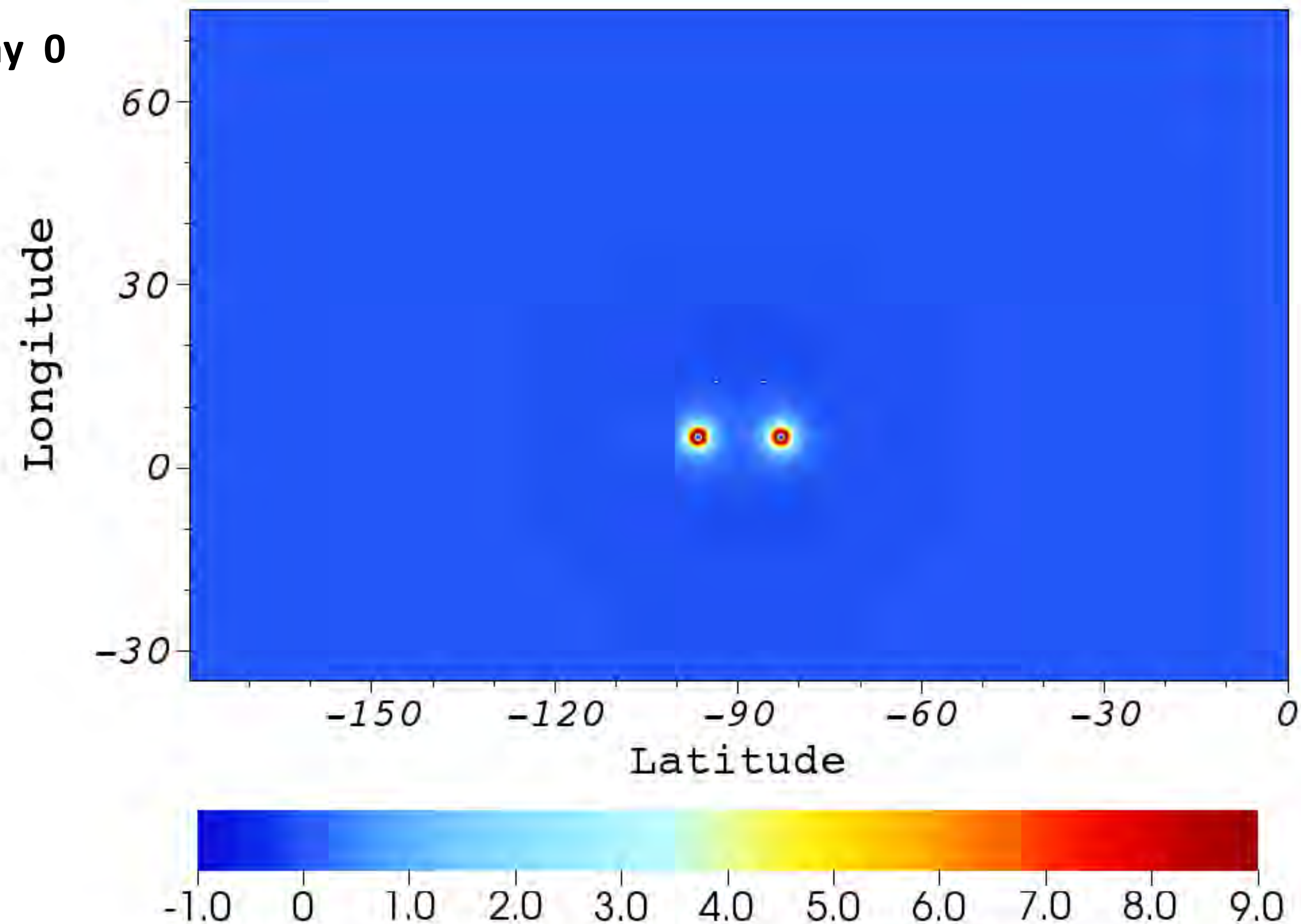
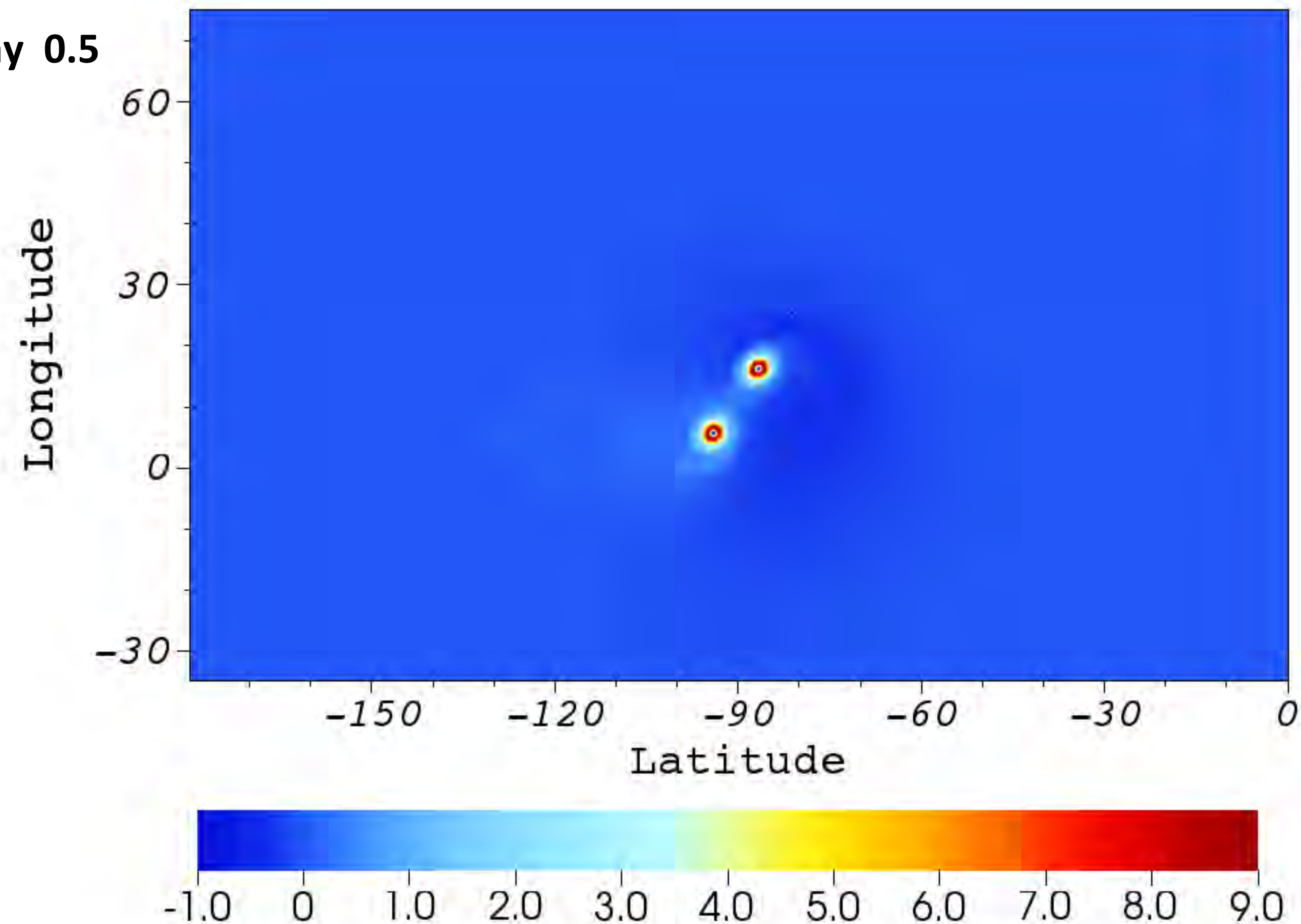
Day 0



Vorticity in units x10^{-4} s^{-1}

Day 0.5



Vorticity in units x10^{-4} s^{-1}

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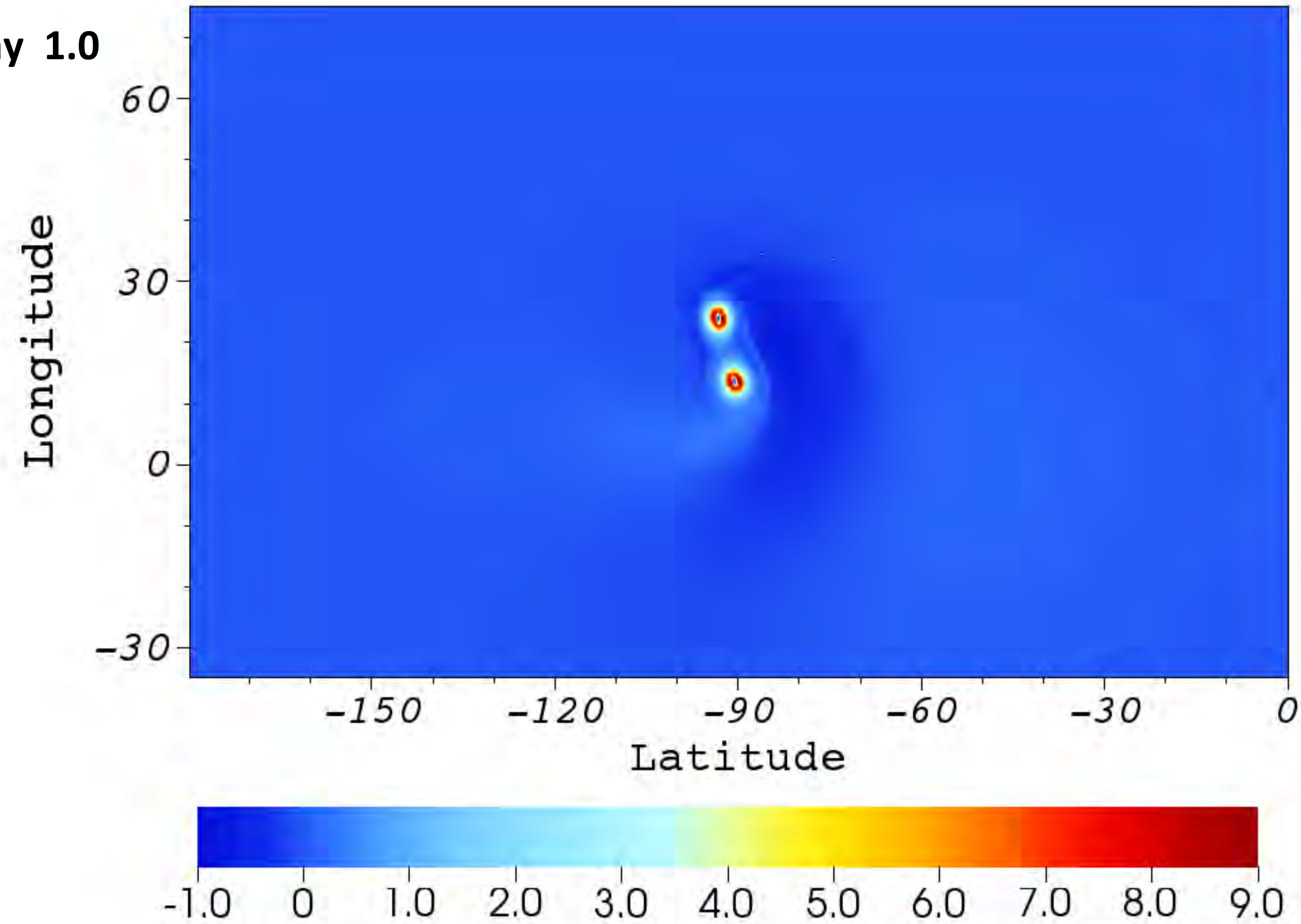
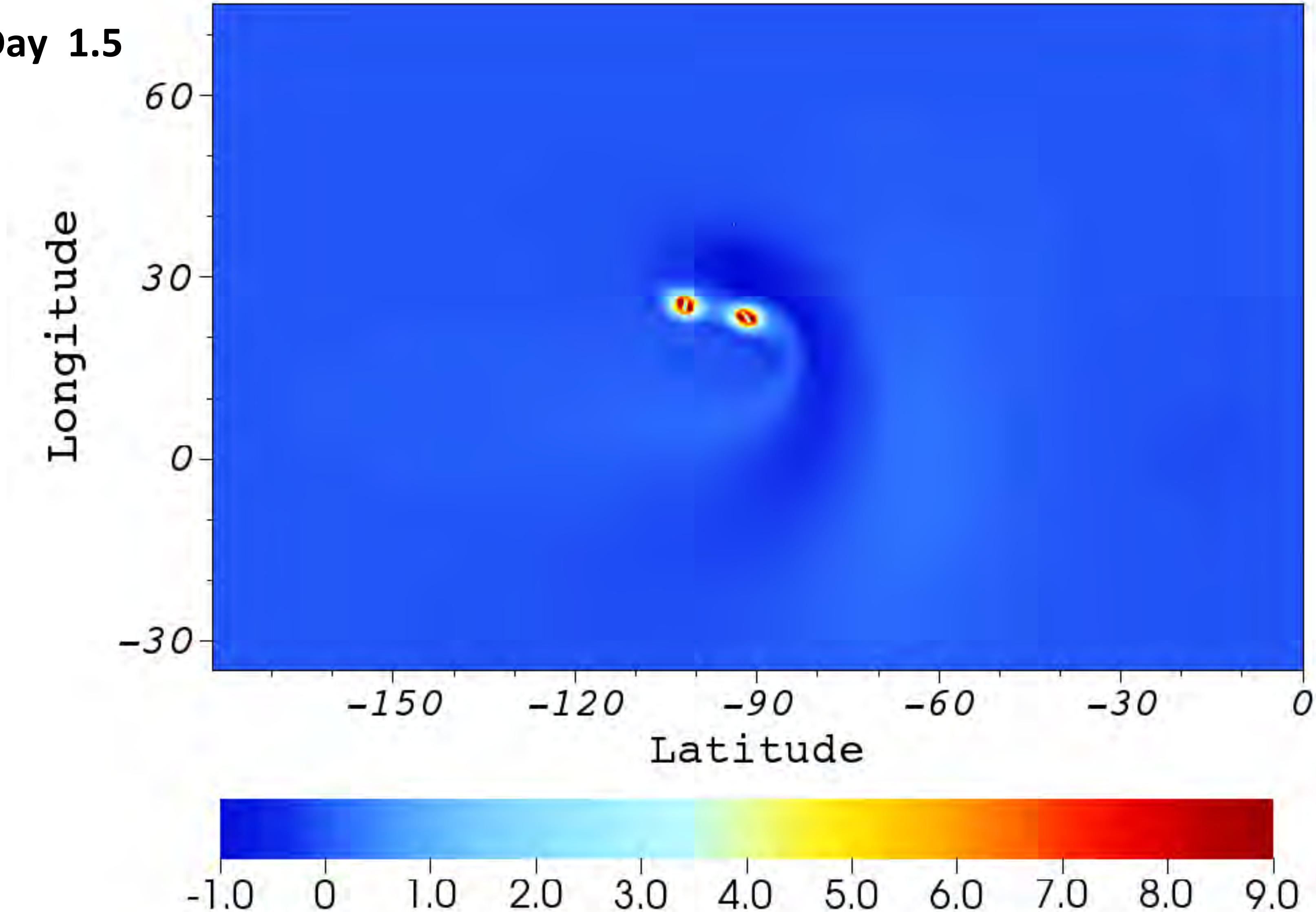
Day 1.0



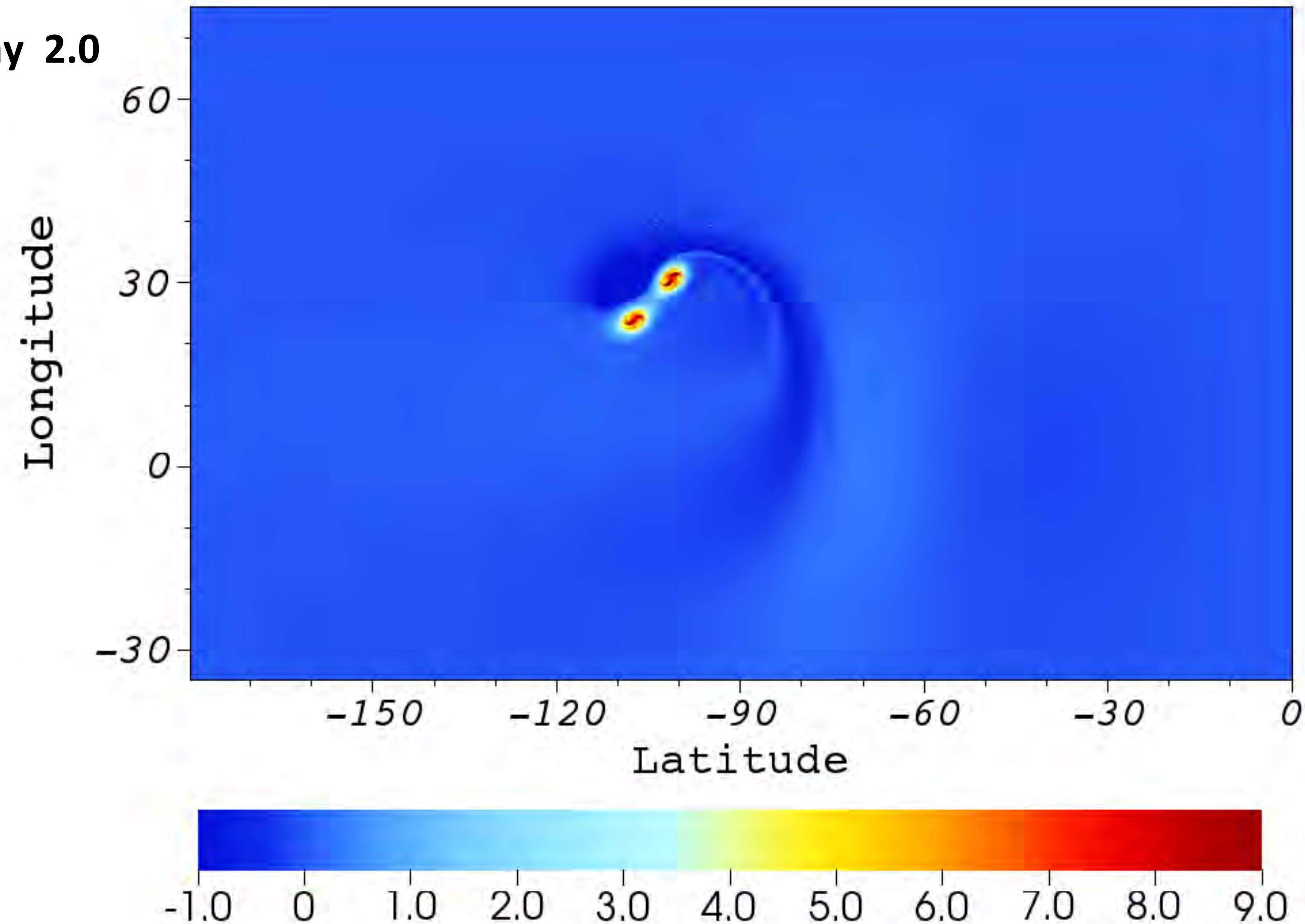
Vorticity in units x10^{-4} s^{-1}

Day 1.5



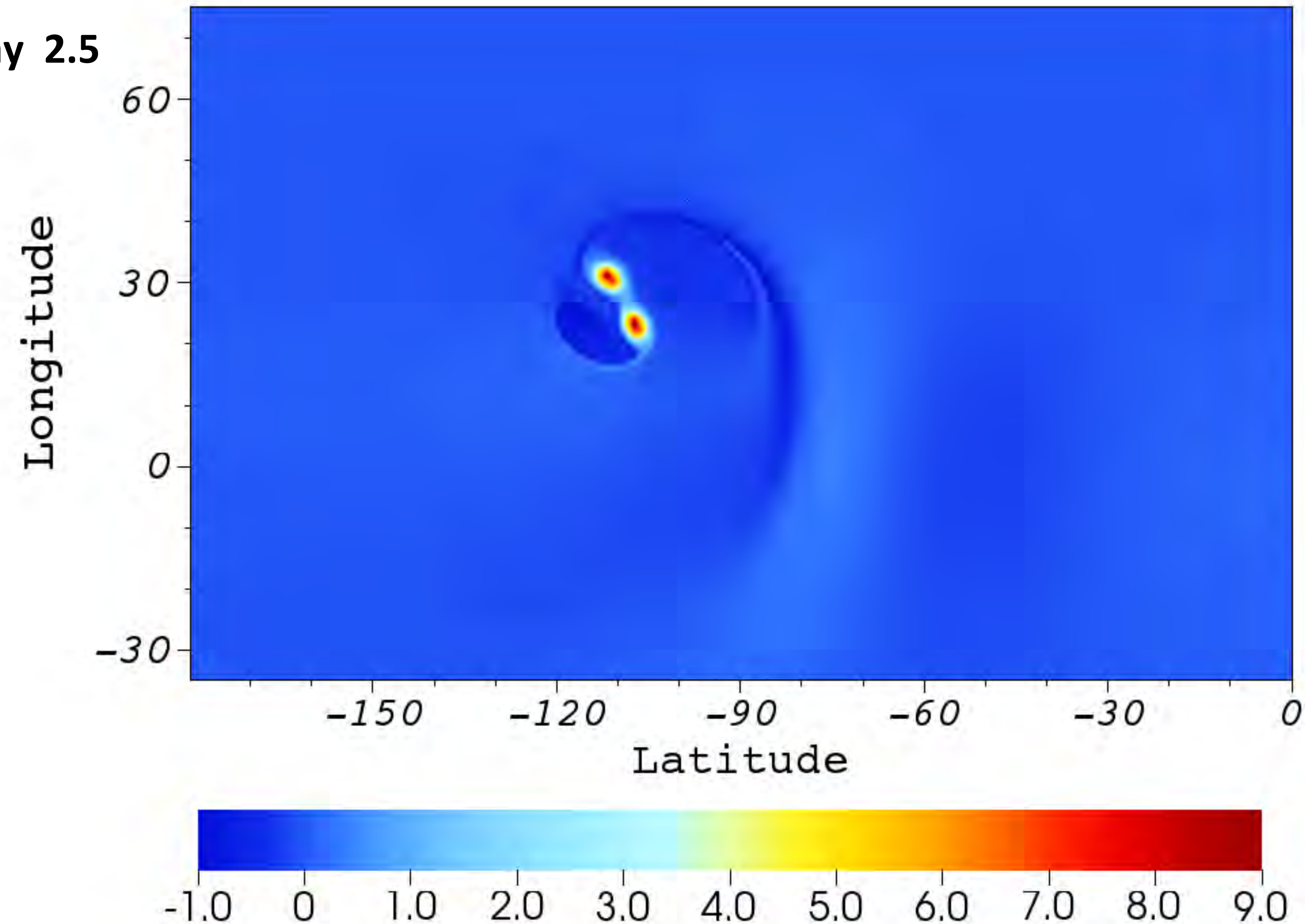
Vorticity in units $x10^{-4}$ s^{-1}

Day 2.0

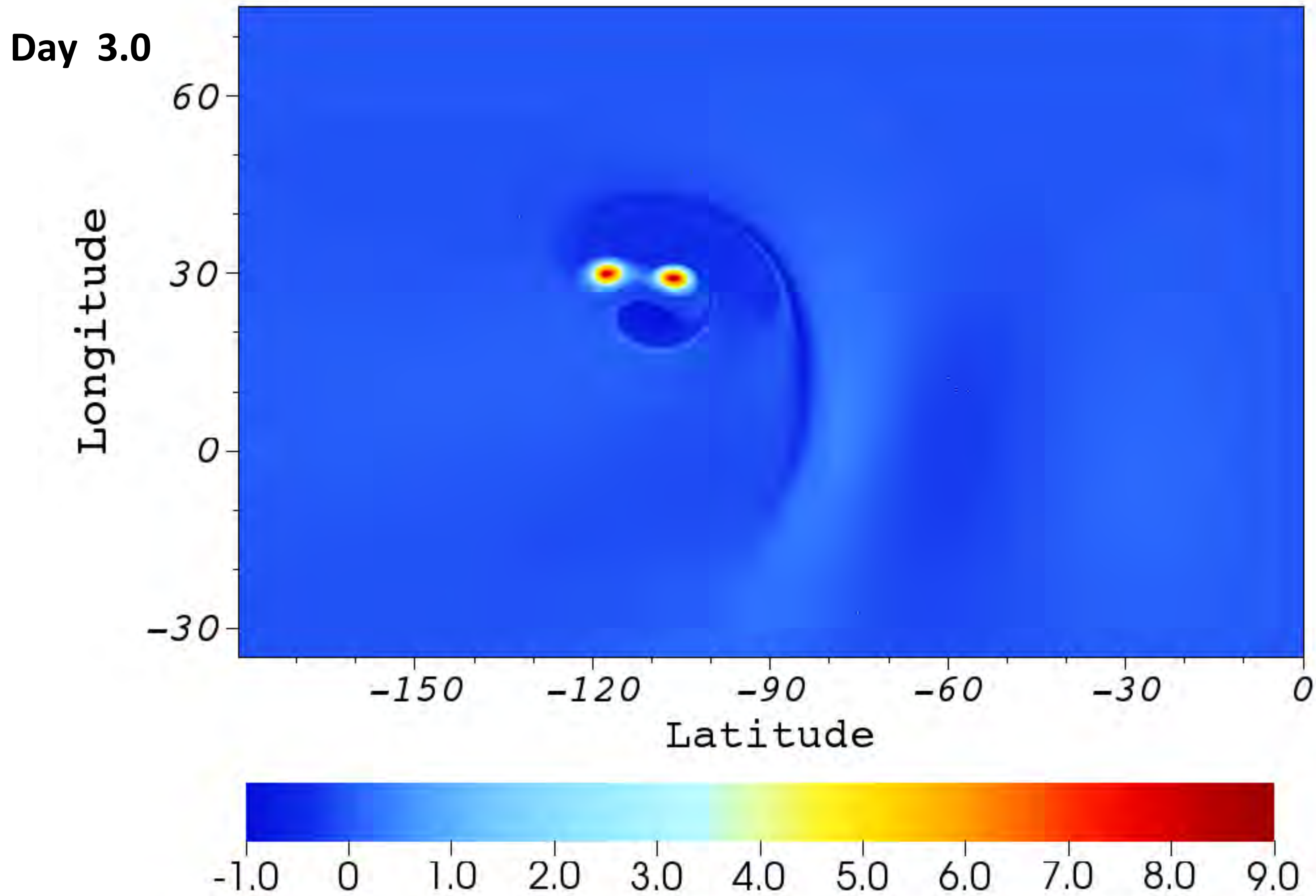


Vorticity in units x10^{-4} s^{-1}

Day 2.5

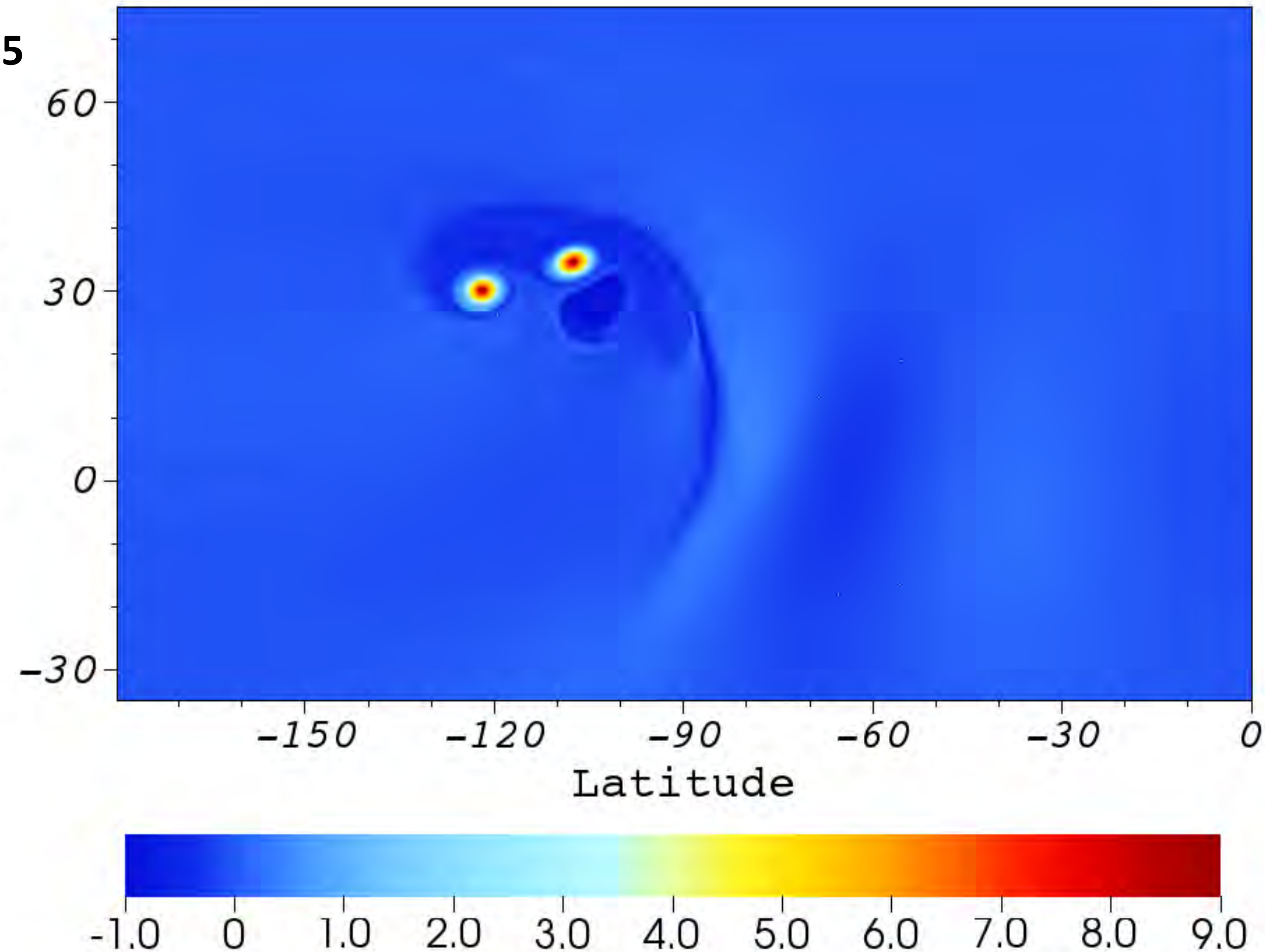


Vorticity in units x10^{-4} s^{-1}



Vorticity in units x10^{-4} s^{-1}

Day 3.5



Vorticity in units x10^{-4} s^{-1}

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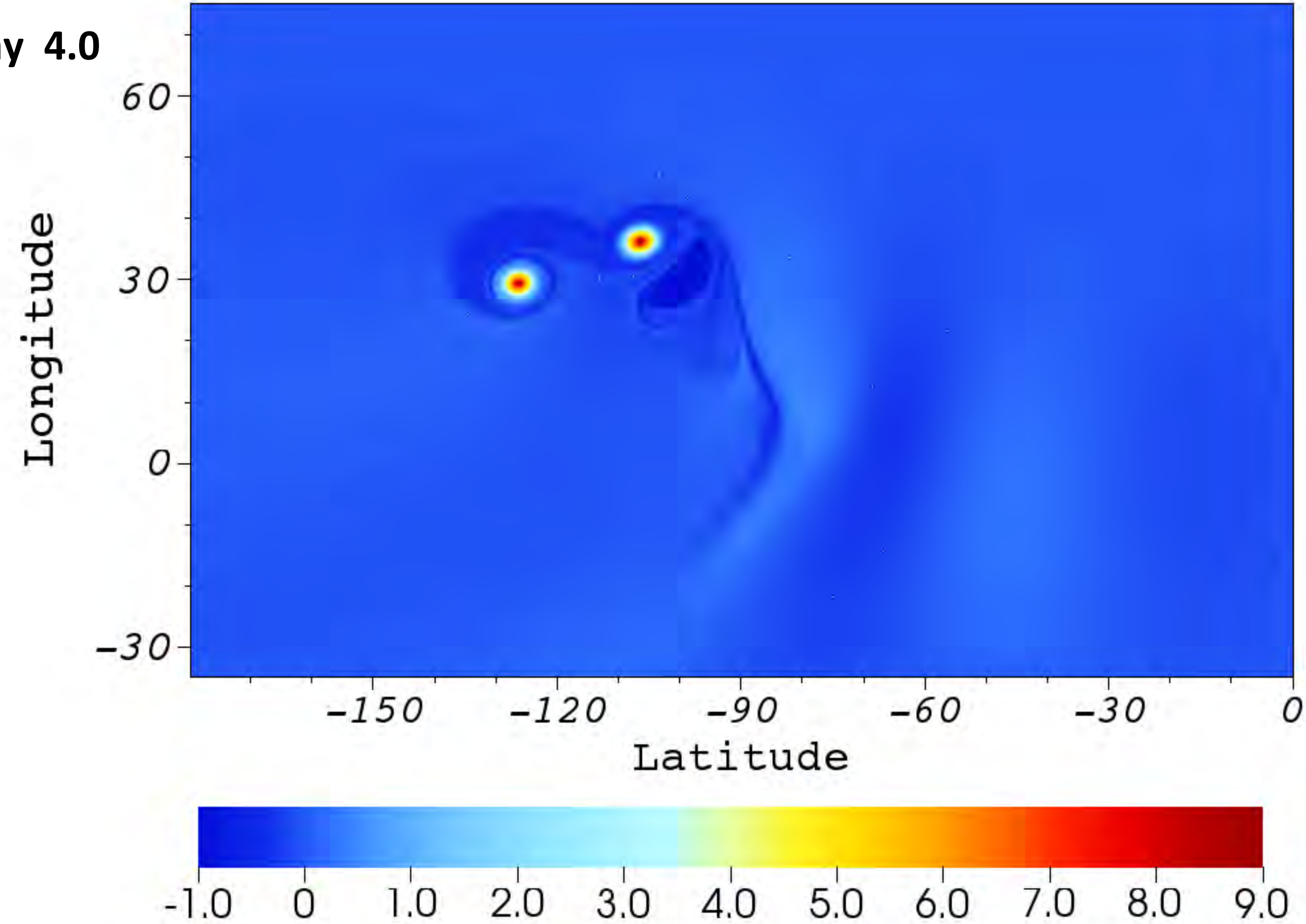
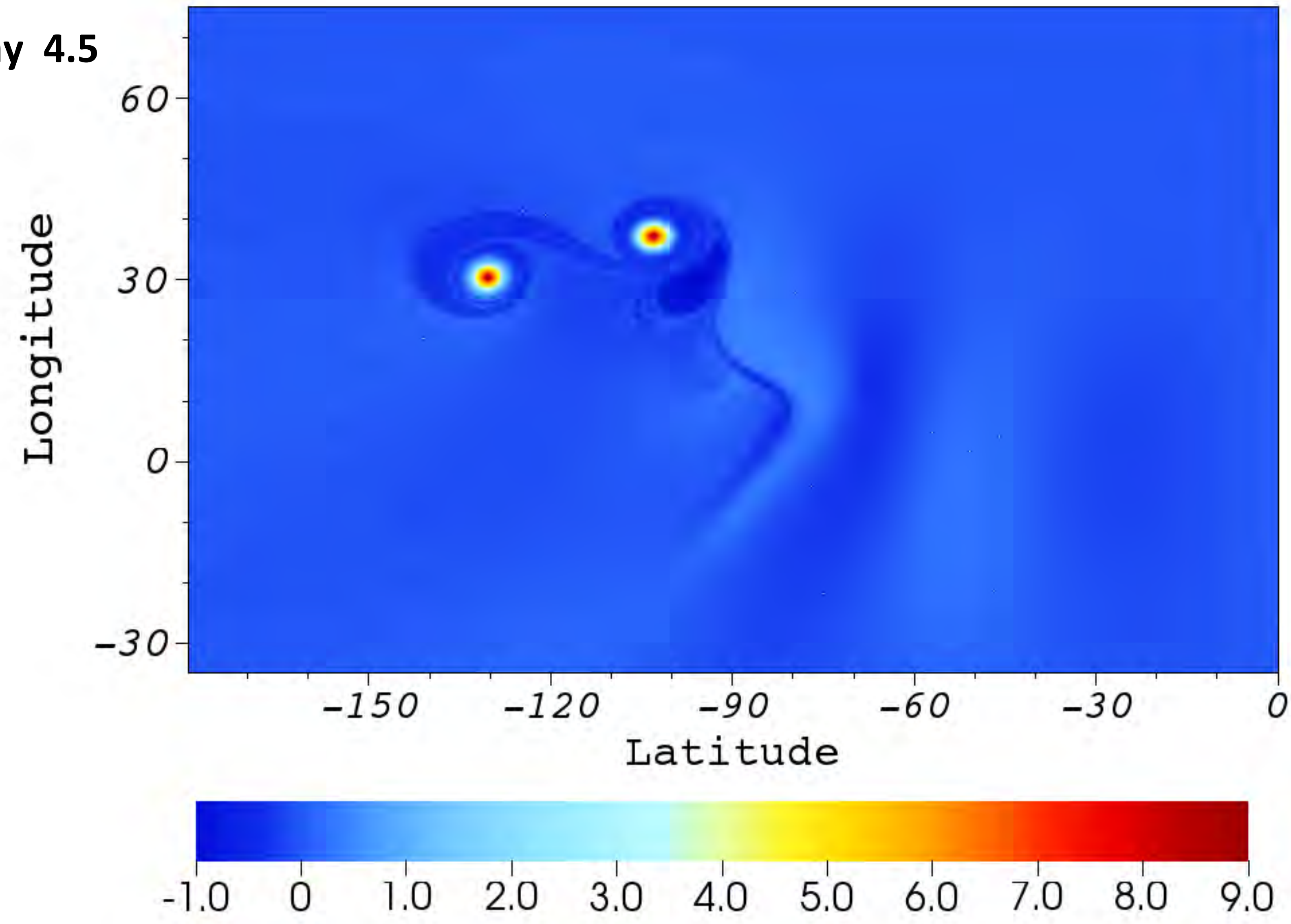
Day 4.0



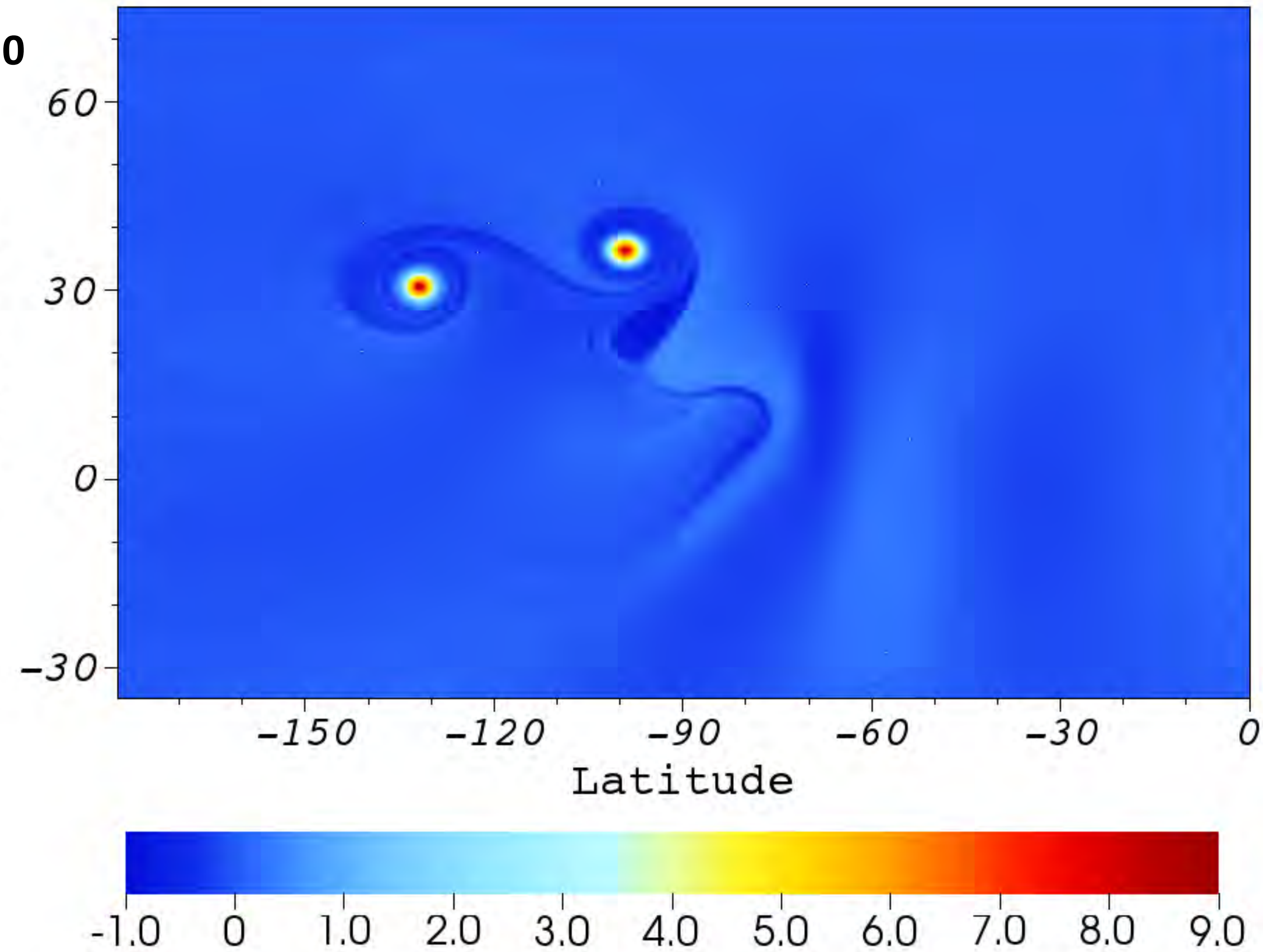
Vorticity in units x10^{-4} s^{-1}

Day 4.5



Vorticity in units $x10^{-4}\ s^{-1}$

Day 5.0



Vorticity in units x10^{-4} s^{-1}

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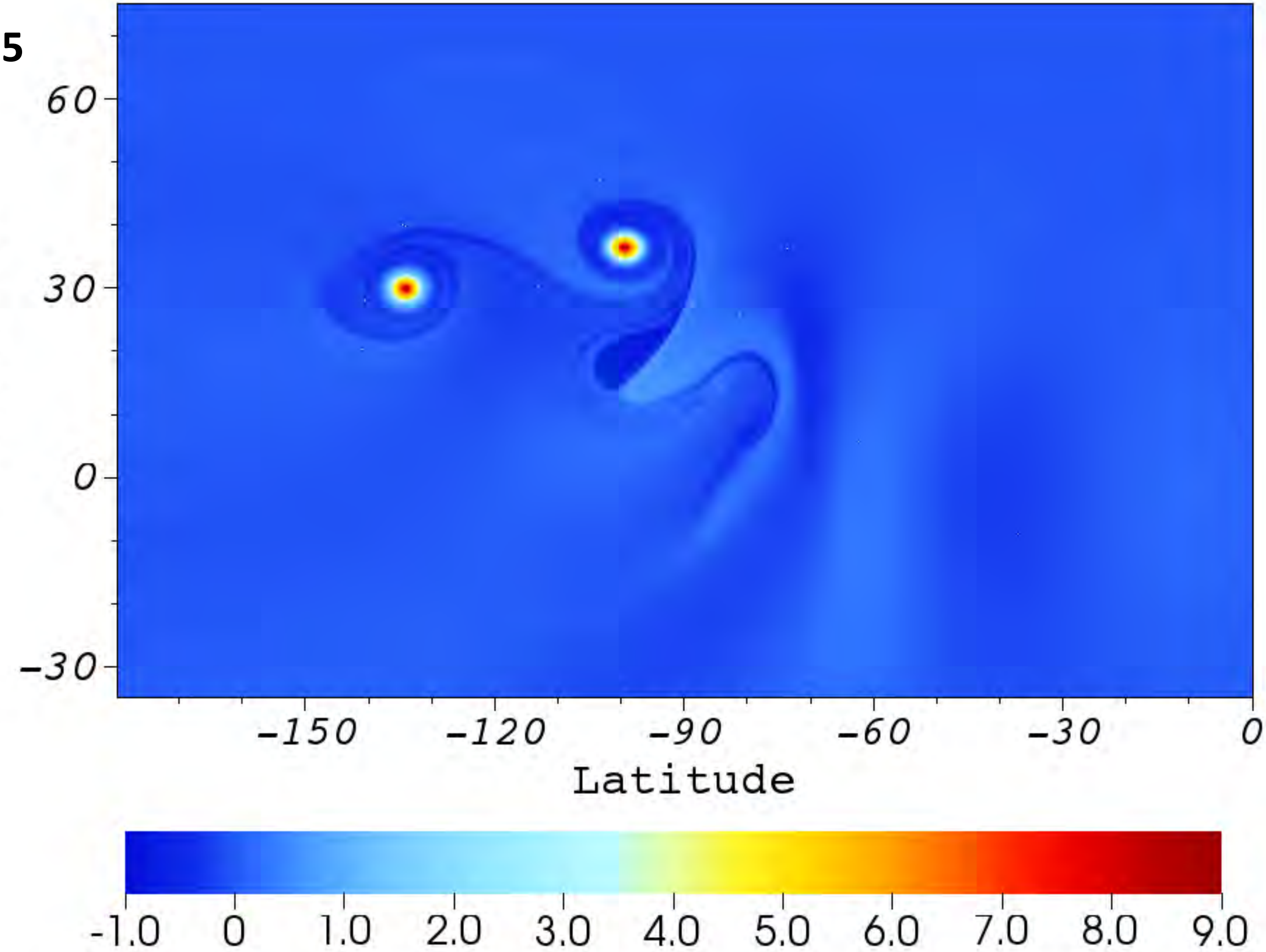
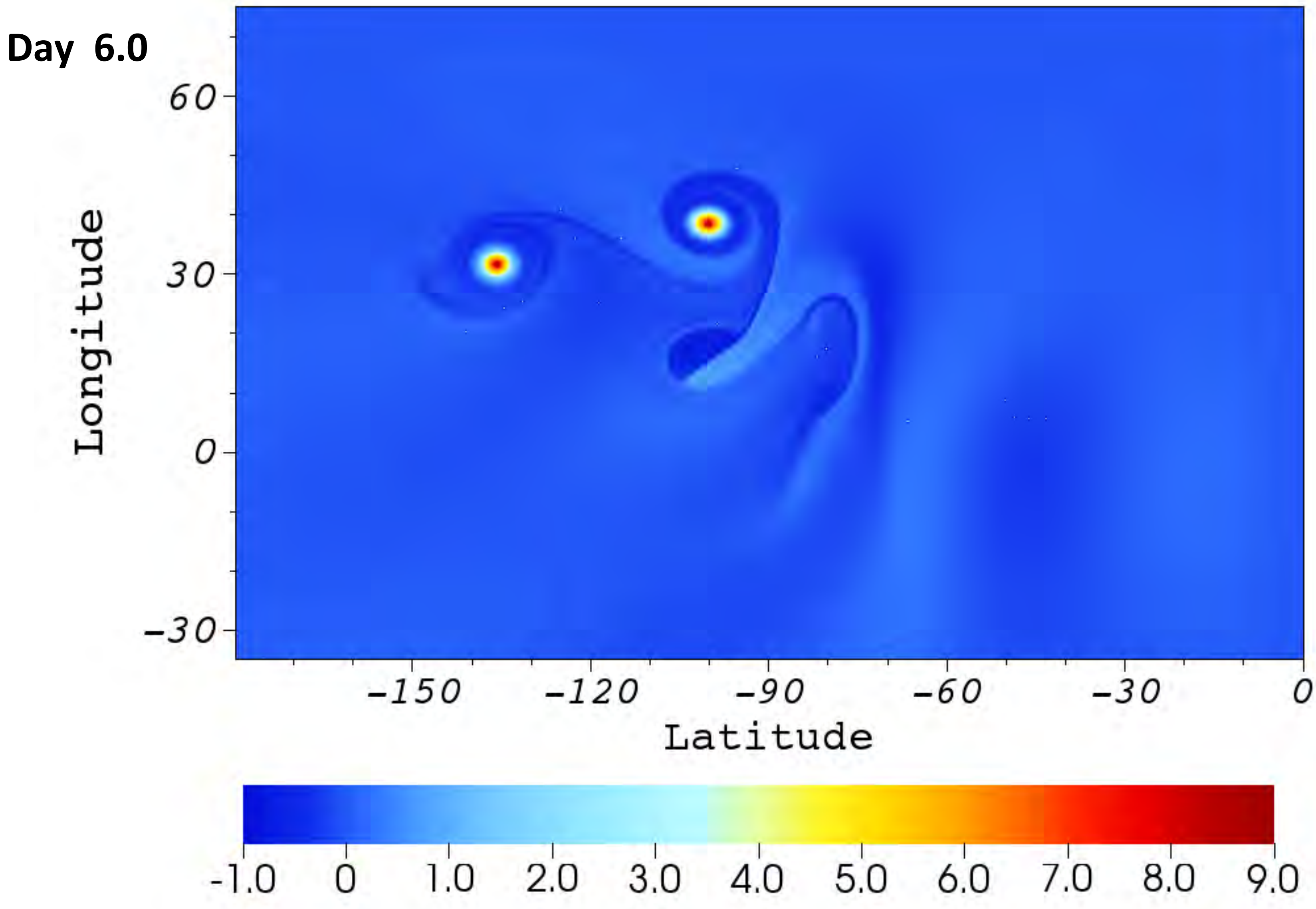
Day 5.5



Vorticity in units x10^{-4} s^{-1}



Vorticity in units x10^{-4} s^{-1}

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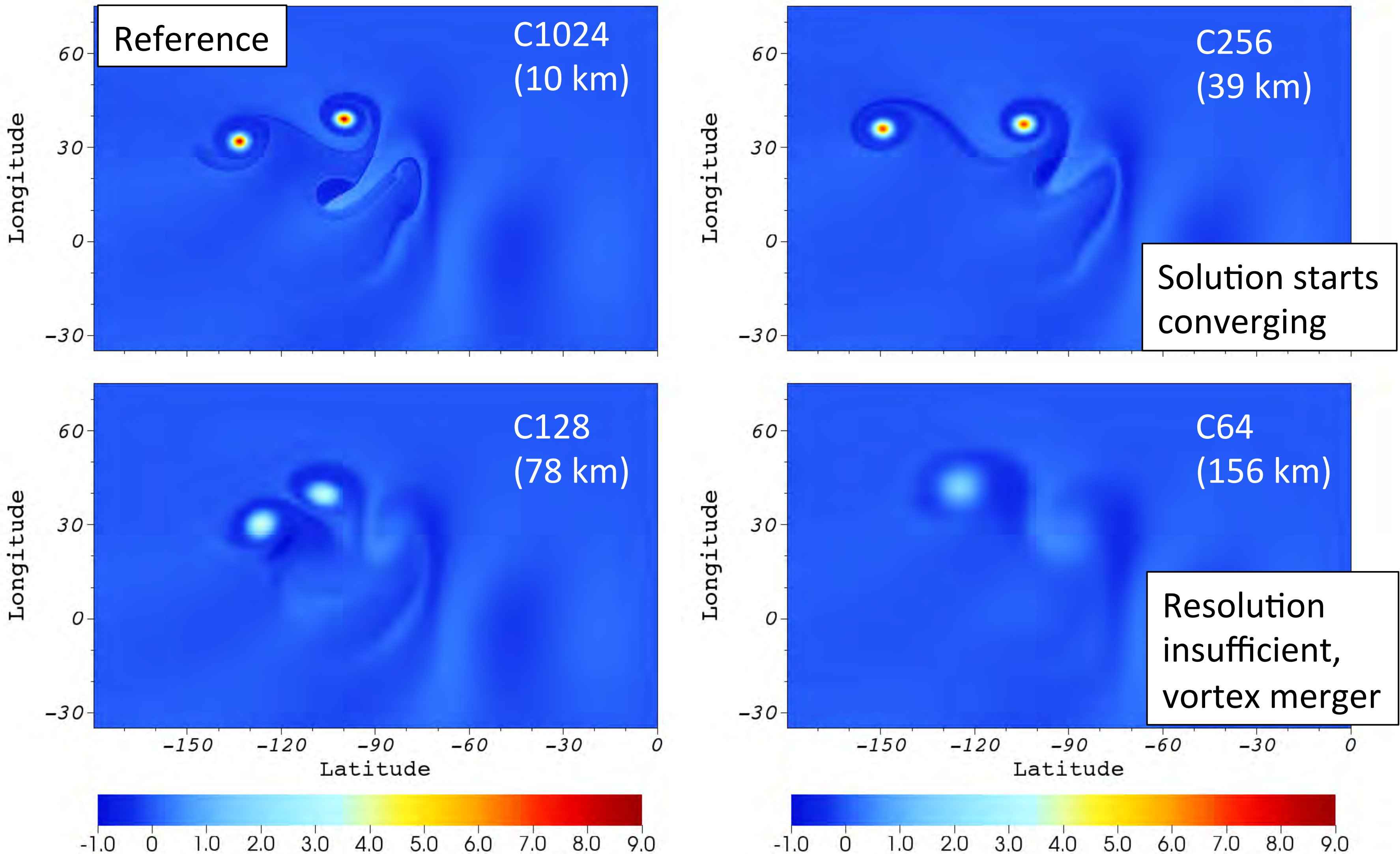
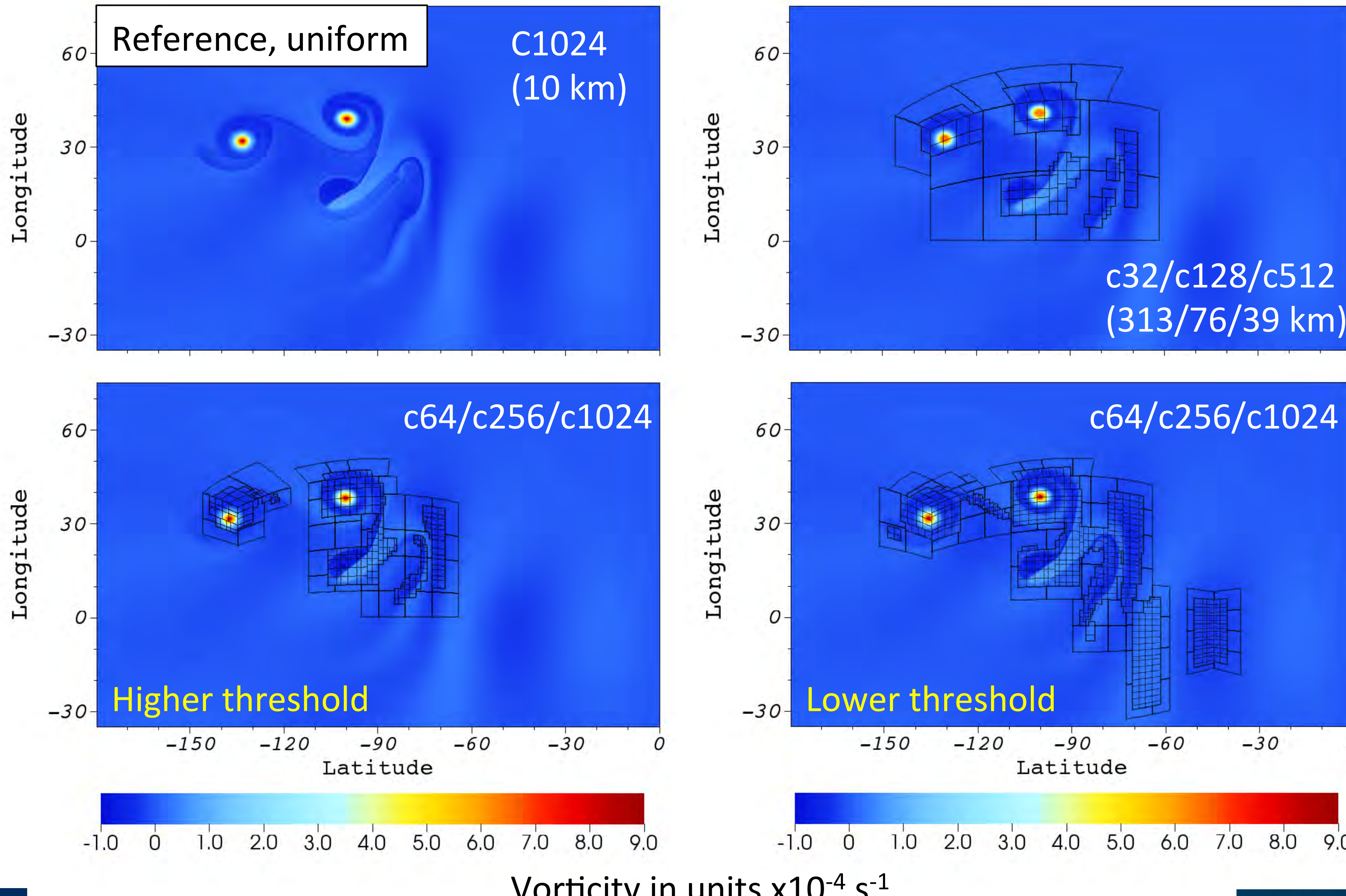
Binary Vortices: Separation Case at Day 6 for uniform resolutions



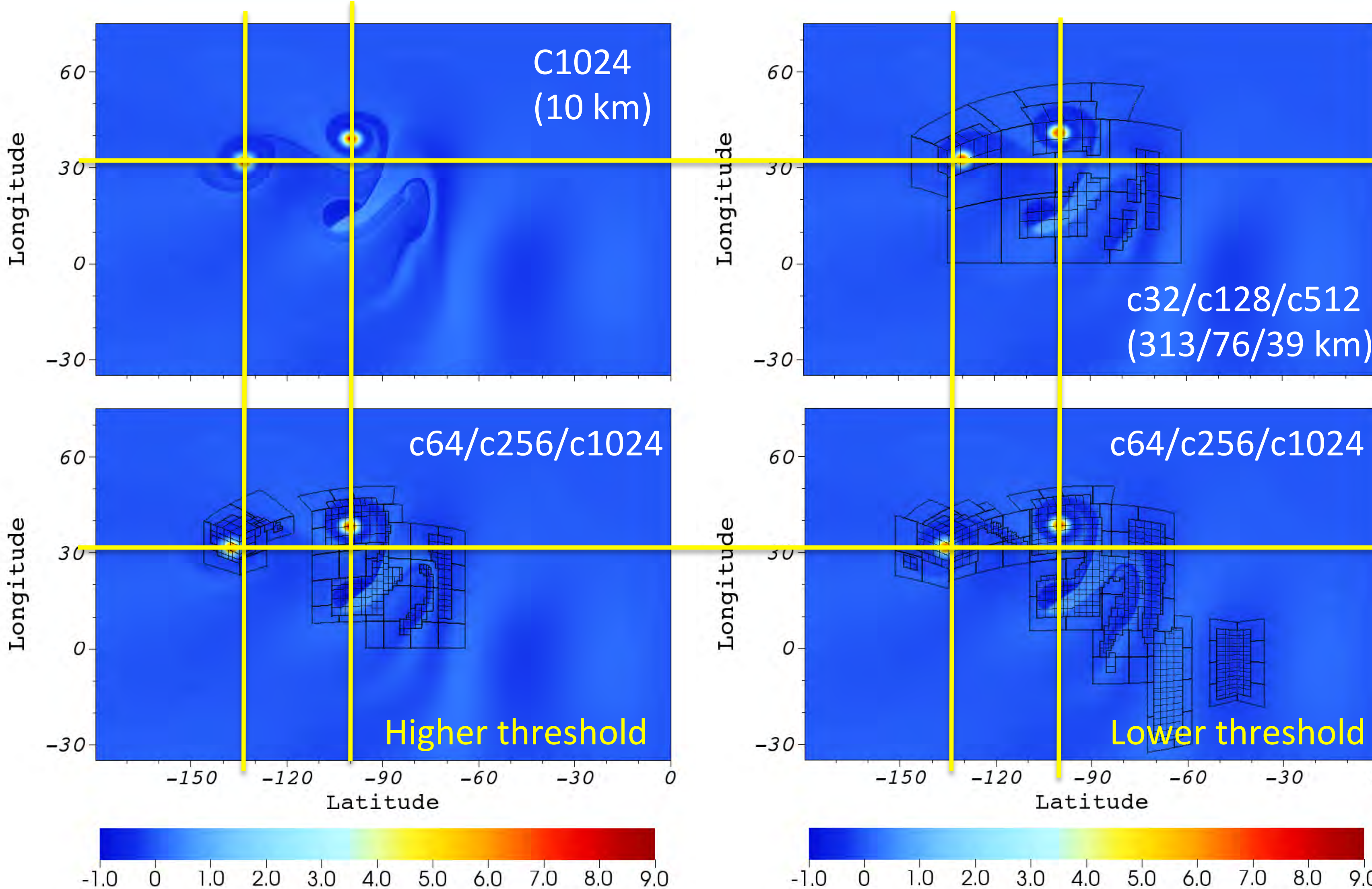
Vorticity in units x10^{-4} s^{-1}

Binary Vortices: Separation Case at Day 6 with AMR



AMR grid is needed to capture the vortex interaction accurately

Binary Vortices: Separation Case at Day 6 with AMR



Vorticity in units x10^{-4} s^{-1}

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AMR grid is needed to capture the vortex interaction accurately

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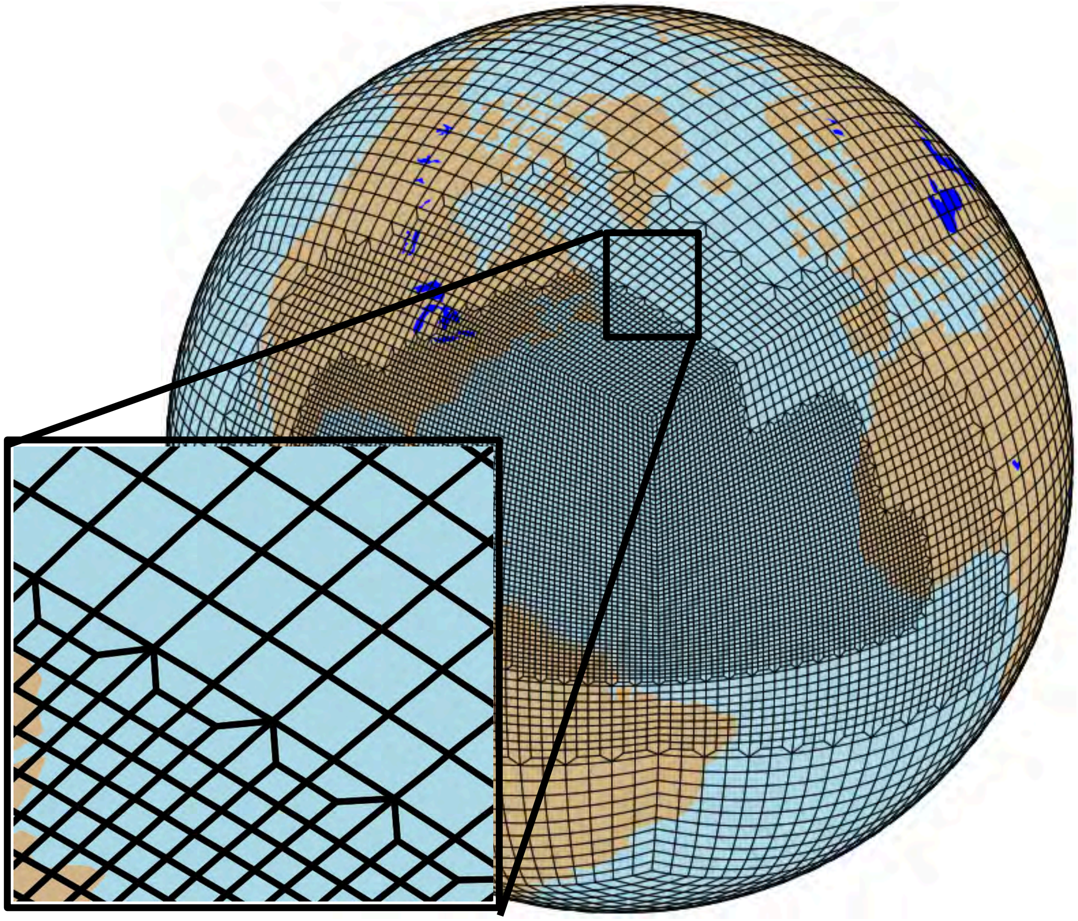
Variable-Resolution Modeling with CAM-SE

Regionally high-resolution in a global framework

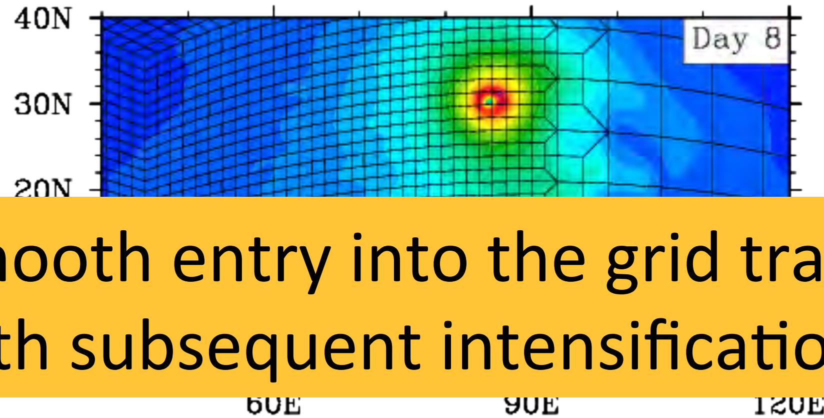


- DoE/NCAR Community Atmosphere Model Spectral Element (CAM-SE) dynamical core
  - Hydrostatic
  - Conforming grid refinement down to 14-7 km
  - Fixed time step
  - Diffusion is scaled
  - 4th-order accurate in the horizontal
  - RK time stepping
  - Cubed-sphere

CAM Aqua-Planet: Transition from 2° -> 0.5°

Idealized tropical vortex:
v = 20 m/s
RMW = 250 km
(Reed and Jablonowski, (MWR, 2011))

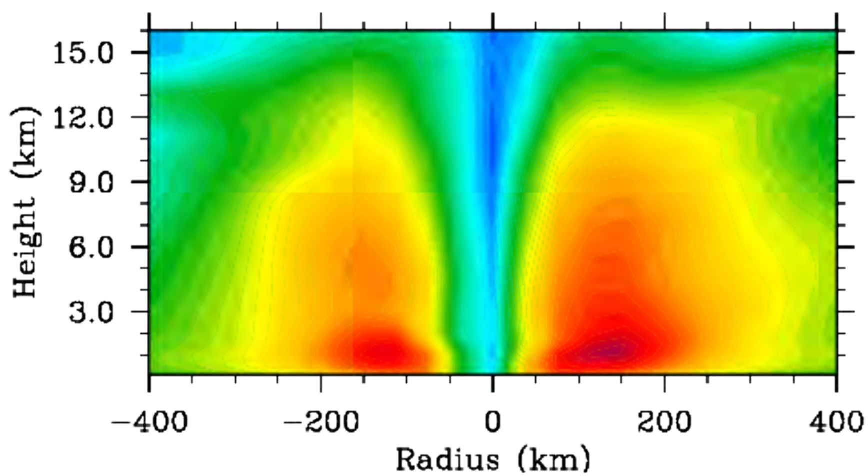
850 mb wind speed (m/s)



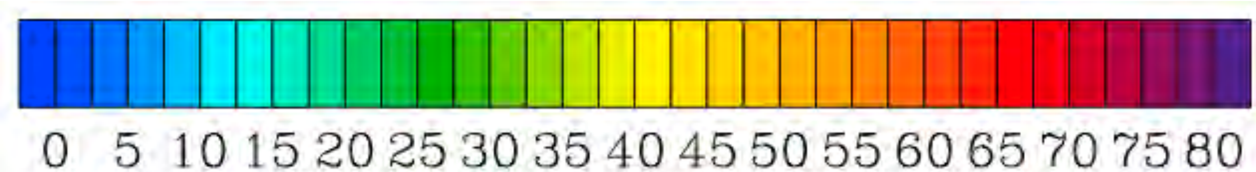
Horizontal cross section

Smooth entry into the grid transition region with subsequent intensification

Key: Looking for relatively symmetric development; no stretching, no filamentation



Latitude-height cross section



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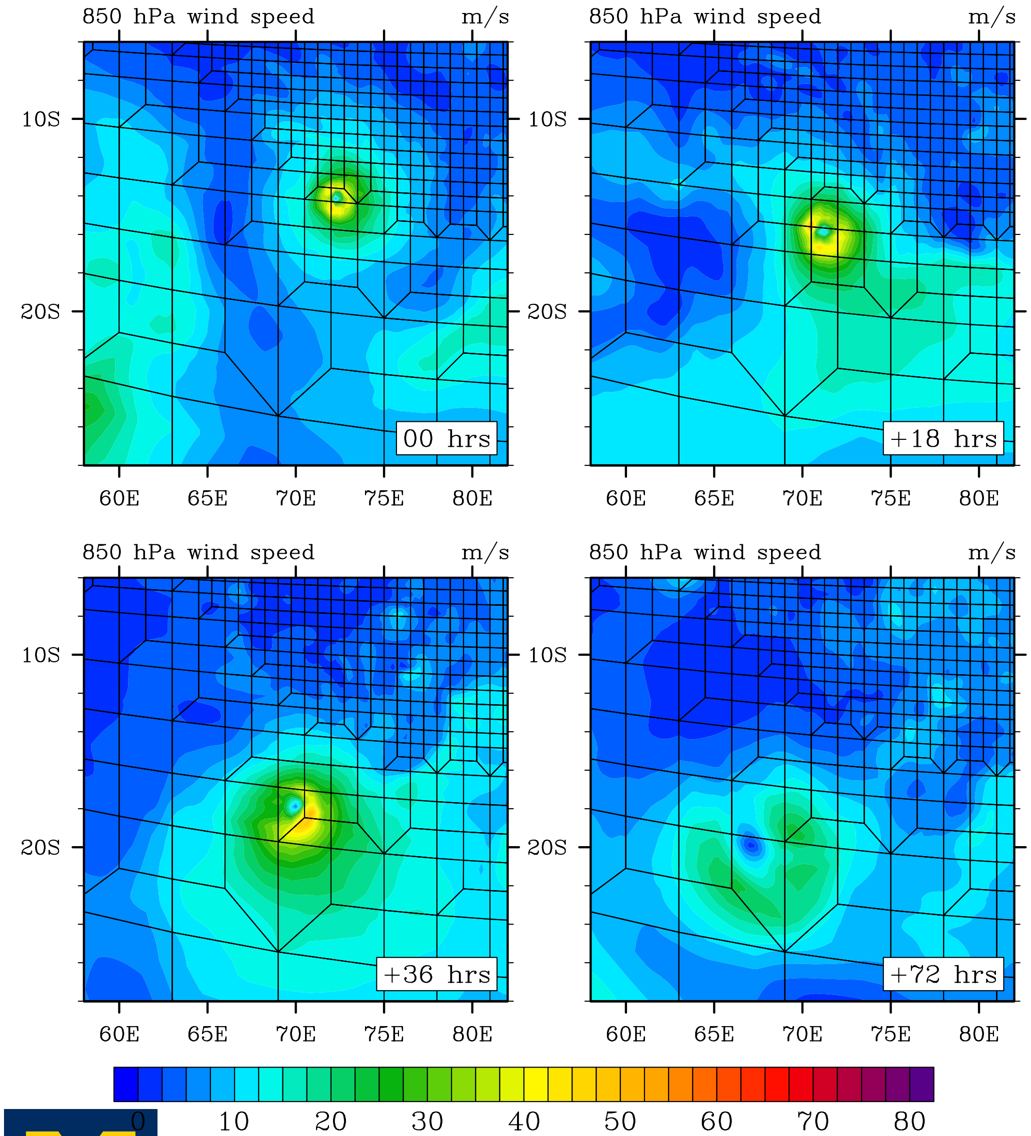
CAM-SE: Example of Tropical Cyclone Leaving Mesh



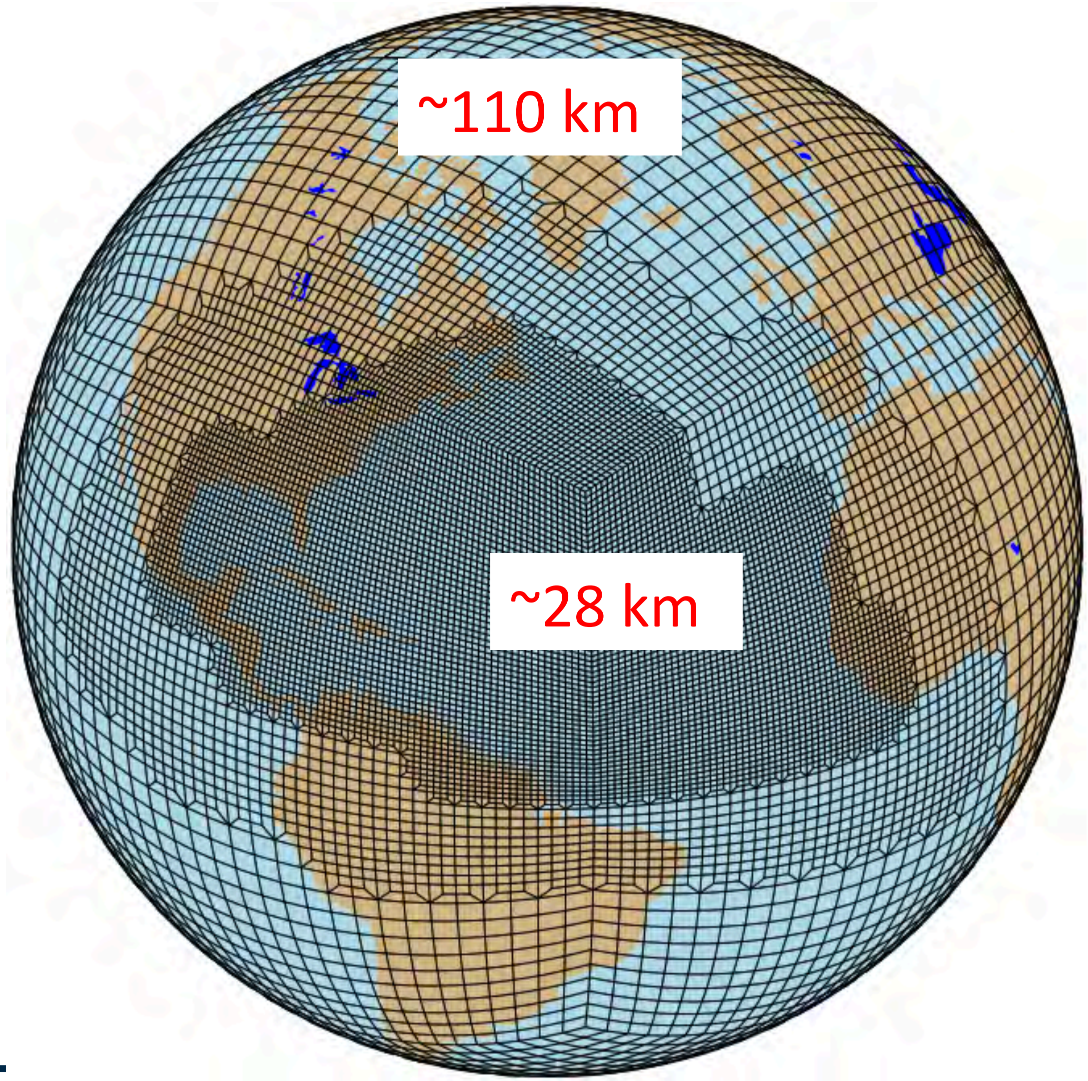
- No observable wave reflection back into refined domain
- Tropical cyclone expectedly weakens as grid spacing becomes larger
- Variable-resolution simulation matches uniform high-resolution run

Full-Physics CAM-SE Assessments

- Zarzycki, Colin M., Michael. N. Levy, Christiane Jablonowski, Mark A. Taylor, James Overfelt, and Paul A. Ullrich, 2014, Aqua Planet Experiments Using CAM's Variable Resolution Dynamical Core. *J. Climate,* Vol. 27, 5481-5503
- Zarzycki, Colin M., C. Jablonowski, M. A. Taylor, 2014: A multidecadal simulation of Atlantic tropical cyclones using a variable-resolution global atmospheric general circulation model. JAMES, Vol. 6, 805-828
- Zarzycki, Colin M., C. Jablonowski, Diana. R. Thatcher, M. A. Taylor, 2015: Effects of localized grid refinement on the general circulation and climatology in the Community Atmosphere Model. J.Climate, Vol. 28, 2777-2803
- Zarzycki, Colin M. and C. Jablonowski, 2015: Experimental tropical cyclone forecasts using a variable-resolution global model. Mon. Wea. Rev., Vol. 143, 4012-4037
- Zarzycki, C. M., D. R. Thatcher and C. Jablonowski, 2016: Objective tropical cyclone extratropical transition detection in high-resolution reanalysis and climate model data, J. Adv. Model. Earth Syst., revised

CAM-SE: Long-Term Climate Simulations

- Atmospheric Model Intercomparison Project (AMIP) protocols
  - Observed SST, O_3, aerosol, solar forcing, etc.
  - 1980-2002 (23 years)
- Atlantic Refinement



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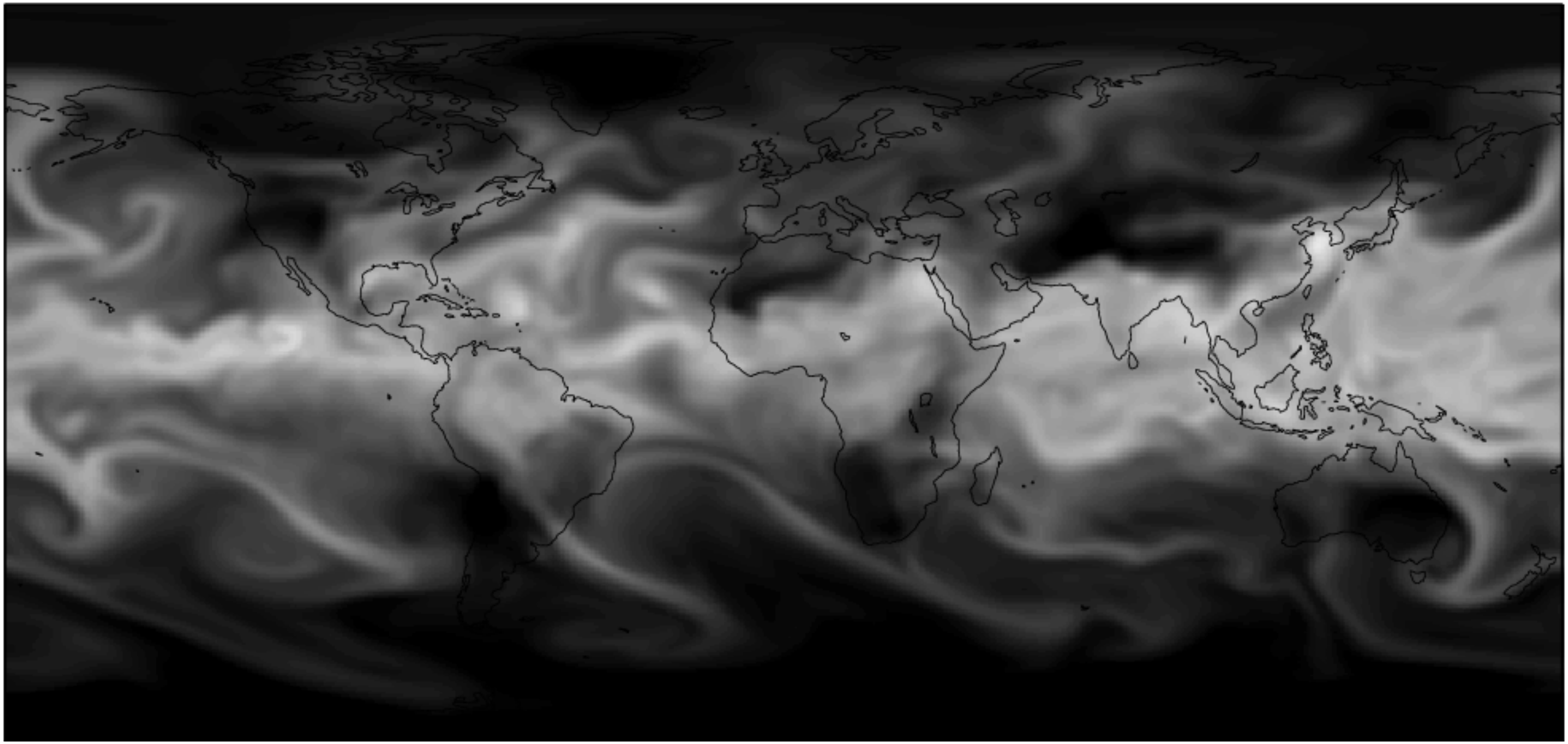
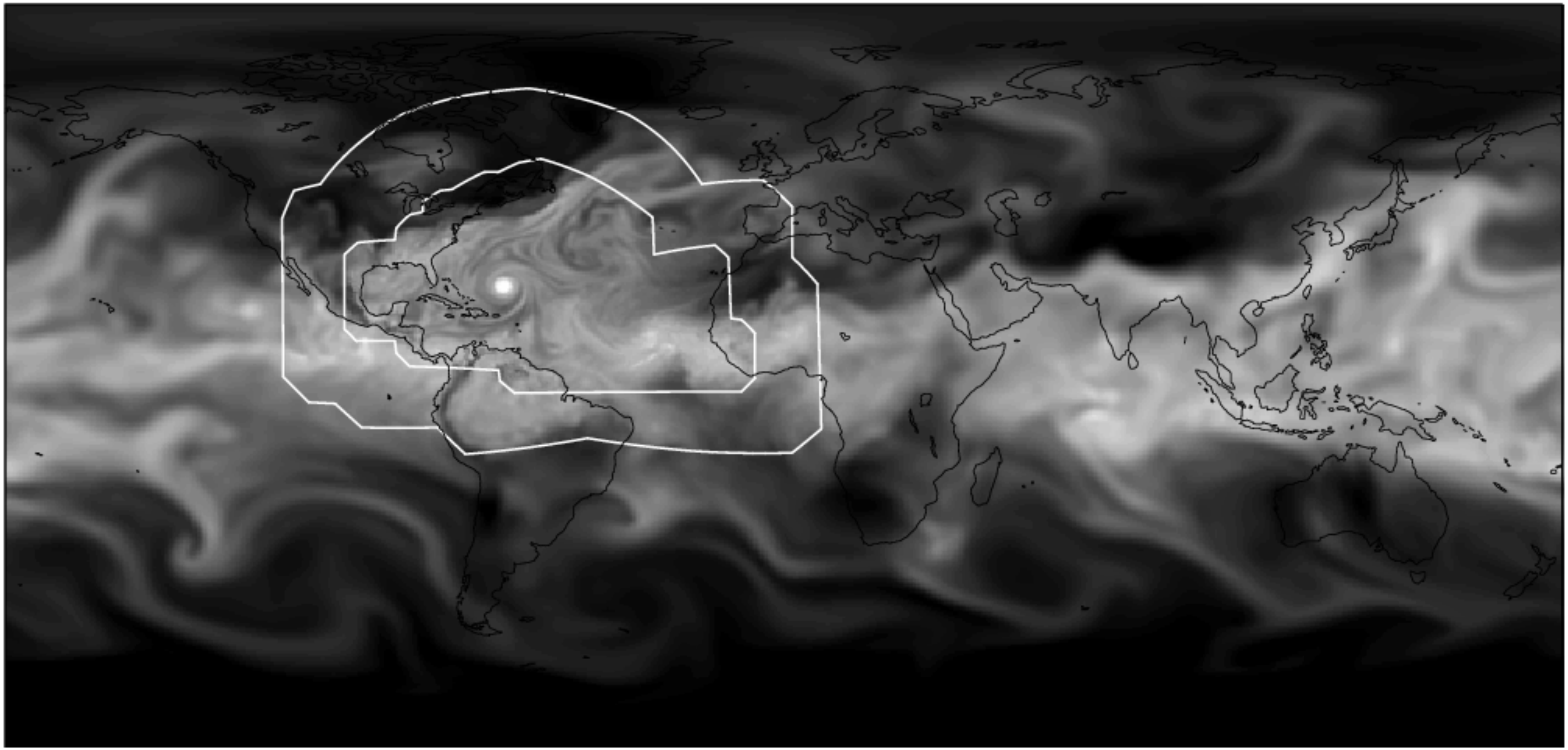
Uniform global simulation: 110 km

Total precipitable water (TPW), Sept 1-16



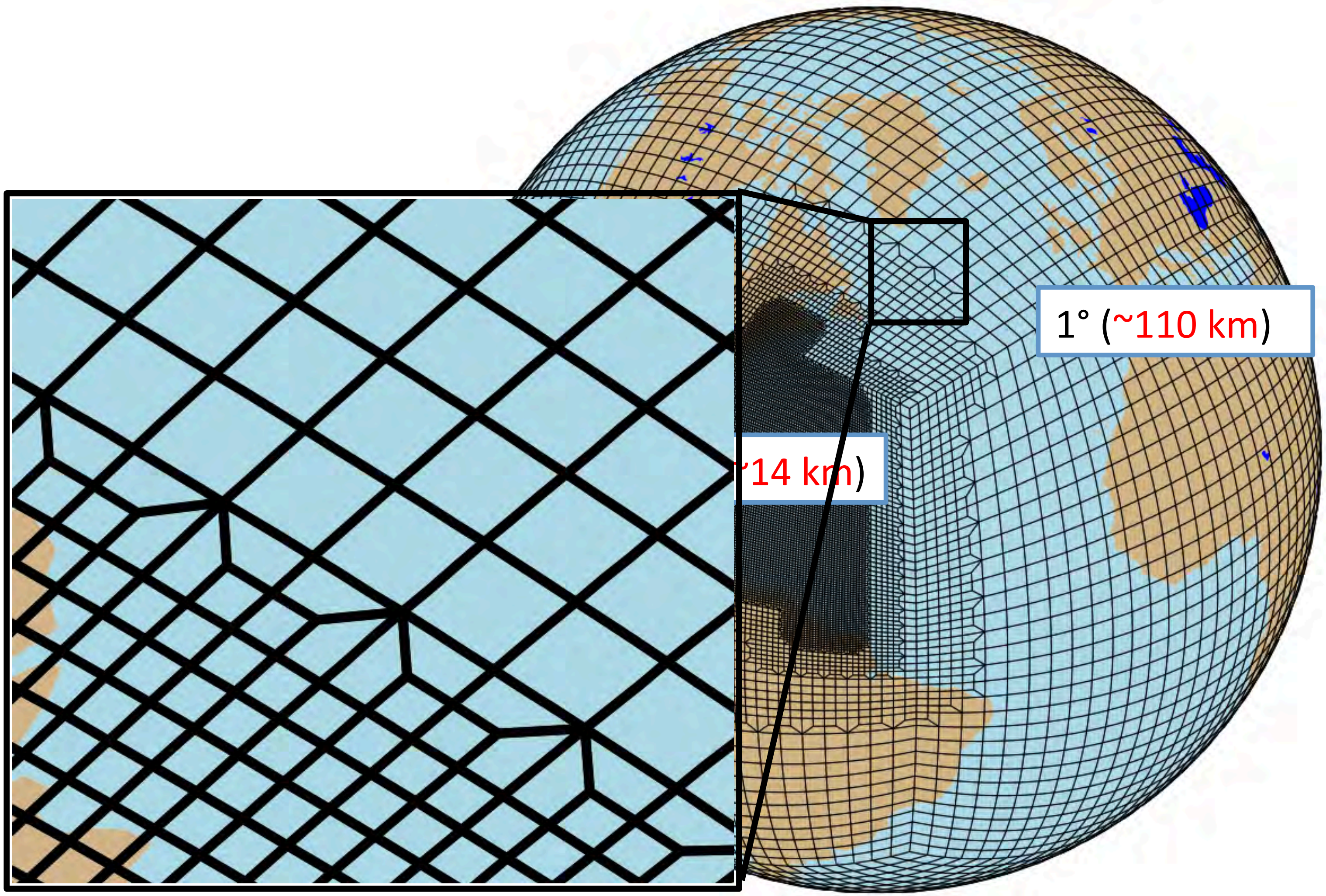
Multi-resolution global circulation (28 km)

Spontaneous generation of tropical cyclones in high-resolution domain!



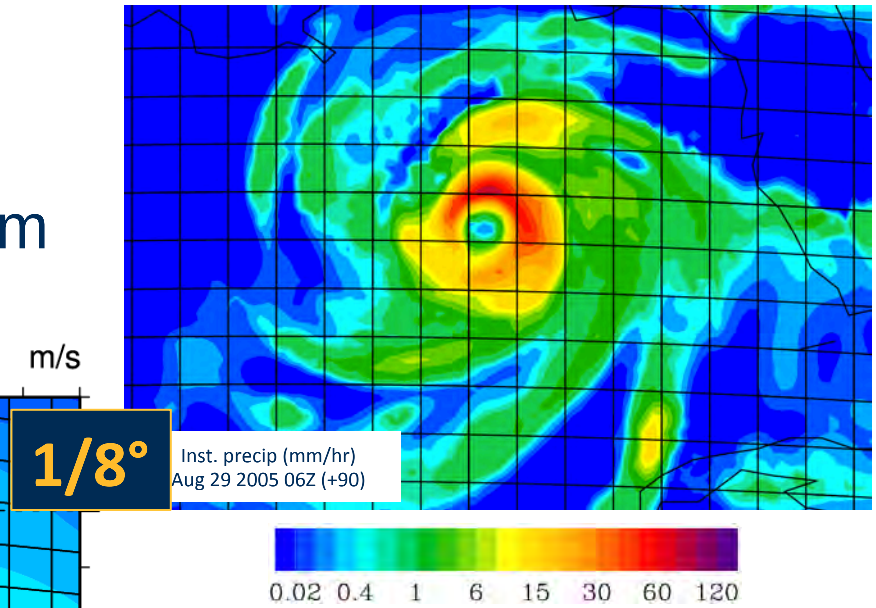
Total precipitable water (TPW), Sept 1-16

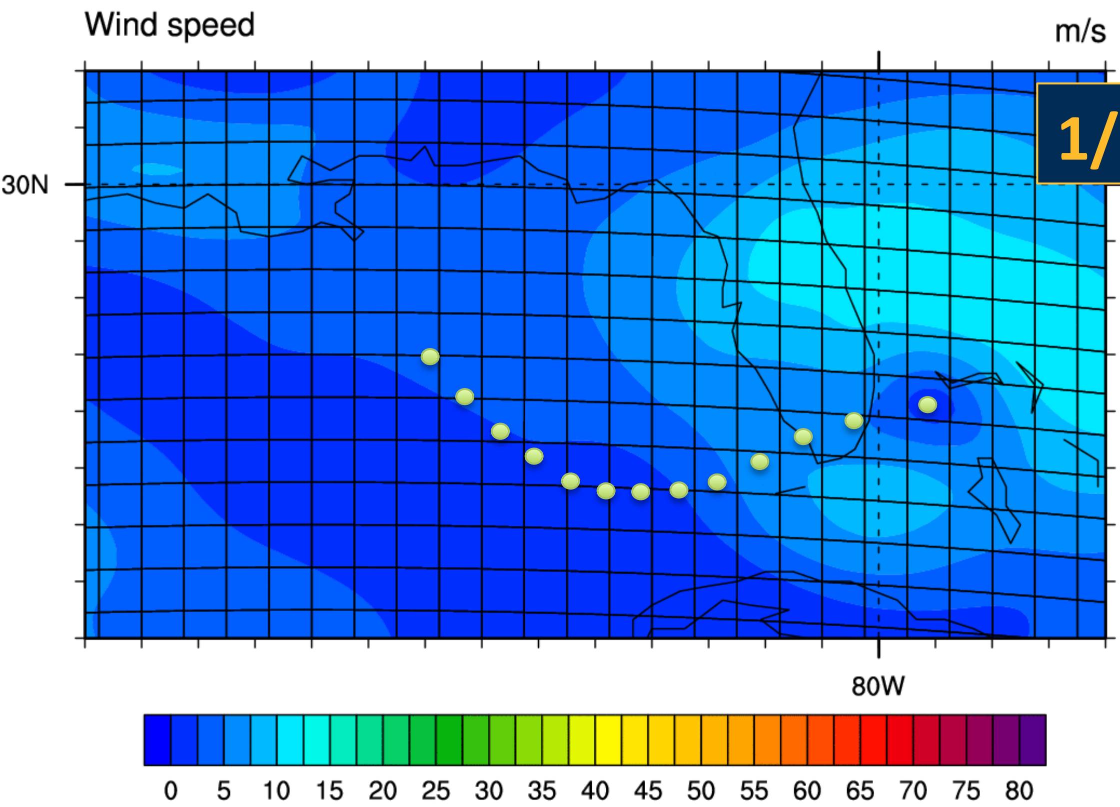
High Resolution For Forecast Experiments

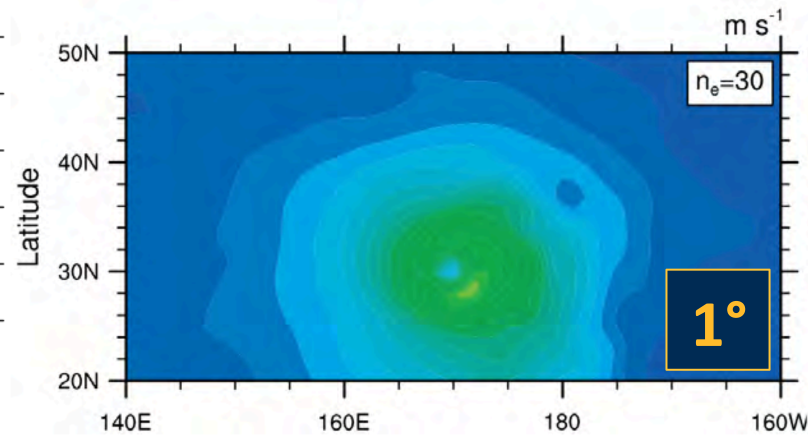


High-res deterministic simulations

- Hurricane Katrina (2005)
- Initialized from ERA-Interim reanalysis -> 8/25 12Z (~115 hours before landfall), Δx=14 km







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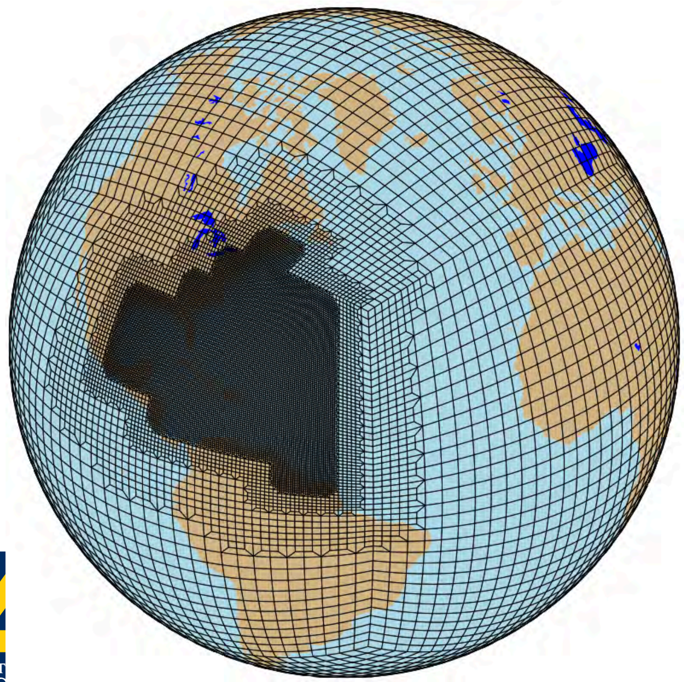
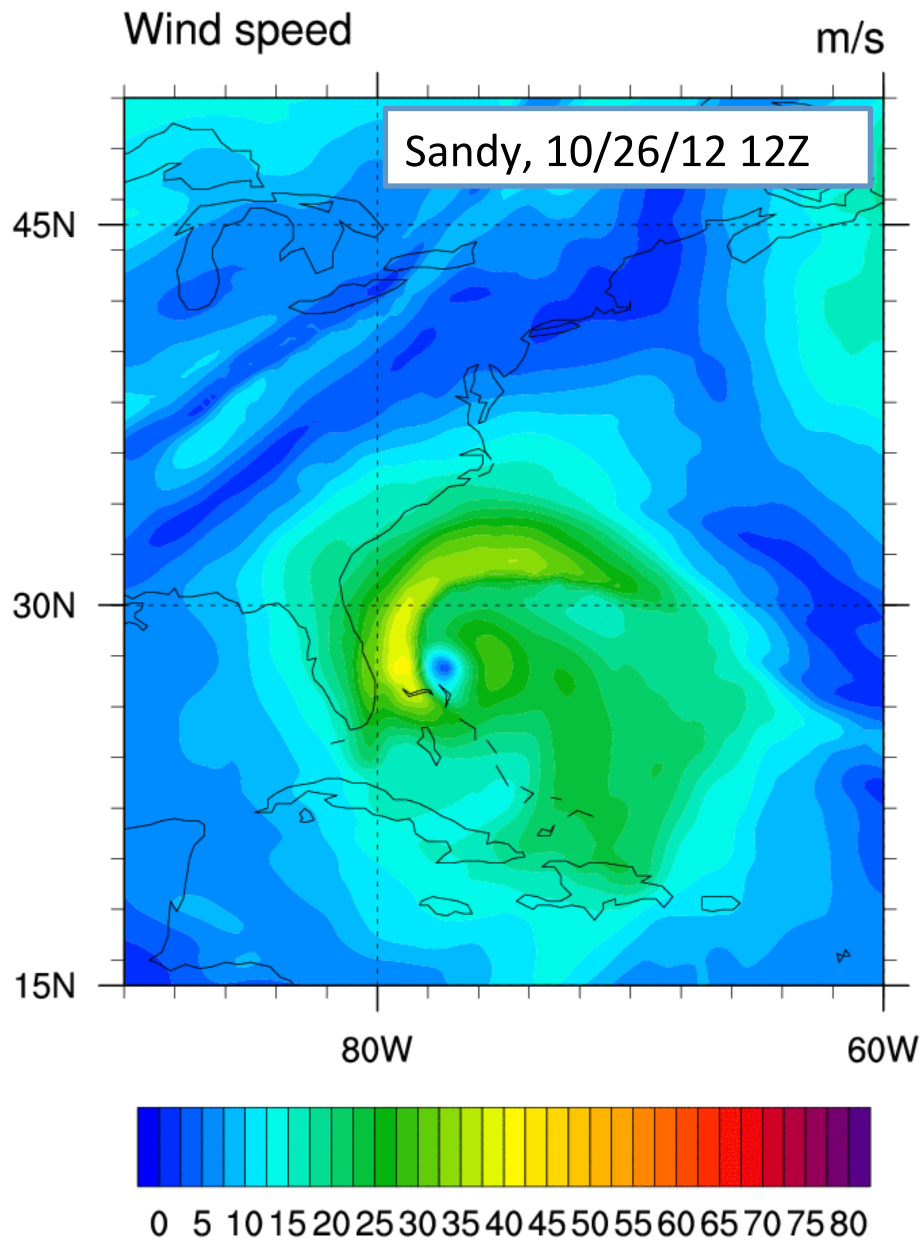
High-Res Deterministic Simulations

- CAM-SE "forecast mode"
- Equivalent 1° (110 km) global grid refined by a factor of 8 to 1/8°(~14 km) over western Atlantic Ocean

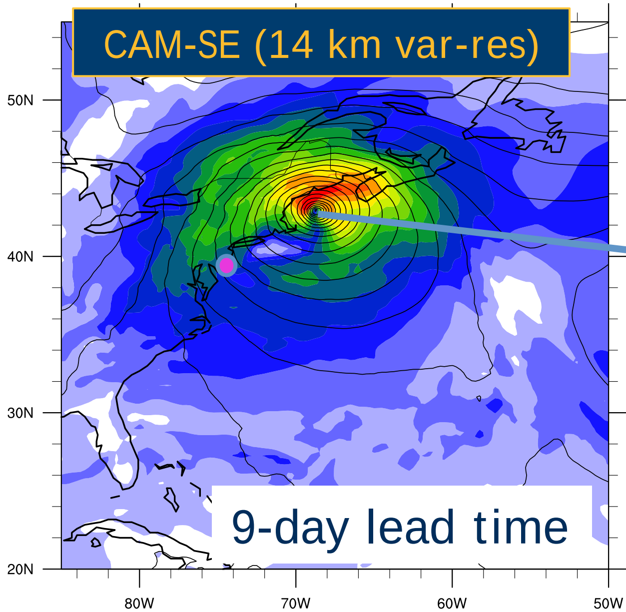




10-Day Tropical Cyclone Forecasts: Sandy

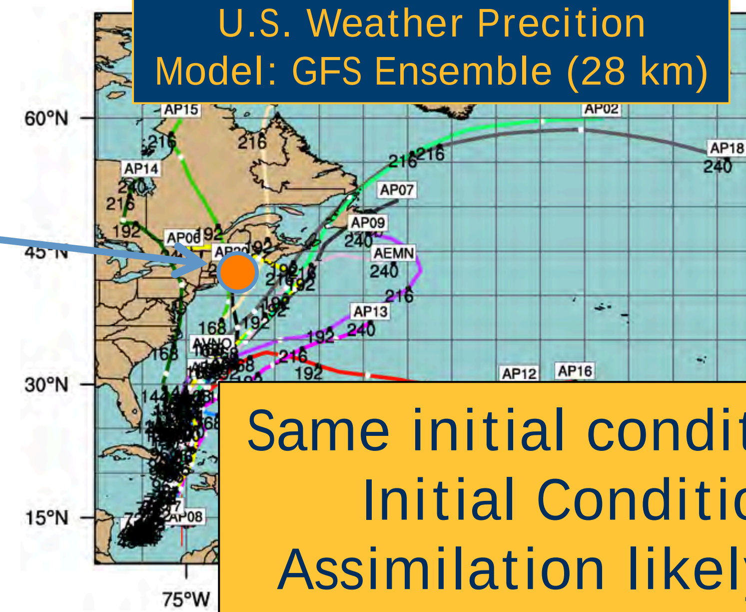
2012-10-21

CAM-SE (14 km var-res)



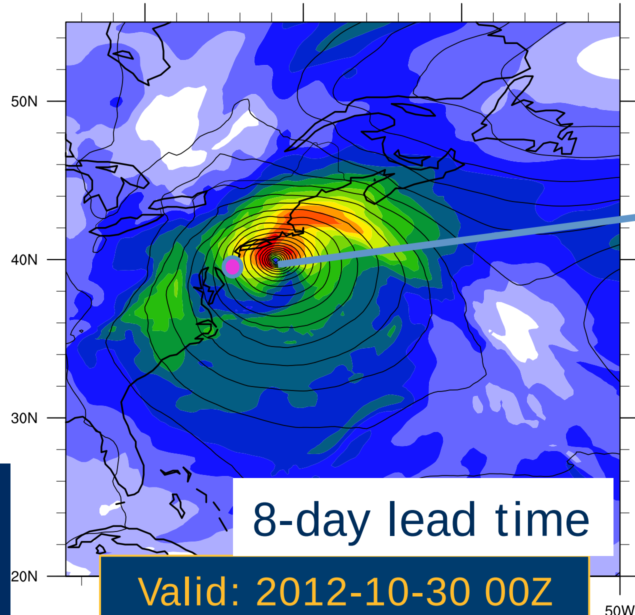
9-day lead time

U.S. Weather Precition Model: GFS Ensemble (28 km)



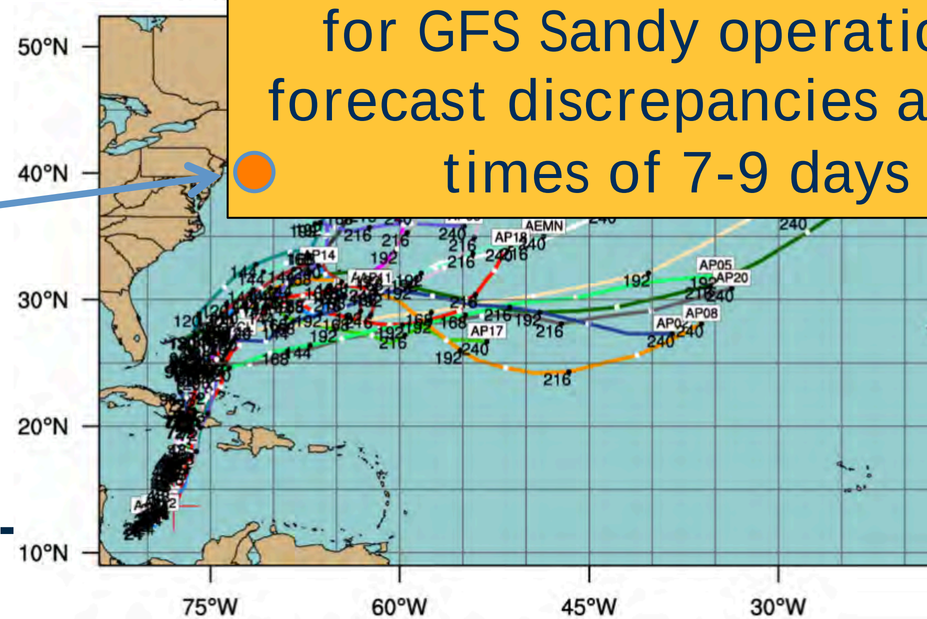
Global Forecast System (GFS) tracks courtesy of RAL Tropical Cyclone Guidance Project (TCGP)

2012-10-22



8-day lead time

Valid: 2012-10-30 00Z



Same initial conditions as GFS: Initial Conditions/Data Assimilation likely not cause for GFS Sandy operational forecast discrepancies at lead times of 7-9 days

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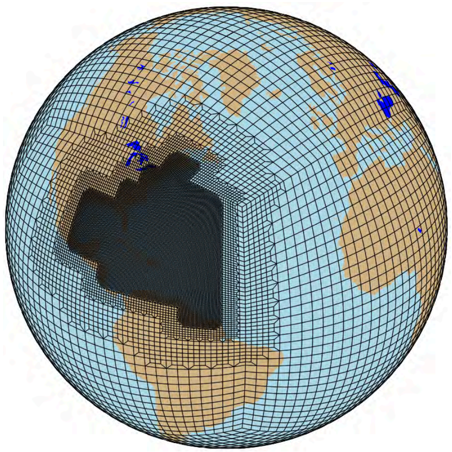
Computational Benefits: CAM-SE



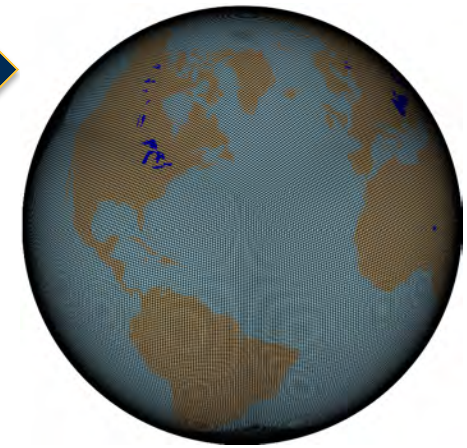
345,600 elements

÷

18,584 elements

=

~18



- Atmosphere: ~15-20x speedup with variable-resolution vs. 1/8° uniform grid
  - Scales with number of elements and fixed compute load
- For same cost of global uniform/quasi-uniform...
  - Higher regional resolution
  - Additional ensemble simulations
  - Longer model runs

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Seamless GCM Modeling: Going Forward

- Variable-resolution, highly-scalable dynamical cores (such as CAM-SE) provide opportunities to improve regional climate simulations today: computationally attractive
- AMR approach is in research mode, looks promising
- High-order methods help suppress grid imprinting
- Some areas that need attention:
  - Where do we put high-resolution for non-localized features? Are there teleconnections?
  - Treatment of topography in variable-resolution/AMR models needs attention (e.g. topography filtering).
  - Treatment of moisture and grid-scale interactions needs a lot of attention.

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Seamless: Challenges and Opportunities

- ‘Seamless’ GCM design challenges:
  - Hydrostatic assumption breaks down ~ 10 km:
    - non-hydrostatic designs are a future necessity
  - Most physical parameterization were not built for the local/regional scales
    - their built-in assumptions might break down
    - new physical parameterizations are needed
  - When do we need to turn parameterizations on/off?
  - How do we handle the grey zone (1-10 km) or, in general, marginally-resolved scales?
  - Is 1 km (cloud-permitting/resolving) grid spacing computationally & physically feasible? Probably yes with AMR or variable-resolution approaches!

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Additional References

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- Williamson, D. L., J. B. Drake, J. J. Hack, R. Jakob, and P. N. Swartrauber, 1992: A standard test set for numerical approximations to the shallow water equations in spherical geometry. Journal of Computational Physics, 102, 211–224