Tropical cyclones in GCMs

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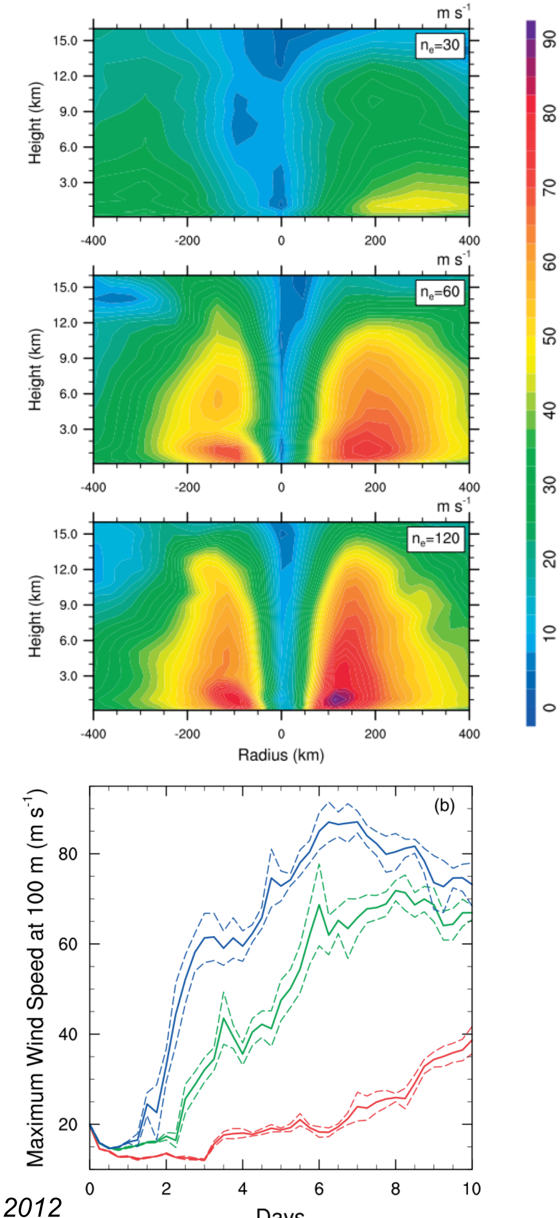
- Modeling of tropical cyclones (TCs) in General Circulation Models (GCMs) historically difficult
  - Essentially impossible at ~>75-100 km to resolve "realistic" TCs
- Even today, still **significant computational demand** to simulate even at 25-50 km
  - Fixed SST models broaching ~25 km spacing
  - Climate models for AR5 (coupled, non-timeslice), ~50-200 km



Reed et al., 2012

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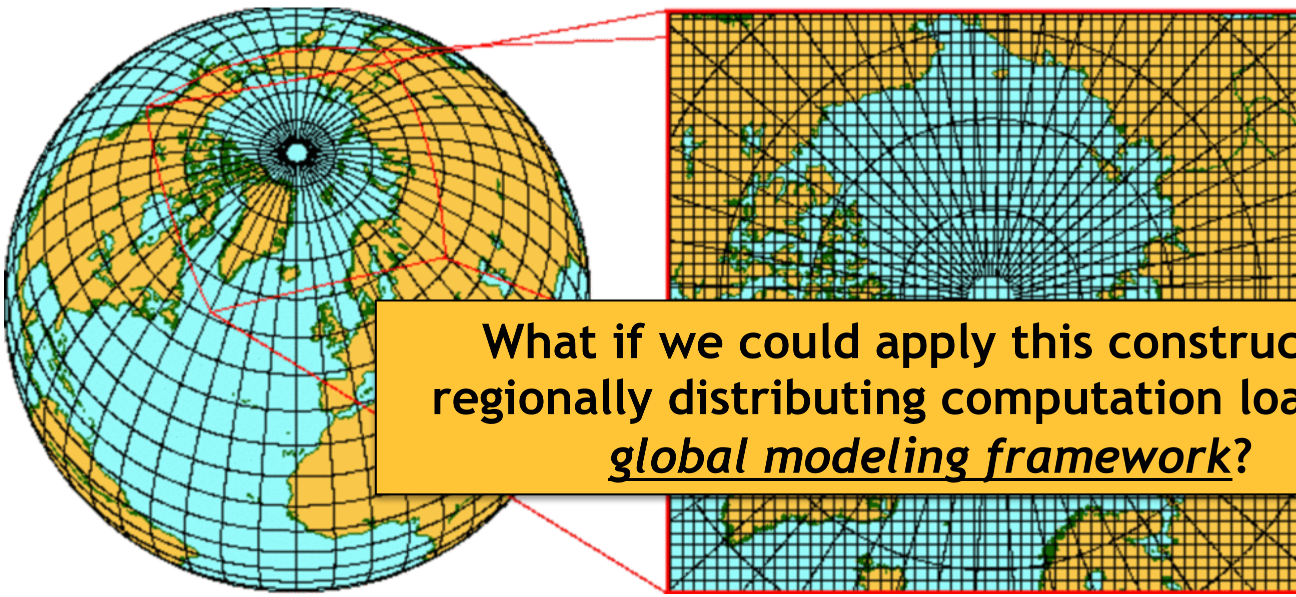
Limited area models

- One solution? Limited area models (LAMs)
  - Focus computing power in area of interest
    - Higher resolution!
  - Require *boundary conditions (BCs)*
    - Errors in BCs propagate into nest
    - BCs (such as relaxation BCs) well-posed?
    - Different model (including different dynamical core, physics package, etc.) produces BCs
  - One-way nests: TCs not allowed to be active players in the climate system

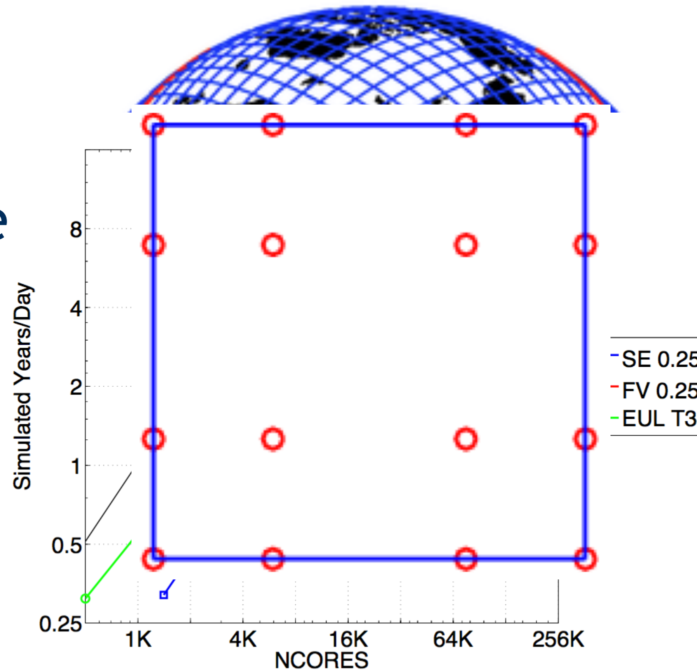


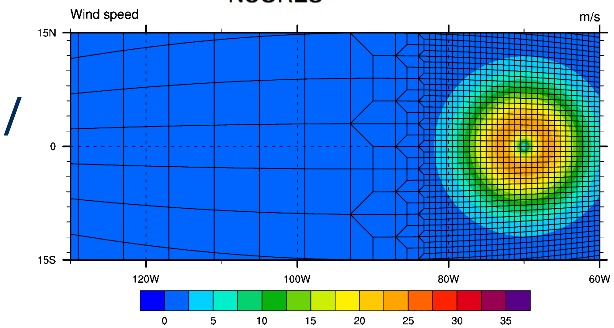
What if we could apply this construct of regionally distributing computation load in a *global modeling framework*?

AWI

Variable-resolution CAM-SE

- Variable-resolution GCMs
  - High resolution regions embedded (stretching/nesting) while maintaining unified model
  - Straightforward to conserve mass/energy
  - Target computing resources
- NSF/DoE <u>C</u>ommunity <u>A</u>tmosphere <u>M</u>odel <u>S</u>pectral <u>E</u>lement (CAM-SE) dynamical core
  - Cubed-sphere grid
    - quasi-uniform
    - no pole convergence/necessary filtering
  - Primitive eqns in local spectral space
    - Easily load-balanced w/ minimal communication
  - Flexible framework for grid nesting
  - No required boundary conditions
  - High-order numerics accurately move flow in/out of high-resolution nests
  - Multiple high-resolution regions
    - Teleconnections





Refined grids on the cubed sphere

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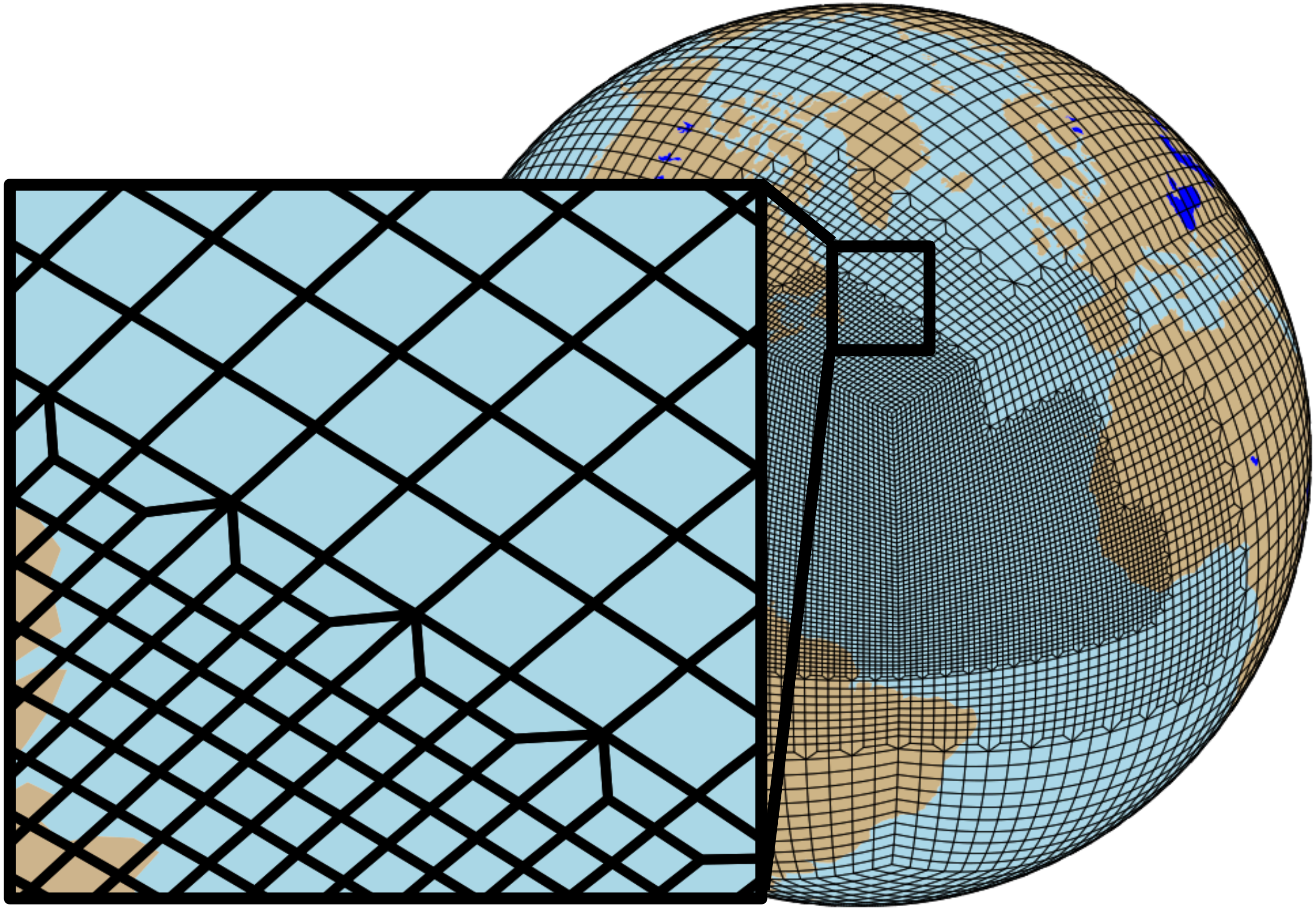
- Atlantic refinement: 1° (~110 km) x 4 (2^2) (fine = 0.25° = ~26 km)
- Static refinement
- CUBIT (Sandia) refinement package



Climate simulations

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- NCAR **C**ommunity **E**arth **S**ystem **M**odel (CESM) framework
- **A**tmospheric **M**odel **I**ntercomparison **P**roject (AMIP) protocols
  - 1980-2002 (23 years) completed as of today
  - Observed SST, O_3, aerosol, solar forcing, etc.
- CPL7 tri-grid coupler (Craig *et al*. 2011)
  - Land: **FV0.9°x1.25°** - active
  - Ocean/Ice: **gx1v6 (~1°)** - prescribed
- CAM-SE
  - Timestep globally restricted to finest grid scale
  - Stock CAM5 physics
    - **Parameterization scalability caveats apply!**
  - 192 cores (hybrid OpenMP/MPI) NCAR Bluefire = ~0.5 SYPD
    - ~200,000 core hours
- Cyclone tracking
  - Uses GFDL method first proposed by Vitart (1997) and modified by Knutson *et al*., (2007)
  - Searches for vorticity max, wind max, pressure min, warm core - needs to persist >= 2 days at <= 45° latitude
    - **Using 17 m/s (lowest model level) as wind threshold**

Coupled climate simulations

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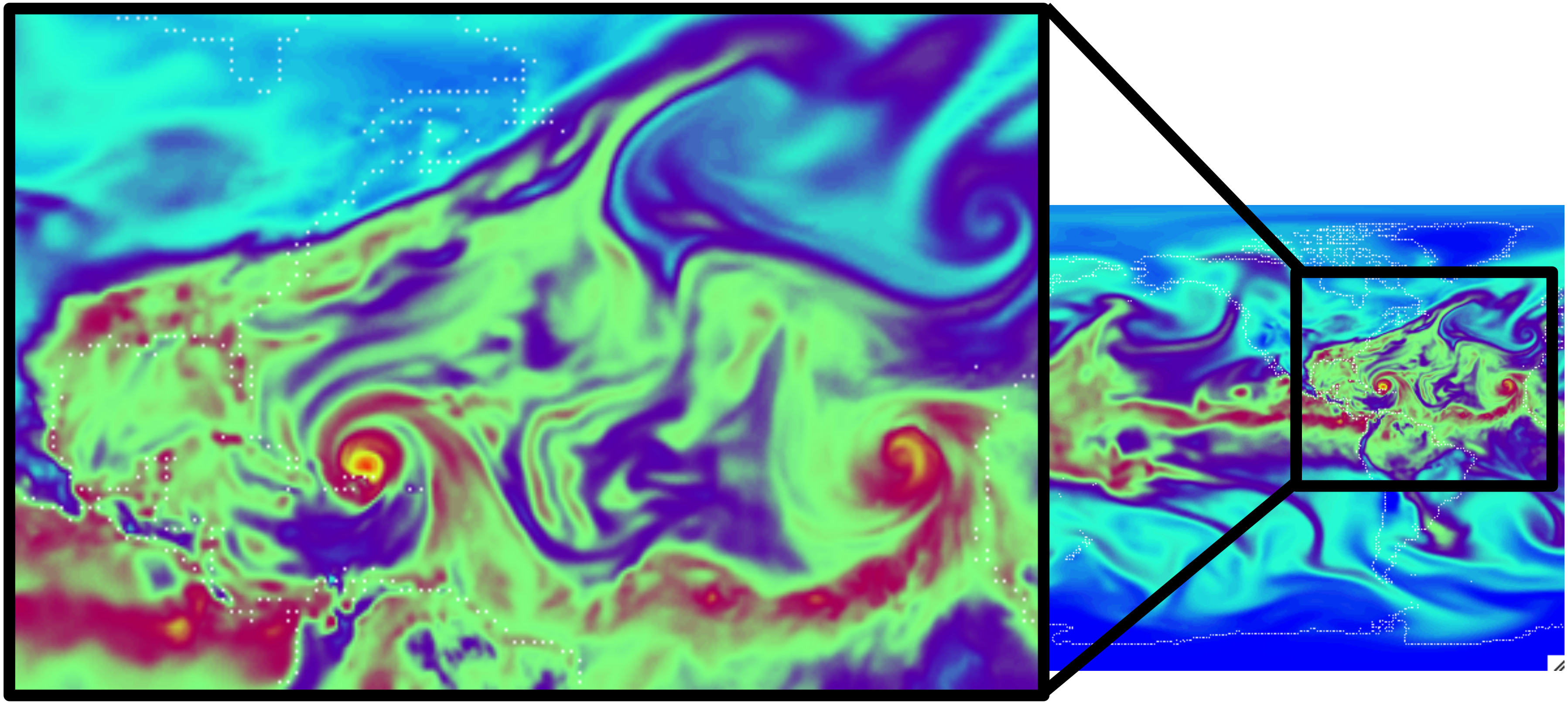

Precipitable water, 9/5/1980

10-day movie

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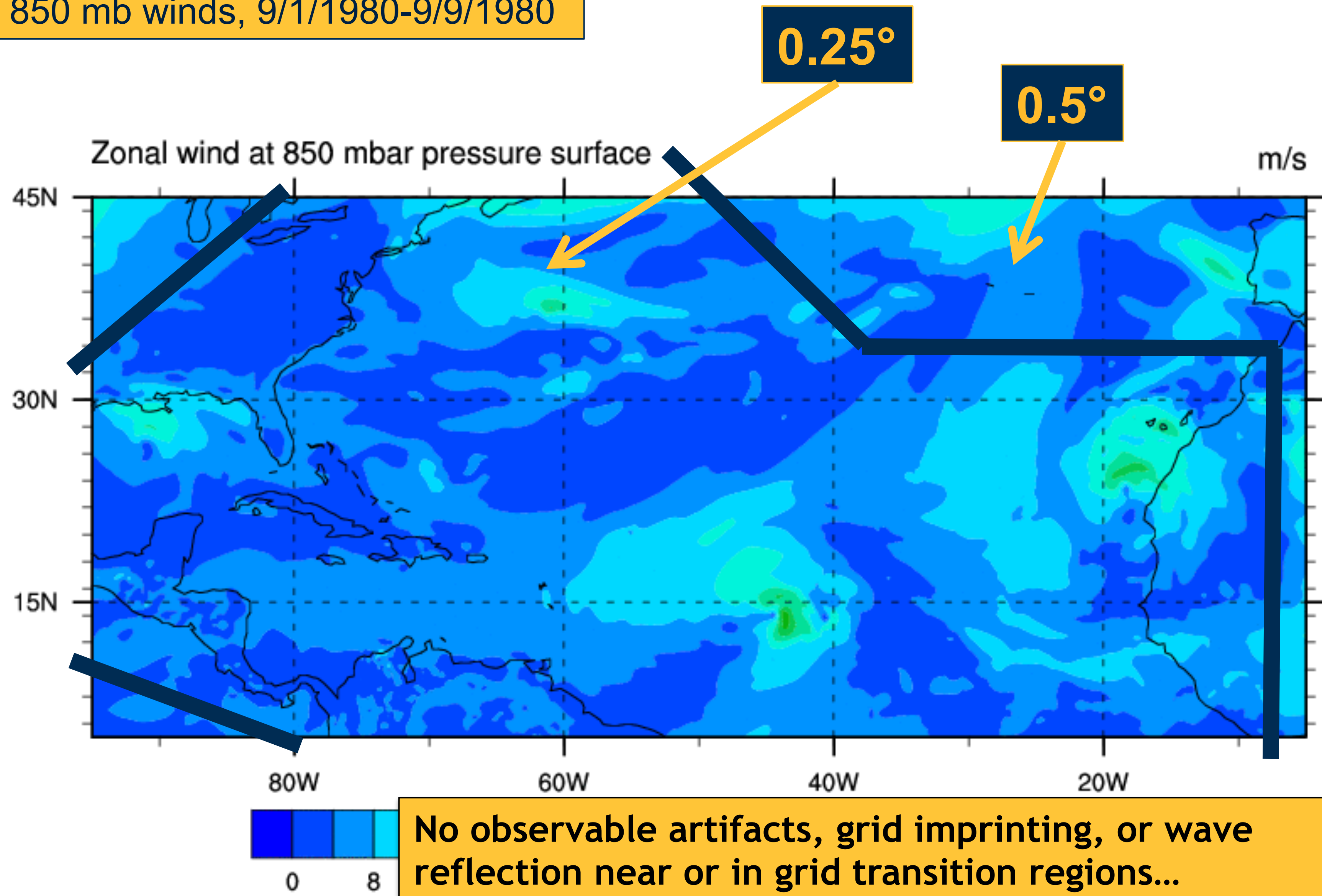
850 mb winds, 9/1/1980-9/9/1980



No observable artifacts, grid imprinting, or wave reflection near or in grid transition regions…

What does resolution buy?

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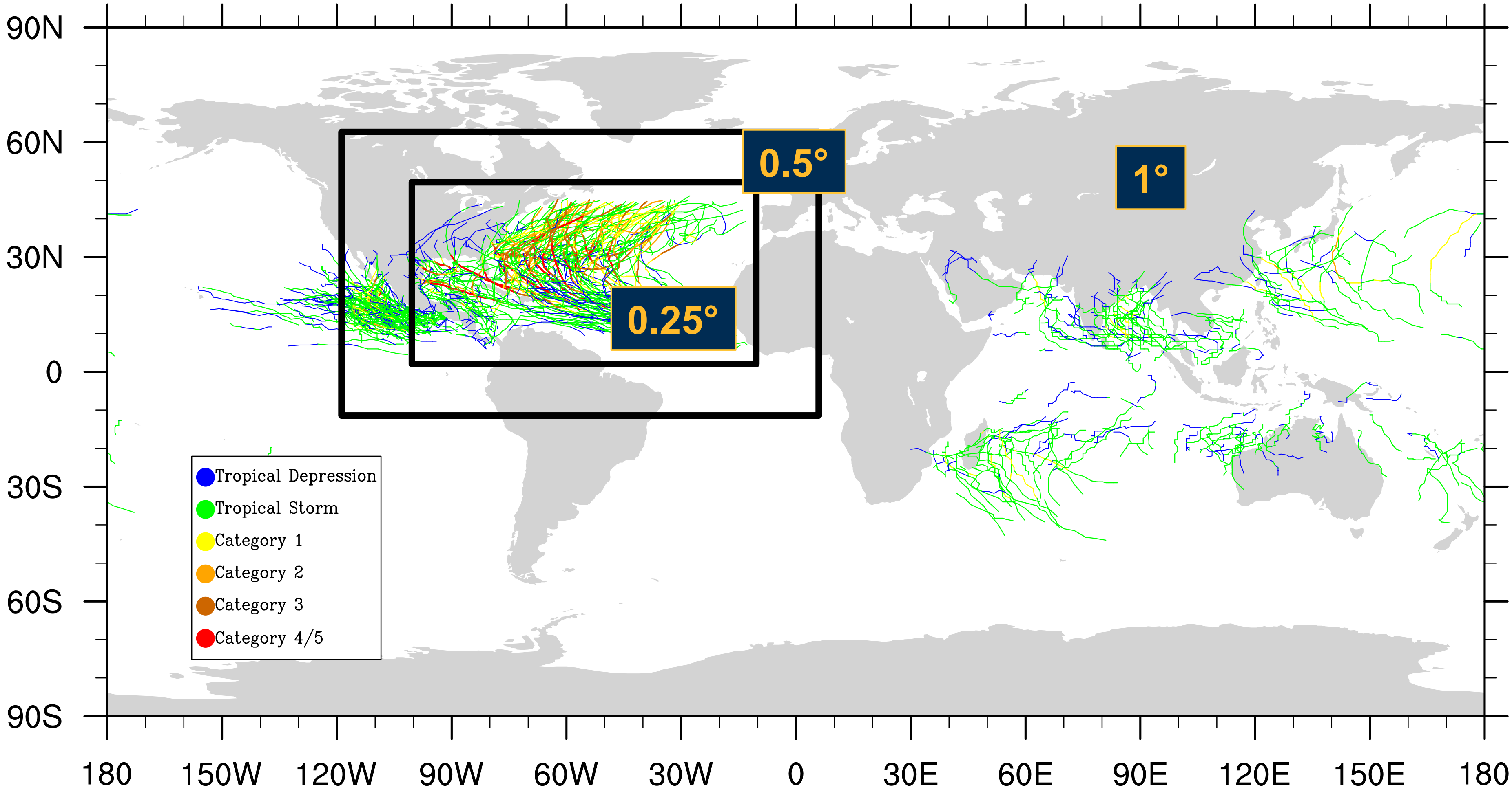

Structural differences

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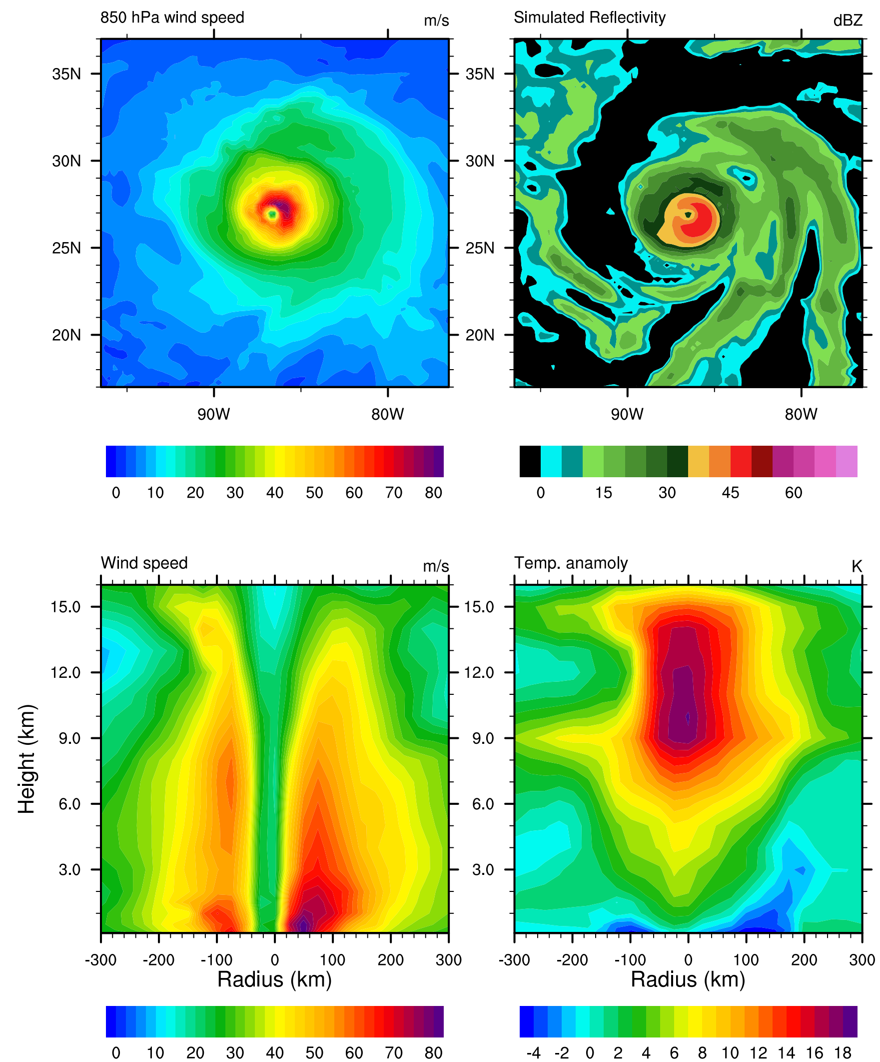
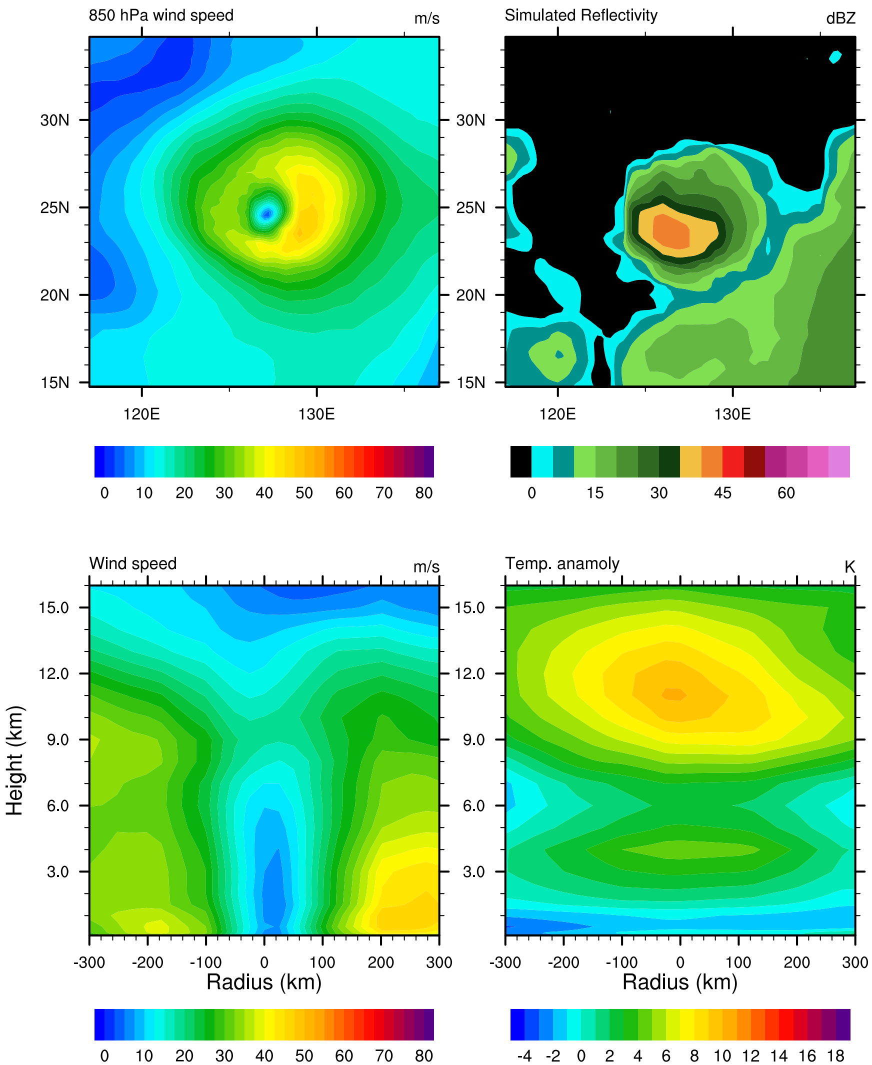
WATL - 0.25°





WPAC - 1°

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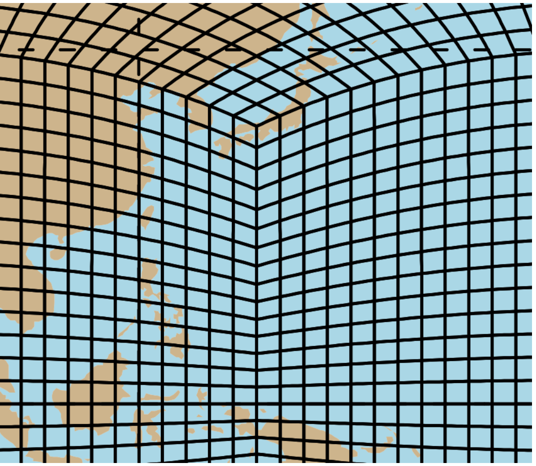
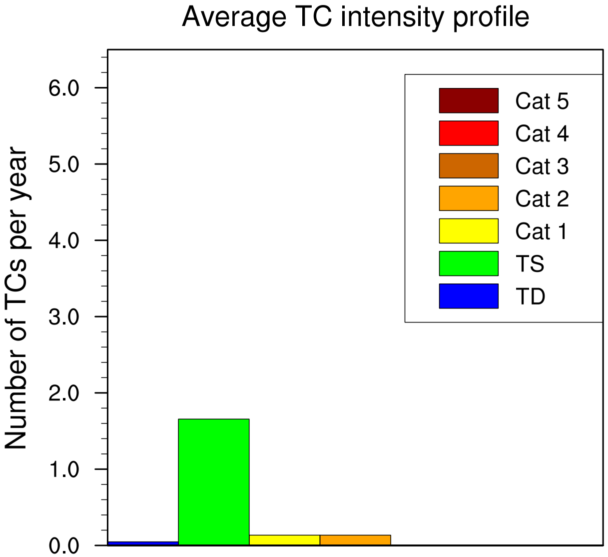
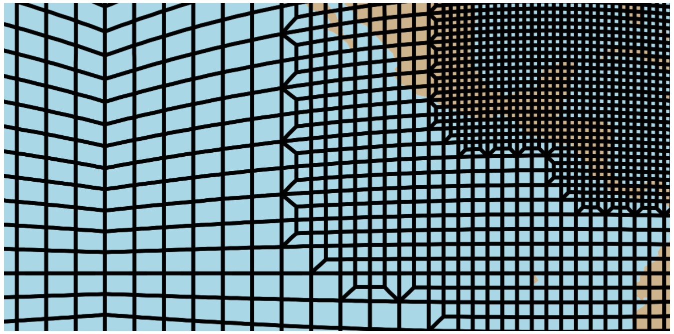
Intensity as function of basin/resolution

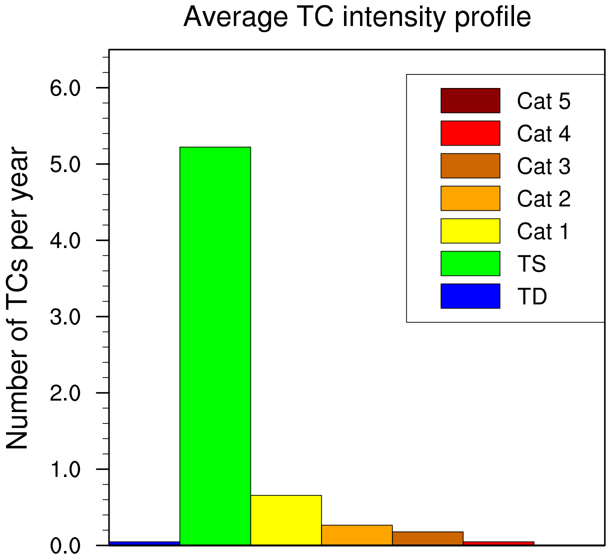
WPAC – 1°



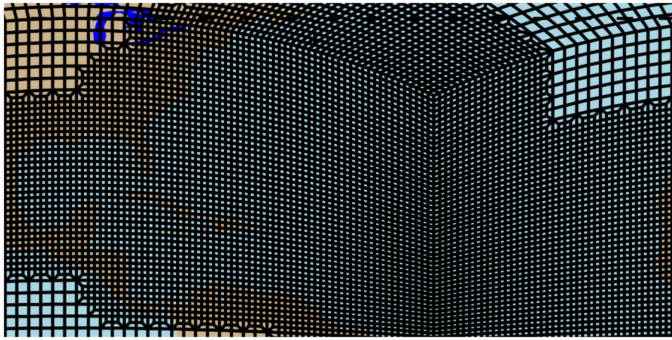


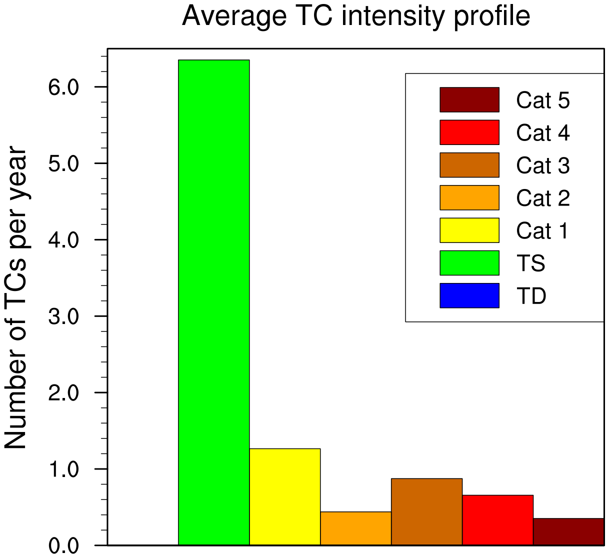
EPAC – 0.5°





NATL – 0.25°





Spatial distribution of TCs

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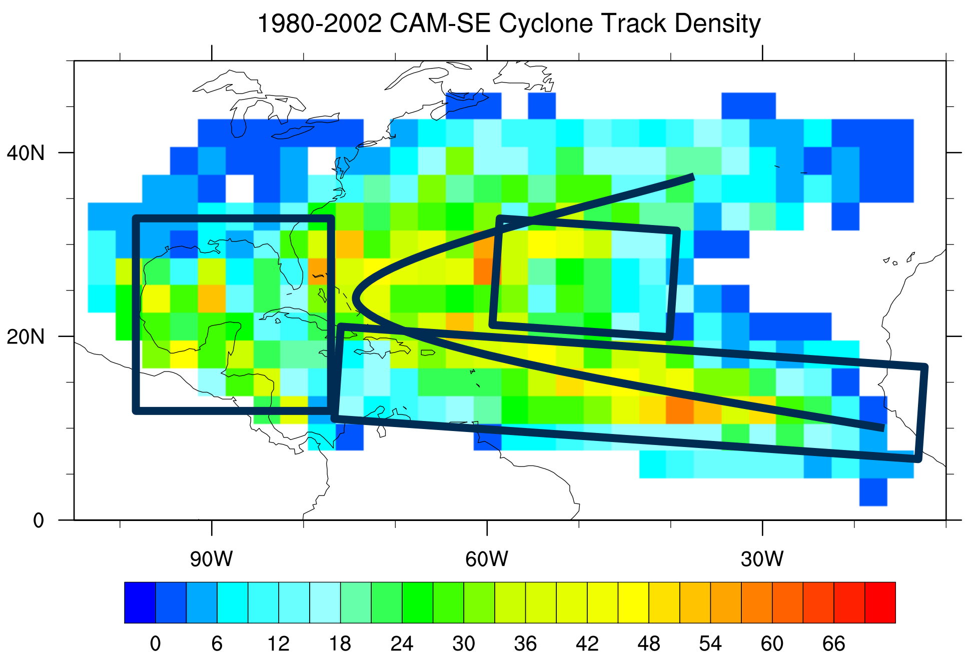
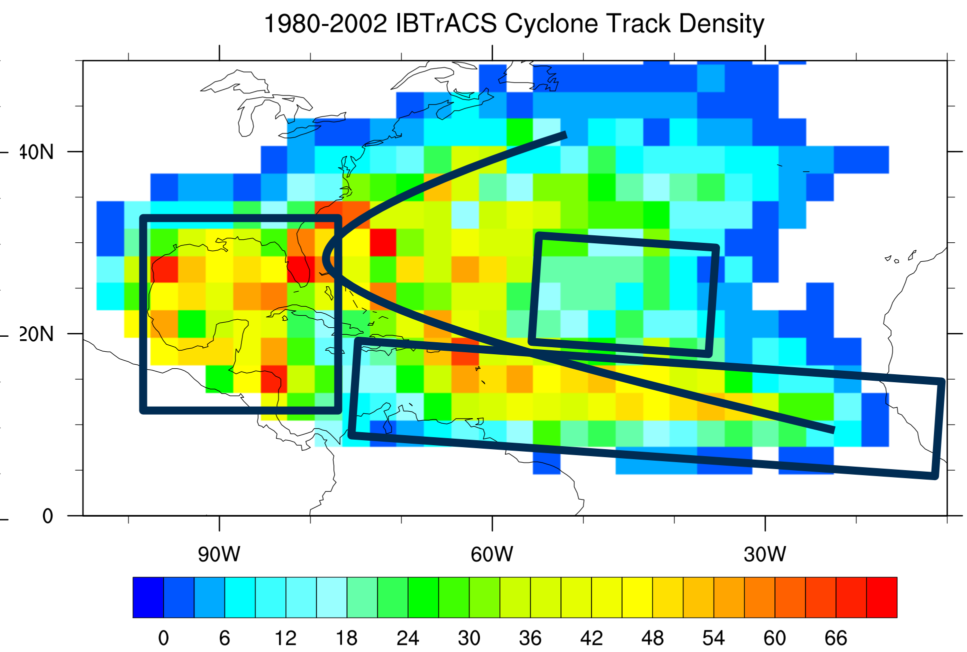
- 3°x3° track density (number of times TC was a "hit" in each lat/lon bin)
  - CAM-SE represents Cape Verde systems well, mid-Atlantic "hole"
  - Recurvature too far west, Gulf/W. Caribbean density biased low

CAM-SE (simulated)



HURDAT (observed)



Interannual and pressure-wind performance

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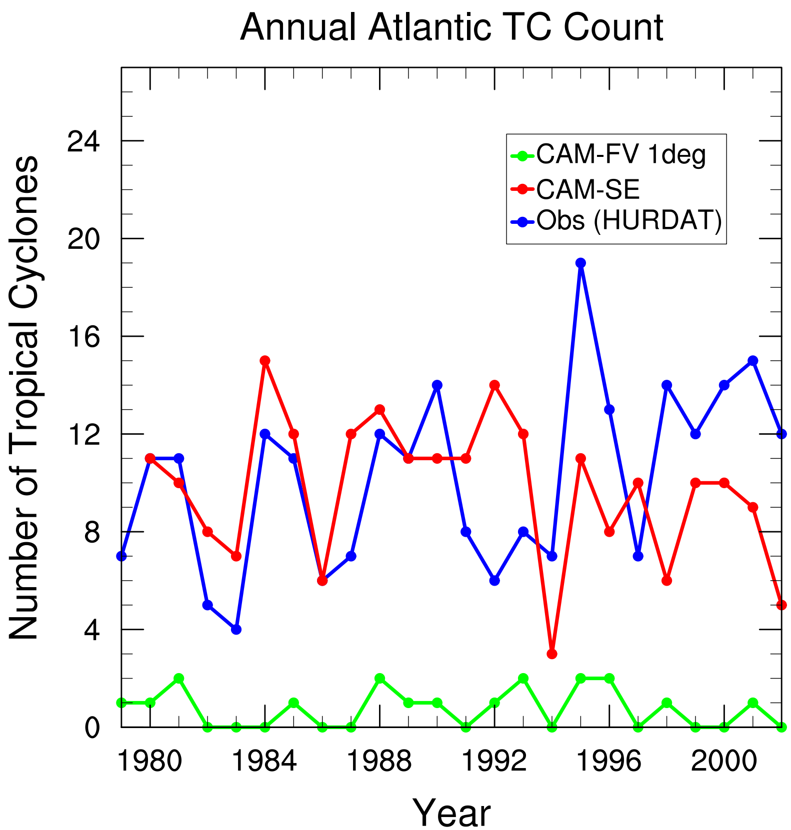
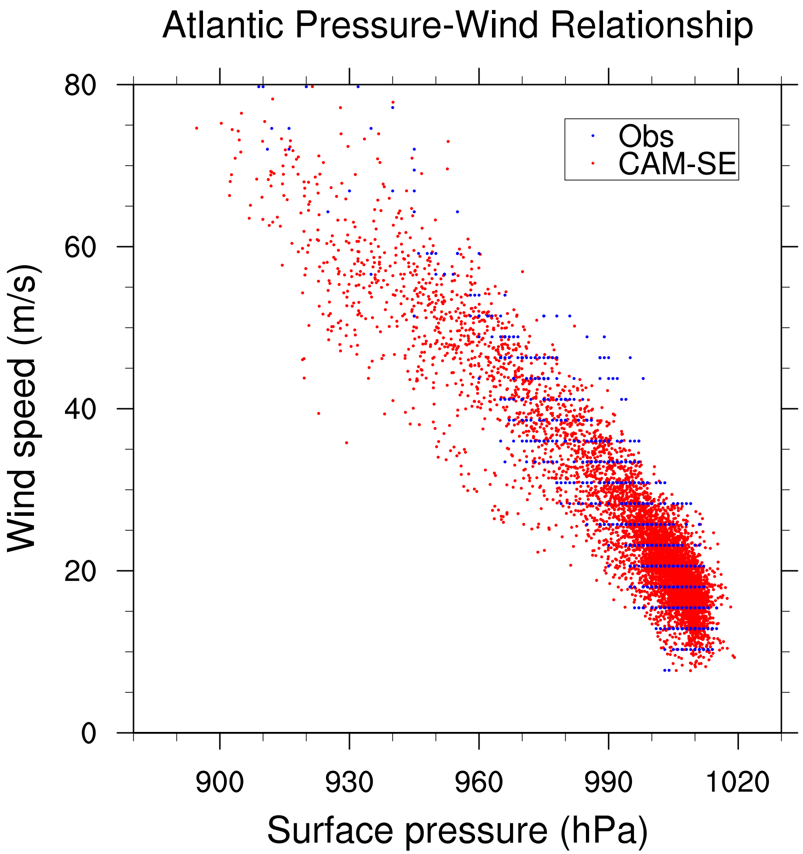


- Resolution absolutely needed to achieve “realistic” TC counts
  - Observational dataset?
  - Ensembles necessary?



- Pressure-wind relationship well matched at 0.25° in refined model; does this still hold at higher (hydrostatic) resolutions?

CAM-FV 1° simulations courtesy of Wehner et al., LBNL

Synoptic correlation

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$$GP = |10^5\eta|^{3/2}\left(\frac{\mathcal{H}}{50}\right)^3\left(\frac{V_{pot}}{70}\right)^3(1+0.1V_{shear})^{-2}$$

- Use basin-average Genesis Potential Index (GPI) to correlate model results to reanalysis data
- Complete global 1° CAM-SE simulations…
- High correlation implies synoptic environment not affected by refinement

Refined grid-NCEP correlations

Basin	Monthly	Ann. Avg.	TC Season
NATL	0.85	0.41	0.57
EPAC	0.82	0.50	0.42
CPAC	0.33	0.61	0.56
WPAC	0.87	0.59	0.56
NIO	0.36	-0.08	-0.01
SIO	0.30	-0.04	-0.31
SPAC	0.44	0.44	0.00

Refined grid-1 deg CAM correlations

Basin	Monthly	Ann. Avg.	TC Season
NATL	0.97	0.93	0.93
EPAC	0.92	0.84	0.72
CPAC	0.94	0.98	0.97
WPAC	0.93	0.77	0.66
NIO	0.77	0.68	0.77
SIO	0.78	0.64	0.14
SPAC	0.87	0.73	0.69

Computational benefits

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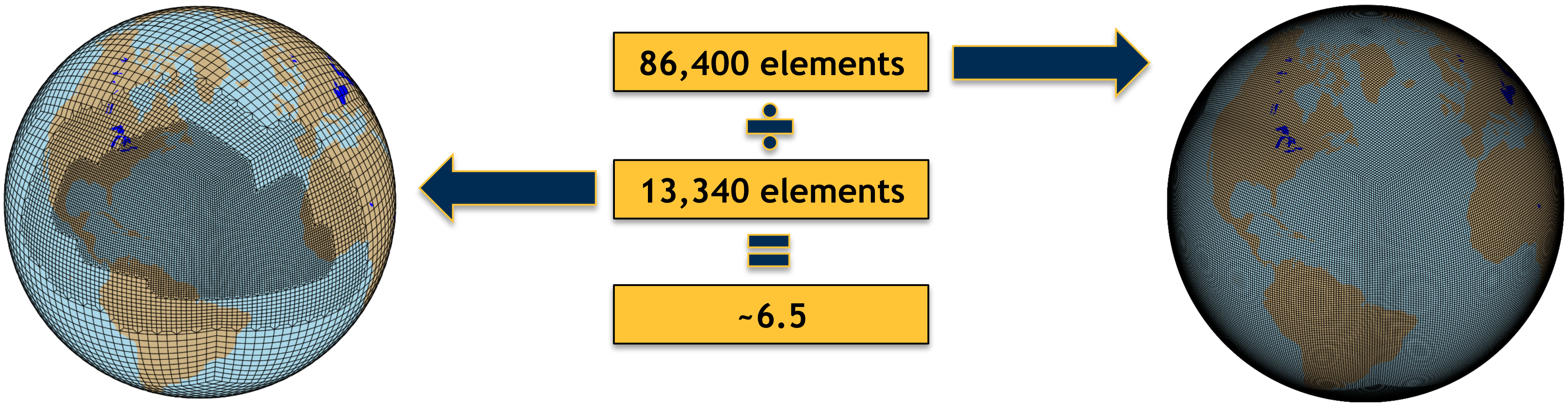

- Atm: ~**6-7x speedup** with variable-resolution vs. 1/4° uniform grid
  - Eliminating tri-grid coupler could save ~10-20% lost in flux remapping
- For same cost of global uniform/quasi-uniform…
  - Higher regional resolution
  - Additional ensemble simulations
  - Longer model runs
- Potential to get "best of both worlds" between global models, limited area models?
  - Higher resolution to resolve cyclone intensity, vertical structure (regional models)
  - Physically consistent, 2-way interaction, global synoptic flow (global models)

Var-res challenges going forward

- Hydrostatic model
  - Hydrostatic assumption breaks down ~ 10 km (Hall, Nair, NCAR)
- Topography
  - Spectral methods generally require some smoothing for stability
  - How to "differentially smooth?" such that we aren't under/oversmooth
- Refinement criteria/location
  - Where do we put high-resolution for non-localized features?
  - Ex: Do mountain-effected Rossby waves control Atlantic recurvature?
- Physical parameterizations
  - Scale-aware
  - How to handle regimes where parameterizations turn on/off?

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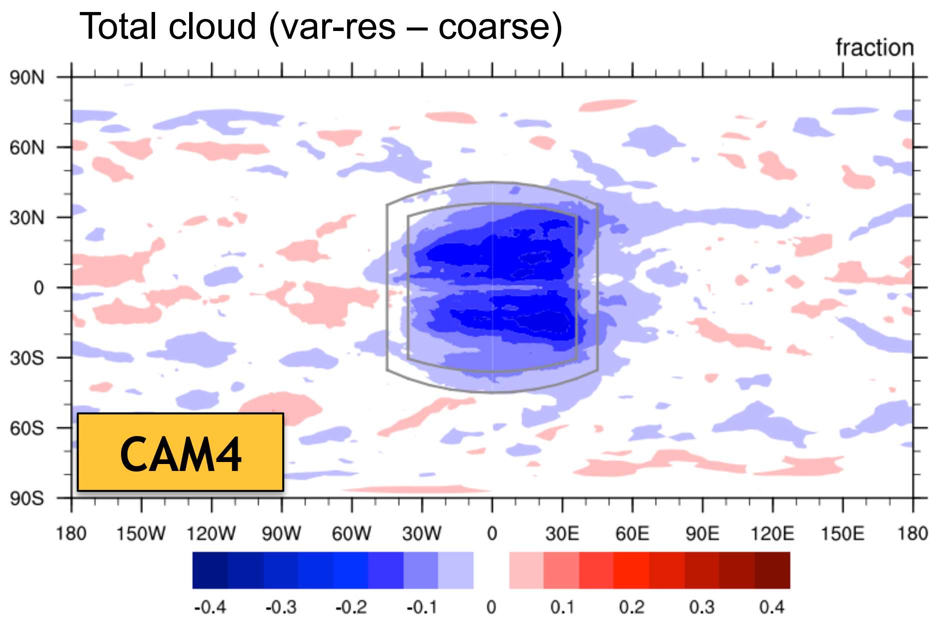
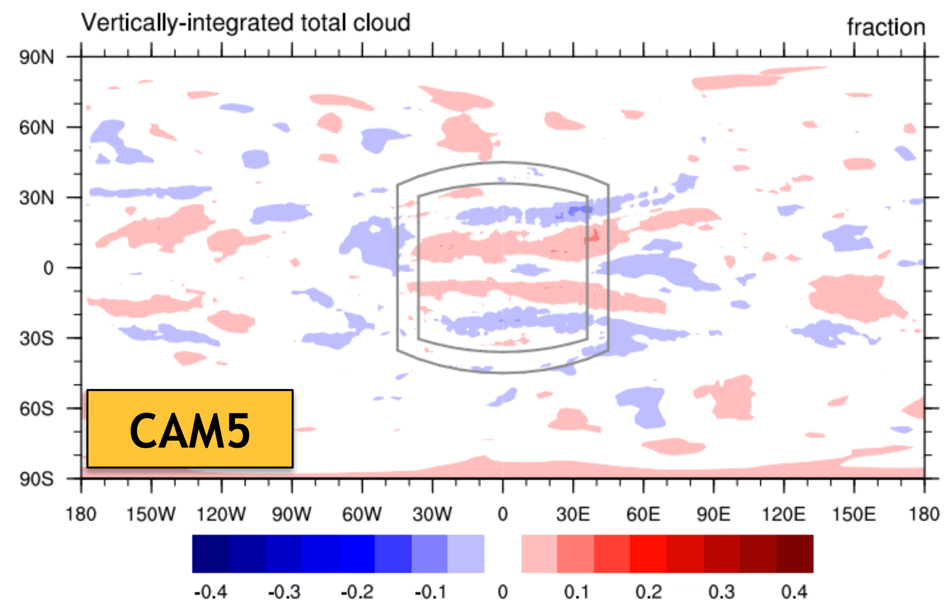
Physical parameterizations



CAM4 runs from Levy, Overfelt, Taylor

- Aquaplanet, 2° refined to 0.25° on cube face
- 48-month average total cloud
- With CAM4 physics, Gill response evident as parameterizations “feel” resolution

- CAM5 physics an improvement
- Caveat: Only looking at clouds/precip and above hydrostatic threshold



Summary

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- Variable-resolution, highly-scalable dynamical cores (such as CAM-SE) may provide opportunities to improve regional climate simulations
- AMIP simulations using observed SSTs with high-resolution nests over Atlantic model realistic TC structure and observationally-reasonable average storm counts and spatial distribution
- Synoptic environment highly correlated to lower resolution simulation (identical forcing) -> indicates resolution not harming already resolved dynamics
- Significant model runtime speedup over globally uniform nest (depending on level and spatial extent of refinement)
  - Provides pathway to:
    - Higher resolution
    - Ensemble simulations

BACKUP SLIDES

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- Nothing by nonsense from here on out.

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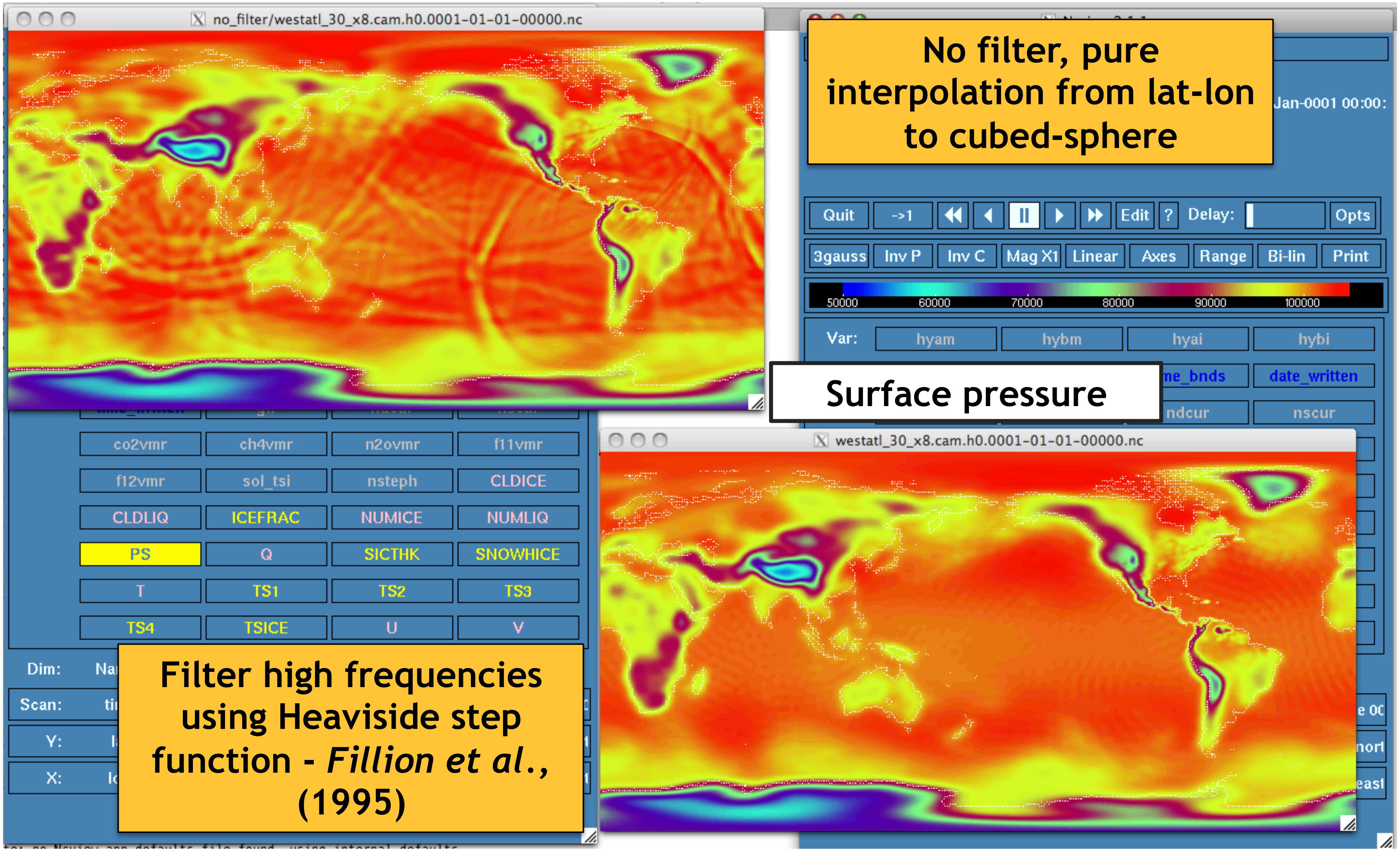
Application of digital filter



No filter, pure interpolation from lat-lon to cubed-sphere

Surface pressure

Filter high frequencies using Heaviside step function - *Fillion et al.*, (1995)

Variable-resolution CAM-SE

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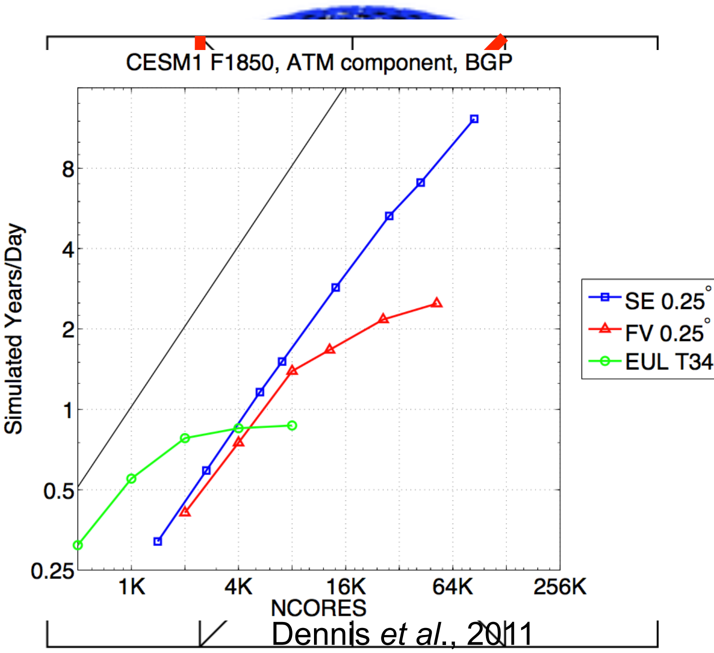
- Variable resolution feature recently implemented in NSF/DoE Community Atmosphere Model (CAM) Spectral Element (SE) dynamical core
- Cubed-sphere grid
  - Quasi-uniform, no pole convergence/necessary filtering
  - *Highly scalable* to thousands of cores
- **Conforming refinement**
  - Every edge shared by only two elements
- **Unstructured**
  - Domain not tiled in (i,j) fashion
- **Static refinement**
  - Grid refined during initialization, does not follow atmospheric features



Levy et al., PDES, 2010

Why tropical cyclone forecasts?

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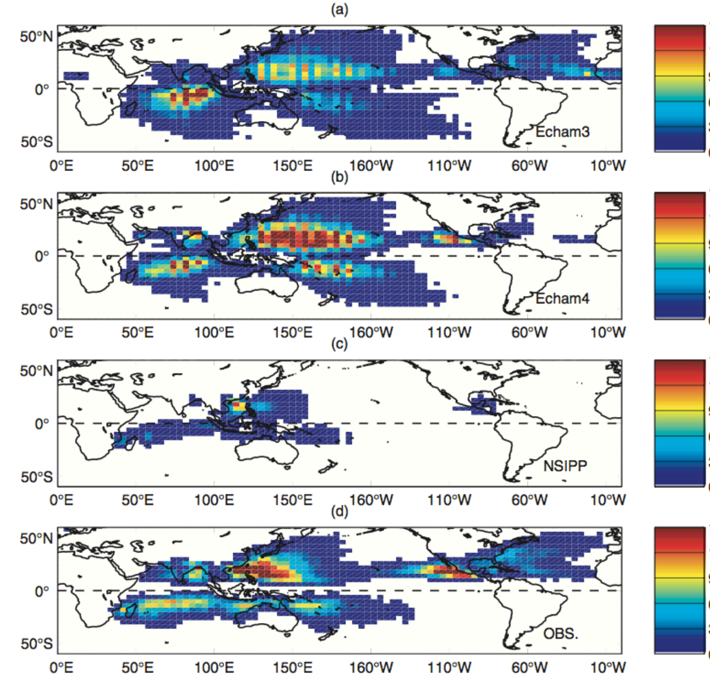
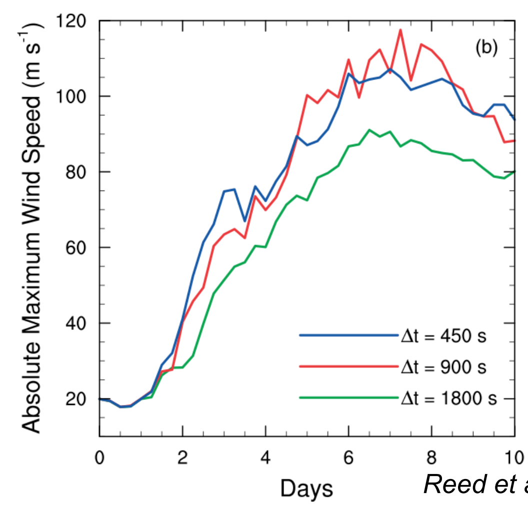
- Test dynamical core as a potential future tool in NWP applications
  - Speed is a priority
  - For TCs, LAMs/GCMs have opposing pros/cons
  - "Franklin: Regional models (HWRF, GFDL) not being used because structure of Sandy not well-represented." – NHC media call 10/26/12
- Provides fine-grained information on model biases (e.g., storm track, intensity) which can be useful in understanding uncertainty in TC climate forecasts (Knutson *et al.*, 2010)
- Allows for high-resolution testbed to develop/tune physical parameterizations



Camargo et al., 2005



Reed et al., 2012

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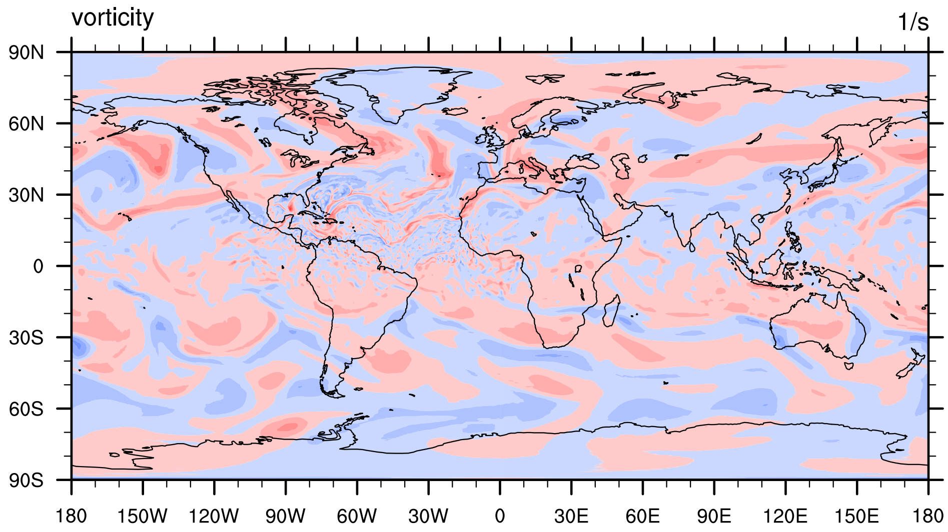
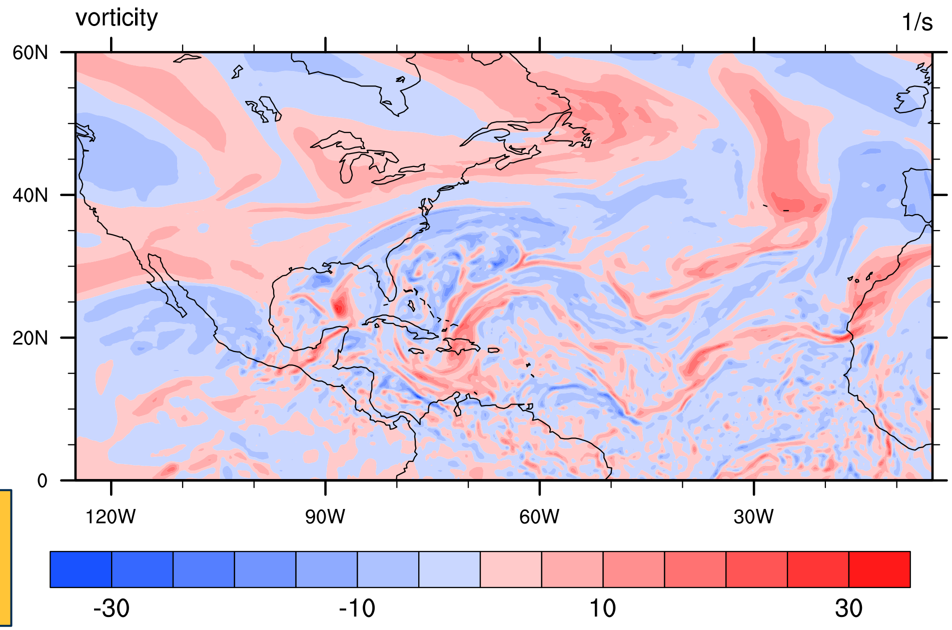
Vorticity structure





200 mb vorticity, 9/27/2002

High-res deterministic simulations

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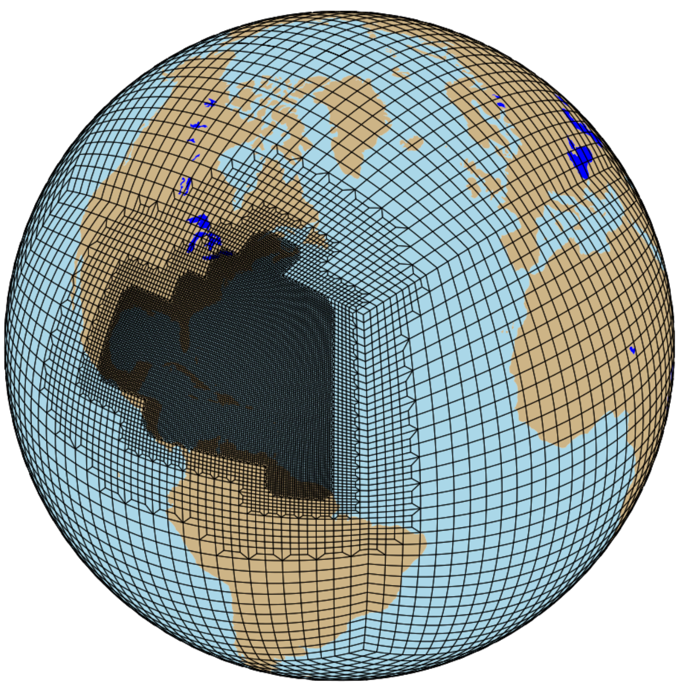
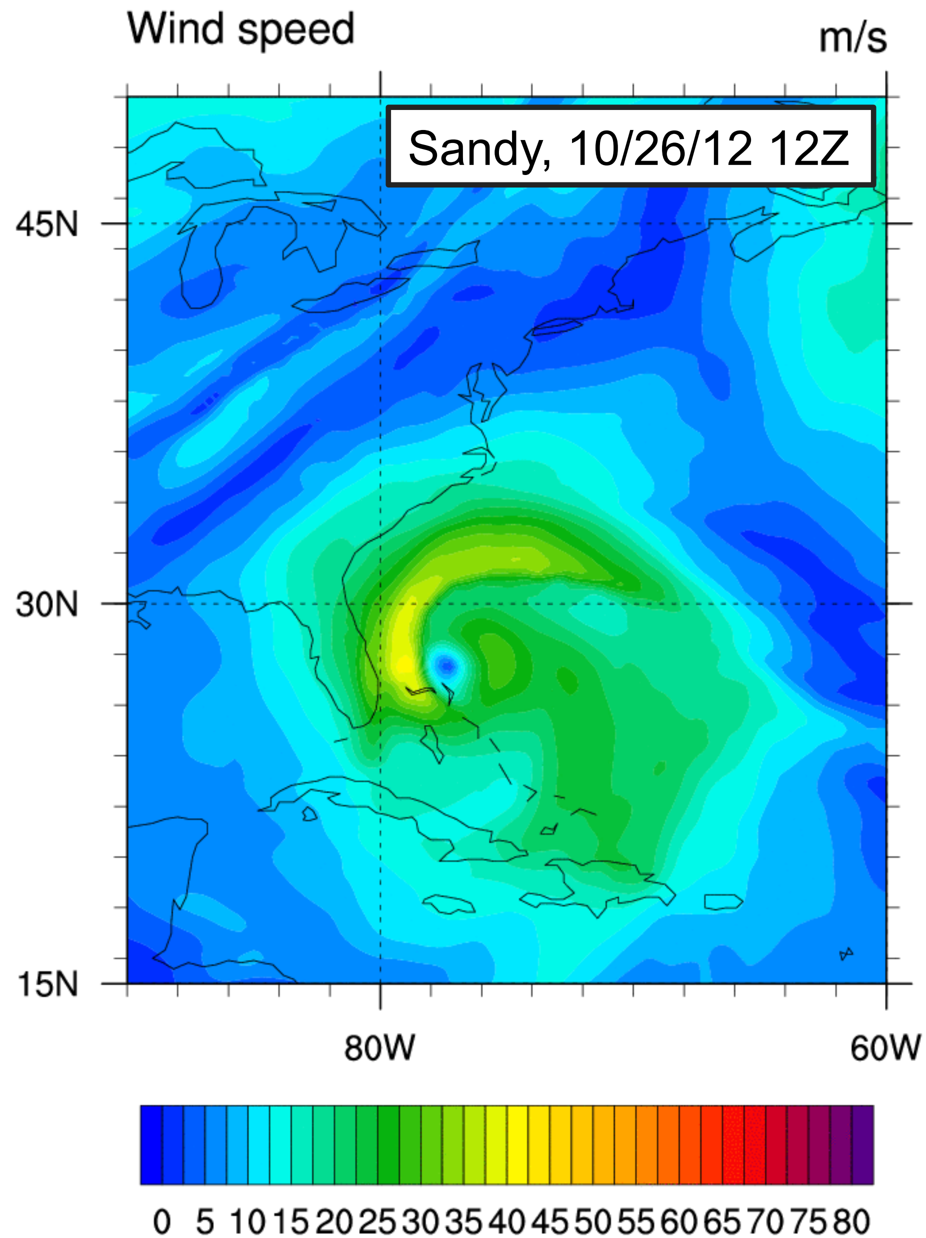
- CAM-SE "forecast mode"
- Equivalent 1° global grid refined by a factor of 8 to 1/8° (~13 km) over western Atlantic Ocean





High-res deterministic simulations

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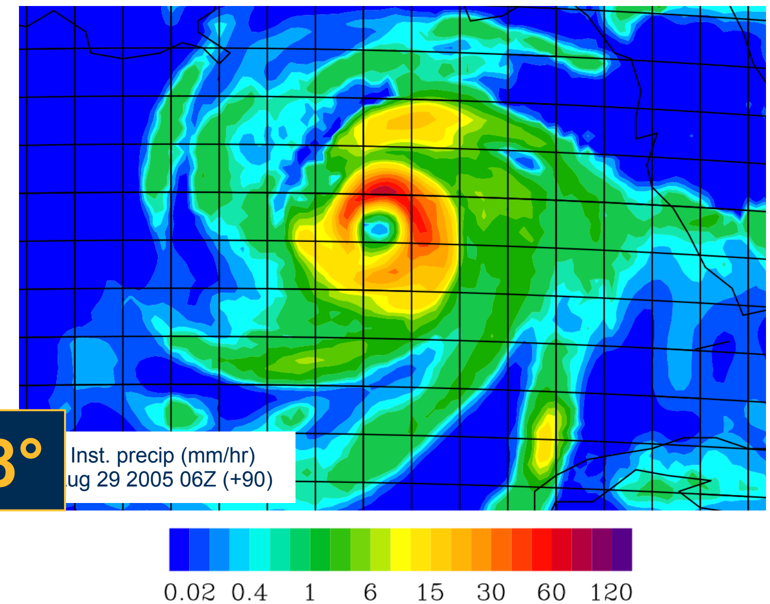
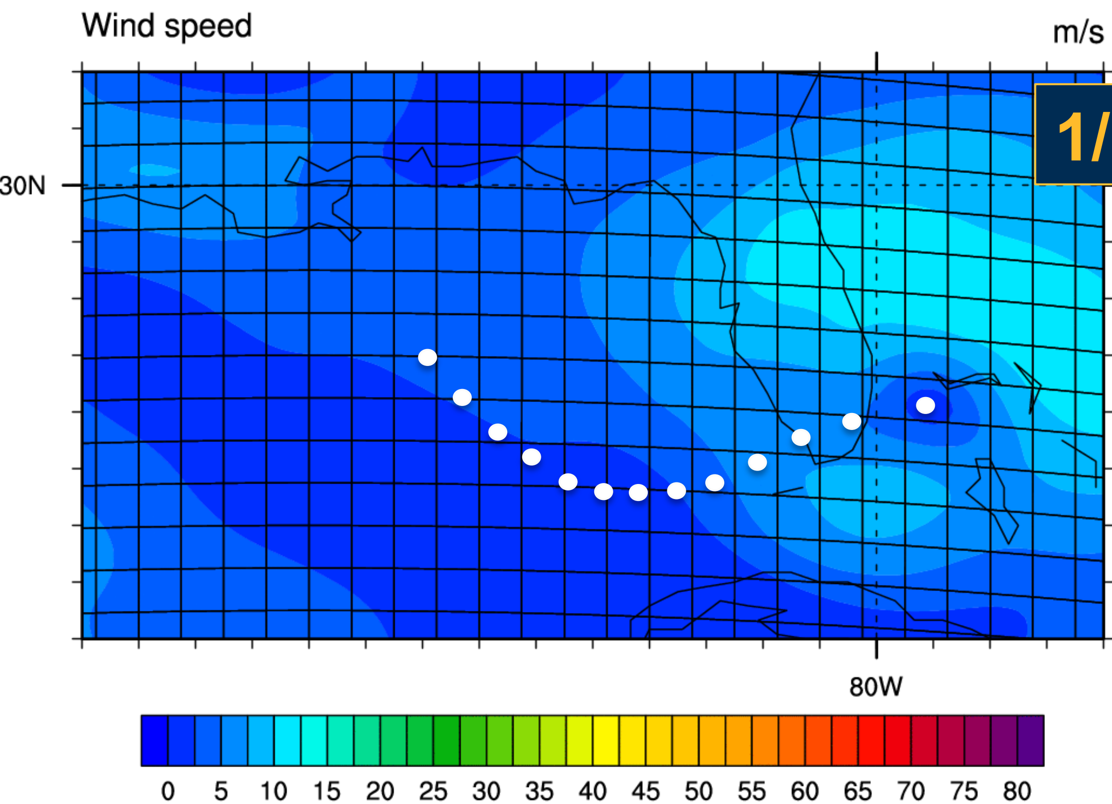
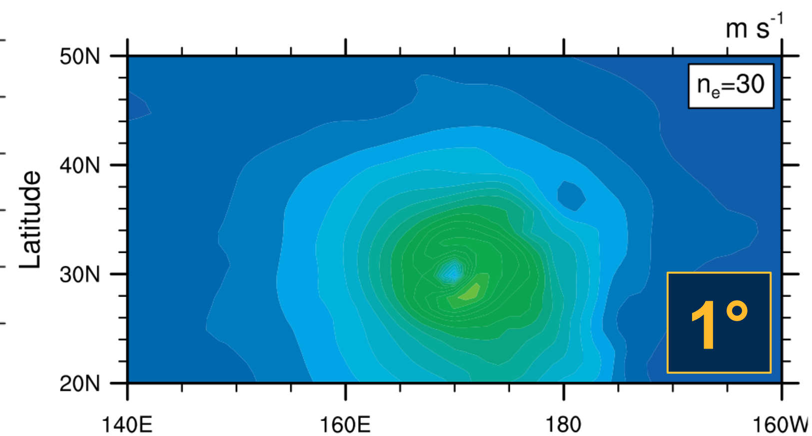
- Hurricane Katrina (2005)
- Initialized from ERA-Interim reanalysis -> 8/25 12Z (~115 hours before landfall)







Courtesy K. Reed

High-res deterministic simulations setup

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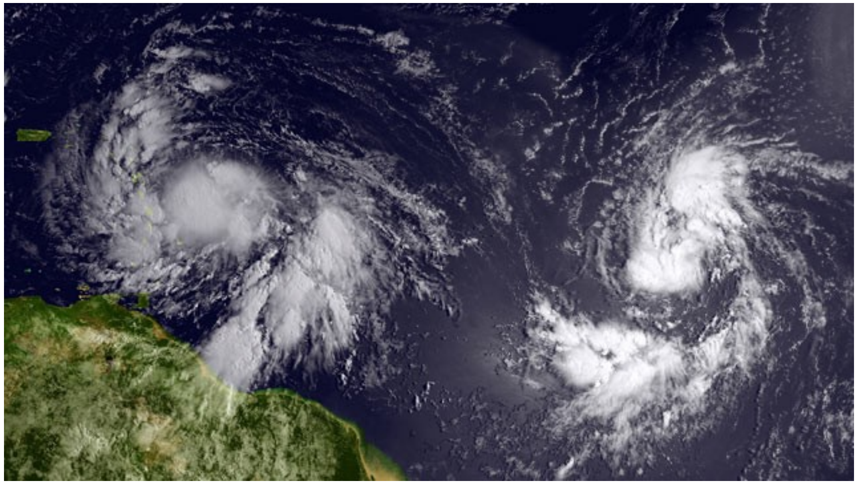
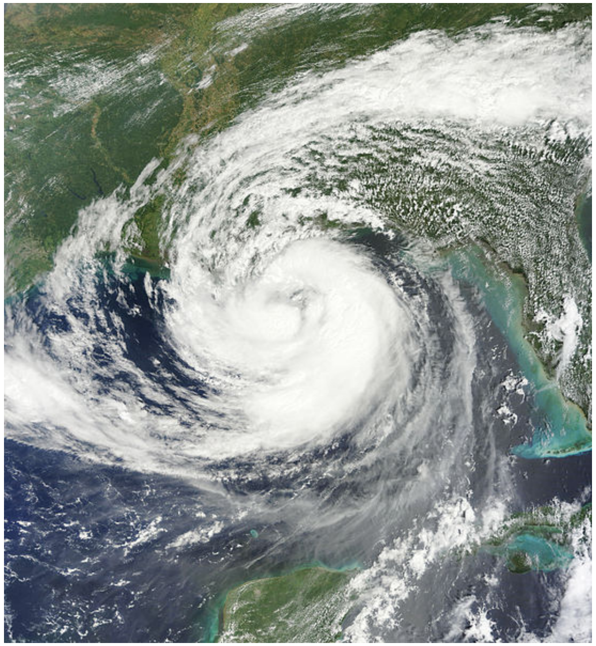
- **Hurricane Isaac** simulations: 00Z each day from 08/22/12 to 08/26/12
    - 120 hour forecasts
- Global Forecast System (GFS) analysis (atm + SSTs) interpolated to CAM-SE grid
- Simulation -> ~3 hours wall clock time
    - 256 cores (4 nodes) on NCAR Bluefire (IBM)



NASA MODIS



Hurricane Isaac forecasts

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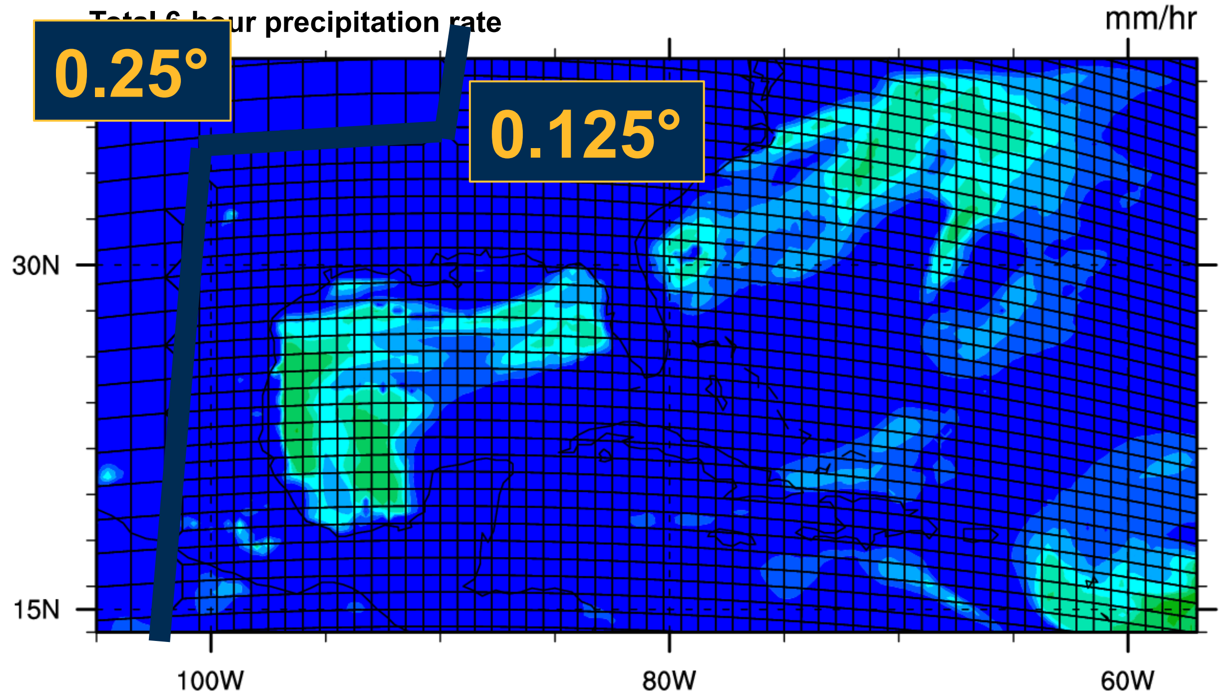
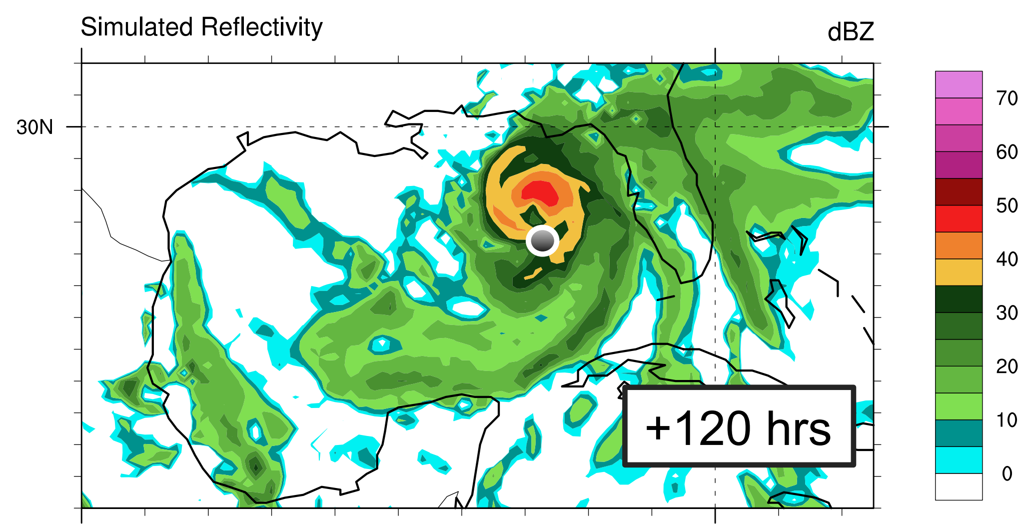


- 08/22/12, 00Z (earliest simulation)



Hurricane Isaac forecast track errors

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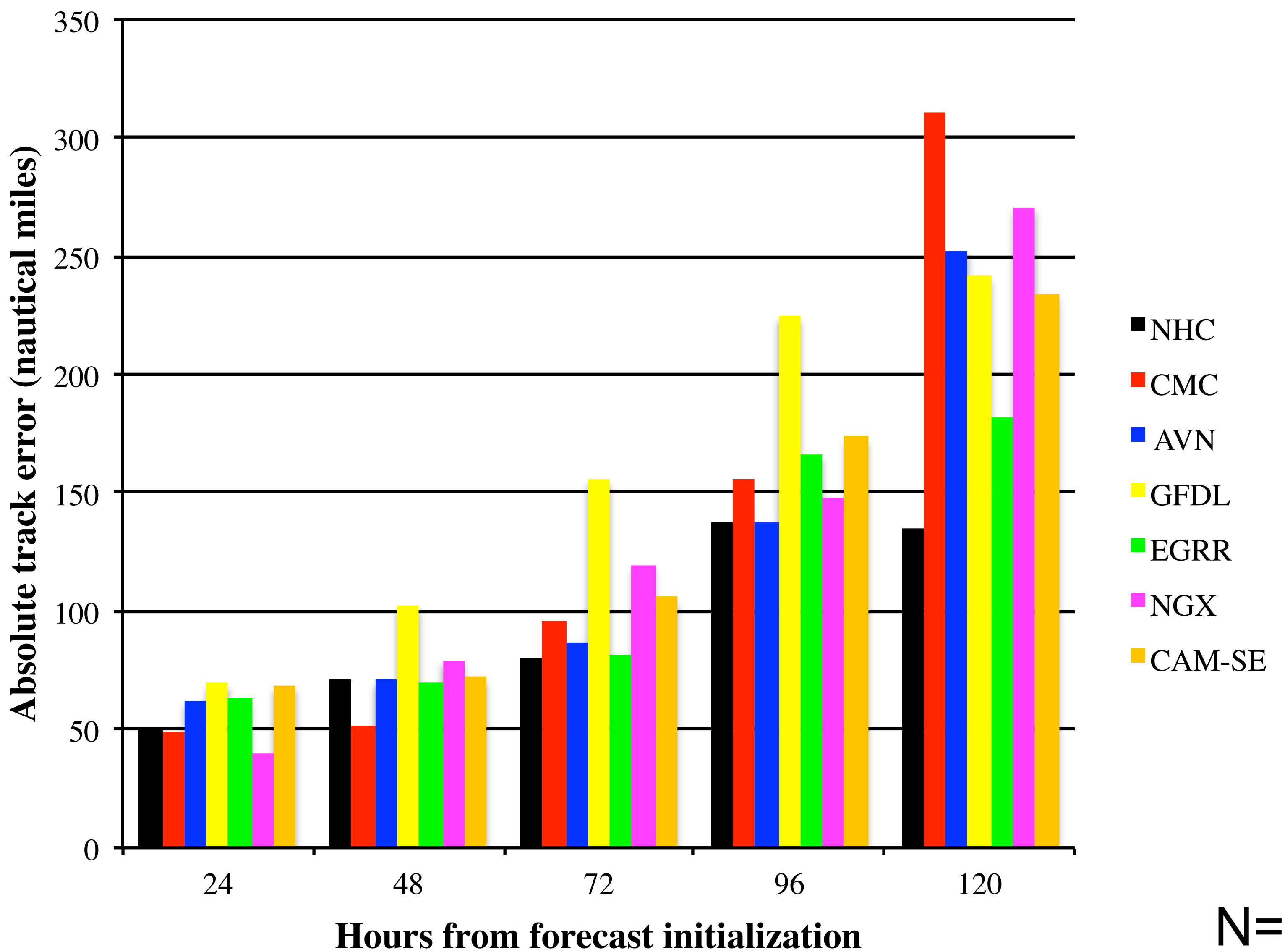

N=5!

Computational benefits

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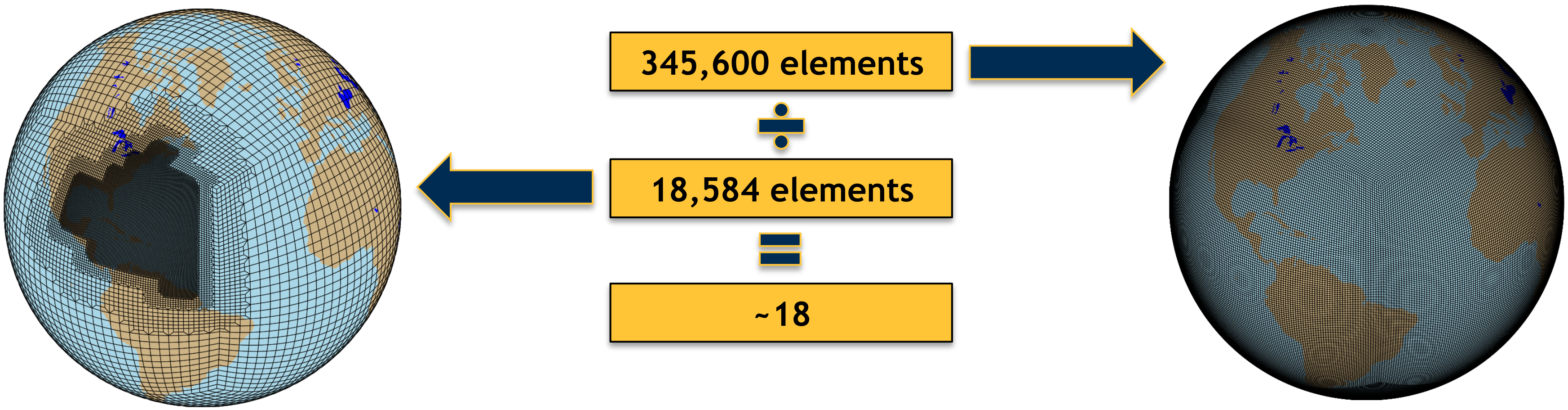

- Atm: ~**15-20x speedup** with variable-resolution vs. 1/8° uniform grid
  - Scales with number of elements and fixed compute load
- For same cost of global uniform/quasi-uniform…
  - Higher regional resolution
  - Additional ensemble simulations
  - Longer model runs
- Combine best features of global models, limited area models?
  - Higher resolution to resolve cyclone intensity, vertical structure (regional models)
  - Physically consistent, 2-way interaction, global synoptic flow (global models)