Adaptive Mesh Refinement for Tropical Cyclone Prediction

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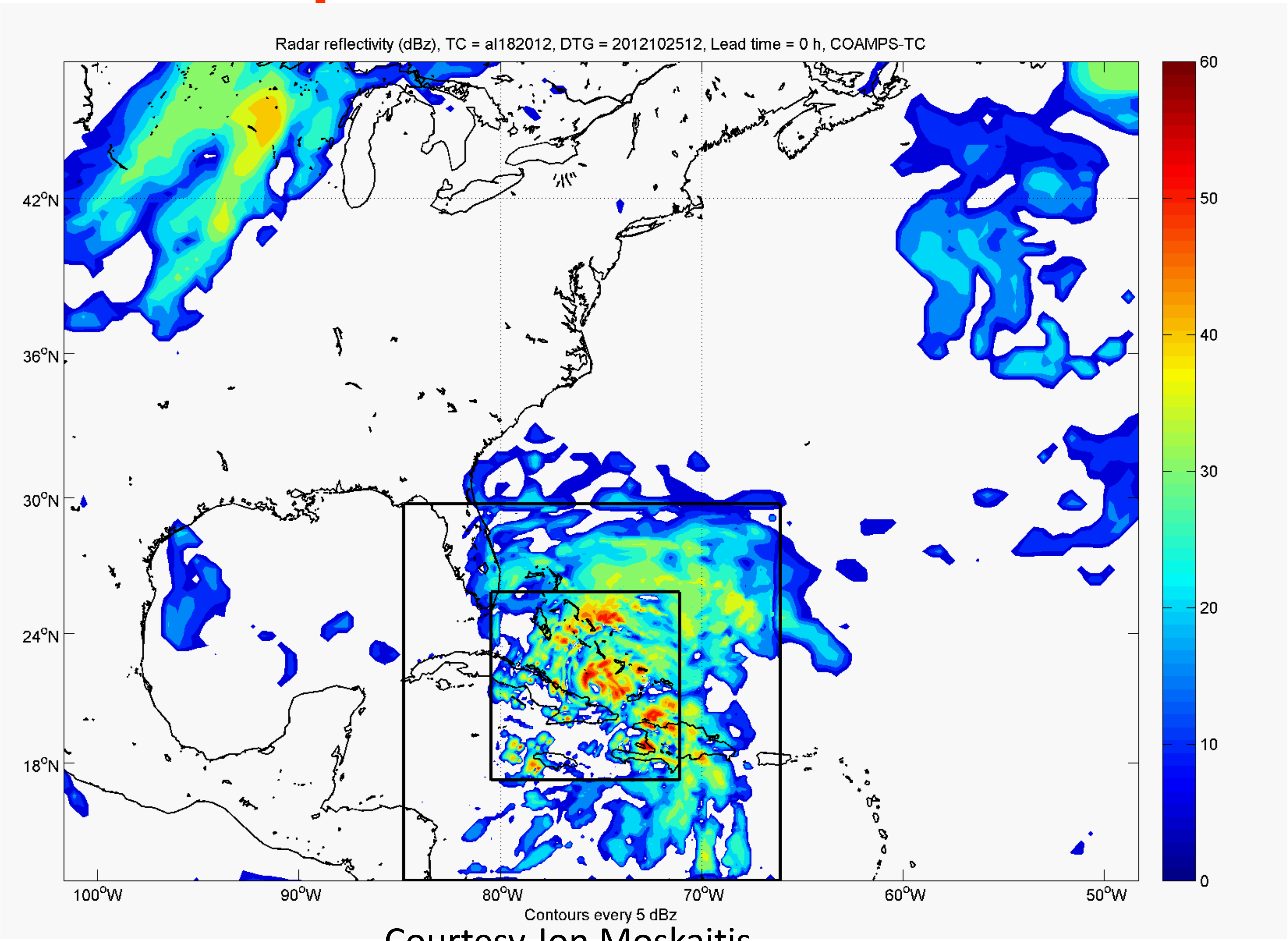
Introduction

- Next generation atmospheric models require a unified approach
  - Spatial: microscale to global
  - Temporal: weather to climate
- Tropical cyclones (TCs) require:
  - Fine resolution in their core for resolving processes responsible for intensity
  - Coarser resolution generally ok for synoptic scale features responsible for track
- Typical current mesoscale models used multiple nested grid approach. Drawbacks:
  - Multiple lateral boundaries
  - Inefficiency doing same forecast multiple times
  - Nest feedback / lateral boundary blending
  - Scaling

Multiple Nests in COAMPS-TC



Courtesy Jon Moskaitis

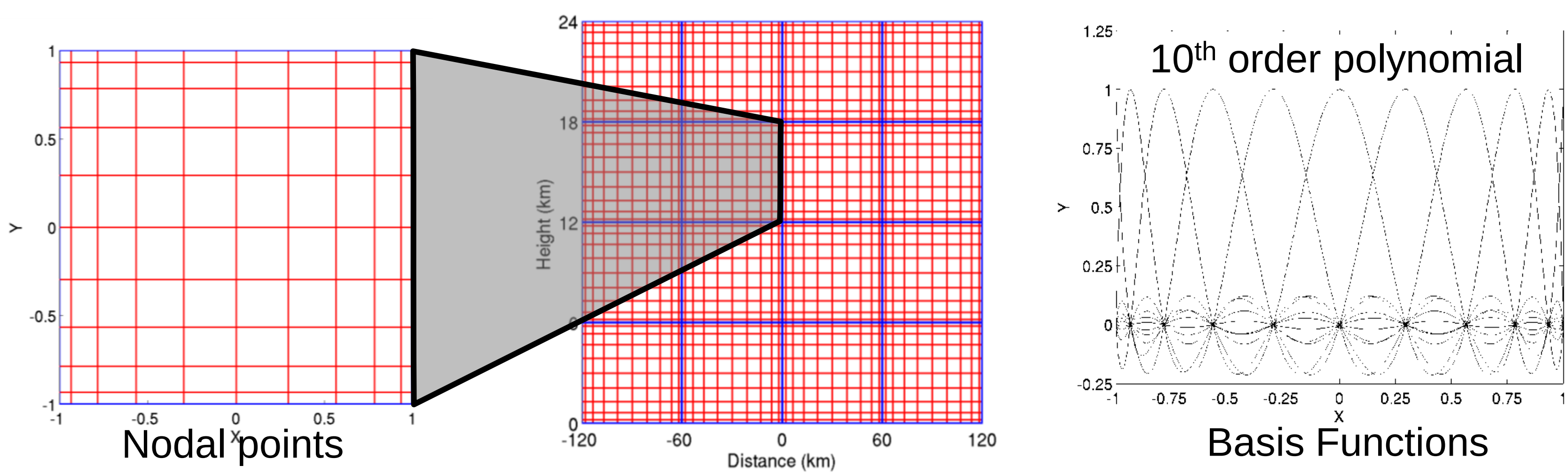
Simulated radar reflectivity from multiple nest forecast of Hurricane Sandy (2012) in a nested NWP mesoscale model (45-15-5 km, 15 and 5 km meshes move with TC)

Objective

- Examine capability of Adaptive Mesh Refinement (AMR) for tropical cyclone prediction in idealized framework
  - Compare AMR vs. Non-AMR (at highest AMR resolution) for accuracy of simulated phenomenon
  - Compare AMR vs. Non-AMR with regard to speed-up
- Test cases:
  - 1. Advecting tropical cyclone vortex
  - 2. Barotropic instability of an ITCZ-like shear zone, genesis of TC-like vortices
  - 3. Barotropic instability of the hurricane eyewall, eye-eyewall dynamics
- AMR Criterion
  - Refine and coarsen elements based on a potential vorticity (PV) threshold
  - PV chosen since inertia-gravity waves have zero PV (will not refine mesh for inertia-gravity wave)

Model: NUMA

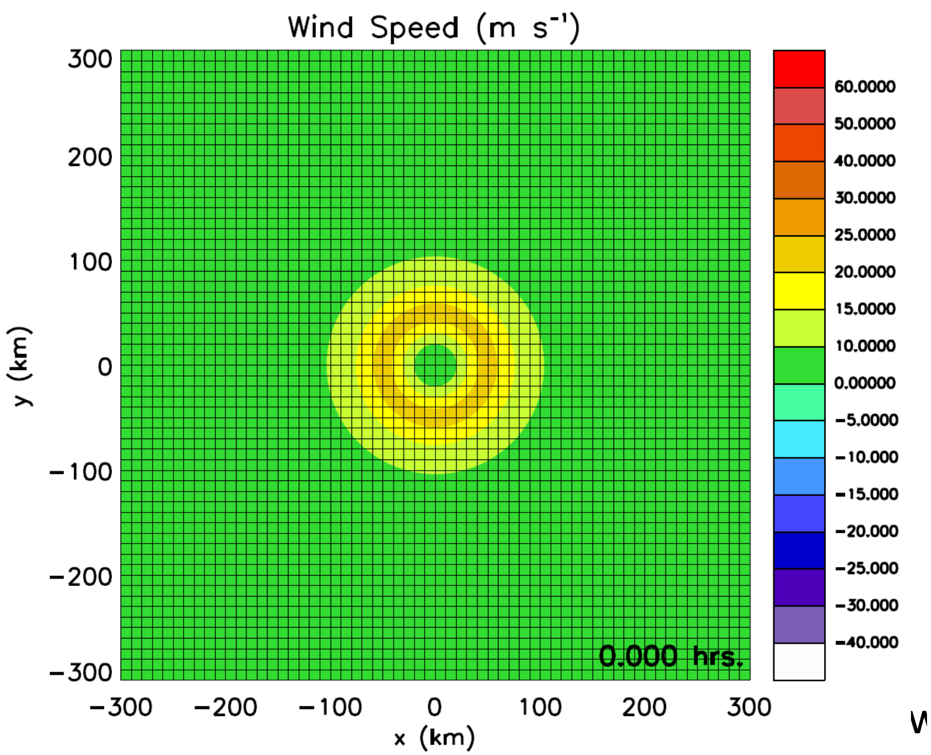
- **NUMA**: **N**on-hydrostatic **U**nified **M**odel of the **A**tmosphere (Giraldo and Restelli 2008)
- Shallow water model of NUMA (*f*-plane)
  - Continuous or Discontinuous Galerkin Methods
  - High order, accurate, highly scalable
  - Unstructured grids, AMR (Kopera and Giraldo 2014)



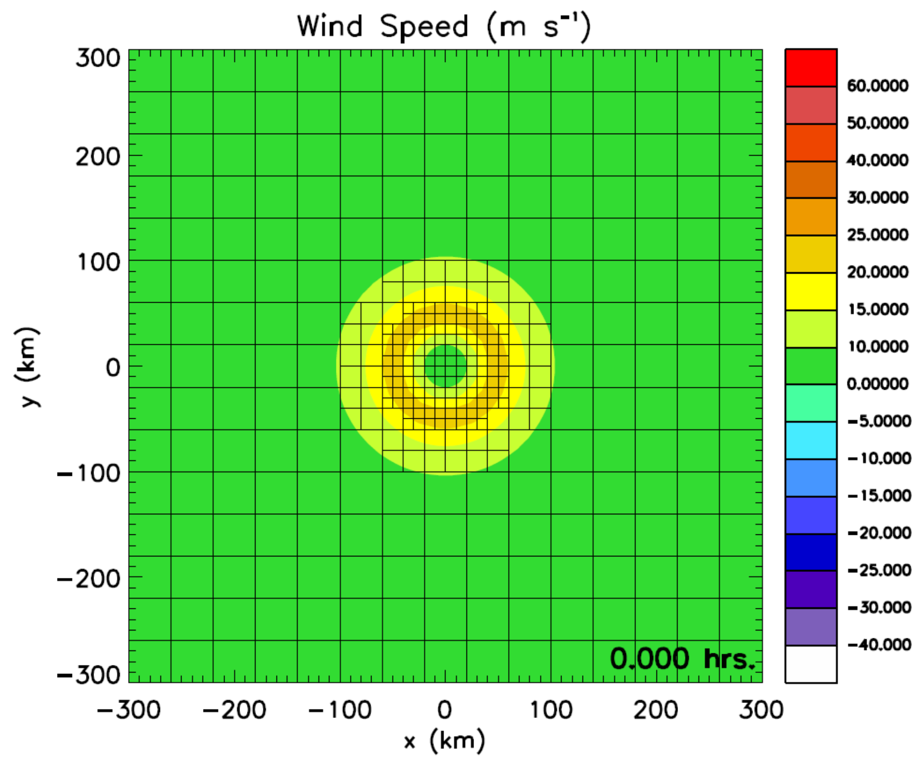
1. Advecting vortex

Initial Conditions:

NO AMR HIGH



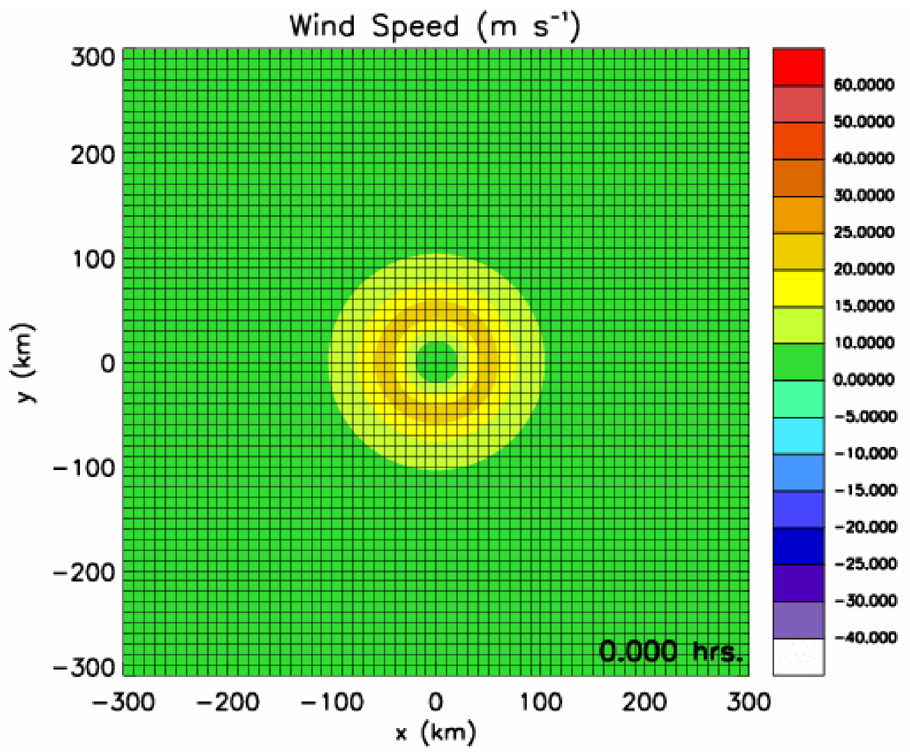
AMR



No adaptive mesh refinement (**NO AMR HIGH**) vs. adaptive mesh refinement (**AMR**)
Shallow Water NUMA, CG, *f*-plane, 2 mesh refinements max
5th order polynomials, RK4, initial dt=3 s, adapt mesh to PV, inviscid, nodal filter
Highest horizontal resolution ~ 2km

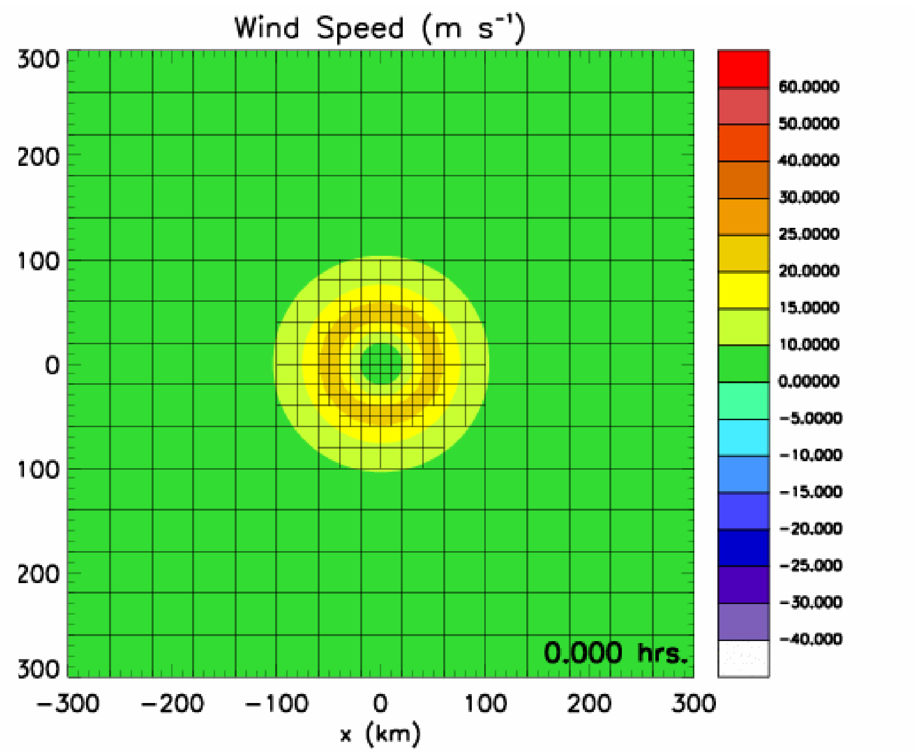
1. Advecting vortex

<u>NO AMR HIGH</u>



CPU time: 2.2 h

<u>AMR</u>



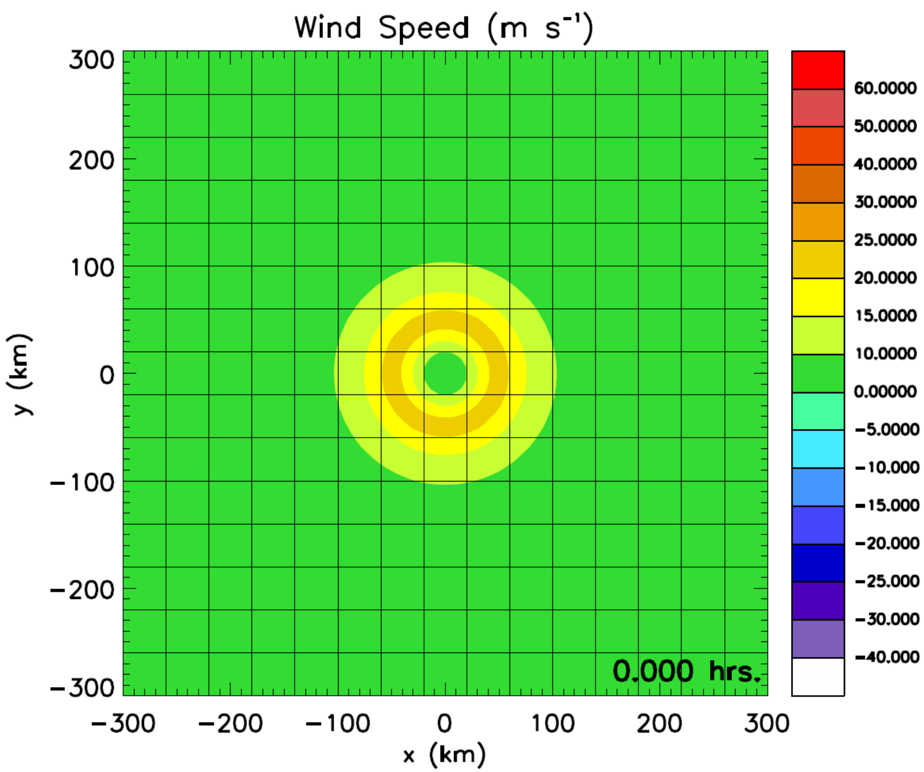
CPU time: 0.43 h

AMR is over 5 times faster than NO AMR HIGH, and resolves the vortex core well

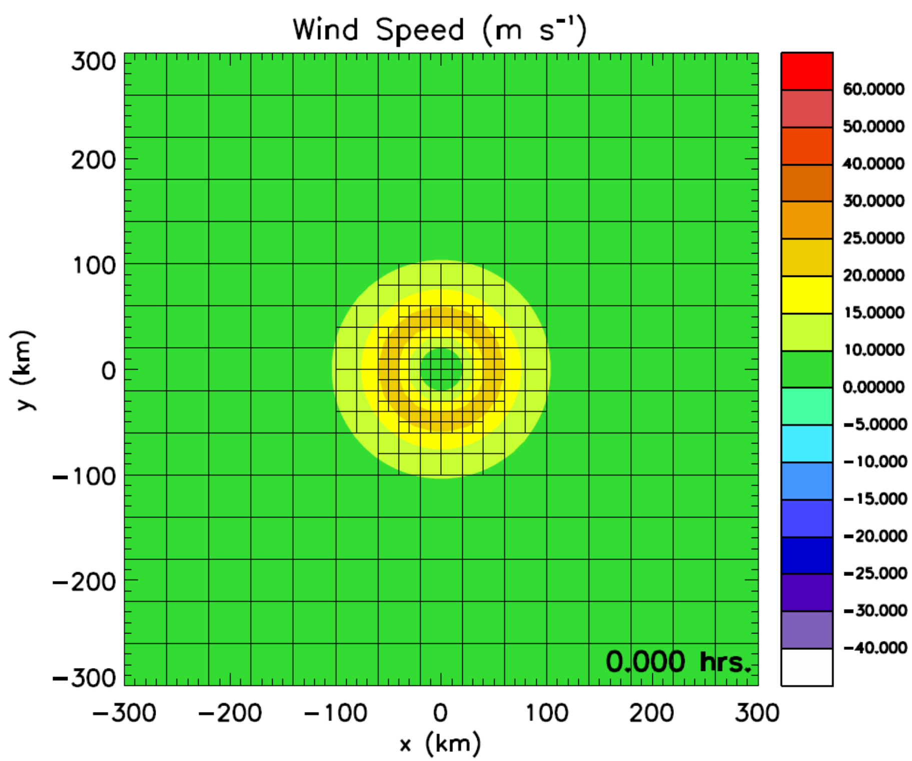
1. Advecting vortex

Initial Conditions

NO AMR COARSE

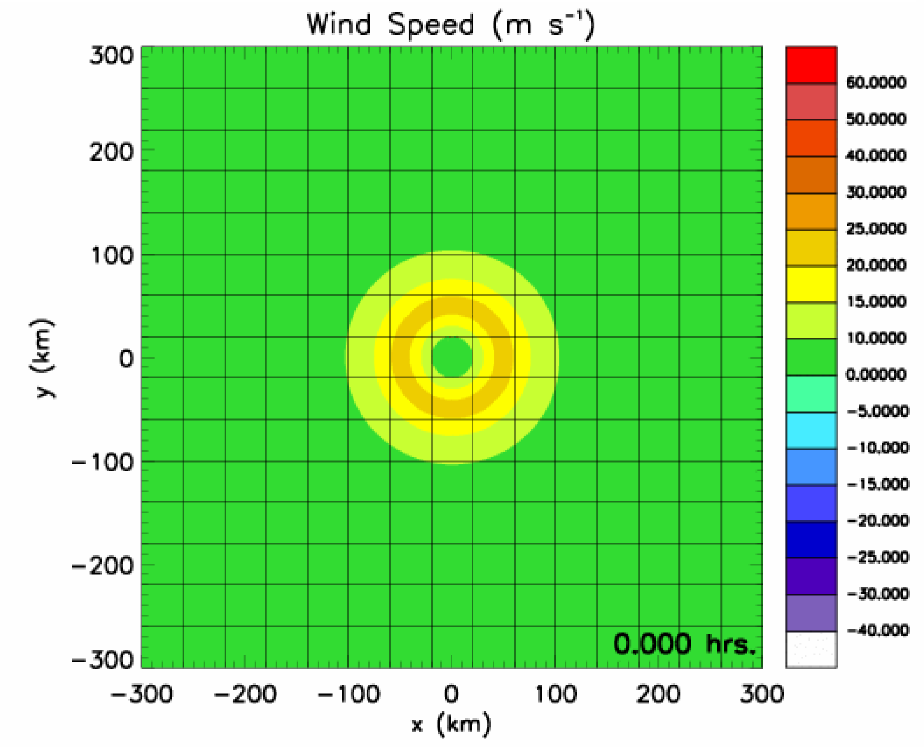


AMR



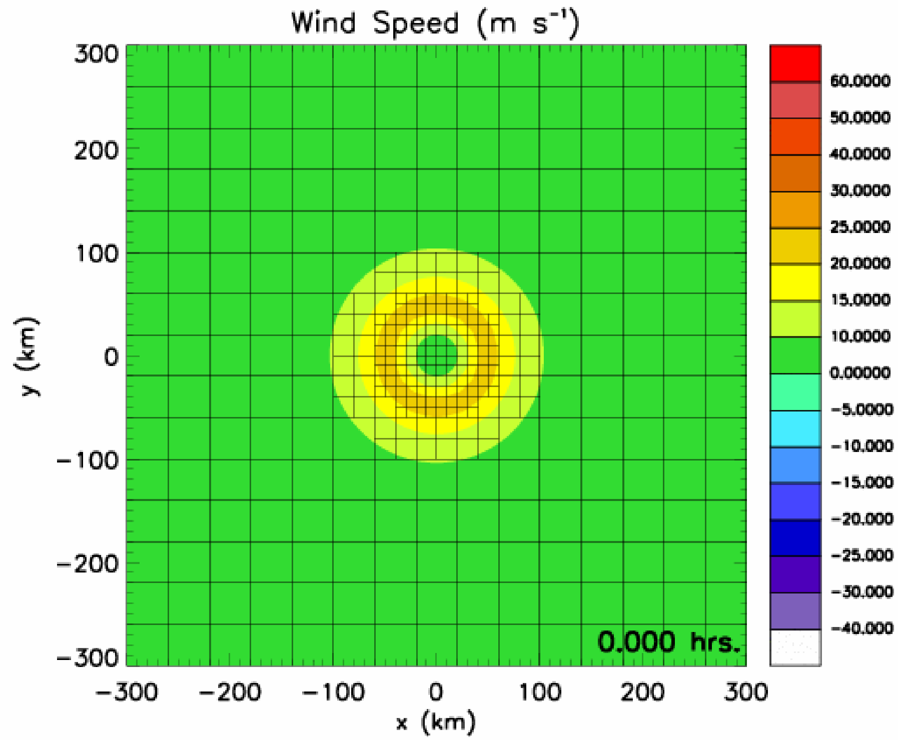
1. Advecting vortex

NO AMR COARSE



CPU time: 0.1 h

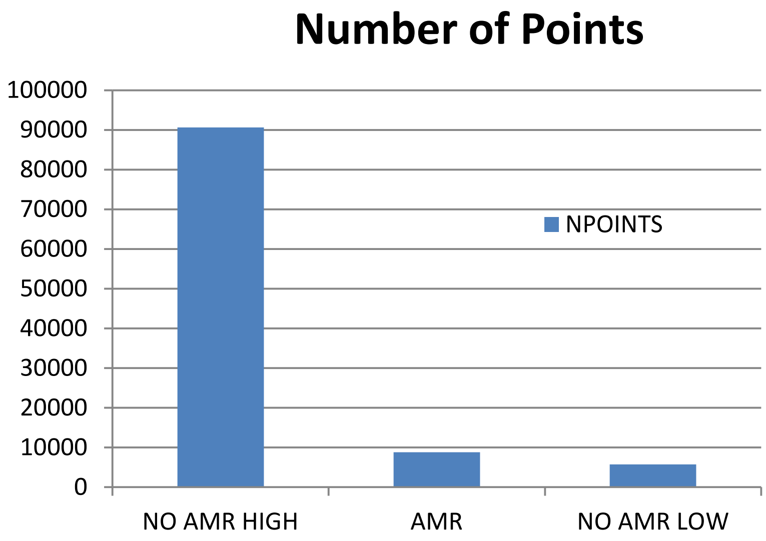
AMR

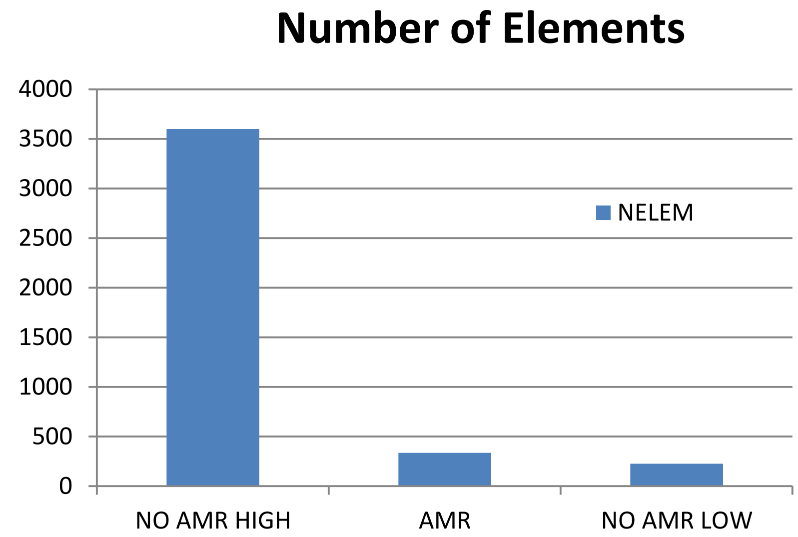


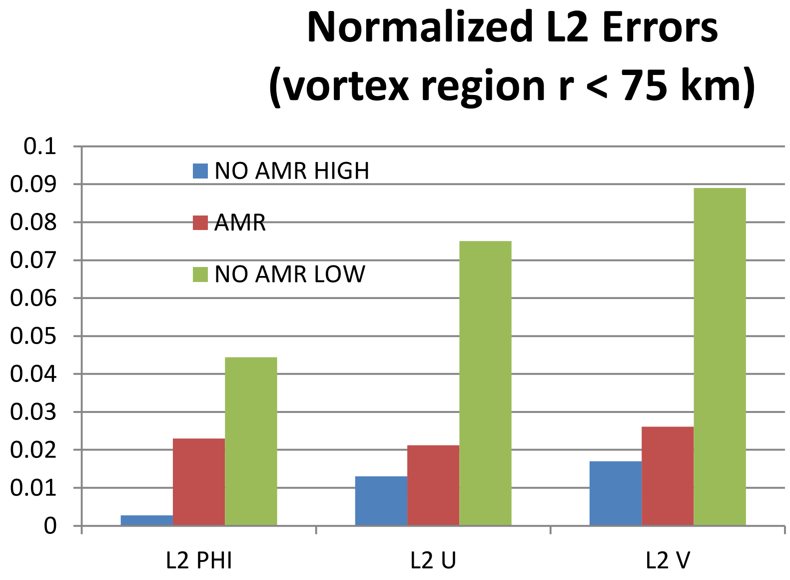
CPU time: 0.43 h

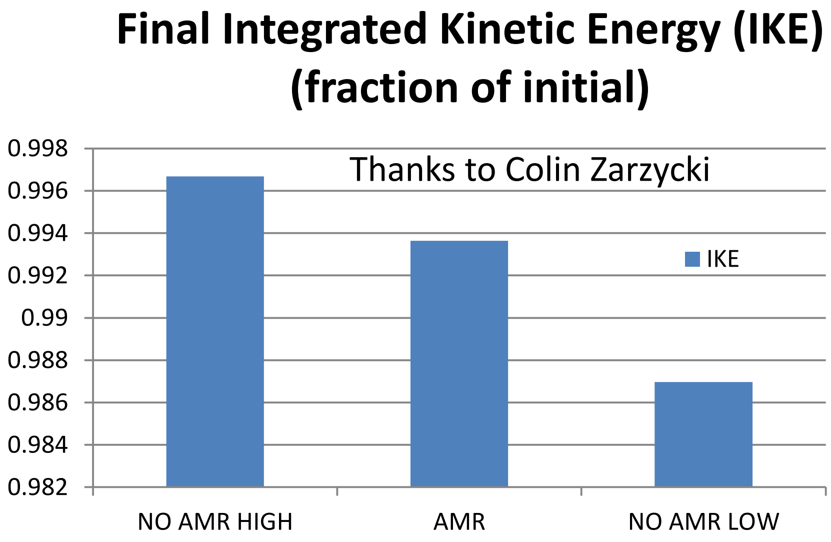
NO AMR COARSE 4 times faster than AMR, but significant errors in vortex core region

Quantifying Results









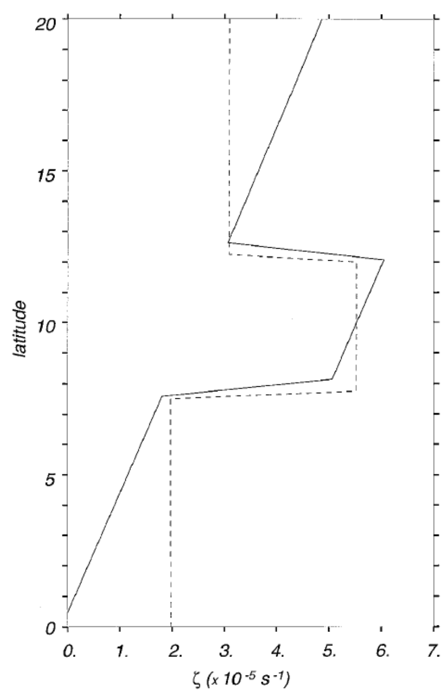
AMR Simulation L2 Errors are similar to NO AMR HIGH in vortex region

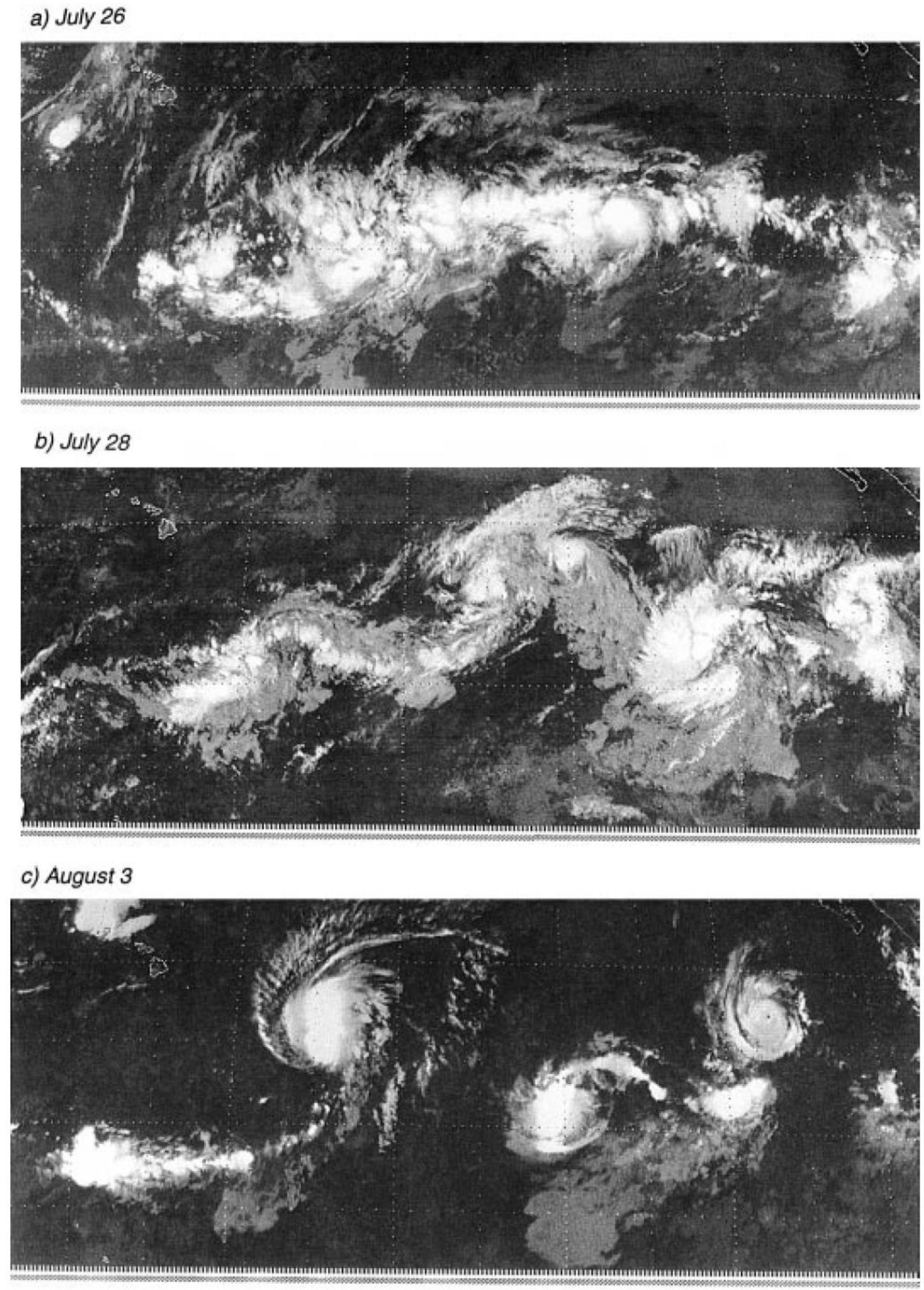
The Inter-Tropical Convergence Zone (ITCZ)

- AMR could be useful to resolve evolving localized small-scale deep convection and vorticity in ITCZ
- Coarser resolution is ok for resolving subtropical highs in descending branch of Hadley Circulation

The intertropical convergence zone can become barotropically unstable leading to a break down, and formation of multiple tropical cyclones

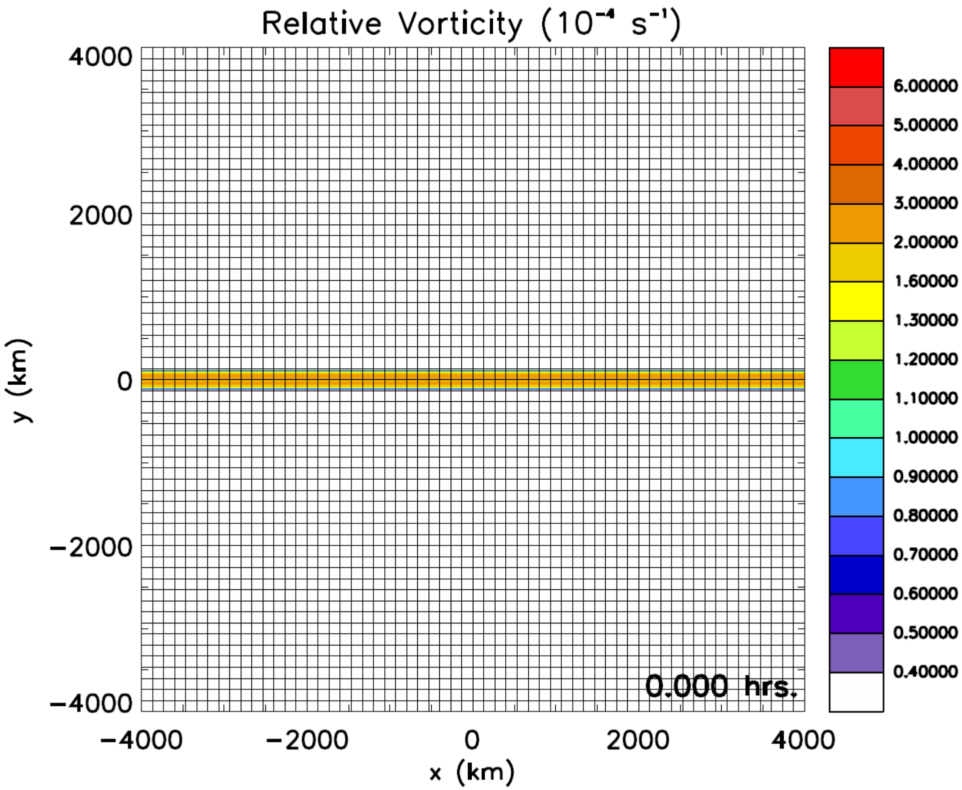
Ferreira and Schubert (1997) J. Atmos.Sci.

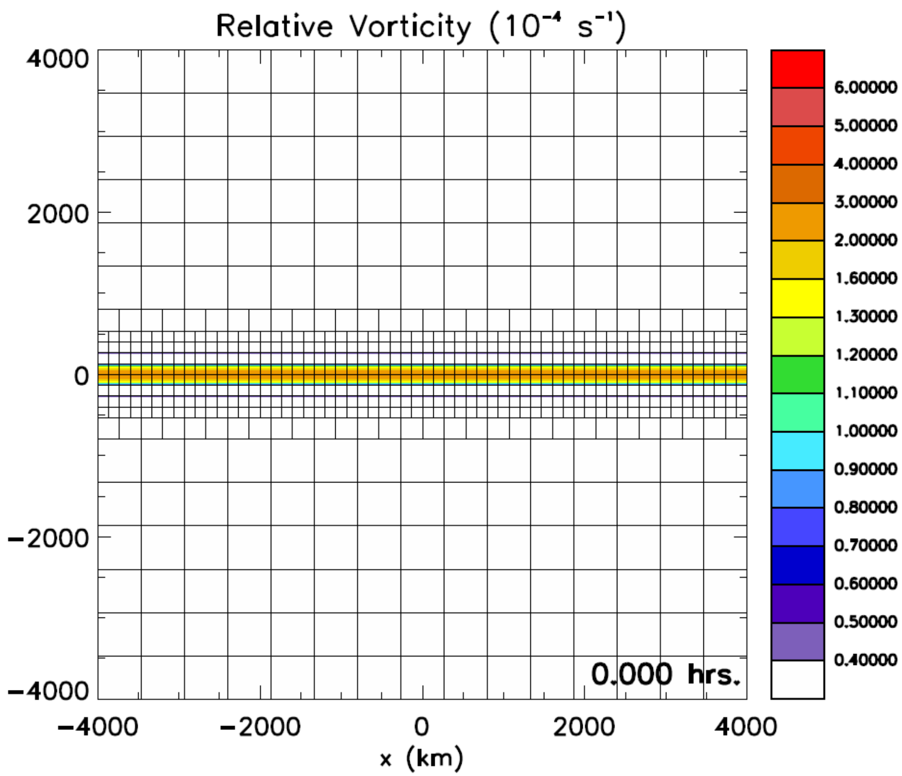




2. Barotropic Instability of the ITCZ

NO AMR HIGH | **Initial Conditions** | **AMR**



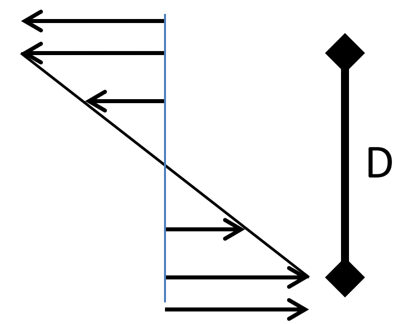


40 m/s of cyclonic shear over D=200 km width
Random broadband small perturbation added

$$0.5kD = 0.3984$$

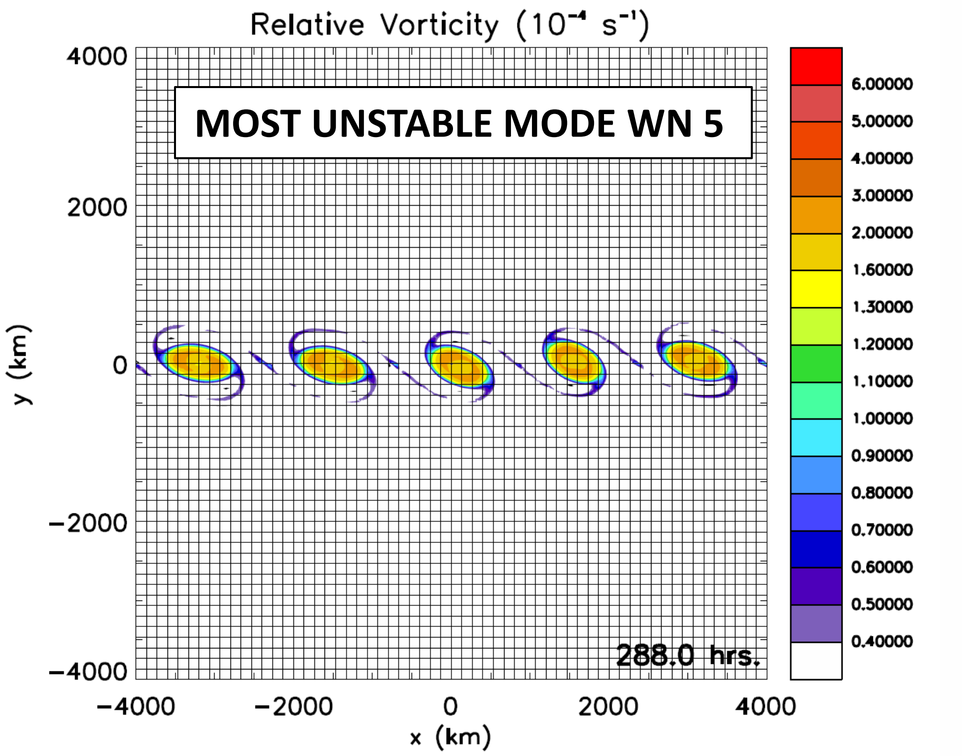
Theory: Most Unstable Mode (L=1577 km, WN 5)
e-folding time (7 hours)

$$kc_i = \frac{0.2012U}{0.5D}$$



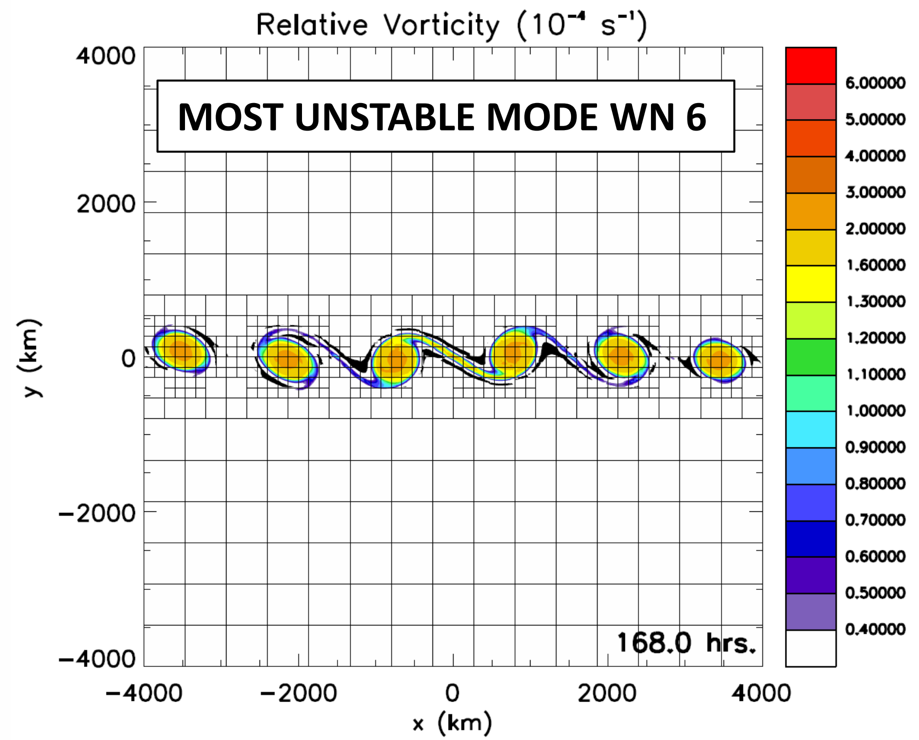
2. Barotropic Instability of the ITCZ

NO AMR HIGH



CPU time: 12.3 h

AMR

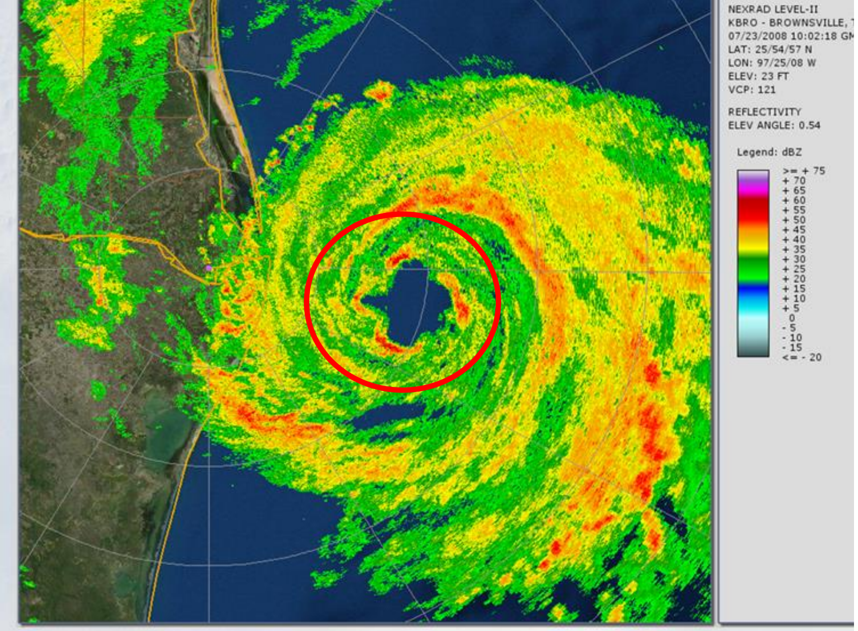


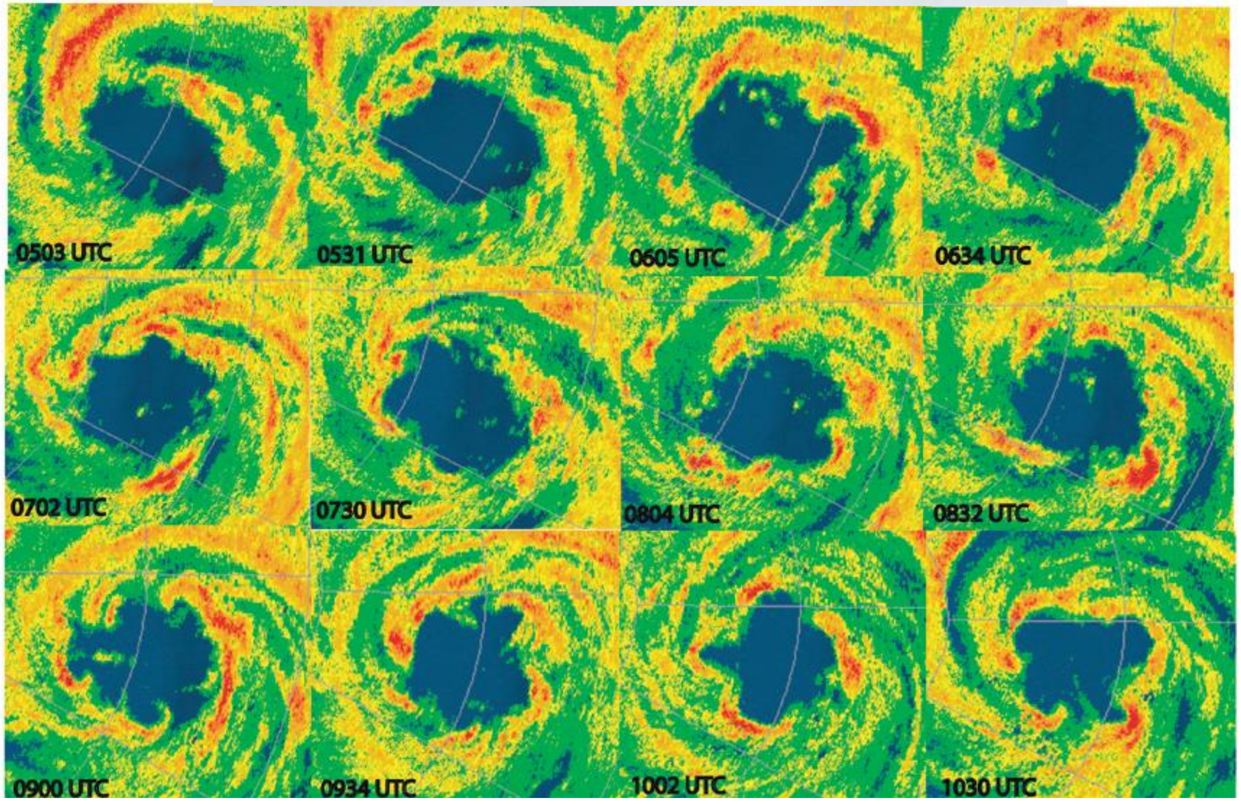
CPU time: 3.3 h

AMR useful for resolving ITCZ-like PV strip and its barotropic instability and break down
Instability happens faster in AMR simulation, higher most unstable mode (WN 6)
Factor of 4 speedup

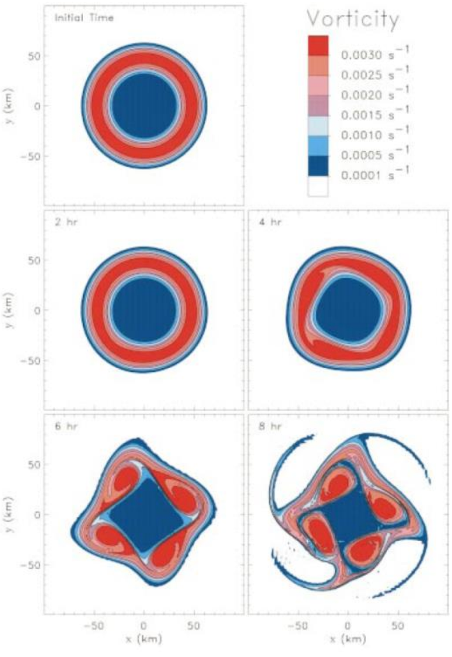
The hurricane eyewall often becomes barotropically unstable, and breaks down, leading to polygonal eyewalls and mesovortices.

Hendricks et at. (2012), Mon. Wea. Rev., for Hurricane Dolly (2008)



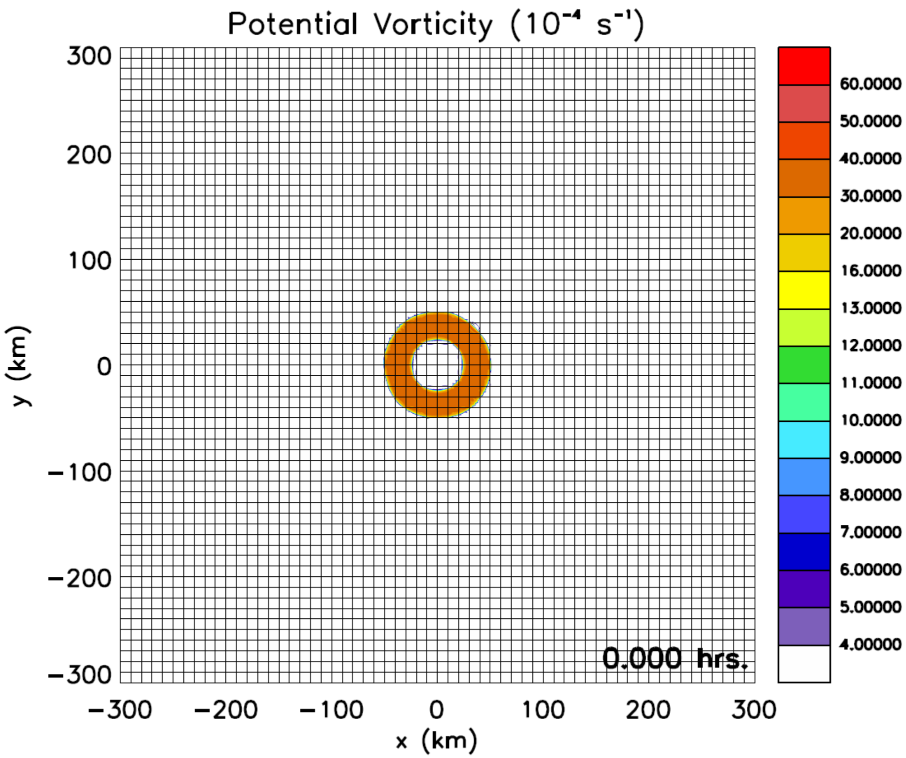


Schubert et al. (1999)

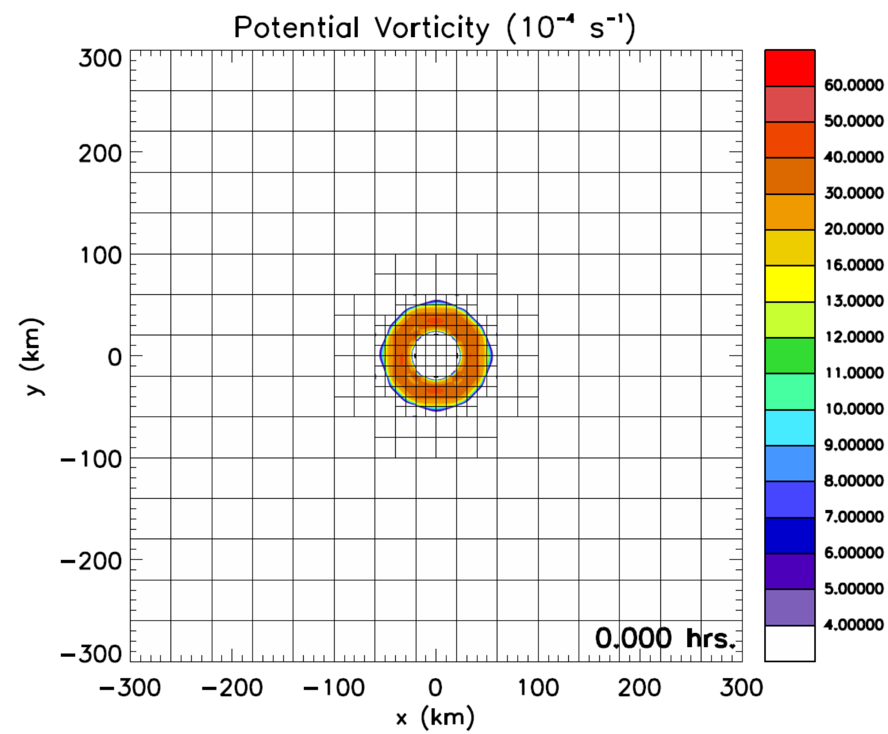


3. Barotropic Instability of the Eyewall

NO AMR HIGH



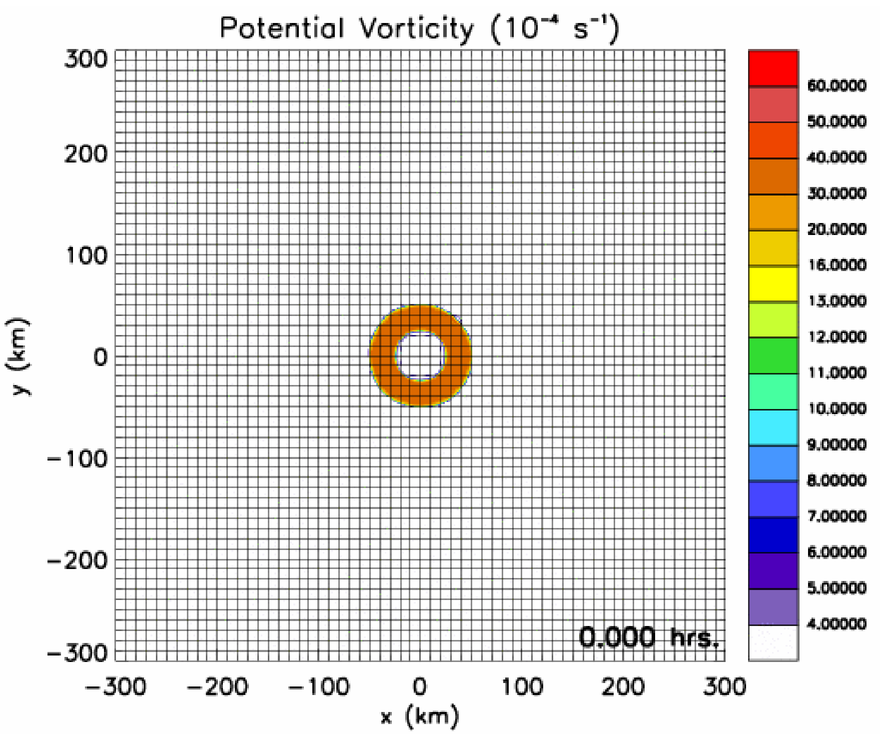
AMR



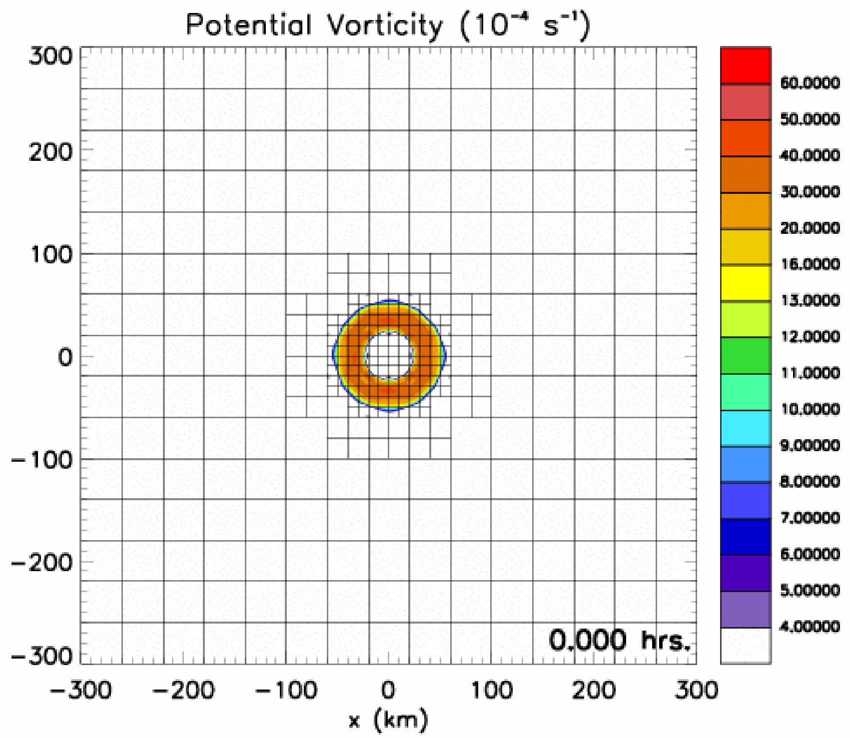
Thick PV ring, most unstable to azimuthal wavenumber m=3

3. Barotropic Instability of the Eyewall

NO AMR HIGH

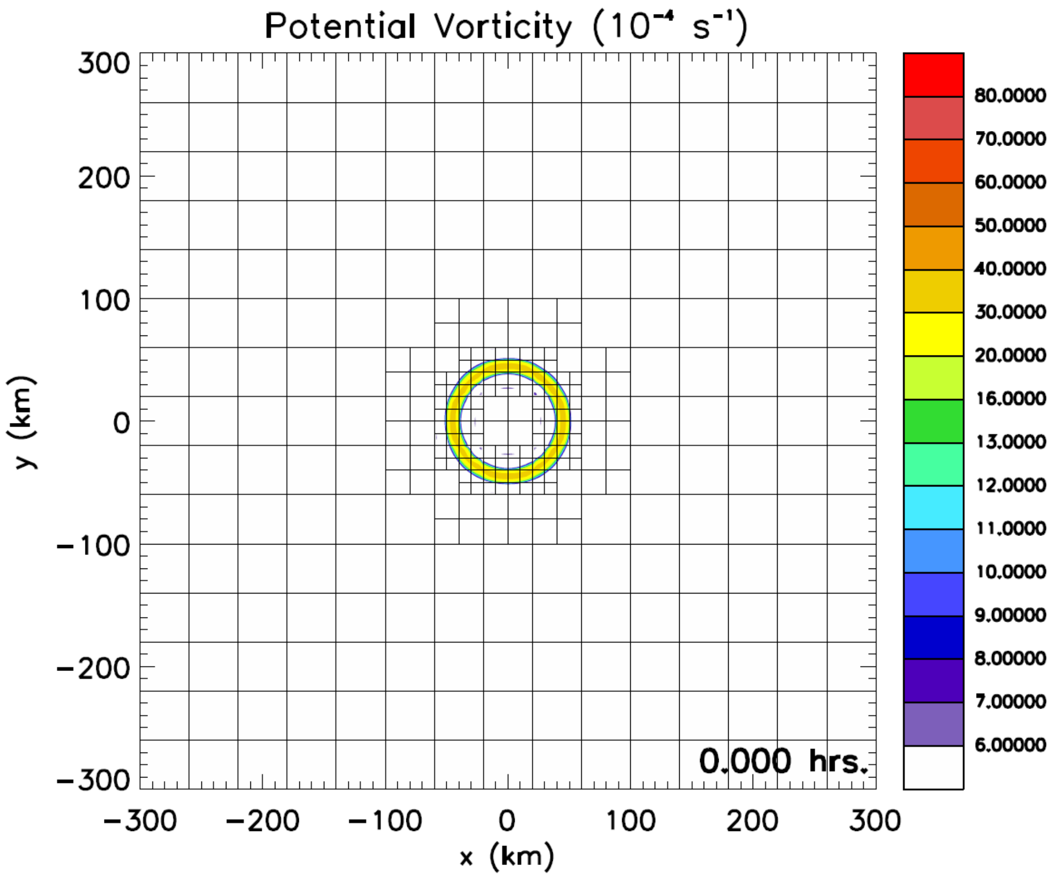


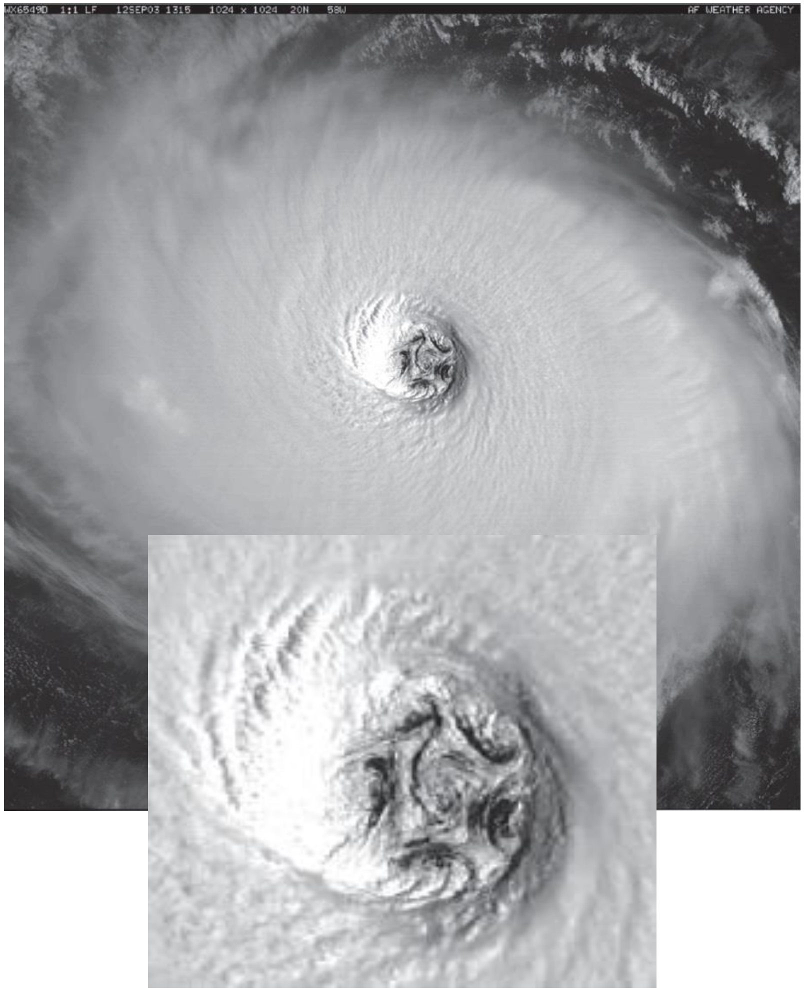
AMR



- Can resolve eyewall and inner-core processes using AMR
- AMR simulations reproduces most unstable mode of WN 3
- Instability proceeds faster in AMR simulation

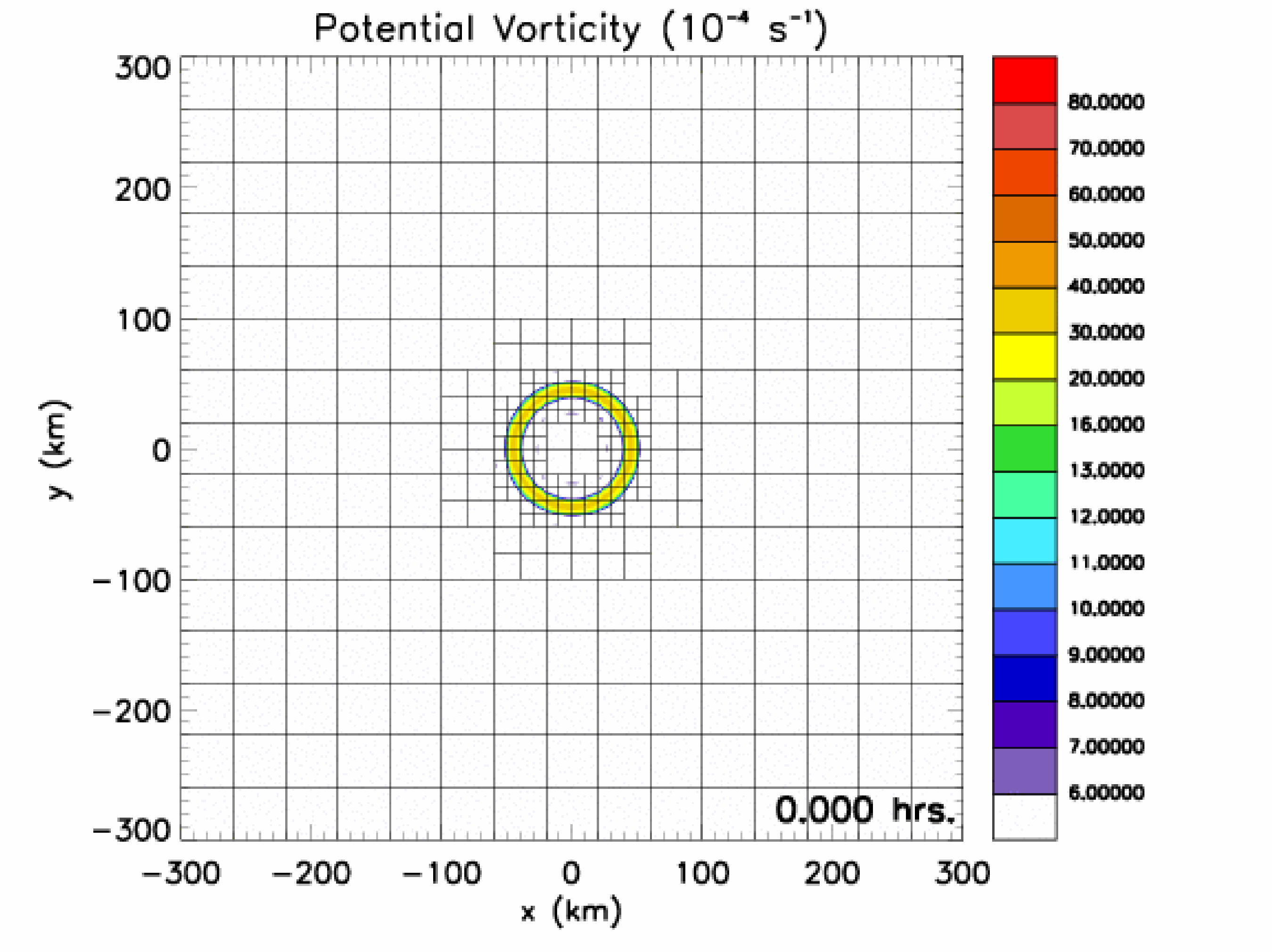
3. Barotropic Instability of the Eyewall
AMR with 8th order polynomials





Hurricane eyewall can often take the form of a thin PV ring, which tends to break down rapidly to long lived eye mesovortices

3. Barotropic Instability of Eyewall (thin ring) AMR with 8th order polynomials



AMR can be useful for resolving hurricane inner-core dynamics (eyewall breakdown into multiple eye mesovortices), while saving on computational expense in rest of domain

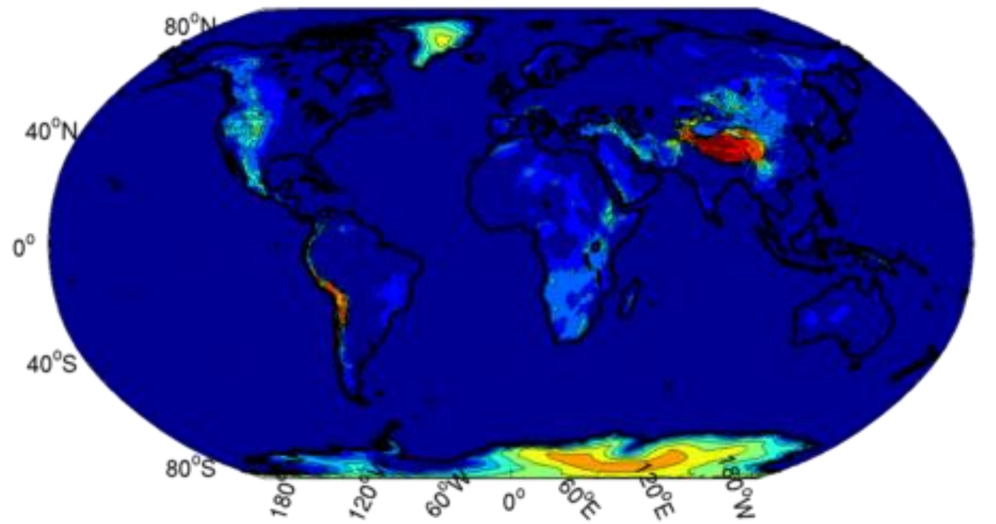
Navy Next Generation Model

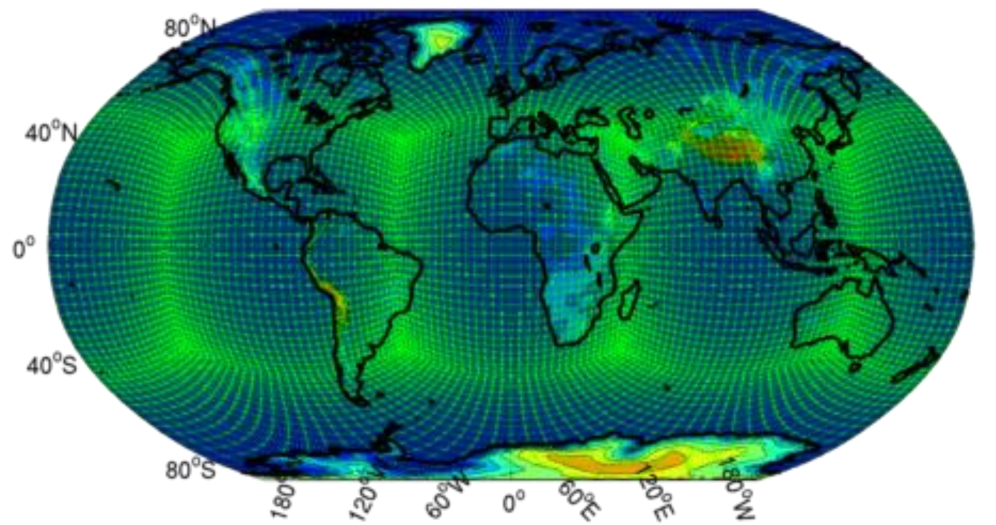
- Naval Research Laboratory currently investigating new generation dynamical cores under the Earth System Prediction Capability (ESPC)
- Using NUMA as the dynamical core, NRL is developing a new NWP system
  - 3D spectral element model
  - Highly accurate and scalable
  - **NEPTUNE**: **N**avy **E**nvironmental **P**rediction sys**T**em **U**tilizing the **N**UMA Cor**E**
  - A suite of physical parameterizations has been added
  - Real data initialization capability
  - Flexible grids (cube sphere, icosahedral, etc.)
  - Eventually, with have AMR included, and ocean component
  - Coordinating with both DCMIP and HIWPP

NEPTUNE Database Fields

Database Fields

- Monthly Climatological Fields:
  - ✓ Surface roughness
  - ✓ Albedo
  - ✓ SST
  - ✓ Ground Temperature
  - ✓ Ground Wetness
  - ✓ Ice Temperature
- Static Fields:
  - ✓ Terrain (40 km resolution)
  - ✓ Land-sea mask
  - ✓ Terrain Roughness
- Fields are read and transferred to the NEPTUNE grid using either bi-cubic interpolation or grid-box mean values, depending on the resolution of the input relative to the model grid (cubed-sphere grid shown)



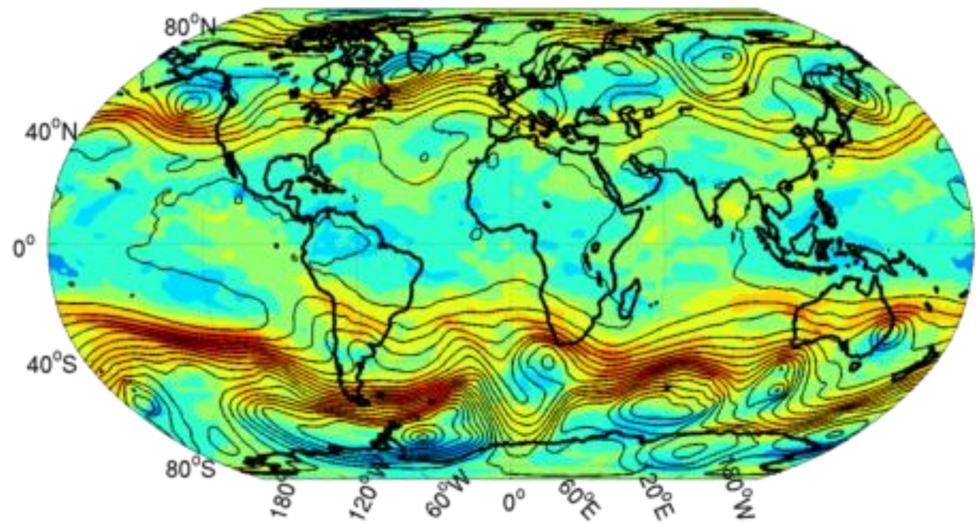


NEPTUNE Initial Conditions

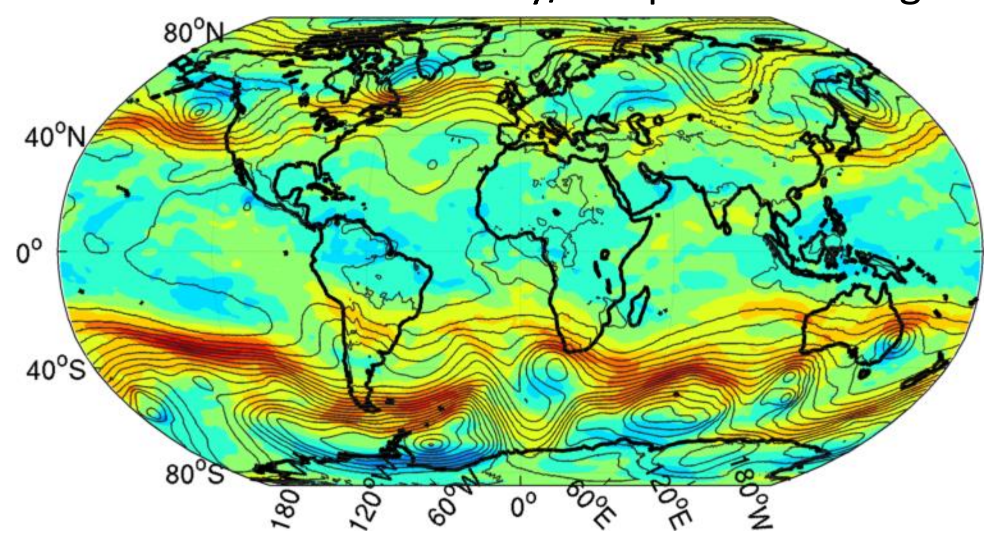
Initial and Boundary Conditions

- Read 0.5° isobaric fields:
  - ✓ Geopotential Height
  - ✓ Zonal Velocity
  - ✓ Meridional Velocity
  - ✓ Air Temperature
  - ✓ Vapor Pressure
- Interpolate to NEPTUNE grid using tri-cubic interpolation
  - ➢ Interpolate deviations from standard atmosphere
  - ➢ Use hydrostatic extrapolation for areas above/below NAVGEM output
- Convert to NEPTUNE prognostic variables:
  - ✓ Density
  - ✓ Zonal Velocity
  - ✓ Meridional Velocity
  - ✓ Vertical Velocity
  - ✓ Potential Temperature
  - ✓ Mixing Ratio

NAVGEM 500hPa Zonal Velocity/Geopotential Height

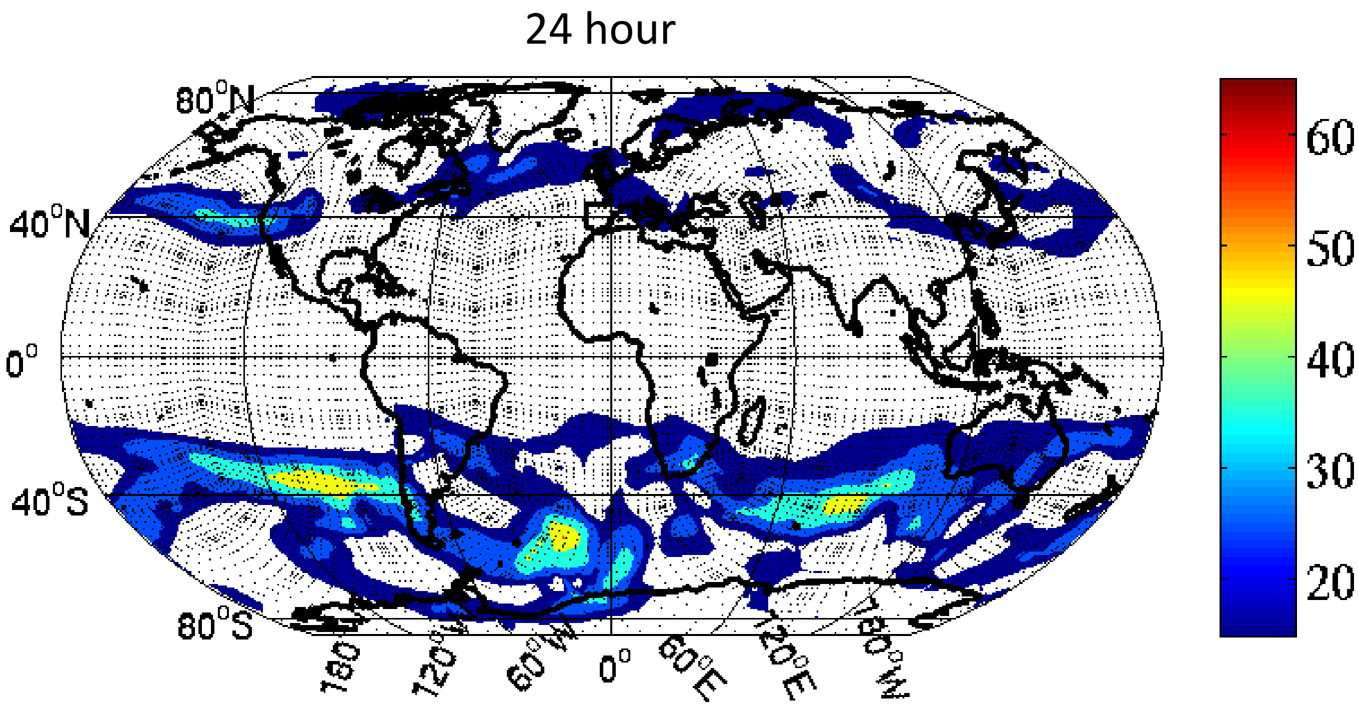


NEPTUNE 500hPa Zonal Velocity/Geopotential Height



NEPTUNE Real Data Simulation

Δx=~100 km, 0-24 h fcst from 00Z 25 June 2013
500-hPa Wind Speed (m s^{-1})



First 3D Spectral Element (SE in x, y, z) Real Data Meteorological Forecast in the World.

Summary

- Adaptive Mesh Refinement (AMR) examined for TC simulations in NUMA CG shallow water model
- AMR allows capability to resolve TC processes with significant speed-up over non-AMR simulations at highest resolution
  - The resolution is where you need it
- No loss in overall accuracy of phenomenon using AMR vs. non-AMR in region of interest
  - Barotropic instability proceeds quicker in AMR simulations (needs further investigation)
- AMR in next generation models replace the need for the complexity of multiple moving nests
- Navy next generation model based on NUMA core (NEPTUNE)
  - Will have AMR in the future