GFDL's finite-volume Cubed-Sphere Dycore: *Basic formulation, performance, and its applications in weather & climate modeling*

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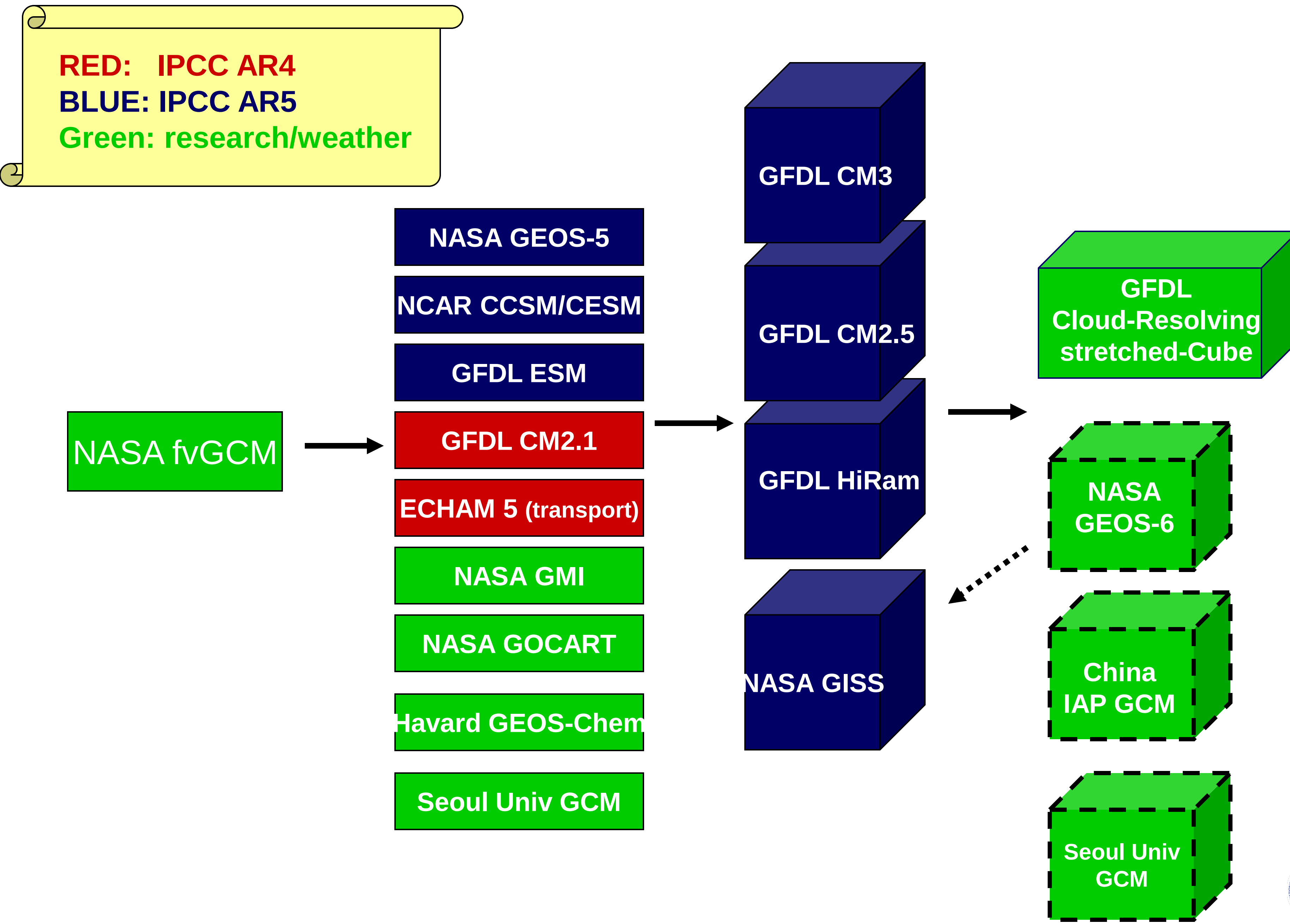
- **Model genealogy**
- **Improved FV algorithms on the cubed-sphere and the scaling performance**
- **New capability: Global "regional climate models"**
  I. Stretch-grid
  II. 2-way nested regional-global
- **Ultra-high resolution climate simulations and seasonal hurricane predictions**

CESM Atmosphere Model Working Group Meeting, 1-3 Feb 2012

Recent GFDL publications using the cubed-sphere dycore

1. Chen, J H., and Shian-Jiann Lin, June 2011: **The remarkable predictability of inter-annual variability of Atlantic hurricanes during the past decade**. *Geophysical Research Letters*, **38**, L11804, DOI:10.1029/2011GL047629.
2. Donner, Leo J., Bruce Wyman, Richard S Hemler, Larry W Horowitz, Yi Ming, Ming Zhao, J-C Golaz, Paul Ginoux, Shian-Jiann Lin, M Daniel Schwarzkopf, John Austin, G Alaka, W F Cooke, Thomas L Delworth, Stuart Freidenreich, C Tony Gordon, Stephen M Griffies, Isaac M Held, William J Hurlin, Stephen A Klein, Thomas R Knutson, Amy R Langenhorst, H C Lee, Y Lin, B I Magi, Sergey Malyshev, P C D Milly, V Naik, Mary Jo Nath, R Pincus, Jeff J Ploshay, V Ramaswamy, Charles J Seman, Elena Shevliakova, Joseph J Sirutis, William F Stern, Ronald J Stouffer, R John Wilson, Michael Winton, Andrew T Wittenberg, and Fanrong Zeng, July 2011: **The dynamical core, physical parameterizations, and basic simulation characteristics of the atmospheric component AM3 of the GFDL Global Coupled Model CM3**. *Journal of Climate*, **24(13)**, DOI:10.1175/2011JCLI3955.1.
3. Gall, J S., I Ginis, Shian-Jiann Lin, Timothy Marchok, and J H Chen, December 2011: **Experimental tropical cyclone prediction using the GFDL 25km resolution global atmospheric model**. *Weather and Forecasting*, **26(6)**, DOI:10.1175/WAF-D-10-05015.1.
4. Zhao, Ming, Isaac M Held, Shian-Jiann Lin, and Gabriel A Vecchi, December 2009: **Simulations of global hurricane climatology, interannual variability, and response to global warming using a 50km resolution GCM**. *Journal of Climate*, **22(24)**, DOI:10.1175/2009JCLI3049.1.
5. Delworth, Thomas L., Anthony Rosati, Whit G Anderson, Alistair Adcroft, Ventakramani Balaji, Rusty Benson, Keith W Dixon, Stephen M Griffies, H C Lee, Ronald C Pacanowski, Gabriel A Vecchi, Andrew T Wittenberg, Fanrong Zeng, and Rong Zhang, *in press*: **Simulated climate and climate change in the GFDL CM2.5 high-resolution coupled climate model**. *Journal of Climate*. DOI:10.1175/JCLI-D-11-00316.1. 11/11.
6. Putman, W M., and Shian-Jiann Lin, 2007: **Finite-volume transport on various cubed-sphere grids**. *Journal of Computational Physics*, **227(1)**, 55-78.
7. Golaz, J-C, M Salzmann, Leo J Donner, Larry W Horowitz, Yi Ming, and Ming Zhao, July 2011: **Sensitivity of the aerosol indirect effect to subgrid variability in the cloud parameterization of the GFDL Atmosphere General Circulation Model AM3**. *Journal of Climate*, **24(13)**, DOI:10.1175/2010JCLI3945.1.
8. Salzmann, M, Yi Ming, J-C Golaz, Paul Ginoux, H Morrison, A Gettelman, M Krämer, and Leo J Donner, August 2010: **Two-moment bulk stratiform cloud microphysics in the GFDL AM3 GCM: description, evaluation, and sensitivity tests**. *Atmospheric Chemistry and Physics*, **10(16)**, 8037-8064.
9. Fang, Y, Arlene M Fiore, Larry W Horowitz, Anand Gnanadesikan, Isaac M Held, G Chen, Gabriel A Vecchi, and Hiram Levy II, September 2011: **The impacts of changing transport and precipitation on pollutant distributions in a future climate**. *Journal of Geophysical Research*, **116**, D18303, DOI:10.1029/2011JD015642.
10. Held, Isaac M., and Ming Zhao, October 2011: **The response of tropical cyclone statistics to an increase in CO2 with fixed sea surface temperatures**. *Journal of Climate*, **24(20)**, DOI:10.1175/JCLI-D-11-00050.1.
11. Vecchi, Gabriel A., Ming Zhao, H Wang, G Villarini, Anthony Rosati, A Kumar, Isaac M Held, and Rich Gudgel, April 2011: **Statistical-dynamical predictions of seasonal North Atlantic hurricane activity**. *Monthly Weather Review*, **139(4)**, DOI:10.1175/2010MWR3499.1.
12. Zhao, Ming, and Isaac M Held, *in press*: **TC-permitting GCM simulations of hurricane frequency response to sea surface temperature anomalies projected for the late 21st century**. *Journal of Climate*. DOI:10.1175/JCLI-D-11-00313.1. 11/11.
13. Zhao, Ming, Isaac M Held, and Gabriel A Vecchi, October 2010: **Retrospective forecasts of the hurricane season using a global atmospheric model assuming persistence of SST anomalies**. *Monthly Weather Review*, **138(10)**, DOI:10.1175/2010MWR3366.1.
14. Zhao, Ming, and Isaac M Held, December 2010: **An analysis of the effect of global warming on the intensity of Atlantic hurricanes using a GCM with statistical refinement**. *Journal of Climate*, **23(23)**, DOI:10.1175/2010JCLI3837.1.
15. Zhao, Ming, Isaac M Held, Shian-Jiann Lin, and Gabriel A Vecchi, December 2009: **Simulations of global hurricane climatology, interannual variability, and response to global warming using a 50km resolution GCM**. *Journal of Climate*, **22(24)**, DOI:10.1175/2009JCLI3049.1.
16. Jiang, X, Ming Zhao, and William F Stern, et al., *in press*: **Simulation of the intraseasonal variability over the Eastern Pacific ITCZ in climate models**. *Climate Dynamics*. DOI:10.1007/s00382-011-1098-x. 5/11.
17. Li, T, M Kwon, and Ming Zhao, et al., November 2010: **Global warming shifts Pacific tropical cyclone location**. *Geophysical Research Letters*, **37**, L21804, DOI:10.1029/2010GL045124.
18. Griffies, Stephen M., Michael Winton, Leo J Donner, Larry W Horowitz, S M Downes, Riccardo Farneti, Anand Gnanadesikan, William J Hurlin, H C Lee, Z Liang, J B Palter, Bonita L Samuels, Andrew T Wittenberg, Bruce Wyman, J Yin, and N Zadeh, July 2011: **The GFDL CM3 Coupled Climate Model: Characteristics of the ocean and sea ice simulations**. *Journal of Climate*, **24(13)**, DOI:10.1175/2011JCLI3964.1.

The Finite-Volume model family tree



The GFDL Cubed-Sphere dynamical Core

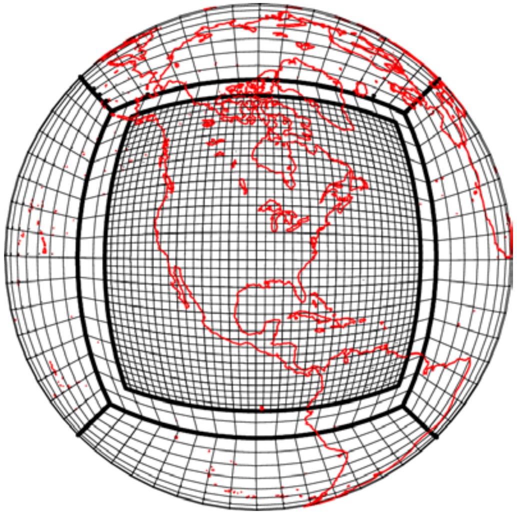
Based on the Lin-Rood FV algorithms with the following mods:

- Cubed-Sphere geometry (Putman and Lin 2007) with two variable-resolution options (stretched and 2-way regional global nesting)
- Improved accuracy in vertical remapping with 2-delta-z constraint
- 4^{th} order remapping/interpolation between D and C grids
- 4^{th} order pressure gradient
- A new "alpha" parameter to control time weighting (fully backward with alpha = 0) → improved representation of gravity waves
- Optional del-n damping on divergence (n=2, 4, 6, 8)
  Warning: *use of del-2 divergence damping may suppress QBO in low resolution simulations*

Two alternatives to achieve ultra-high resolution within the GFDL cubed-sphere model

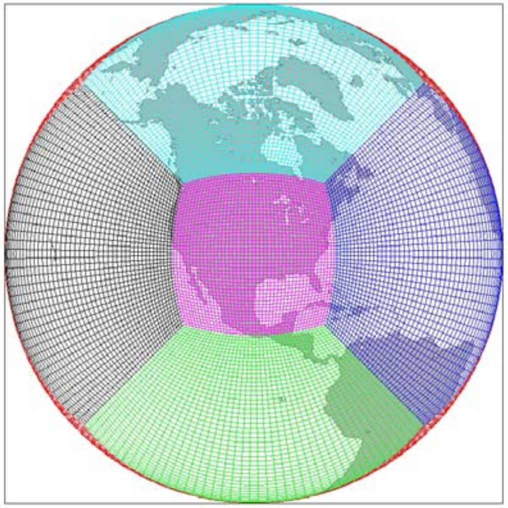
I. Multi-grid:

- **3X grid-size reduction with minimal impact to throughput using *non-overlapping CPUs for the 7th tile***
- **Regional component can be run independently (for down-scaling) or coupled with global grid to allow feedback**



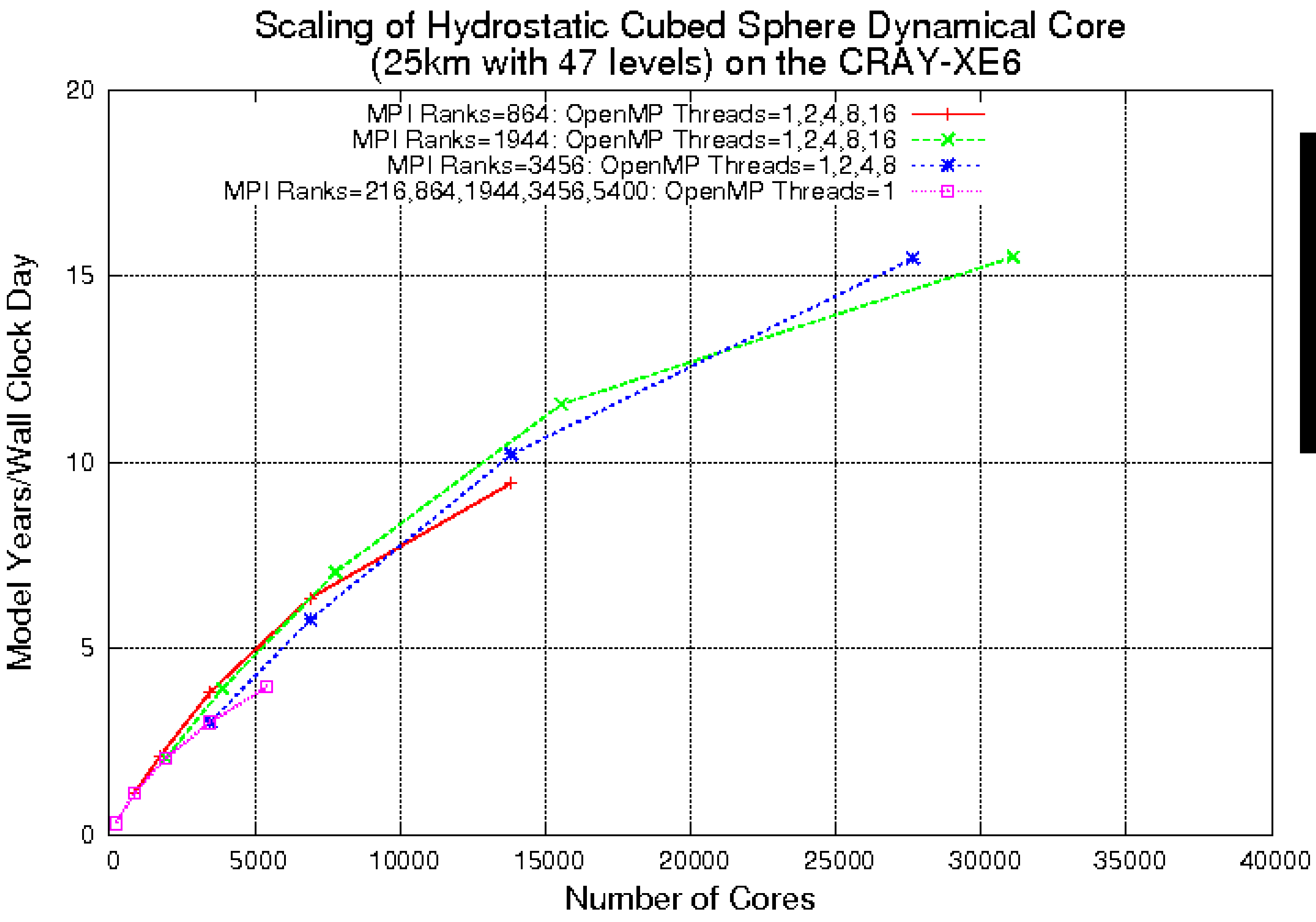
II. Stretched grid

Single-grid model with smooth transition in resolution with 3X grid-size reduction in target region; 3X enlargement on the back side



C360 (~ 25 km) L47; Held-Suarez with 4 tracers

on CRAY XE6

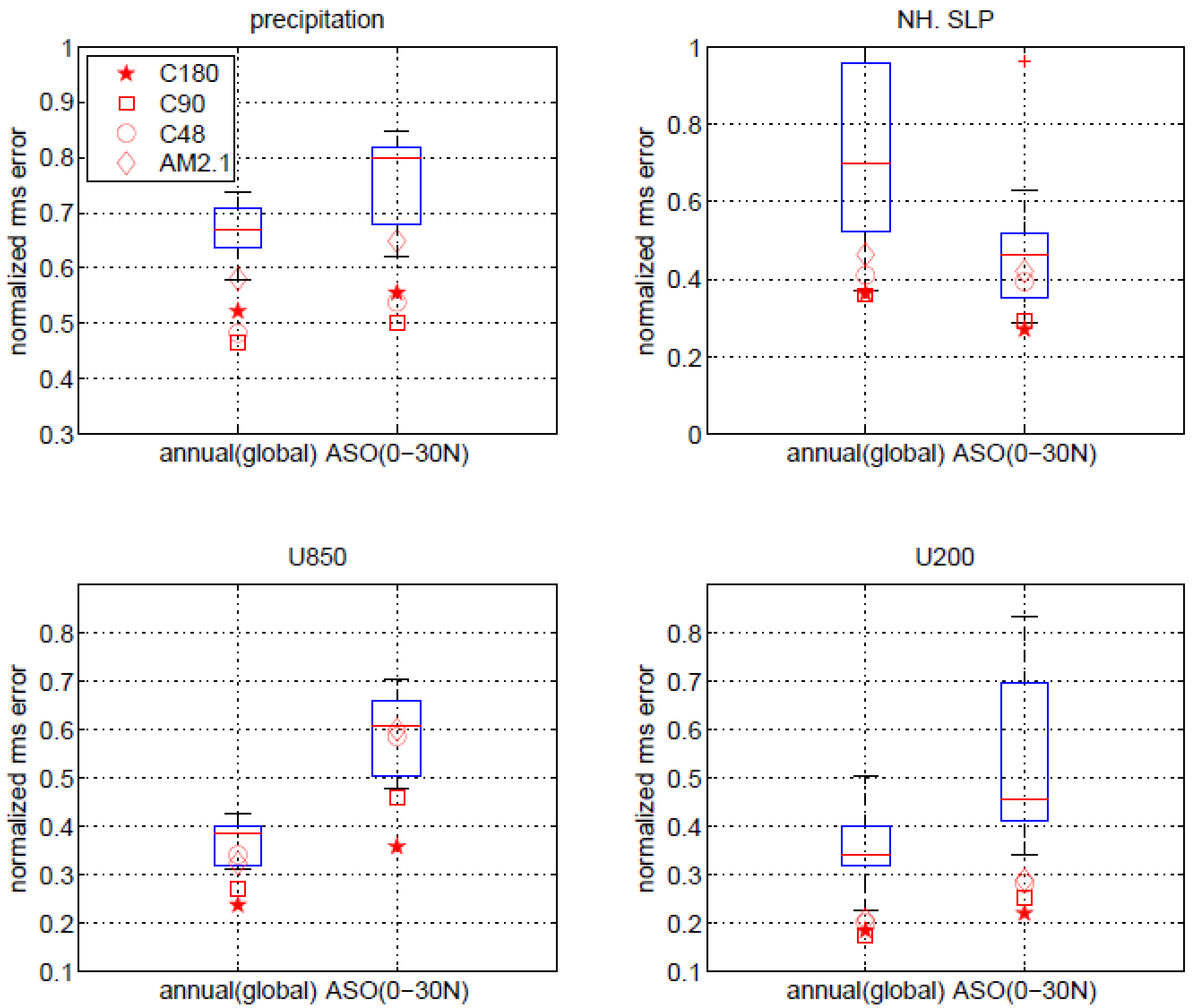


Notes:

- New NOAA "climate super-computer" not yet optimized for OpenMP
- Tracer transport scales better than the rest of the model components

Climate Model inter-comparisons:

GFDL finite-volume models vs. 10 other IPCC AR4 models (Zhao et al 2009)



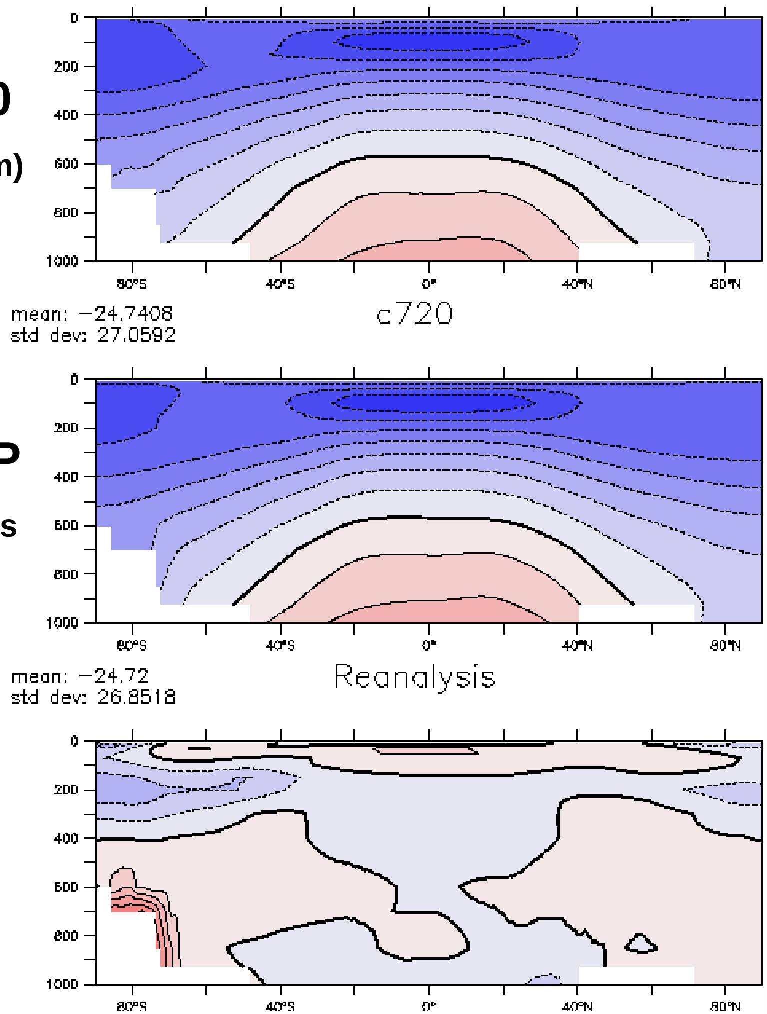
Annual mean Temperature

C720

(12.5 km)

NCEP

analysis



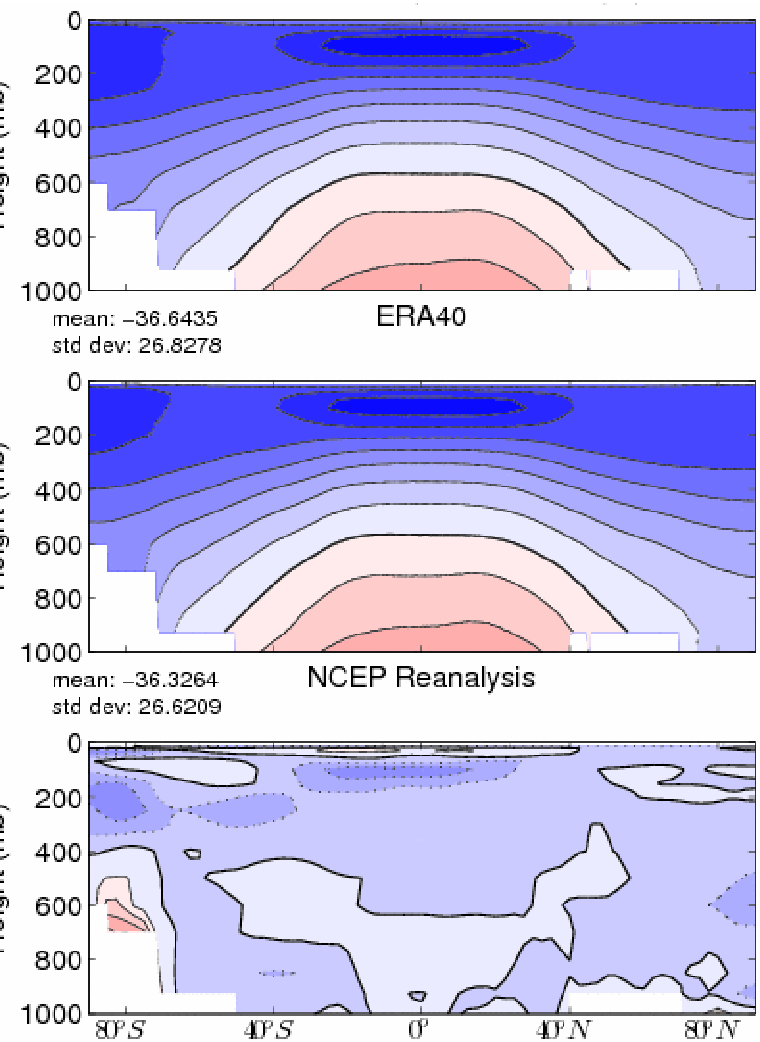
RMSE=1.60 (deg.)

ECMWF

analysis

NCEP

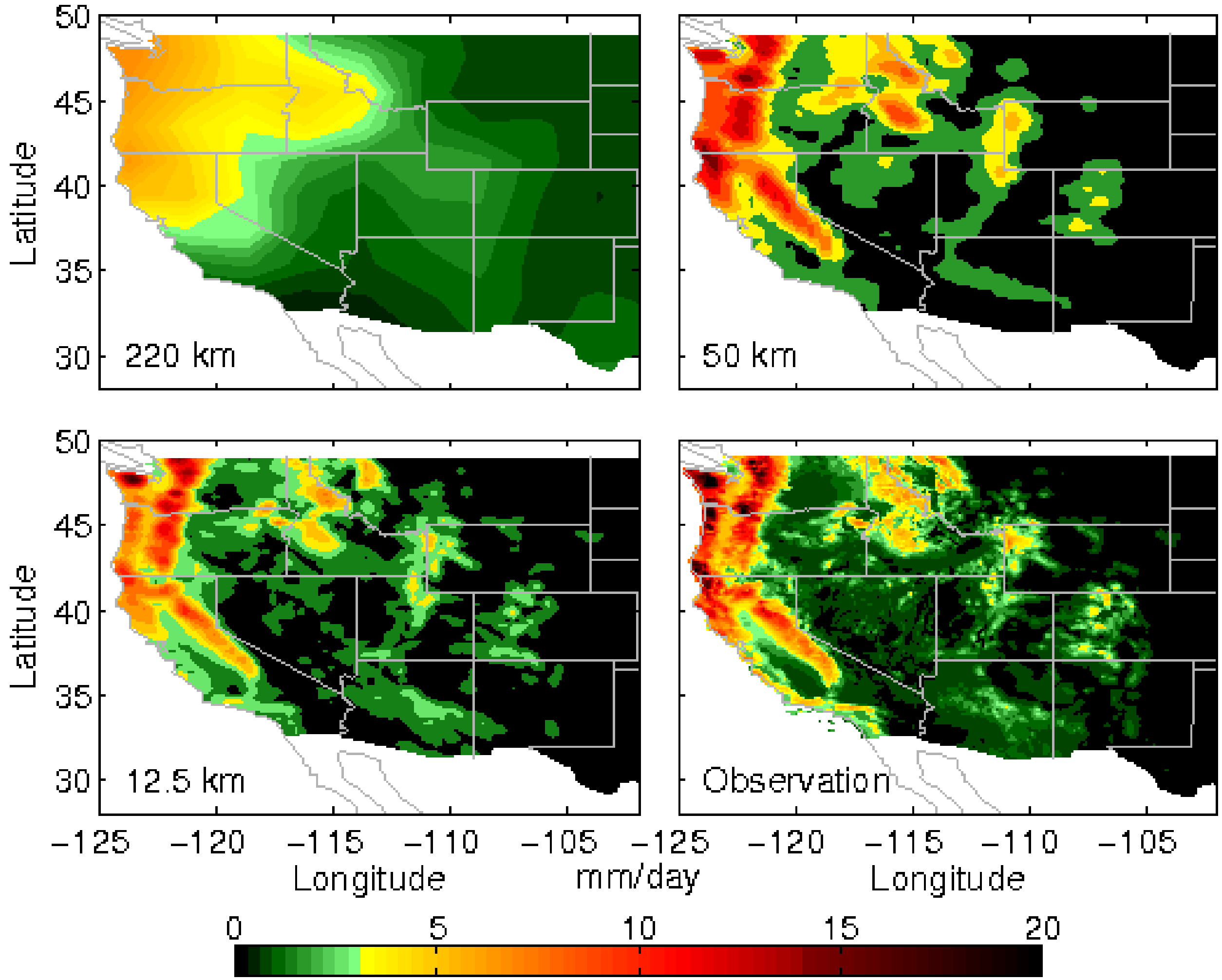
analysis



RMSE=0.88

DJF precipitation in Western US:

GFDL models vs. PRISM



GFDL AM2 (220 km)

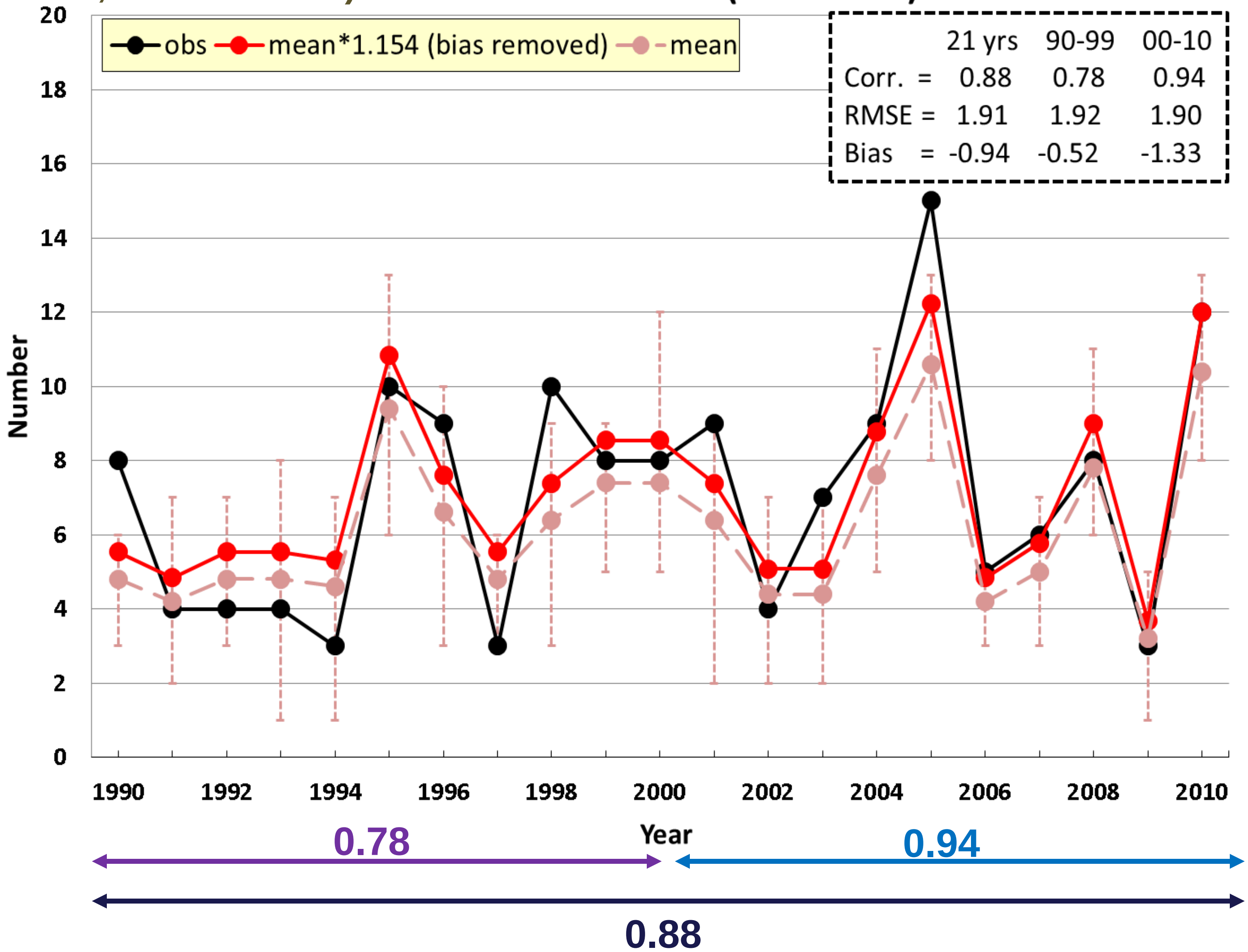
50-km GFDL HiRAM

12.5-km GFDL HiRAM

PRISM (obs)

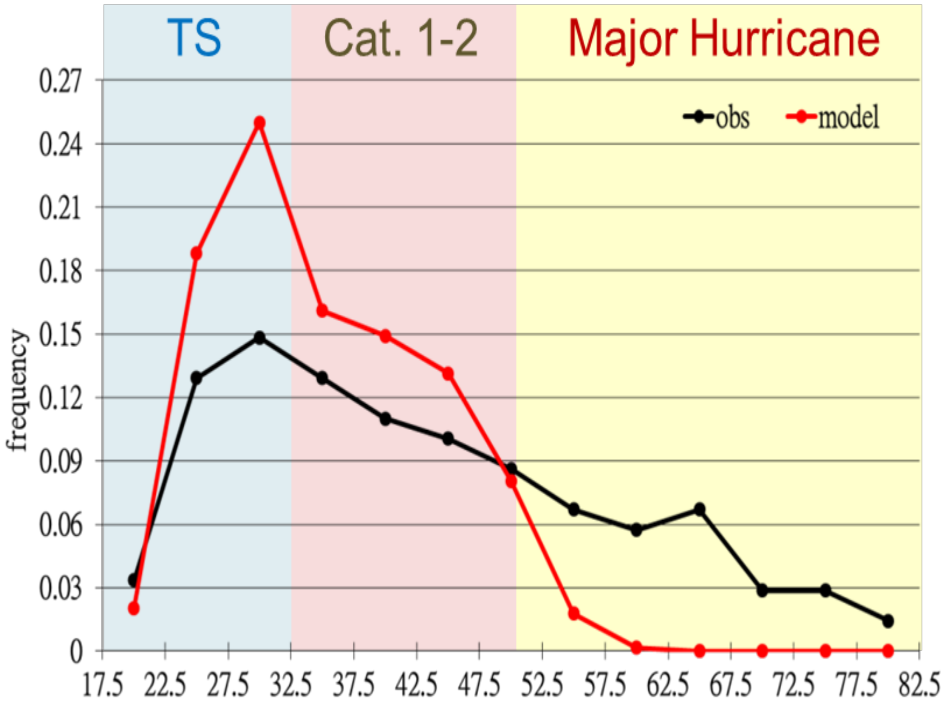
Seasonal (July-November) hurricane predictions 1990-2010

(five months, five members) **North Atlantic Basin (Hurricanes)**

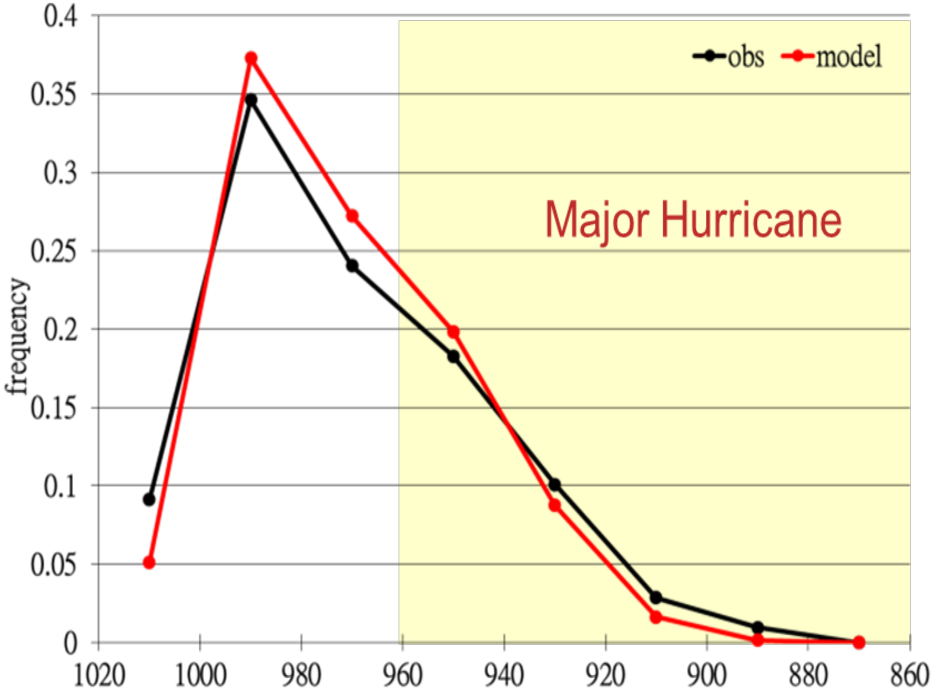


Predicted PDF of the Tropical Cyclones intensity
(all basins 1990-2010)

10-m wind



Central pressure



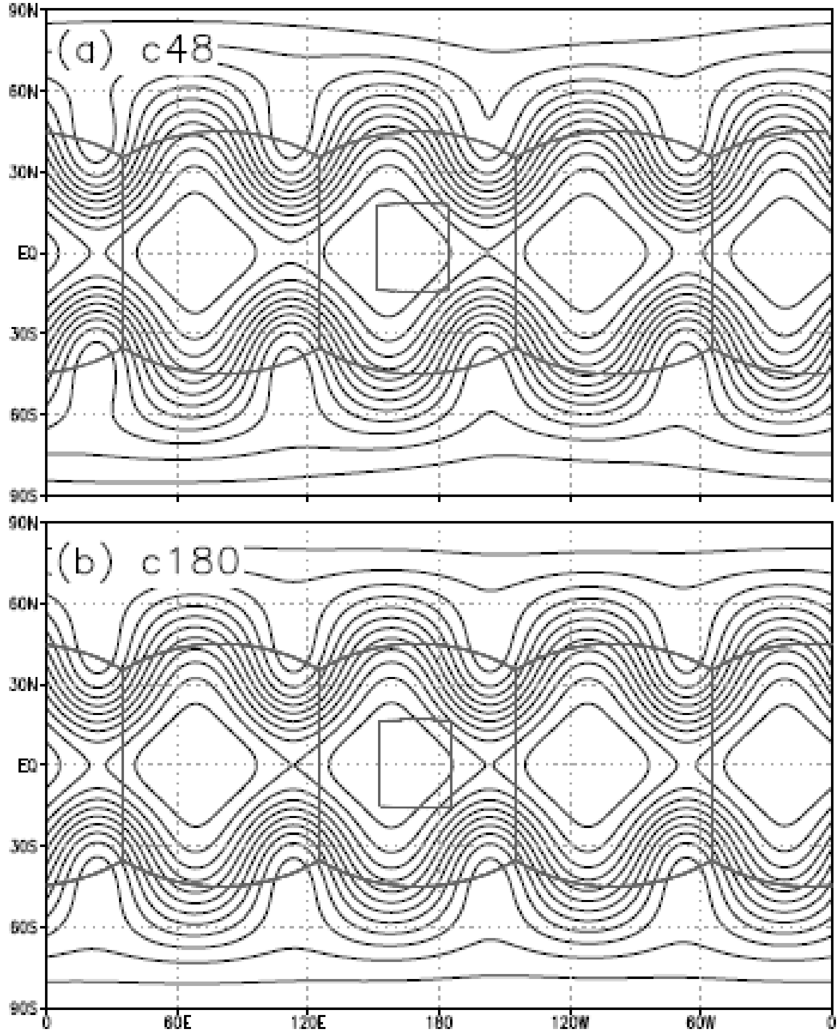
(Chen & Lin, submitted)

Final notes

- The FV core on the cubed-sphere grid is an evolution/refinement of an existing product, not a brand new development.
  - There are some grid imprint at edges of the cubed sphere
  - Overall numerical accuracy is much improved as compared to the “lat-lon” core
- Scaling performance is excellent on platforms that can take advantage of non-blocking message passing (such as the new NOAA climate machine C2)
- Tracer transport is more efficient (and less numerical diffusion) than the old (frozen) FV lat-lon core
- Two variable resolution options (via stretched or regional-global 2-way nesting; or both); can also be run in doubly periodic domain
- Grid generation, terrain filters, vertical remapping and horizontal interpolation of ICs are built into the cubed-sphere core (therefore, parallelized) → no offline tools needed
- CESM implementation:
  - GFDL will support the effort
  - NCAR?

Testing the (non) impact of 2-way nesting on large-scale:

Rossby wave-4 at day 14



(Harris and Lin, manuscript submitted)

FIG. 5. Height at 14 d in the shallow-water Rossby-Haurwitz wave test (Willianson test case 6, contour interval = 2 m) for a (a) c48 nested grid simulation and (b) a c180 nested grid simulation.

Enhancing regional resolution in a global modeling framework

Simulations of lee vortices west of Island of Hawaii

C360 uniform resolution **C120 2-way nested grid** **C120 uniform resolution**

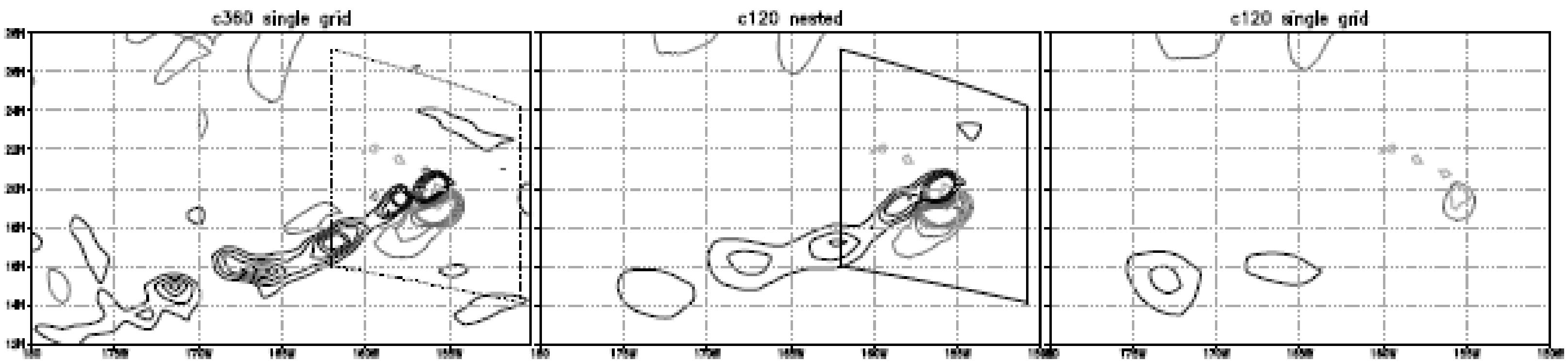


FIG. 15. Surface vorticity (contour interval 10^{-5} s^{-1}, negative values in gray, values above 5×10^{-5} s^{-1} not plotted) at $t = 72$ h in simulations initialized at 0000 UTC on 1 August 2010. Hawaii is at center-right in each panel. Dotted line in left-most panel shows where the nest would be in the nested-grid c120 simulation.

Harris and Lin 2011, *Mon. Wea. Rev*. submitted