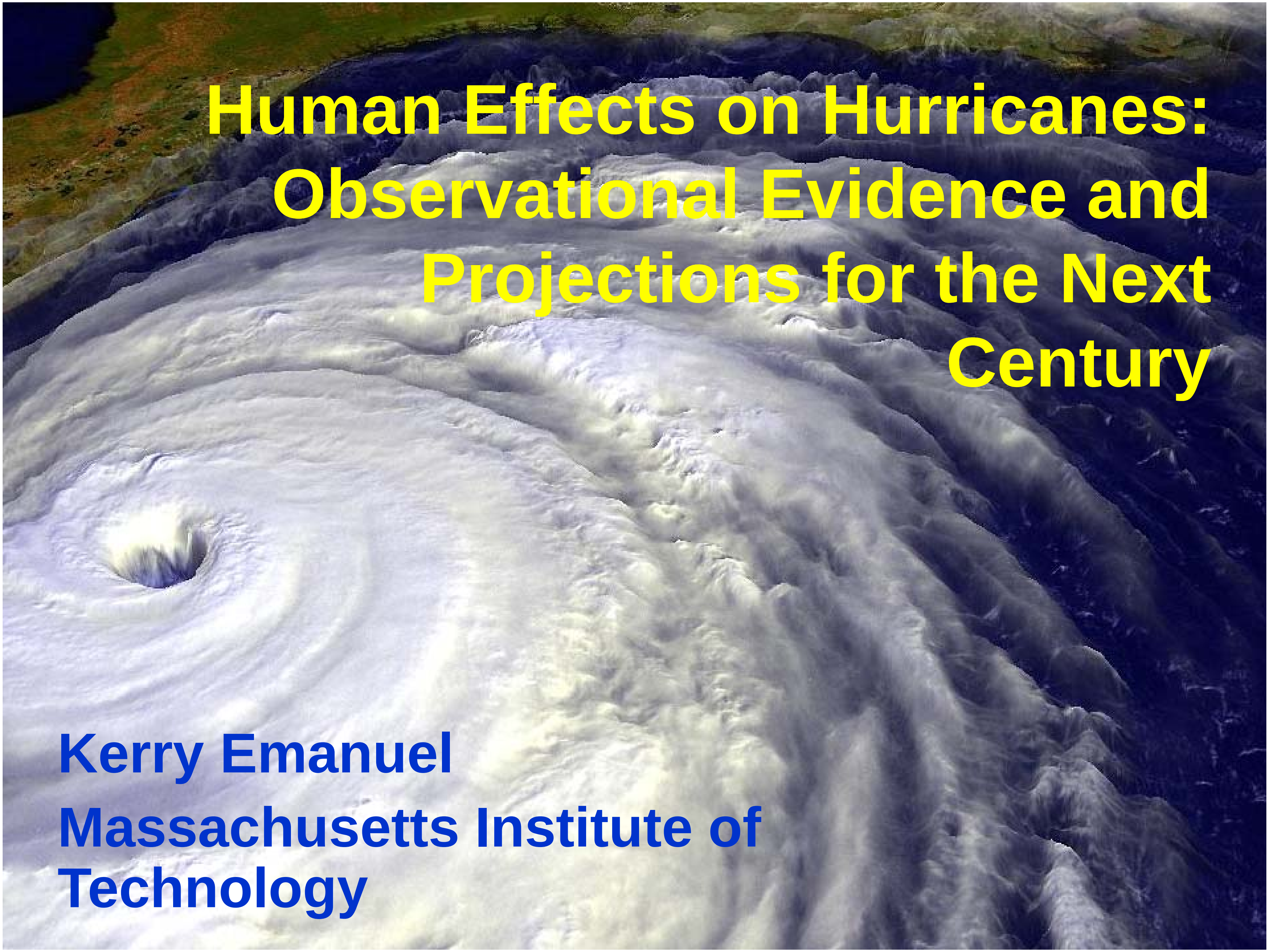


Human Effects on Hurricanes: Observational Evidence and Projections for the Next Century

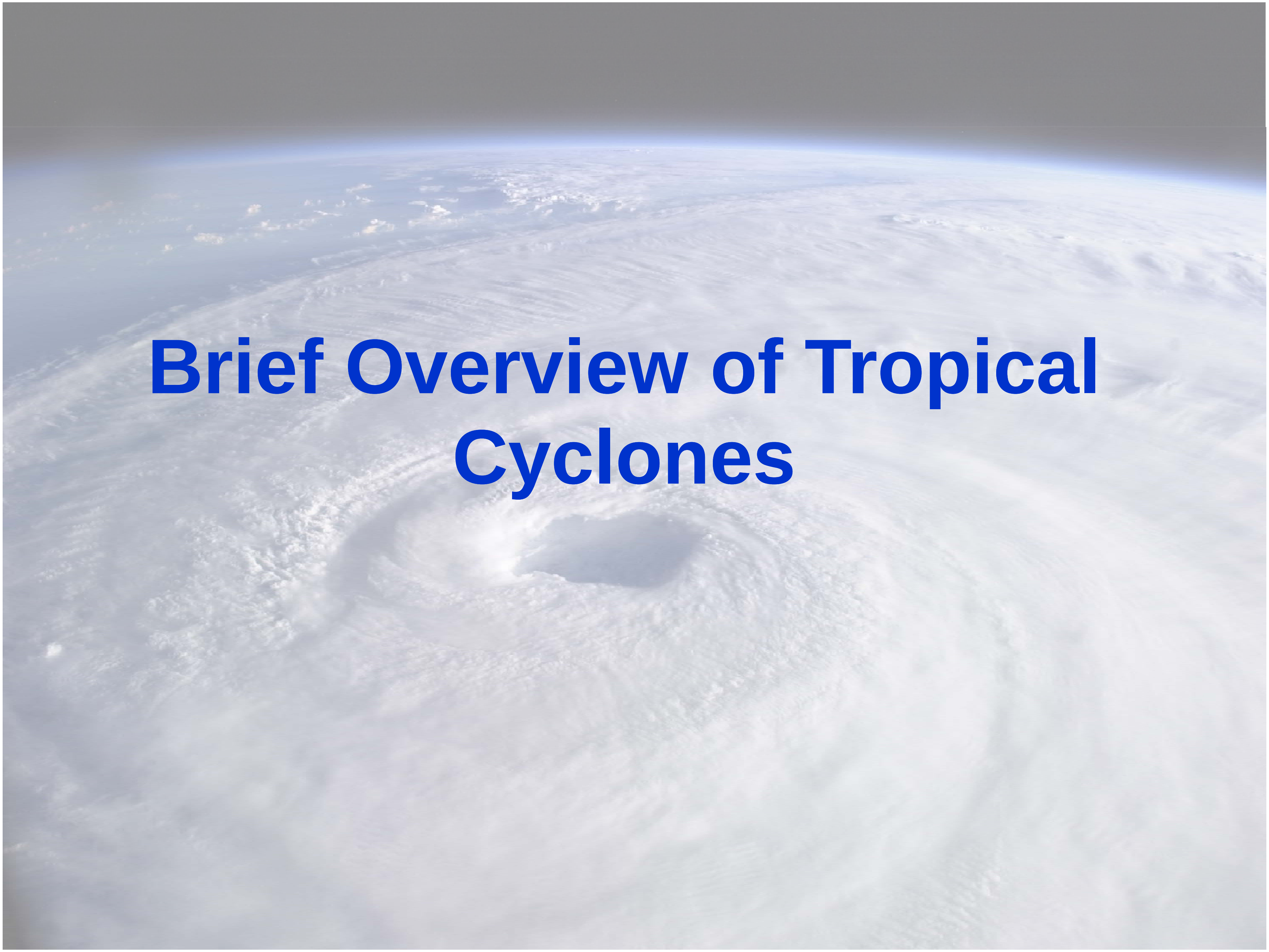
Kerry Emanuel

Massachusetts Institute of Technology

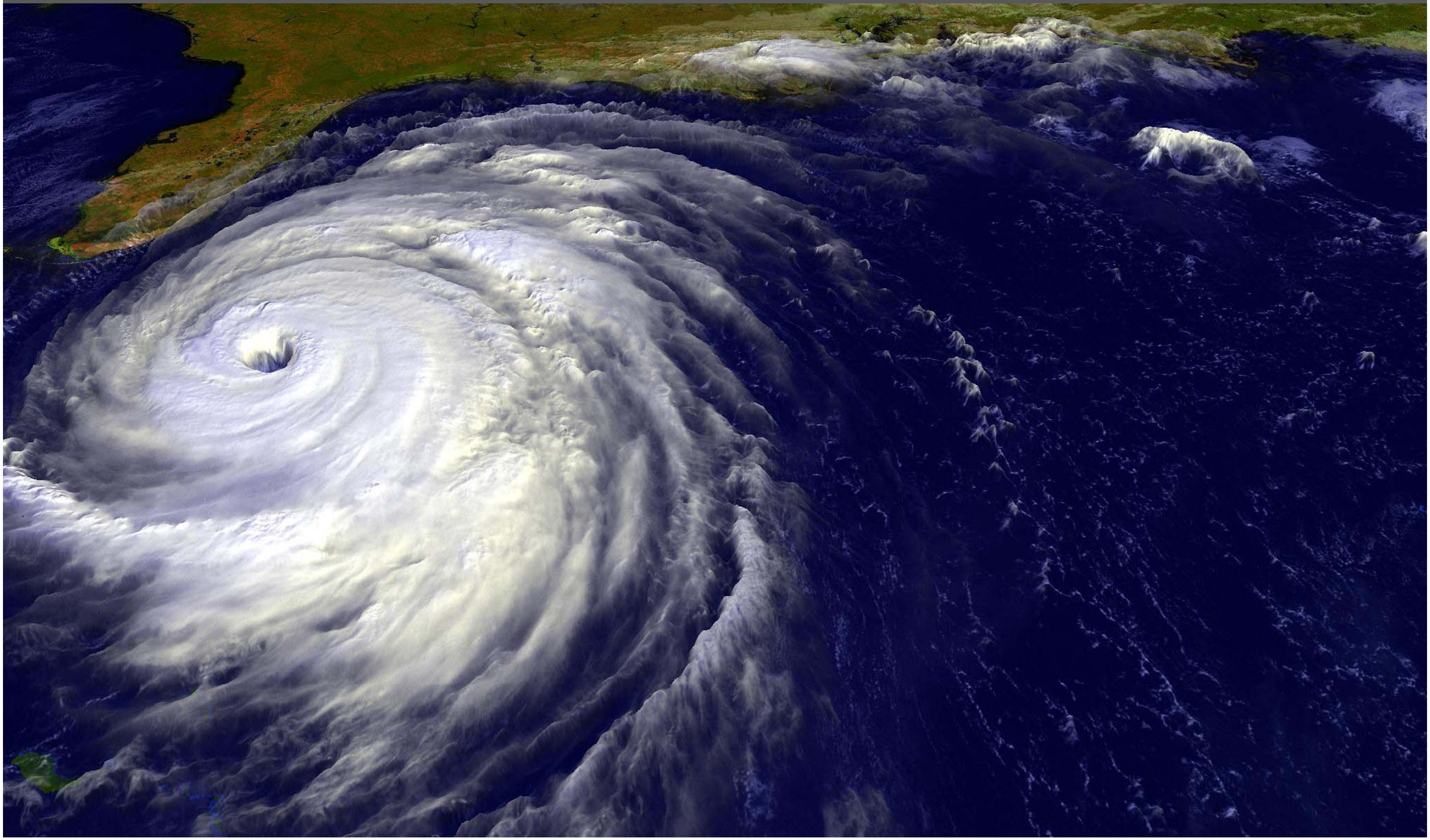
Issues

- **What processes control rates of formation of tropical cyclones?**
- **What processes control the actual and “potential” intensities of TCs?**
- **What have TCs been like in the past, and how will they be affected by global warming?**

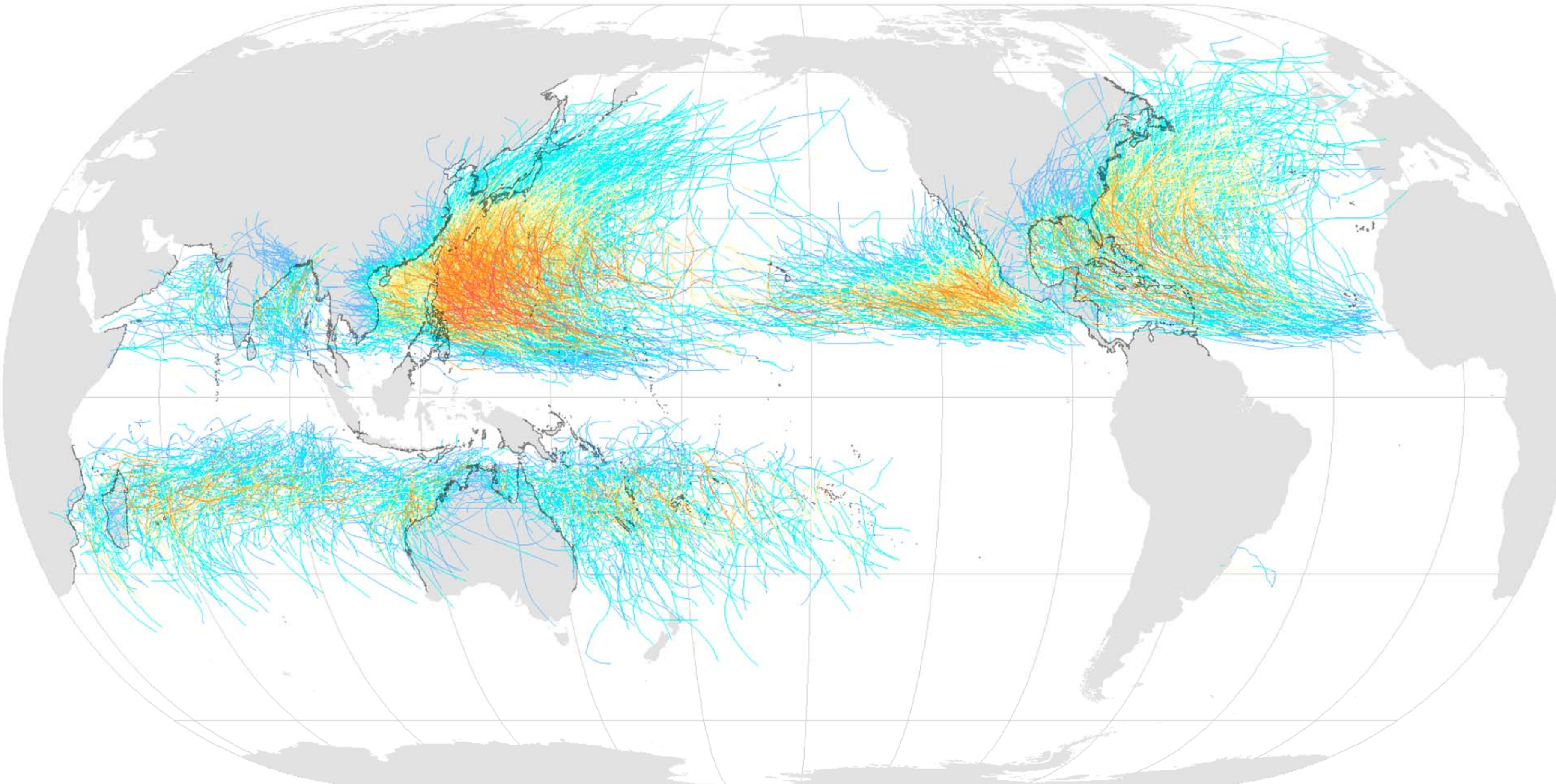
Brief Overview of Tropical Cyclones



The View from Space

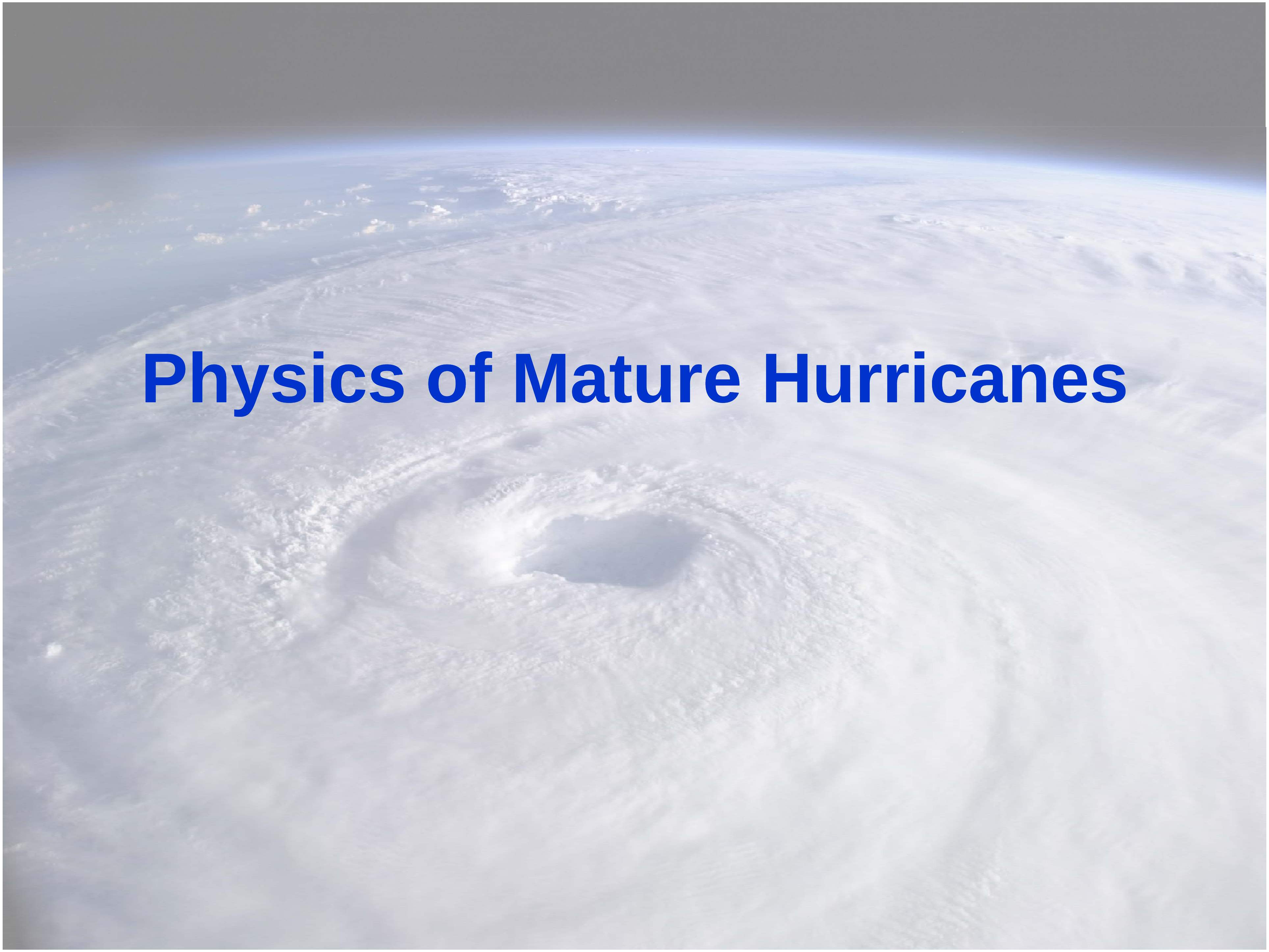


Tropical Cyclones, 1945–2006

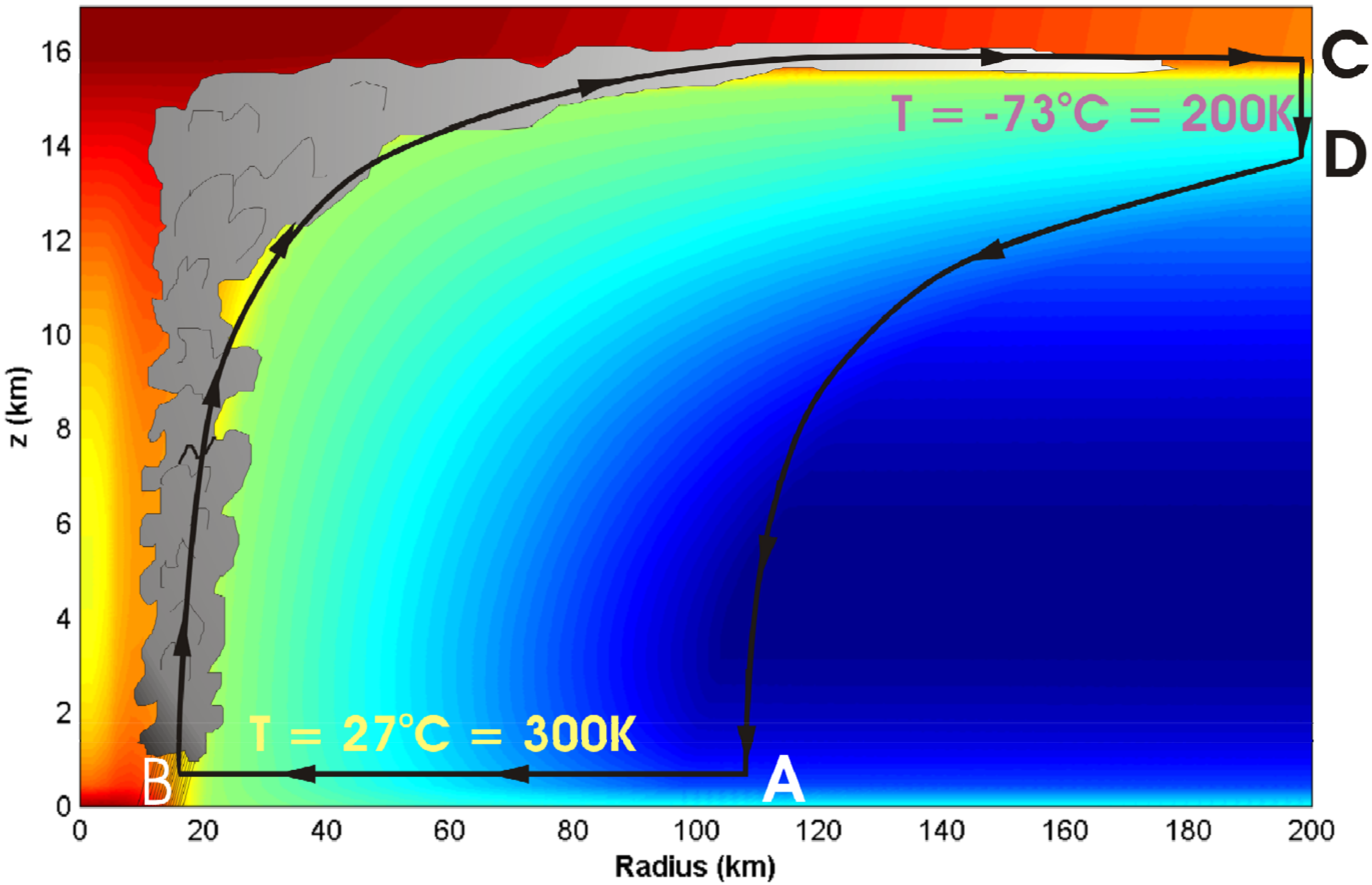


Saffir-Simpson Hurricane Scale:

tropical depression	tropical storm	hurricane category 1	hurricane category 2	hurricane category 3	hurricane category 4	hurricane category 5


Physics of Mature Hurricanes

Energy Production



Theoretical Upper Bound on Hurricane Maximum Wind Speed:

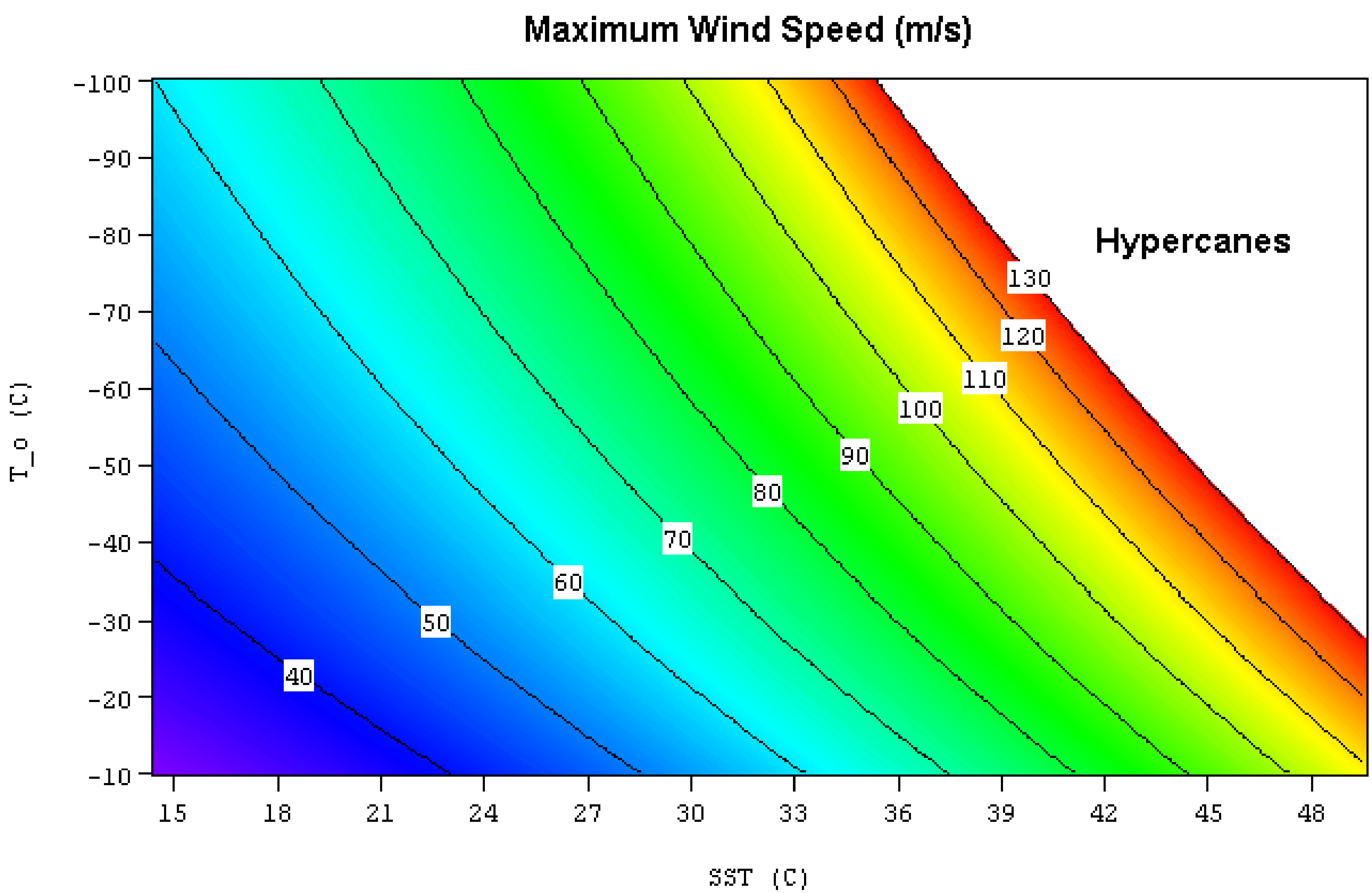
$$|V_{pot}|^2 \cong \frac{C_k}{C_D} \frac{T_s - T_o}{T_o} \left(k_0^* - k \right)$$

Surface temperature

Ratio of exchange coefficients of enthalpy and momentum

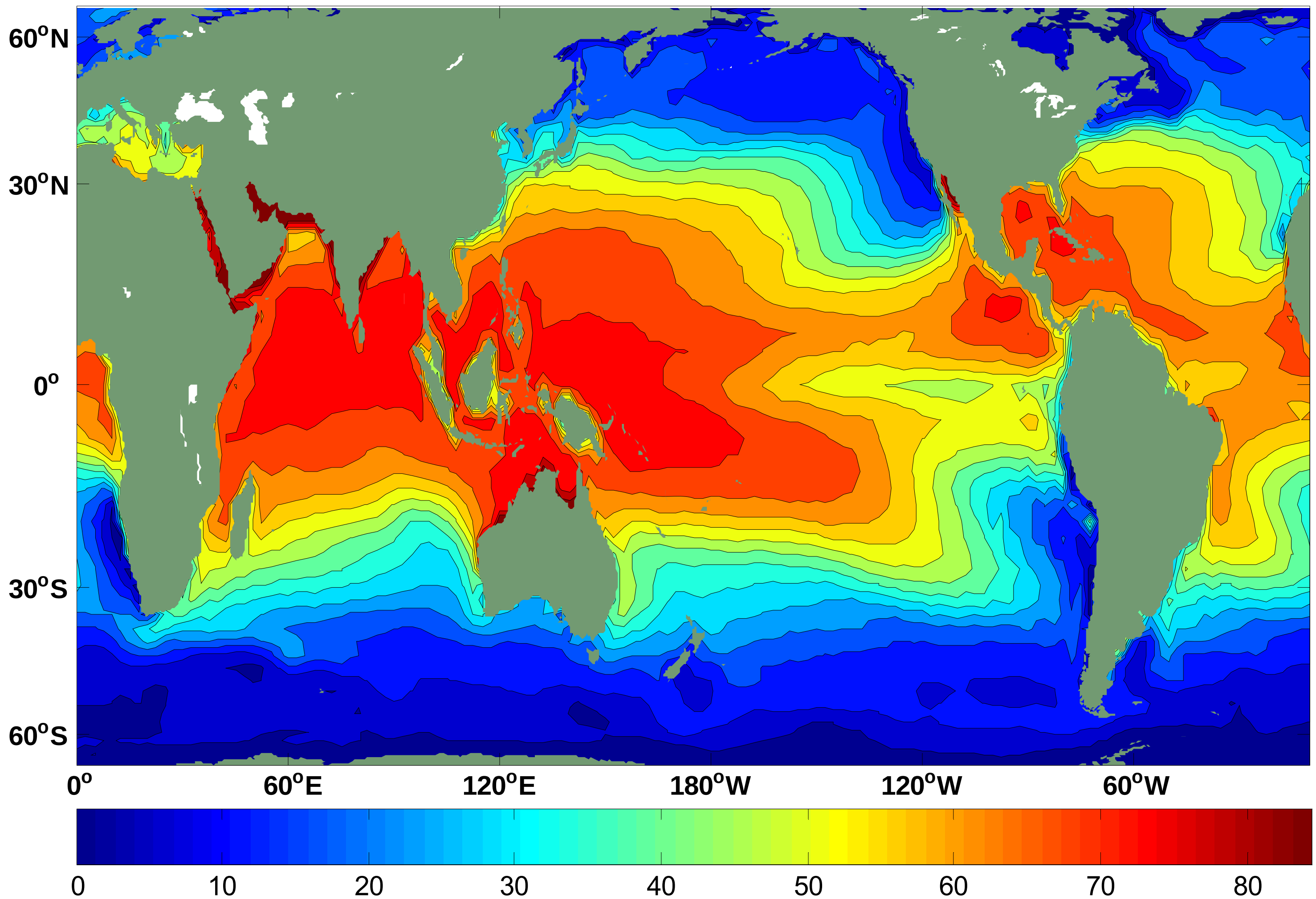
Outflow temperature

Air-sea enthalpy disequilibrium

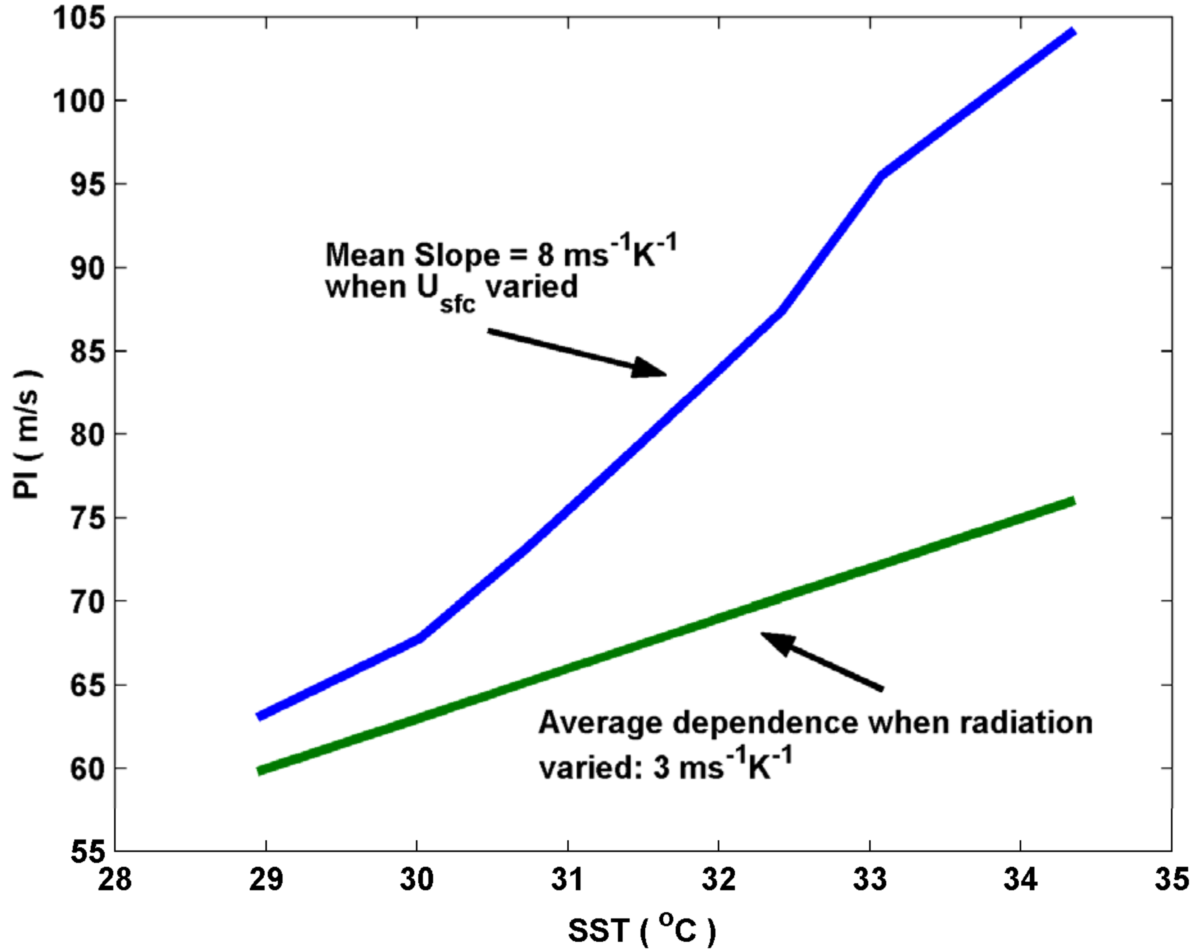


$\mathscr{K}$ = 0.75 C_k/C_D = 1.2

Annual Maximum Potential Intensity (m/s)



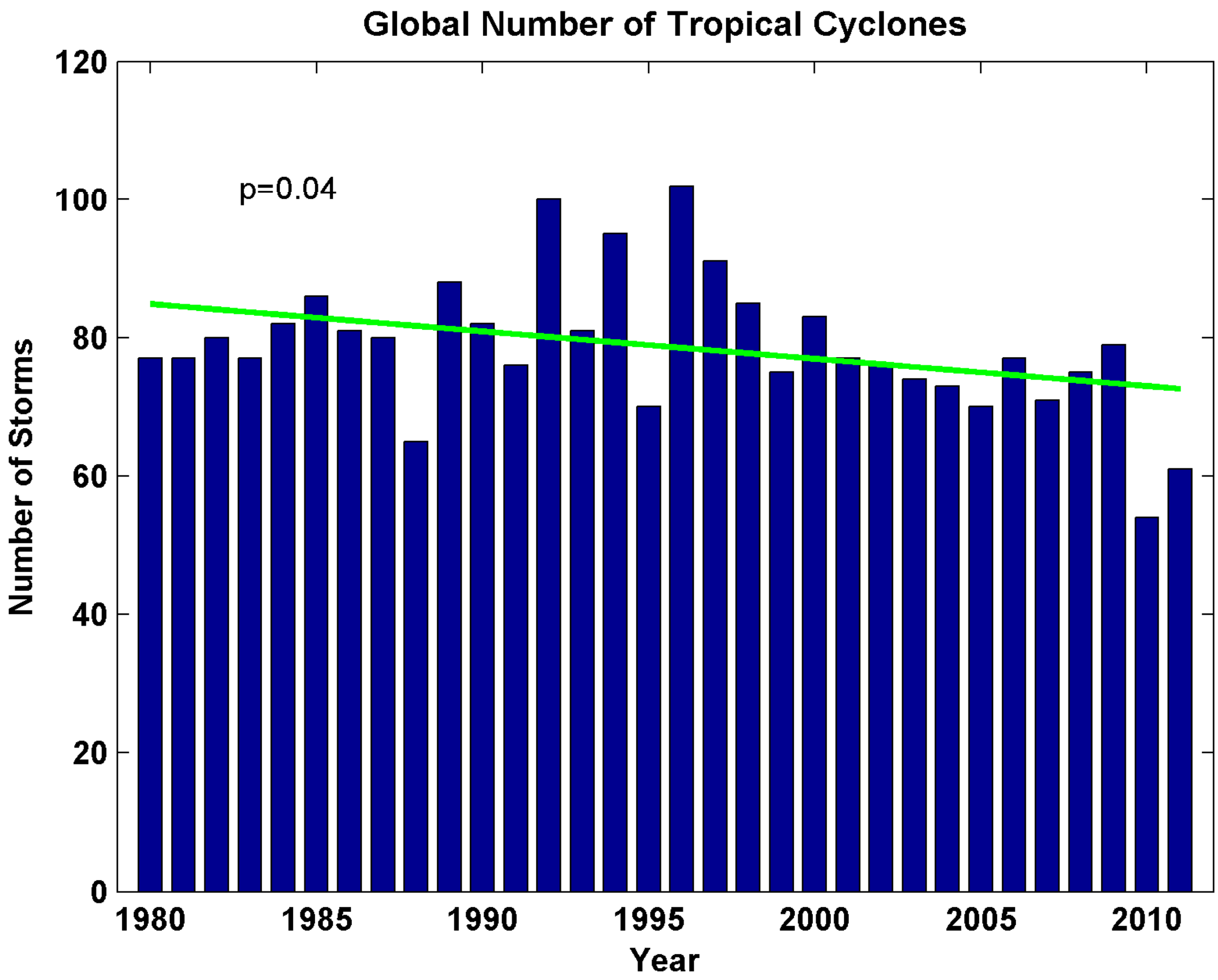
Potential Intensity is not a function of SST *per se*



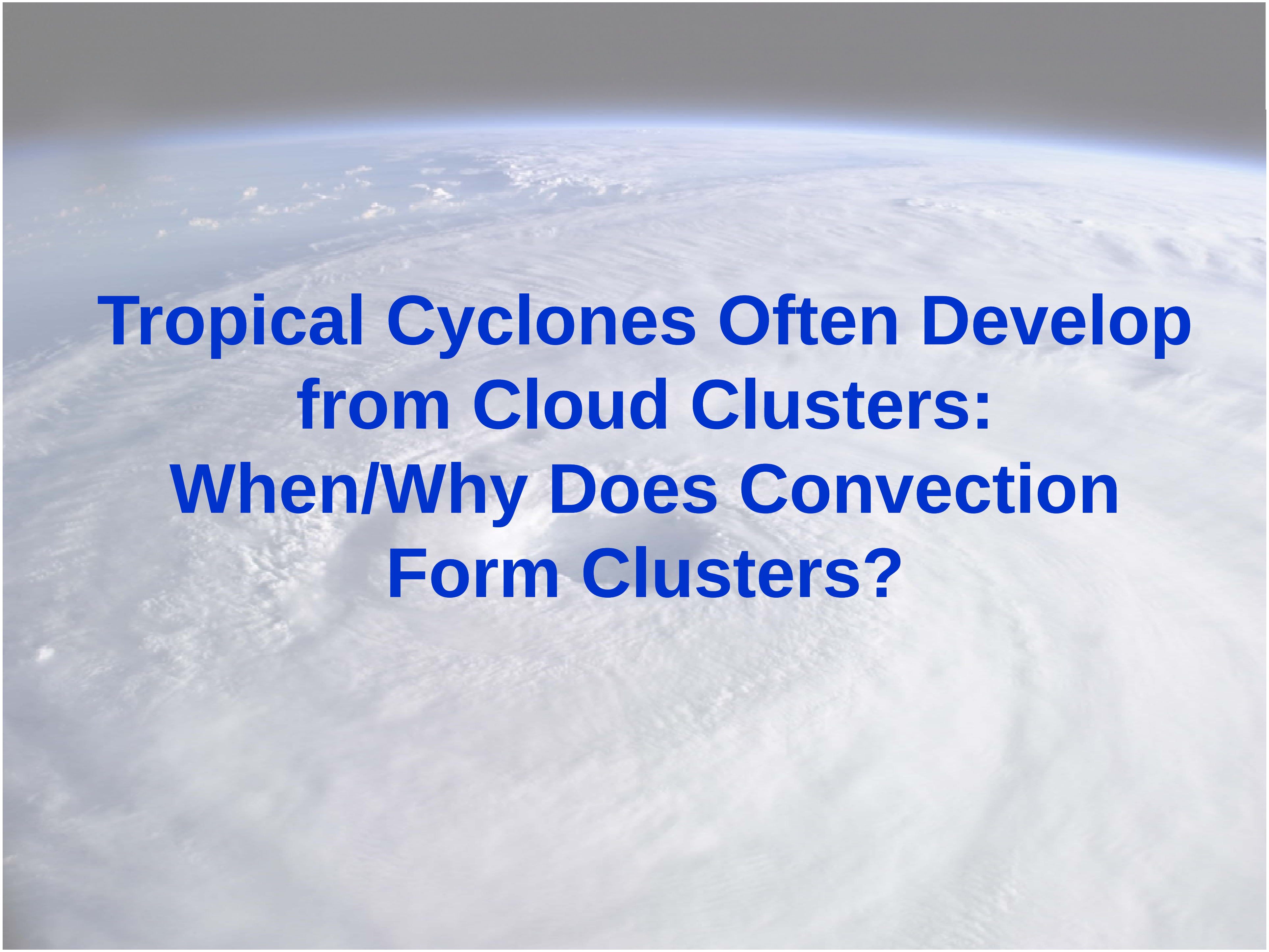
Showing potential intensity vs. SST, varying mean surface wind (blue) and CO_2 content (green)

The Genesis Puzzle

Global Tropical Cyclone Frequency, 1980-2011



Data Sources: NOAA/TPC and NAVY/JTWC



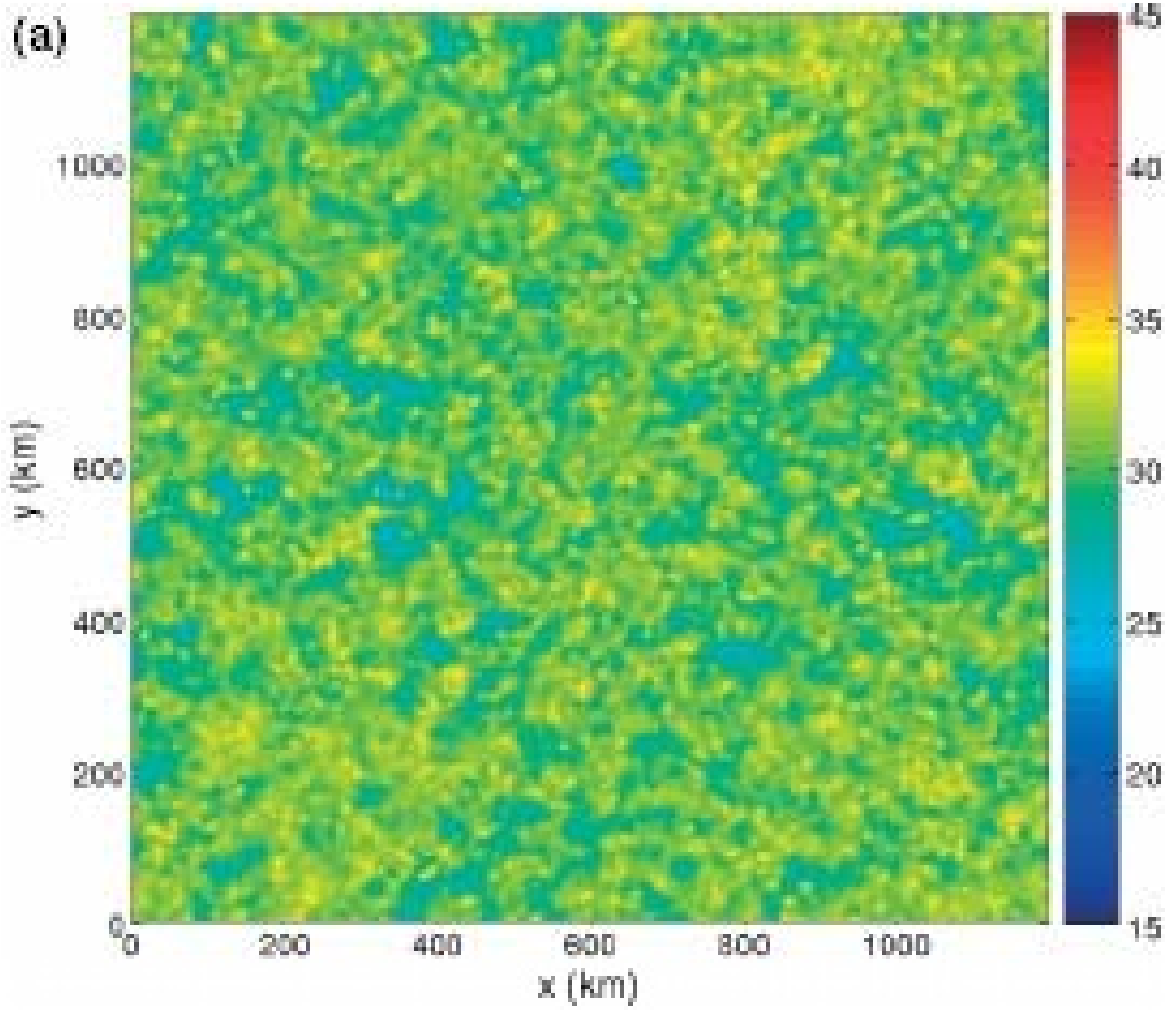
Tropical Cyclones Often Develop from Cloud Clusters: When/Why Does Convection Form Clusters?

Monsoonal Thunderstorms, Bangladesh and India July 1985

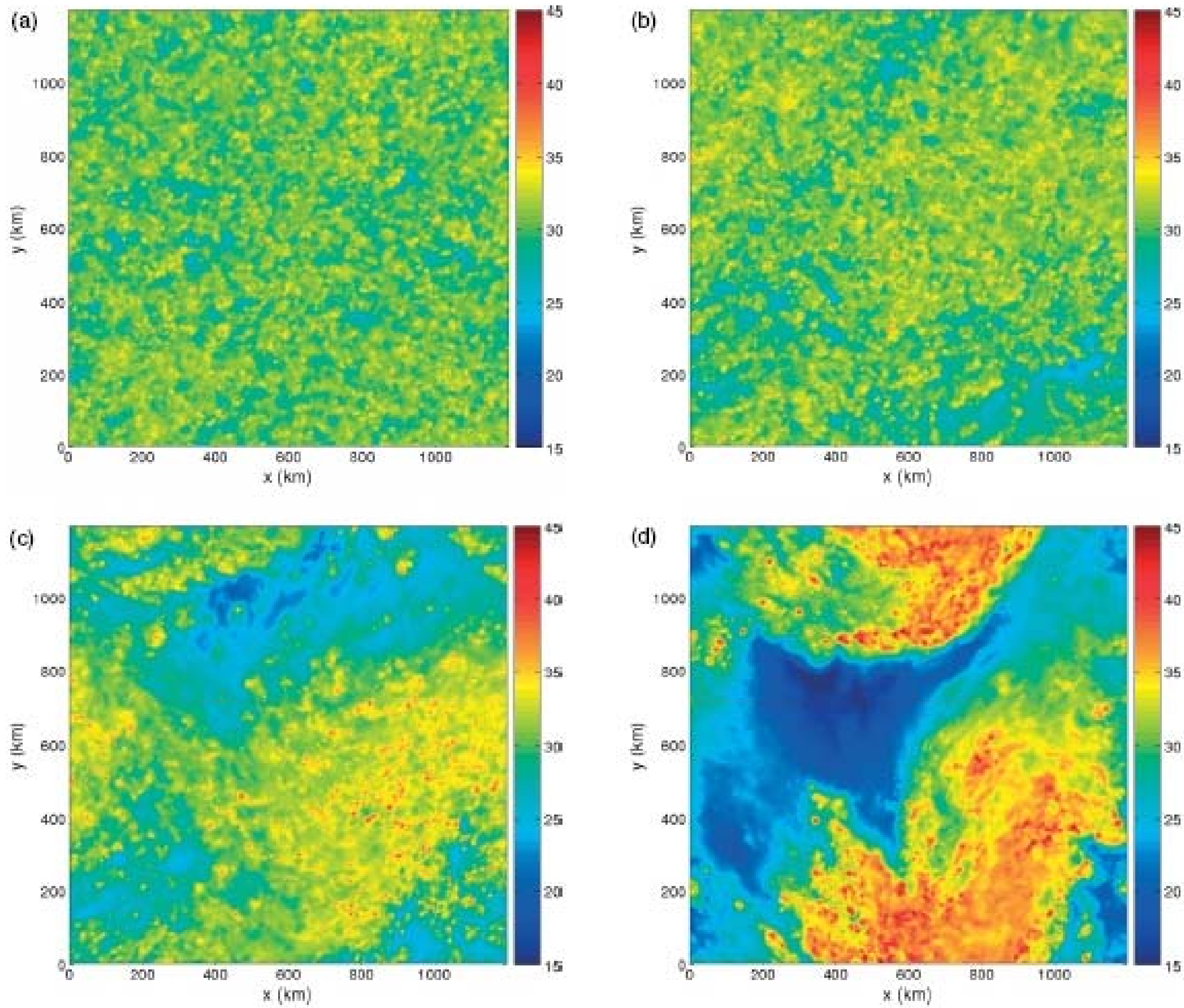
Simplest Statistical Equilibrium State:

Radiative-Convective Equilibrium

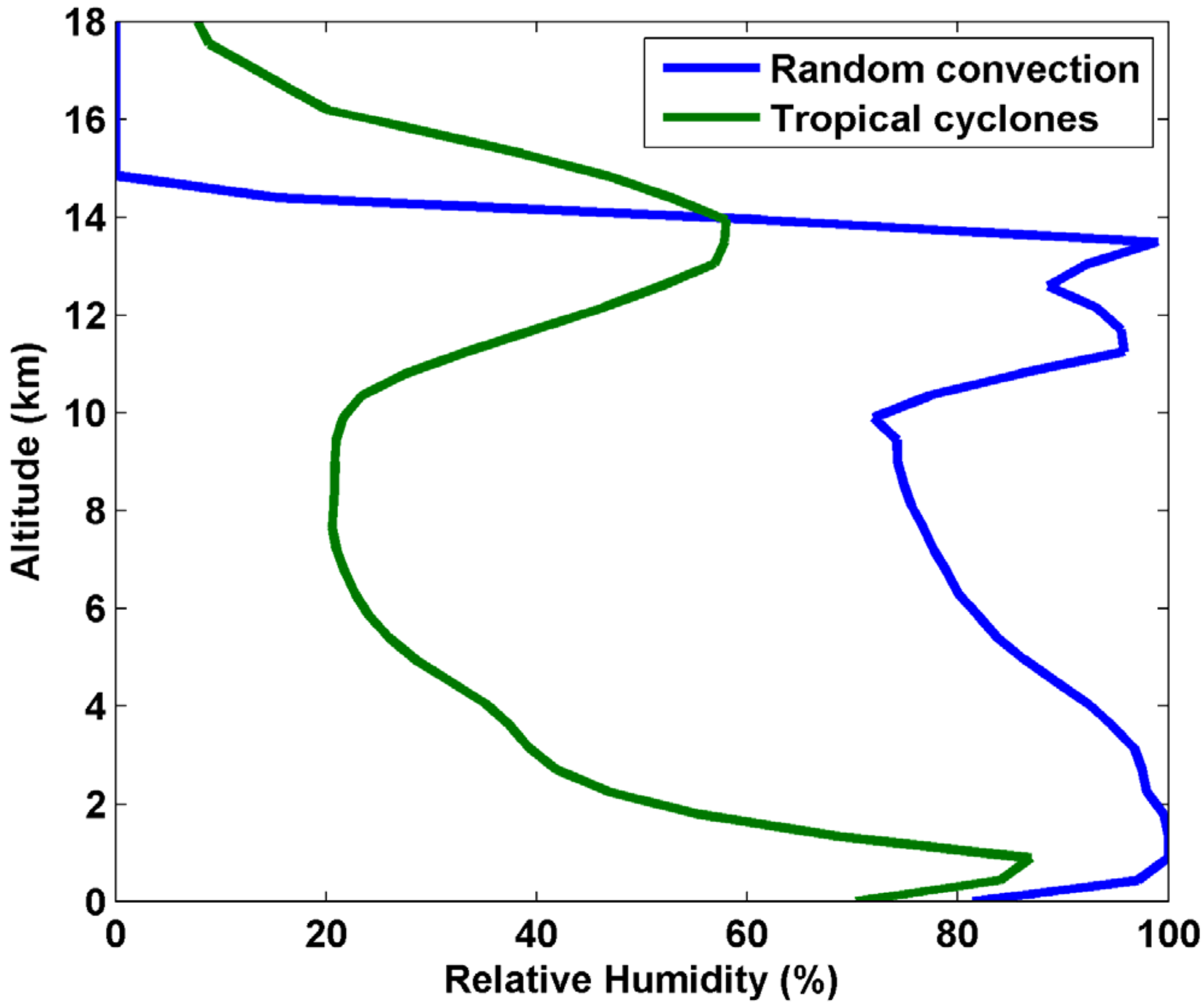
Vertically integrated water vapor at 4 days (Nolan et al., QJRMS, 2007)



Vertically integrated water vapor at 4 (a), 6 (b), 8 (c), and 10 (d) days (Nolan et al., QJRMS, 2007)

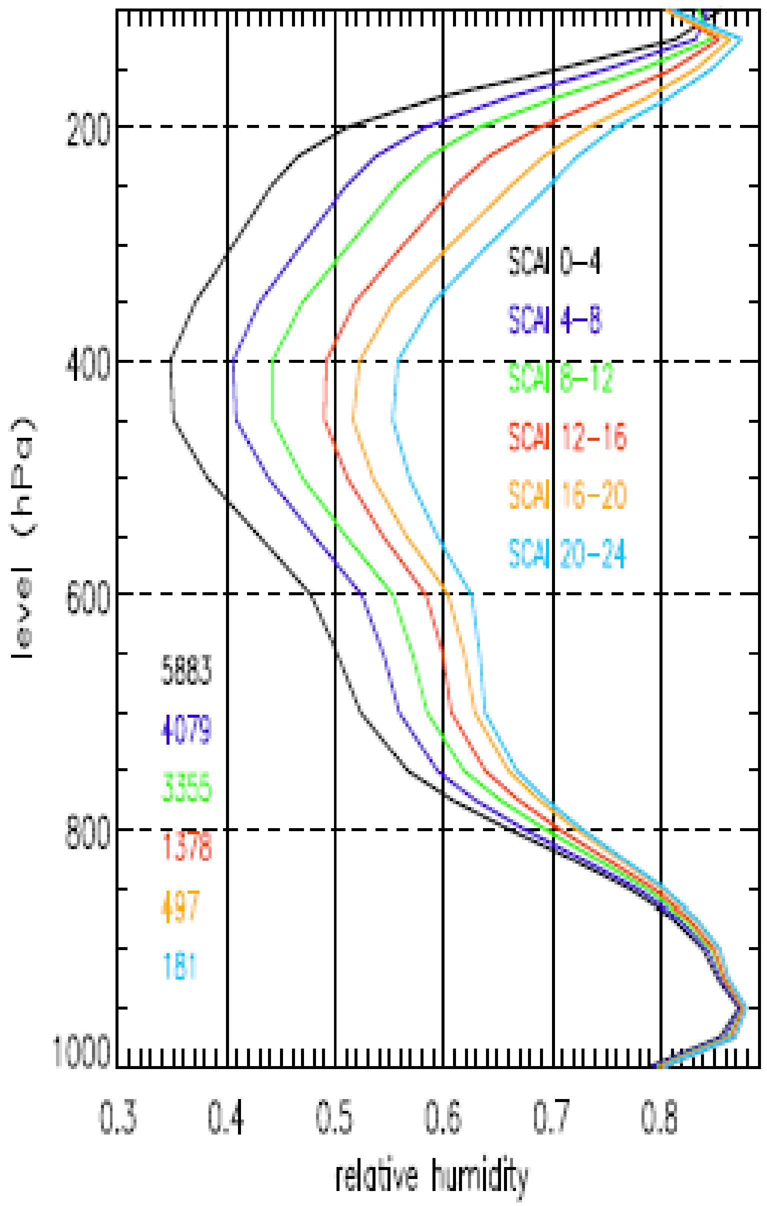


Nolan et al., QJRMS, 2007



Variation of tropical relative humidity profiles with a Simple Convective Aggregation Index (SCAI).

Courtesy Isabelle Tobin, Sandrine Bony, and Remy Roca



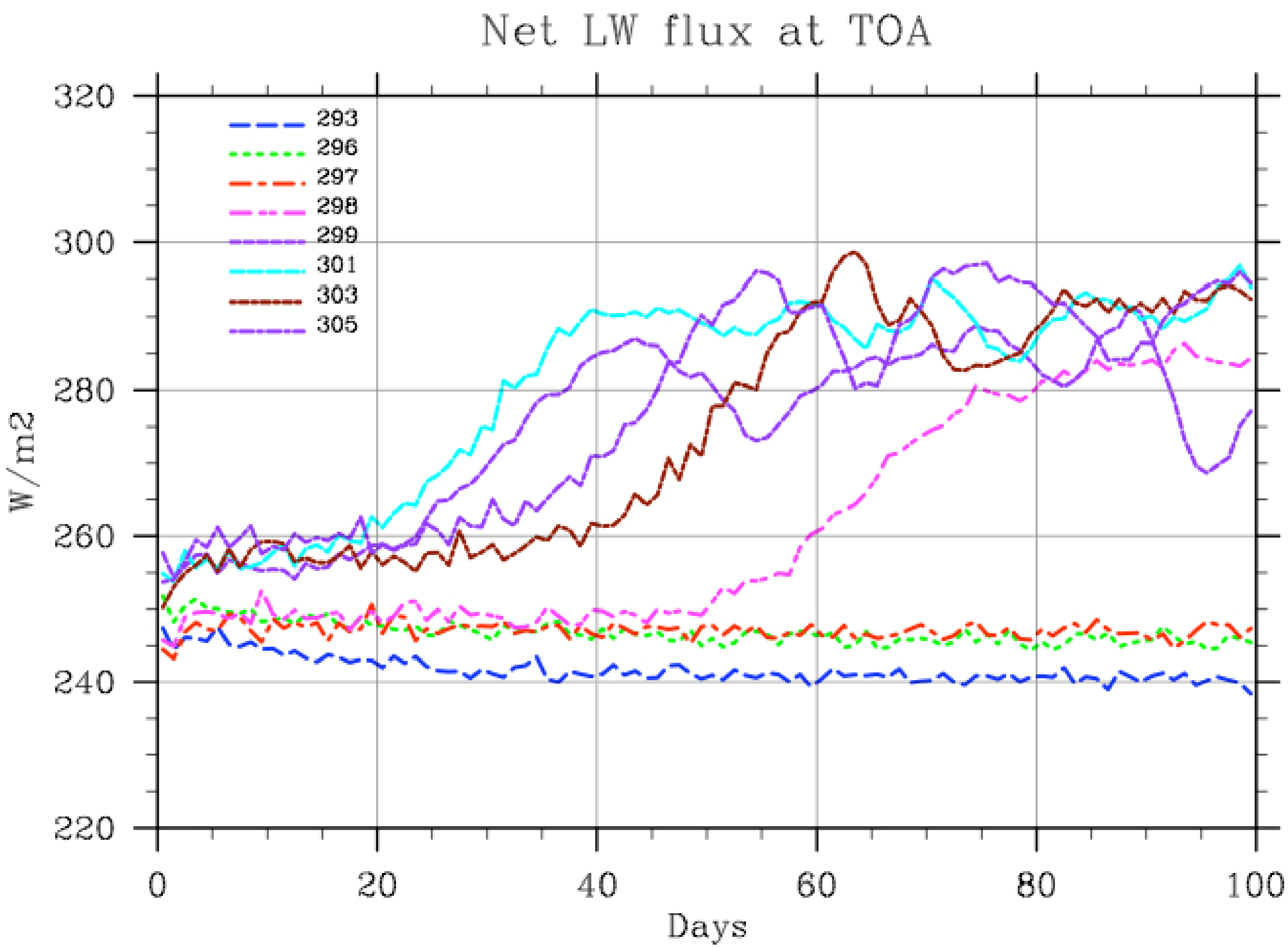
Empirical Necessary Conditions for Self-Aggregation

(after Held et al., 1993; Bretherton et al., 2005; Nolan et al.; 2007)

- Small vertical shear of horizontal wind
- Interaction of radiation with clouds and/or water vapor
- Feedback of convective downdraft surface winds on surface fluxes
- Sufficiently high surface temperature

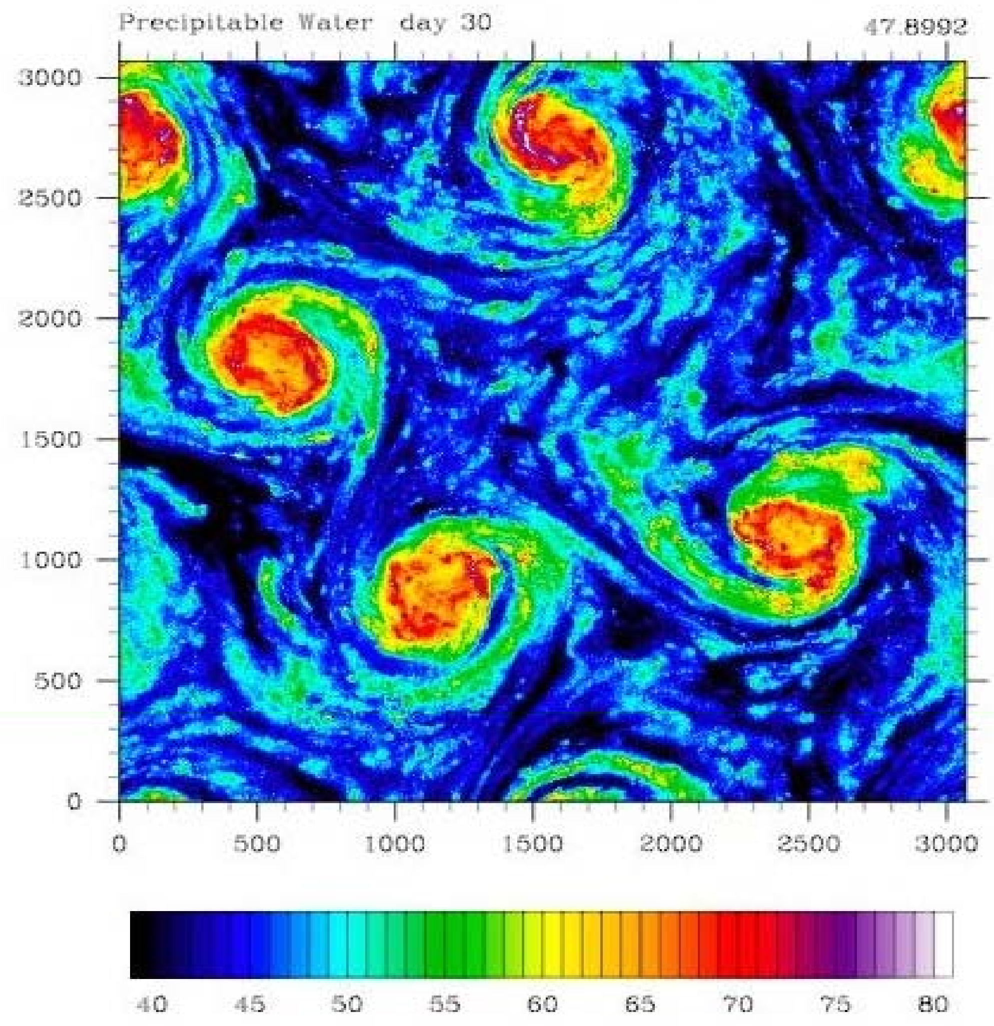
Self-Aggregation is Temperature-Dependent

(Nolan et al., 2007; Emanuel and Khairoutdinov, in preparation, 2012)



Extension to Rotating Planet

Distance between vortex centers scales as V_{pot}/f



TC-World Scaling

- Frequency ~ $\frac{f^2}{V_{pot}^2}$
- Intensity ~ V_{pot}
- Power Dissipation ~ $V_{pot} f^2$

Hypothesis

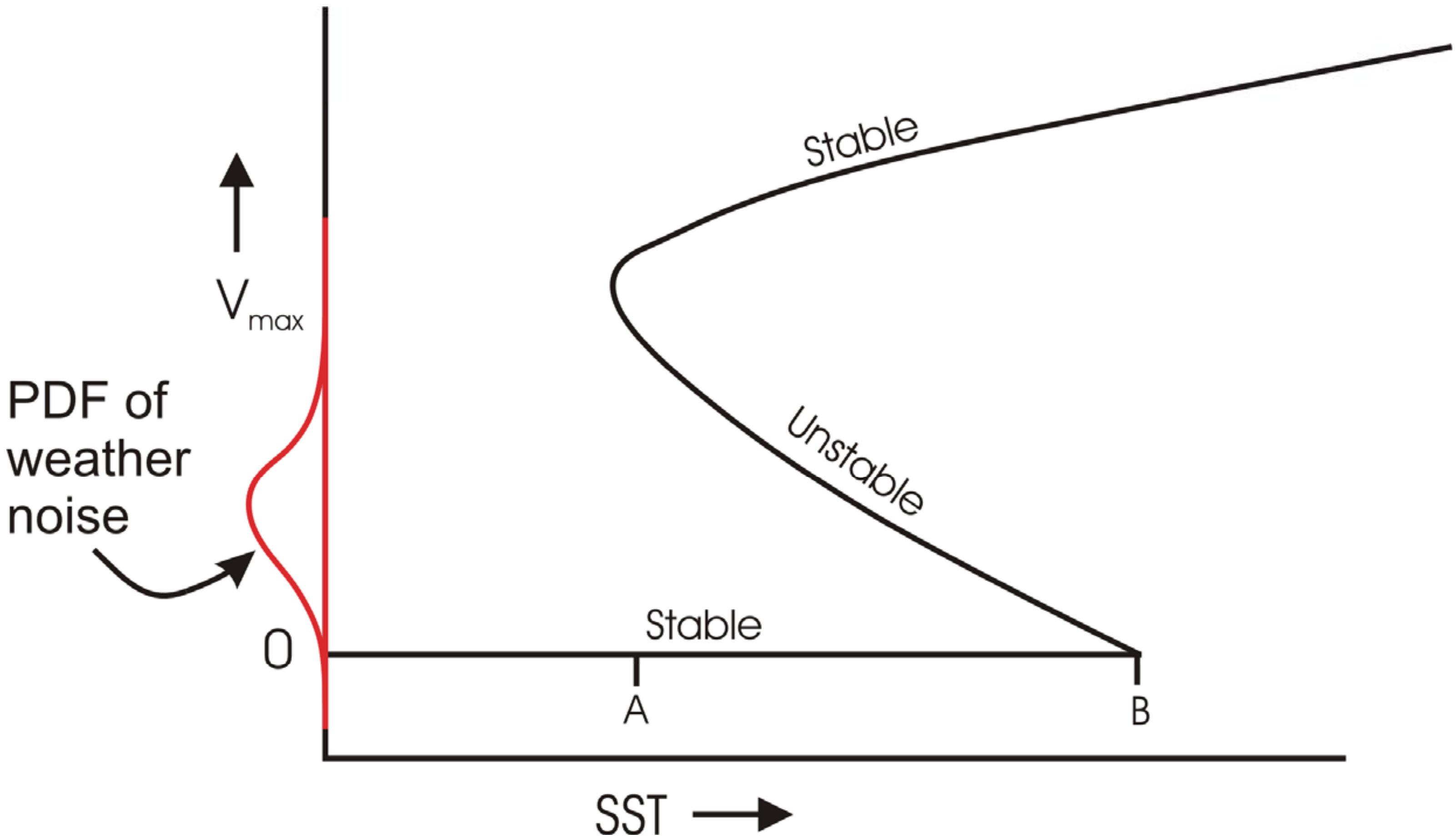
- At high temperature, convection self-aggregates
- →Horizontally averaged humidity drops dramatically
- →Reduced greenhouse effect cools system
- →Convection disaggregates
- →Humidity increases, system warms
- →System wants to be near phase transition to aggregated state

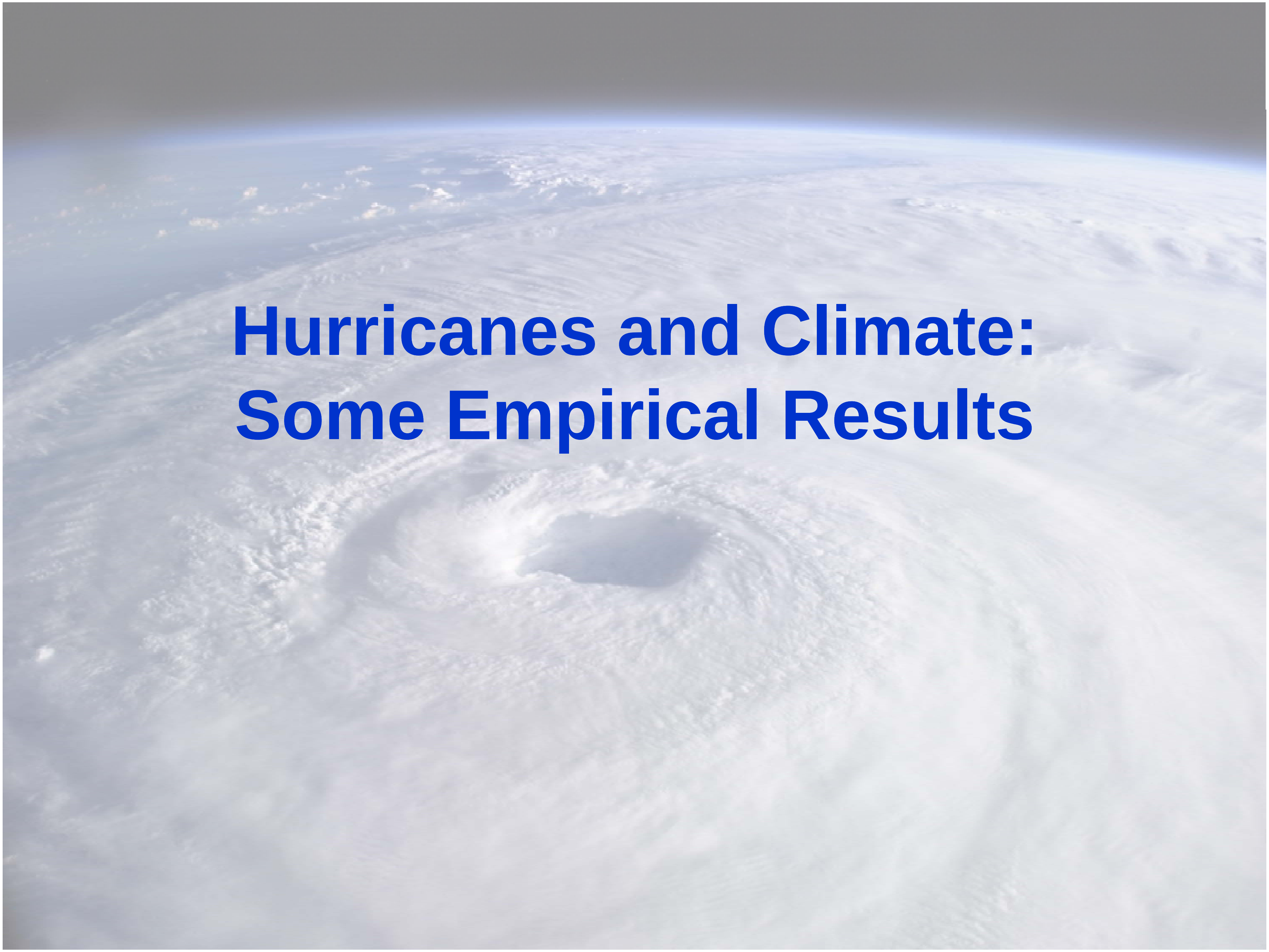
Recipe for Self-Organized Criticality

(First proposed by David Neelin, but by different mechanism)

- System should reside near critical threshold for self-aggregation
- Convective cluster size should follow power law distribution

Hypothetical Subcritical Bifurcation




Hurricanes and Climate:
Some Empirical Results

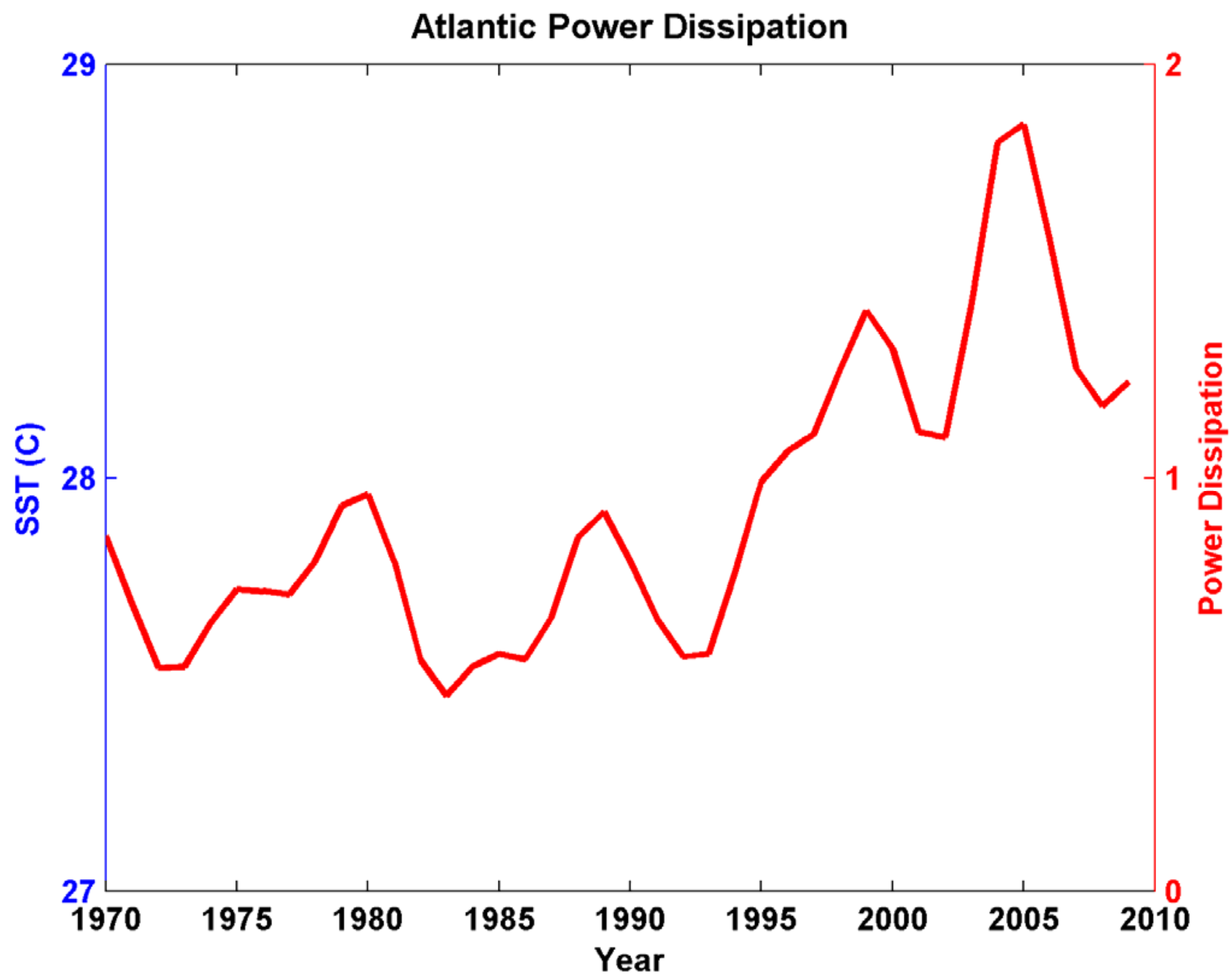
Intensity Metric:

Hurricane Power
(Power Dissipation Index)

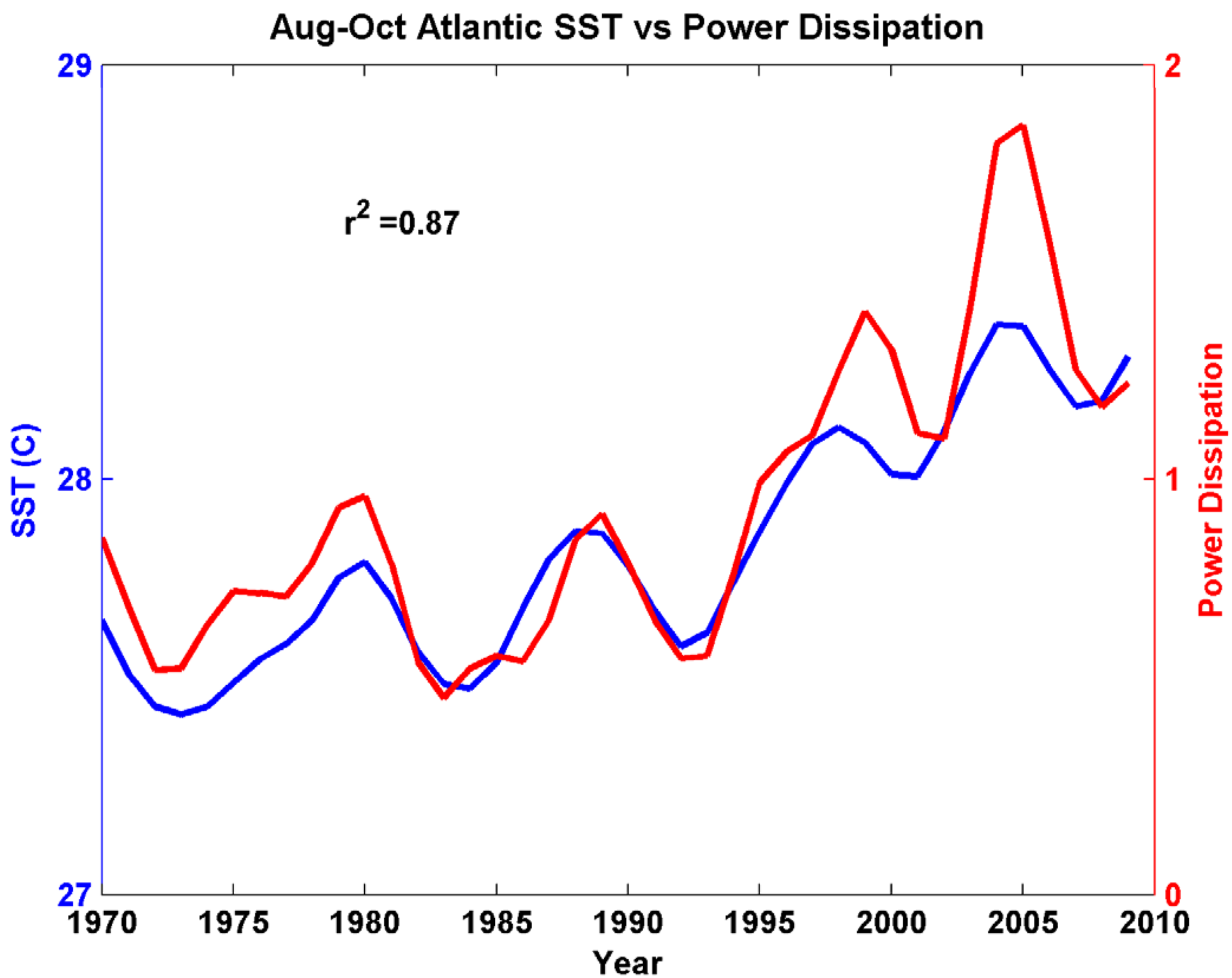
$$PDI \equiv \int_0^{\tau} V_{max}^3 \, dt$$

A measure of the total frictional dissipation of kinetic energy in the hurricane boundary layer over the lifetime of the storm

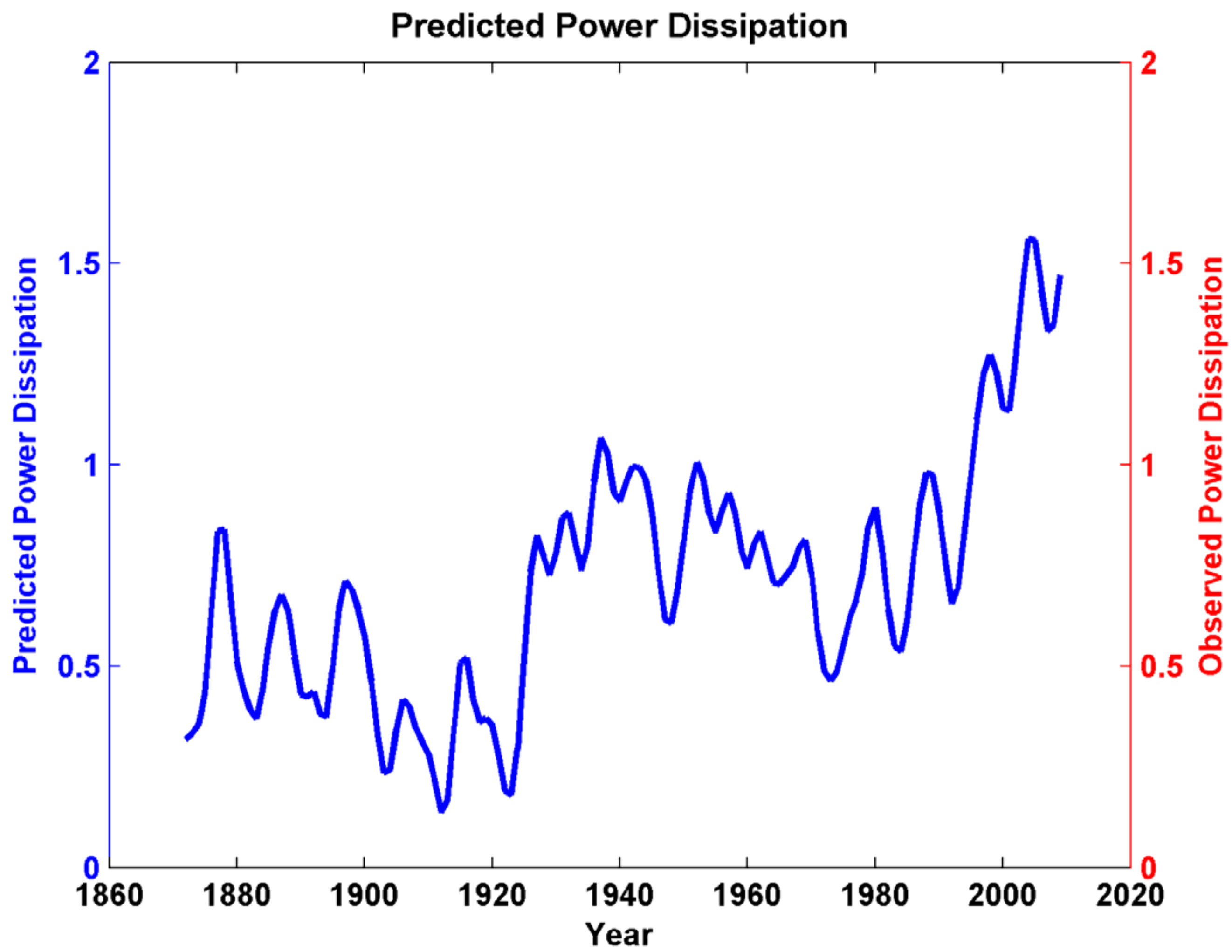
Atlantic Tropical Cyclone Power Dissipation during an era of high quality measurements, 1970-2011 (smoothed with 1-3-4-3-1 filter)



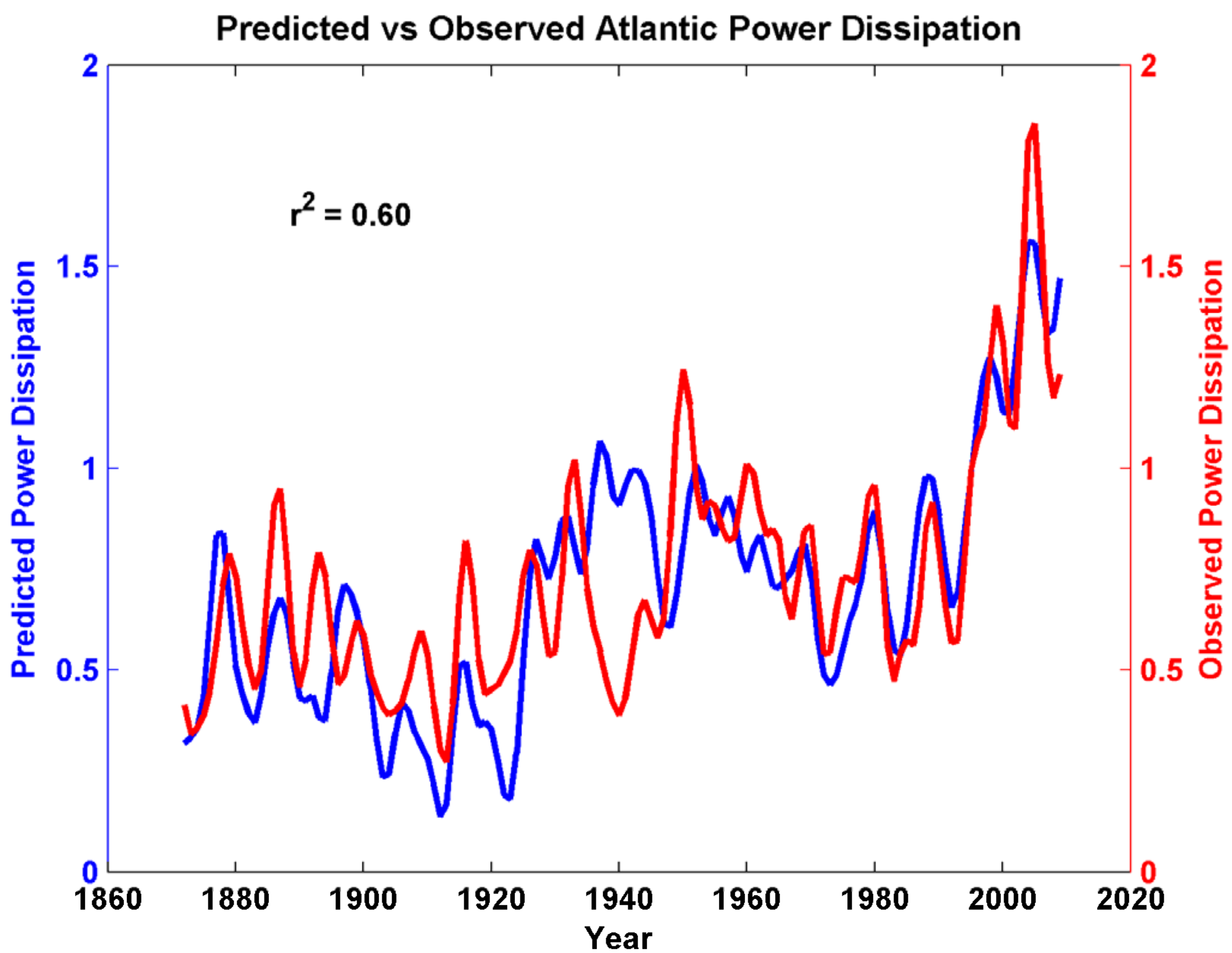
Atlantic Tropical Cyclone Power Dissipation and Sea Surface Temperature during an era of high quality measurements, 1970-2011 (smoothed with 1-3-4-3-1 filter)

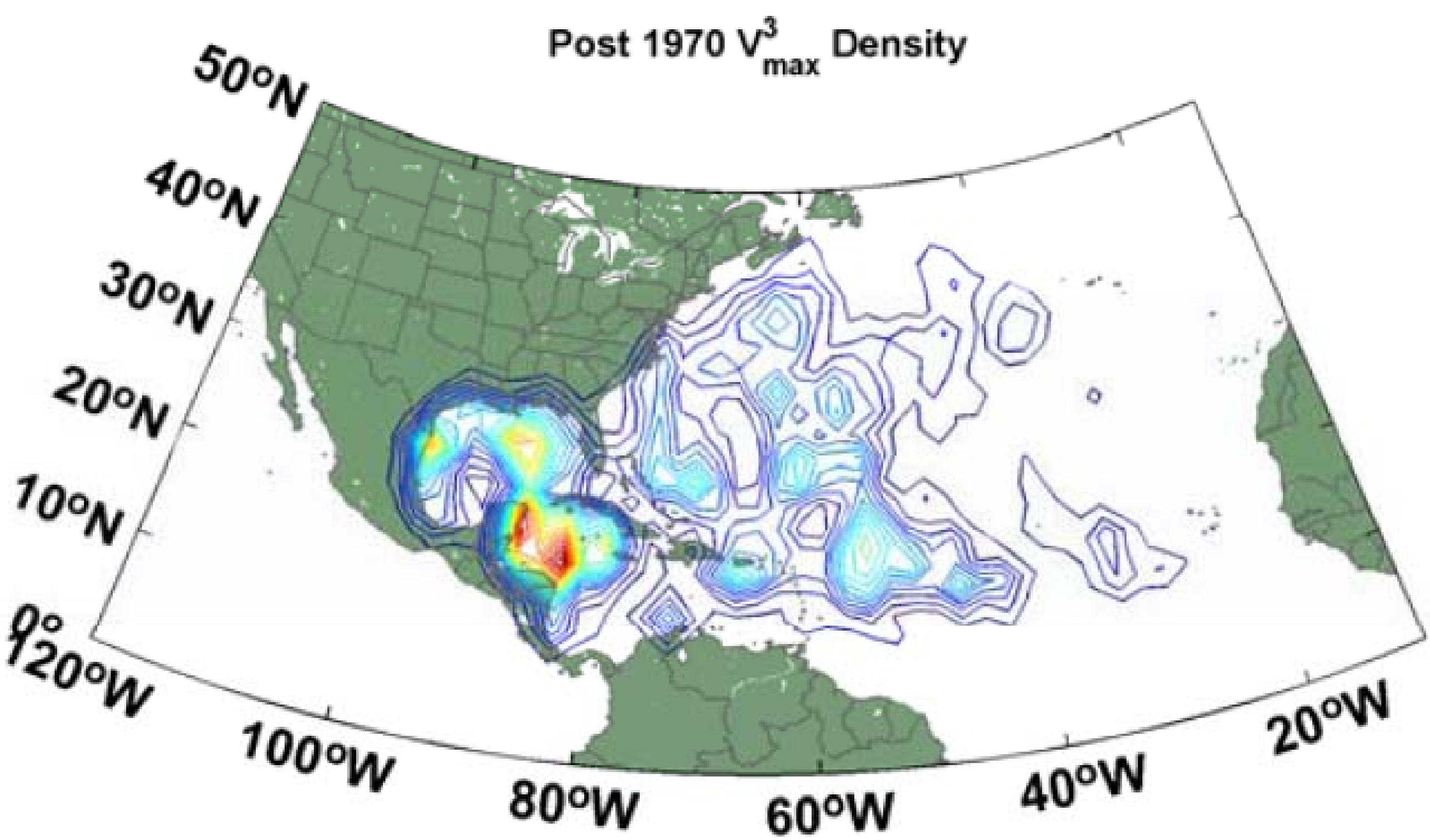


Use Linear Regression to Predict Power Dissipation back to 1870 based on SST:

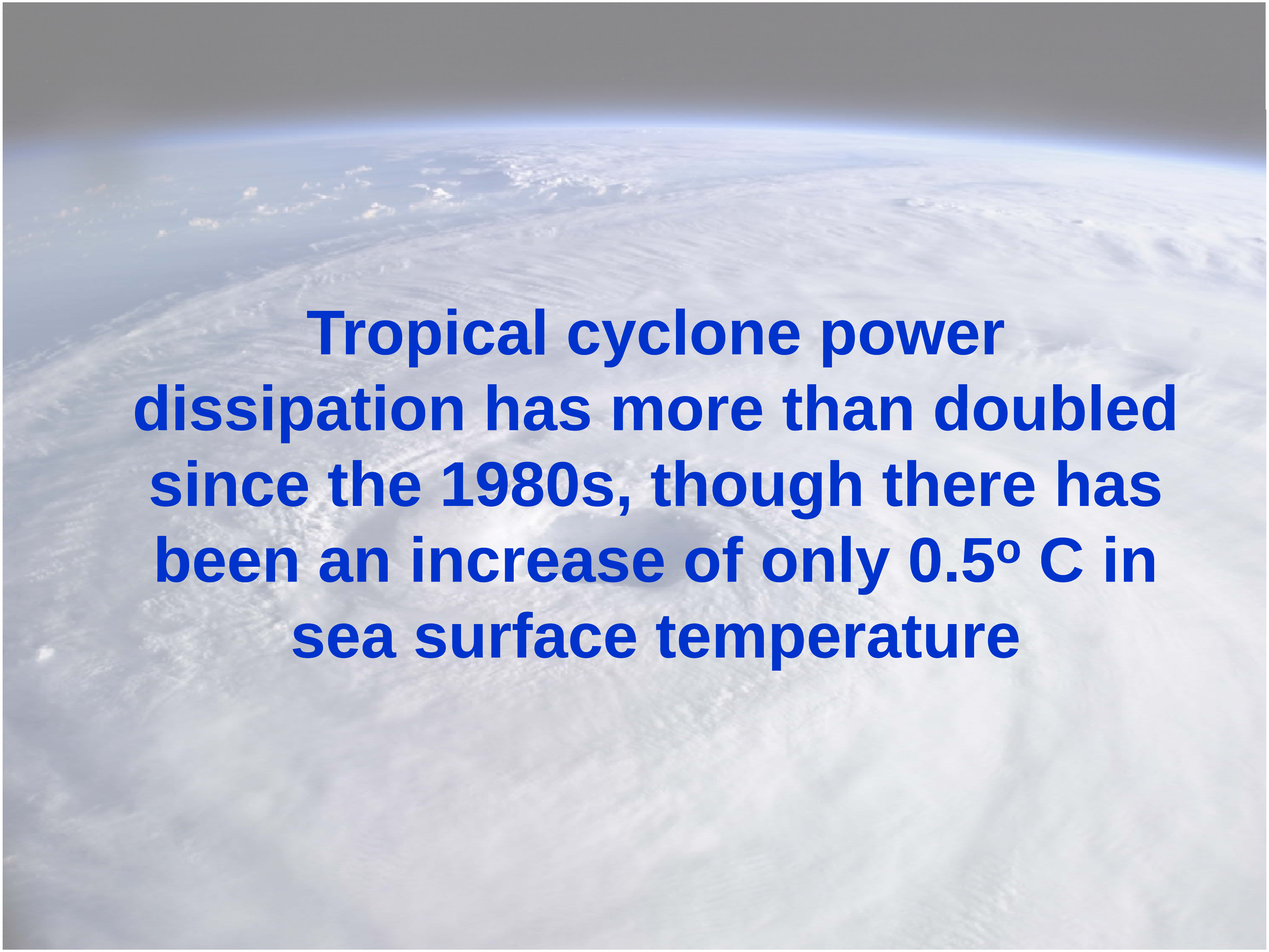


Now Compare to Observed Power Dissipation

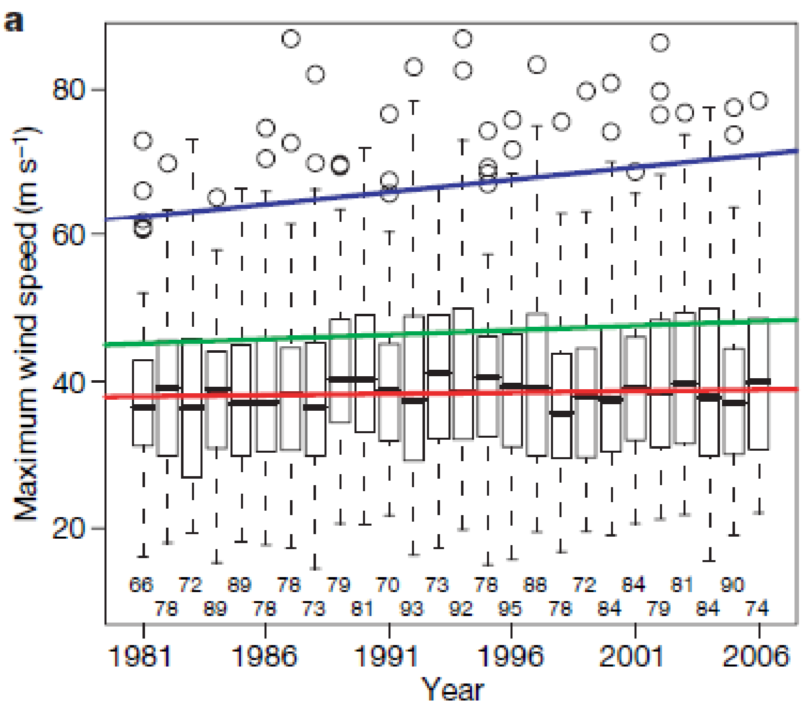




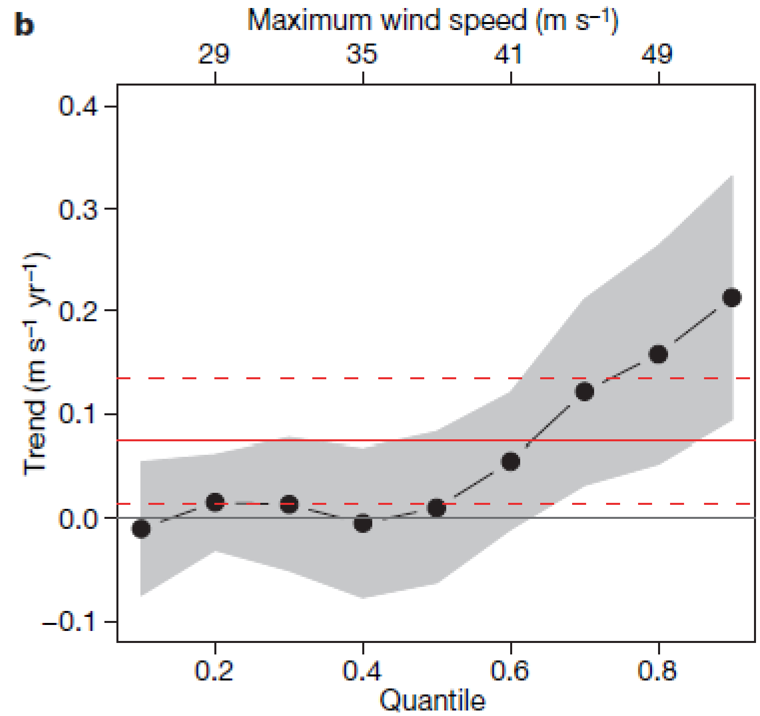
Post 1970 V^3_{max} Density
50°N
40°N
30°N
20°N
10°N
0°
120°W
100°W
80°W
60°W
40°W
20°W


Tropical cyclone power dissipation has more than doubled since the 1980s, though there has been an increase of only 0.5^{o} C in sea surface temperature

Analysis of satellite-derived tropical cyclone lifetime-maximum wind speeds

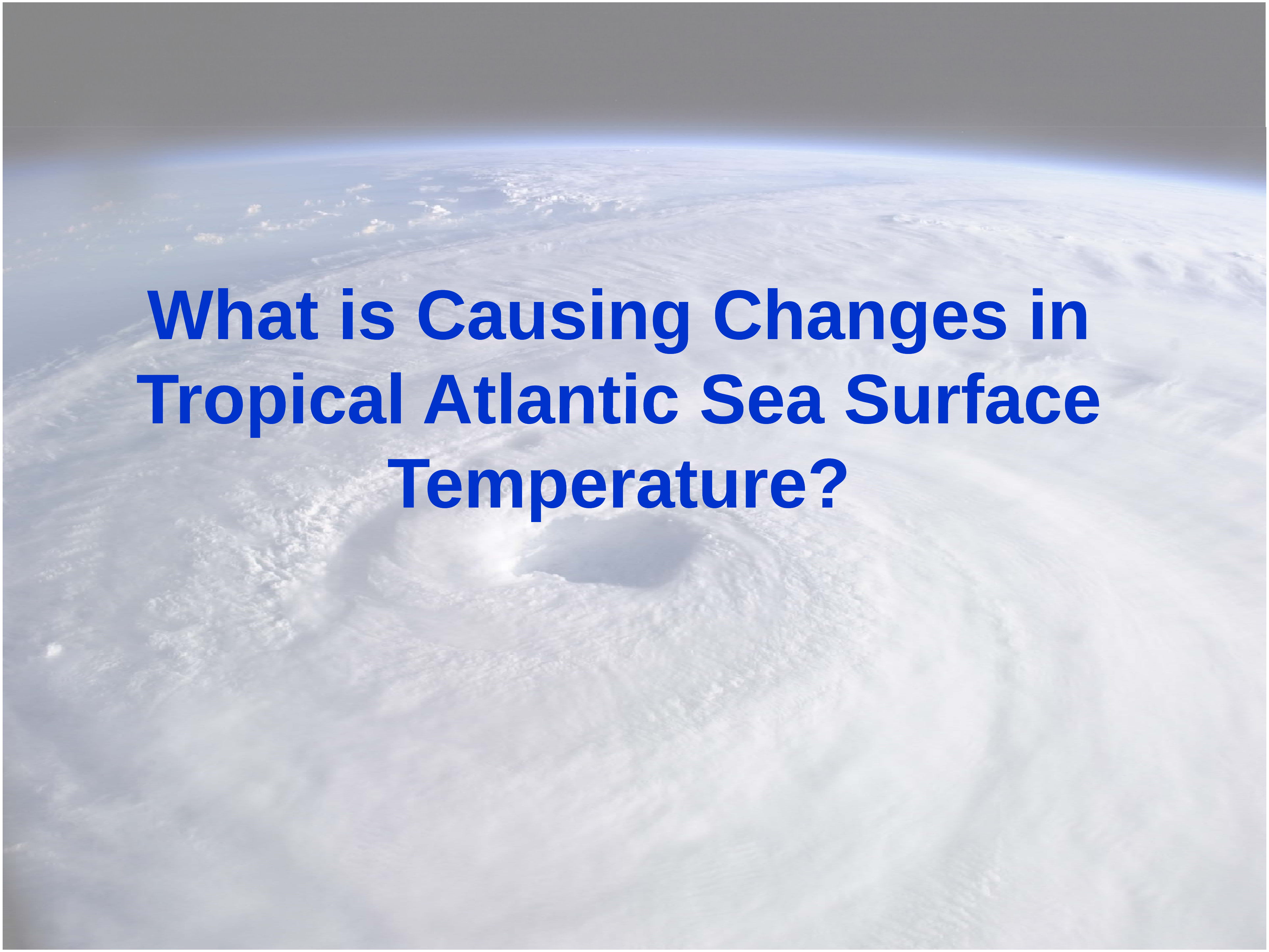


Box plots by year. Trend lines are shown for the median, 0.75 quantile, and 1.5 times the interquartile range

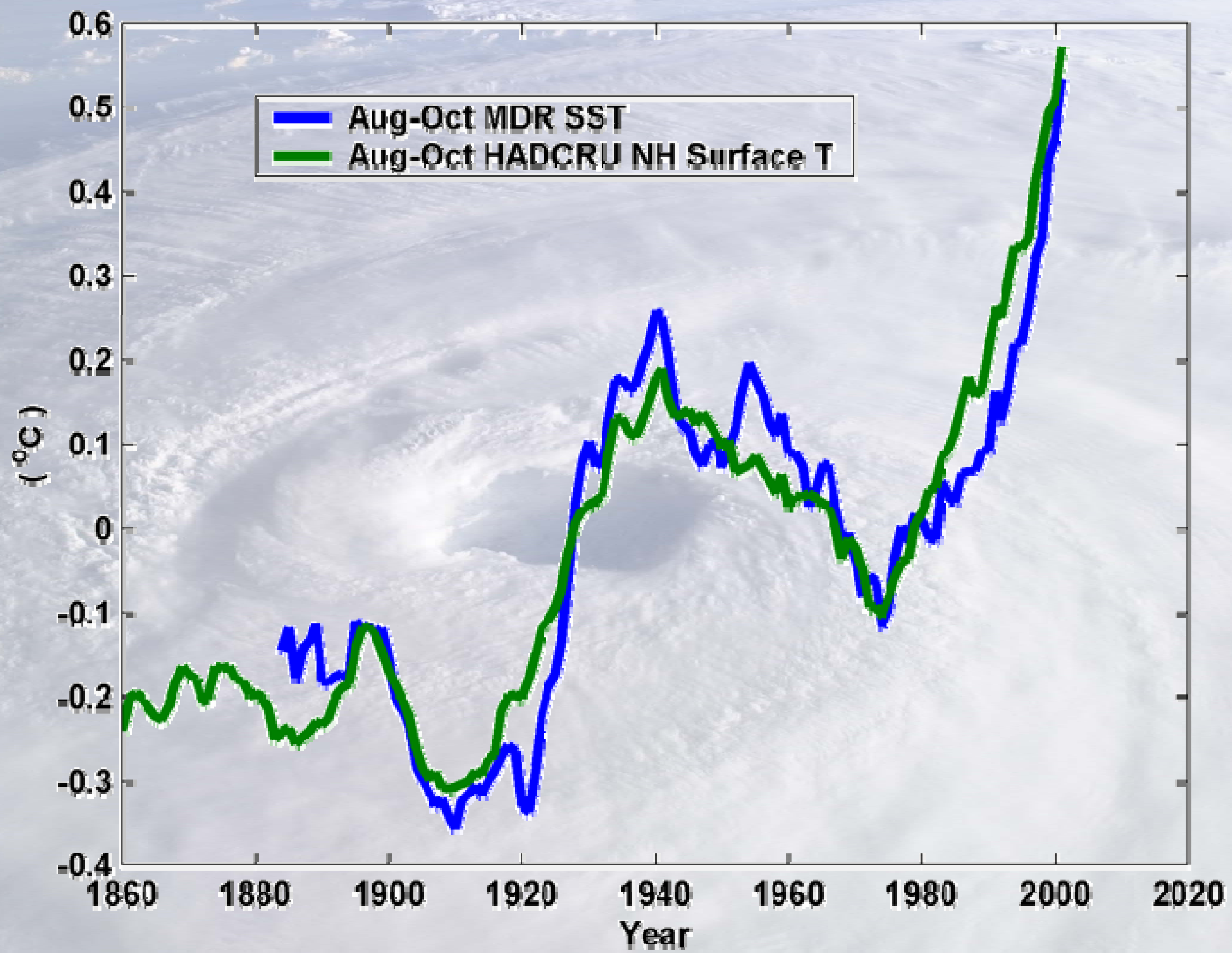


Trends in global satellite-derived tropical cyclone maximum wind speeds by quantile, from 0.1 to 0.9 in increments of 0.1.

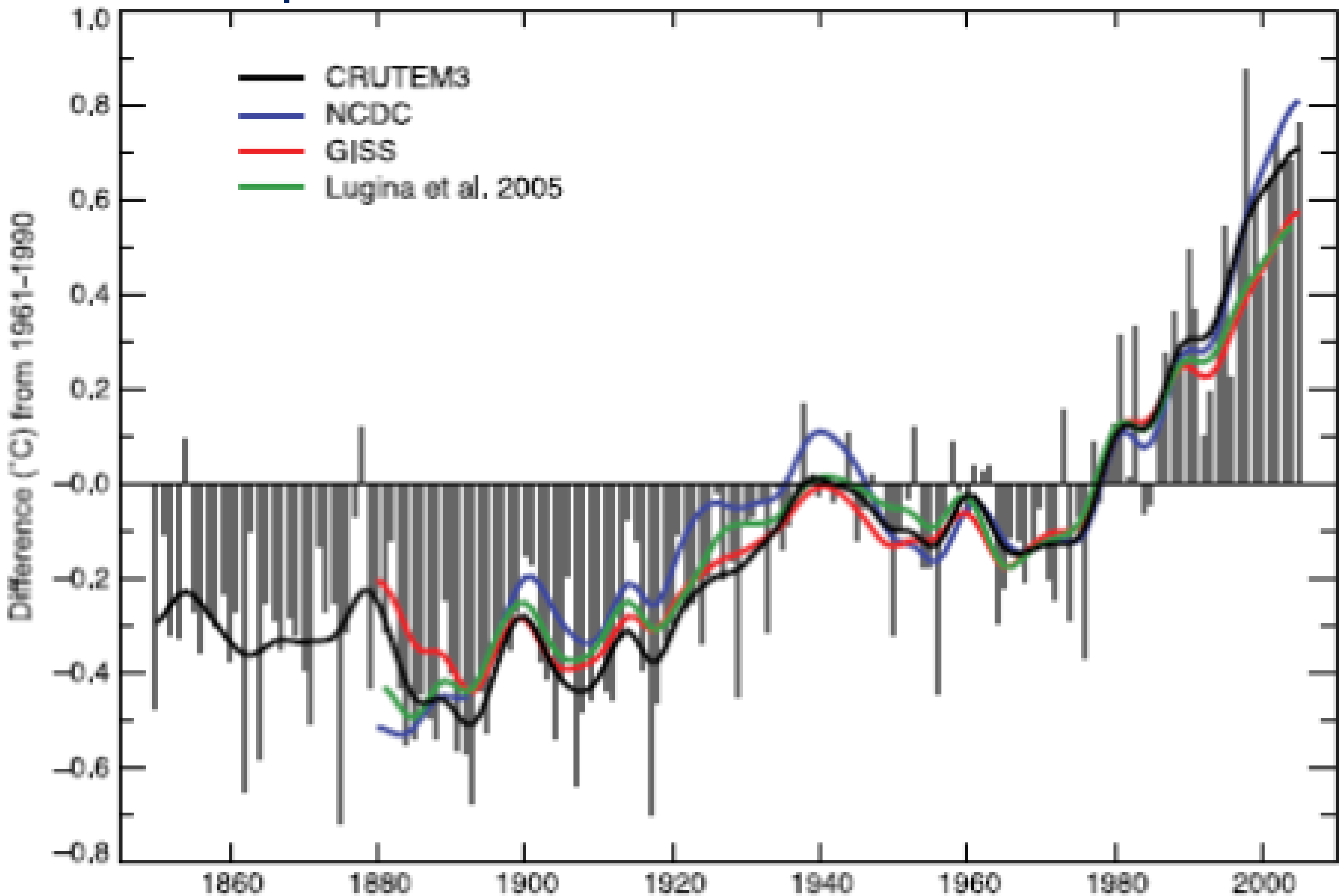
Elsner, Kossin, and Jagger, *Nature*, 2008

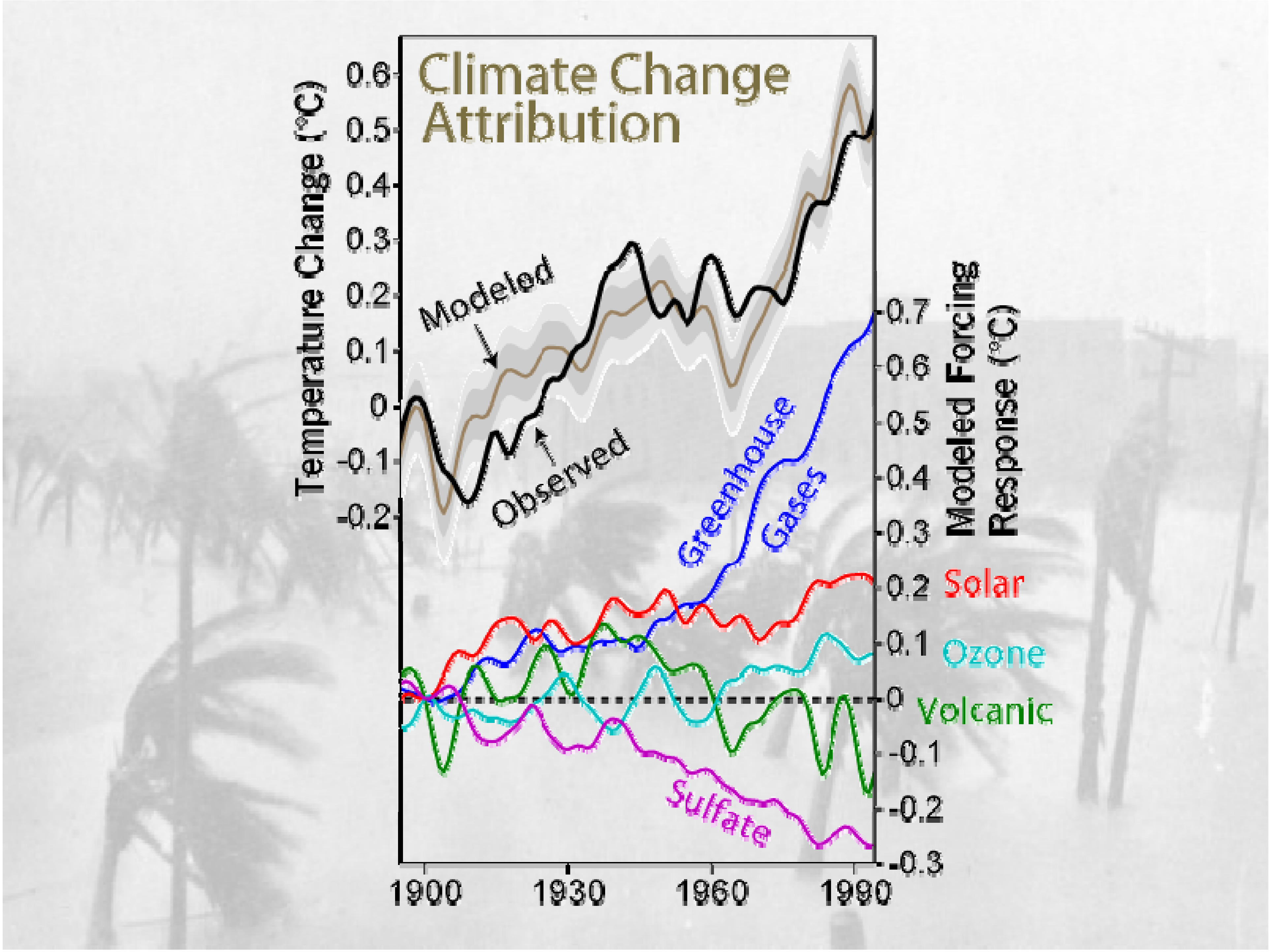

What is Causing Changes in
Tropical Atlantic Sea Surface
Temperature?

10-year Running Average of Aug-Oct Northern Hemisphere Surface Temp and Hurricane Region Ocean Temp



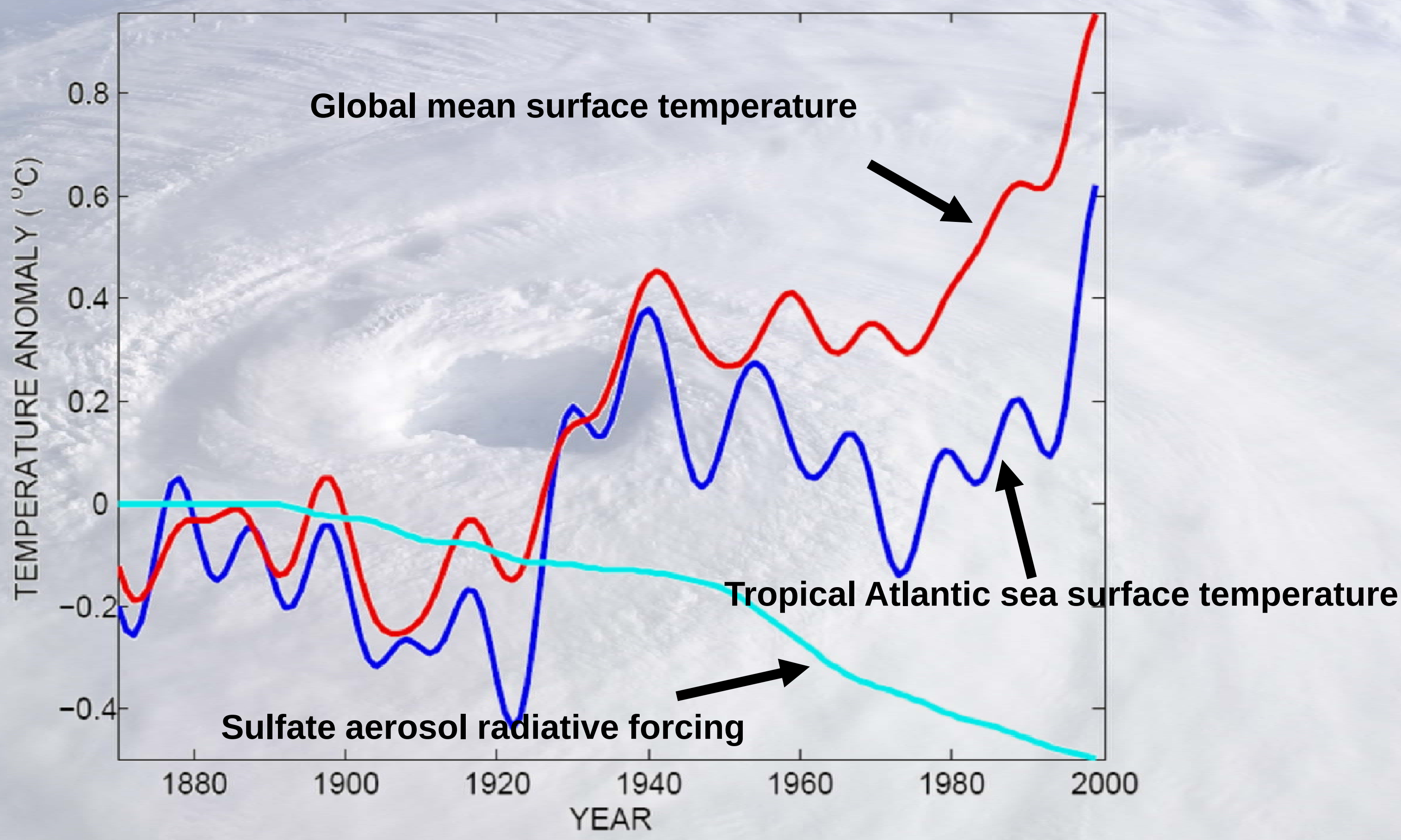
Estimates of Global Mean Surface Temperature from the Instrumental Record





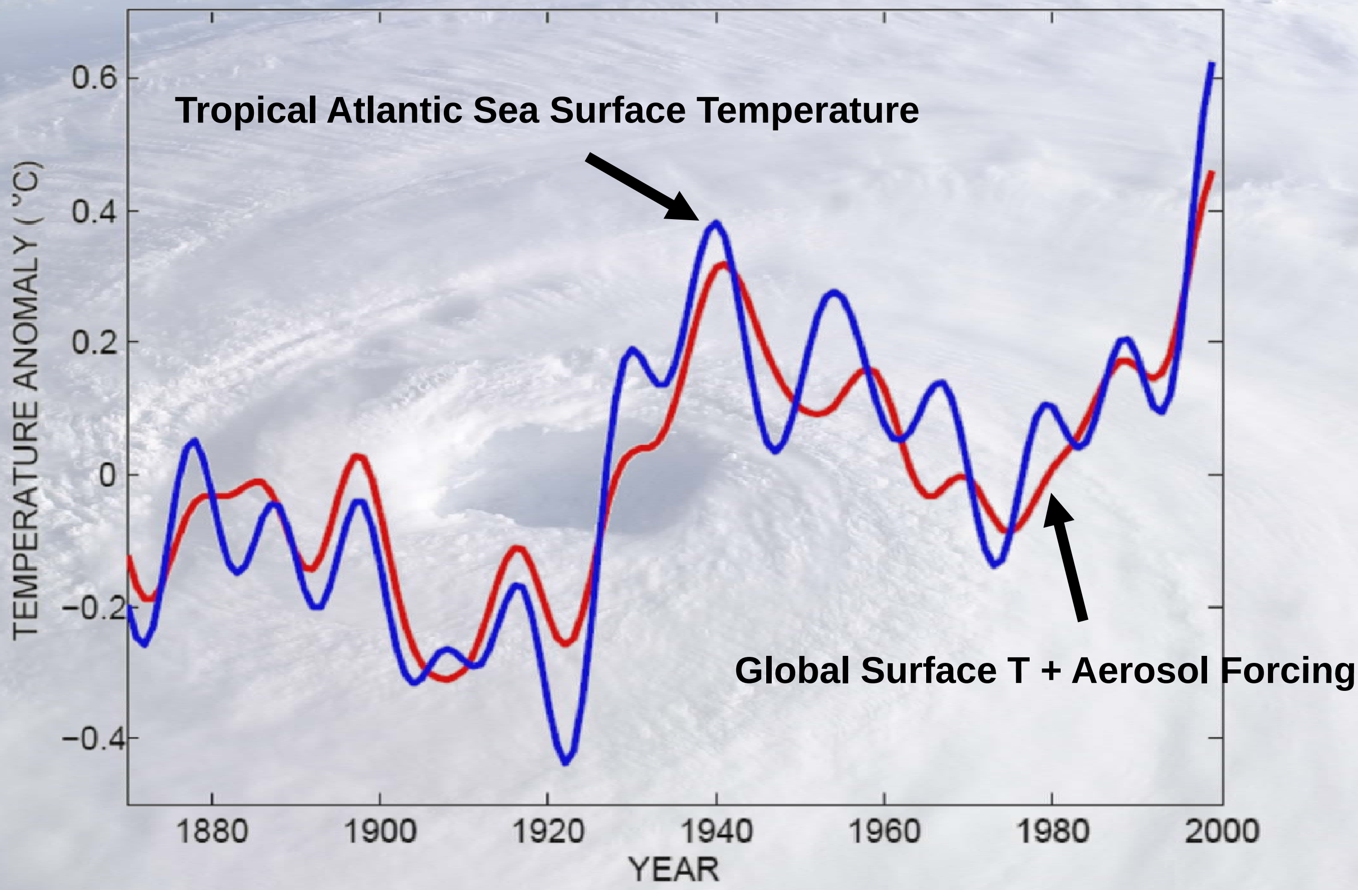
Climate Change
Attribution
Temperature Change (°C)
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
Modeled
Observed
Modeled Forcing
Response (°C)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
Greenhouse
Gases
Solar
Ozone
Volcanic
Sulfate
1900
1930
1960
1990

Tropical Atlantic SST(blue), Global Mean Surface Temperature (red), Aerosol Forcing (aqua)



Mann, M. E., and K. A. Emanuel, 2006. Atlantic hurricane trends linked to climate change. EOS, 87, 233-244.

Best Fit Linear Combination of Global Warming and Aerosol Forcing (red) versus Tropical Atlantic SST (blue)

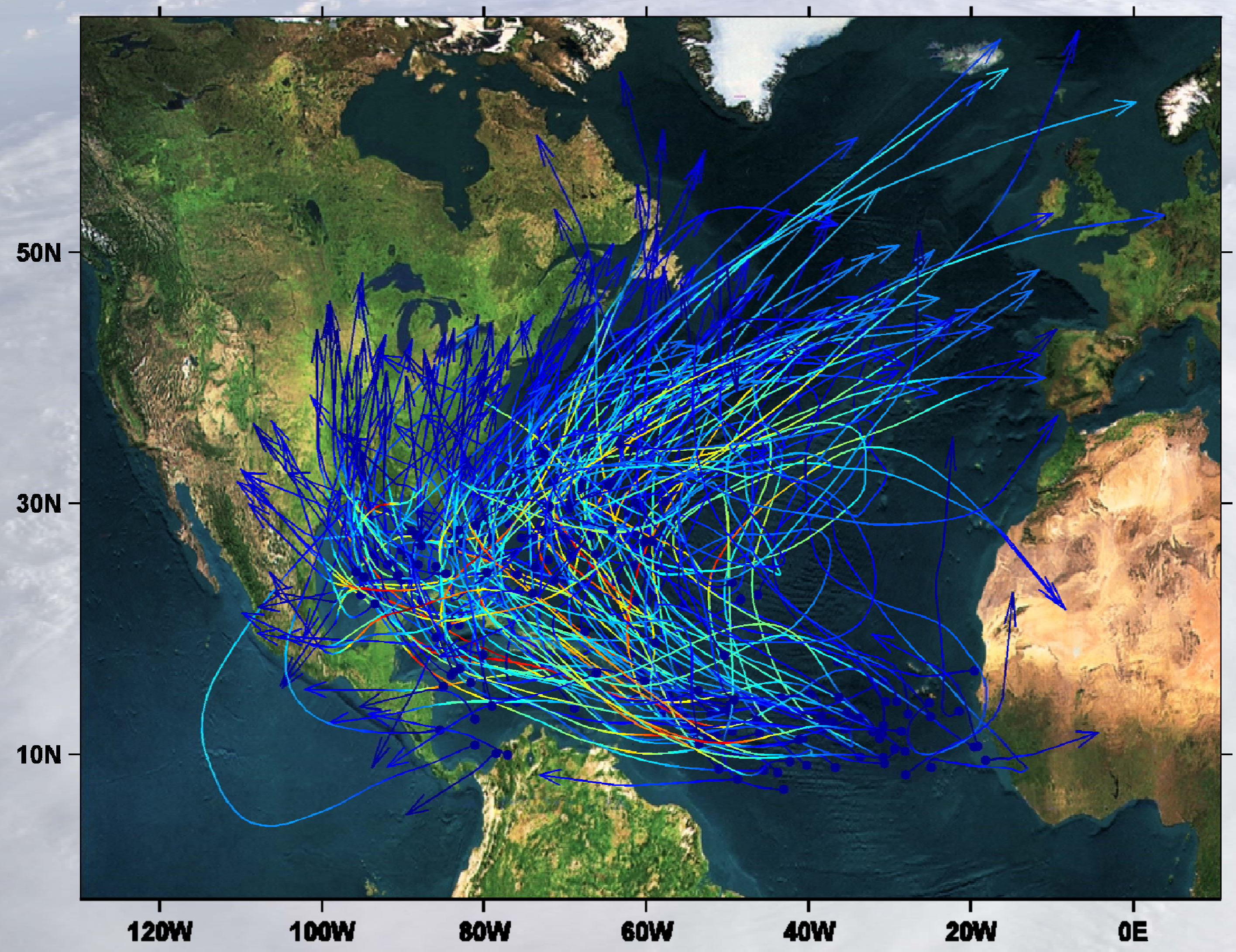


Mann, M. E., and K. A. Emanuel, 2006. Atlantic hurricane trends linked to climate change. EOS, 87, 233-244.

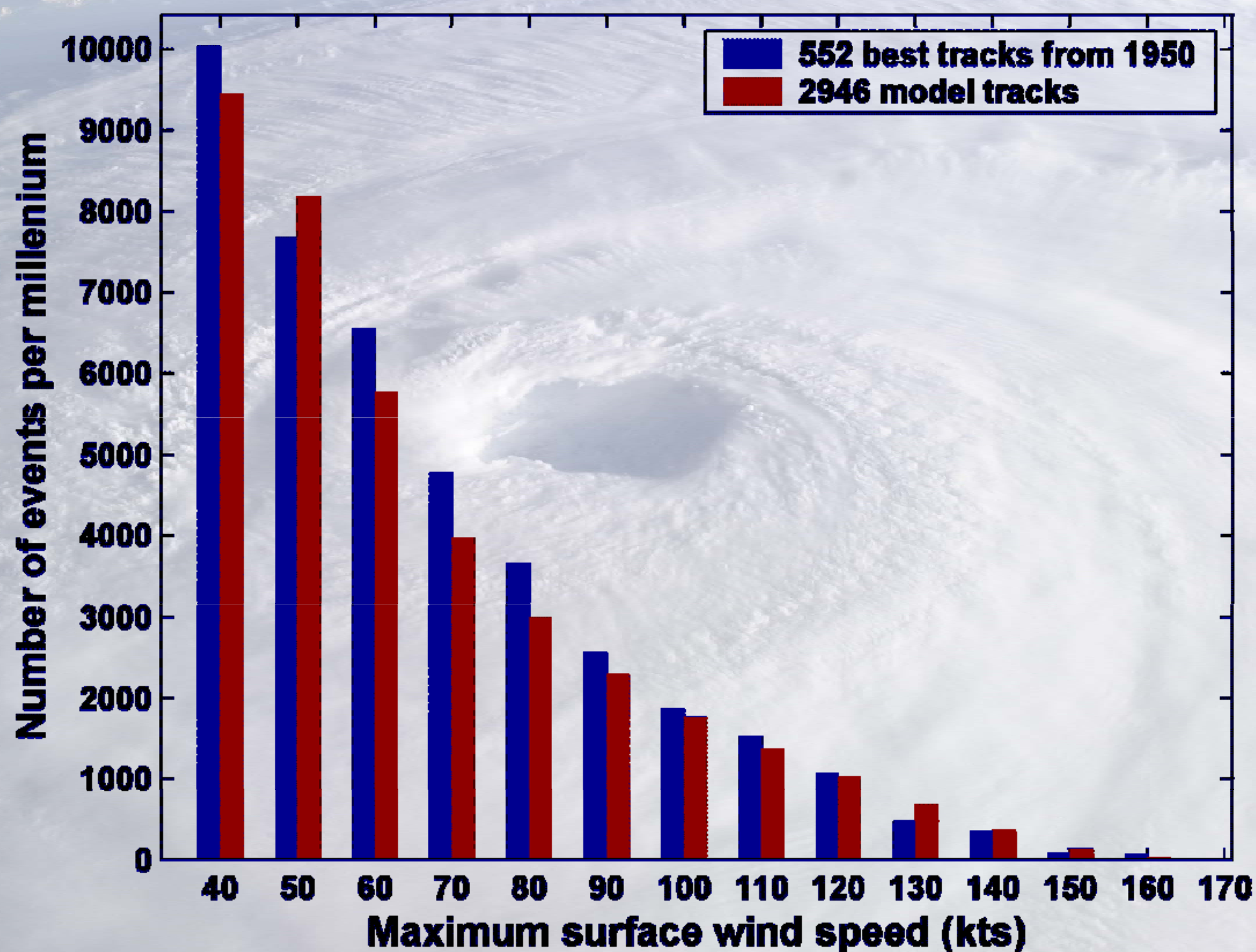
Our Approach to Downscaling Tropical Cyclones from Climate Models

- **Step 1**: Seed each ocean basin with a very large number of weak, randomly located vortices
- **Step 2**: Vortices are assumed to move with the large scale atmospheric flow in which they are embedded
- **Step 3**: Run a coupled, ocean-atmosphere computer model for each vortex, and note how many achieve at least tropical storm strength; discard others
- **Step 4:** Using the small fraction of surviving events, determine storm statistics.

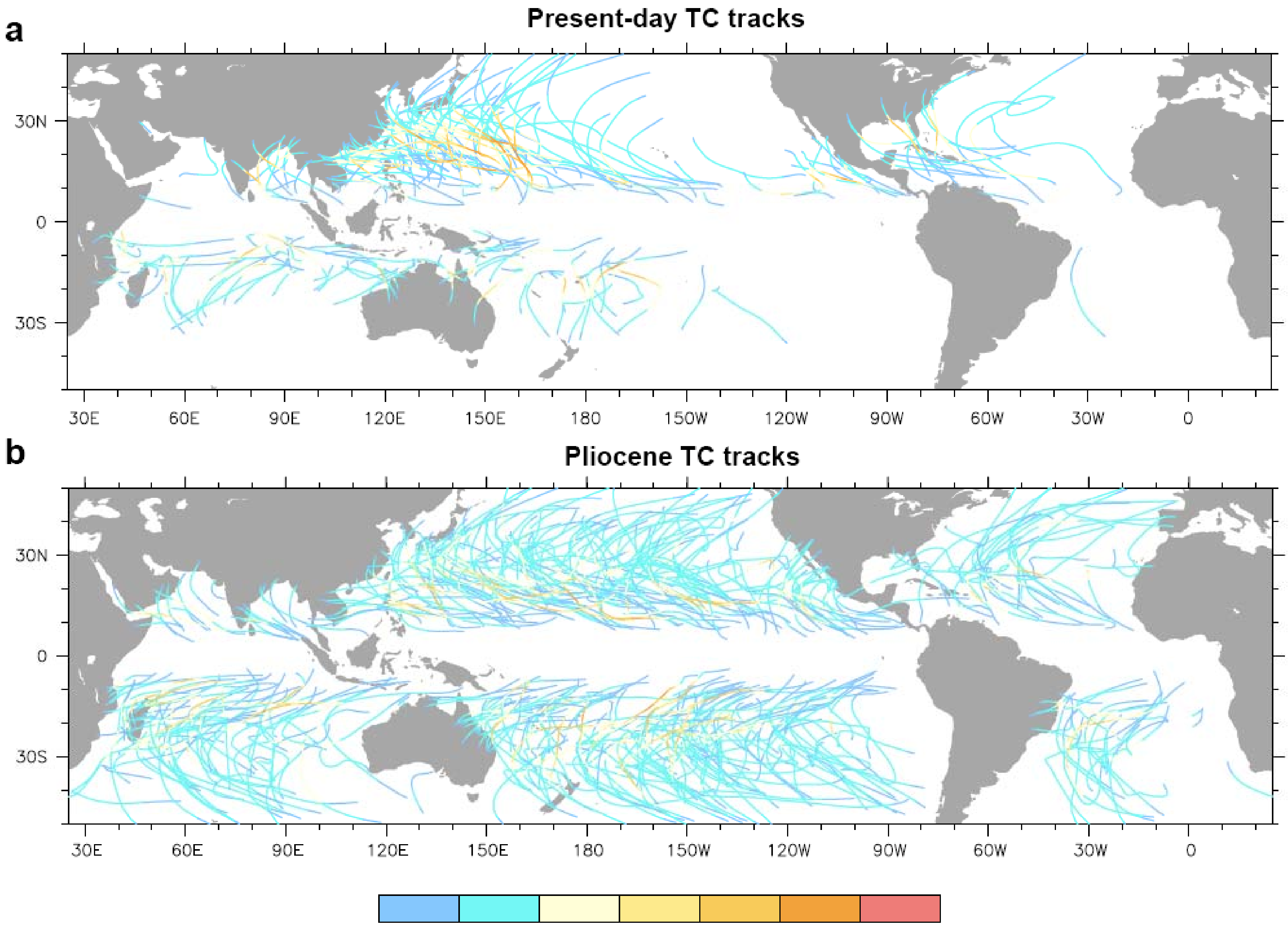
New Downscaling Technique: 200 Synthetic U.S. Landfalling tracks (color coded by S-S Scale)



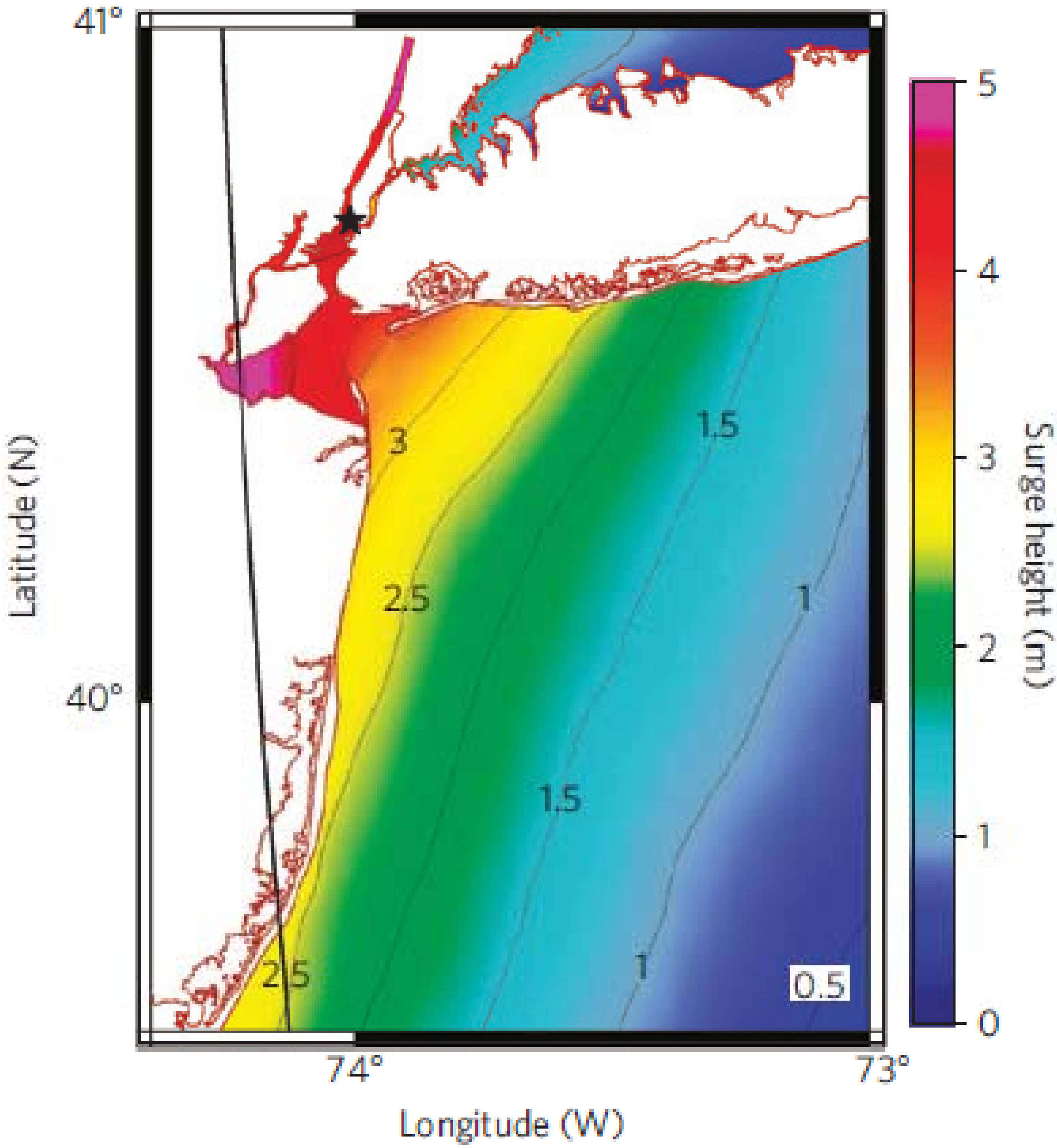
Cumulative Distribution of Storm Lifetime Peak Wind Speed, with Sample of 2946 Synthetic Tracks



Application to Other Climates



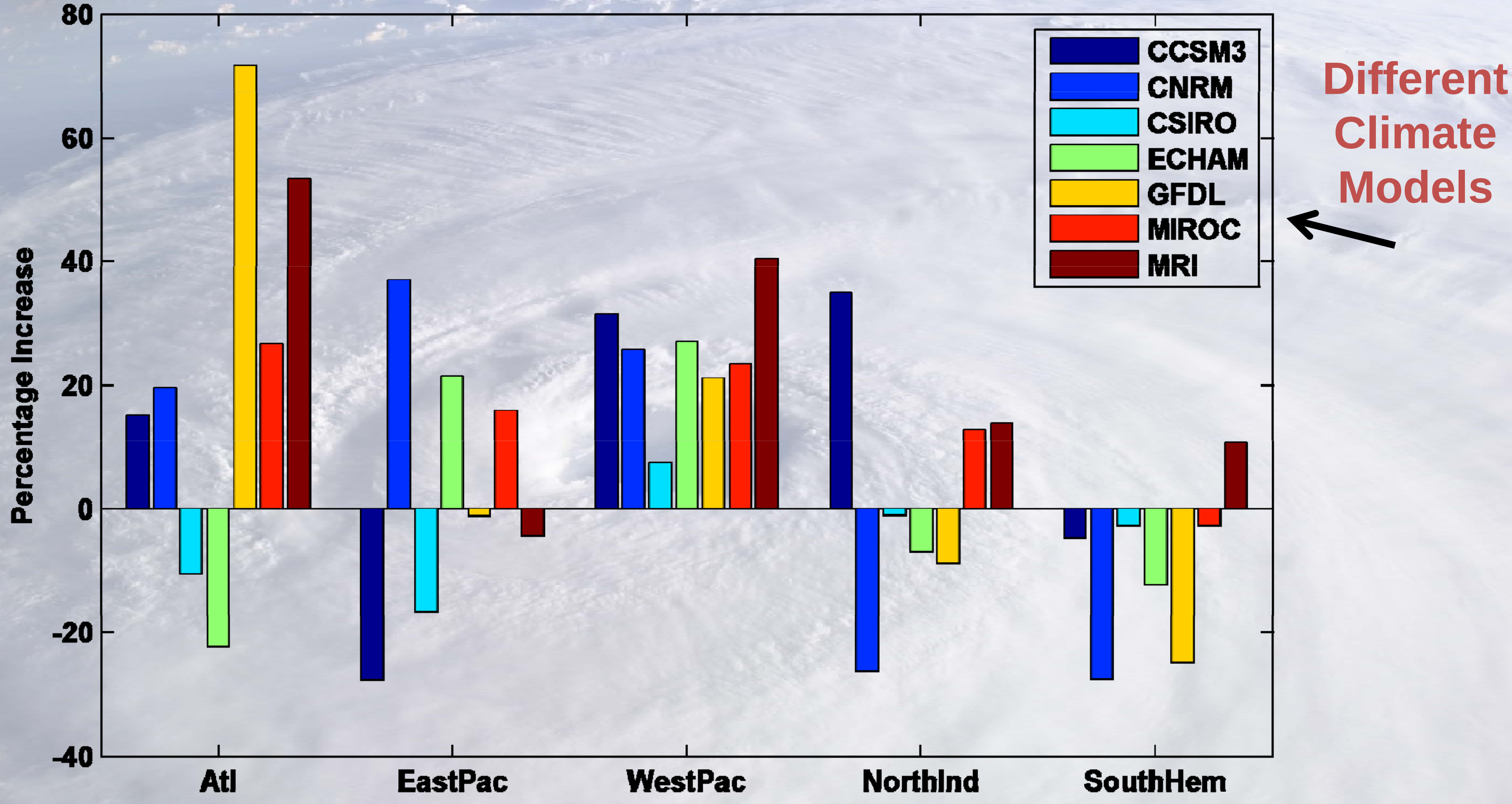
Federov et al., 2010



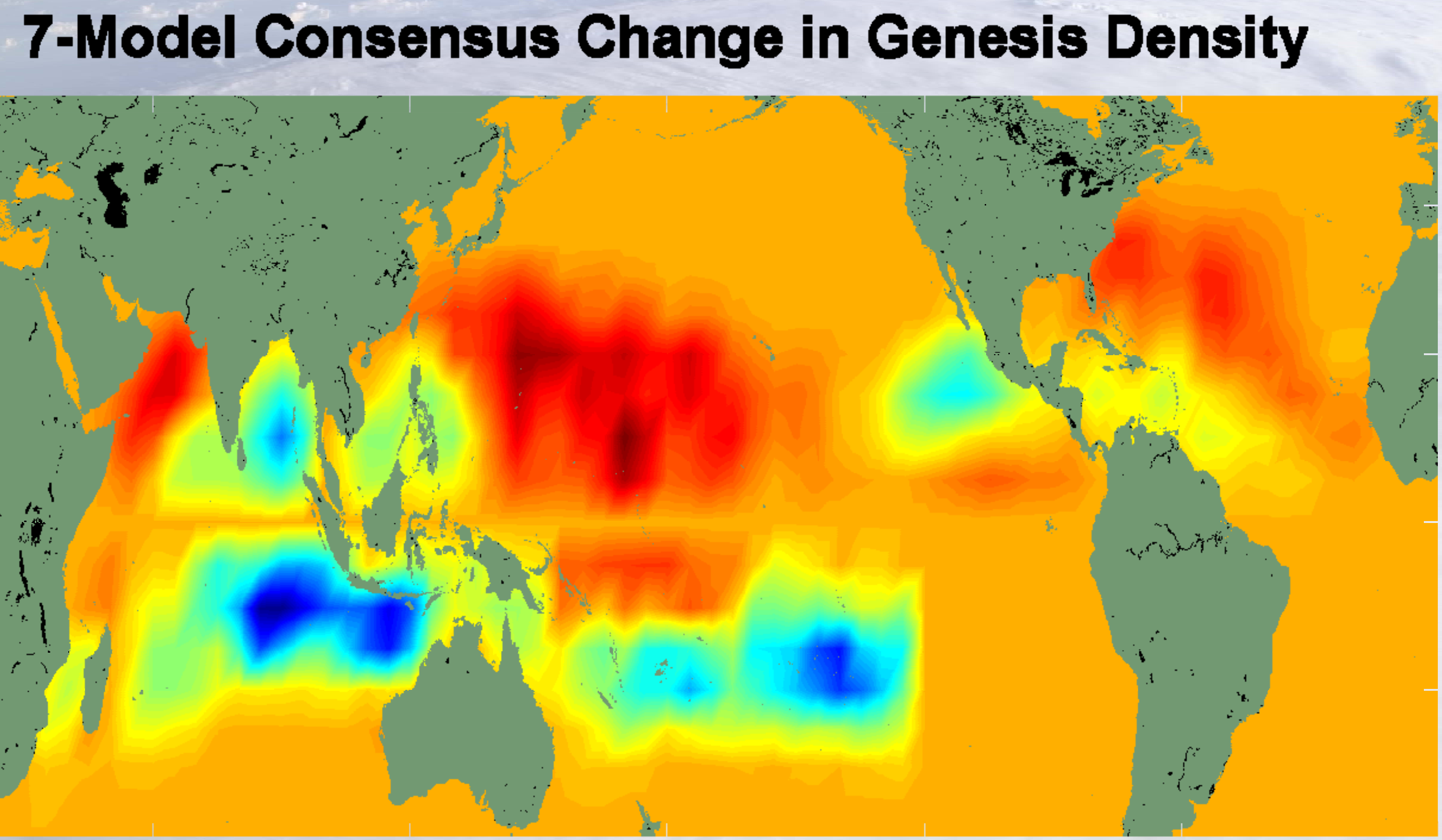
Lin et al., *Nature Climate Change*, 2012

Looking Ahead

Basin-Wide Percentage Change in Power Dissipation



7 Model Consensus Change in Storm Frequency



Lin et al., *Nature Climate Change*, 2012

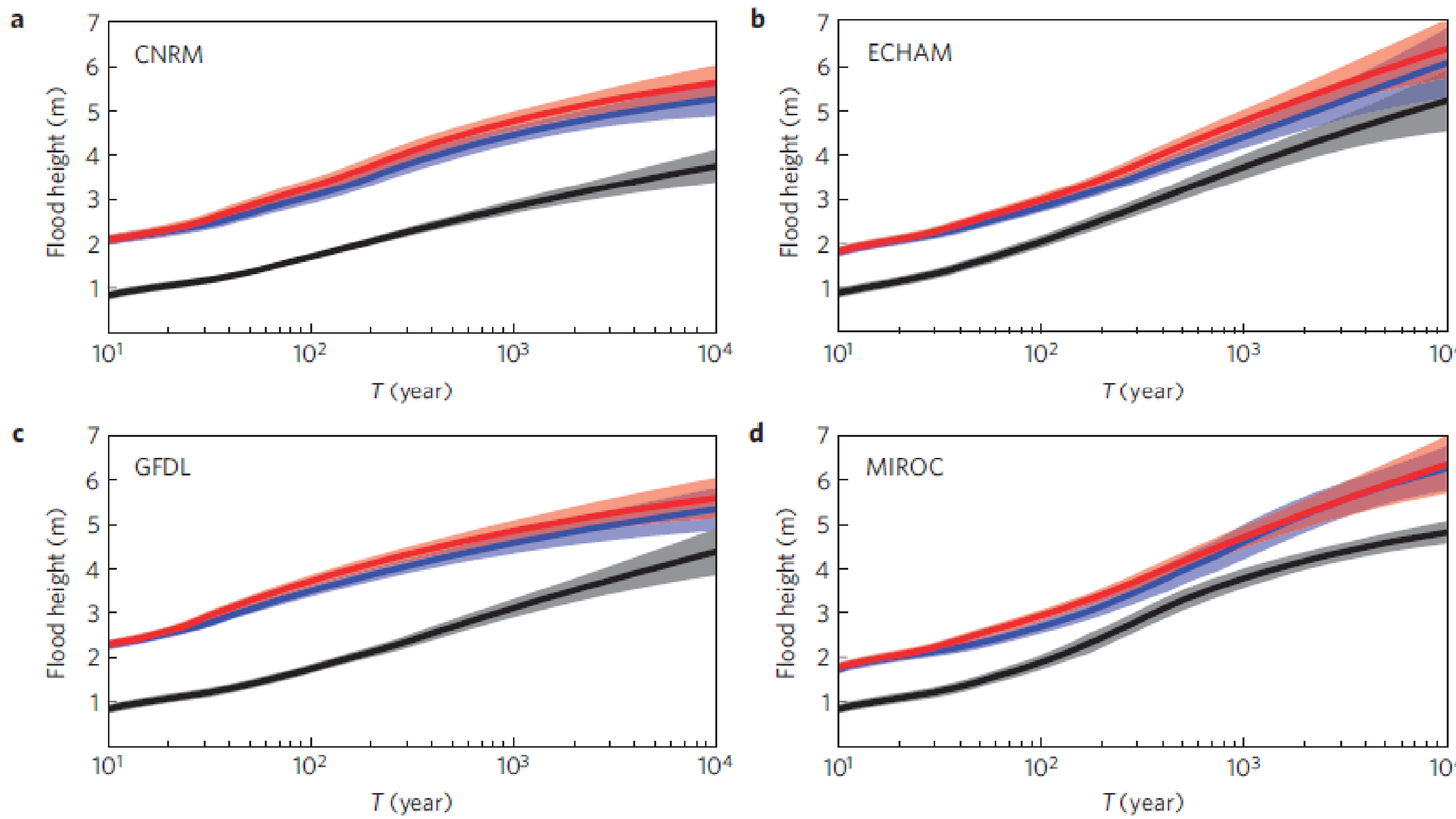
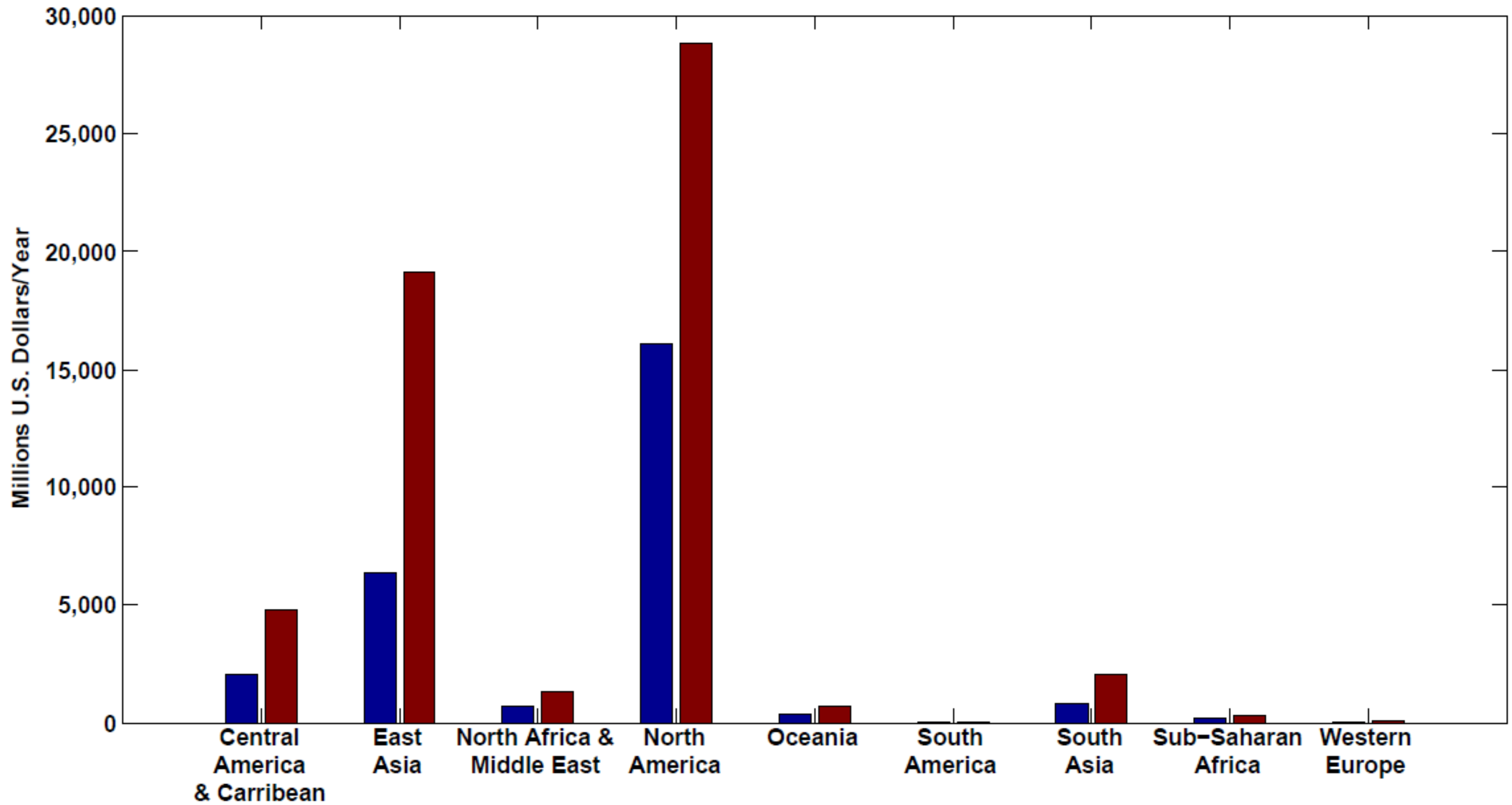


Figure 4 | Estimated flood return levels for the Battery, predicted with each of the four climate models. The black is for the present climate, the blue is for the IPCC A1B climate and the red is for the IPCC A1B climate with R_o increased by 10% and R_m increased by 21%. The shade shows the 90% confidence interval. The SLR for the A1B climate is assumed to be 1 m.

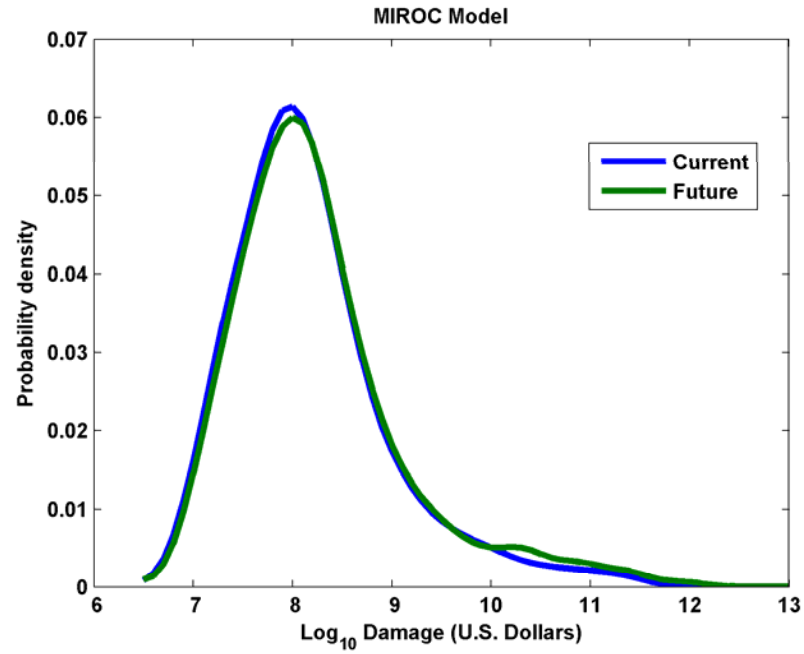
Integrated Assessments

with Robert Mendelsohn, Yale

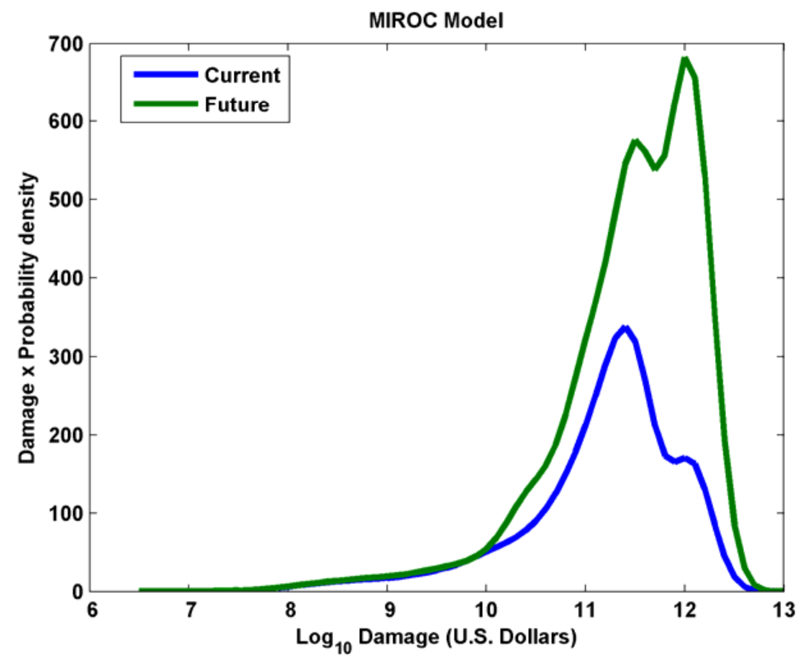


Present and future baseline tropical cyclone damage by region. Changes in income will increase future tropical cyclone damages in 2100 in every region even if climate does not change. Changes are larger in regions experiencing faster economic growth, such as East Asia and the Central America–Caribbean region.

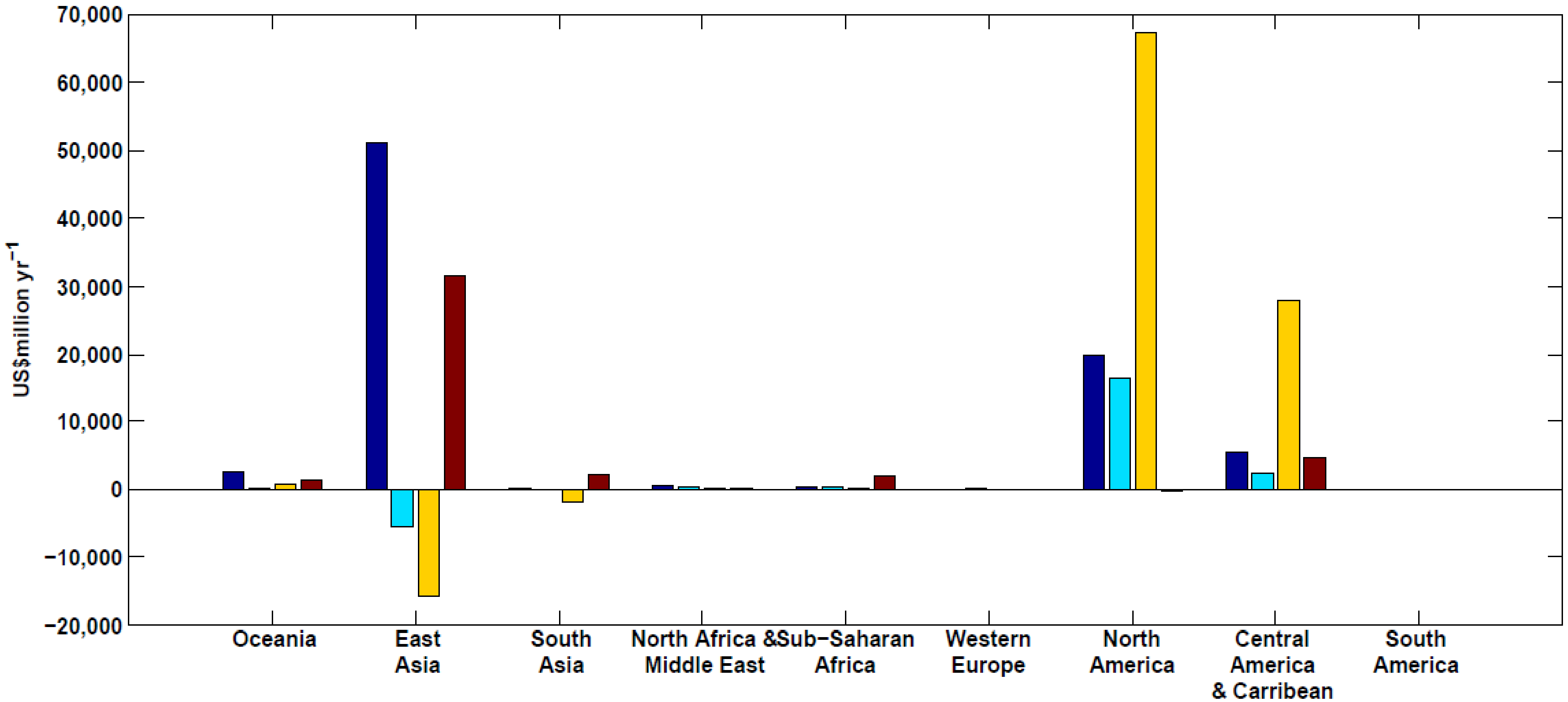
Probability Density of TC Damage, U.S. East Coast



Damage Multiplied by Probability Density of TC Damage, U.S. East Coast

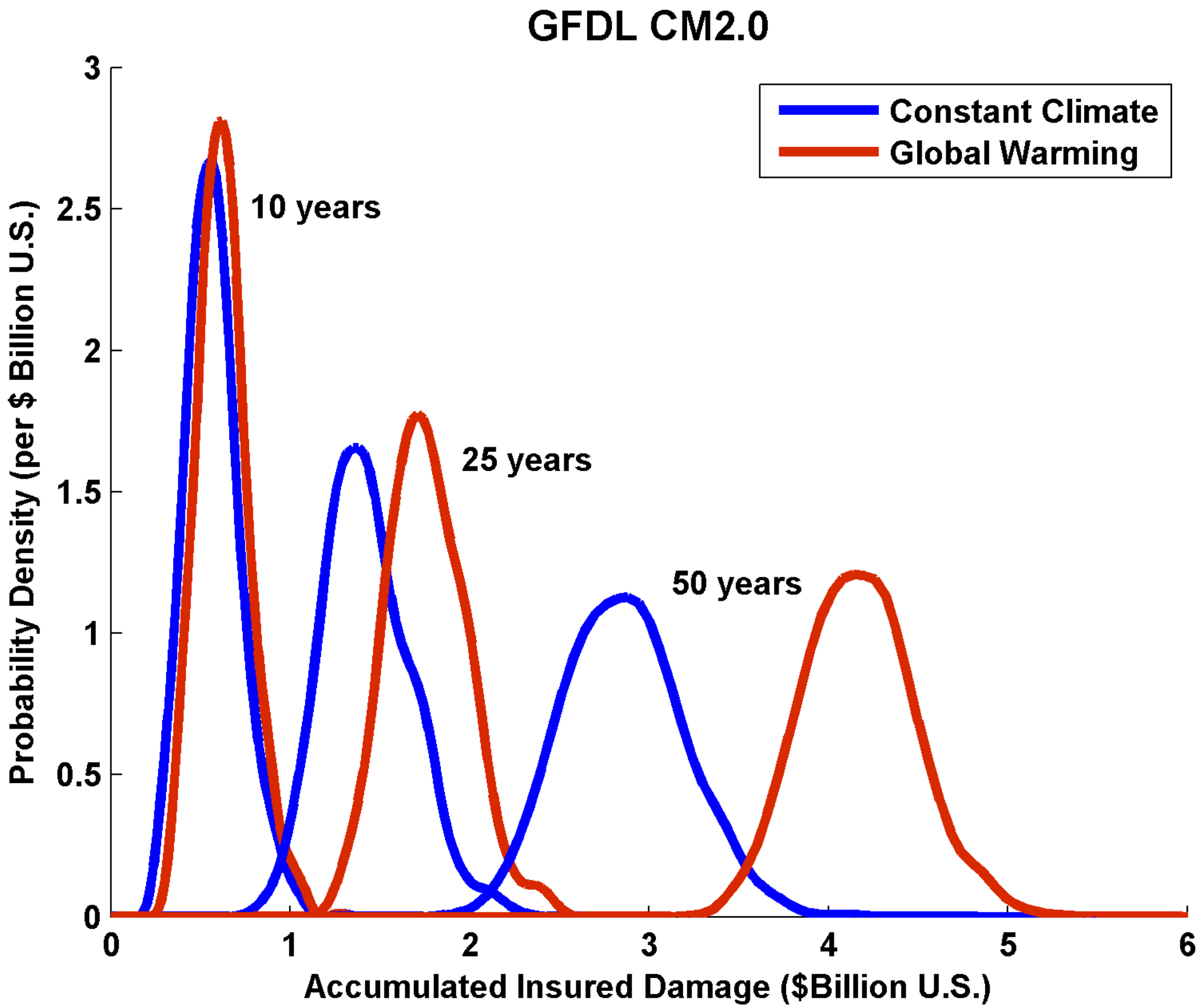


Mendelsohn et al., 2012



Climate change impacts on tropical cyclone damage by region in 2100. Damage is concentrated in North America, East Asia and Central America–Caribbean. Damage is generally higher in the CNRM and GFDL climate scenarios.

Projections of U.S. Insured Damage



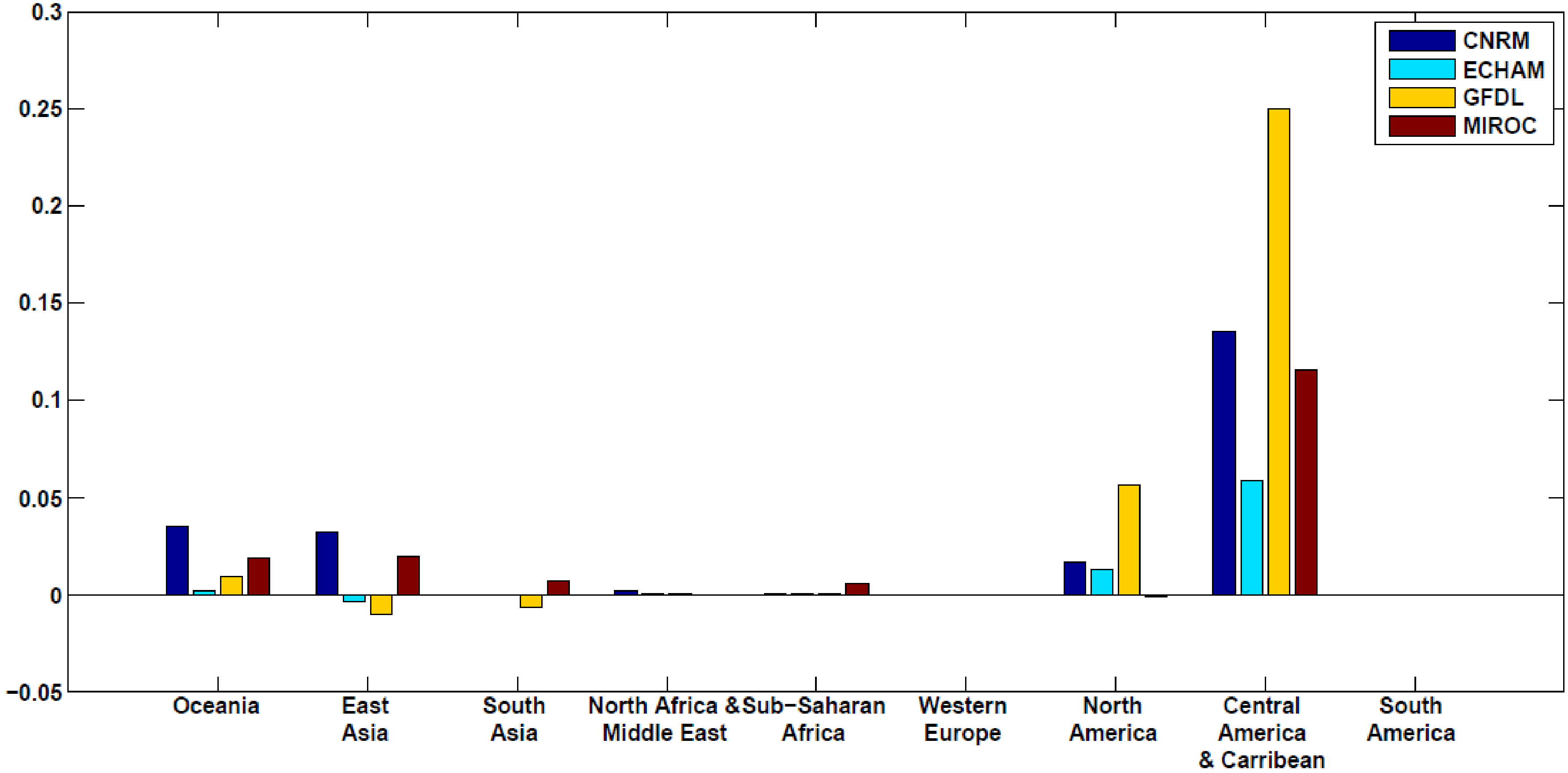
Emanuel, K. A., 2012, *Weather, Climate, and Society*

Summary

- **Hurricane activity is sensitive to climate**
- **Hurricanes and cloud clusters in general may be help to regulate tropical climate, drying the atmosphere and cooling the surface when it becomes too warm**

- **Simple but high resolution coupled TC model can be used to ‘downscale” TC activity from global climate data sets**

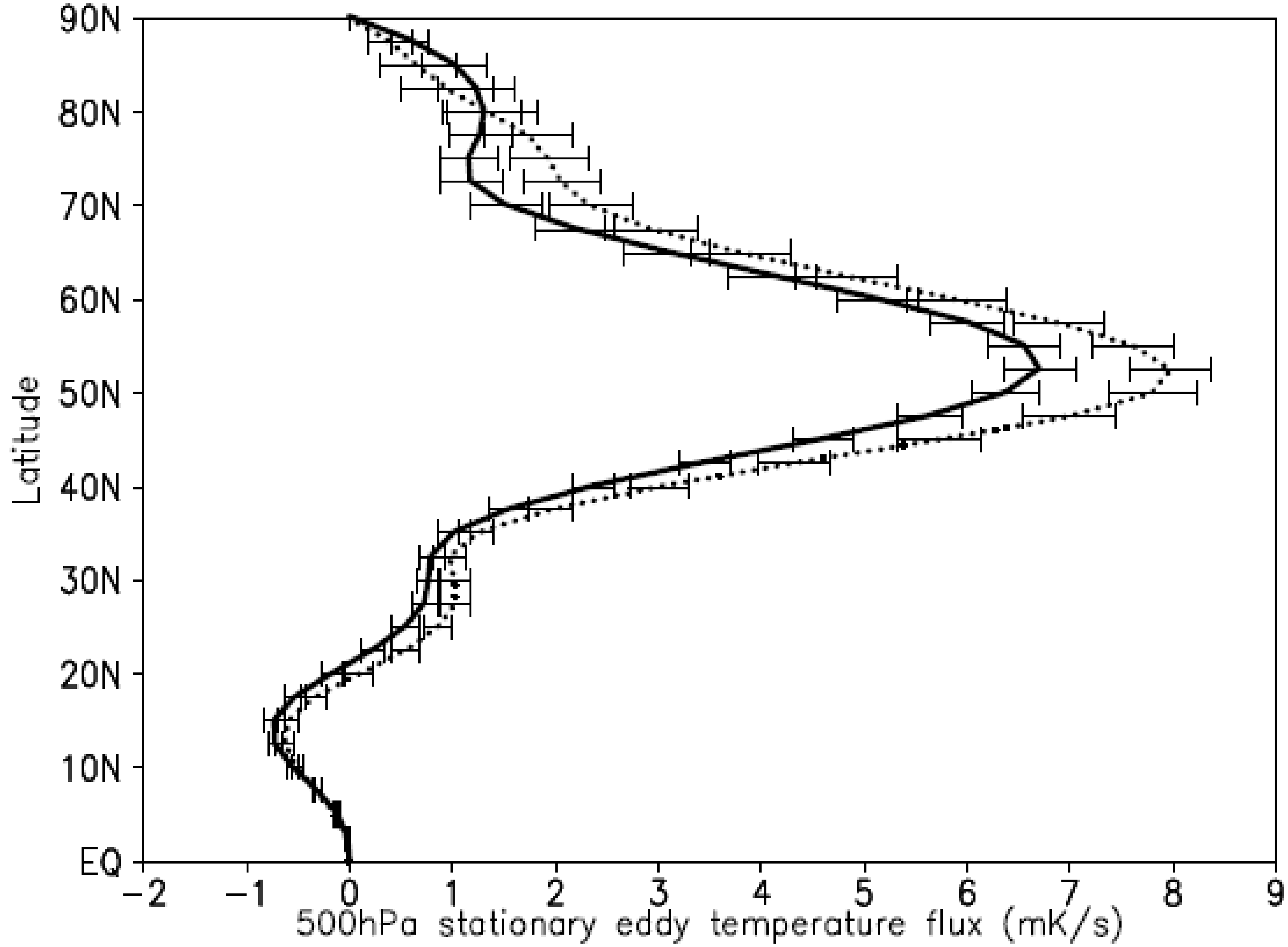
- **Studies based on this downscaling suggest large sensitivity of TCs to climate state, and possibly important changes in TC activity over the next century**



Climate change impacts on tropical cyclone damage divided by GDP by region in 2100. The ratio of damage to GDP is highest in the Caribbean–Central American region but North America, Oceania and East Asia all have above-average ratios.

Feedback of Global Tropical Cyclone Activity on the Climate System

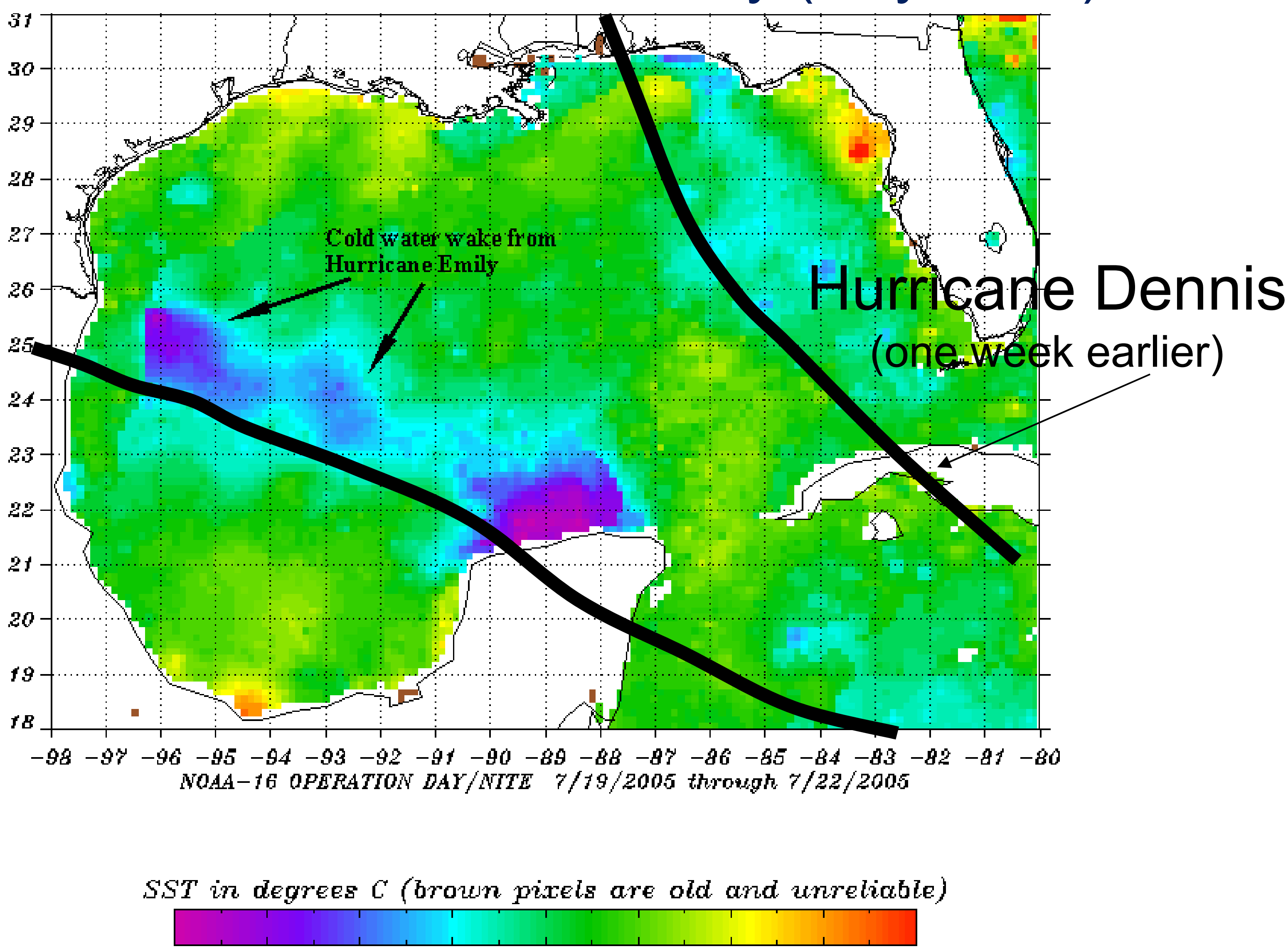
Hart, 2010



500hPa zonal mean meridional temperature flux (mK/s) of the stationary eddies for January through March. The dotted (solid) curve represents the composite mean of the winters following inactive (active) northern hemisphere TC seasons. Error bars represent the standard error of the mean for datasets of size varying from N=9 to 13. Flux calculated using NCAR/NCEP reanalysis for the period 1960-2008

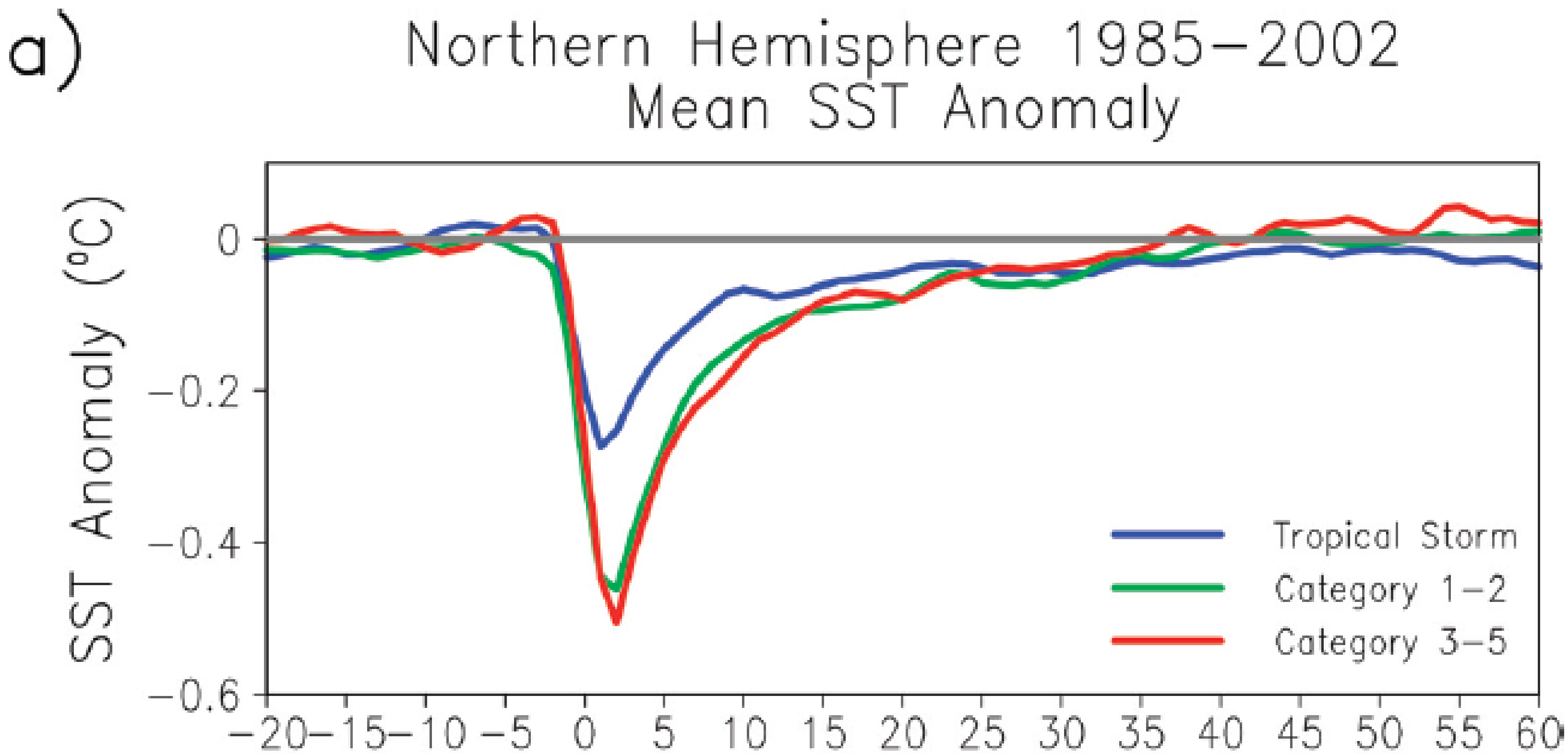
The wake of Hurricane Emily (July 2005)

Sea Surface Temperature in the Wakes of Hurricanes



Source: Rob Korty, CalTech

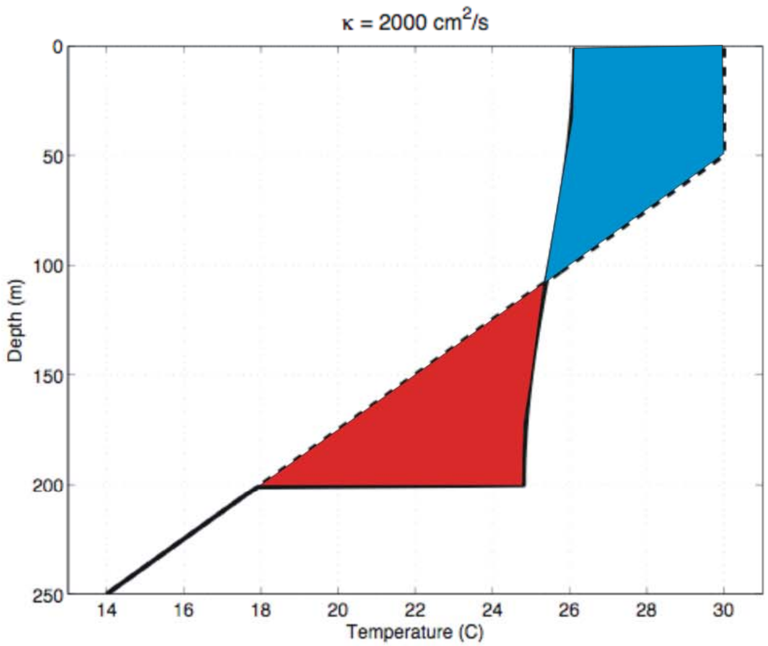
Wake Recovery



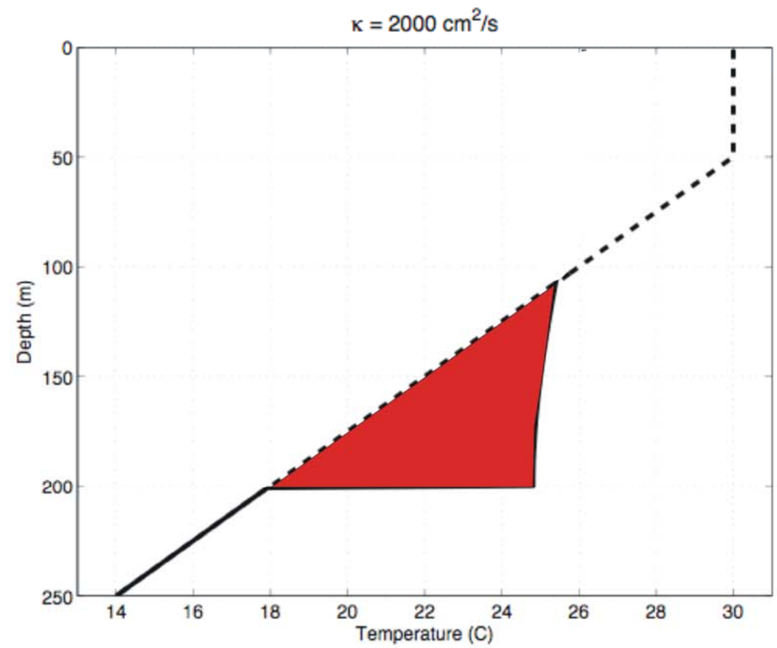
Hart, Maue, and Watson, *Mon. Wea. Rev.*, 2007

Direct mixing by tropical cyclones

Stage 1:
Enthalpy-conserving mixing



Stage 2:
Wake recovery

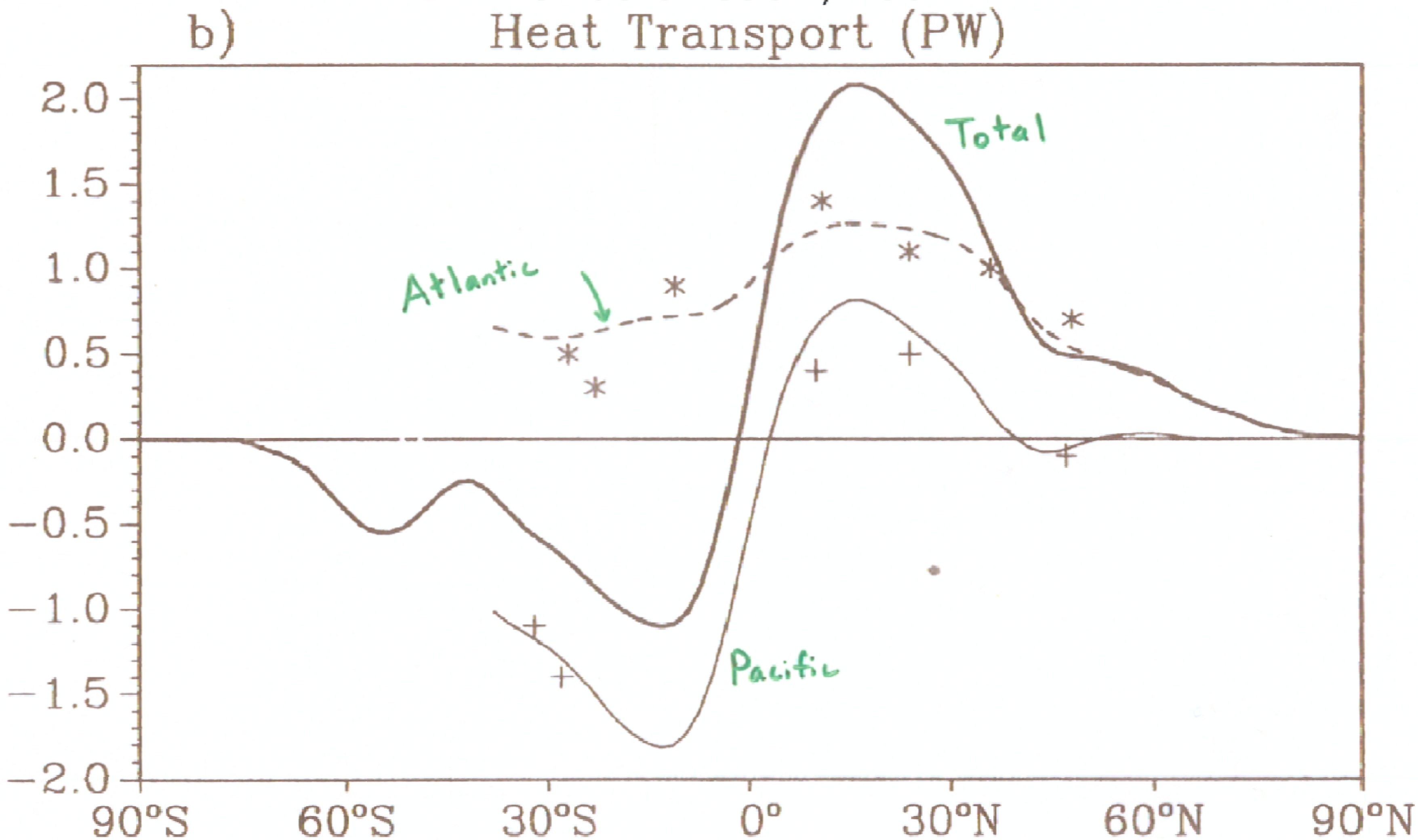


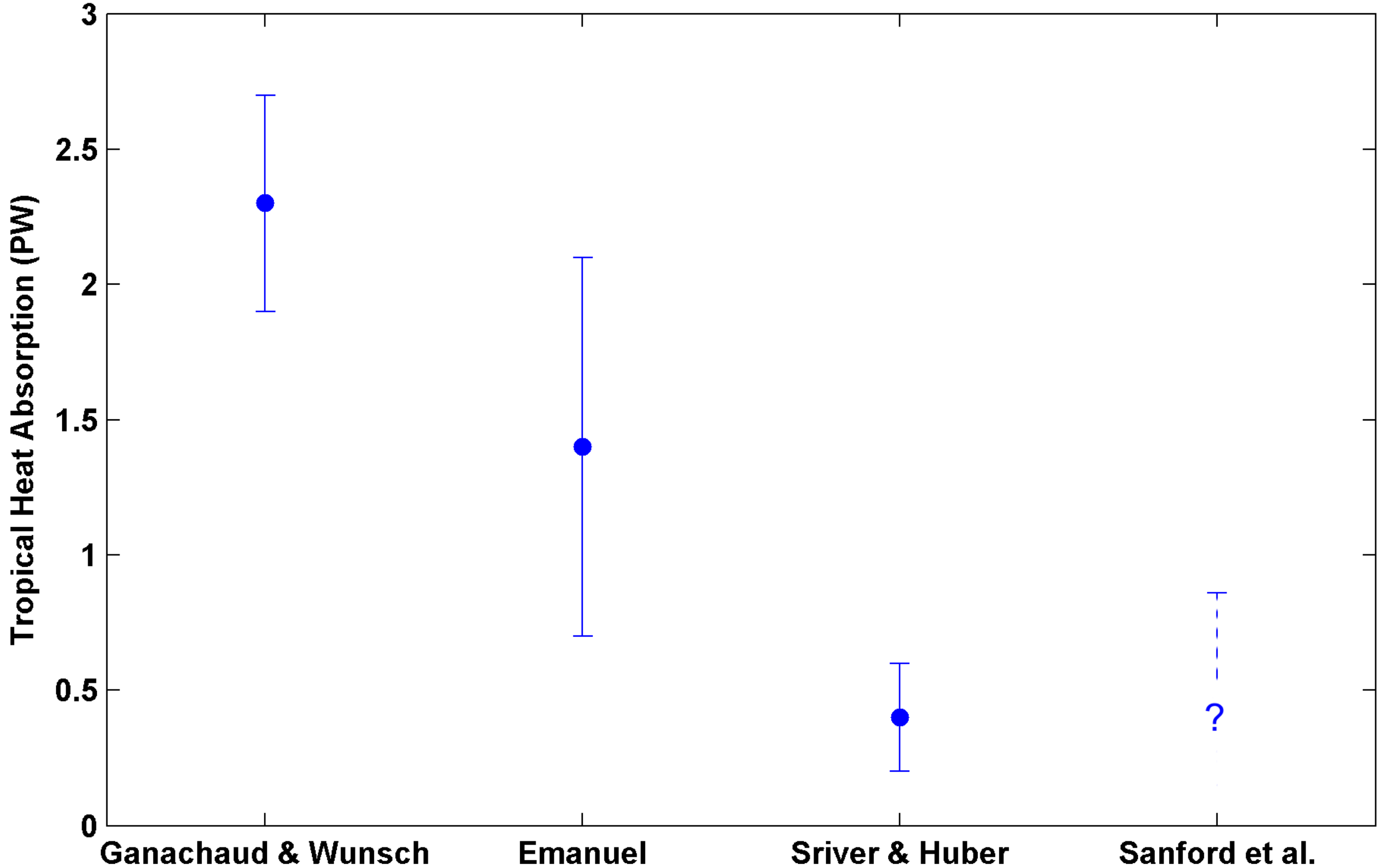
Emanuel (2001) estimated global rate of heat input as 1.4 X 10^{15} Watts

Source: Rob Korty, CalTech

TC Mixing May Induce Much or Most of the Observed Poleward Heat Flux by the Oceans

Trenberth et al., 2001

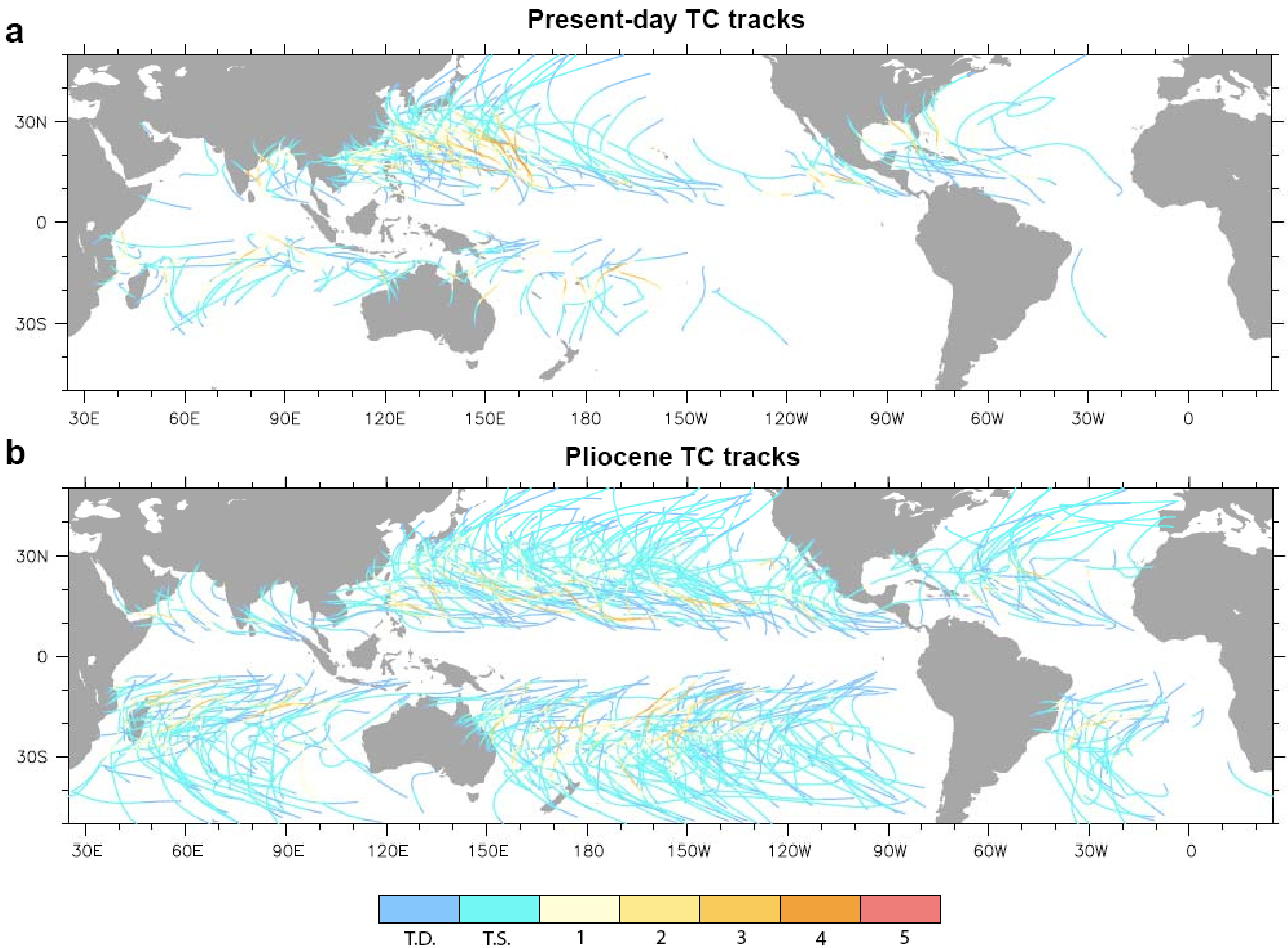




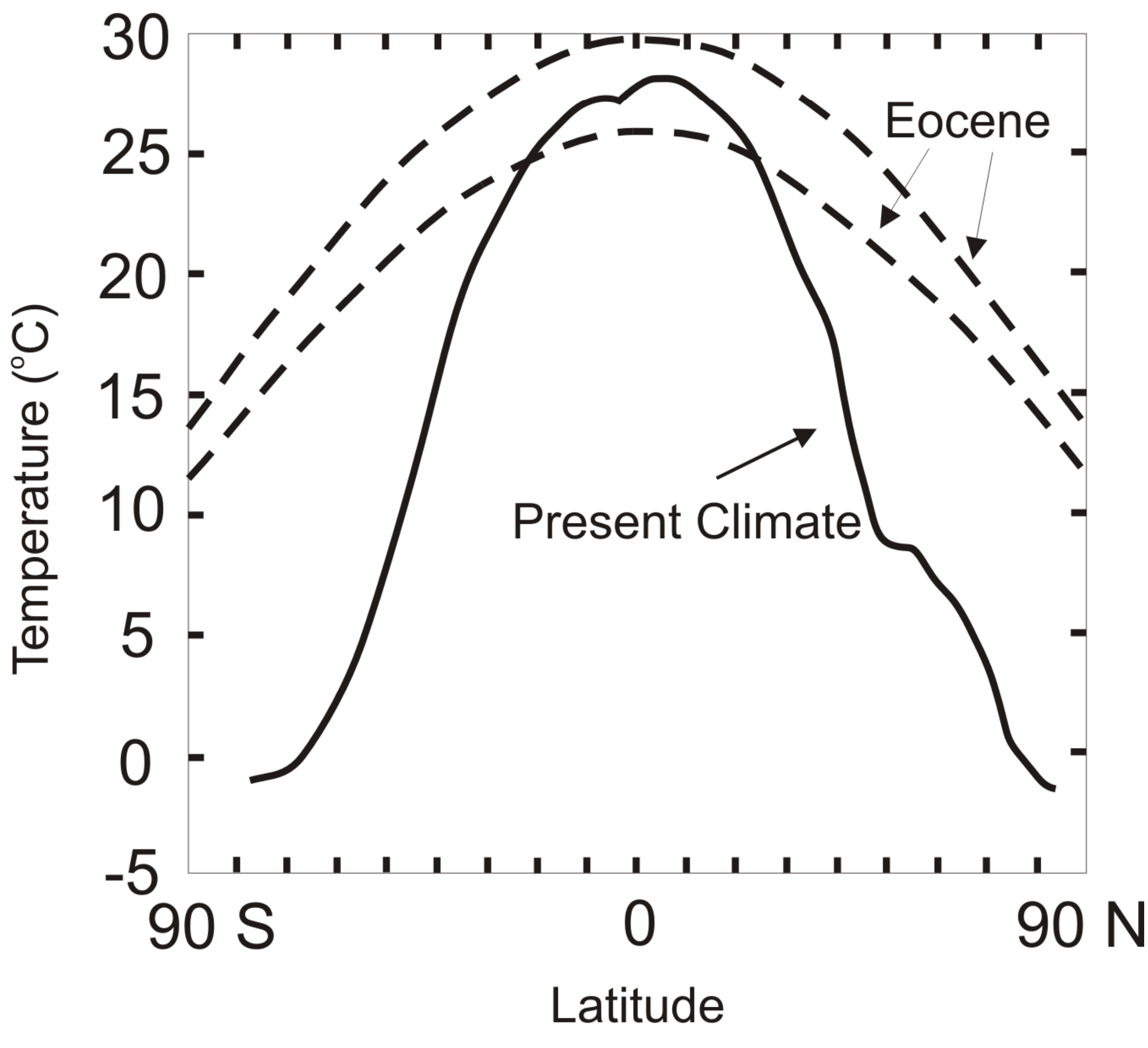
Estimate of total heat uptake by tropical oceans

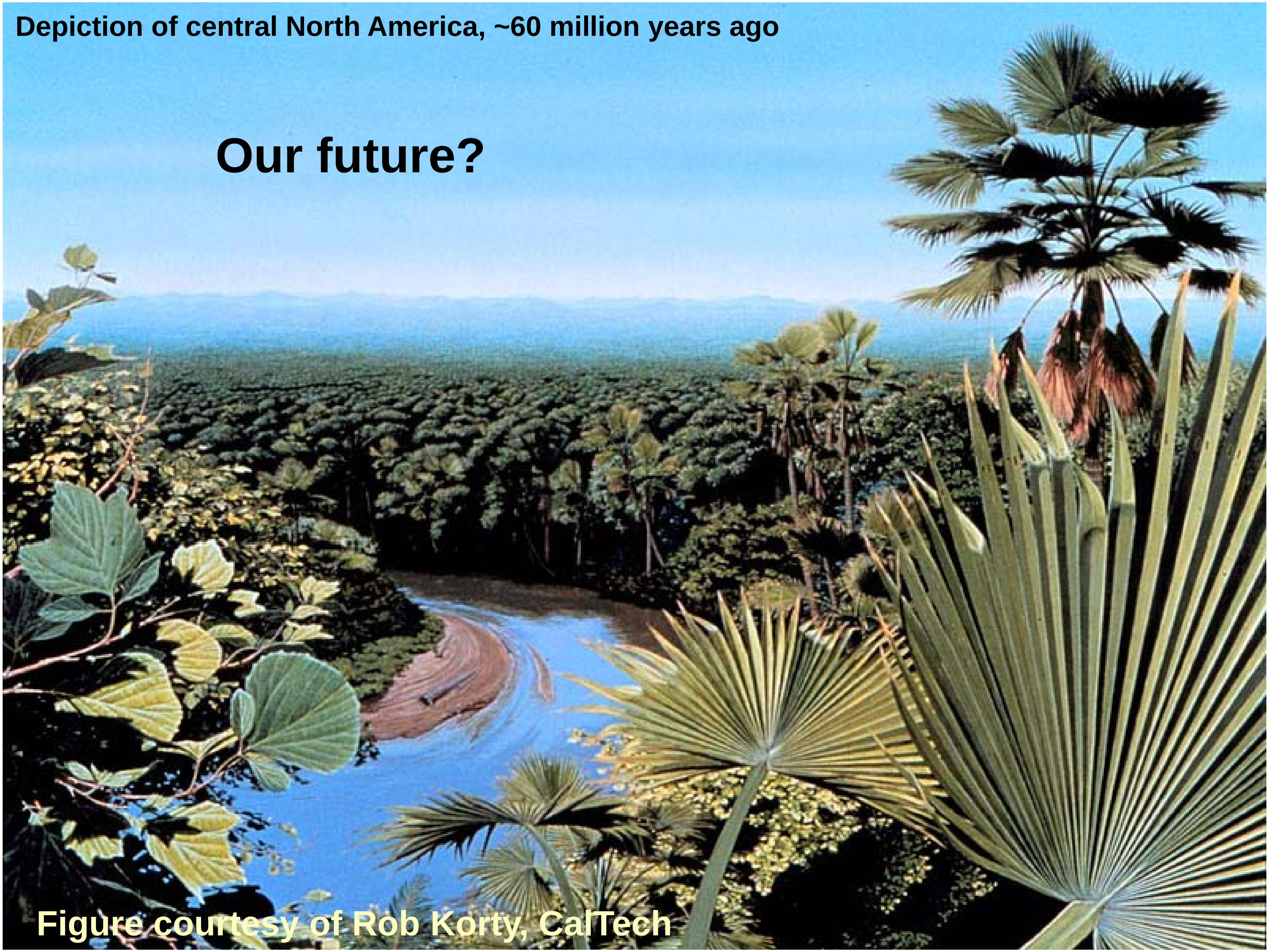
Estimate from satellite-derived wake recoveries

Extrapolation from detailed ocean measurements of one storm

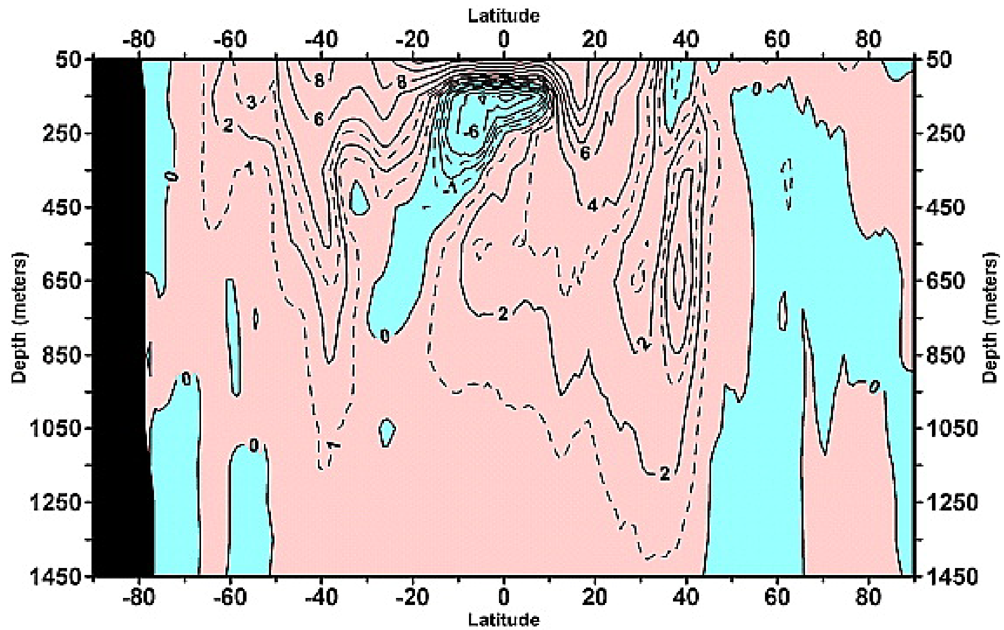

a
Present-day TC tracks
30N
0
30S
30E
60E
90E
120E
150E
180
150W
120W
90W
60W
30W
0
b
Pliocene TC tracks
30N
0
30S
30E
60E
90E
120E
150E
180
150W
120W
90W
60W
30W
0
T.D.
T.S.
1
2
3
4
5

TC-Mixing may be Crucial for High-Latitude Warmth and Low-Latitude Moderation During Warm Climates, such as that of the Eocene

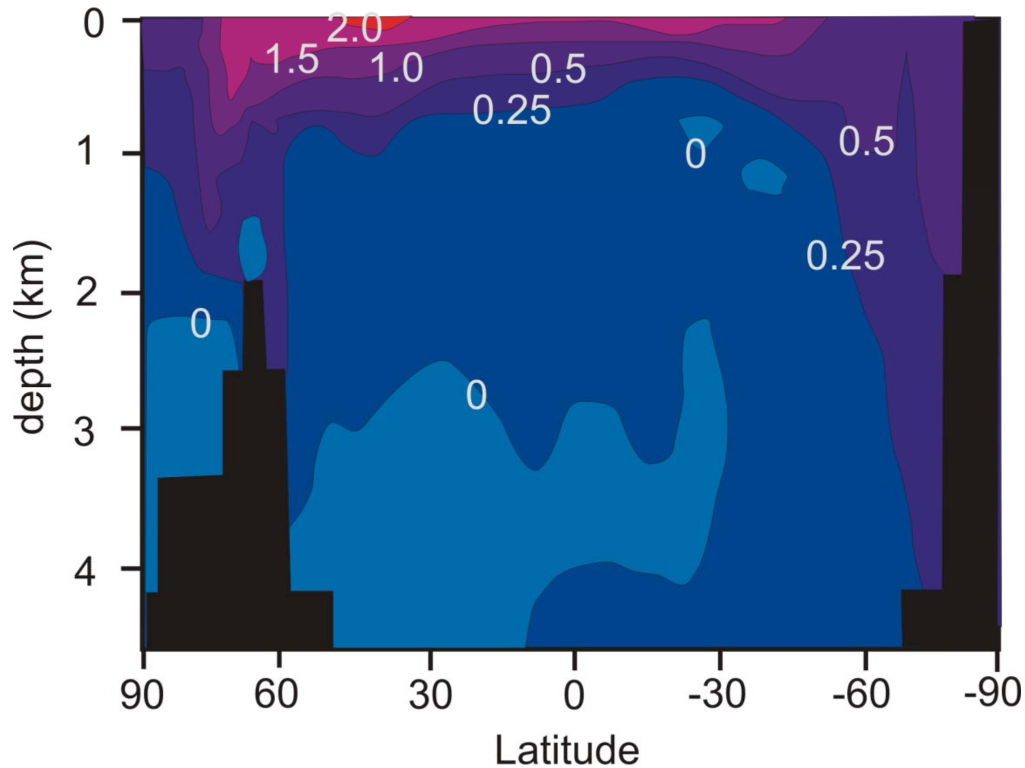



Depiction of central North America, ~60 million years ago
Our future?
Figure courtesy of Rob Korty, CalTech

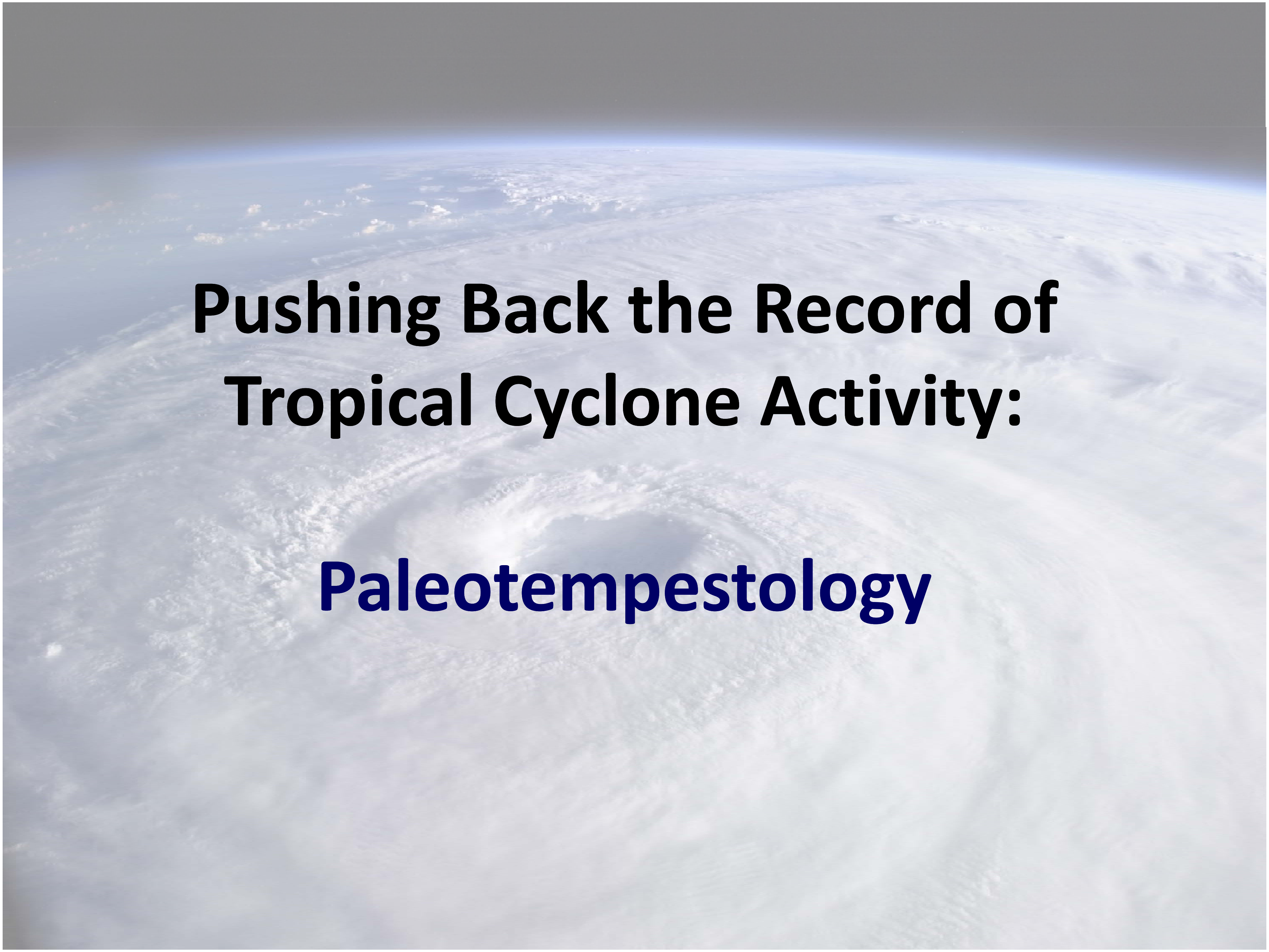
Linear trend (1955–2003) of the zonally integrated heat content of the world ocean by one-degree latitude belts for 100-m thick layers. Source: Levitus et al., 2005



TC-Mixing may explain difference between observed and modeled ocean warming



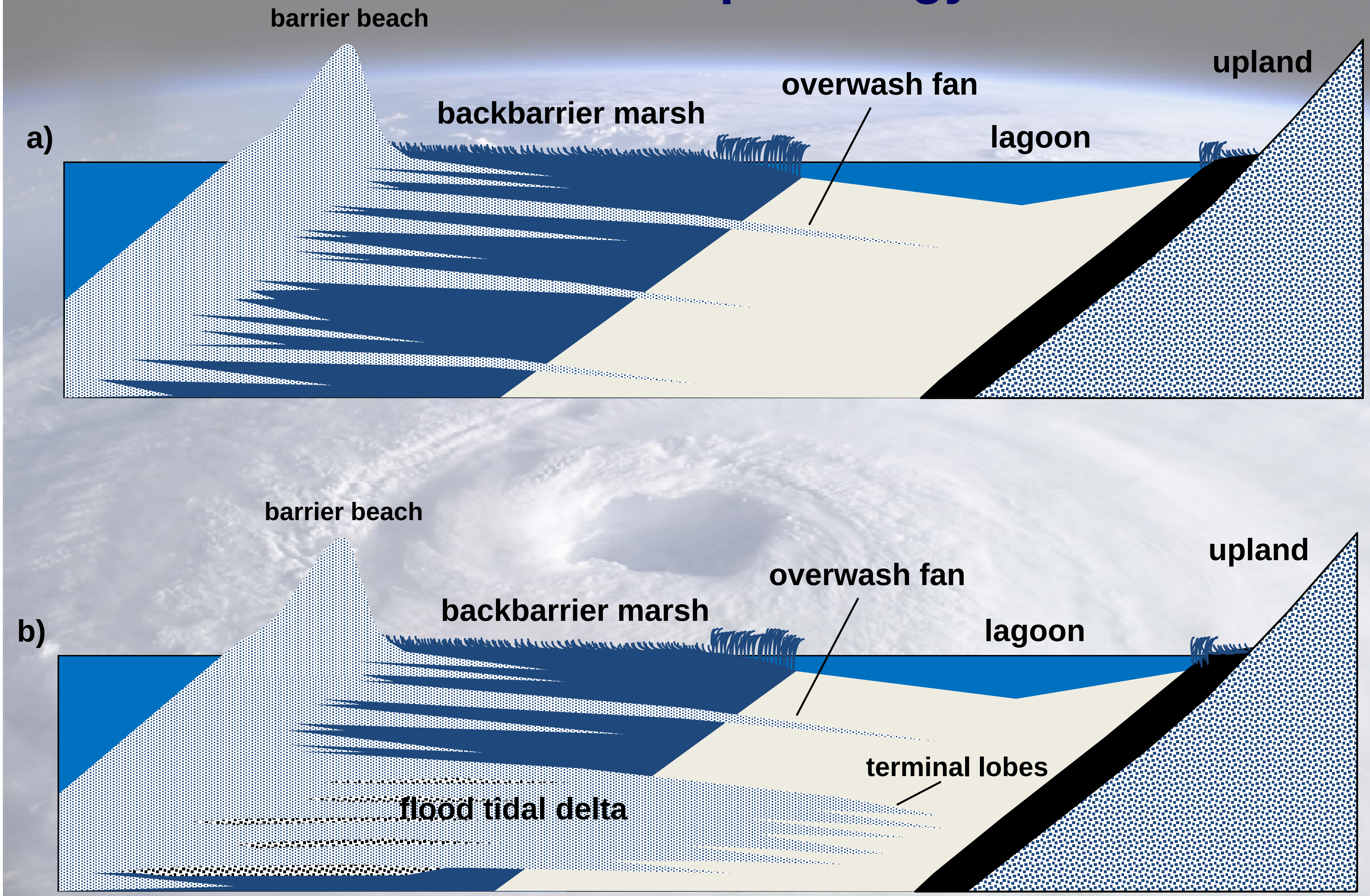
Zonally averaged temperature trend due to global warming in a coupled climate model. Source: Manabe et al, 1991



Pushing Back the Record of Tropical Cyclone Activity:

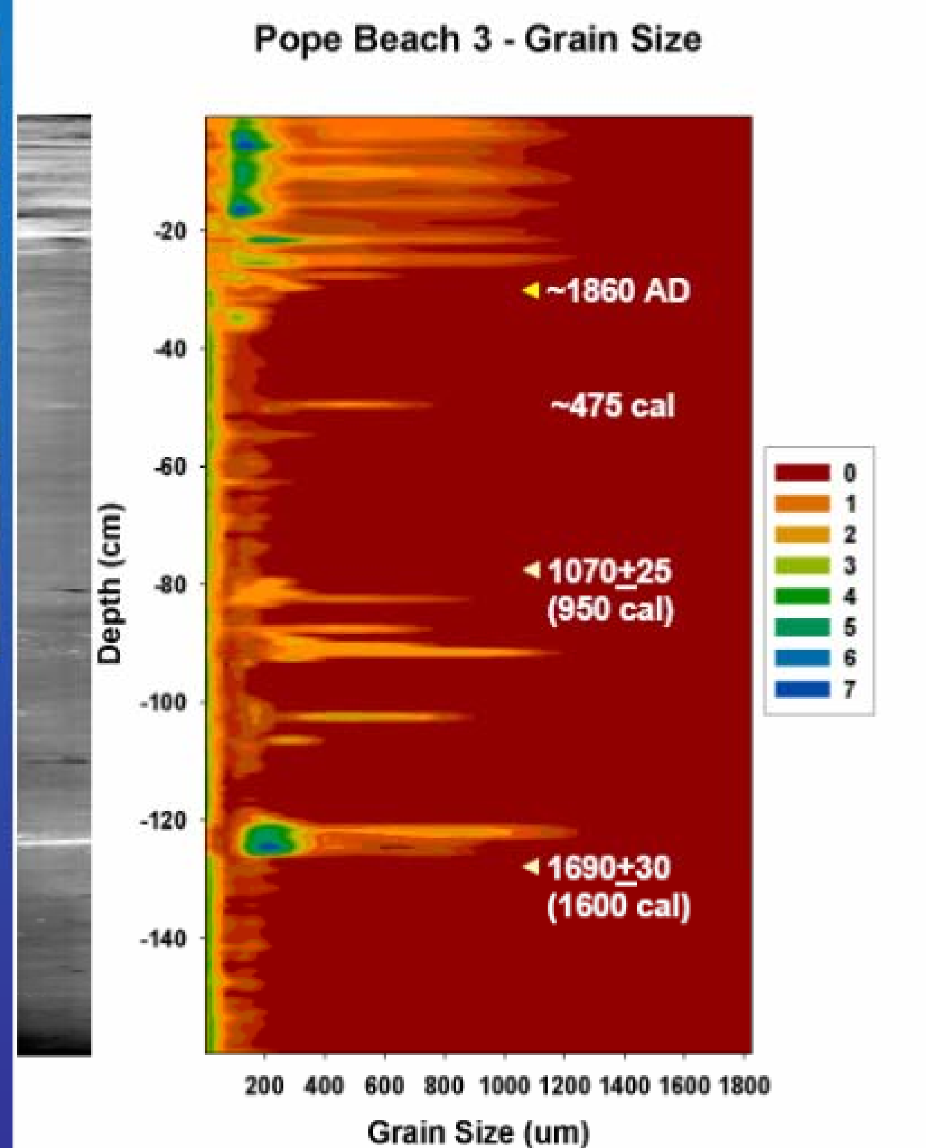
Paleotempestology

Paleotempestology



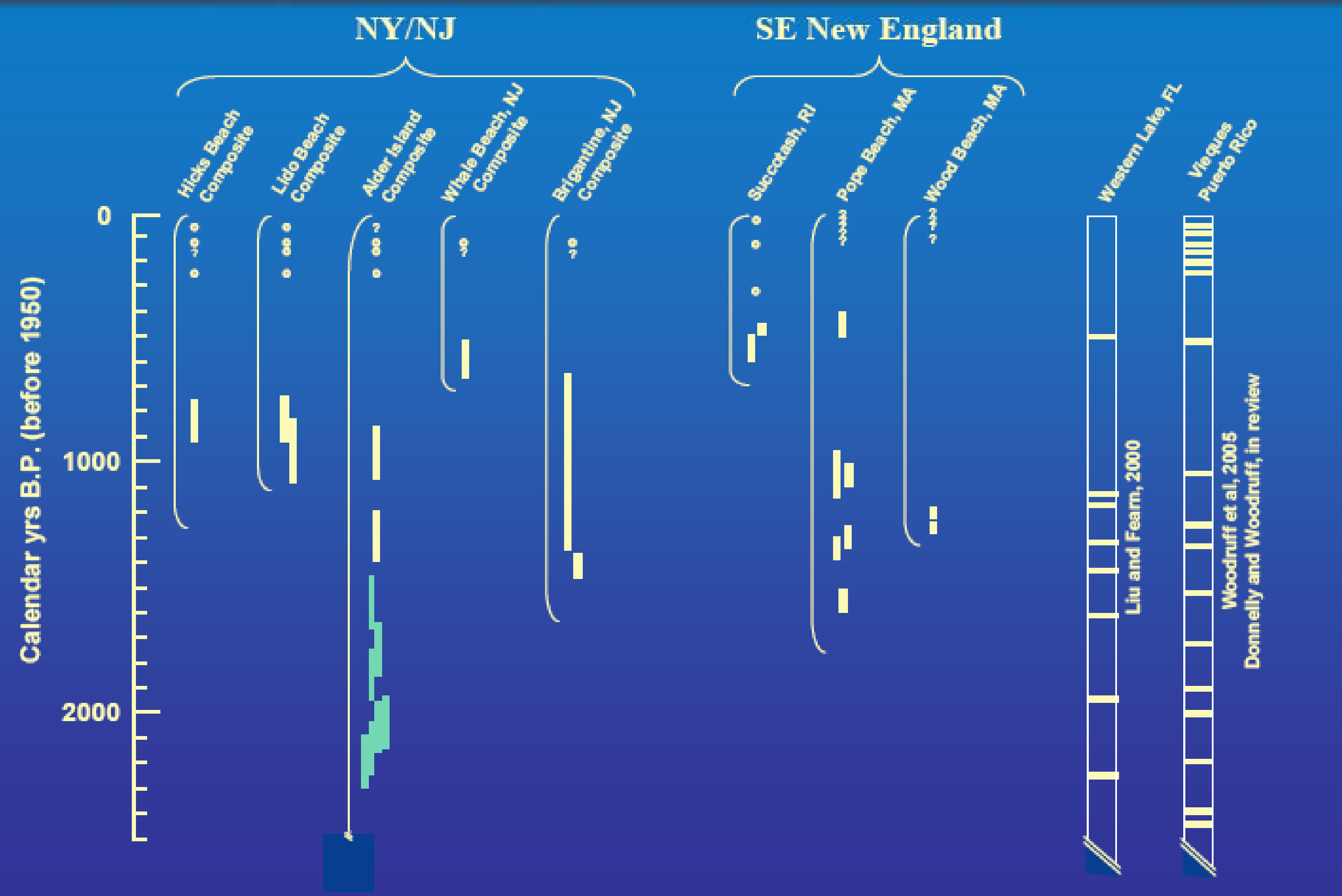
Source: Jeff Donnelly, WHOI

Pope Beach Marsh, Fairhaven, MA

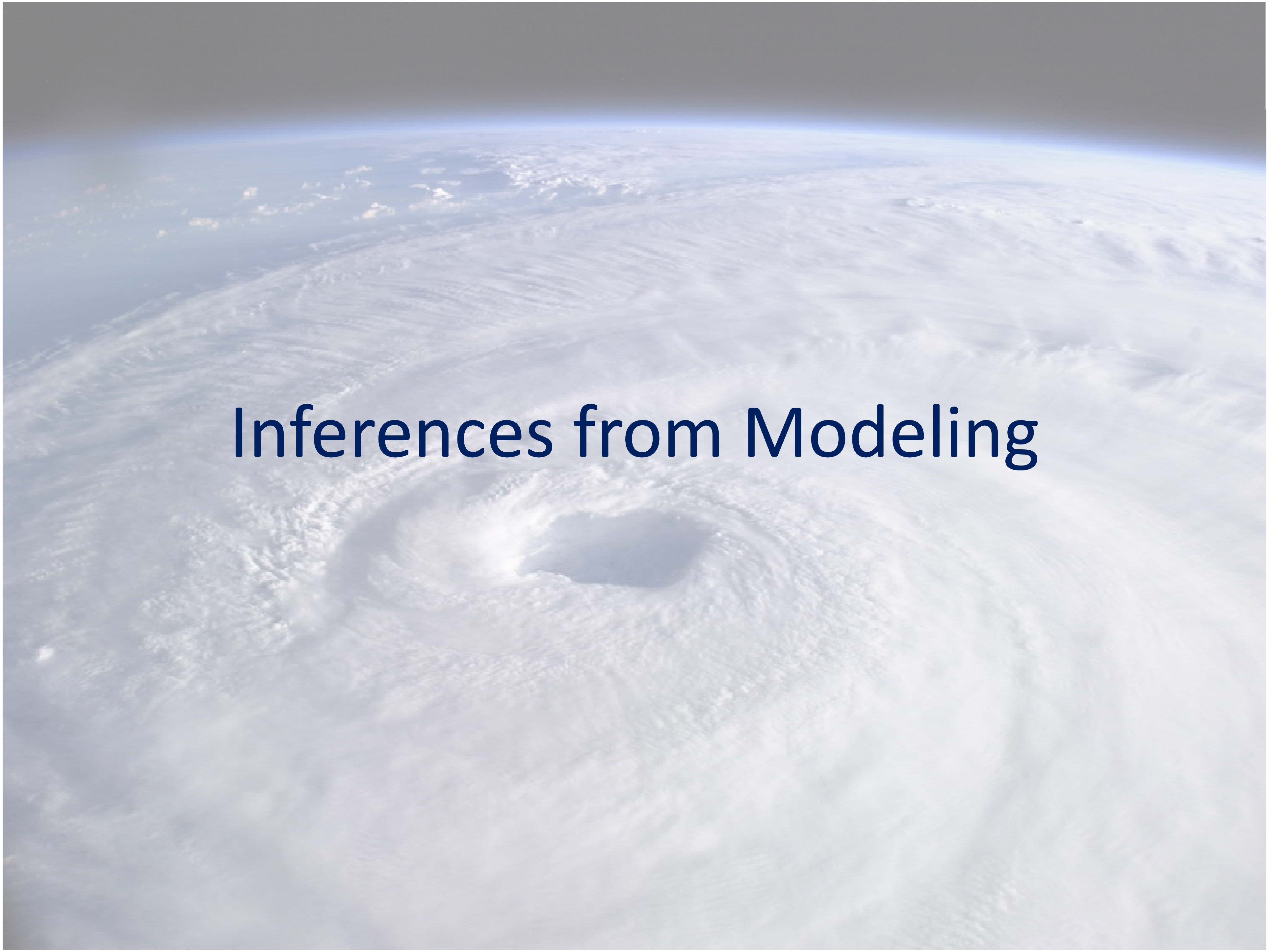


Source: Jeff Donnelly, Jon Woodruff, Phil Lane; WHOI

North Atlantic Synthesis

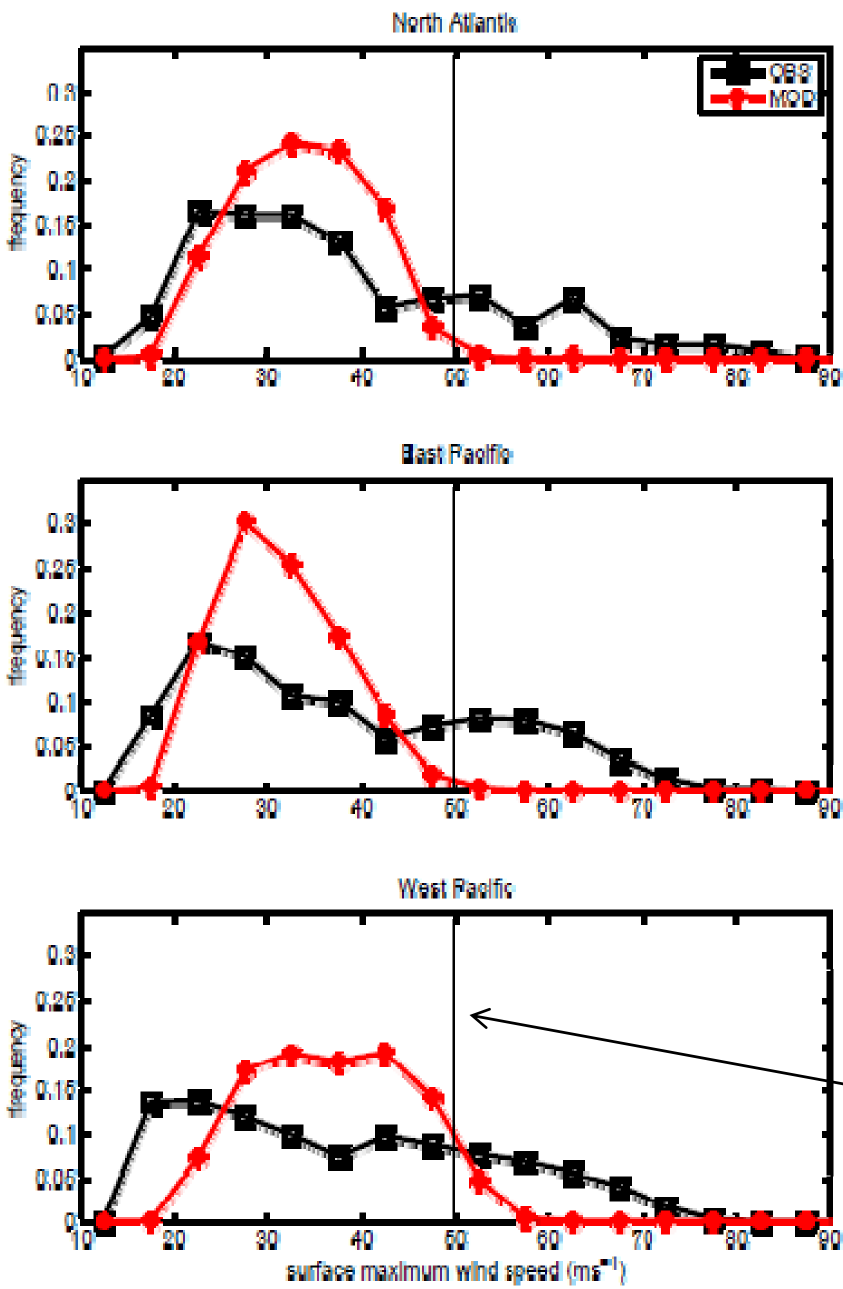


Source: Jeff Donnelly, Jon Woodruff, Phil Lane; WHOI


Inferences from Modeling

The Problem:

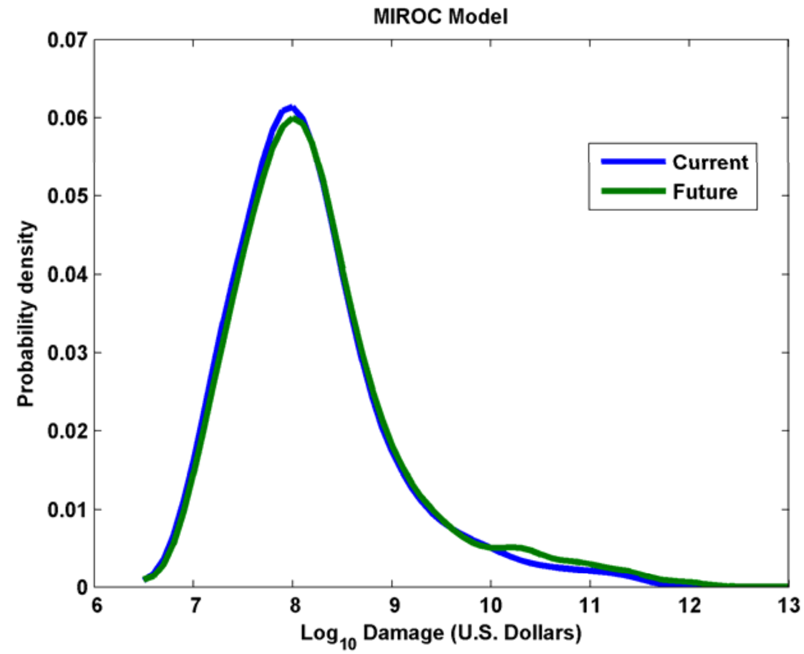
- **Global models are far too coarse to simulate high intensity tropical cyclones**
- **Embedding regional models within global models introduces problems stemming from incompatibility of models, and even regional models are usually too coarse**



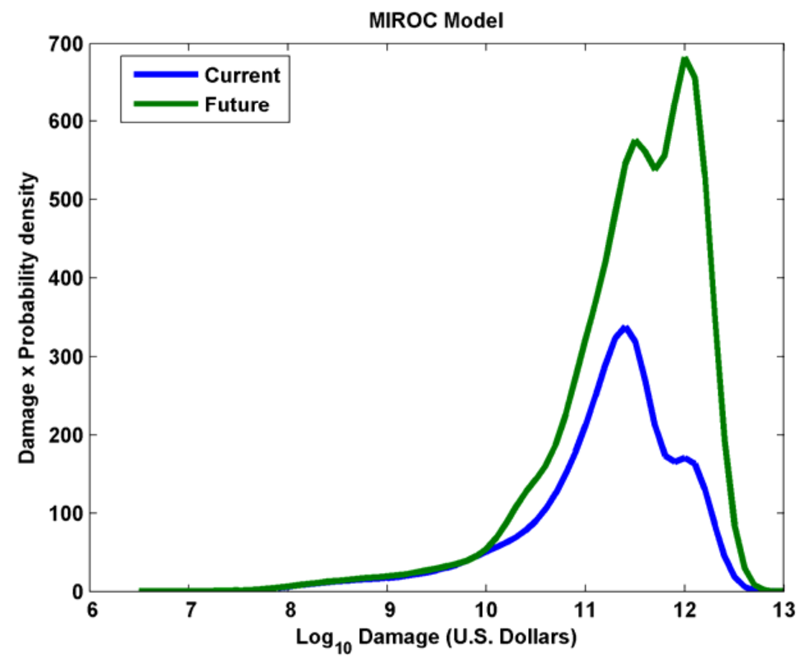
Category 3

Histograms of Tropical Cyclone Intensity as Simulated by a Global Model with 50 km grid point spacing. (Courtesy Isaac Held, GFDL)

Probability Density of TC Damage, U.S. East Coast

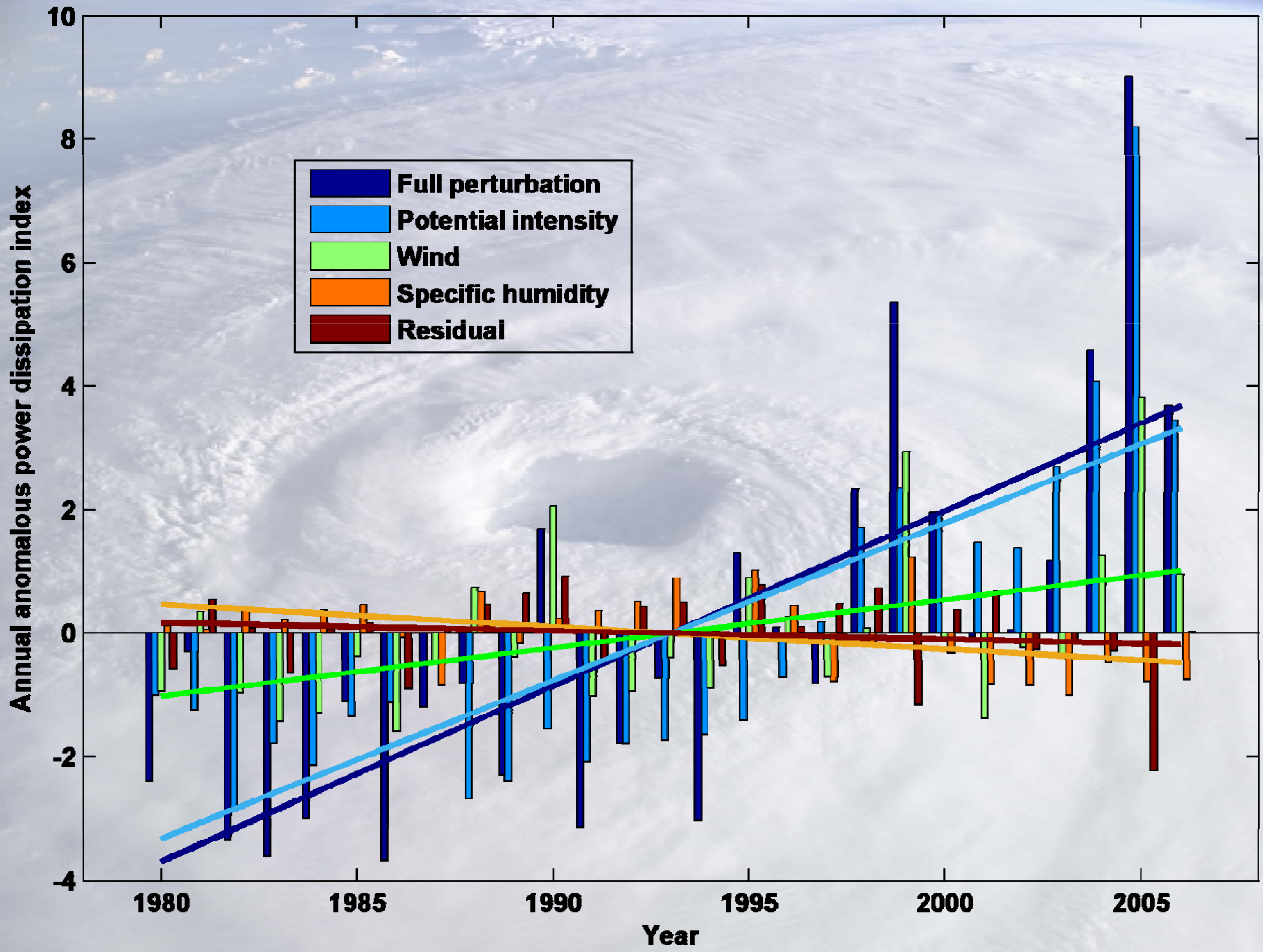


Damage Multiplied by Probability Density of TC Damage, U.S. East Coast

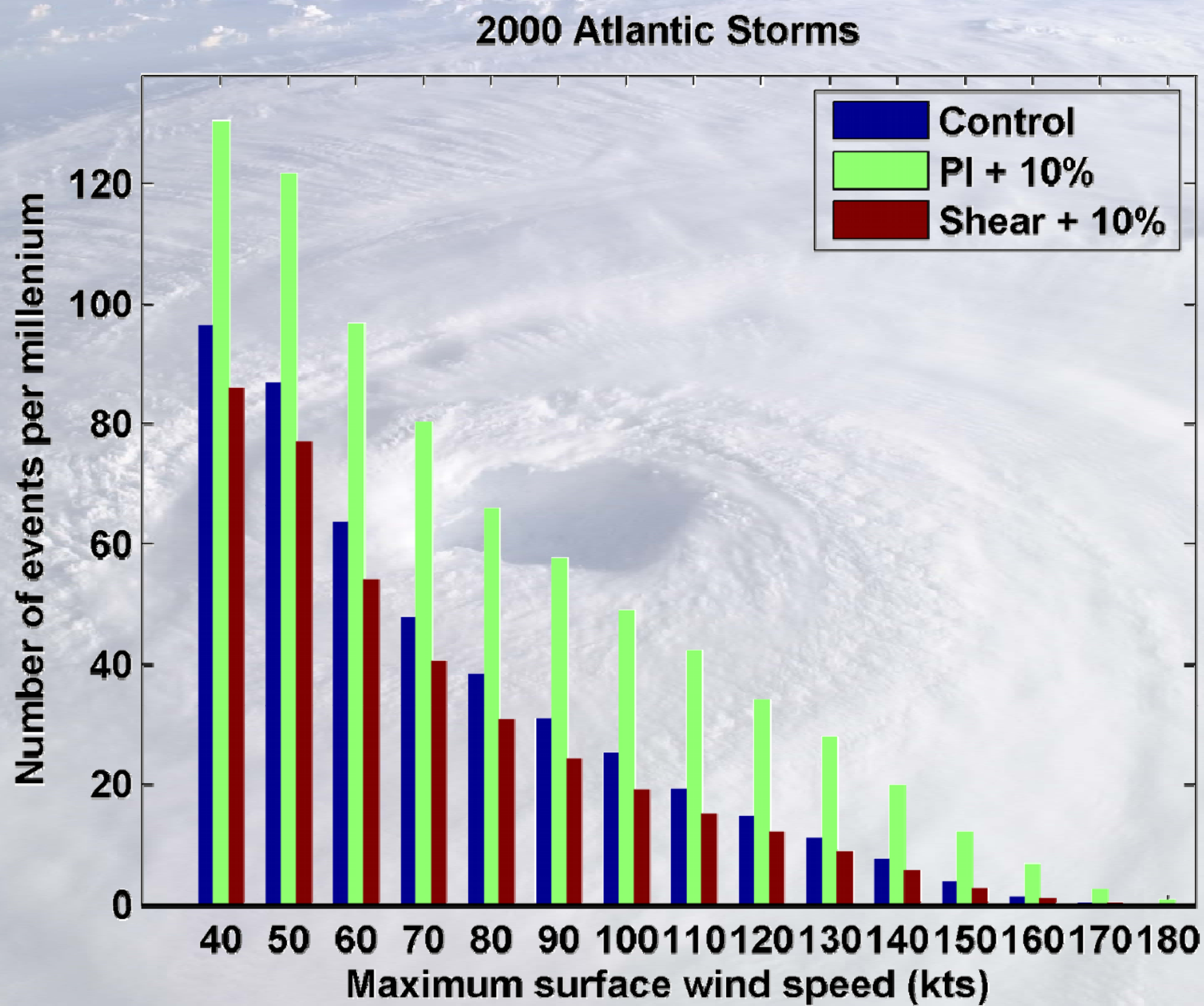


To the extent that they simulate tropical cyclones at all, global models simulate storms that are largely irrelevant to society and to the climate system itself, given that ocean stirring effects are heavily weighted towards the most intense storms

Decomposition of PDI Trends



Sensitivity to Shear and Potential Intensity



Hydrostatic Compensation (following Holloway and Neelin)

Perturbations to moist adiabatic troposphere:

$$\frac{\partial \phi'}{\partial p} = -\alpha' = -\left(\frac{\partial \alpha}{\partial p}\right)_p s^{*'} = -\left(\frac{\partial T}{\partial p}\right)_{s^{*'}} s_b'$$

$$\rightarrow \phi_T' = \left(T_s - T_T\right) s_b'$$

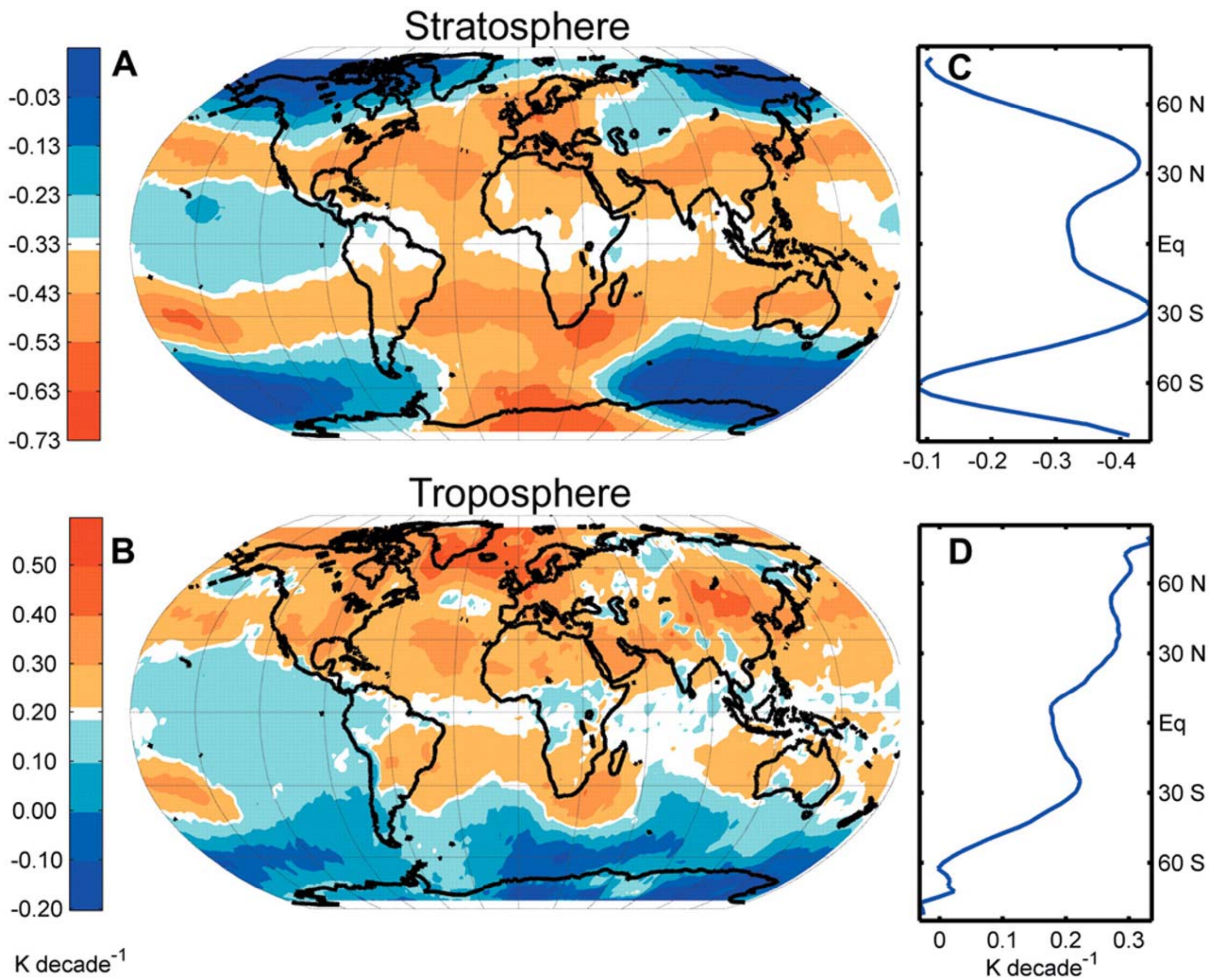
Stratospheric compensation:

$$RT_T' = -\frac{\partial \phi'}{\partial \ln\left(p\right)} \cong -\frac{\phi_T'}{\Delta \ln\left(p\right)} = -\frac{\left(T_s - T_T\right) s_b'}{\Delta \ln\left(p\right)}$$

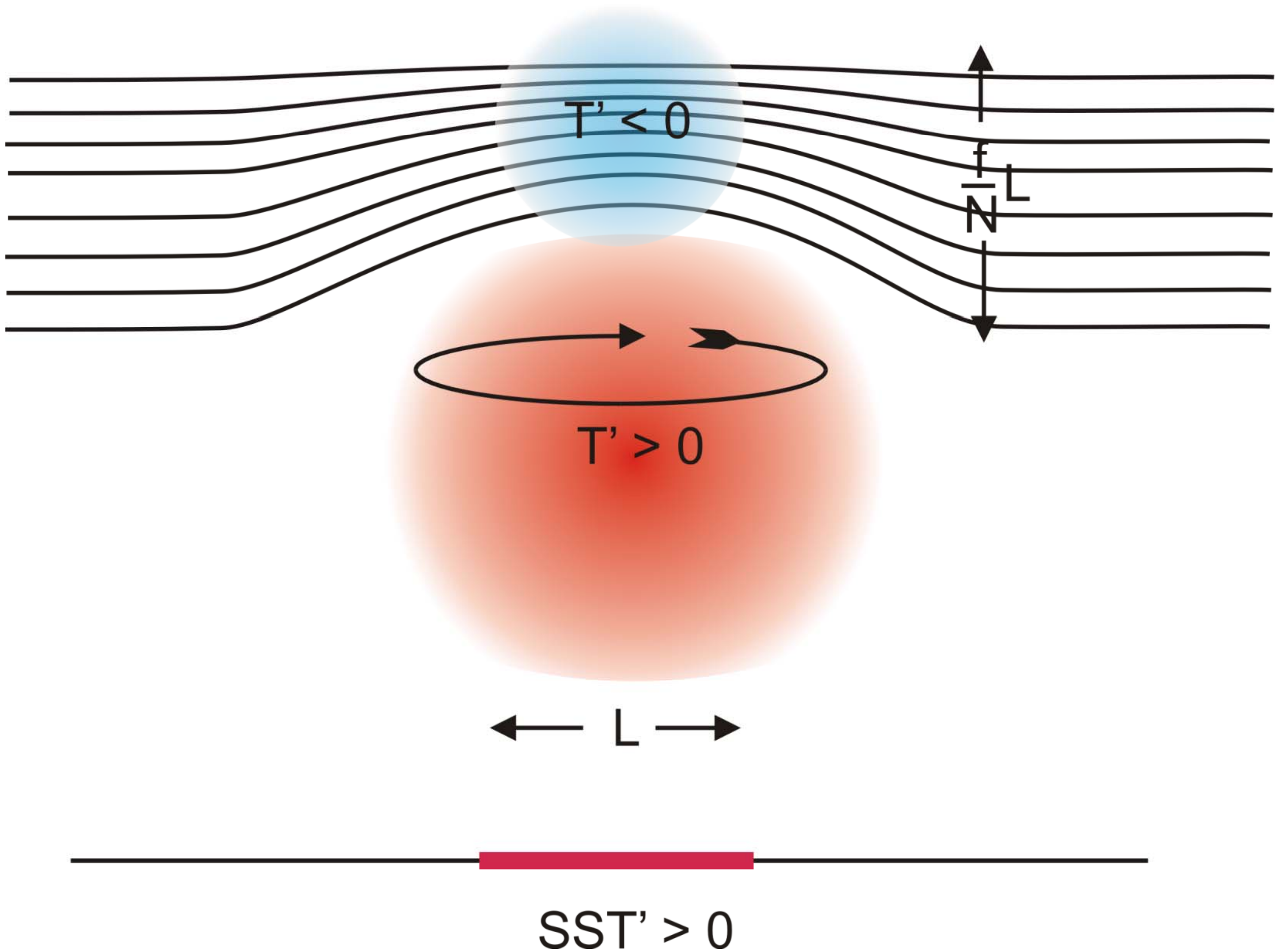
For typical values of the parameters

$$T_T' \approx -T_s'$$

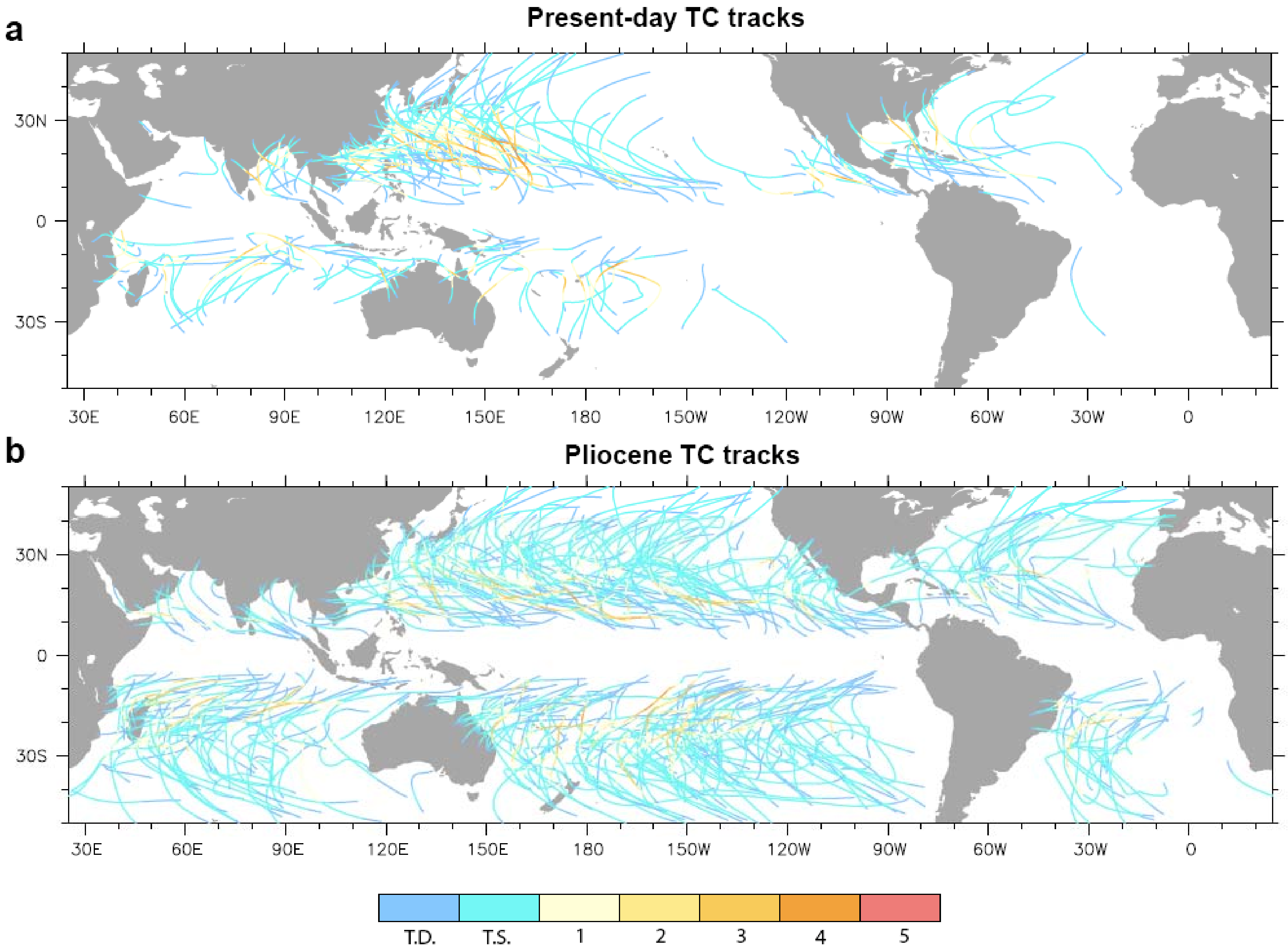
Ozone may not explain spatial pattern of cooling (Fu and Wallace, *Science*, 2006)



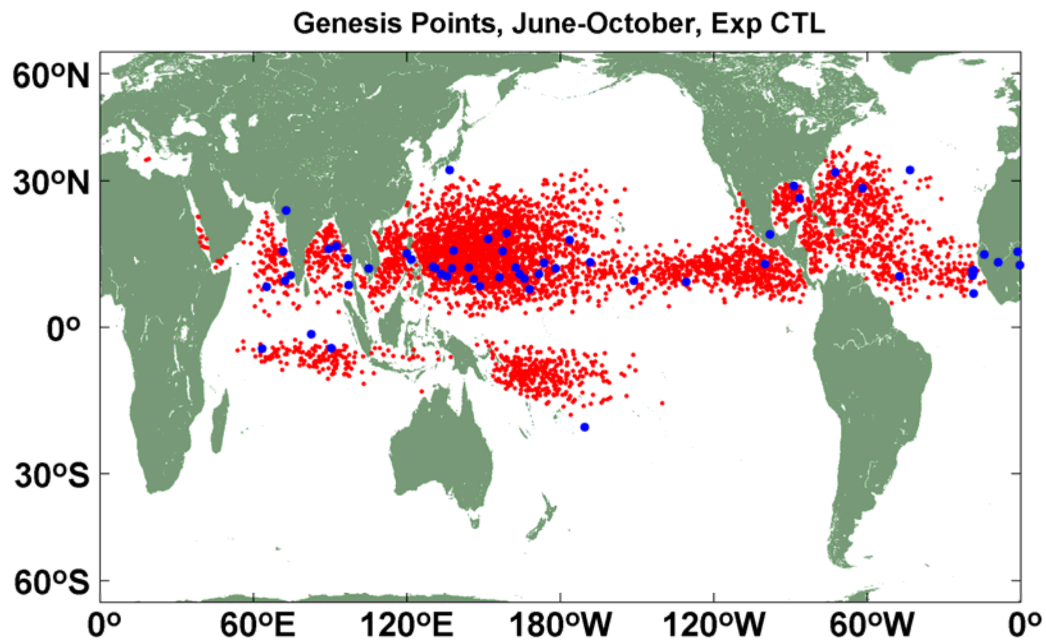
Stratospheric Compensation

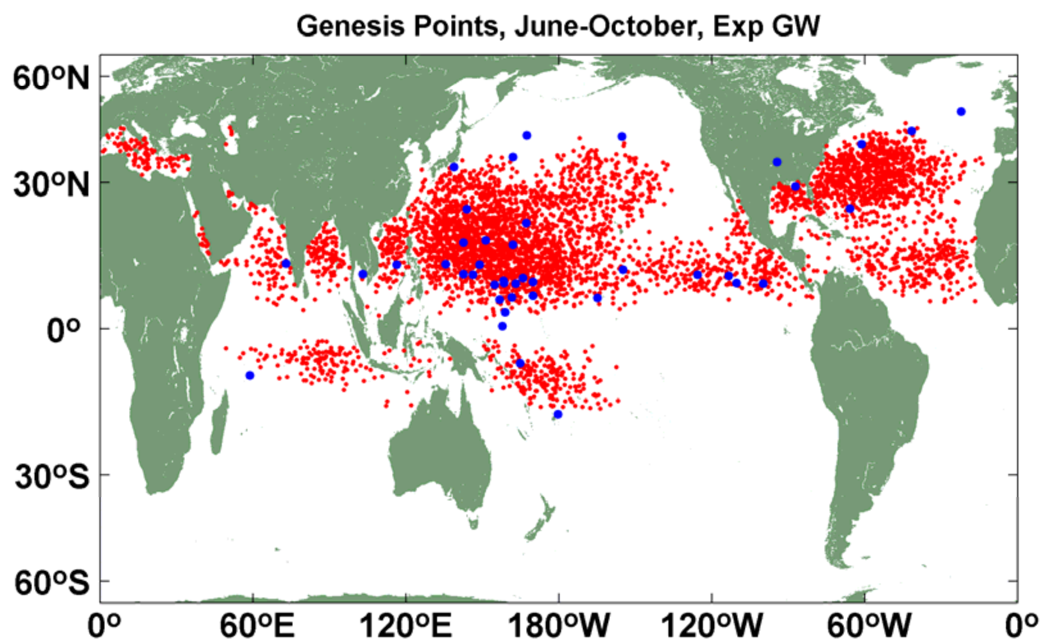


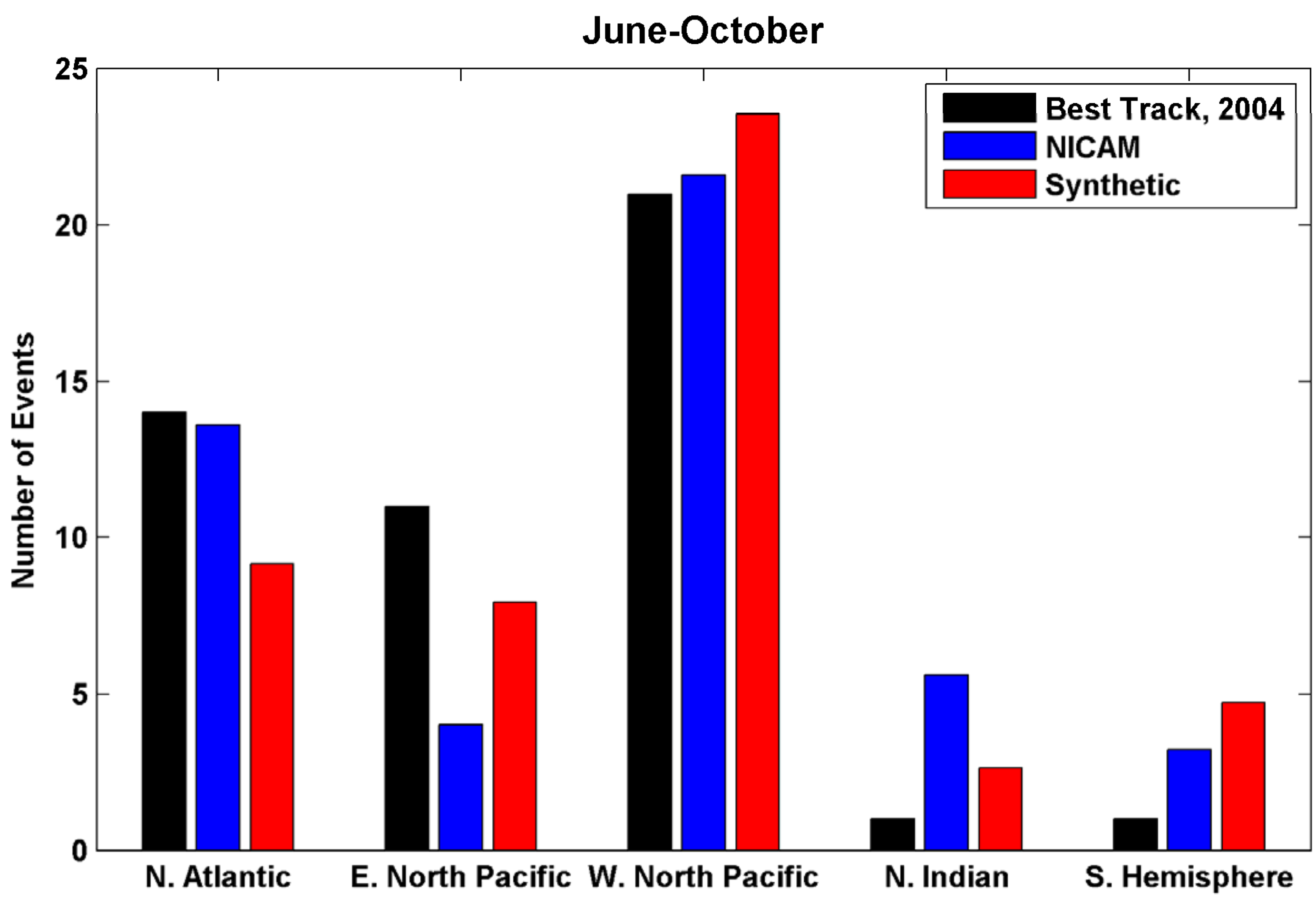
Application to the Climate of the Pliocene



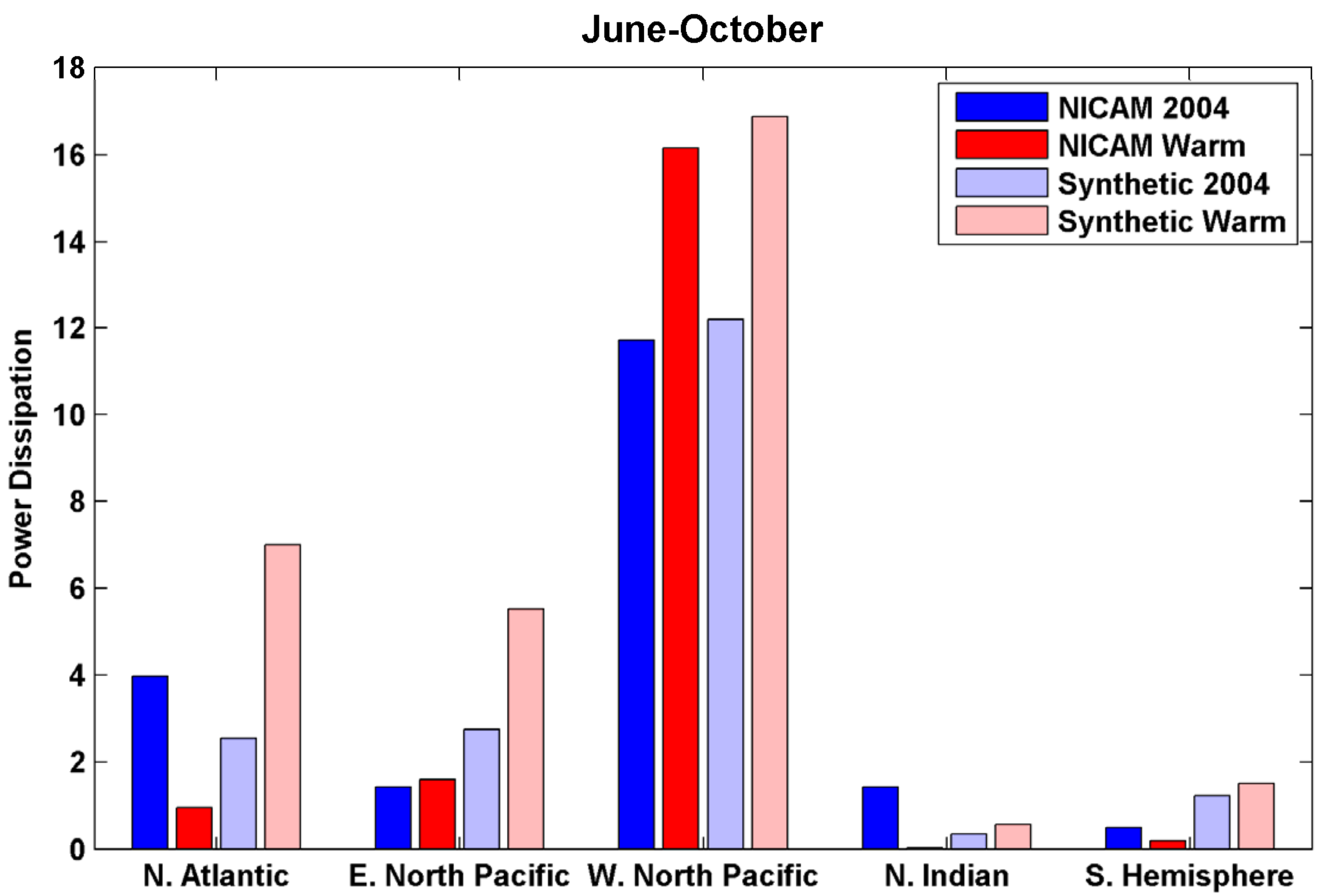
Explicit (blue dots) and downscaled (red dots) genesis points for June-October for Control (top) and Global Warming (bottom) experiments using the 14-km resolution NICAM model. Collaborative work with K. Oouchi.



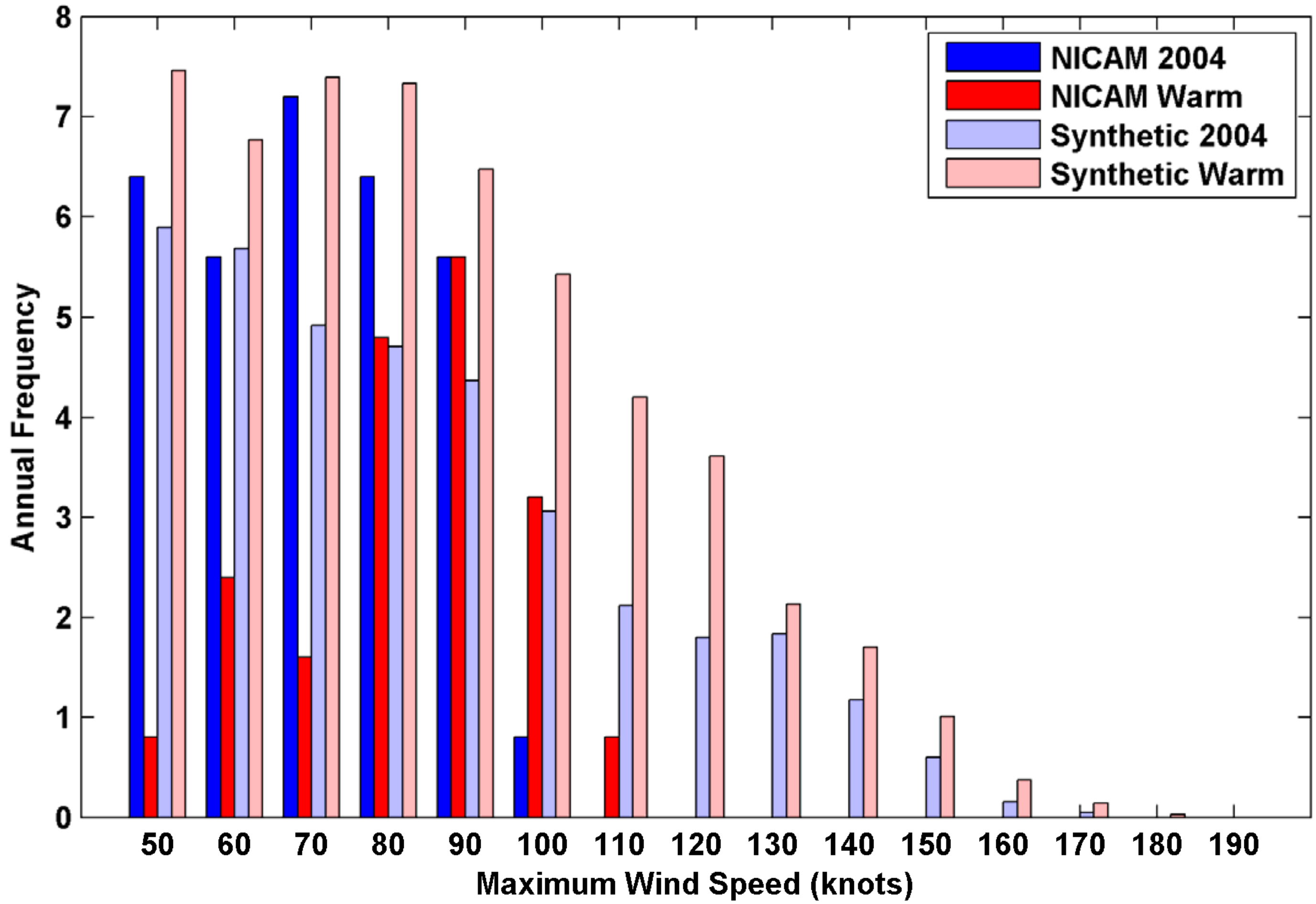



June-October
Number of Events
0
5
10
15
20
25
Best Track, 2004
NICAM
Synthetic
N. Atlantic
E. North Pacific
W. North Pacific
N. Indian
S. Hemisphere

Change in Power Dissipation with Global Warming

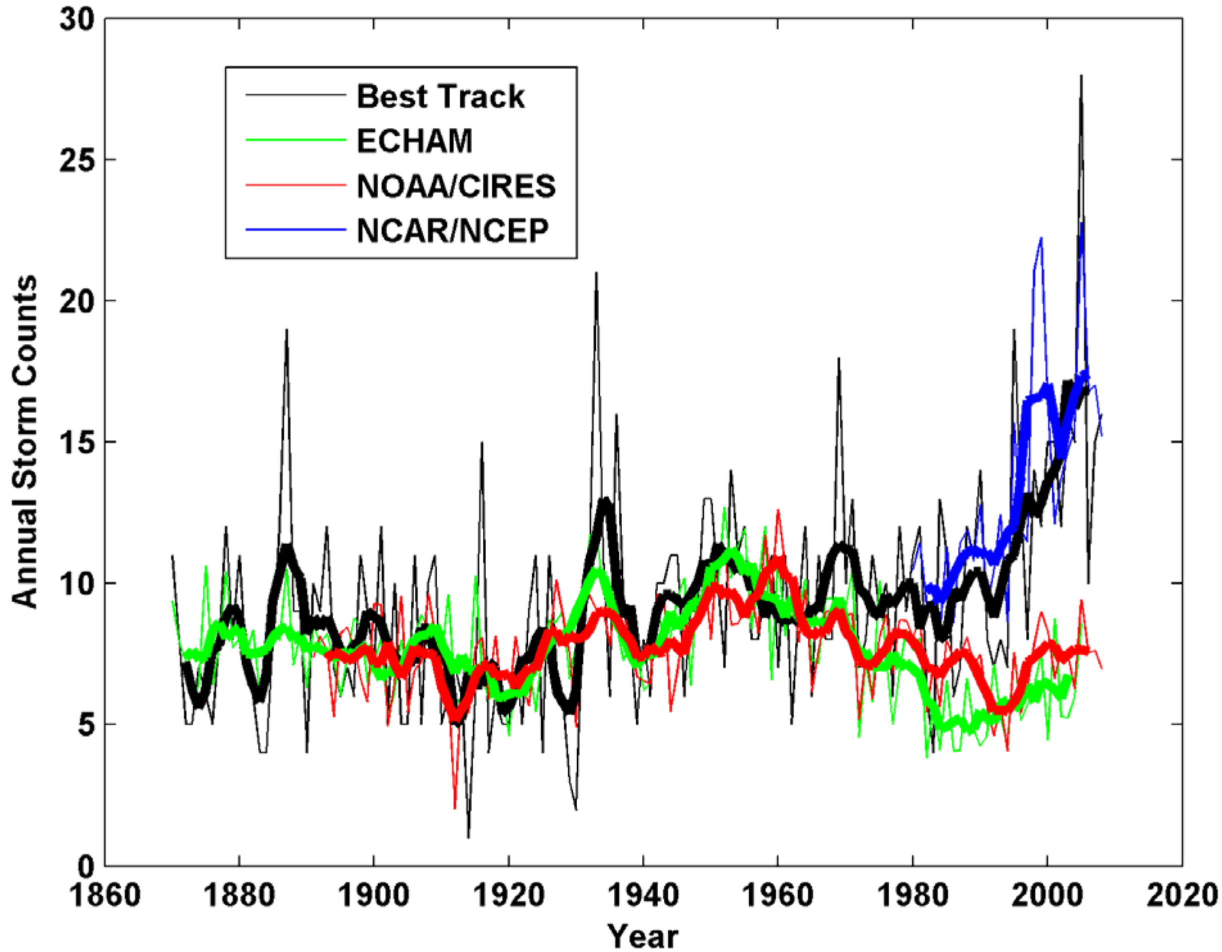


Probability Density by Storm Lifetime Peak Wind Speed, Explicit and Downscaled Events



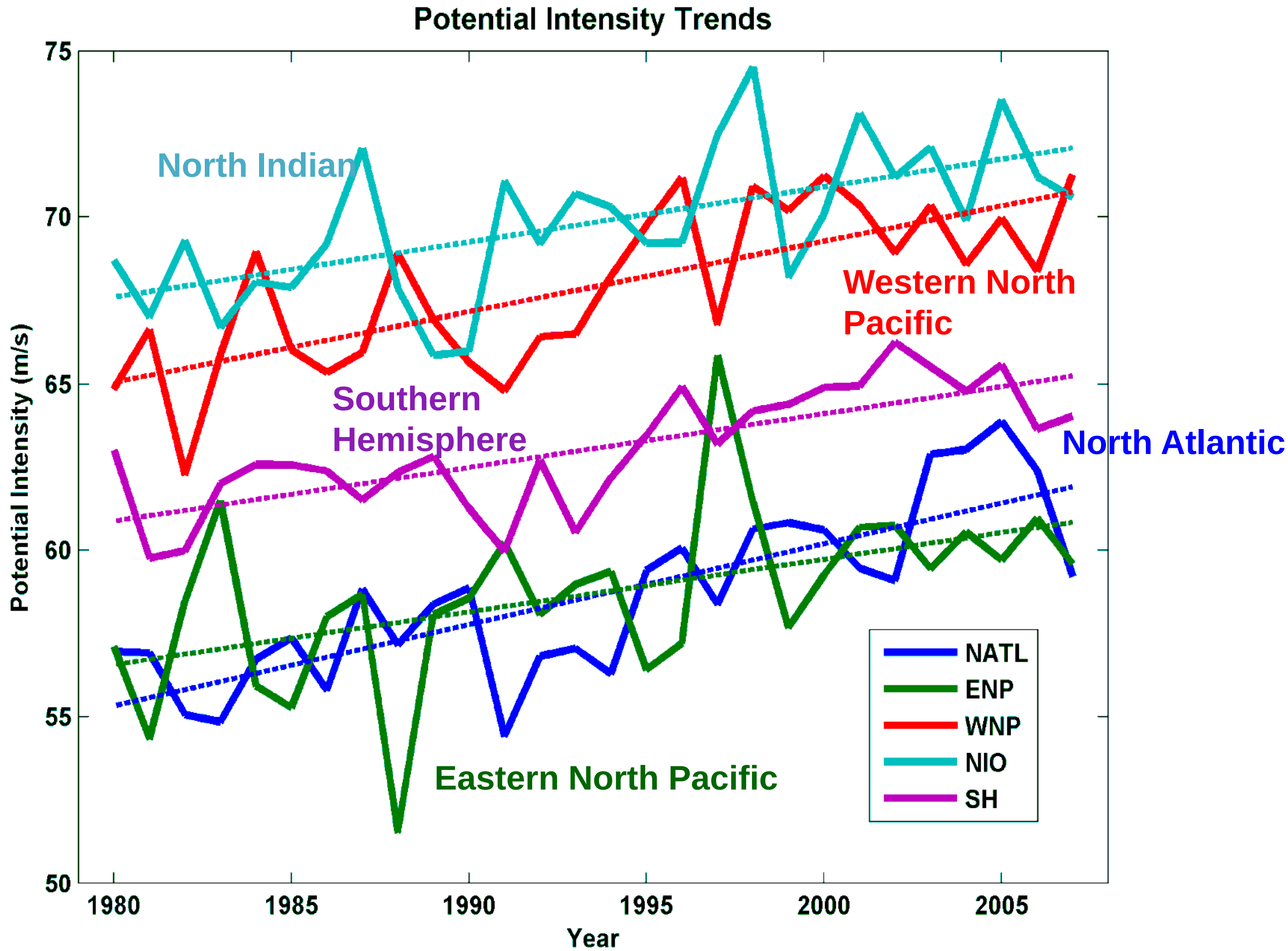
The Importance of Potential Intensity for Genesis and for Storm Intensity

Application to Re-analyses and AGCMs



Annual Atlantic tropical cyclone counts: Unadjusted best-track data (black); and downscaled from the NCAR/NCEP reanalysis, 1980-2008 (blue), the ECHAM 5 simulation, 1870-2005 (green), and the NOAA/CIRES reanalysis, 1891-2008 (red). Thin lines show annual values, thick lines show 5-year running means

Interpretation of Recent Trends in Potential Intensity



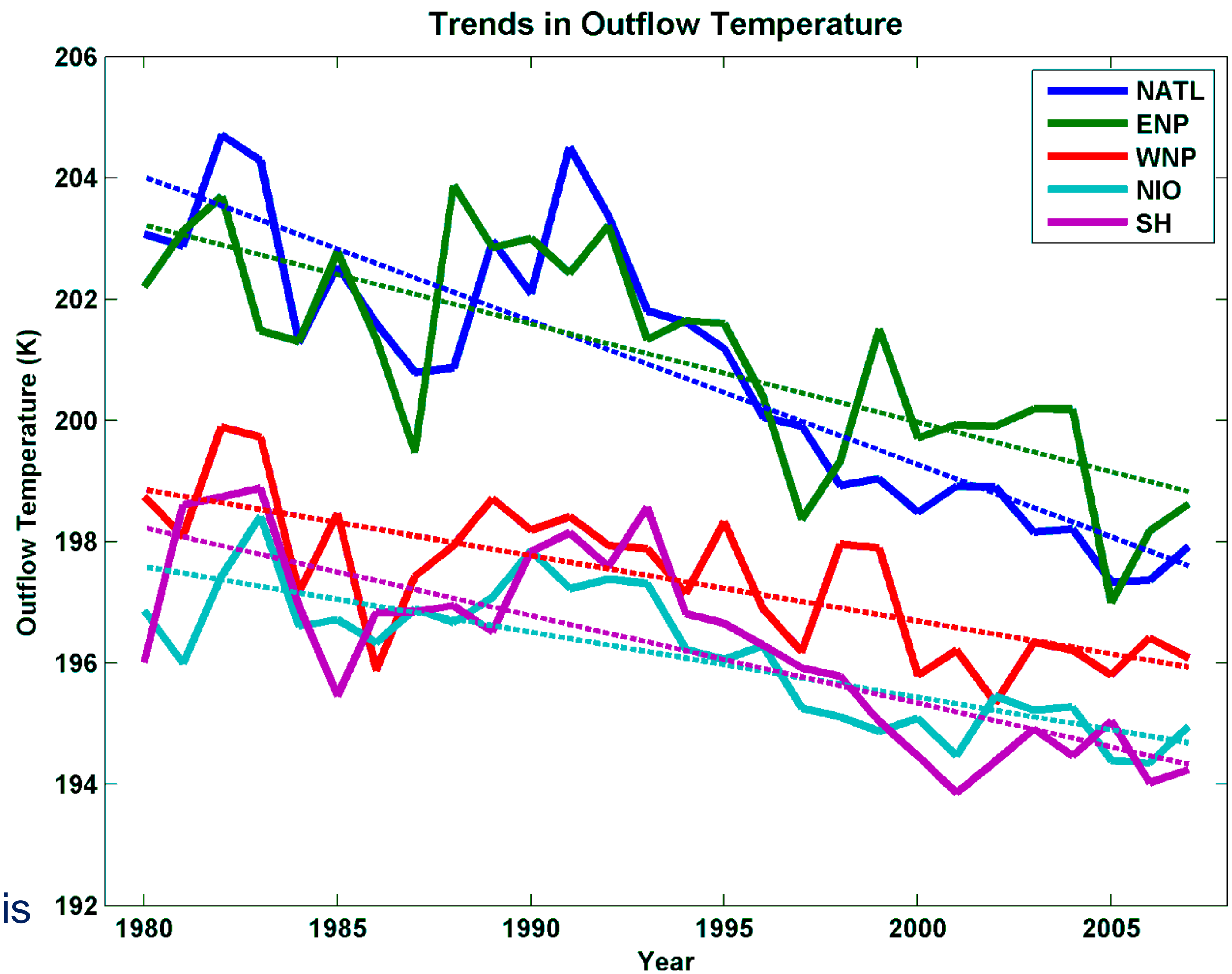
From NCAR/NCEP reanalysis data, 1980-2008

Potential intensity has been increasing by about 12 $ms^{-1}K^{-1}$, compared to accepted value of 4 $ms^{-1}K^{-1}$. What is the source of this discrepancy?

Surface wind speeds have not changed much since 1980. Key variable: Outflow temperature, which in general decreases with:

- Increasing SST
- Decreasing temperature of lower stratosphere and/or troposphere transition layer

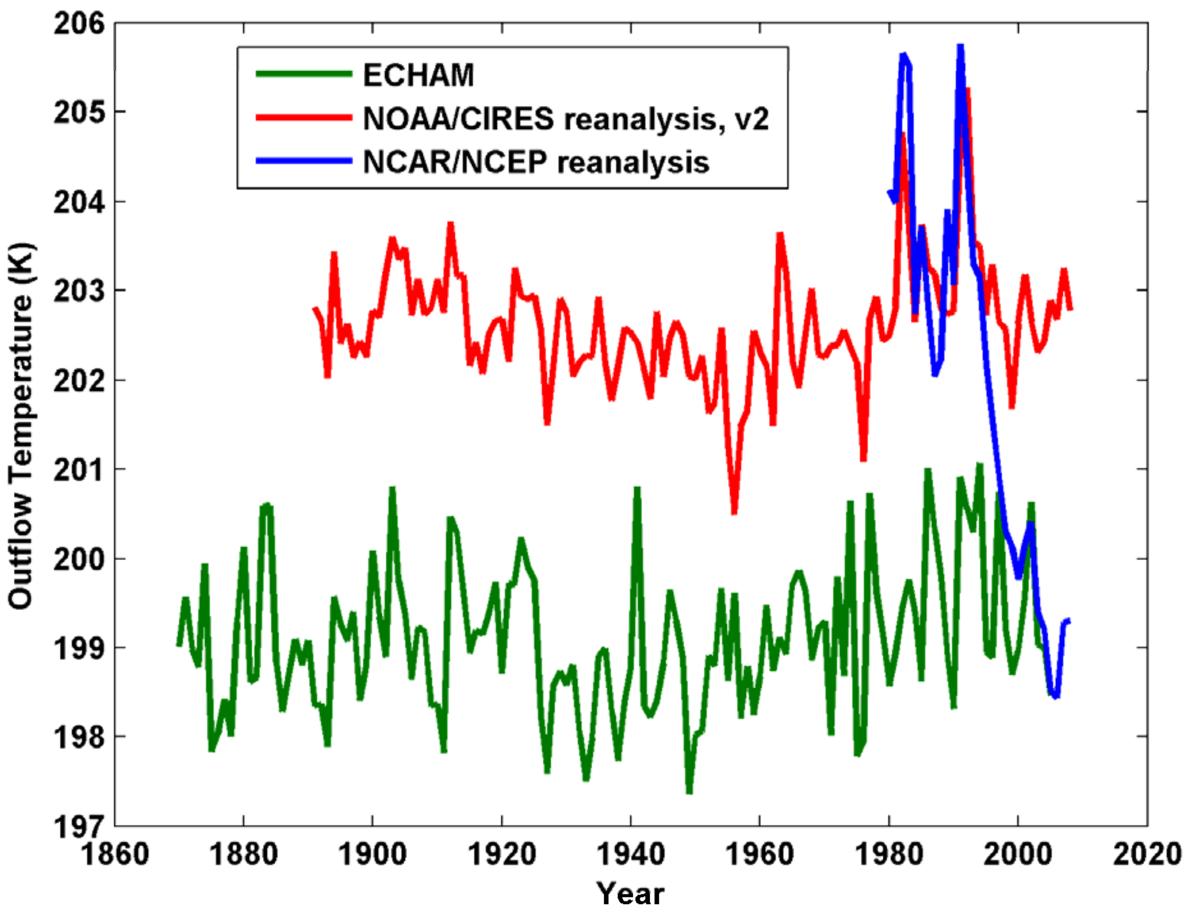
Importance of Trends in Outflow Temperature



From NCEP Reanalysis

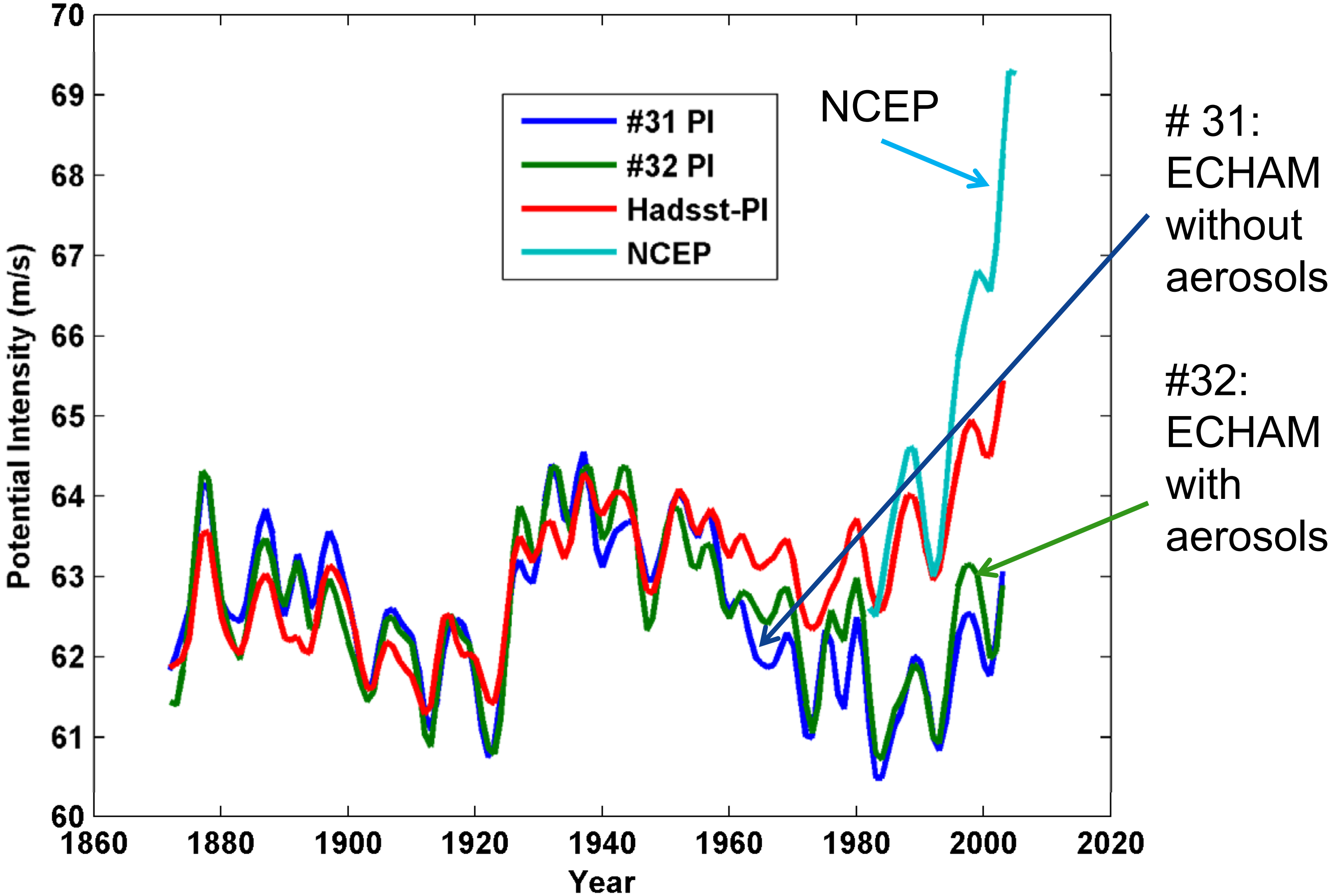
Do Climate Models Capture Lower Stratospheric Cooling?

AGCMs, *driven by observed SSTs*, do not get the cooling!

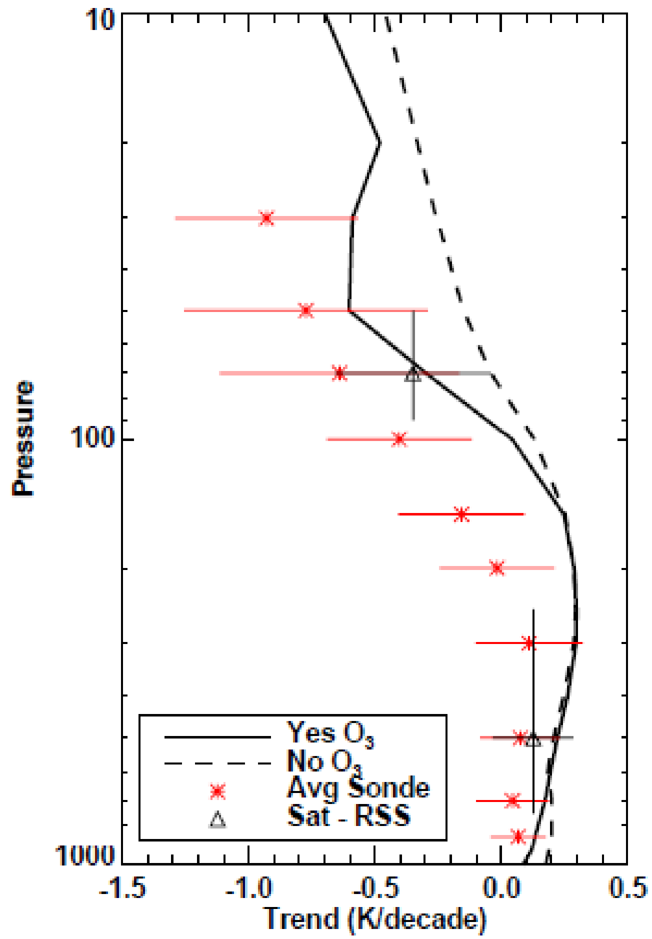


August-October outflow temperatures averaged over the Atlantic MDR from the ECHAM 5 simulation (green), the NOAA/CIRES 20th Century reanalysis, version 2 (red) and the NCAR/NCEP reanalysis (blue)

As a result, they miss the recent increase in potential intensity



1979-1999 Temperature Trends, 30S-30N. Red: Radiosondes; Solid Black: Mean of Models with Ozone; Dashed Black: Mean of Models without Ozone (Cordero and Forster, 2006)



Combine expression for potential intensity, V_{max}, with energy balance of ocean mixed layer:

$$V_{max}^2 = \frac{T_s - T_o}{T_o} \, \frac{F_{rad} - d\nabla \cdot \mathbf{F}_{\mathbf{ocean}}}{C_D \rho \, |\mathbf{V}_\mathbf{s}|}$$

SST (T_s)

Outflow T (T_o)

Net surface radiative flux (F_{rad})

Ocean mixed layer depth (d)

Mixed layer heat flux ($\mathbf{F}_{\mathbf{ocean}}$)

Drag coefficient (C_D)

Mean surface wind speed ($|\mathbf{V}_\mathbf{s}|$)

Valid on time scales > thermal equilibration time of ocean mixed layer (~ 2 years)