Tropical cyclones in high-resolution (Δx~10km) climate simulations: Successes and remaining challenges

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Thanks to: Warren Washington, Jim Hack and DoE for computer time at ORNL

YOTC AMY Symposium, Beijing, May, 2011

Outline

Overview
Storm tracks, intensities, and structure
– *Short runs with CAM5* and *GEOS5*
Emphasis on potentially informative diagnostics …

Sensitivities to Model Physics
Deep Convection Scheme on/off
Condensate loading

Precipitation Objects
A promising approach to understanding cyclogenesis?

Summary and Future Directions

Simulations of Global Hurricane Climatology, Interannual Variability, and Response to Global Warming Using a 50-km Resolution GCM

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(Manuscript received 23 January 2009, in final form 1 June 2009)

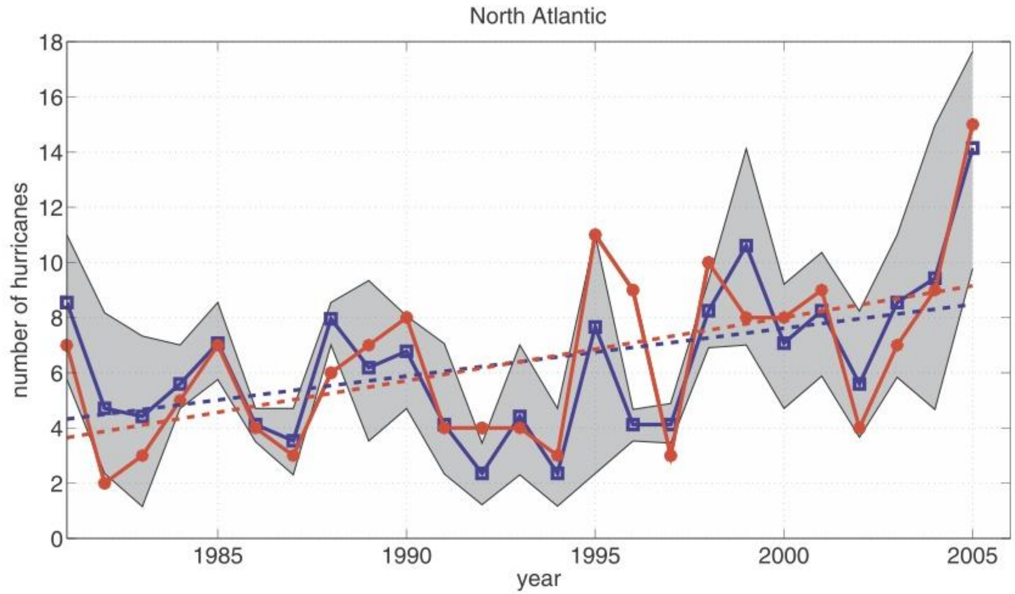

FIG. 7. Interannual variation of hurricane numbers for North Atlantic from 1981 to 2005. IBTrACS observations (Kruk et al. 2010) (red) and four-member ensemble mean (blue); shaded area shows the simulated maximum and minimum number for each year from the four-member integrations. Model time series are normalized by time-independent multiplicative factors so as to reproduce the observed total number. Dotted lines show observed and model (ensemble mean) linear trends.

Models

CAM-5
Zhang-Macfarlane deep convection, Park-Bretherton shallow convection and moist PBL, FV-latlon dycore. Resolution shown here 0.23x0.31

GEOS-5
Relaxed Arakawa-Schubert deep convection with stochastic Tokioka limits on plume entrainment, Lock et al. PBL, FV-cubed sphere. Resolutions shown here ~28,14,7 km

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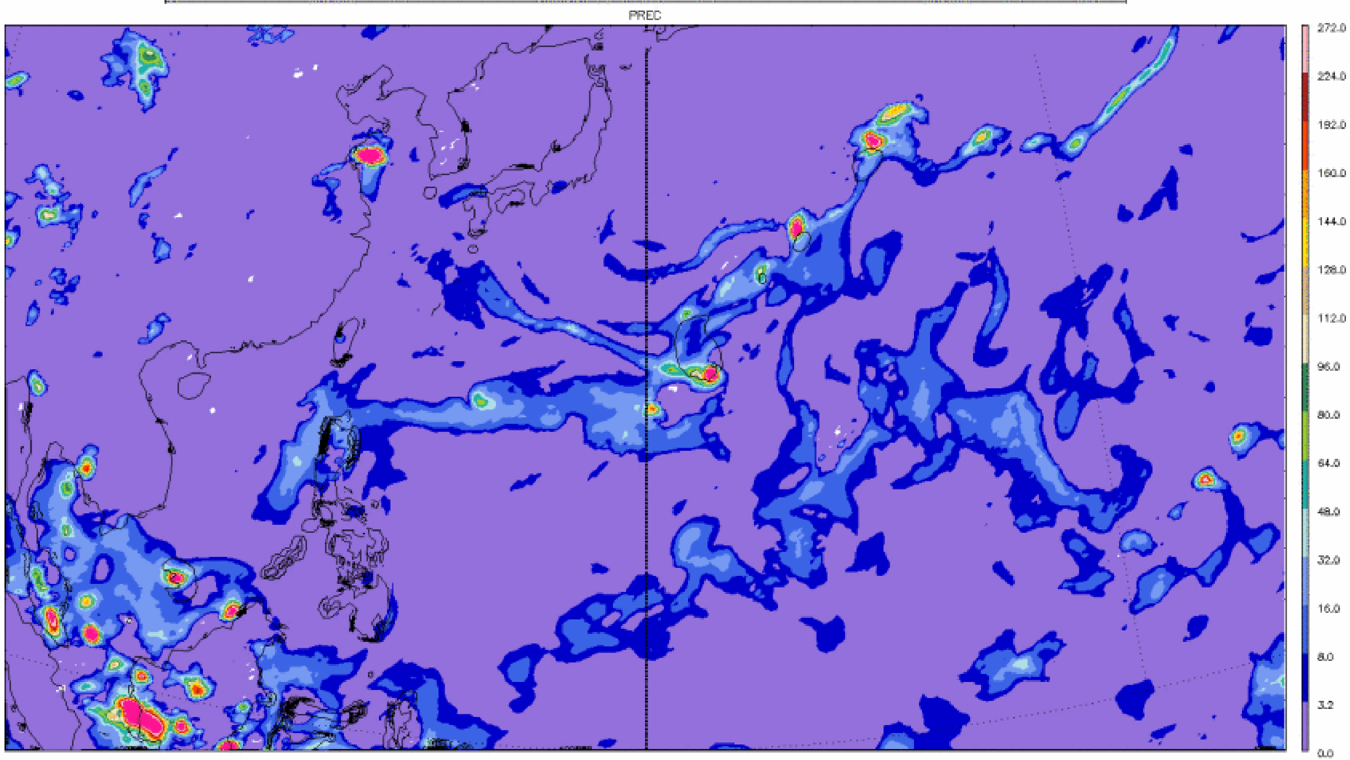

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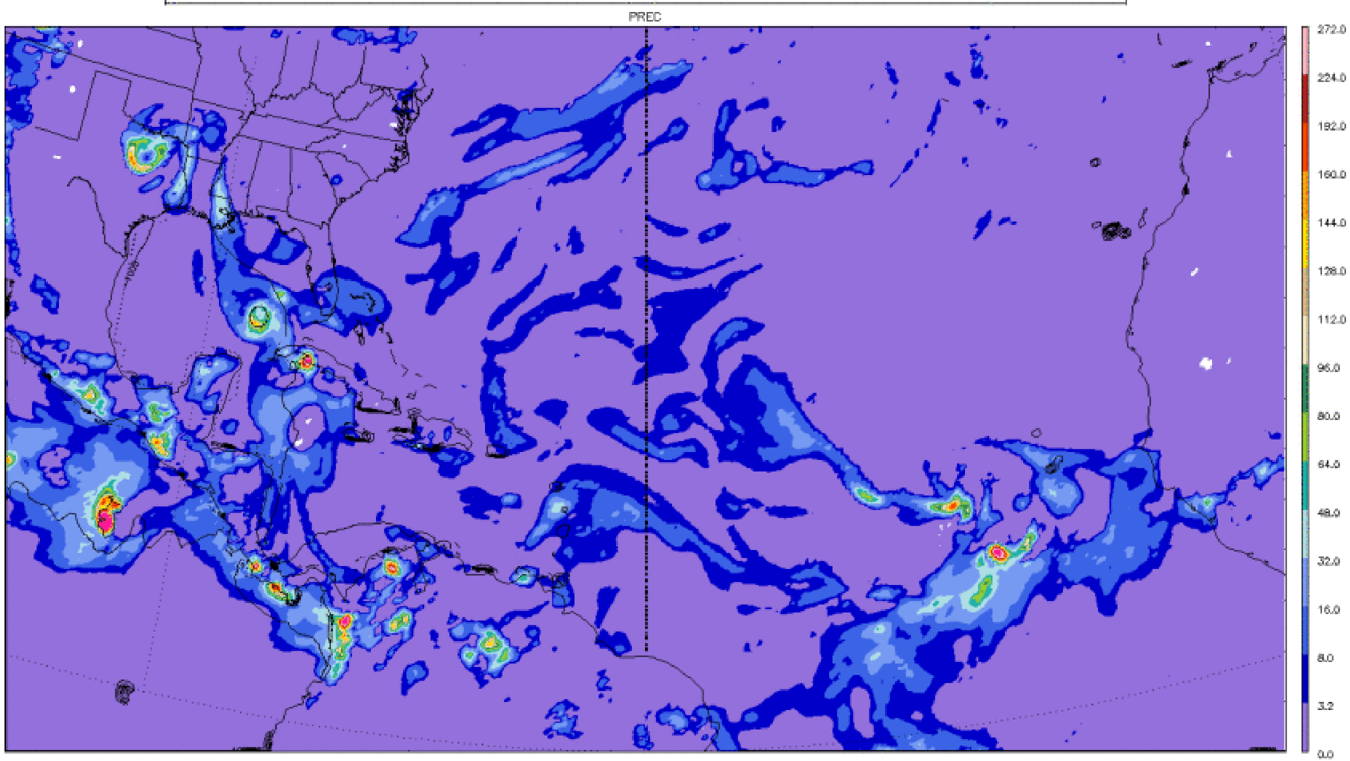


TC Numbers and Tracks

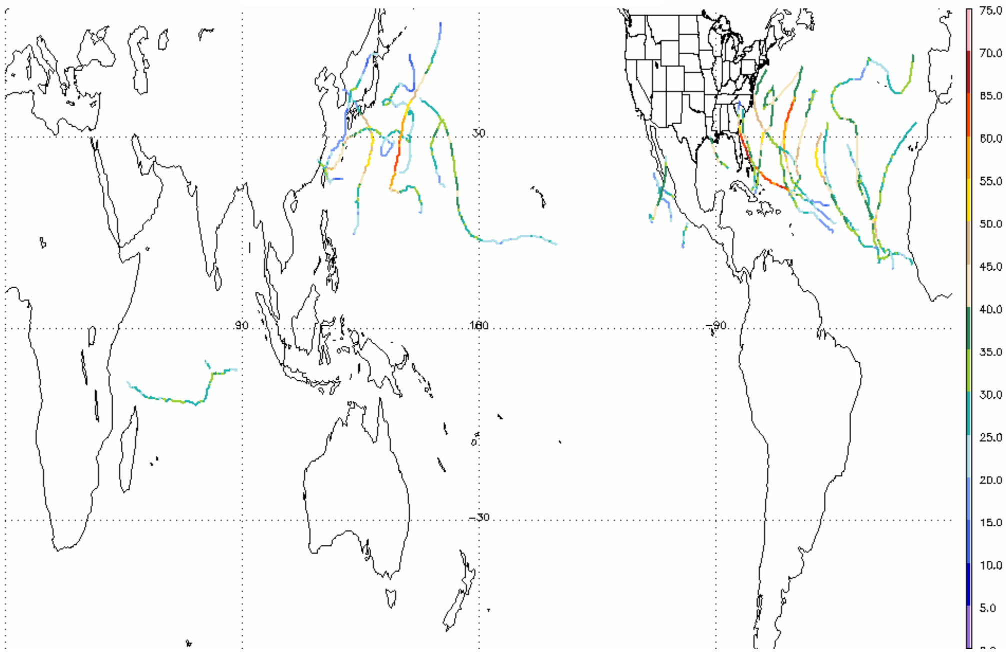
Based on short runs CAM5 and GEOS5 roughly capture correct numbers of storms and distinction between active (2005) and and quiet (2006) Atlantic seasons.

Distribution of tracks seems shifted to the east.

Storms with U>33 ms^{-1}: June 1 to Nov 1 2005

200

Std CAM5 #1



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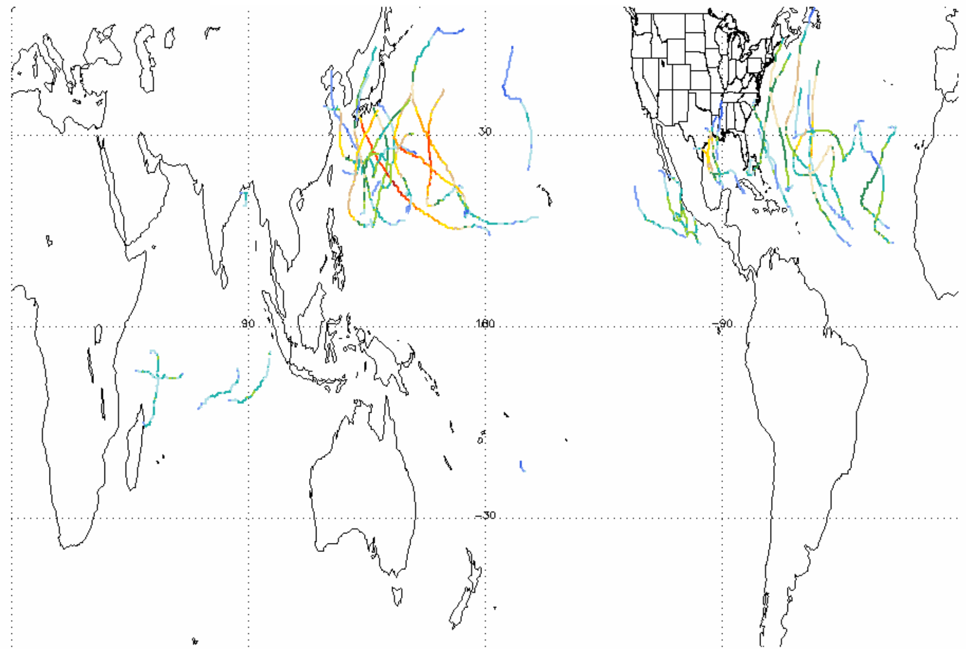

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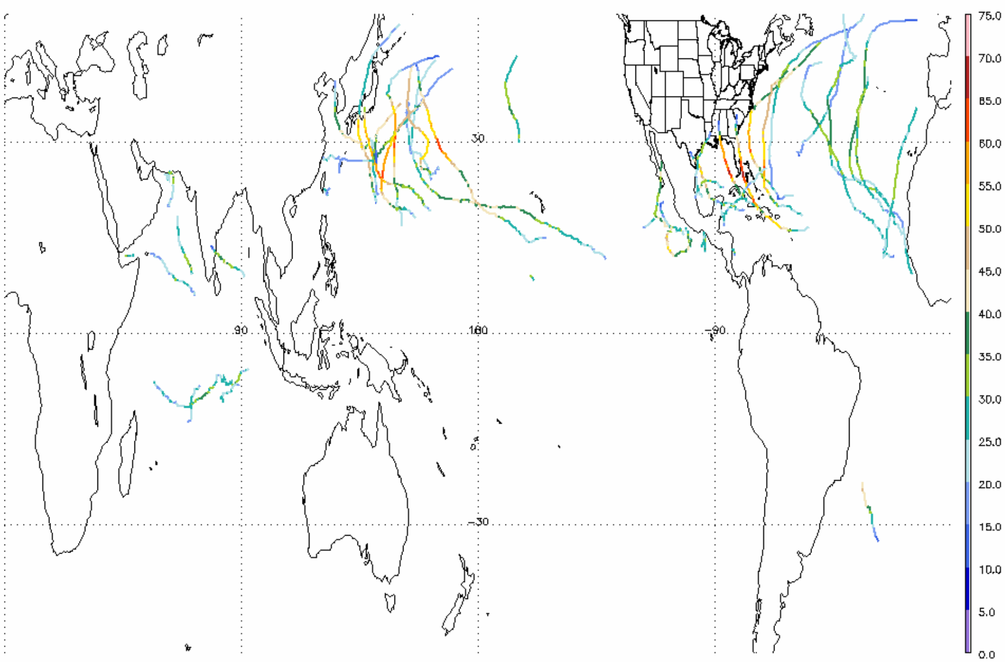
Std CAM5 #3



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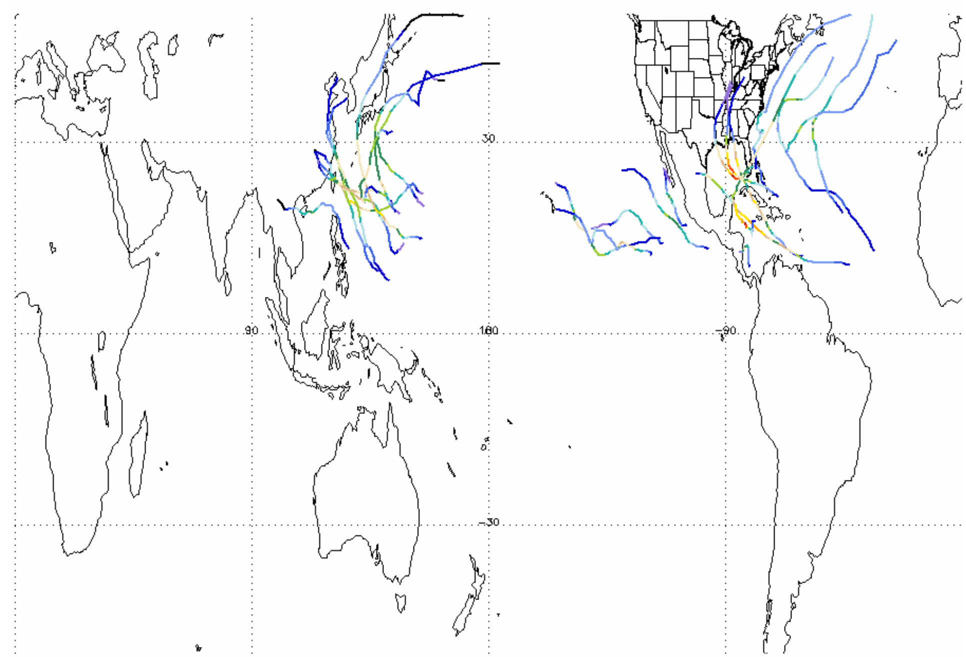
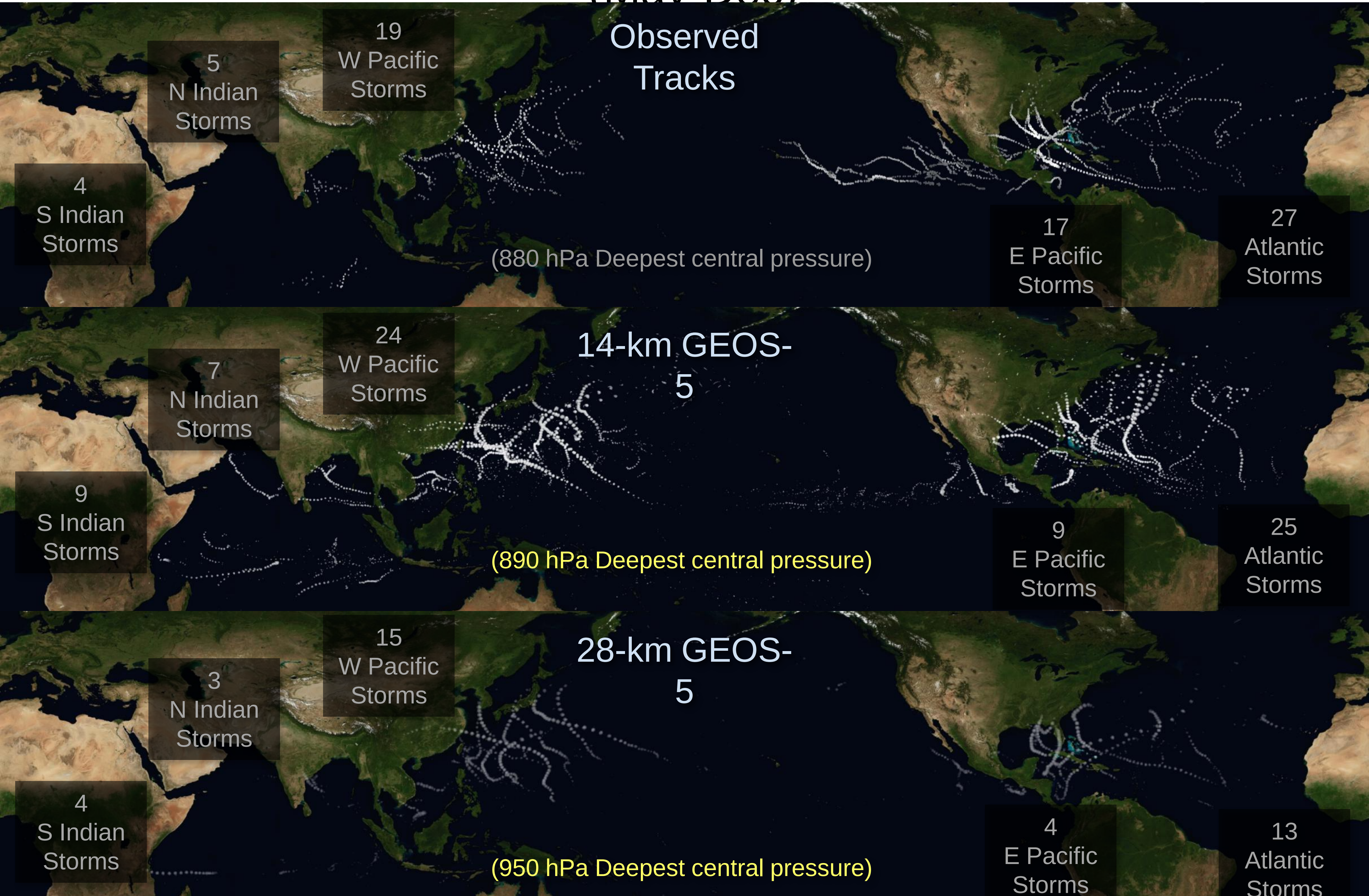
IBTraCS

d>33m/s

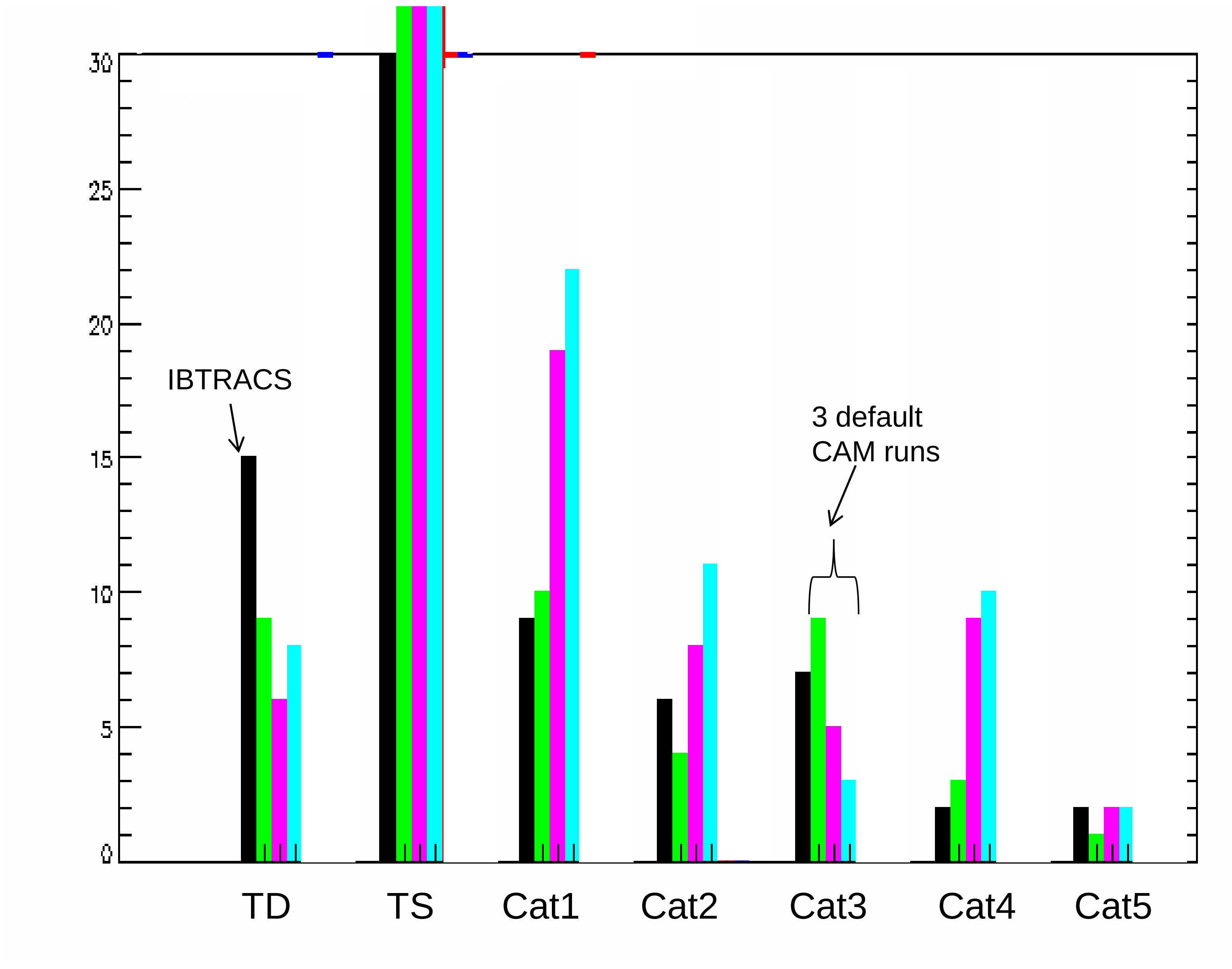


Global Tropical Cyclone Tracks 2005

(May-Dec)



Number of Storms in CAM *(June-Nov 2005)*

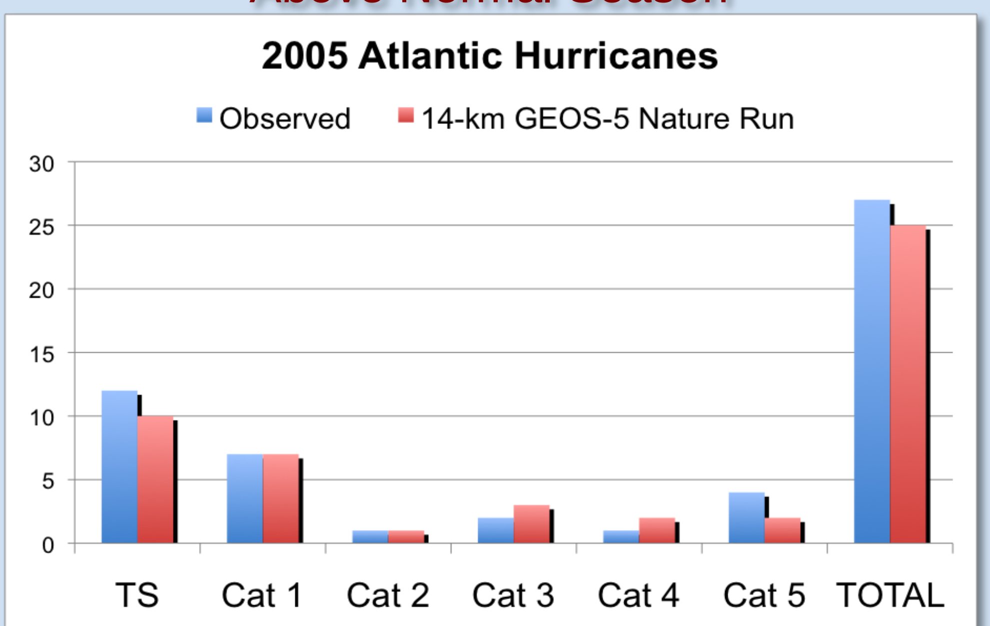


Tropical Cyclones 2005-2006 (May-Dec)

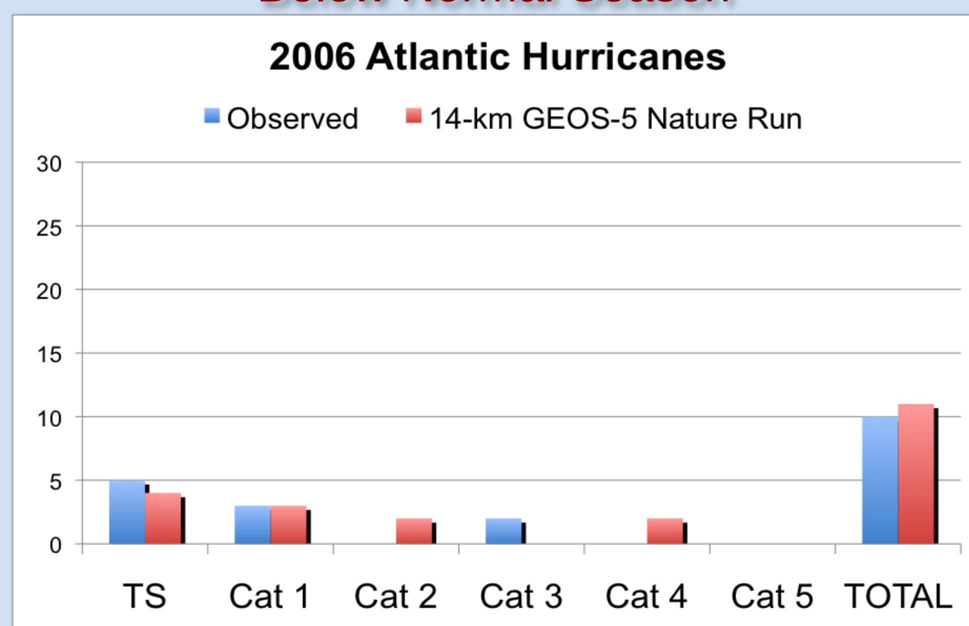
Atlantic Basin Intensities

- GEOS-5 captures the natural variability of tropical cyclone formation
  - In terms of intensity as well as number of storms
- GEOS-5 at high resolution (14-km) shows a capability to develop the most intense tropical cyclones
  - 7 Major Hurricanes (category 3, 4, or 5) in 2005 [7 observed]
  - 2 Major Hurricanes (category 3, 4, or 5) in 2006 [2 observed]

Above Normal Season



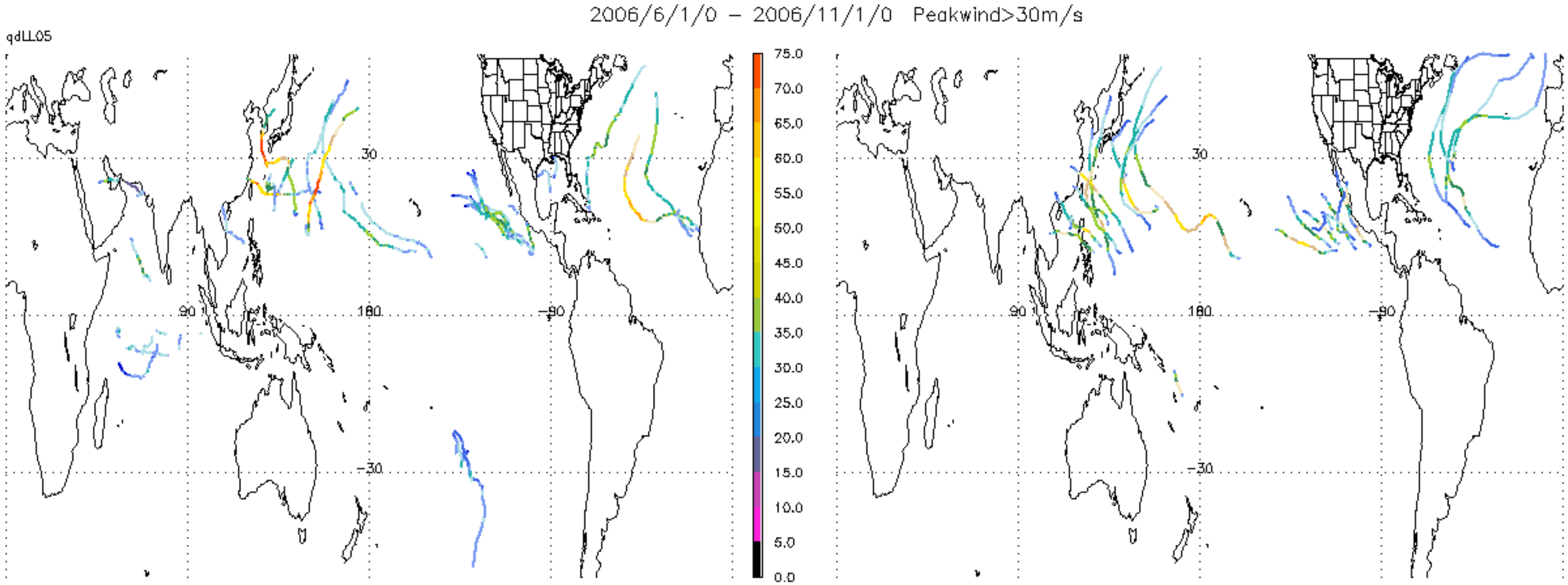
Below Normal Season



2006 Season June-November

CAM5

Obs. (IBTRACS)



CAM also captures weak Atlantic season – somewhat stronger E. Pacific in 2006 season

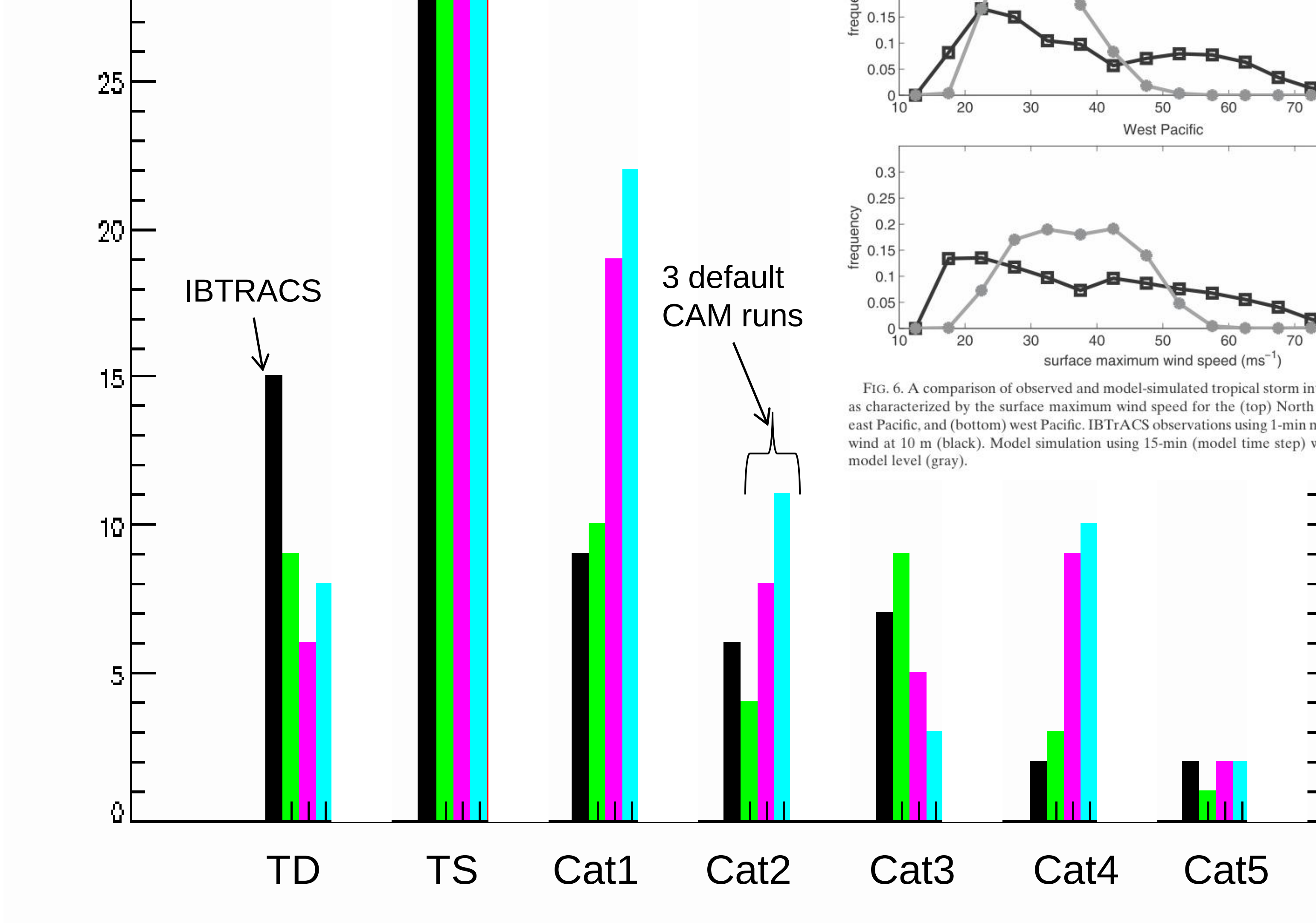
TC Intensities

Intensity is more difficult to capture

Depends on "slowly" varying BCs like SST, and on noisier atmospheric quantities, e.g., shear, dry plumes …

Models tend to produce storms that are more similar to each other than they are in nature (Zhao et al 2009)

Number of Storms in C/



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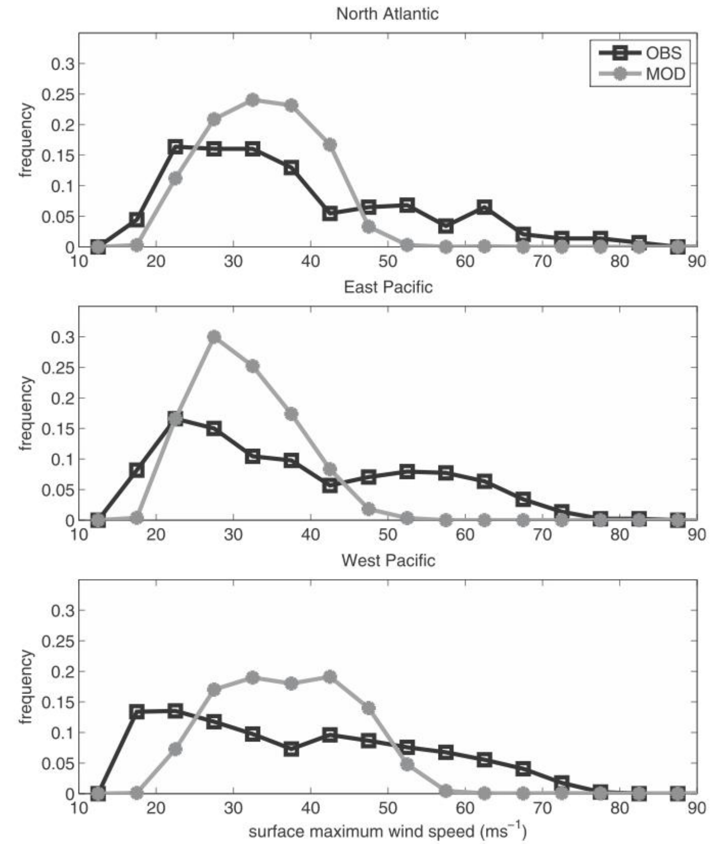
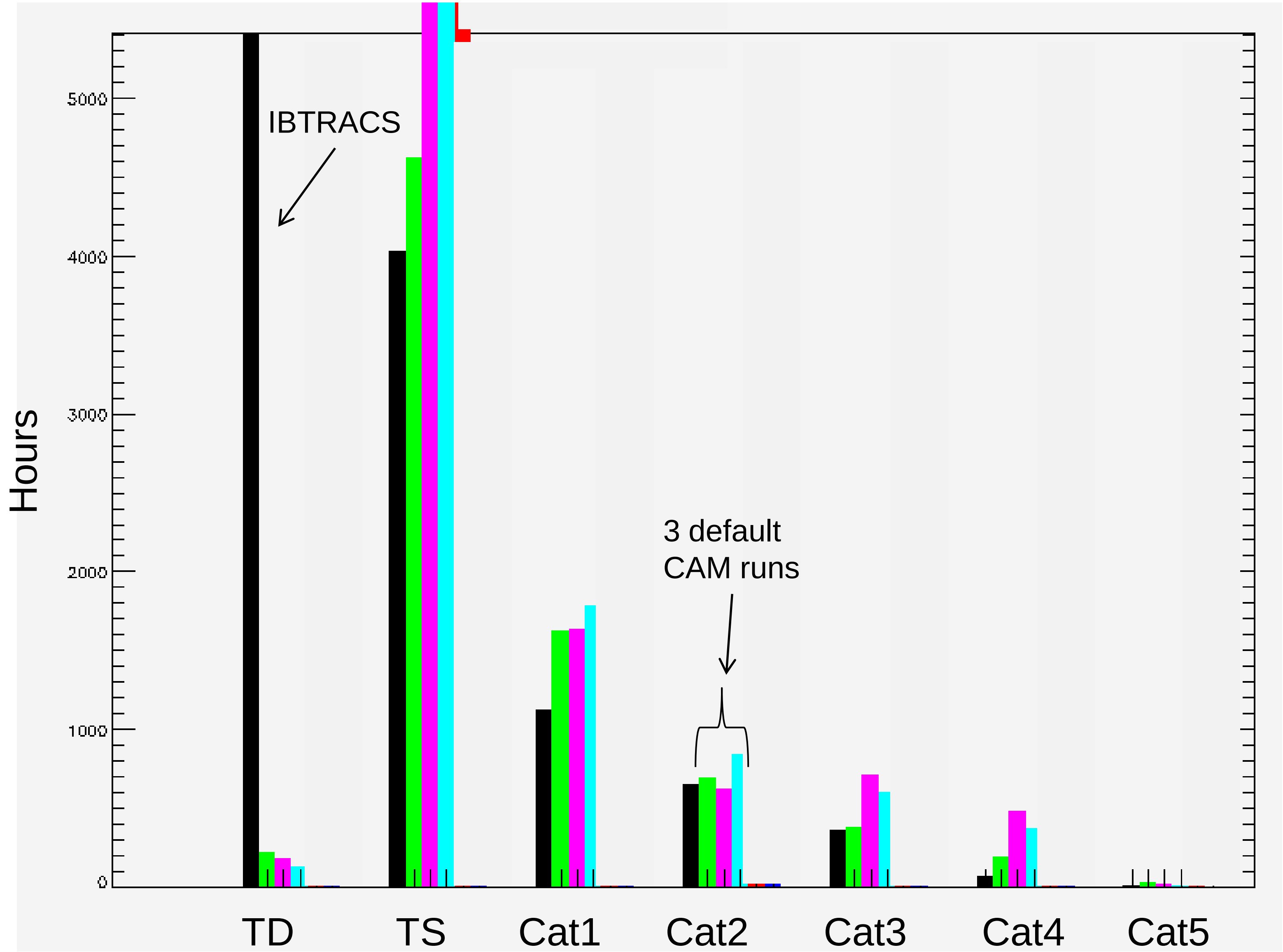
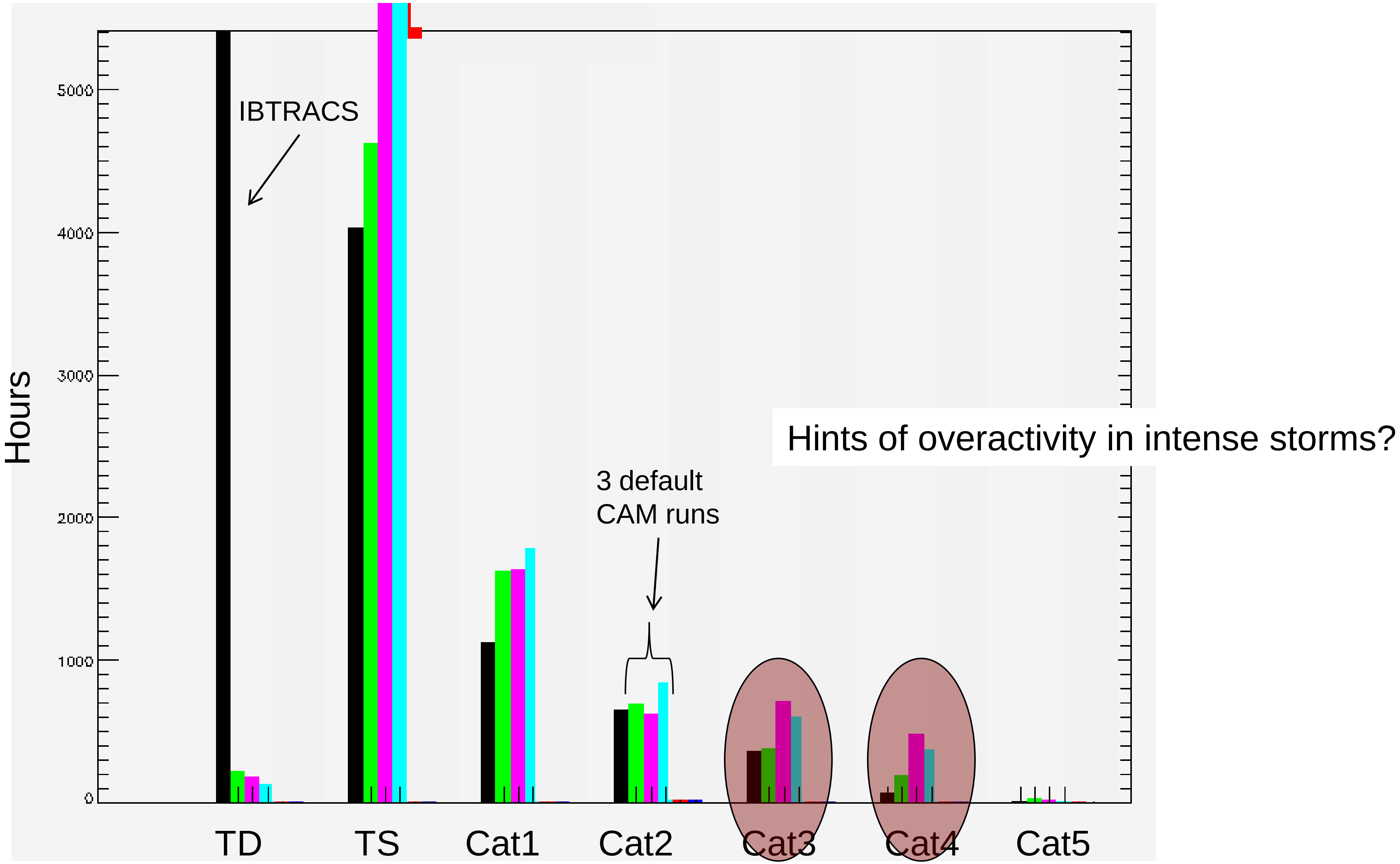


FIG. 6. A comparison of observed and model-simulated tropical storm intensity distribution as characterized by the surface maximum wind speed for the (top) North Atlantic, (middle) east Pacific, and (bottom) west Pacific. IBTrACS observations using 1-min maximum sustained wind at 10 m (black). Model simulation using 15-min (model time step) winds at the lowest model level (gray).

Time (hours) spent at Category (June-Nov 2005)



Time (hours) spent at Category (June-Nov 2005)



Maximum Intensity from Emanuel 1992 …

THE THEORY OF HURRICANES

Kerry A. Emanuel

$$T_s \Delta s_{max} = RT_s \ln \frac{p_a}{p_c} + \frac{L_v}{T_s}(q_c^* - q_a),$$

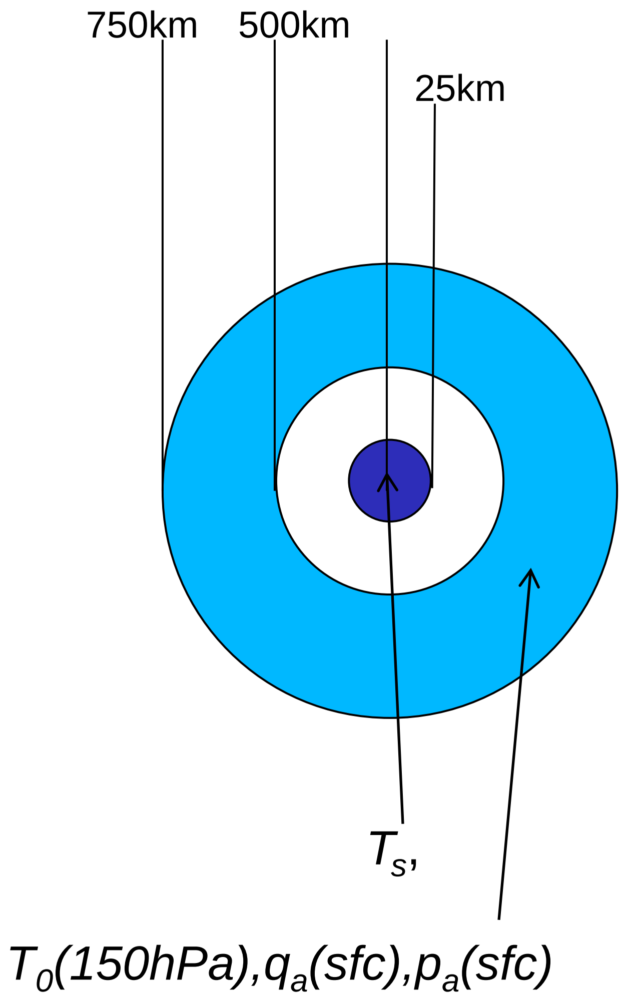
$$q_c^* = \frac{3.802\ \text{mbar}}{p_c} \exp\left[\frac{17.67 T_s}{243.5 + T_s}\right],$$

$$\varepsilon \equiv \frac{T_s - T_o}{T_s}.$$

$$\varepsilon T_s \Delta s = RT_s \ln \frac{p_a}{p_c} + \frac{1}{4} f^2 r_a^2,$$

Annual Reviews
www.annualreviews.org/aronline

Annu. Rev. Fluid Mech. 1991. 23: 179–96



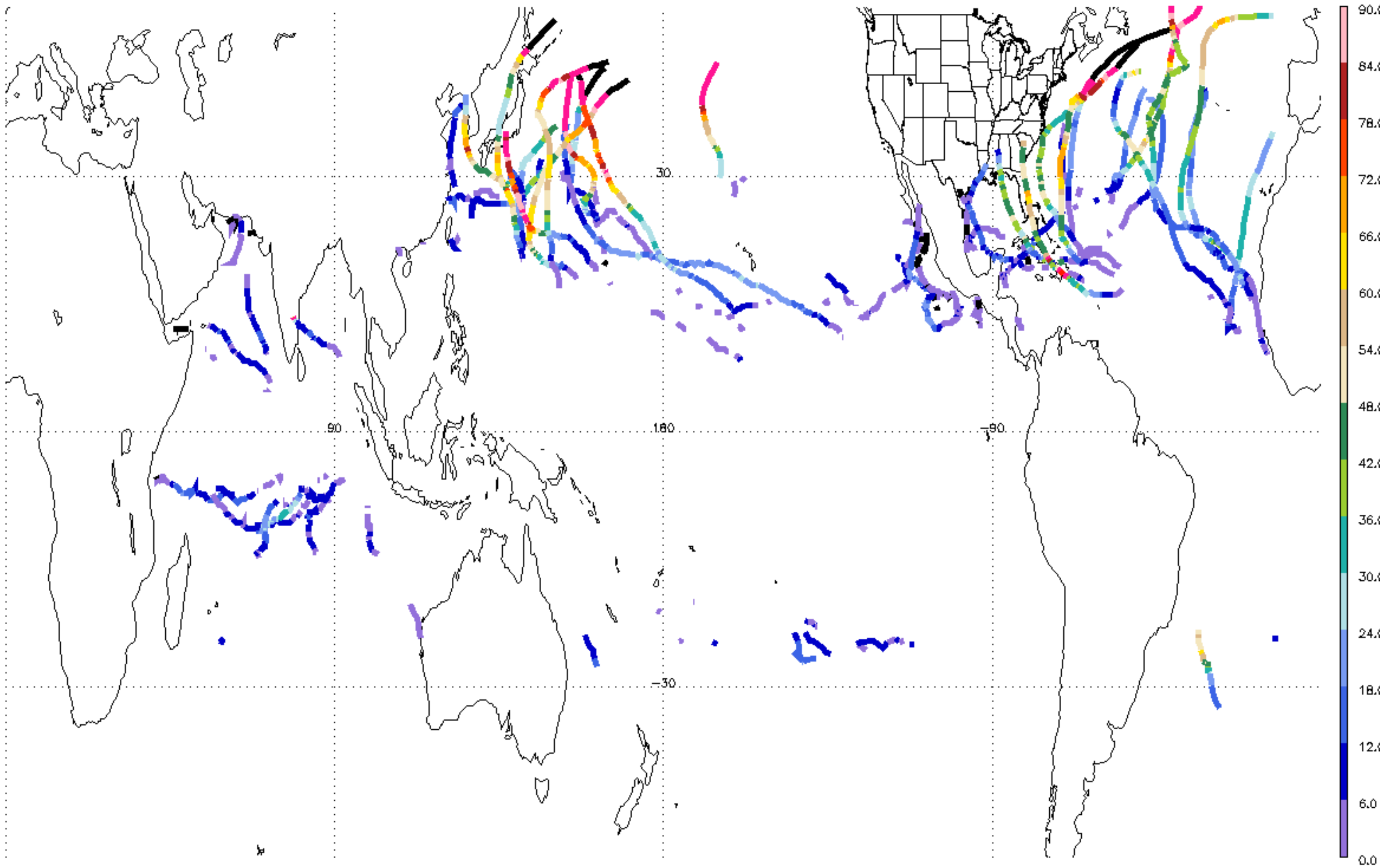
Minimum possible central pressure depends on a few parameters:

-ambient surface pressure
-ambient low-level humidity
-ambient upper-tropospheric temperature
-surface temperature in core region

Percent Maximum Potential Intensity

$$\left(\frac{p_a - p_c}{p_a - p_{\min}}\right) \times 100$$

2005/6/1/0 – 2005/10/31/23 Peakwind>20m/s



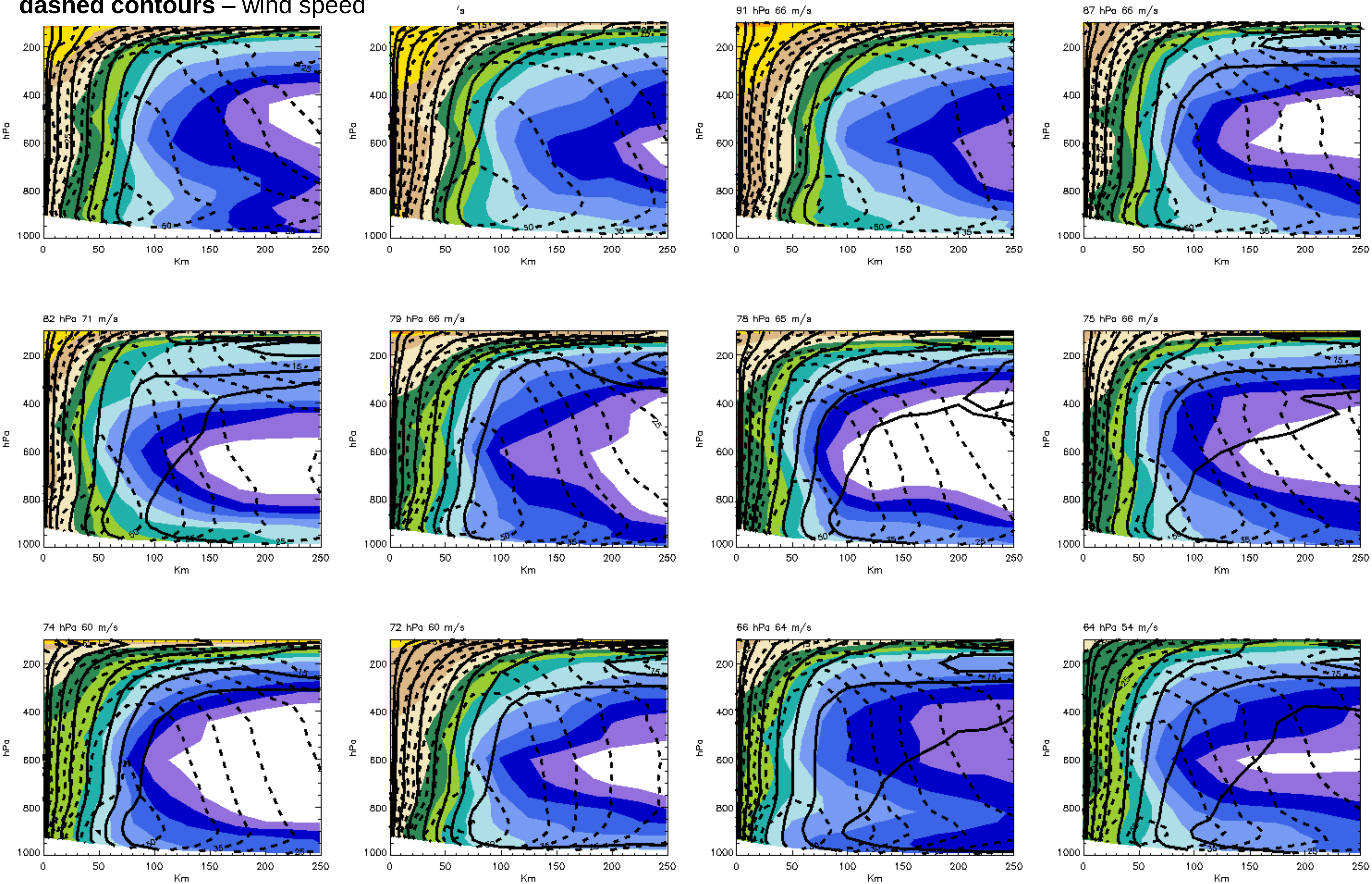
This diagnostic should be relatively straightforward to calculate from re-analysis data as well as model output

Azimuthal means of *s*, *V* and angular mom.

$$s = c_p \log(T) - R\log(p) + \frac{Lq}{T}$$ (e.g. Emanuel, 2003)

Shading - moist entropy *s;*
solid contours - angular momentum
dashed contours – wind speed

Structure at peak intensity



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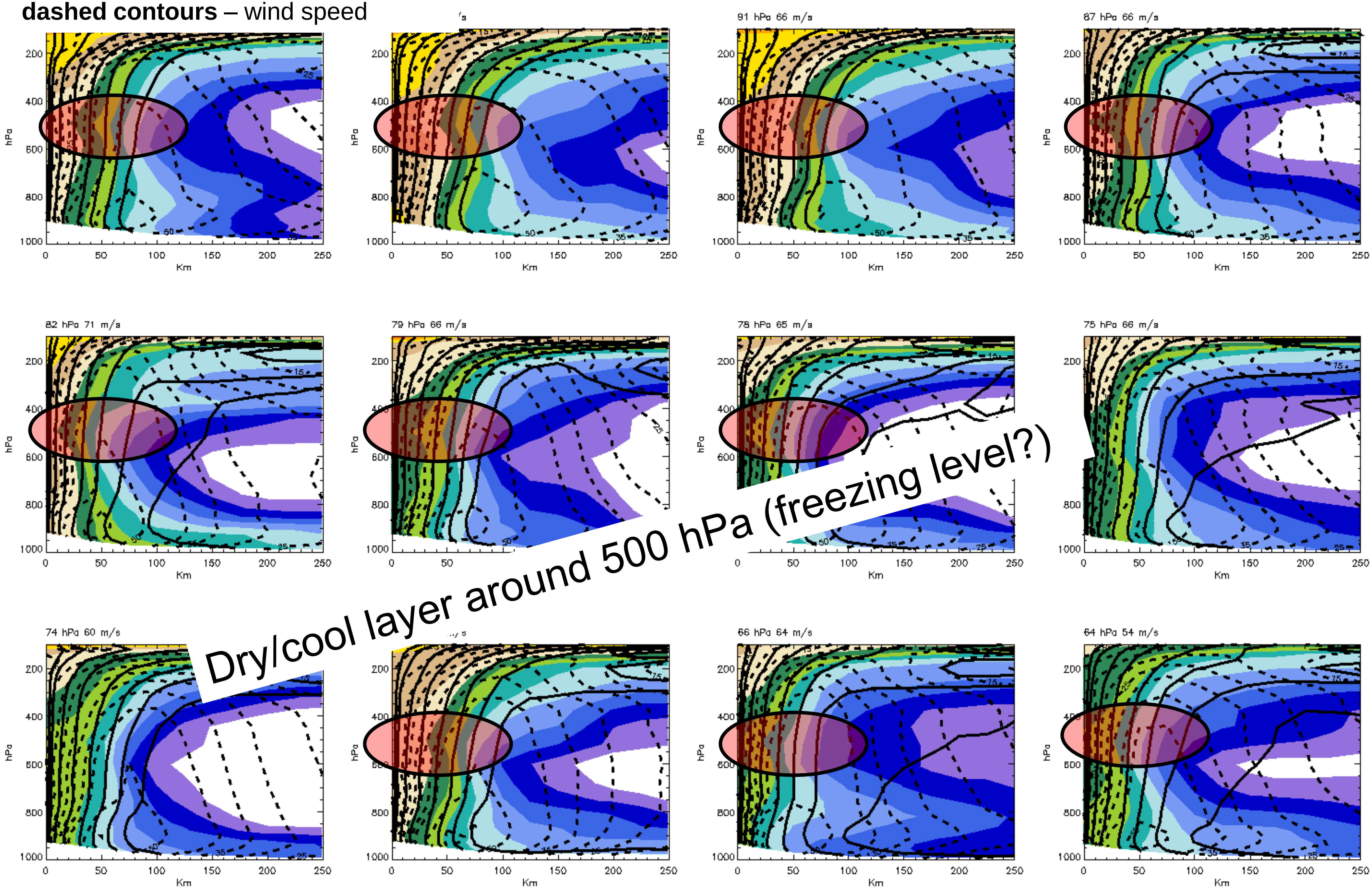
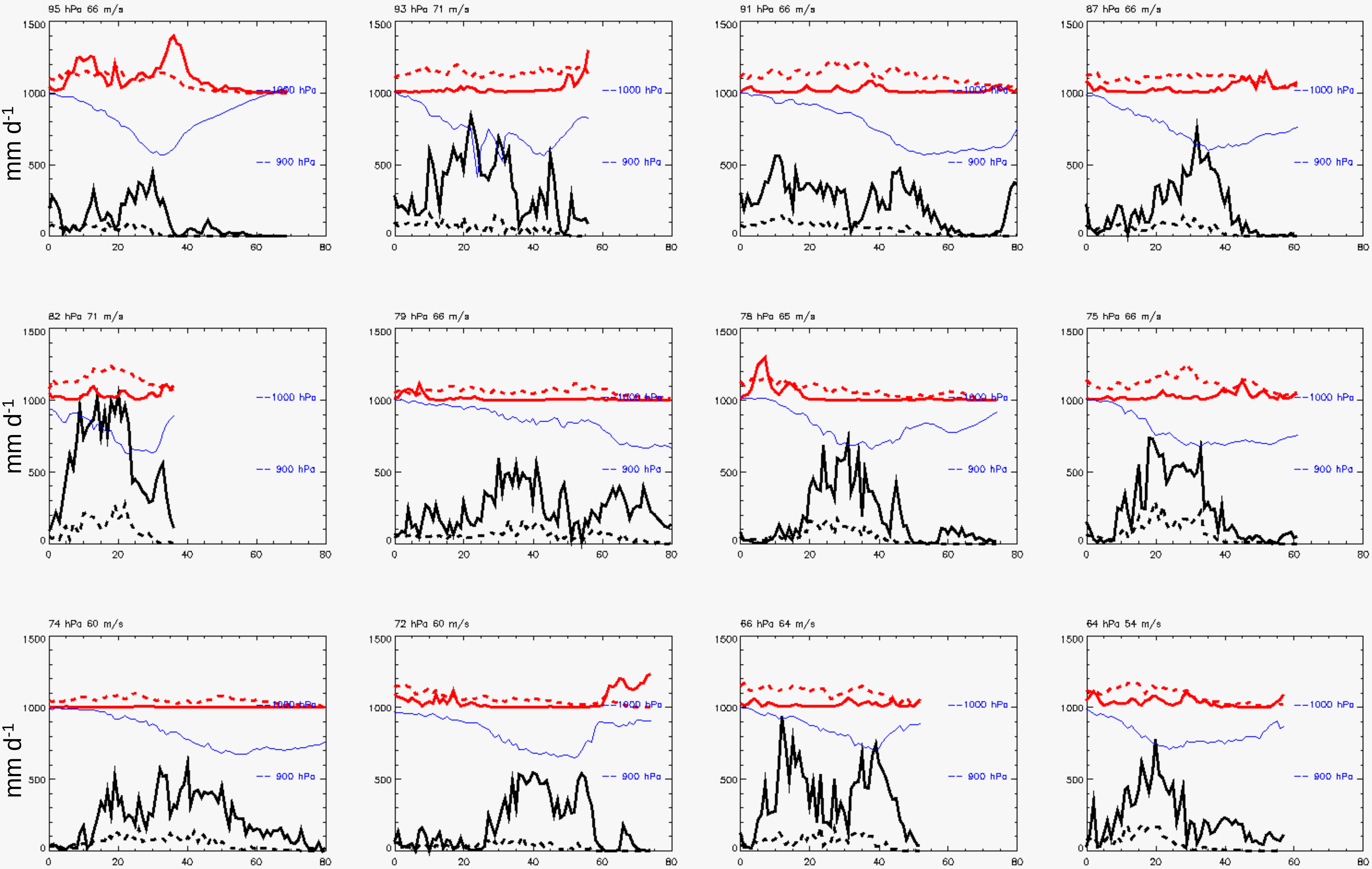


Precipitation time series in storm core (black), storm exterior 250-500km+1000 mm d^{-1} (red).
Convective precip (dashed), Large-scale precip[1] (solid).
Thin blue lines show surface pressure. **Note overwhelming dominance of LS in cores**



Sensitivity to use of Deep Convection Scheme

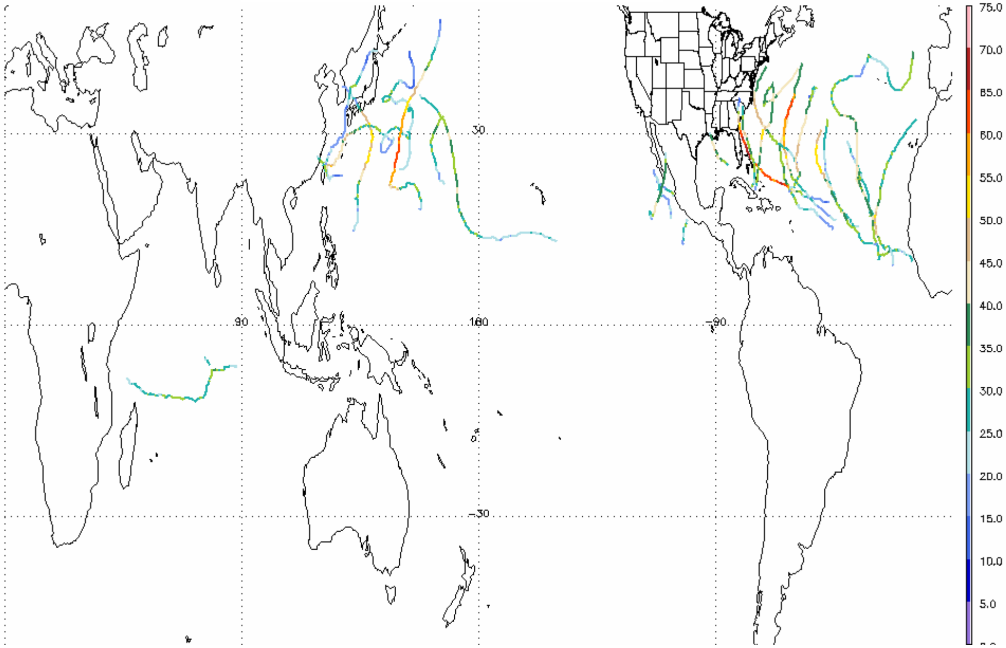
GEOS-5 attempts to hobble deep convection scheme via entrainment limits. GFDL eliminates deep scheme (with tuned shallow scheme). CAM5 precip in TC cores dominated by large-scale.

What happens if deep scheme is removed from CAM?

Storms with U>33 ms^{-1}: June 1 to Nov 1 2005

200

Std CAM5 #1



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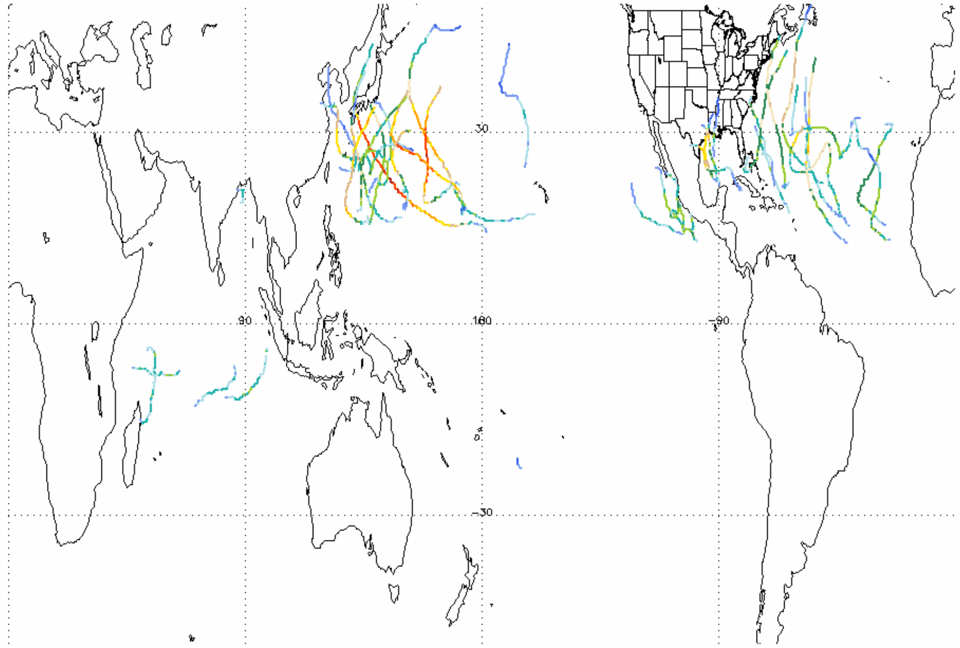

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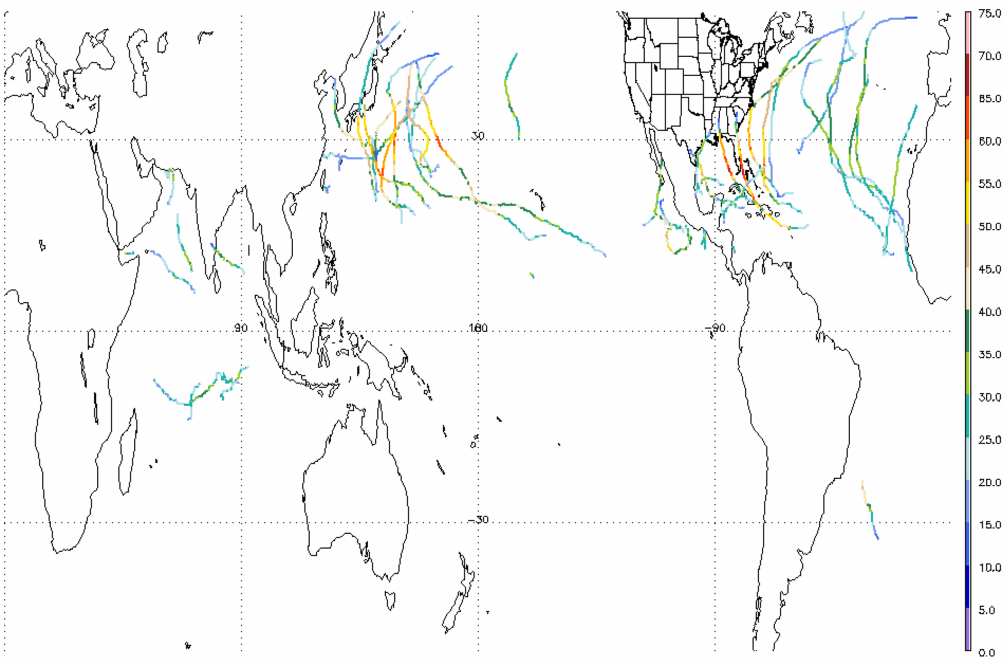
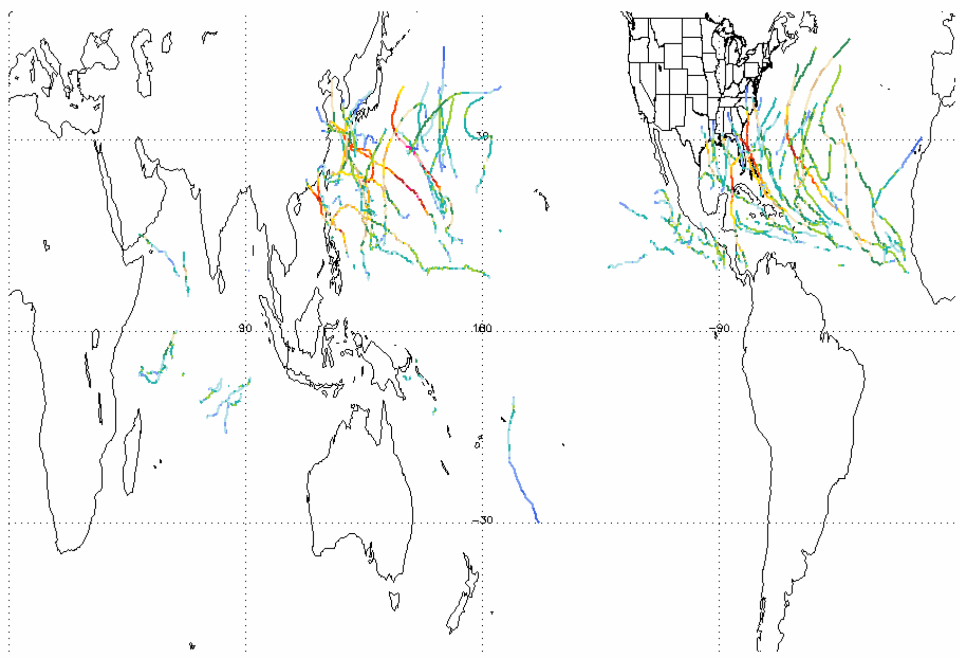
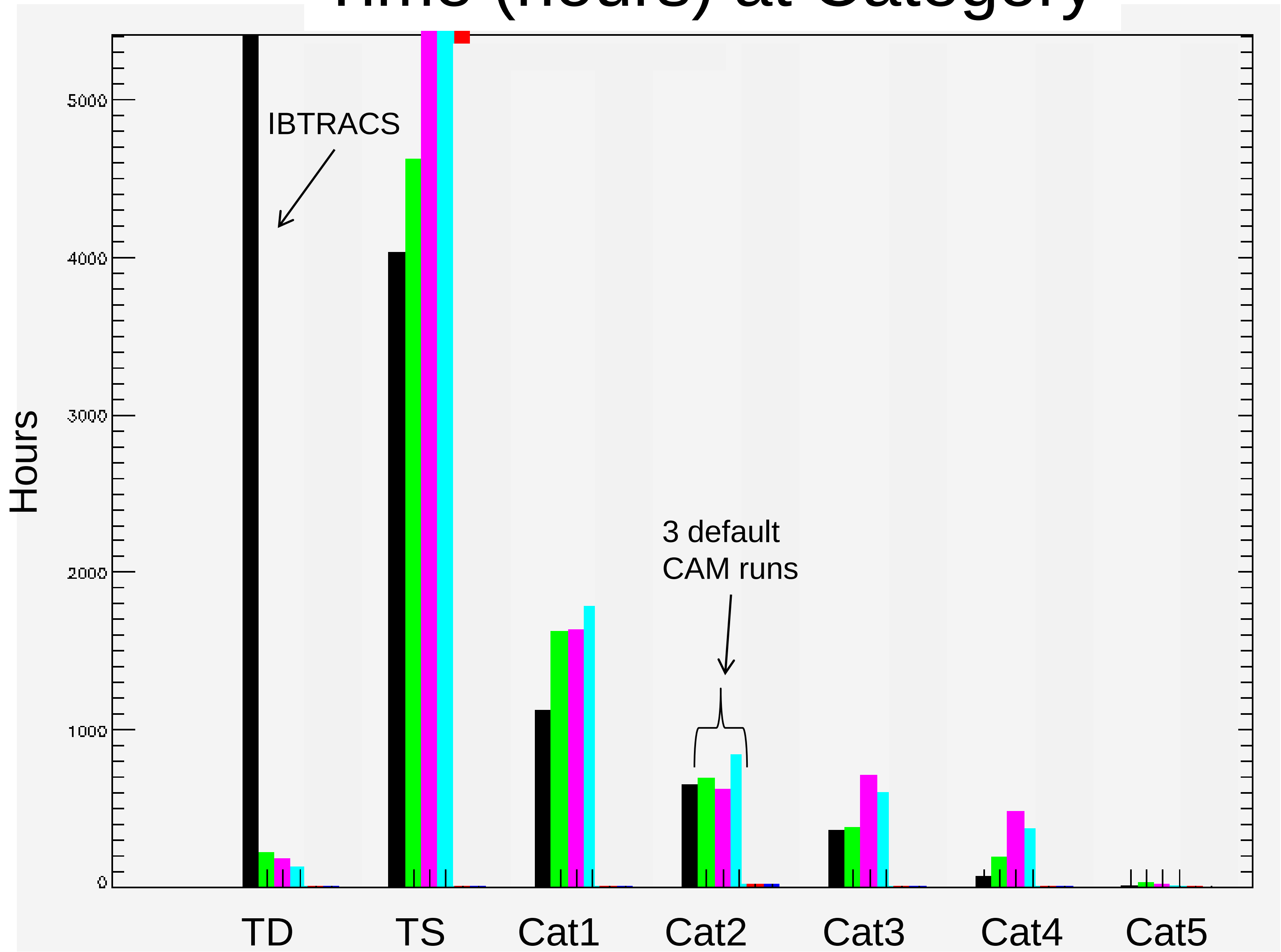


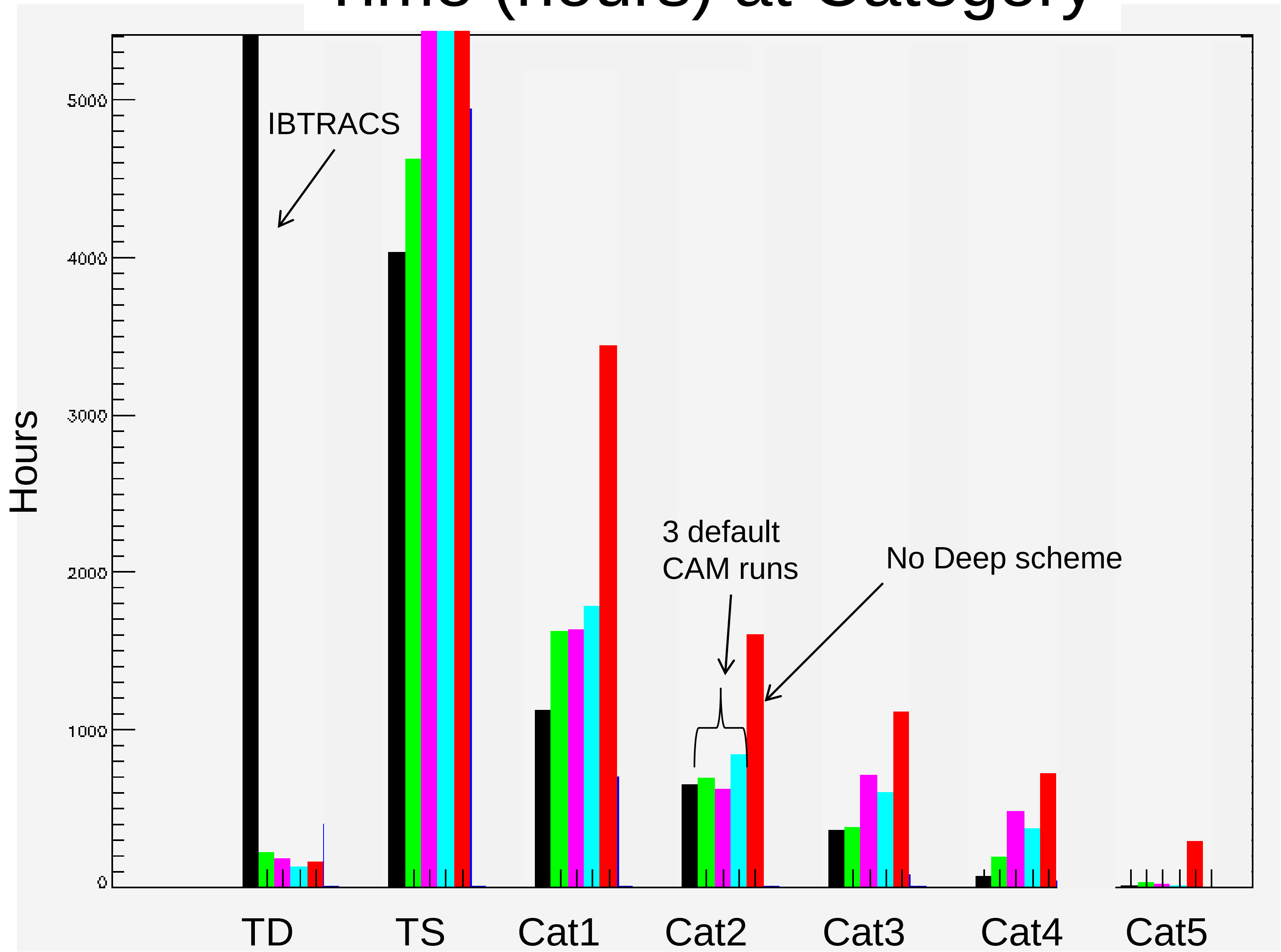
No Deep Convection Scheme



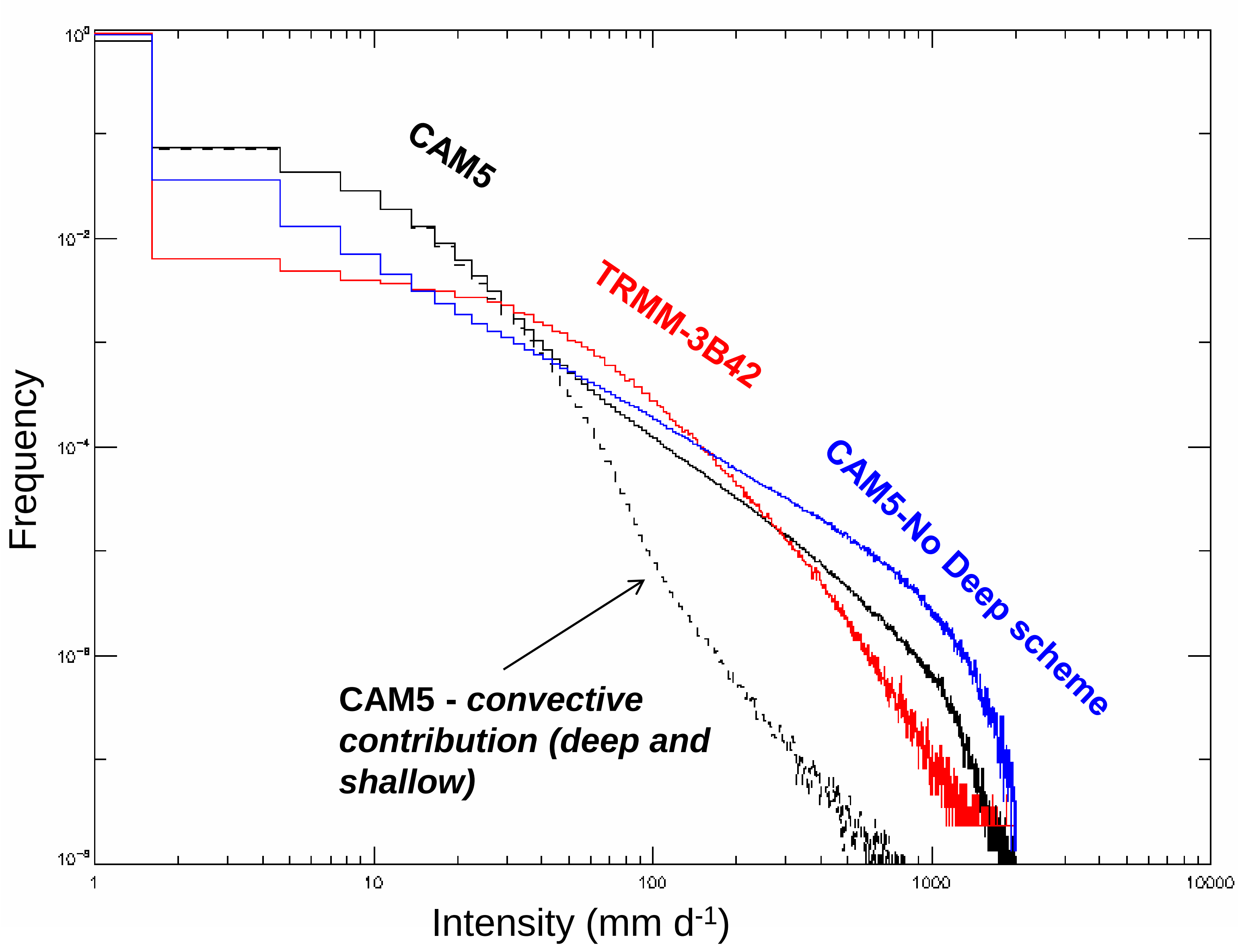
Time (hours) at Category



Time (hours) at Category



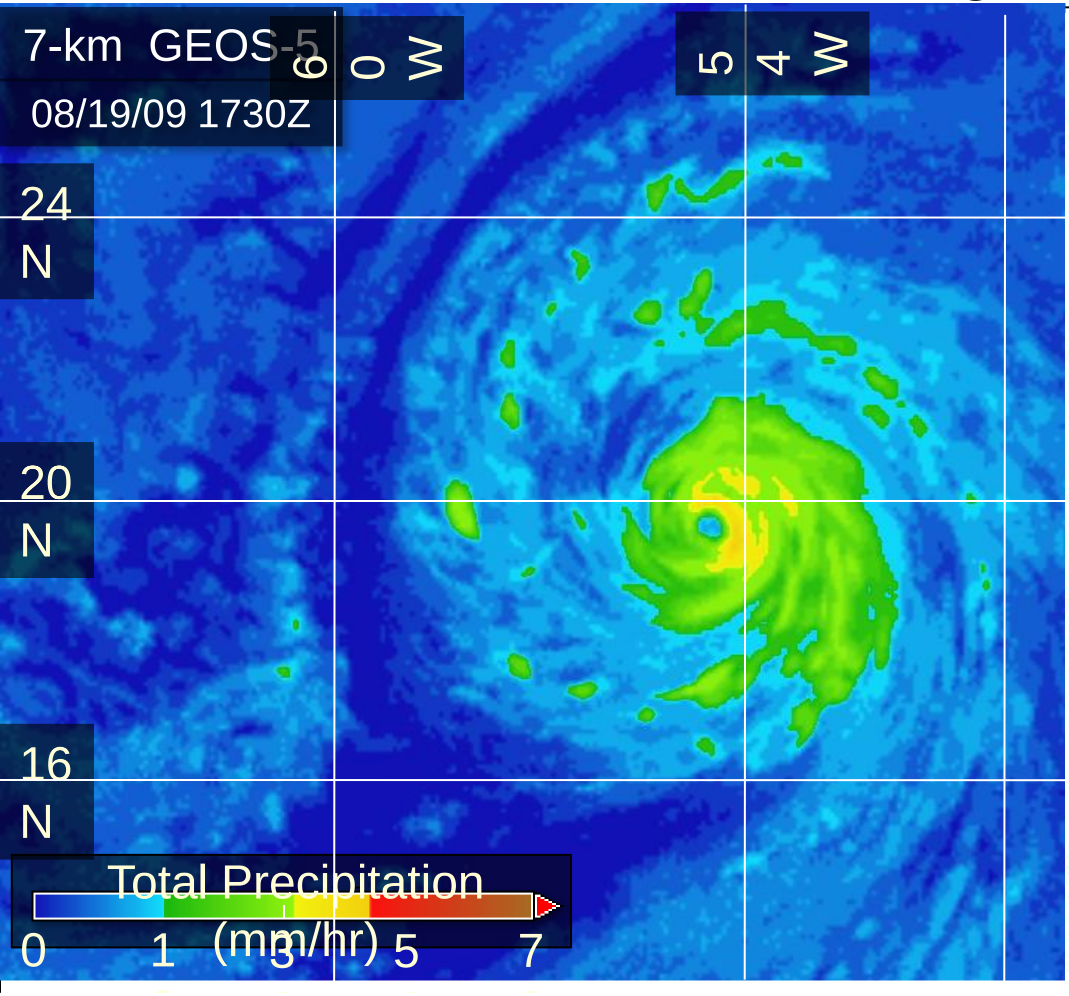
PDFs of tropical precipitation (30S-30N) rates Aug 2005

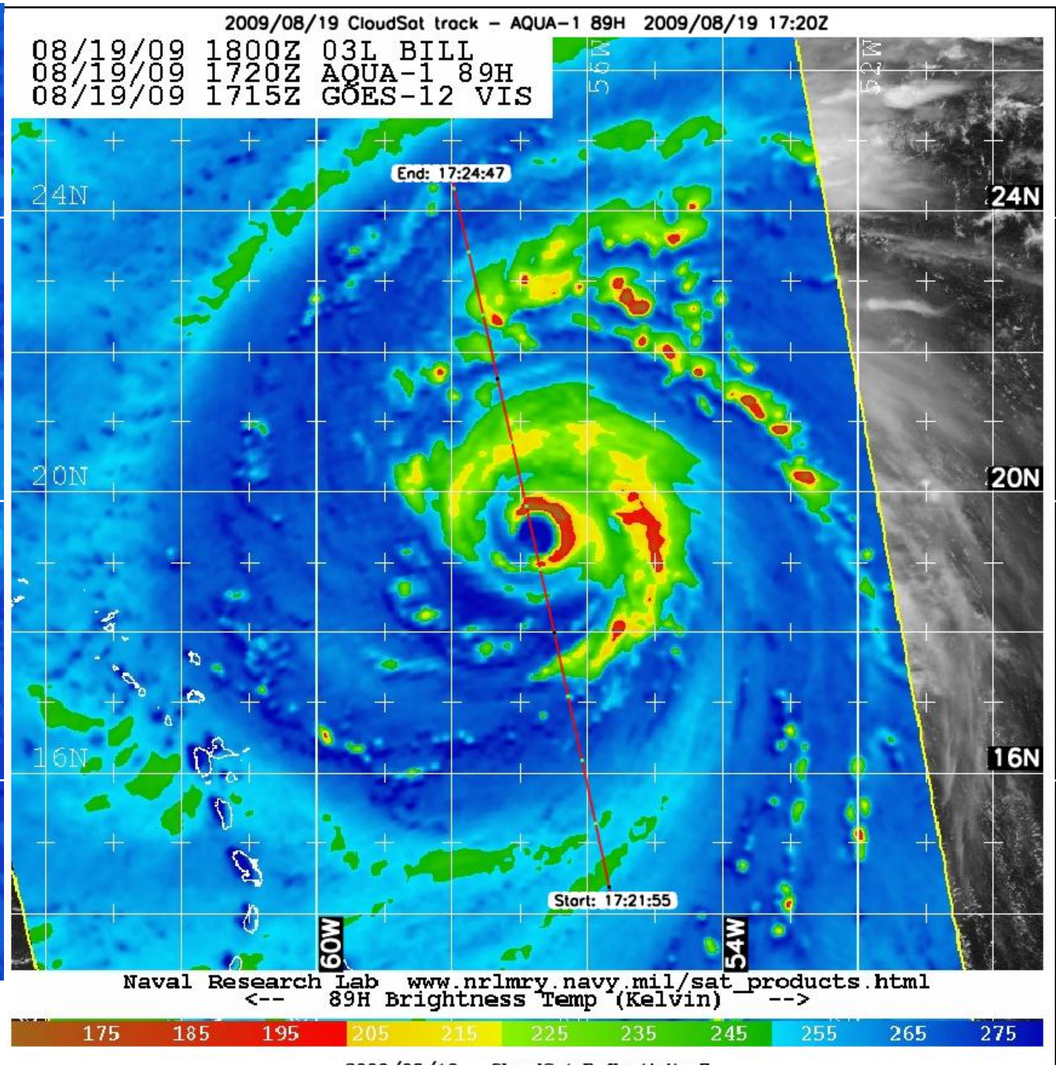


Hurricane Bill

August 2009

69-hr forecast Initialized 2009-08-16 21z





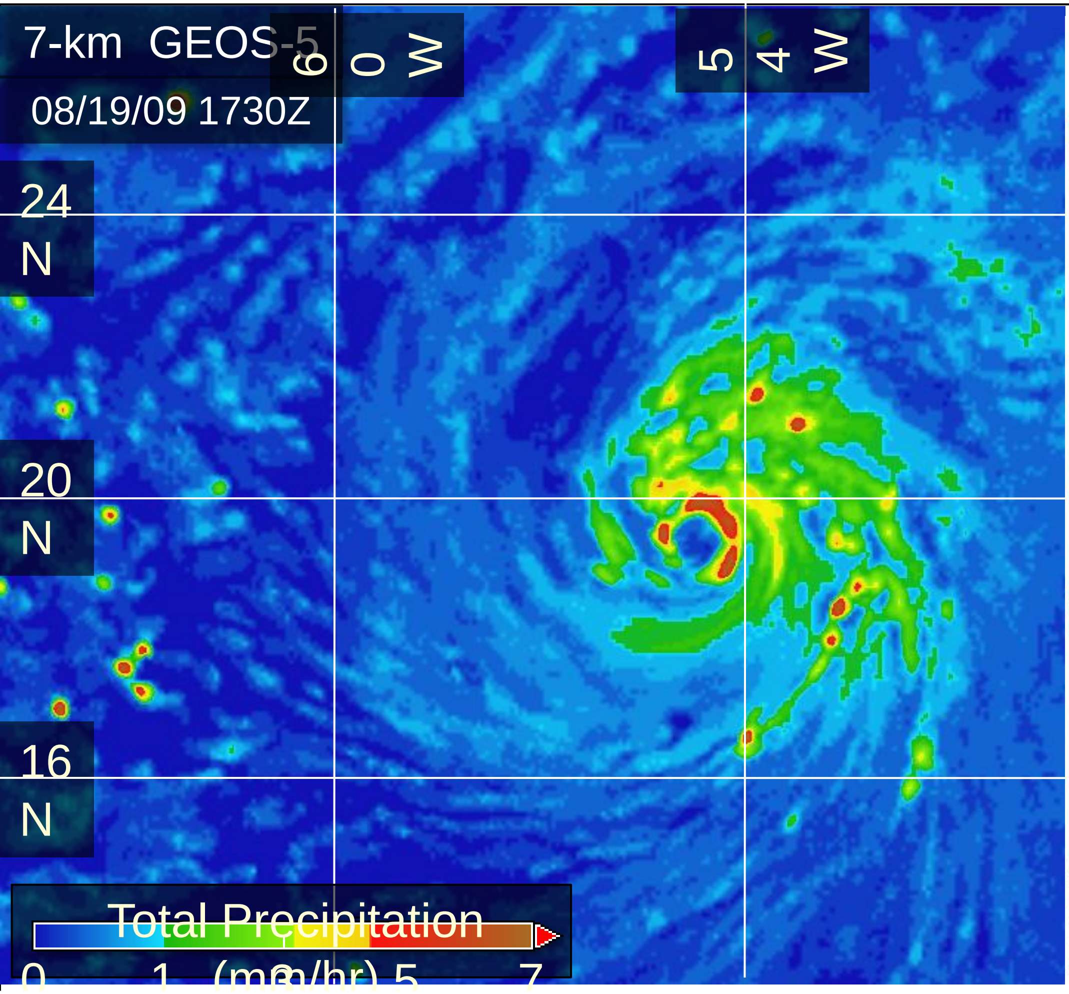
The strong influence of RAS, and a 15 minute time-step for the moist physics leads to problems within the circulation of Hurricane Bill at 7-km resolution:

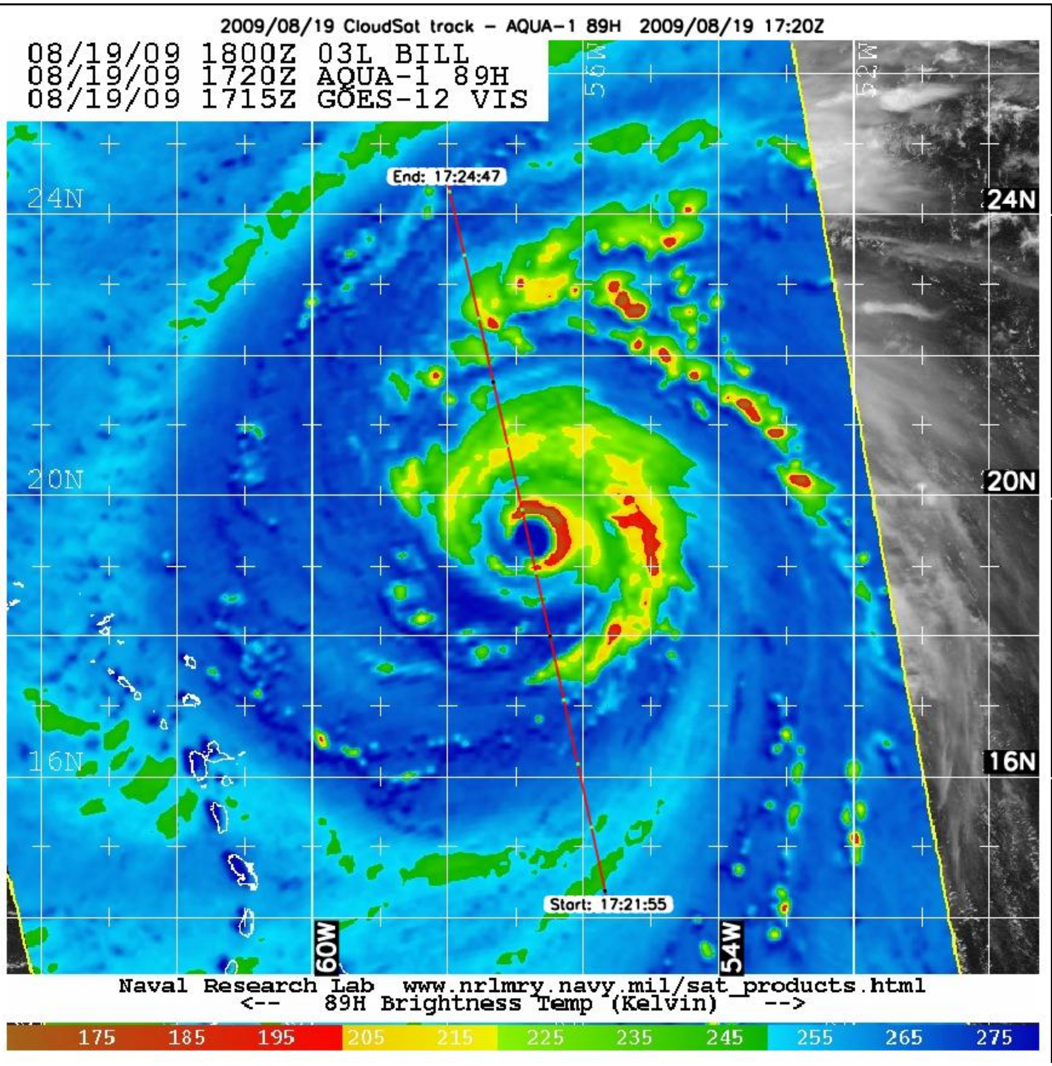
- a lack of deep convective (heavy) precipitation
- an excess of shallow precipitation
- a very small eye, filled with drizzle

Hurricane Bill

August 2009

69-hr forecast Initialized
2009-08-16 21z





Using Tokioka limiter to reduce RAS, and a 120 second time-step for the moist physics improves the convection within Hurricane Bill:

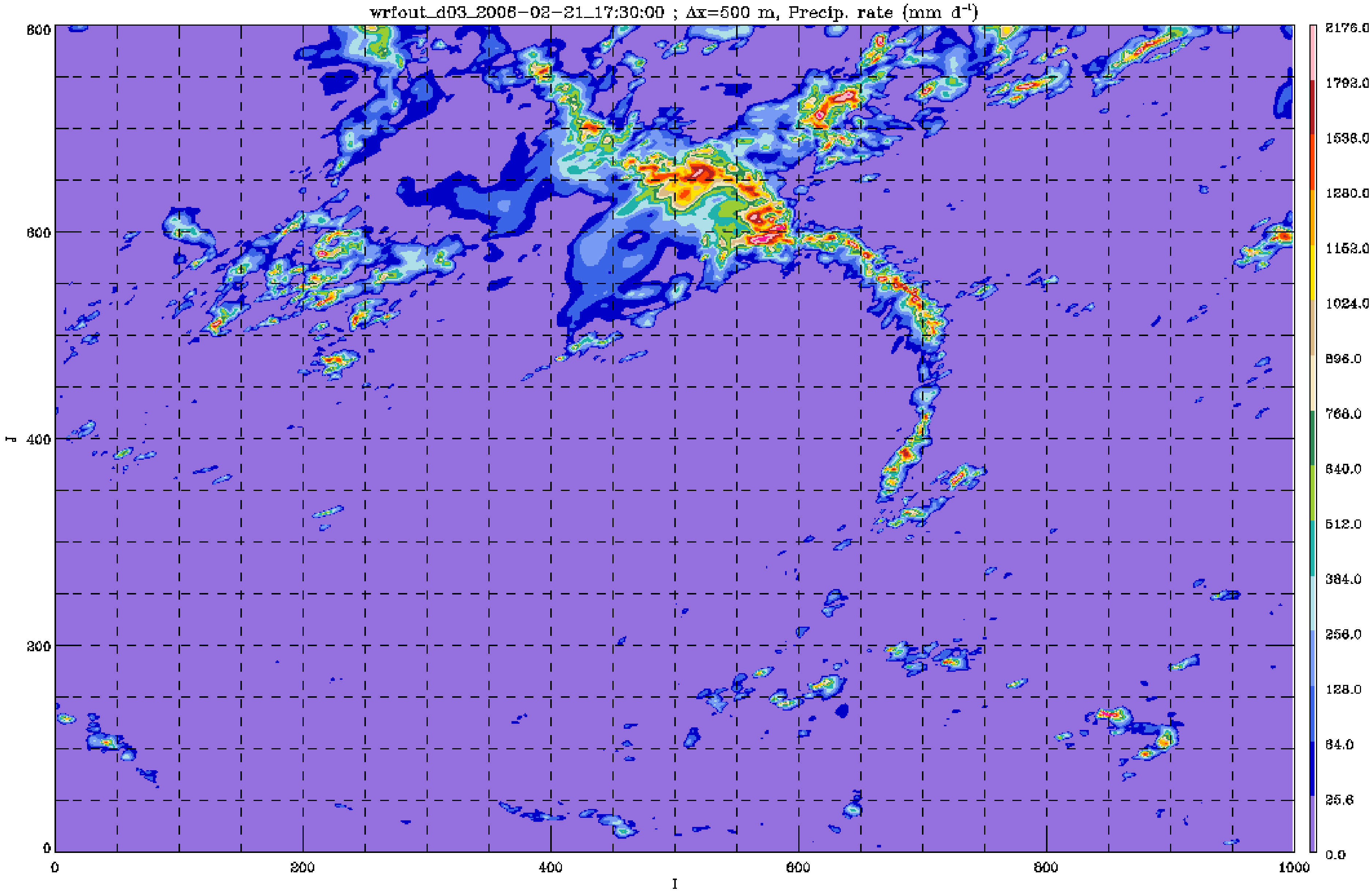
- deep convective precipitation within the eye wall
- Banded structure with embedded convection
- Realistic eye diameter, clear of precipitation

Effects of Condensate Loading

Assessed using 0.5x0.5 km non-hydrostatic WRF simulation

Tropical ocean convective case (TOGA domain Feb 2006)

15-min average precipitation rate (*Hong and Lim 2006 microphysics*)



Dashed lines show 50x50 gp (25km x 25km) squares used to coarse grain WRF fields to produce “high-res AGCM” fields

Hydrostatic Balance w/ and w/out condensate loading

$$\pi_{hyd} = \int_{z}^{z_{top}} \frac{g}{c_p \Theta_{\{v,cond\}}} dz' + \pi_{top}$$

$$p_{hyd} = p_{00}\, \pi_{hyd}^{\;1/\kappa}$$

w/out loading:

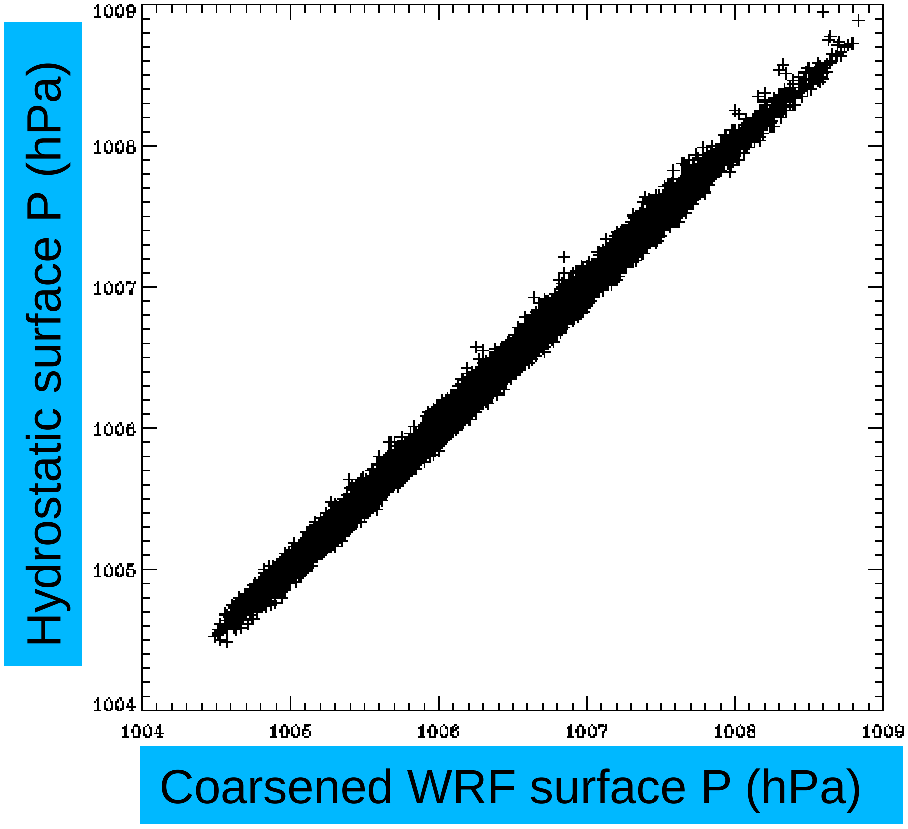
$$\Theta_v = \Theta(1. + 0.61q)$$

with loading:

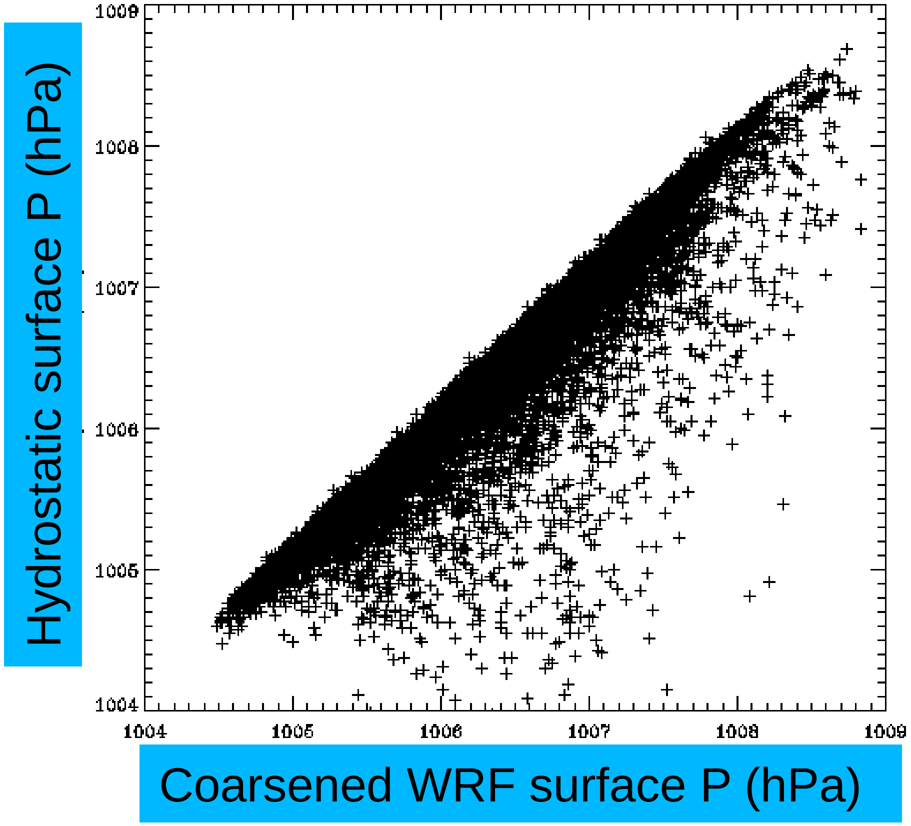
$$\Theta_{cond} = \Theta(1. + 0.61q - q_{liq} - q_{ice} - q_{rain} - q_{graup} - q_{snow})$$

Coarse-grained to (25 km)^2

with loading:



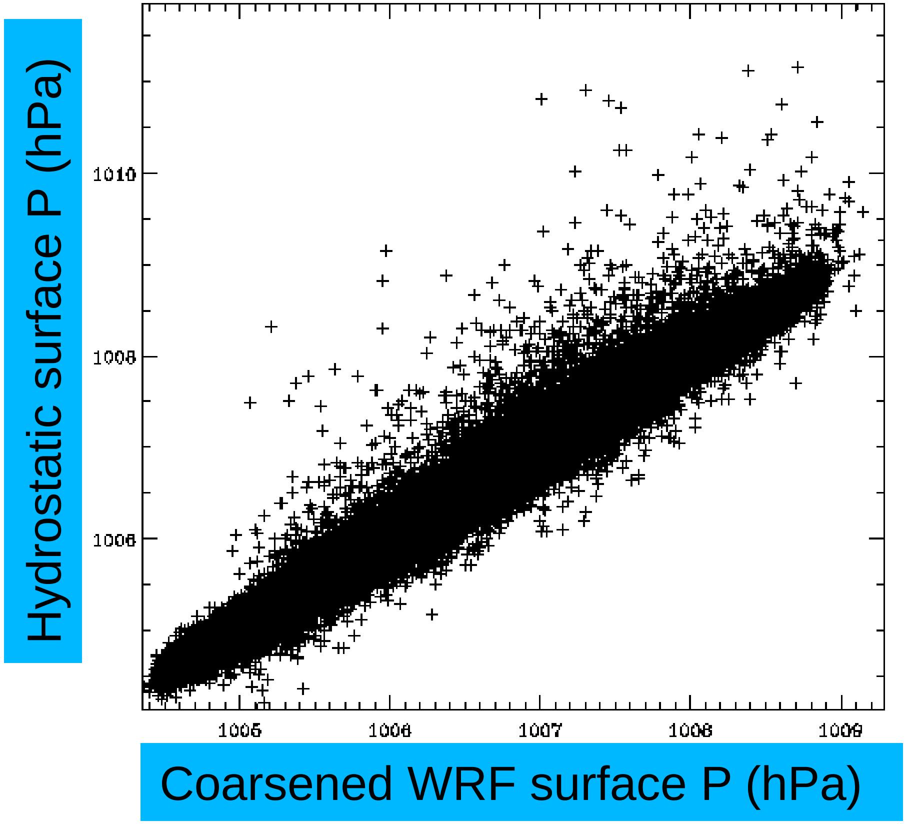
w/out loading:



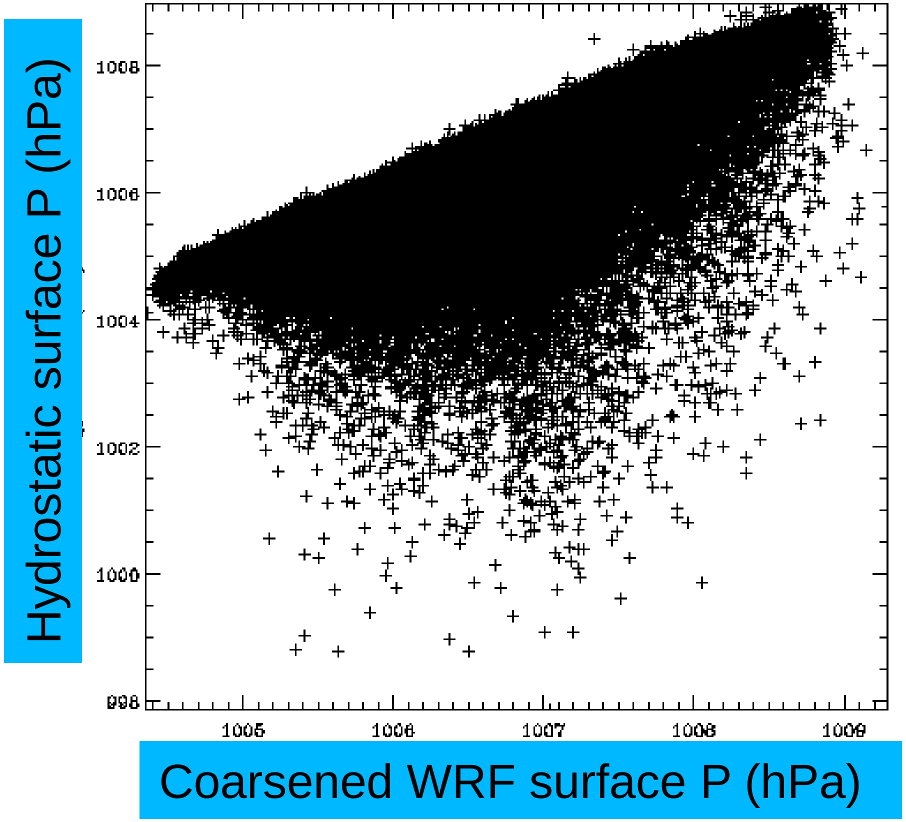
Condensate loading matters – even in (25 km)^2 grid boxes

Coarse-grained to (5 km)^2

with loading:



w/out loading:



Non-hydrostatic effects become detectable

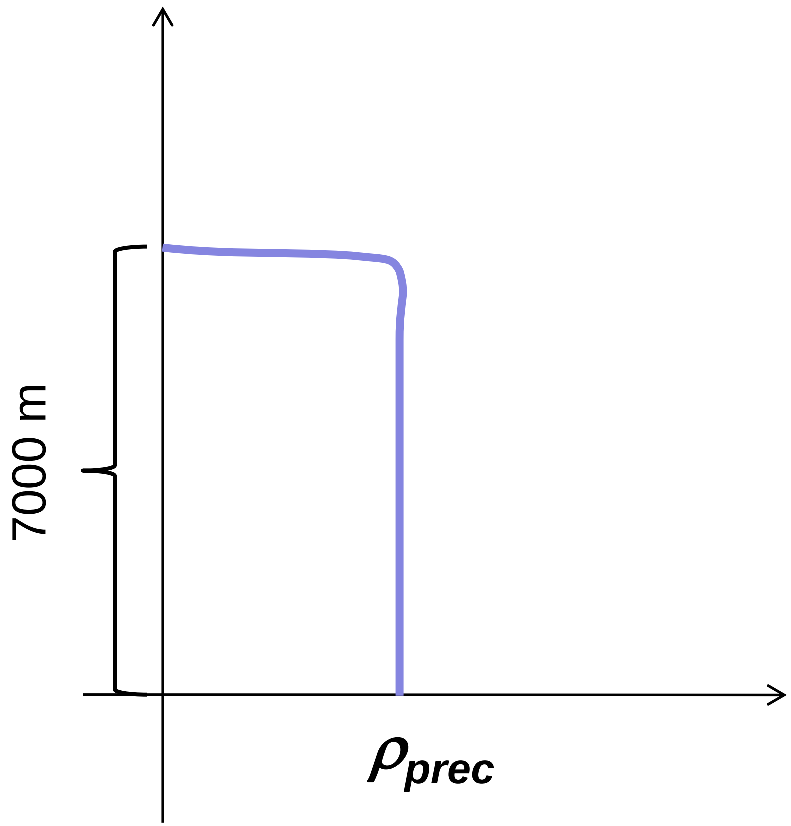
Parameterized precipitation loading

surface precip rate $\Re_{surf}$ *used to diagnose precipitating condensate density* ρ_{prec}

$$for \quad z < 7000m$$

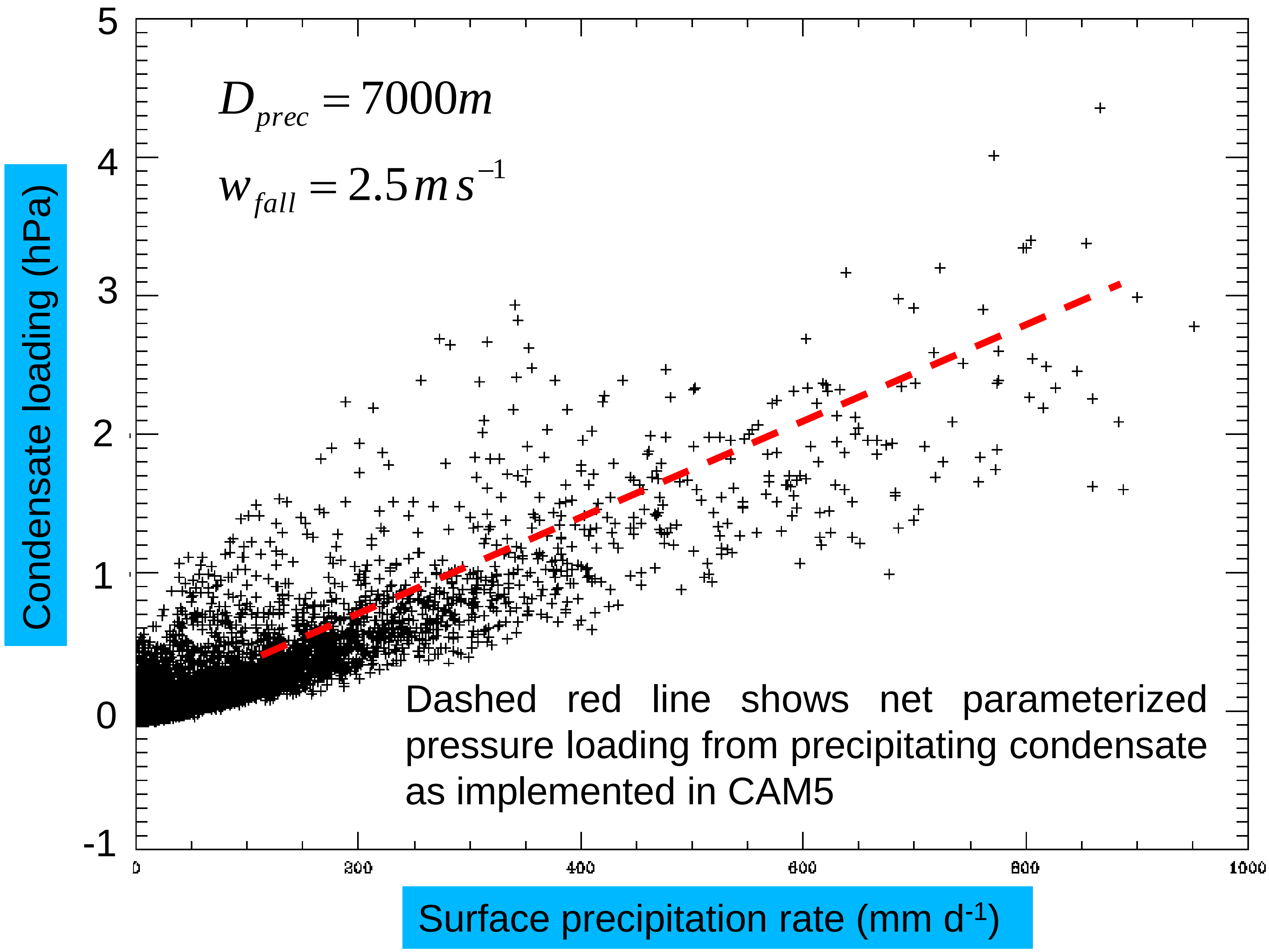
$$\rho_{prec}(x,y,z,t) = \frac{\Re_{surf}(x,y,t)}{w_{fall}}$$

$$p_{prec}(x,y,z,t) = \int_{z}^{7000m} g\rho_{prec}\, dz'$$

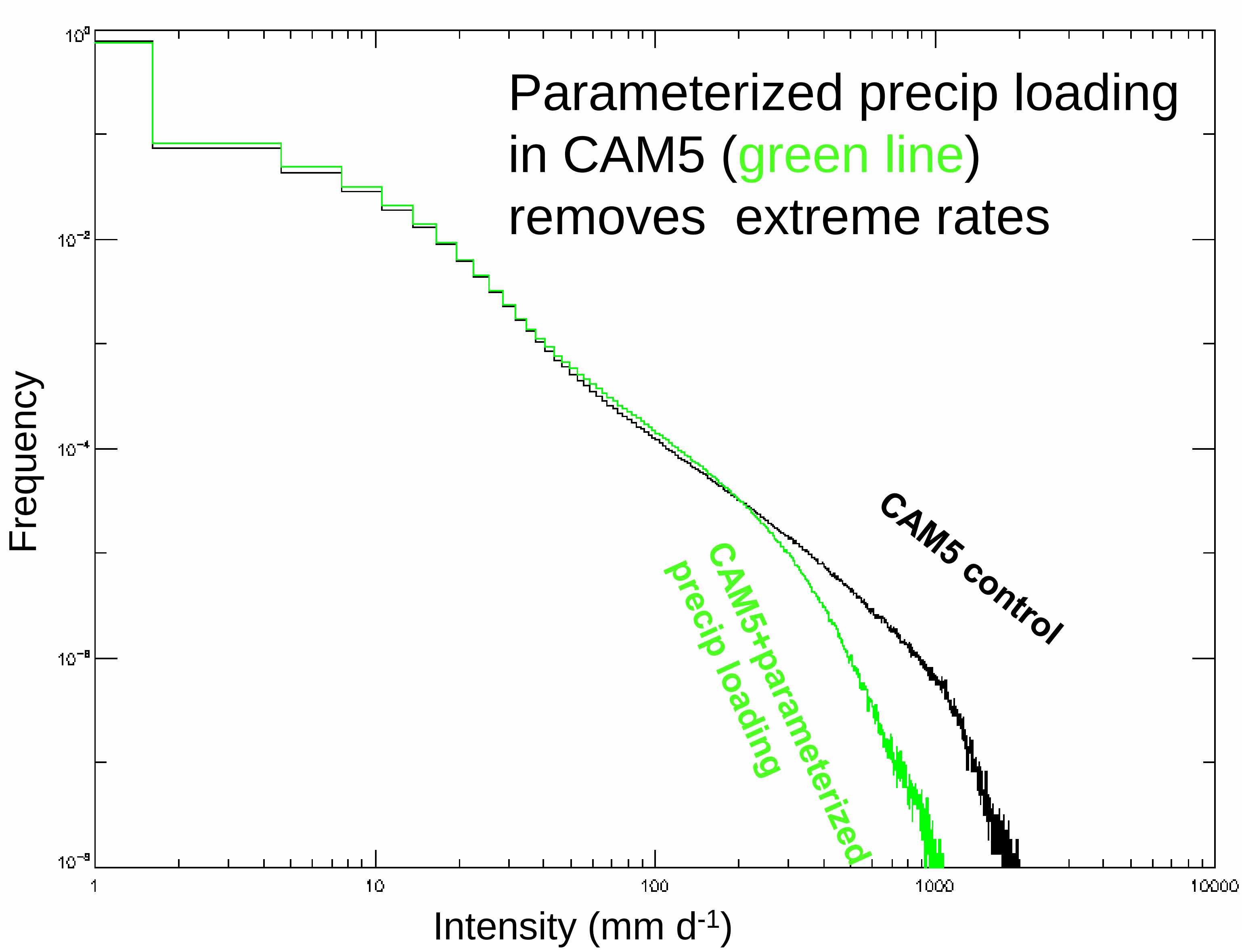


Extra condensate pressure is added to "real" model pressure right before horizontal gradients are calculated, then removed

Net loading at surface (in Pa) as a function of surface precipitation rate – for (25km)^2 resolution



PDFs of tropical precipitation (30S-30N) rates Aug 2005



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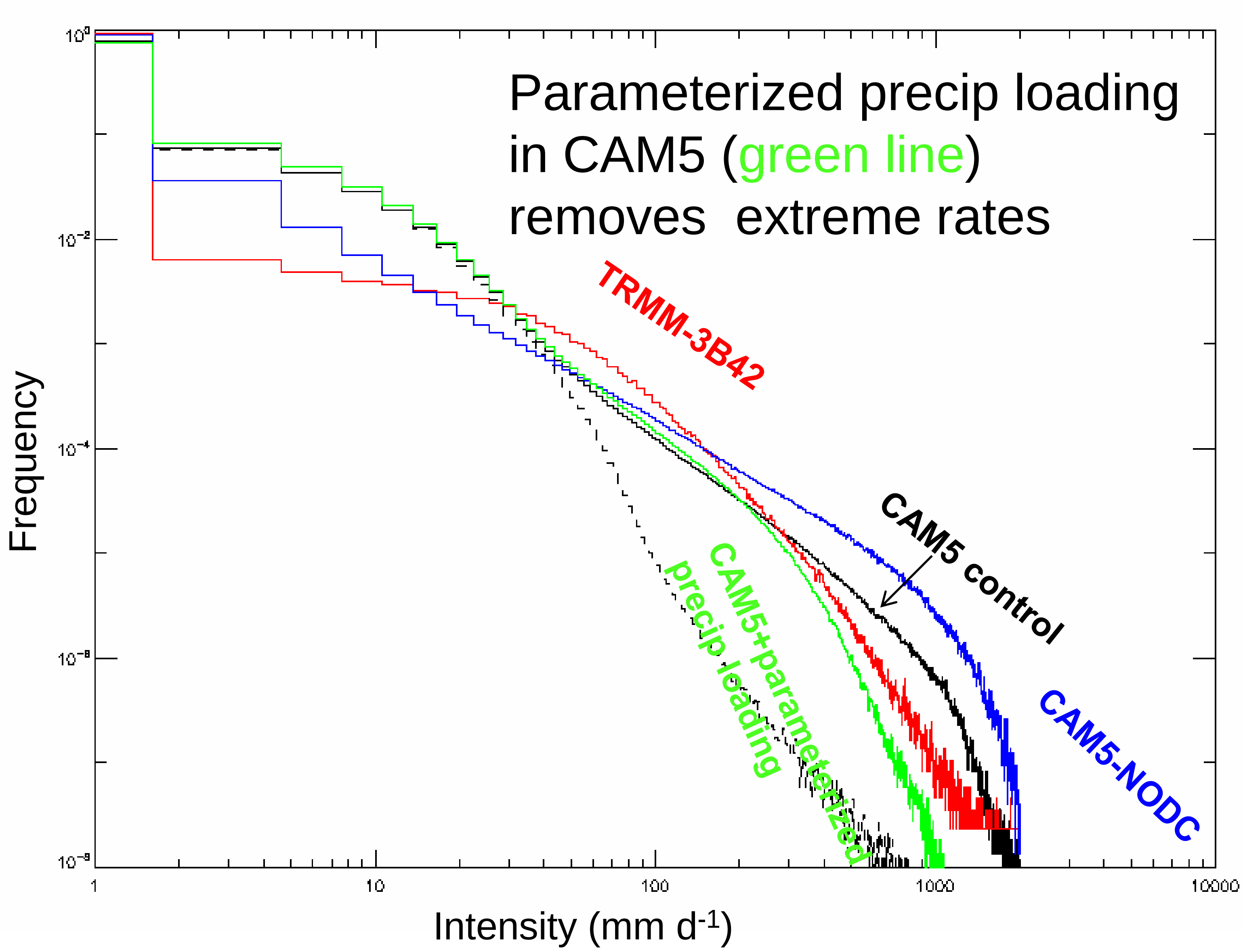
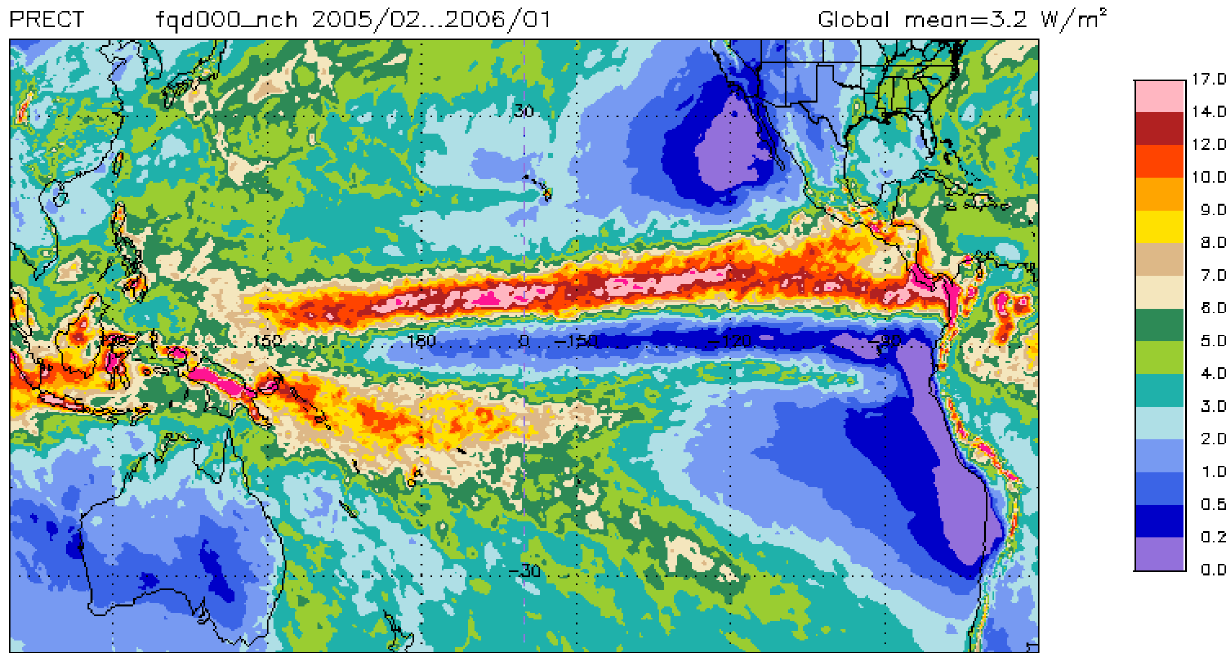
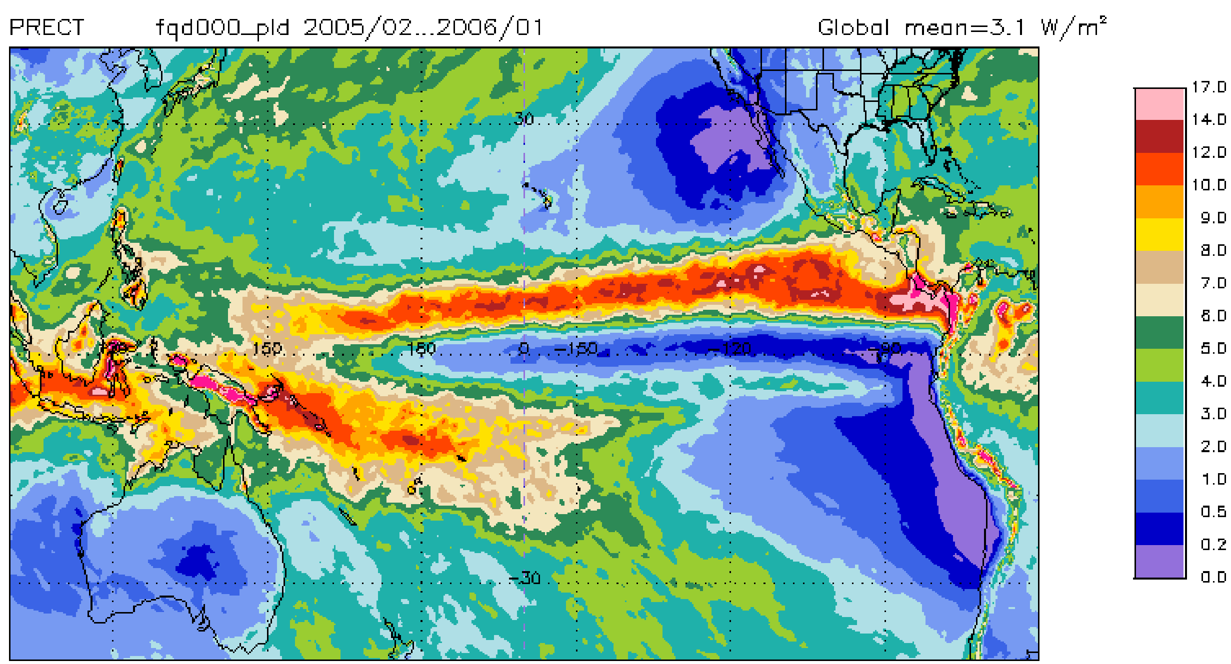


Annual mean precipitation

CAM5 control

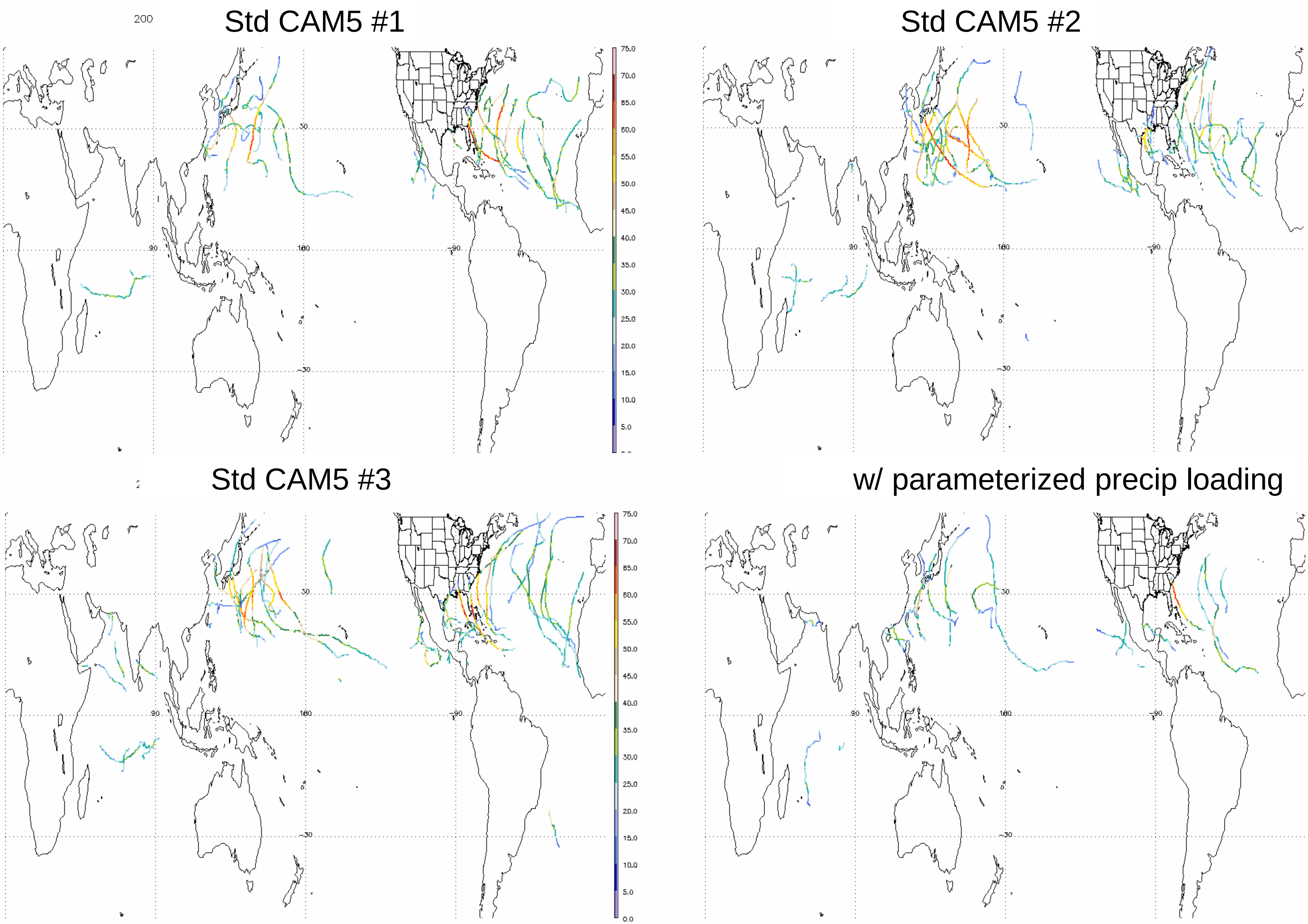


w/ parameterized precipitation loading

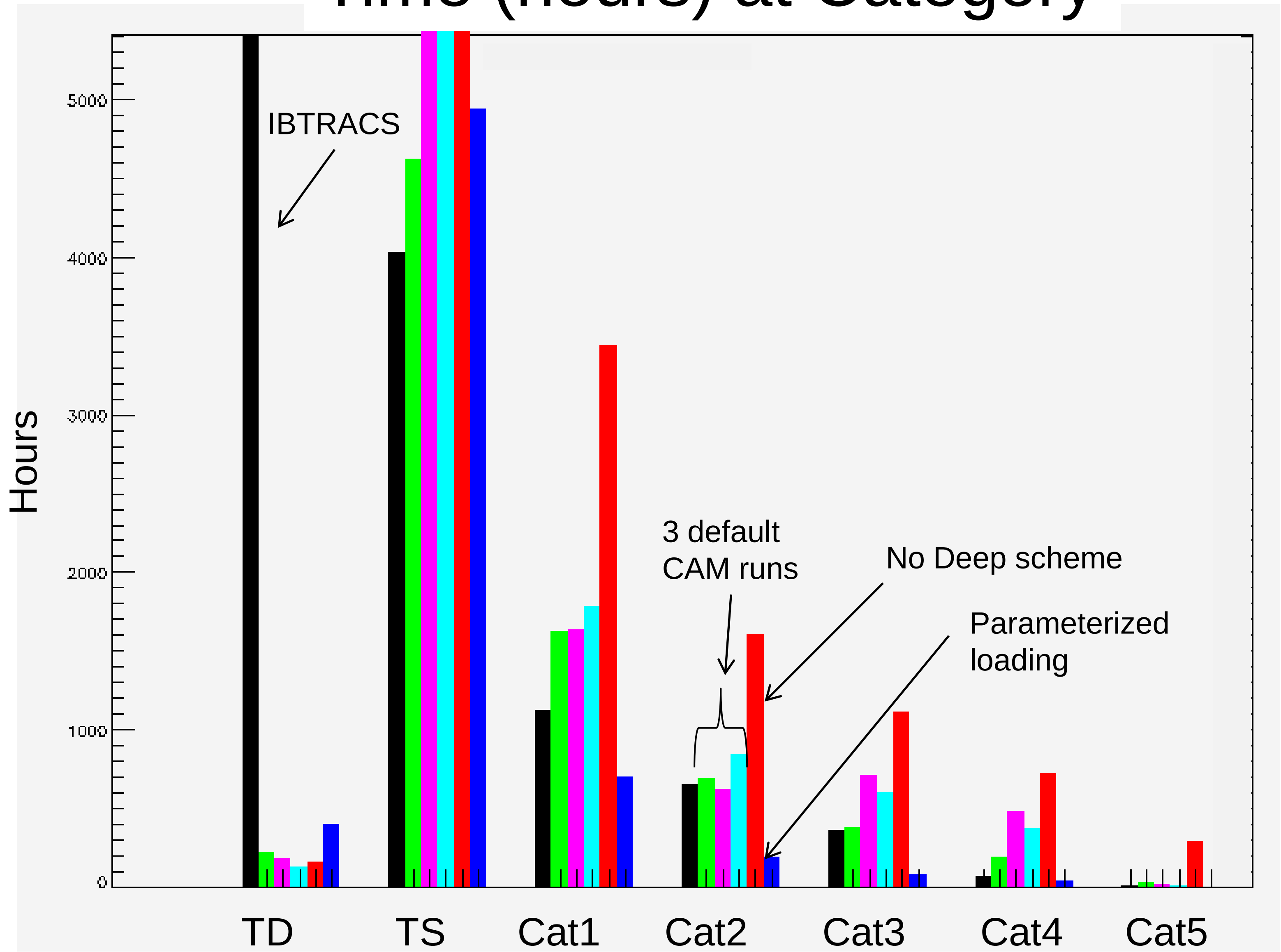


Bad news: TC number also decreases

Storms with U>33 ms^{-1}: June 1 to Nov 1 2005



Time (hours) at Category



Precipitation Loading in perspective

Relatively small perturbation to pressure field in precipitating regions seems to have large effect.

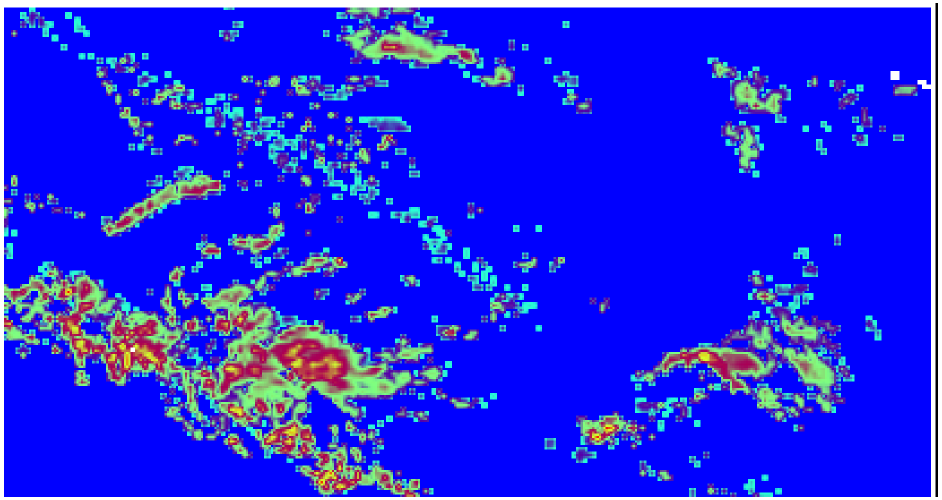
Same pressure increase could be achieved by re-evaporating about 1/8-th of condensate column

Analysis using Precipitation Objects

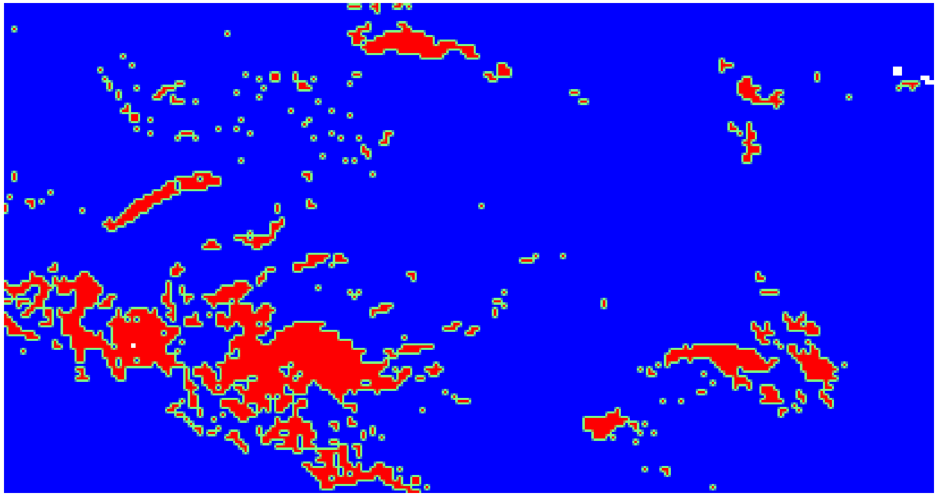
with

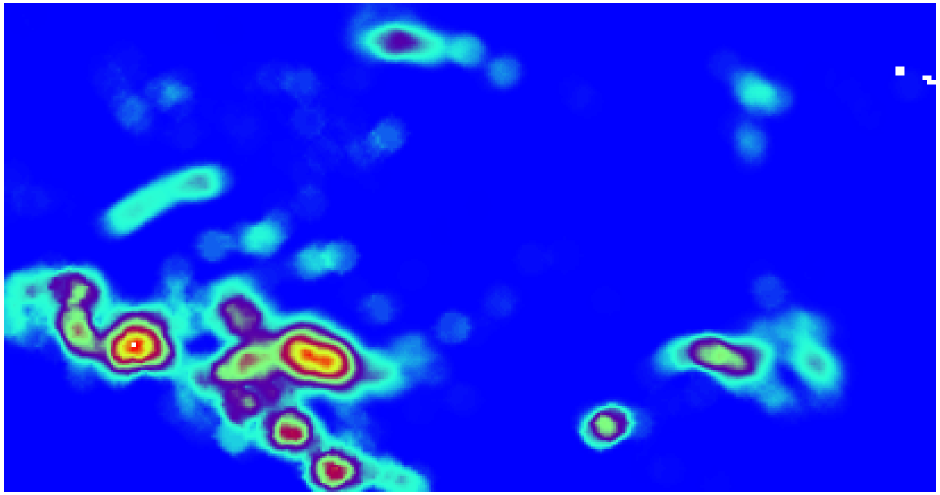
Gregor Skok,
University of Ljubljana
Joe Tribbia
NCAR AMP/CGD

Raw precipitation (snapshot)

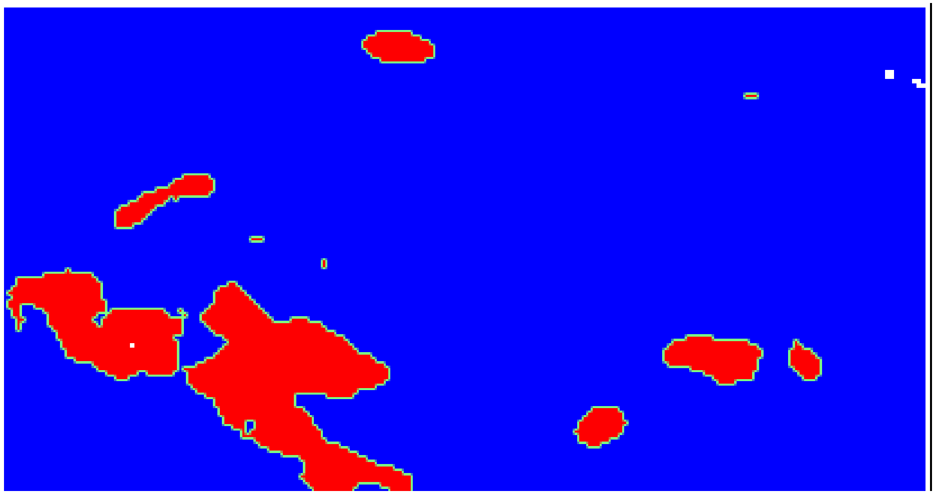


Thresholding only



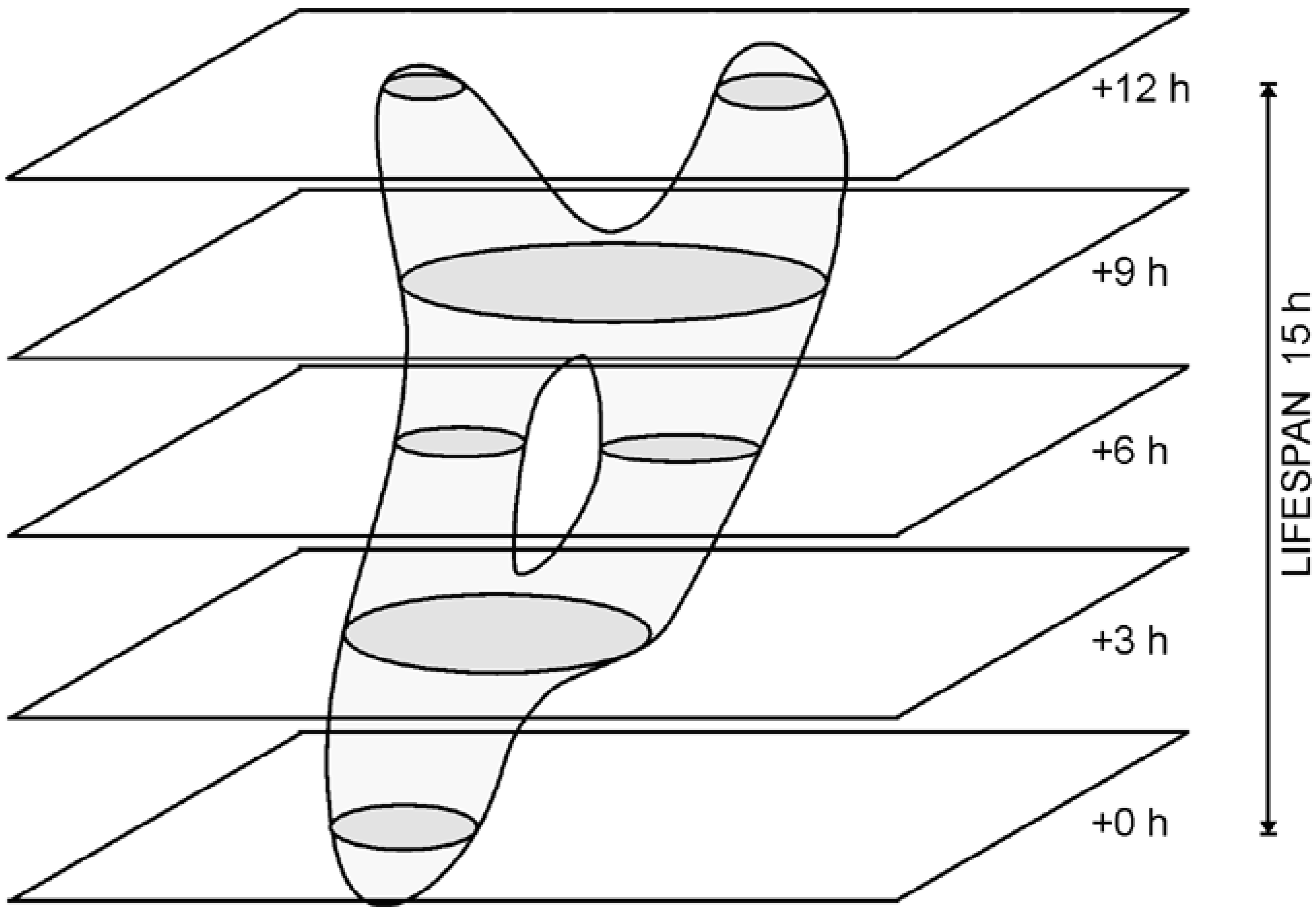


Smoothing with convolution

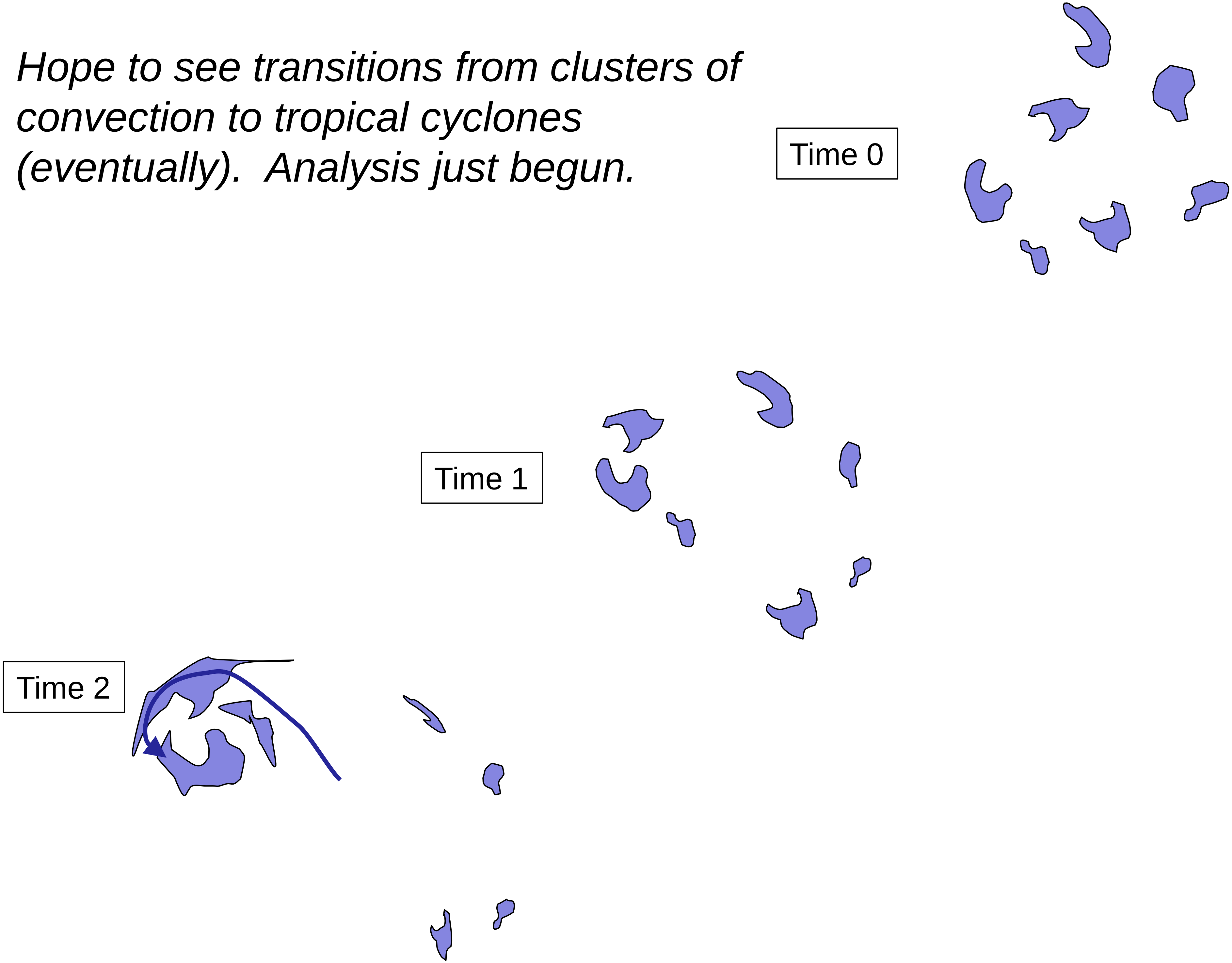


Thresholding after convolution

Objects are tracked in time using overlaps. Could be modified to include search radius.

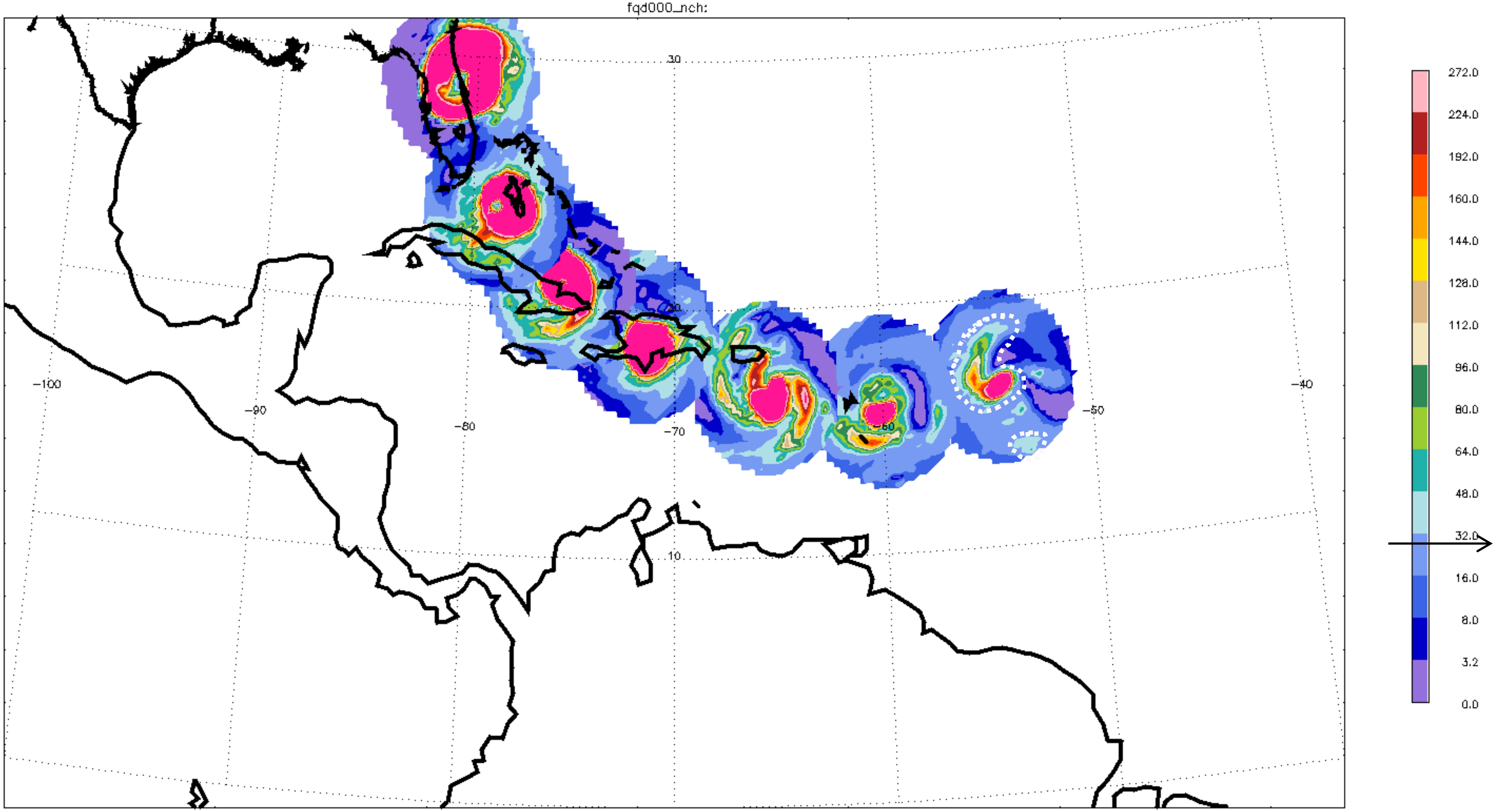


Hope to see transitions from clusters of convection to tropical cyclones (eventually). Analysis just begun.



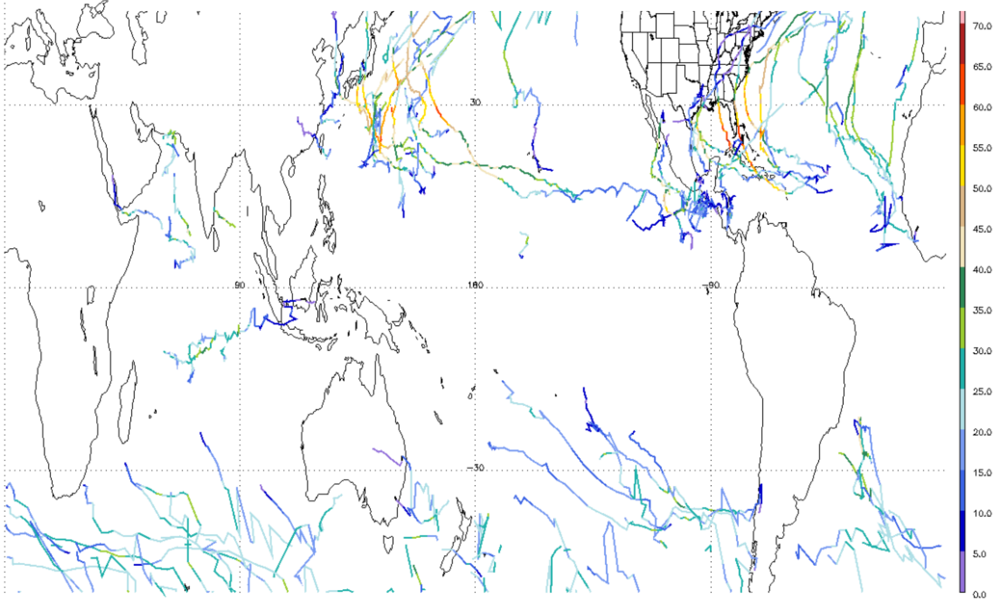
2005_08_28_54000 Local time=10:20 GMT=15:00

fqd000_nch:

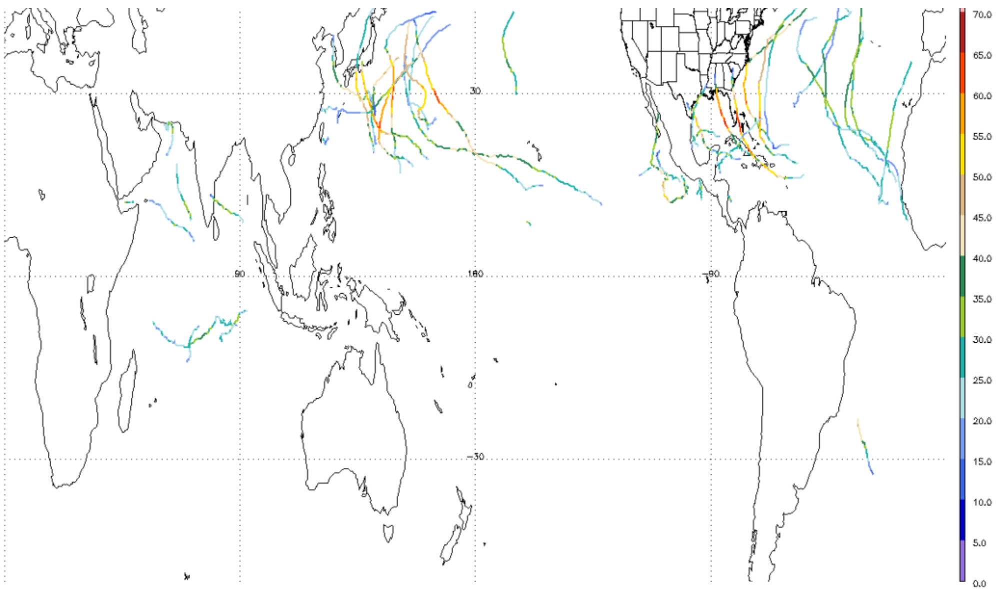


“Feature” tracks June 1 to Nov 1 2005

Precipitation object tracks (that contained winds> 33ms^{-1} at some point)

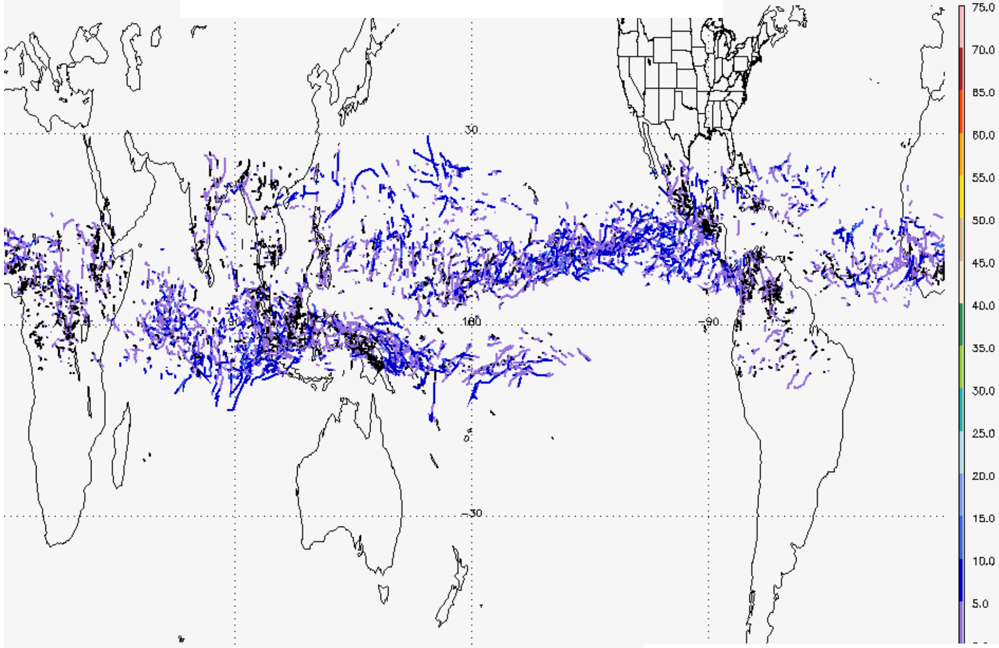


Surface pressure based hurricane/TC tracks (winds>33 ms^{-1} somewhere)

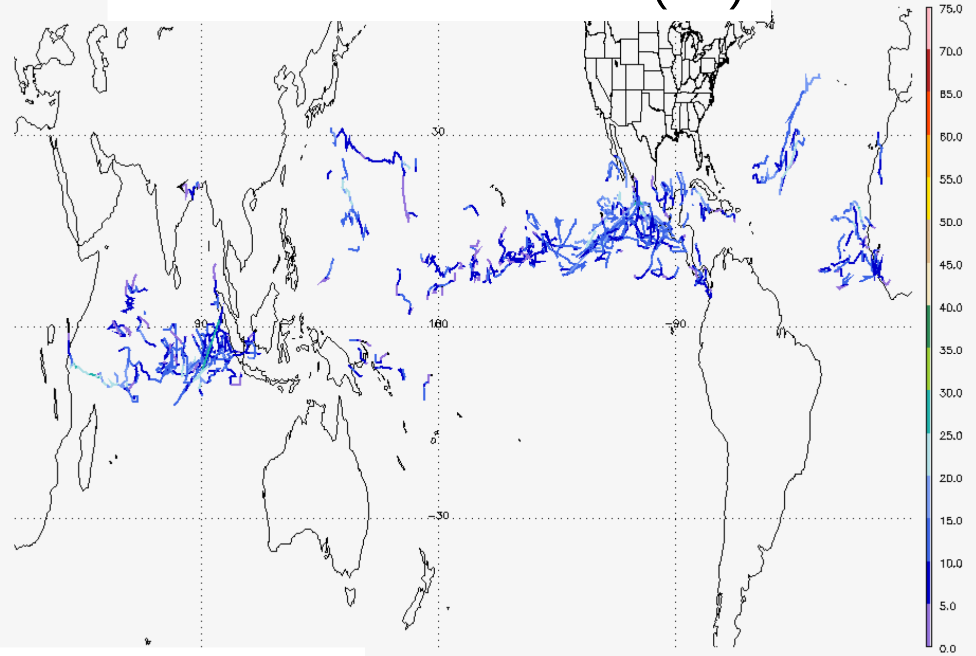


Precip object tracks September 2005 (originating 10S-25N)

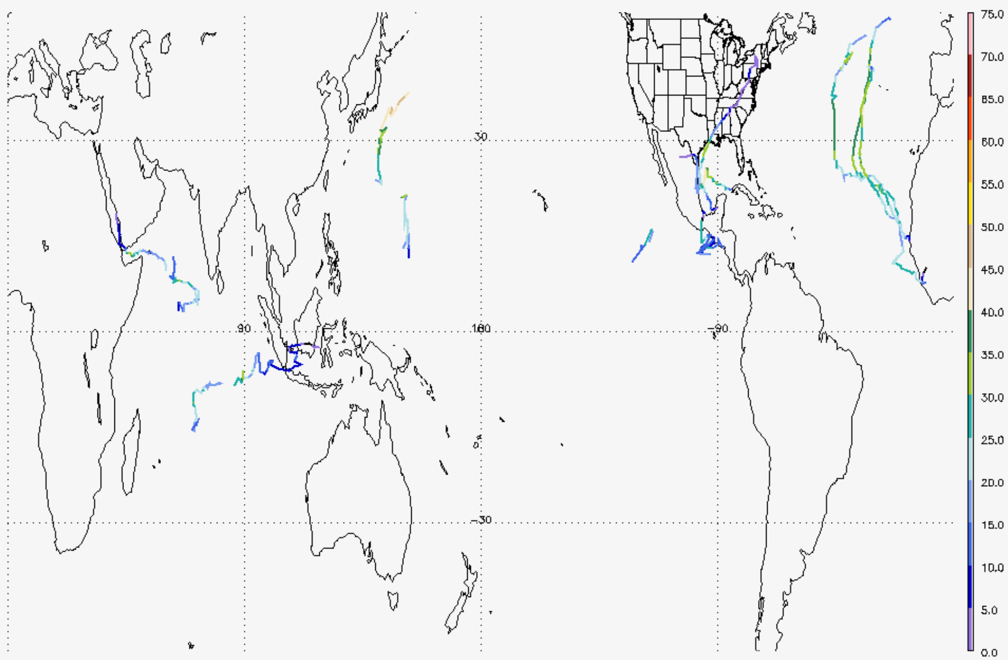
0<Max wind<17 ms^{-1}



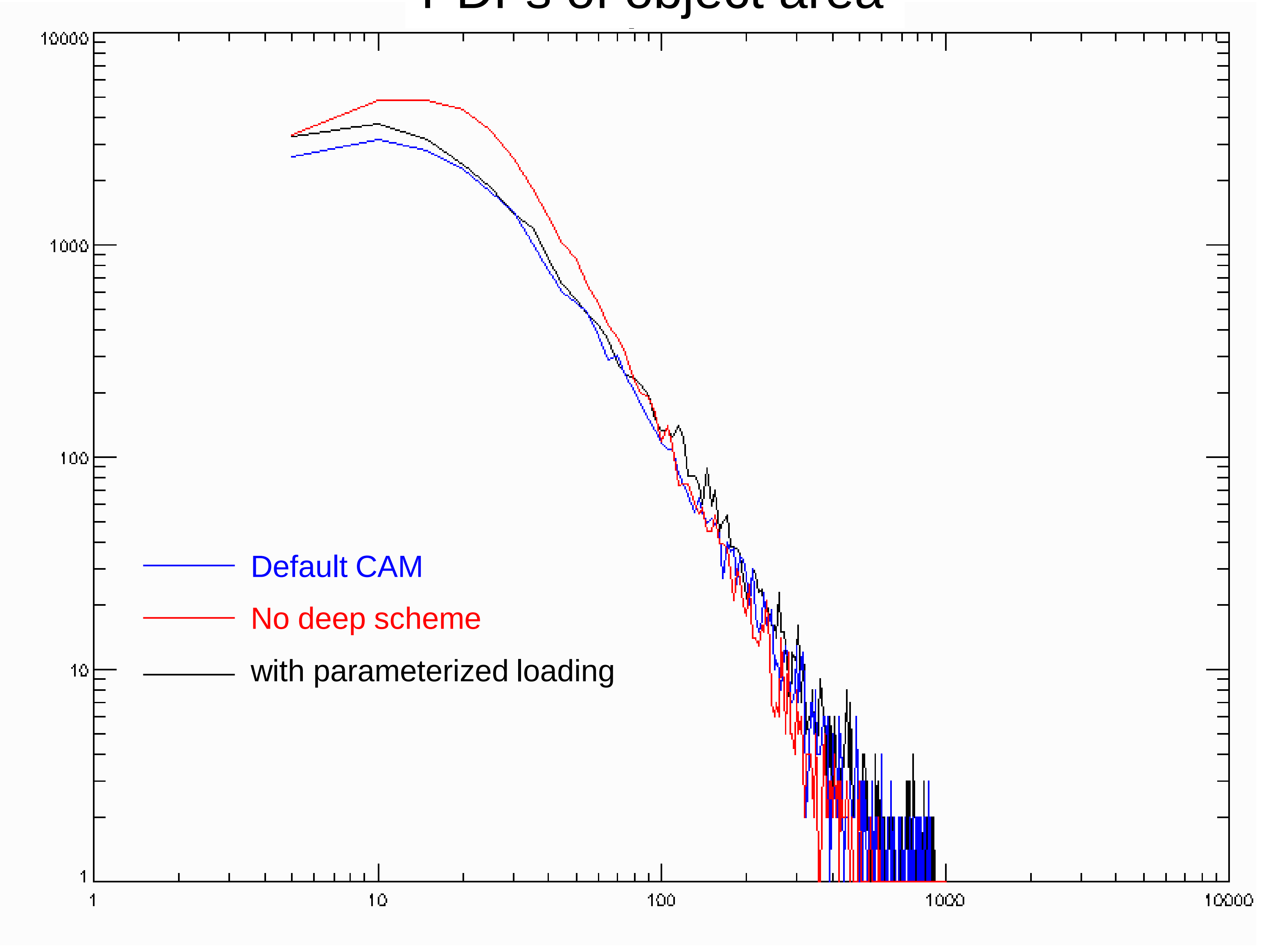
17<Max wind<33 ms^{-1} (TS)



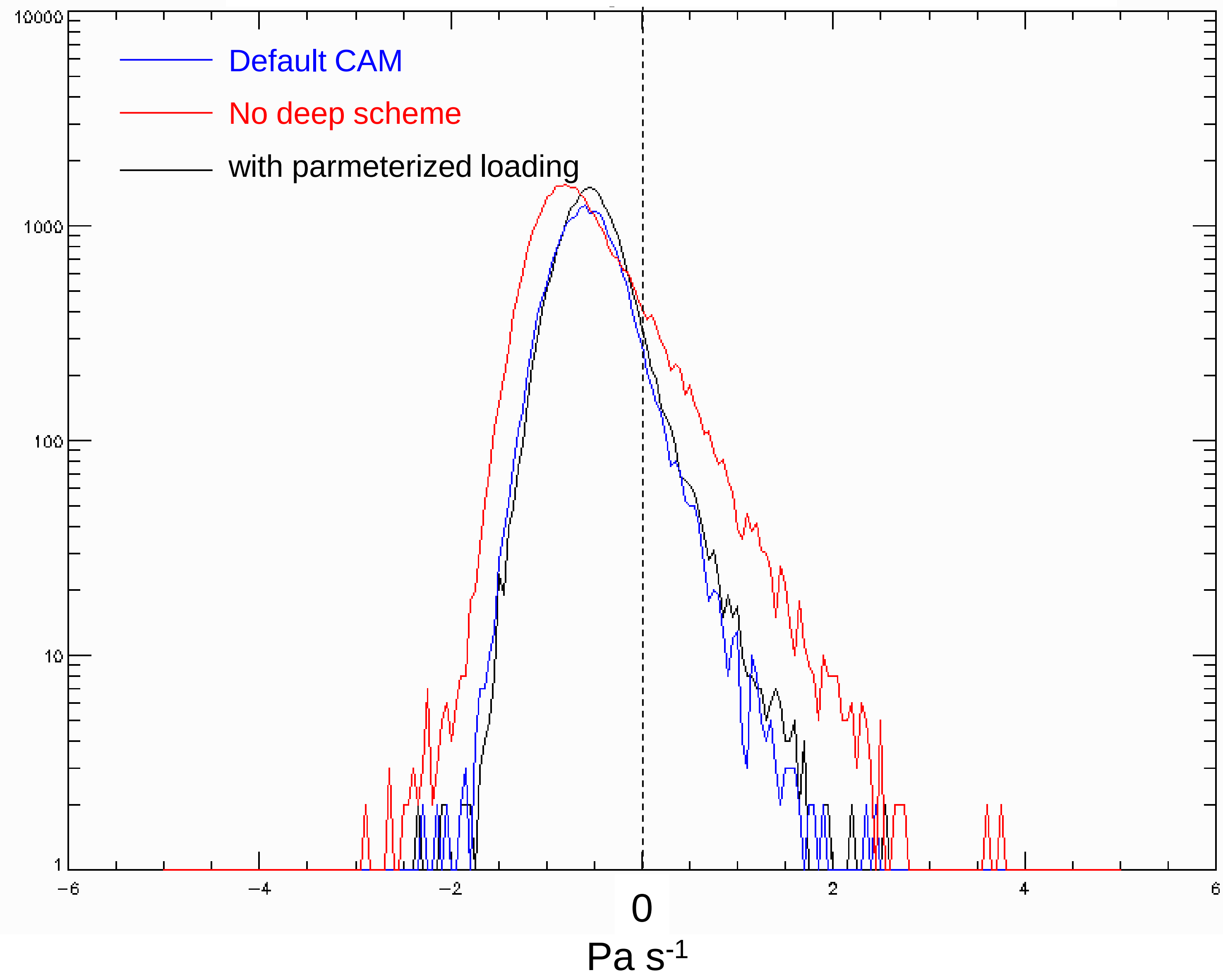
33ms^{-1}<Max wind (TC/hurricane)



PDFs of object area



PDFs of object mean vertical motion



Summary and future directions

Models with $\Delta x \sim 10$km ***can*** capture many important aspects of TC climatology ***but answer depends sensitively on physics tuning***

Time to focus on cyclogenesis processes in ~10 km models

Tracks and intensities may have similar biases in current models, e.g., eastward shift in tracks, not enough variability in intensity

Convection and Clouds in the Tropics

2009-Aug-20 21z 72-hour Forecasts

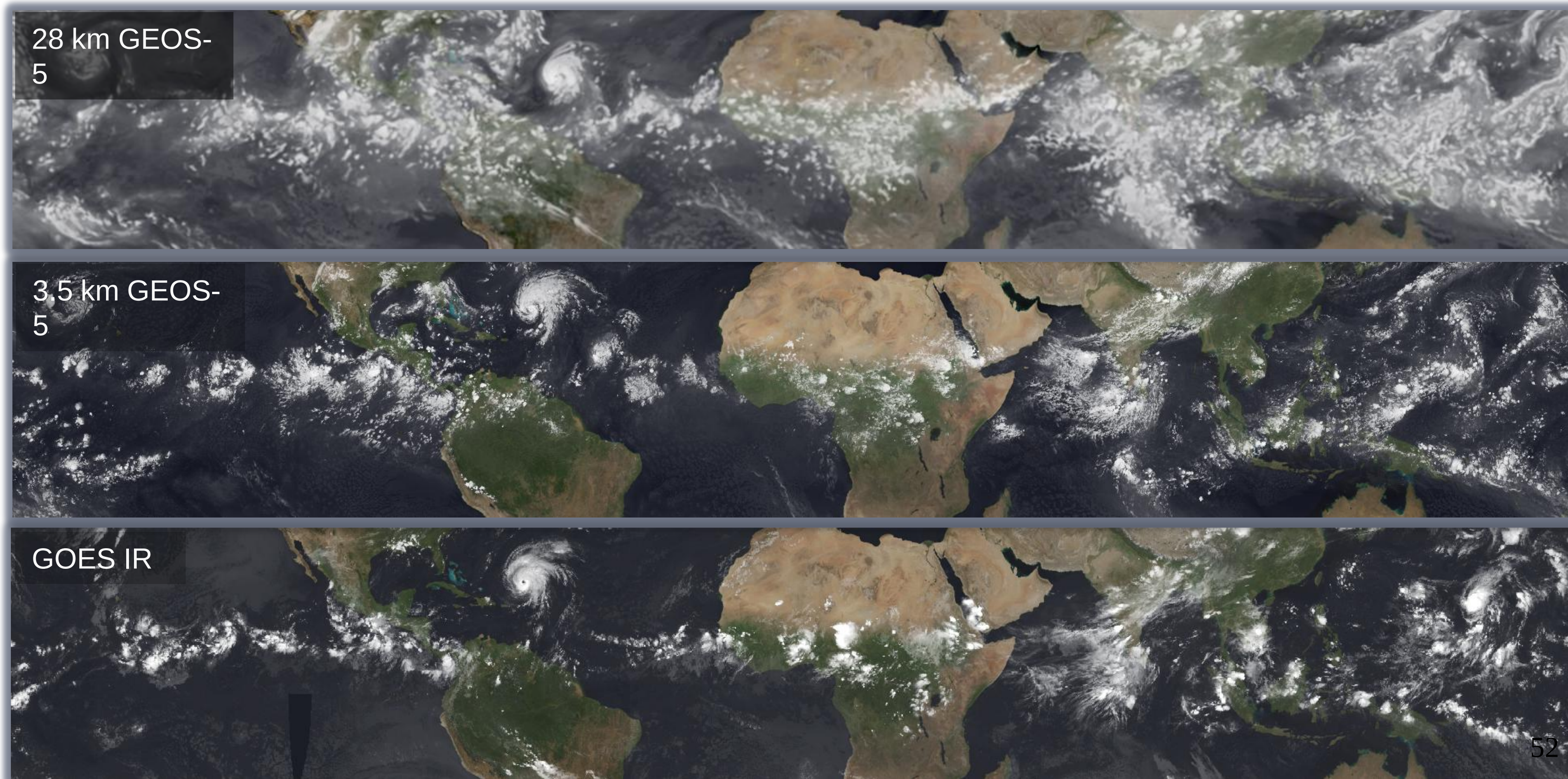
East Pacific ITCZ

Atlantic Hurricane Bill

African Deep Convective Clusters

Indian Monsoon

Pacific Warm Pool



THANK YOU

The NESL Mission is:
To advance understanding of weather, climate, atmospheric composition and processes;
To provide facility support to the wider community; and,
To apply the results to benefit society.

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