Atmospheric Dynamical Core* and Seamless Weather-Climate Modeling

* A “dynamical core” is a numerical representation of the 3D Euler equations on the sphere with a finite degree of freedom

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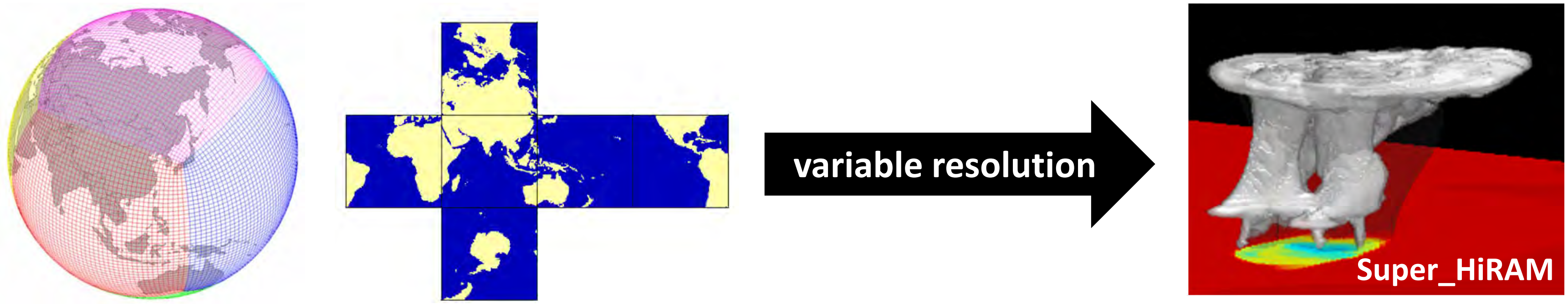
The GFDL non-hydrostatic Finite-Volume core on cubed-sphere (FV3)



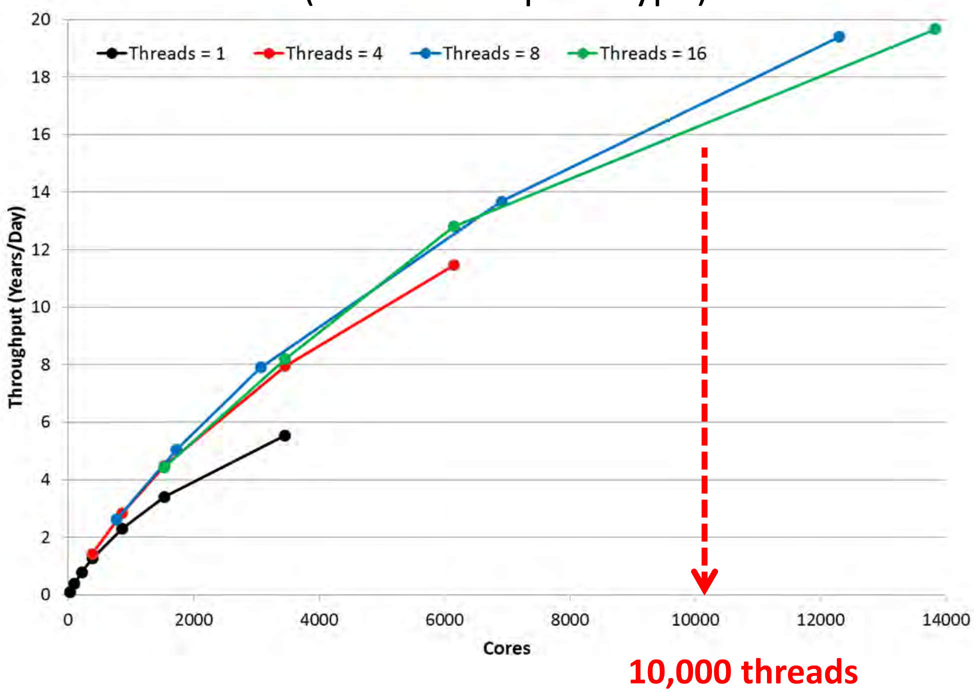
- **Finite-Volume discretization & monotone advection of <u>all</u> prognostic fields (air mass, tracers, and Potential Vorticity)**
  - **Maintain dynamical consistency**
  - **Superior representation of vortical flows (e.g., tropical cyclones, super-cell thunderstorms, and tornadoes)**
- **Vertically Lagrangian discretization (Lin 2004)**
  - **Time step not limited by vertically propagating sound waves & strong updraft/downdraft ; big computational advantage for global cloud-resolving simulations**
- **Configurable as regional, global, or 2-way nested regional-global model**
- **Highly scalable with hybrid (shared & distributed memory) programming**

Million-core scalability *via* hybrid programming

- **The AM4 prototype (50 km with 30 tracers) scales well beyond 10,000 cores (left)**
- **A global cloud-resolving prototype (3.5 km) scales beyond 1 million cores/threads (right)**

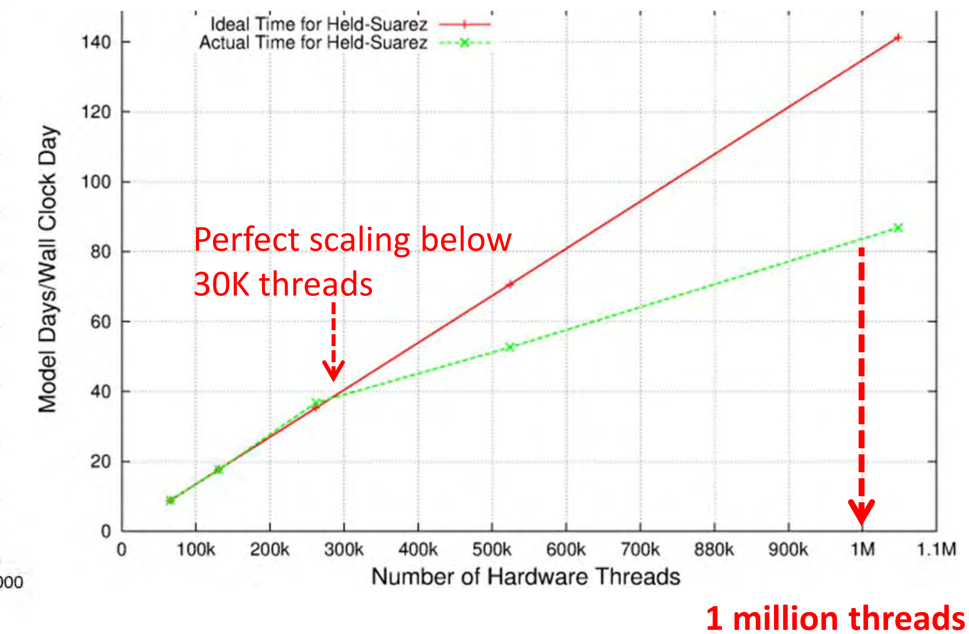
Hydrostatic C192L63 with 30 tracers on GAEA

(50 km AM4 prototype)



Non-hydrostatic C2560L32 on IBM B/G

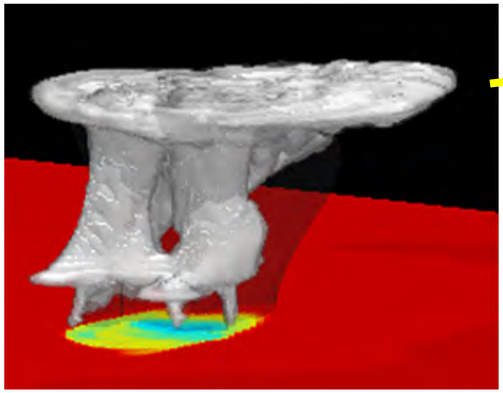
(3.5 km global cloud-permitting prototype)

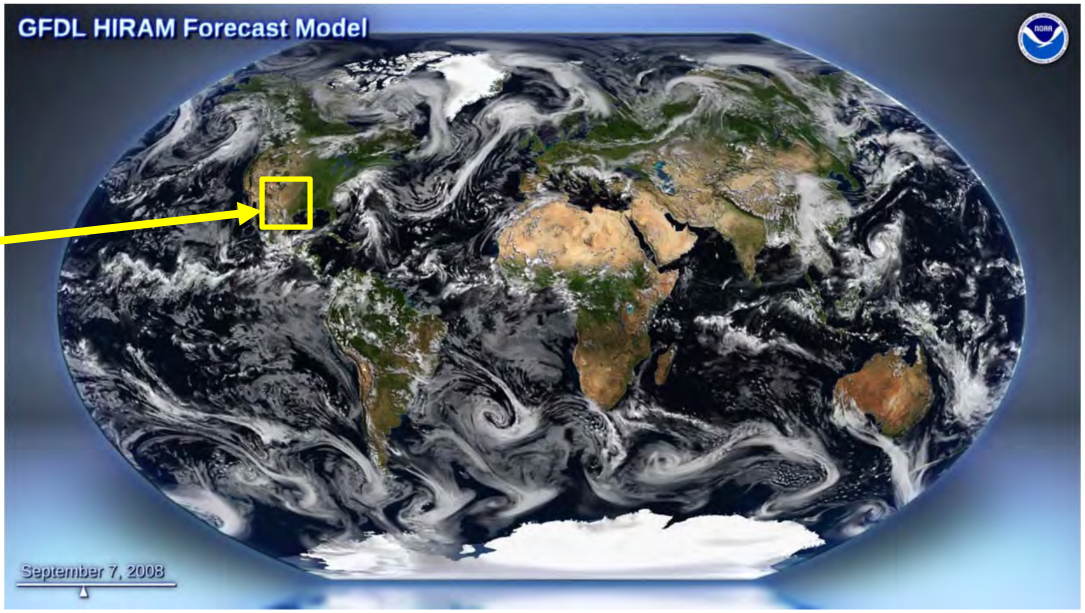


The challenge of building a weather-ready climate modeling system

Capability: **simulations & predictions of high-impact events from the smallest to the largest scale (tornadoes, thunderstorms, hurricanes, MJOs, QBOs, ENSO) all within an “IPCC-class” climate modeling system**

Tornadoes simulated by Super HiRAM





- **Most climate models do not have the correct <u>dynamical</u> and <u>physical mechanisms</u> to represent kilometer-scale flows**
- **A new breed of seamless weather-climate model is being developed at GFDL**

Why global weather-climate models should transition to non-hydrostatic dynamics within the next 5-10 years

- **Reduced (~50%) tropical tropopaue cold bias (even at the "hydrostatic" 50 km resolution!)**

- **Improved typhoon statistics in the western Pacific**

- **Better representation of Kelvin waves (in AM4)**

- **Direct simulation of QBOs without the (artificial) convective gravity wave drag parameterization**

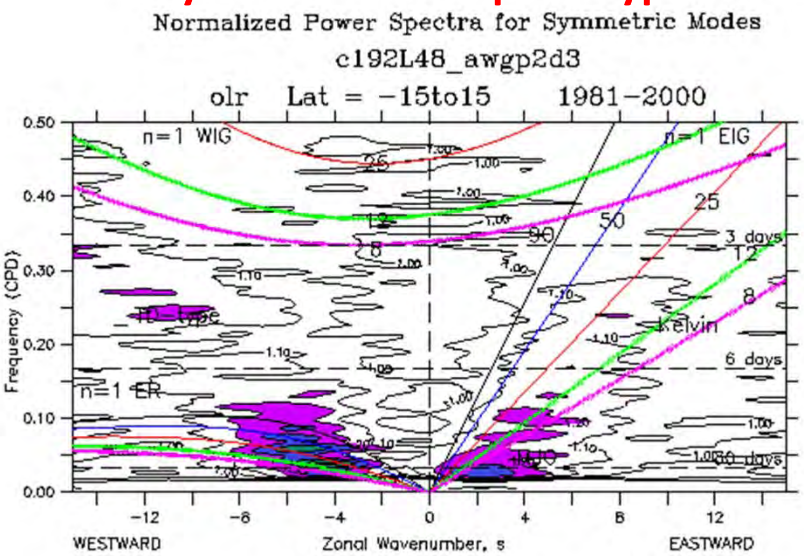
- **Lastly, the resolved motion at sub-10 km is highly non-hydrostatic; for example, hydrostatic models simply can not simulate a local thunder storm**

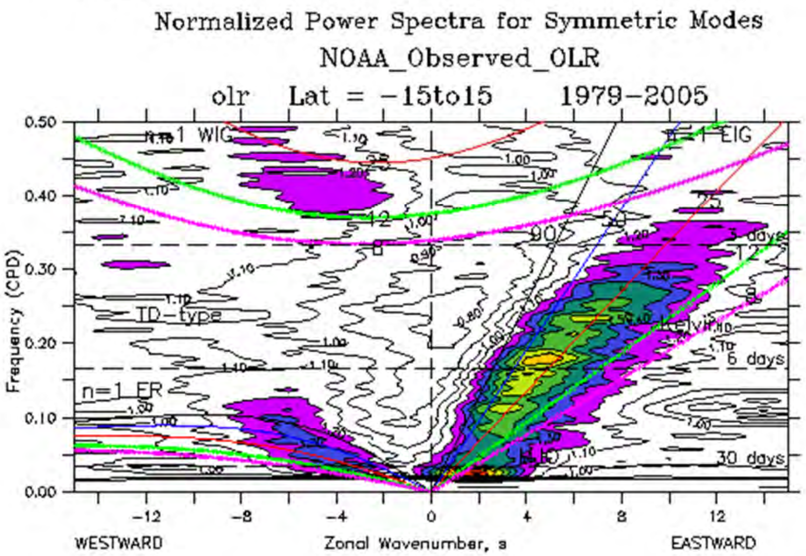
Overall:

similar mean climate but better variability with the non-hydrostatic dynamics

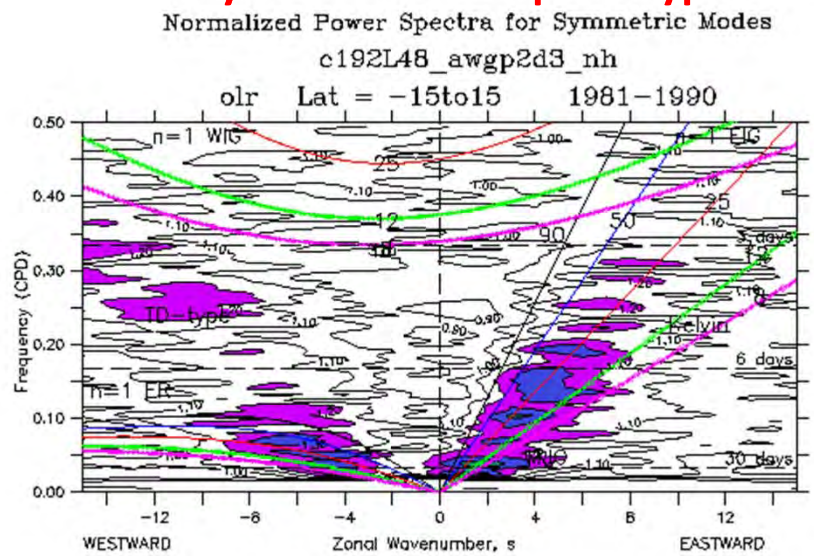
- **Everything being equal, Kelvin waves are better simulated with non-hydrostatic dynamics**
- **No QBOs if the Kelvin waves are too weak**

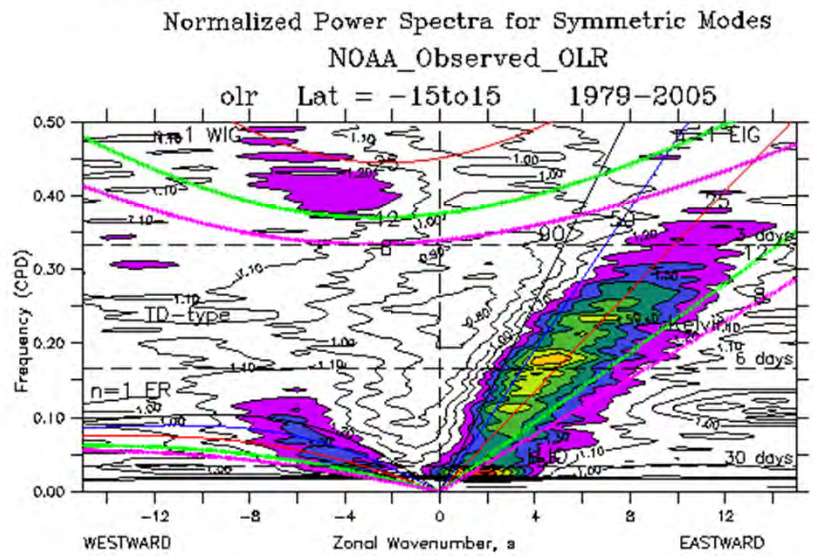
Hydrostatic AM4 prototype



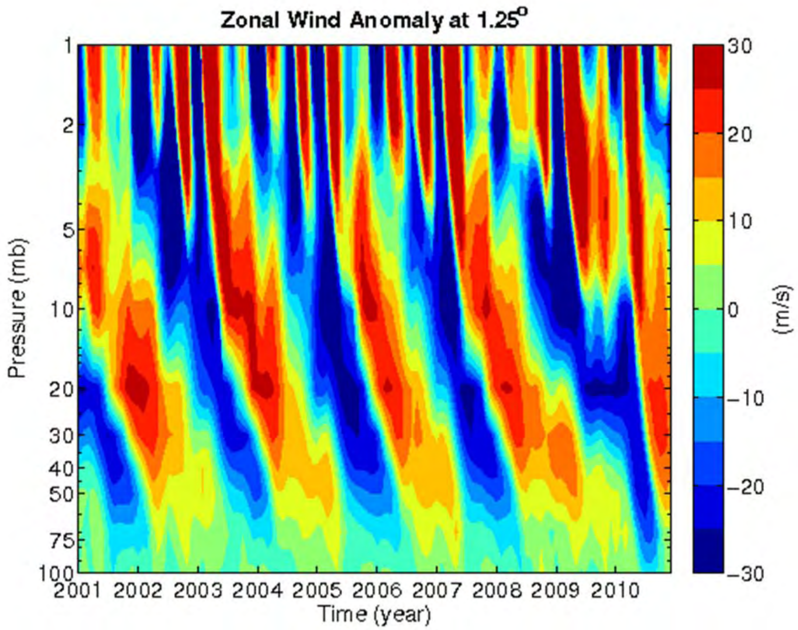


Non-hydrostatic AM4 prototype





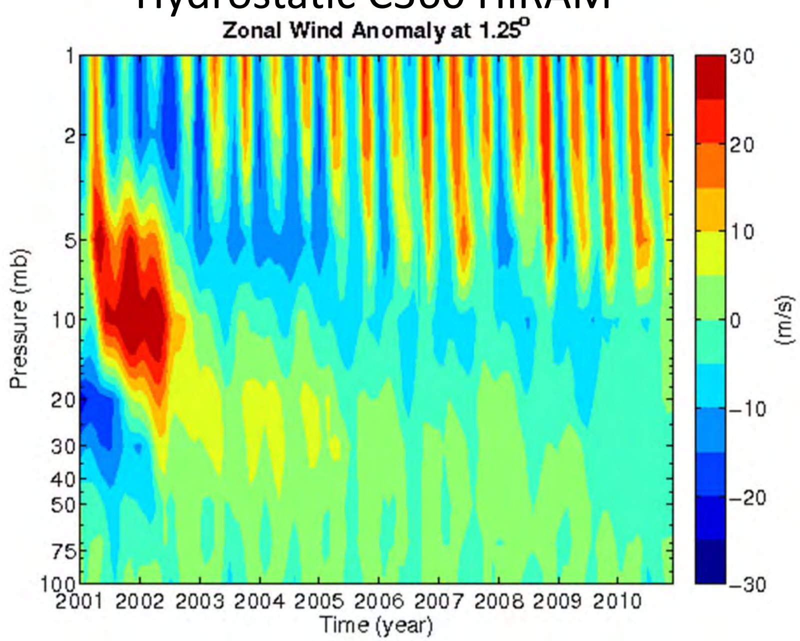
NASA Merra Data (analysis)



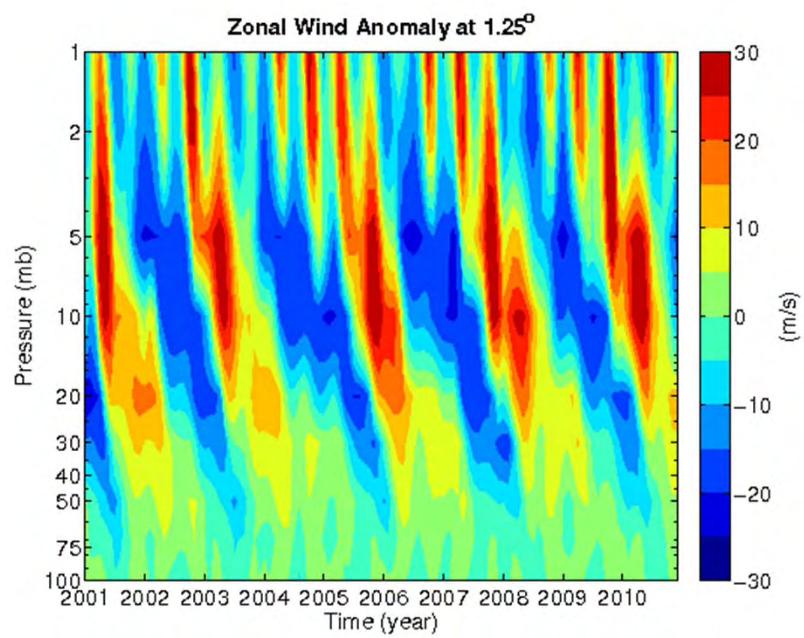
A dramatic impact of the non-hydrostatic dynamics:

- QBOs are difficult to simulate in free-running GCMs with or without convective GWD
- QBOs are believed to have significant impacts to sudden warming, stratospheric ozone, and (some also believe) hurricanes & winter storms

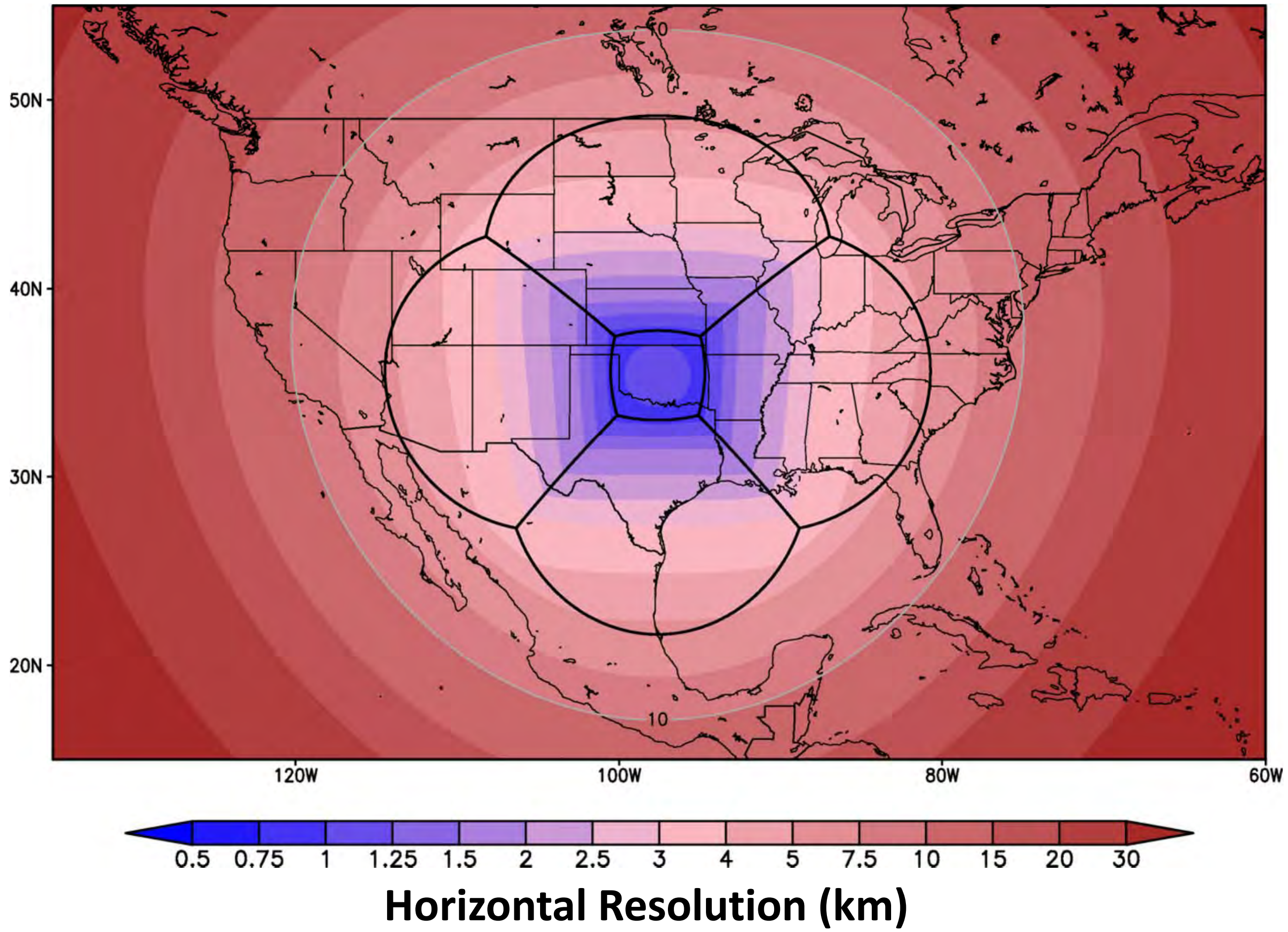
Hydrostatic C360 HiRAM



Non-hydrostatic C360 HiRAM



A 20X-stretched Super HiRAM capable of simulating super-cell & tornadoes



5 tiles (of the cubed-sphere) over NA with ~1 km resolution over Oklahoma, smoothly stretched to 400 km over S. Indian ocean

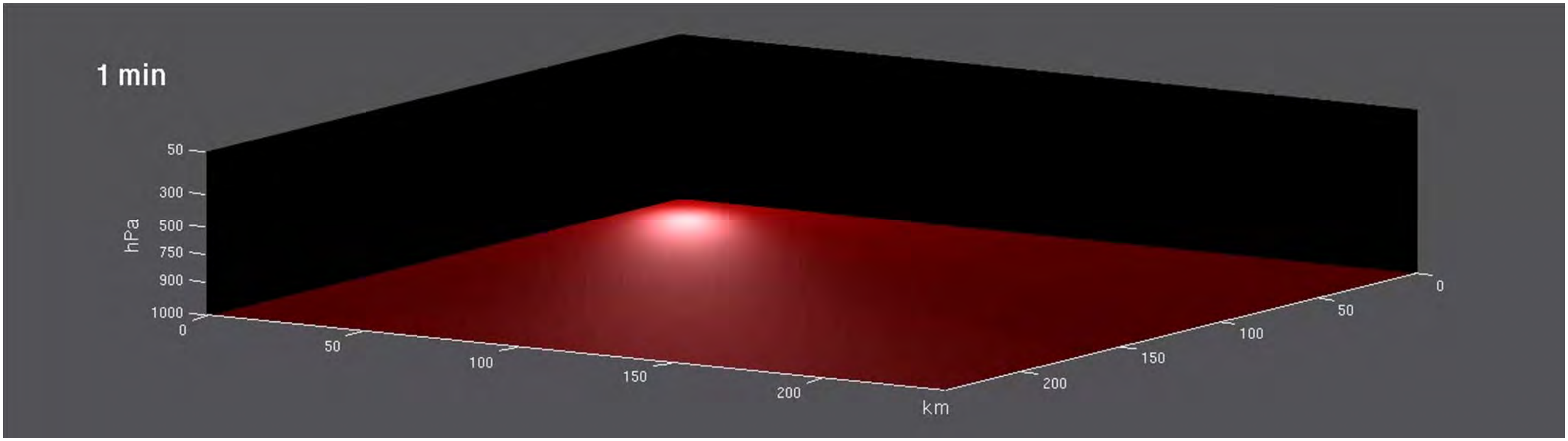
Multiple tornadoes simulated by the variable-resolution Super HiRAM

Dynamics & Physics:

- Non-hydrostatic FV3 & warm-rain micro-physics (nothing else needed)

Initialization:

- Weisman & Klemp sounding (2002) with Toy (2012) quarter-circle hodograph wind profile
- 2^{o} C warm bubble to initiate the updrafts
- Computational cost: 3-hour simulation needs ~ 2 hours (wall clock) using 384 cores (on Gaea)

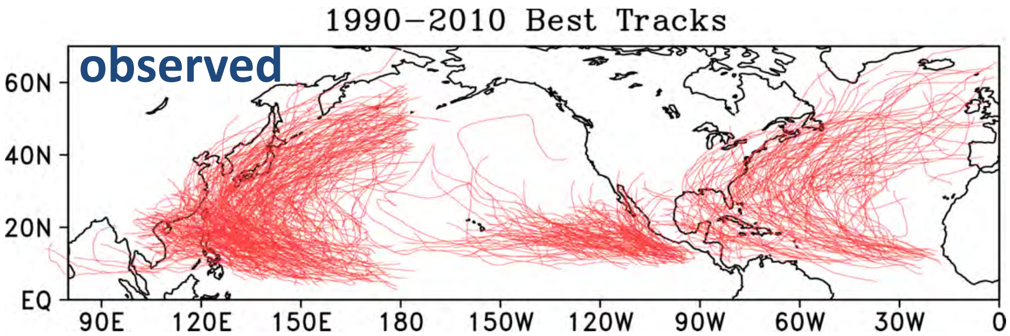


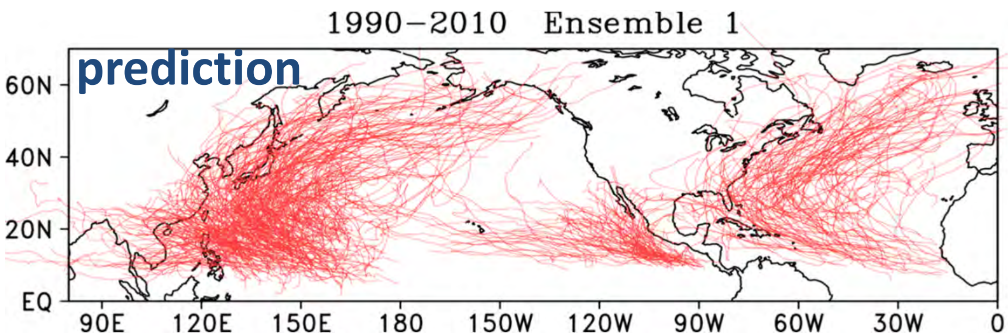
Darker shade: *rain water;* **Lighter shade**: *cloud liquid water*
Bottom shading: *lowest layer air temperature (illustrating cold pool)*

(Animation: L. Harris)

Seasonal hurricane predictions with the (hydrostatic) 25-km HiRAM

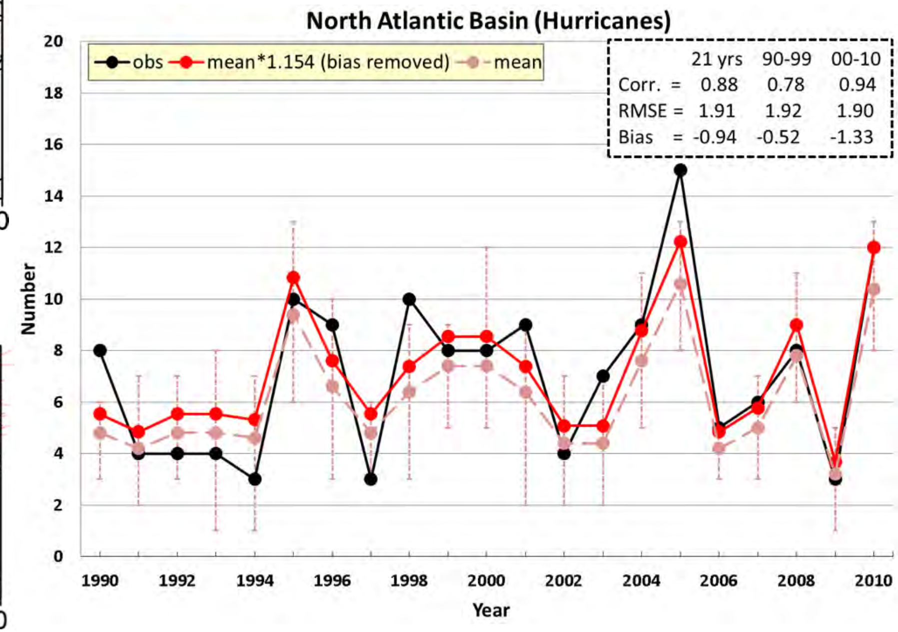
(Chen and Lin 2011, 2013)





1990-2010 (J-A-S-O-N)

Correlation = 0.88

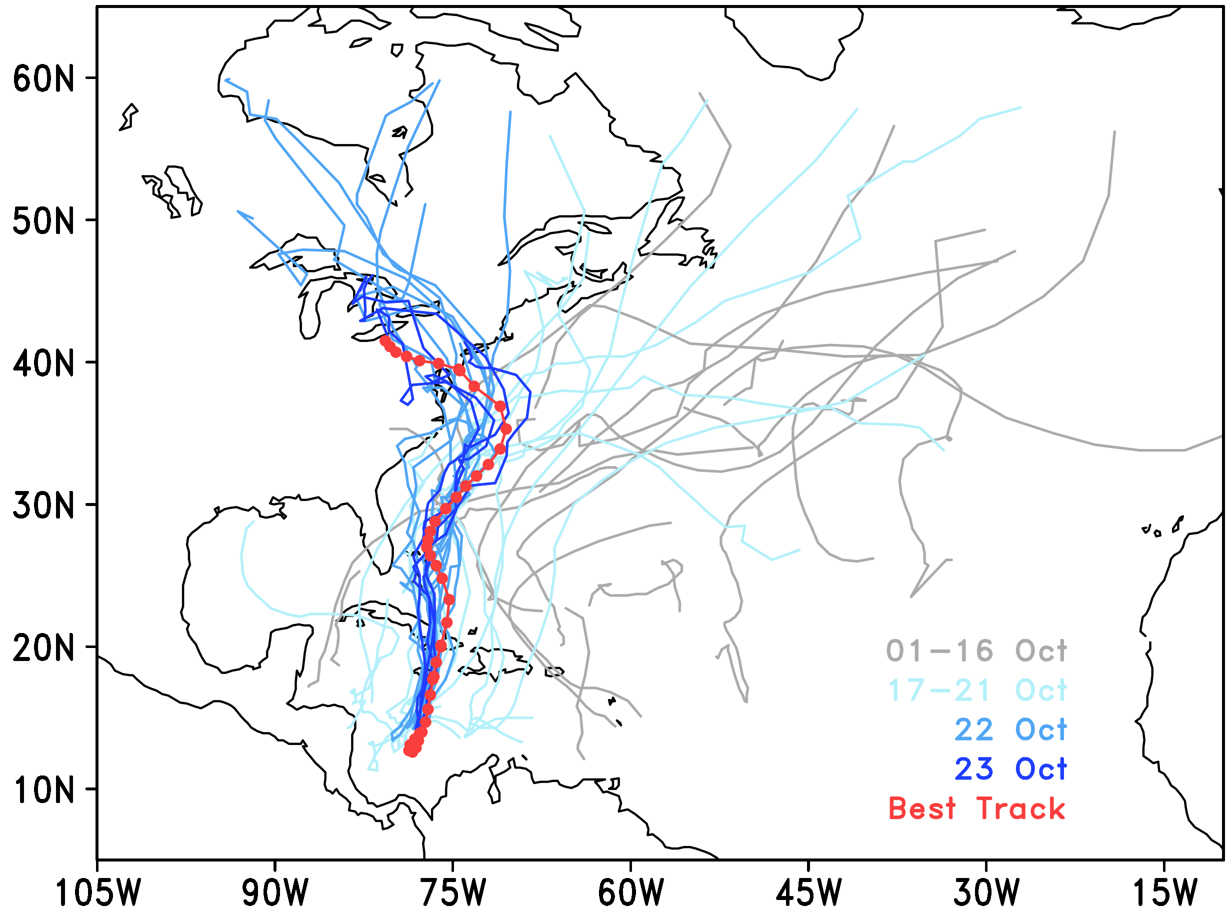


- The highest correlation for the Atlantic hurricanes (vs. observed) in the literature
- Very small negative bias (hurricane counts) in the Atlantic basin
- A moderate positive bias (typhoon counts) in western Pacific (can be fixed if non-hydrostatic core is used)

Sandy Supplemental Project:

Long-range predictions of hurricane Sandy from 1-23 Oct

(25-km non-hydrostatic HiRAM)



Hurricane Sandy (2012)
- **Genesis: 22 Oct**
- **US landfall: 30 Oct**

1. Genesis locations are skillfully predicted after 17th (5 days before genesis)
2. Forecasts after 21 Oct (9 days before landfall) started to exhibit westward turn (the left hook)
3. Skillful landfall locations predicted after 22 Oct

Summary:

1. The state of the GFDL atmosphere dynamical core

1. **Past**: hydrostatic Finite-Volume (FV) core on lat-lon grid (GFDL CM2.1, NASA GEOS-5, and NCAR CCSM)
2. **Present and near future**: FV (with non-hydrostatic option) on the cubed-sphere (HiRAM, CM3, CM4; also used by NASA GEOS-6 and some GISS climate models)
3. **Experimental**: a new and potentially more efficient dynamical core based on a fast Riemann solver (X. Chen's poster)

2. A weather-ready climate modeling framework

- A unified modeling framework with regional-global 2-way nesting capability (poster by Harris)
- **Super High Resolution Atmosphere Model** (**Super HiRAM**):
  - **"seamless" simulation of tornadoes, super-cell T-storms, tropical cyclones, and QBOs using the same modeling system**
- Impacts of non-hydrostatic dynamics in medium resolution (~50 km) climate simulations:

3. Sandy supplemental & High Impact Weather Prediction Project

- **GFDL models are being evaluated for seasonal and sub-seasonal prediction of high-impact weather events (e.g., landfall hurricanes; probability of tornado outbreak), which could also serve as a new metric for climate model evaluation**

Summary-2: supplemental:

- **GFDL is leading the community in the development of a computationally efficient "*weather-ready*" high-resolution climate model that is capable of simulating severe weather events (e.g., thunder storms & tornadoes) previously thought impossible within a global modeling framework**

- **Transition of all climate model to non-hydrostatic should take place within a decade. With the *"million core scalability" reached*, GFDL is ready (if HPC is) for a *km-scale global model, that is capable of super-cell & tornado simulations, for truly seamless weather-climate applications***