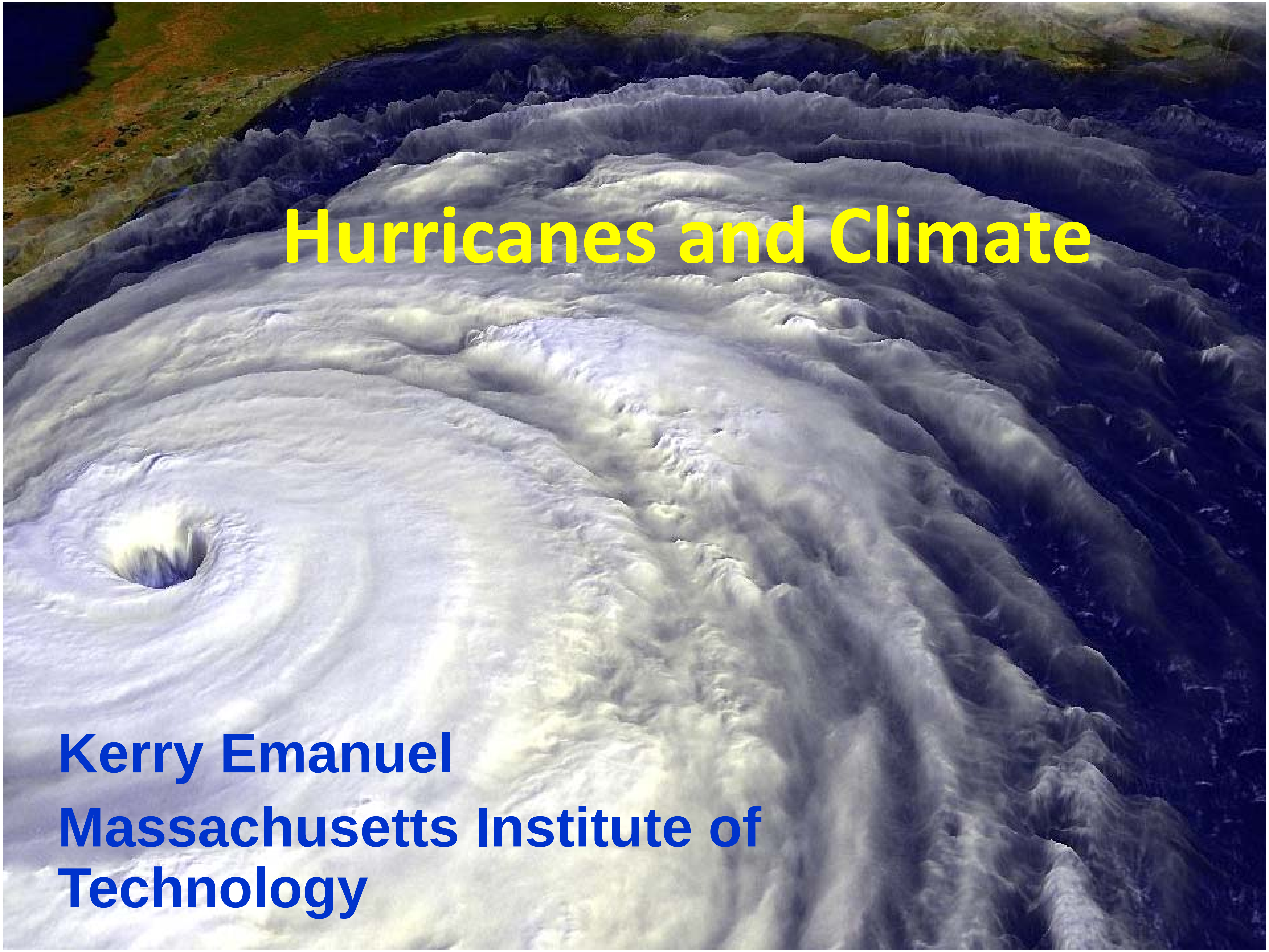


Hurricanes and Climate

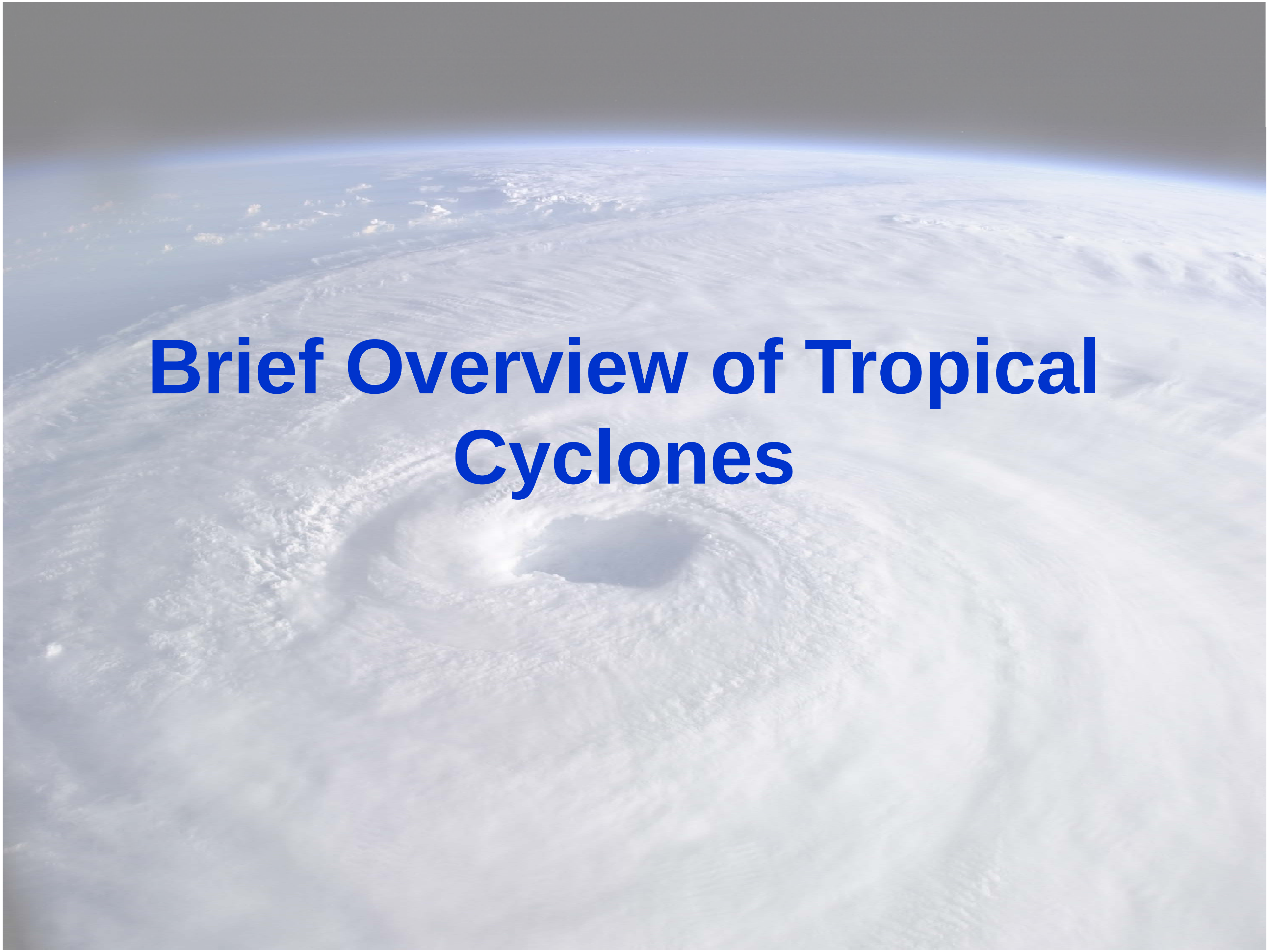
Kerry Emanuel

Massachusetts Institute of Technology

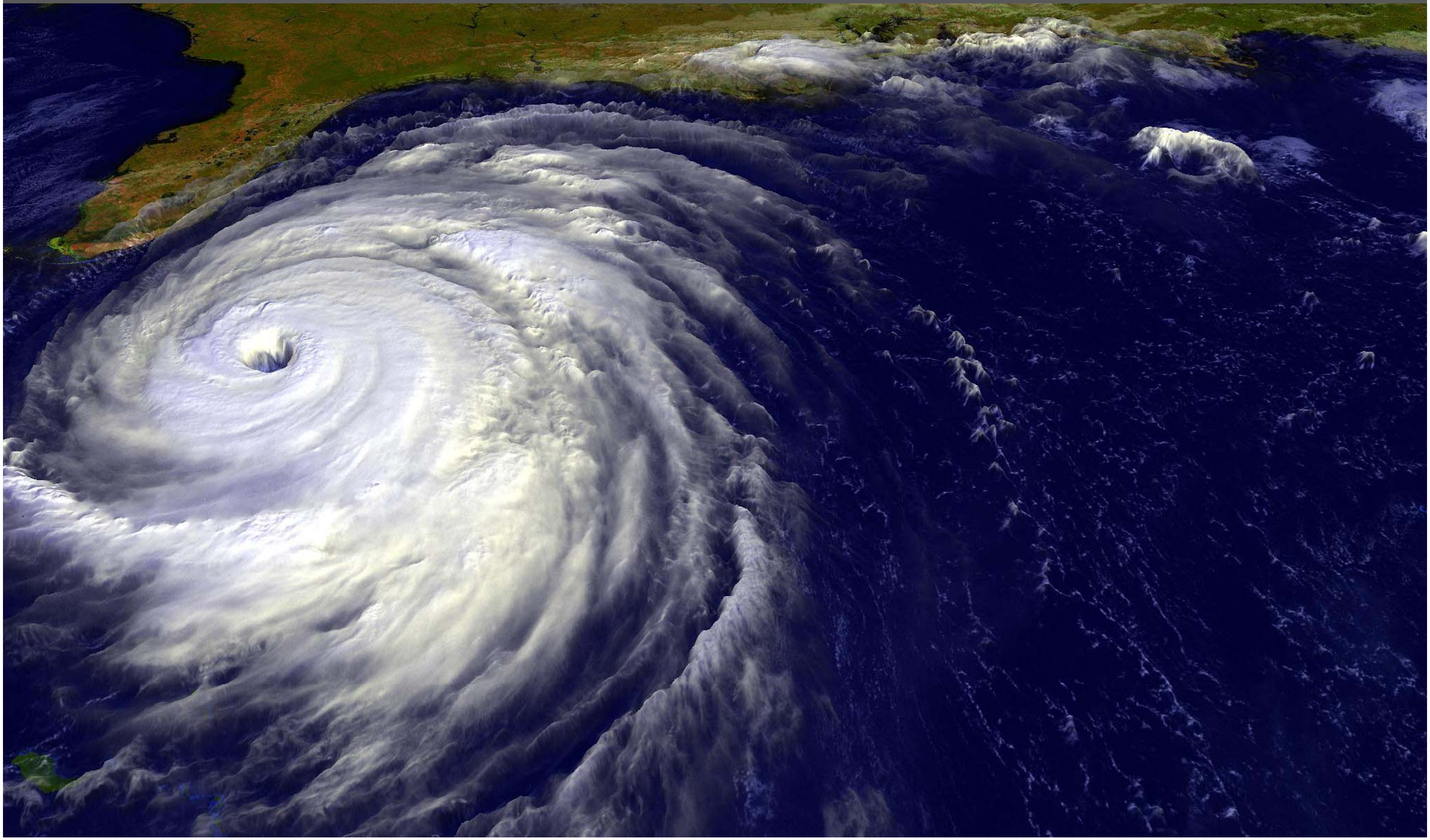
Issues

- **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?**

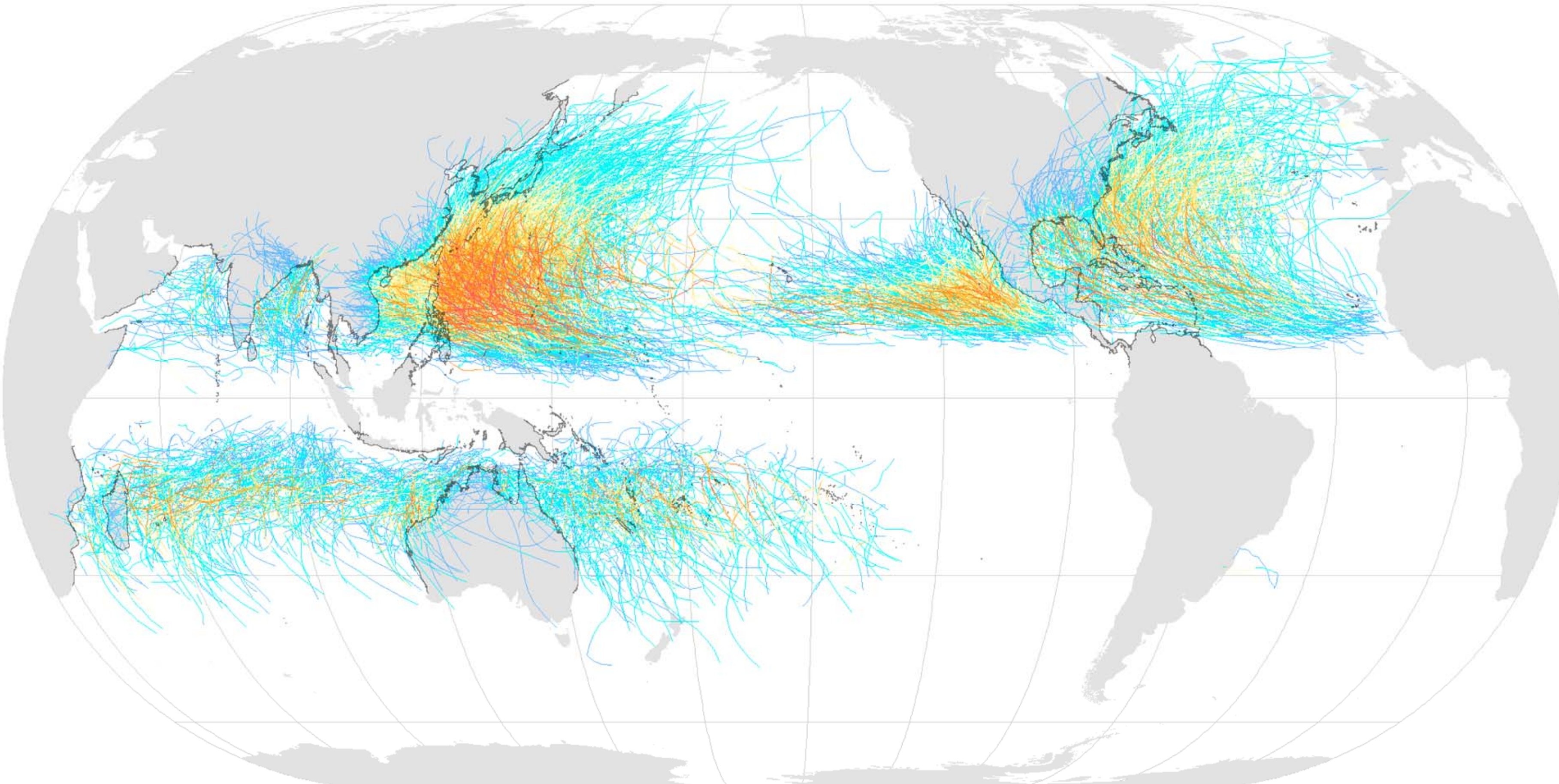
Brief Overview of Tropical Cyclones



The View from Space

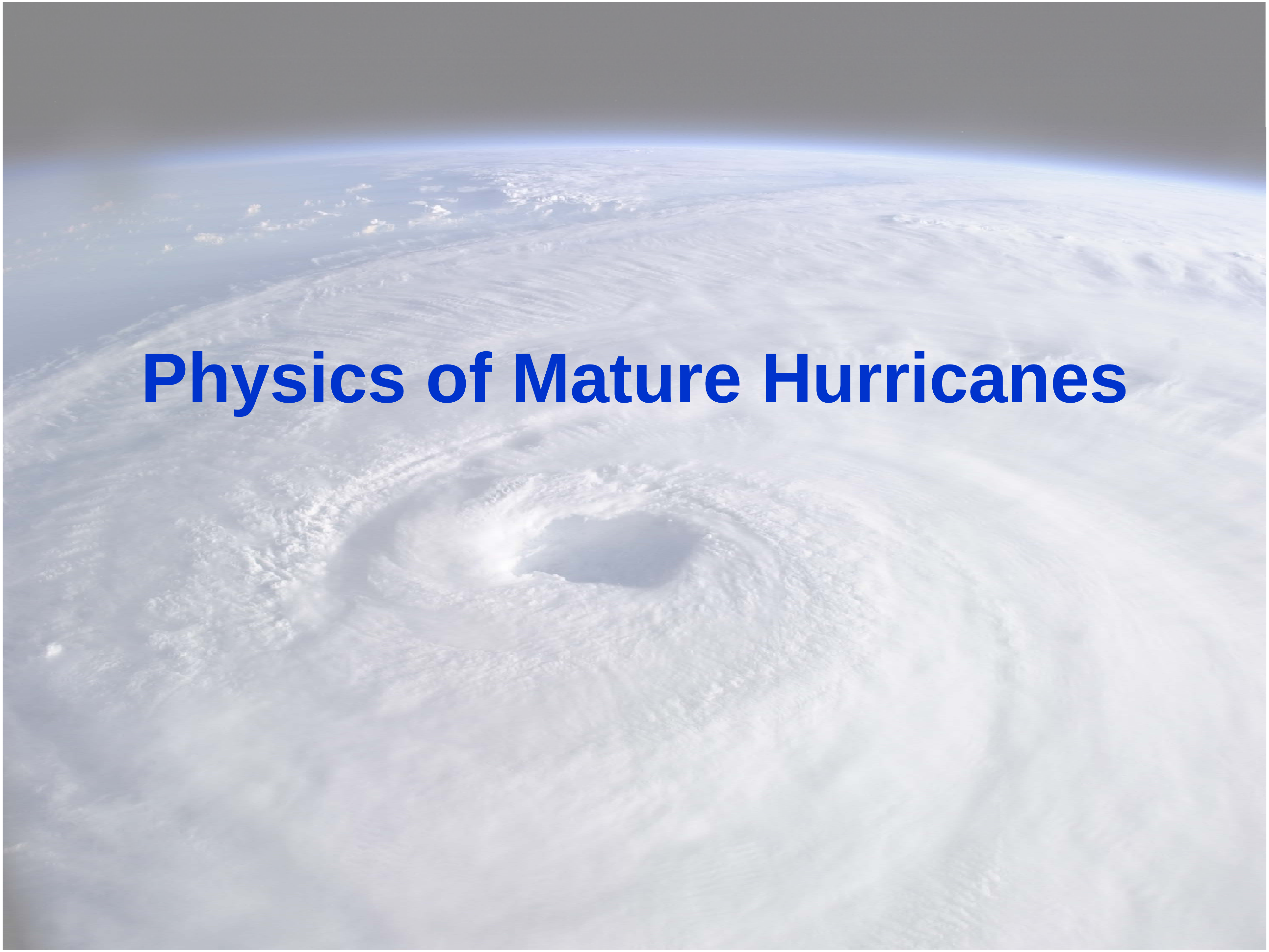


Tropical Cyclones, 1945–2006



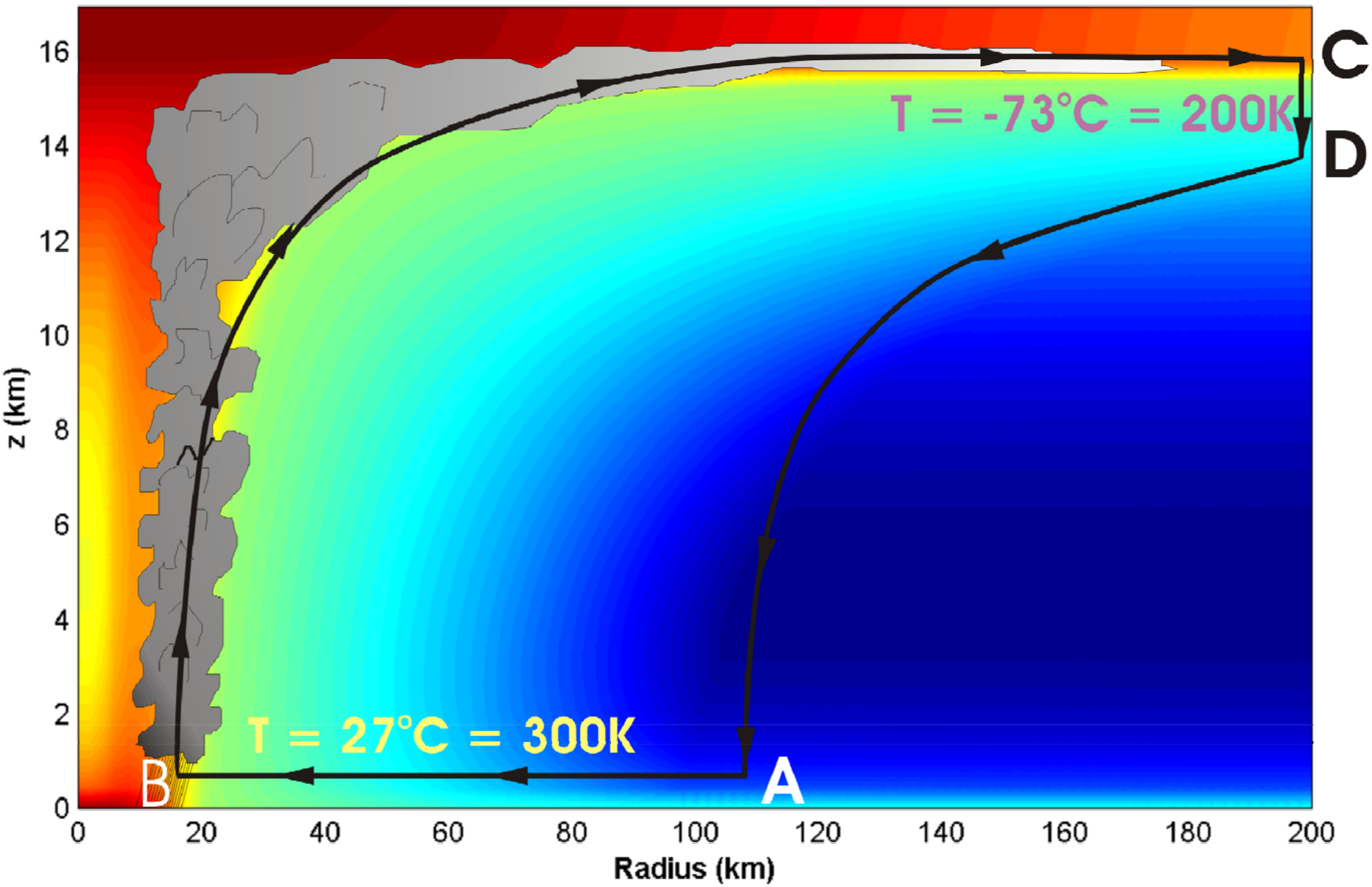
Saffir-Simpson Hurricane Scale:

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



Carnot Theorem: Maximum efficiency results from a particular energy cycle:

- Isothermal expansion
- Adiabatic expansion
- Isothermal compression
- Adiabatic compression

Note: Last leg is not adiabatic in hurricane: Air cools radiatively. But since environmental temperature profile is moist adiabatic, the amount of radiative cooling is the same as if air were saturated and descending moist adiabatically.

Maximum rate of energy production:

$$P = \frac{T_s - T_o}{T_s} \dot{Q}$$

Theoretical Upper Bound on Hurricane Maximum Wind Speed:

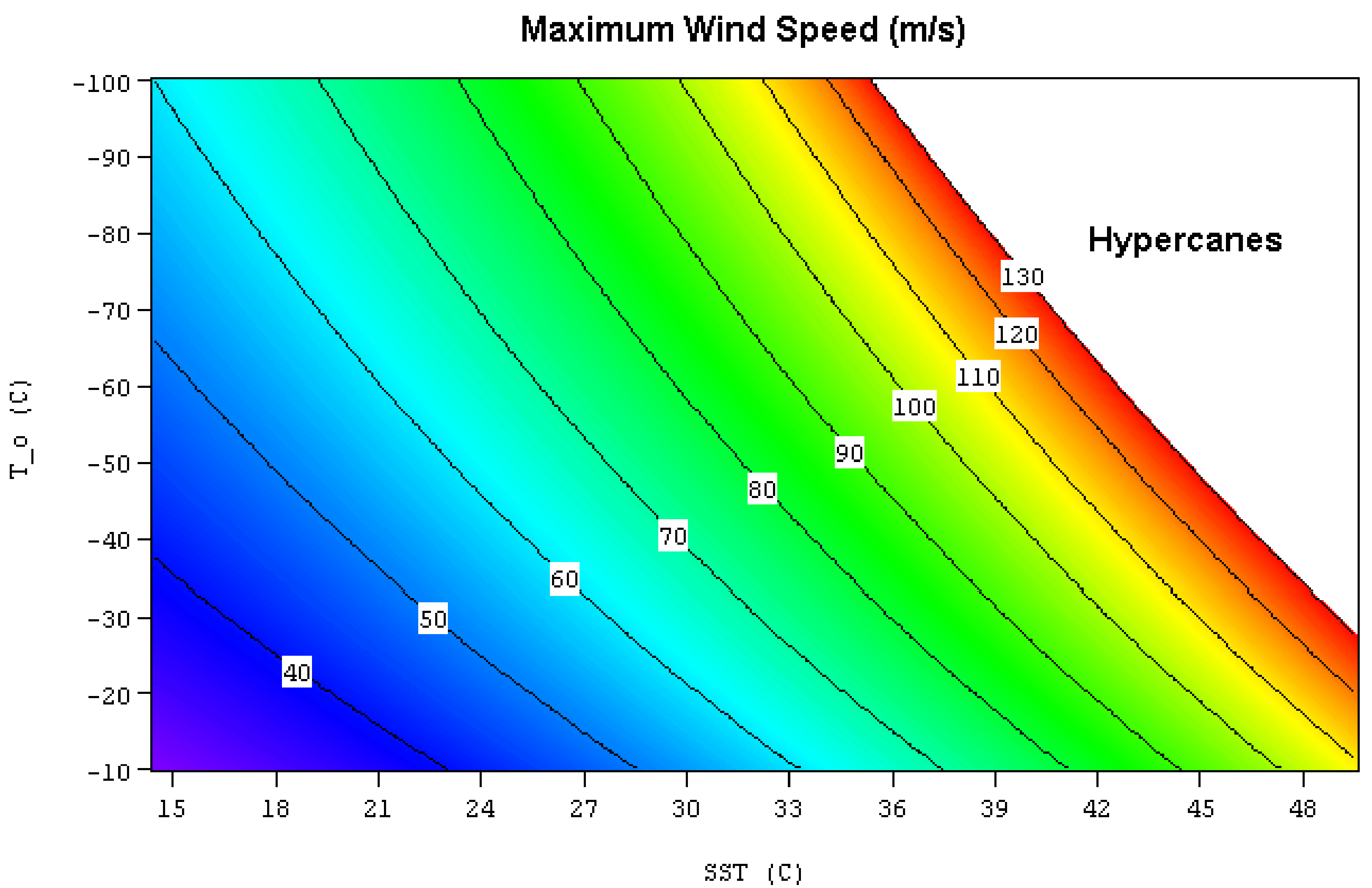
Surface temperature

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

Ratio of exchange coefficients of enthalpy and momentum

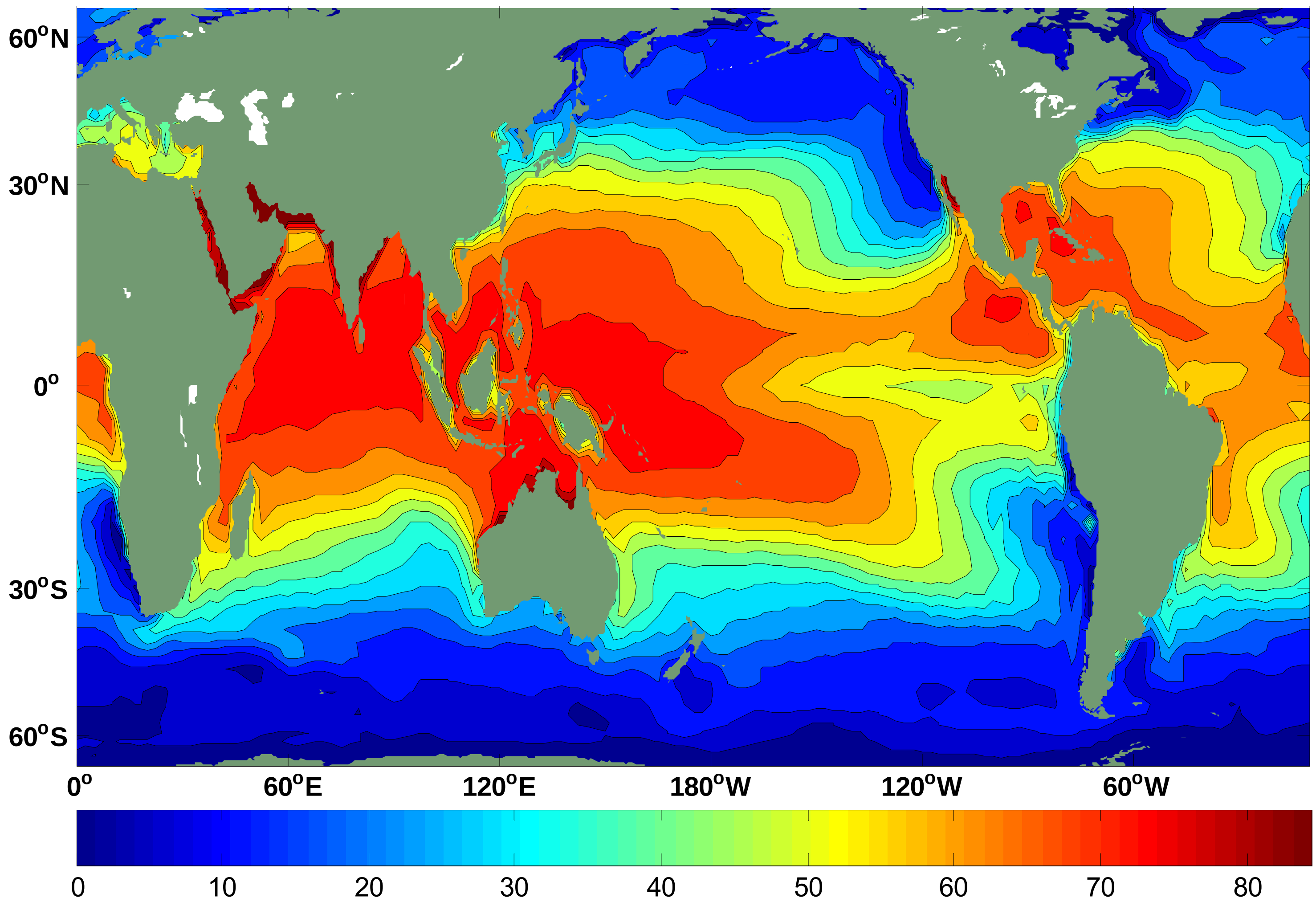
Outflow temperature

Air-sea enthalpy disequilibrium

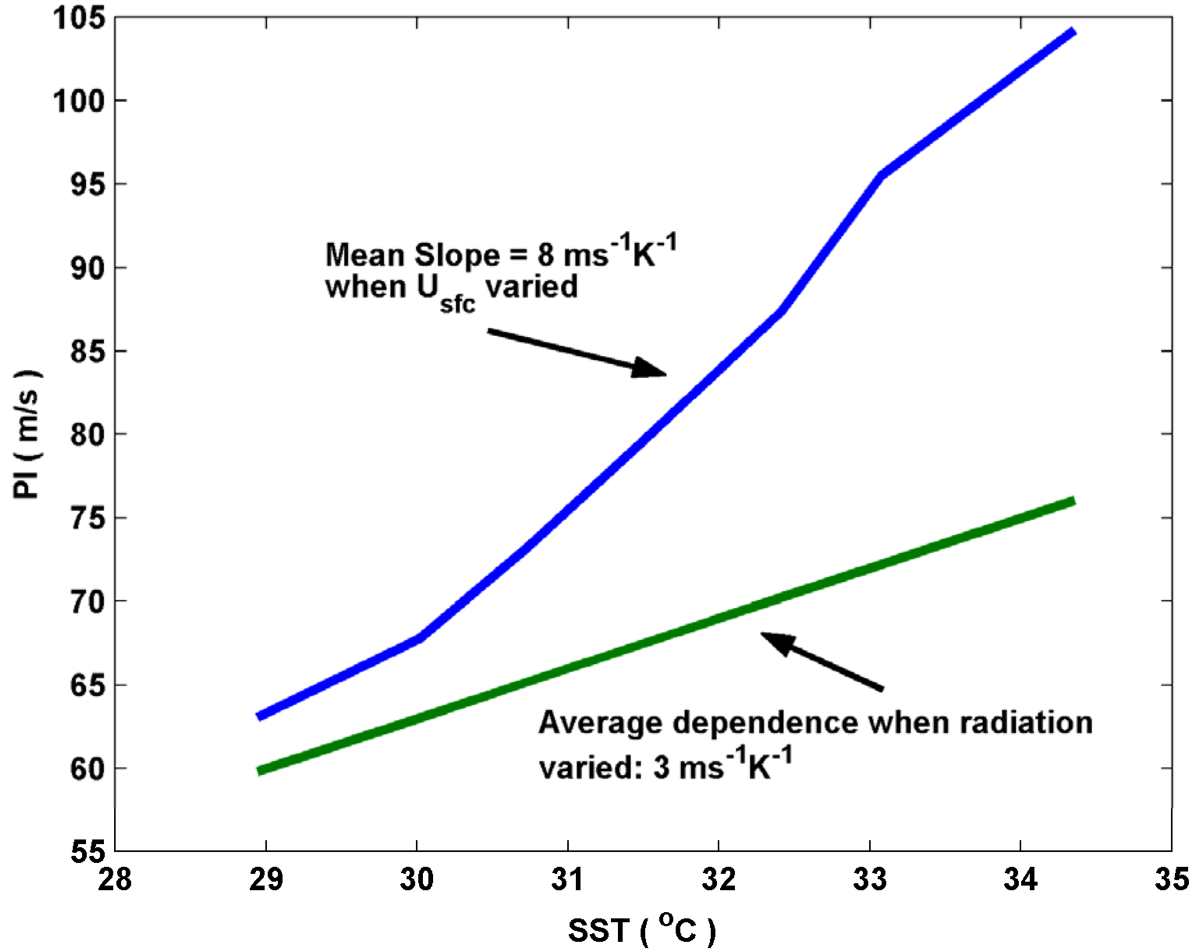


$\mathcal{H} = 0.75 \quad C_k/C_D = 1.2$

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)

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

Net surface radiative flux

SST

Outflow T

Ocean mixed layer depth

Mixed layer heat flux

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

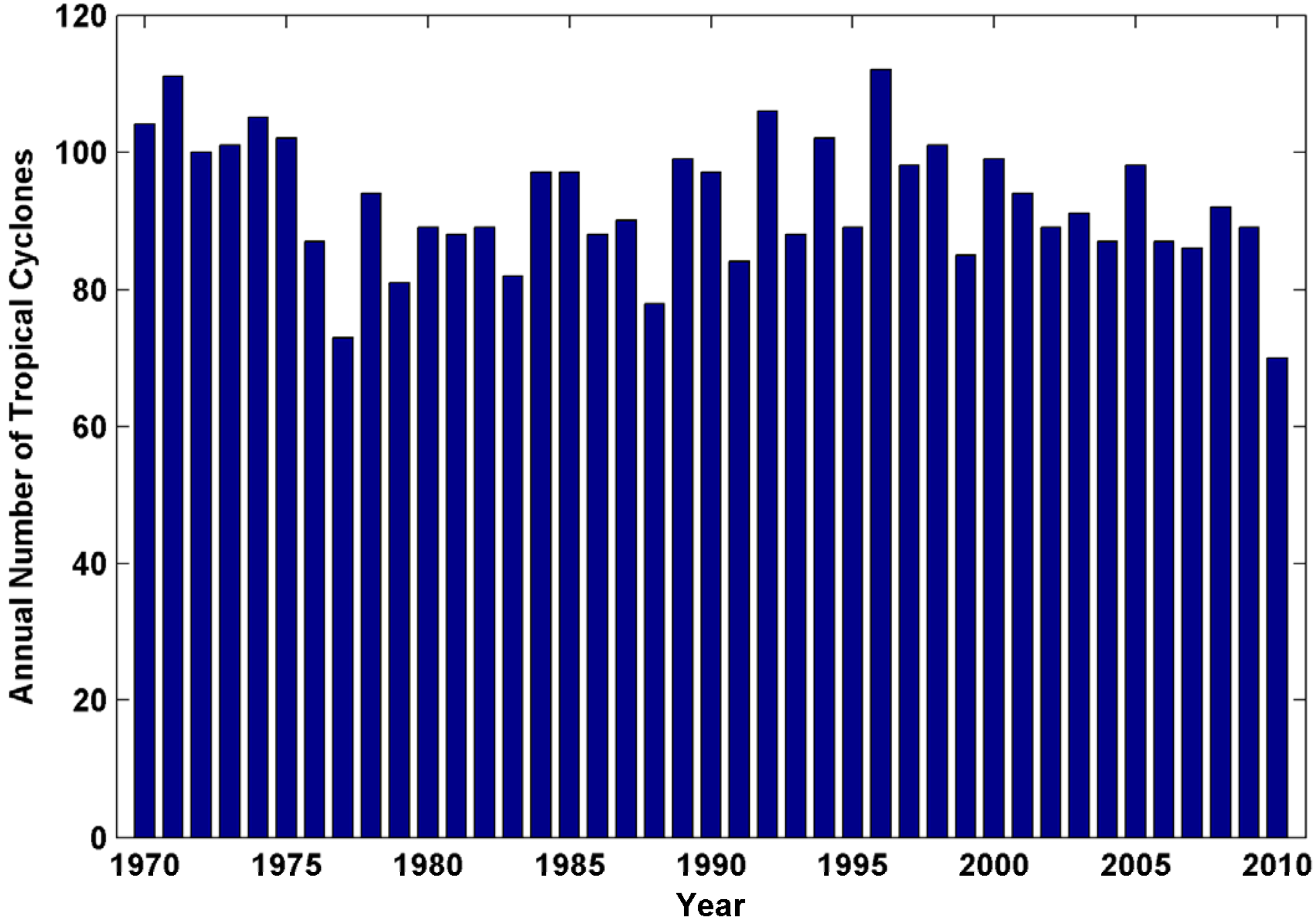
Drag coefficient

Mean surface wind speed

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

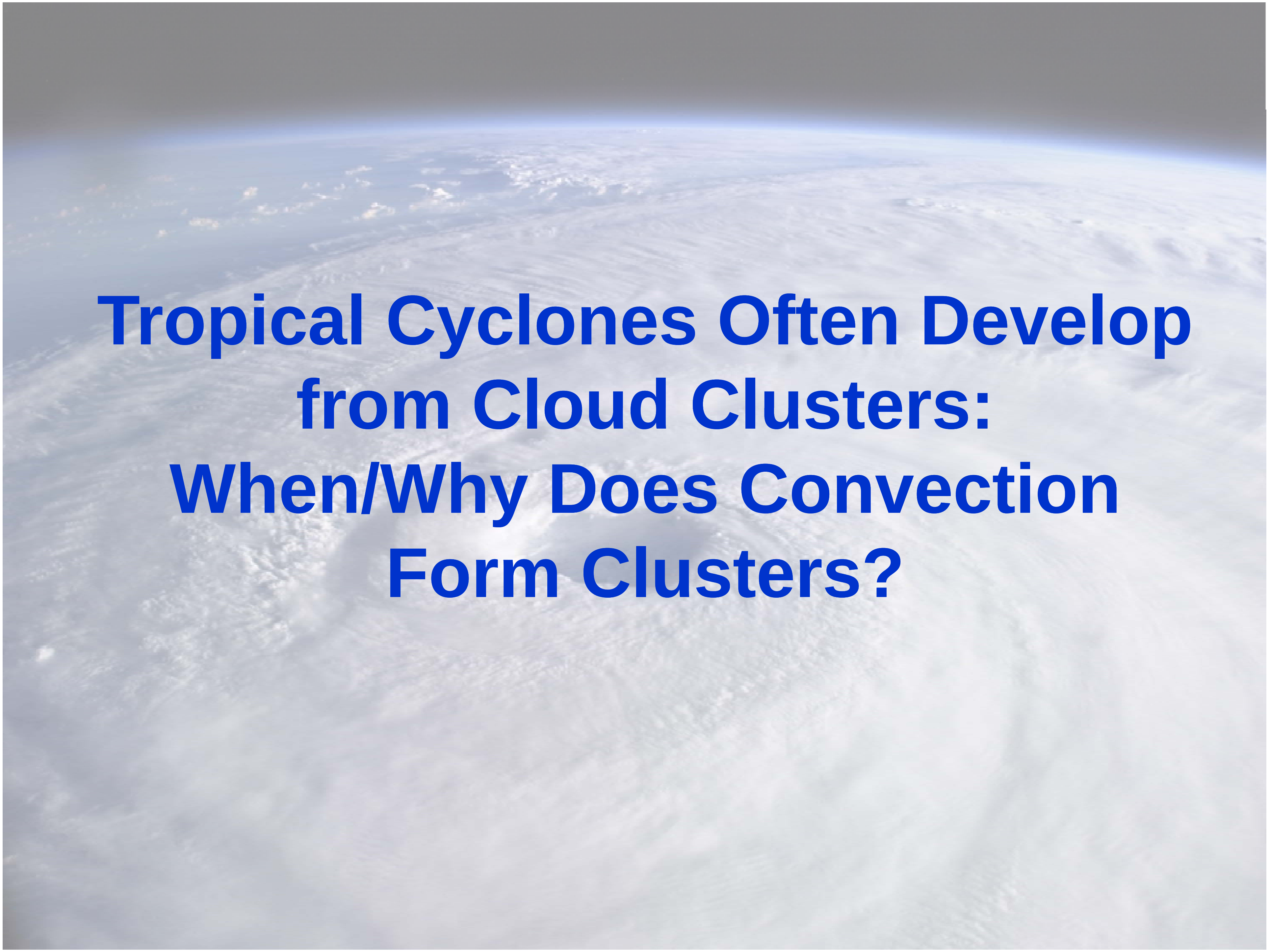

The Genesis Puzzle

No Obvious Trend in Global Hurricane Frequency, 1970-2010

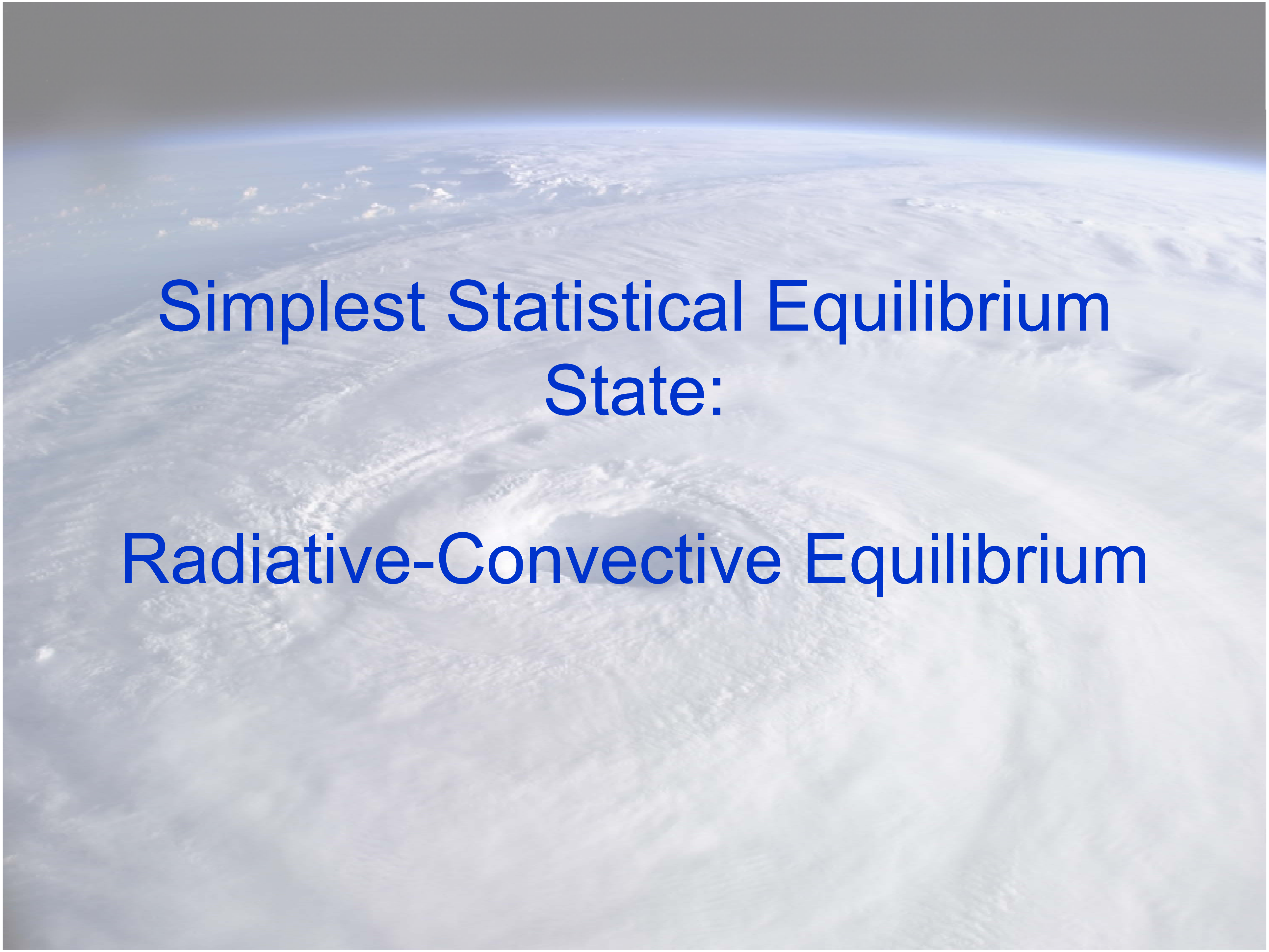


Data Sources: NOAA/TPC and NAVY/JTWC

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



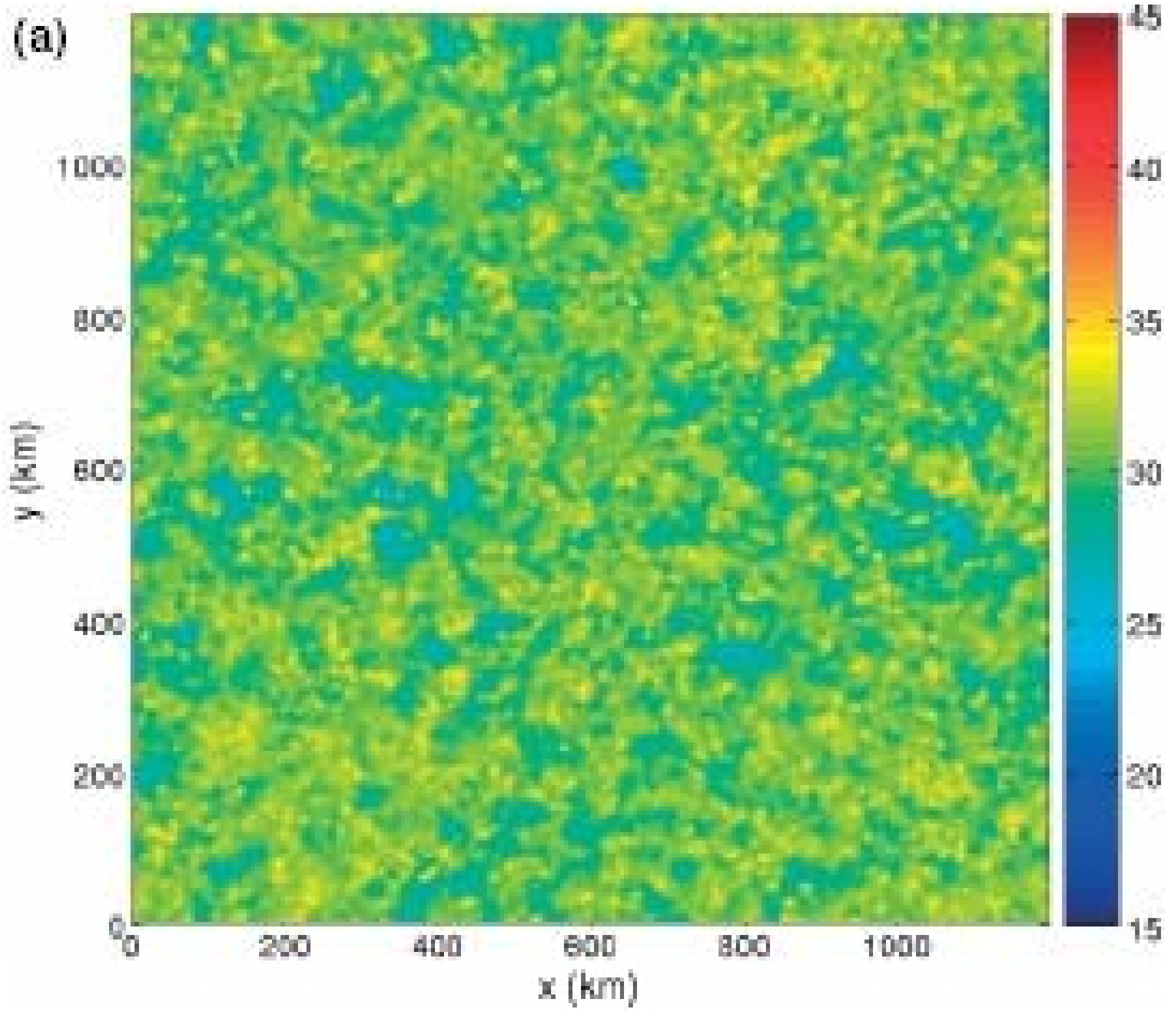
Monsoonal Thunderstorms, Bangladesh and India July 1985



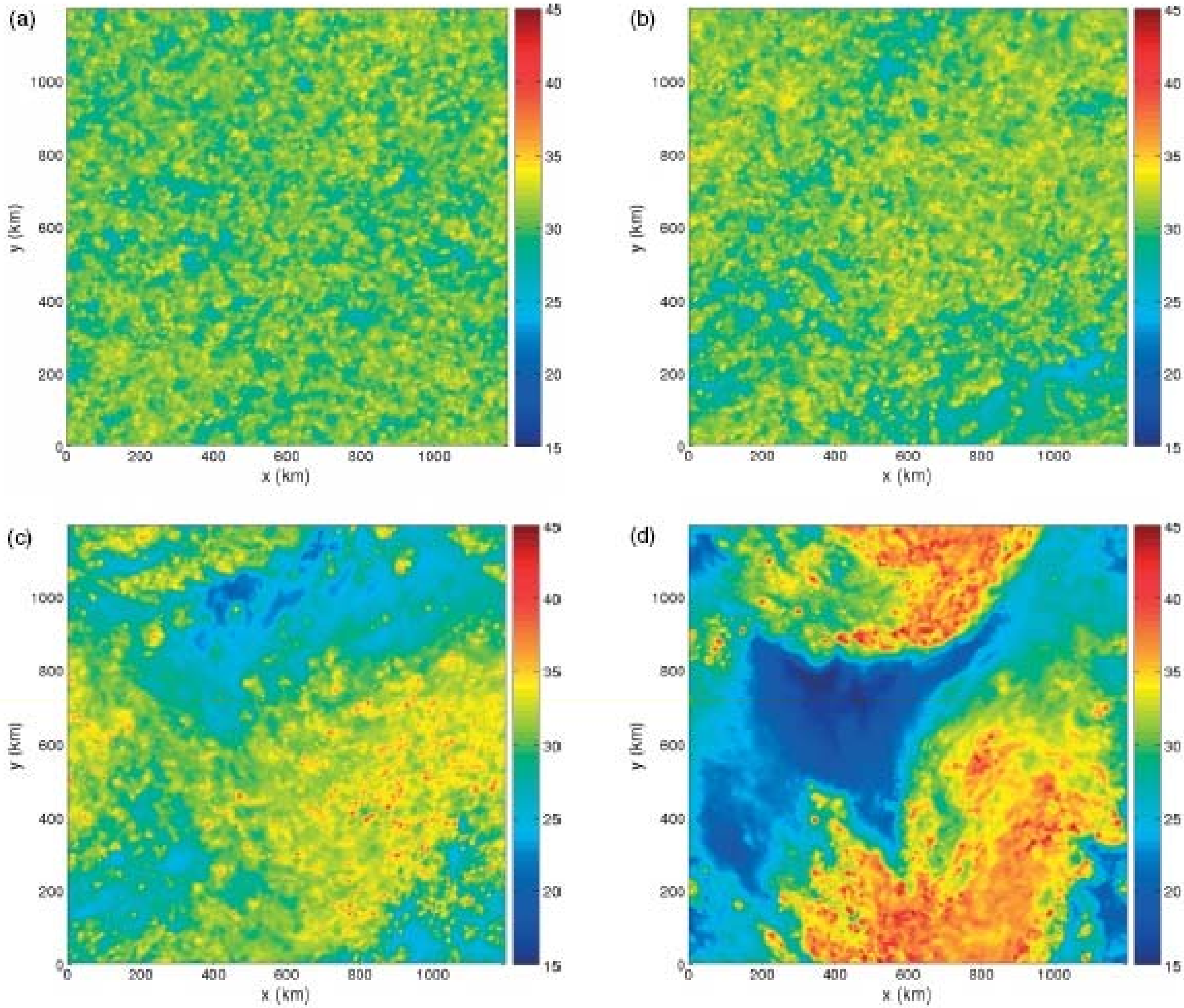
Simplest Statistical Equilibrium State:

Radiative-Convective Equilibrium

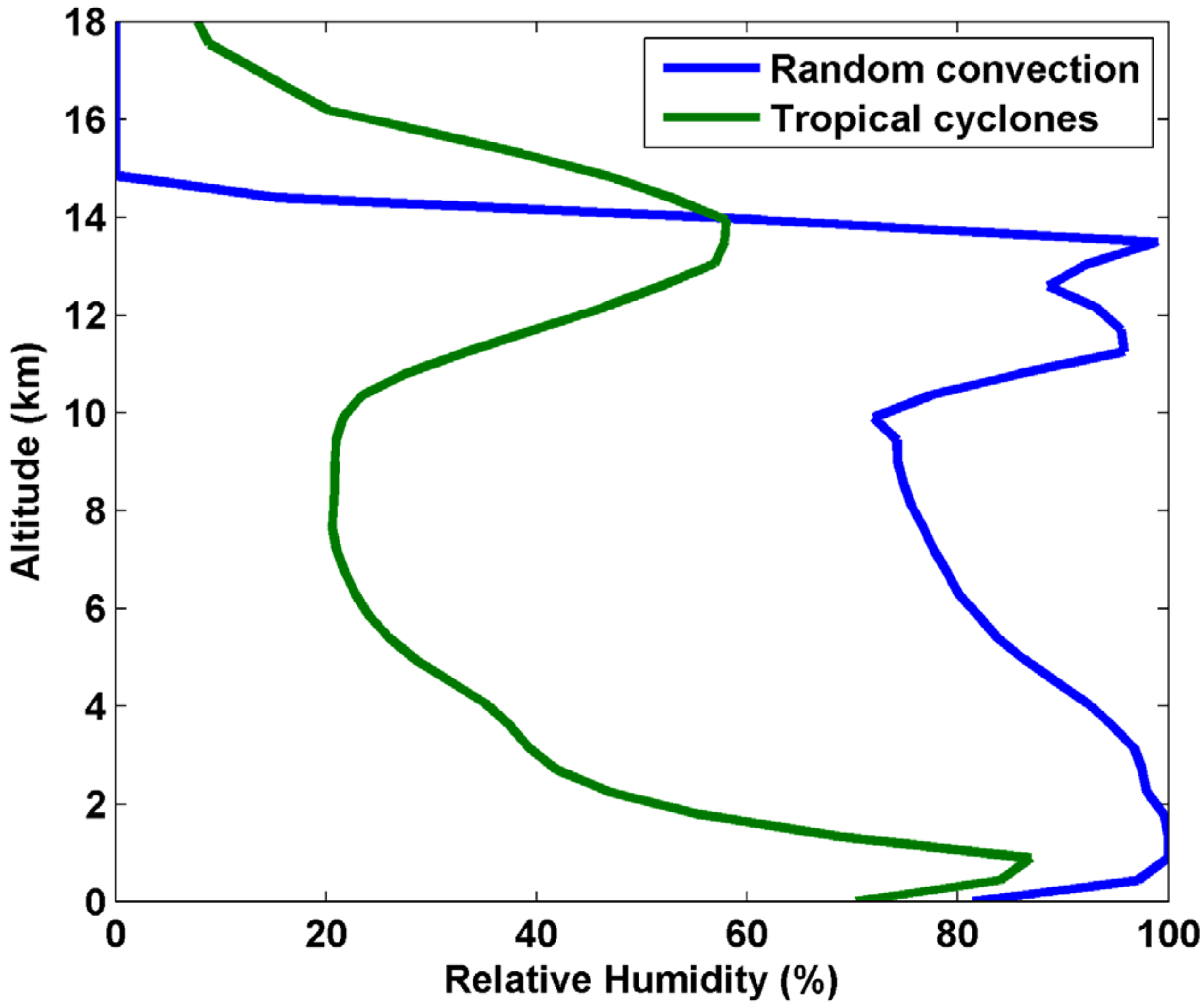
Vertically integrated water vapor at 4 days (Nolan et al., QJRMS, 2007)



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

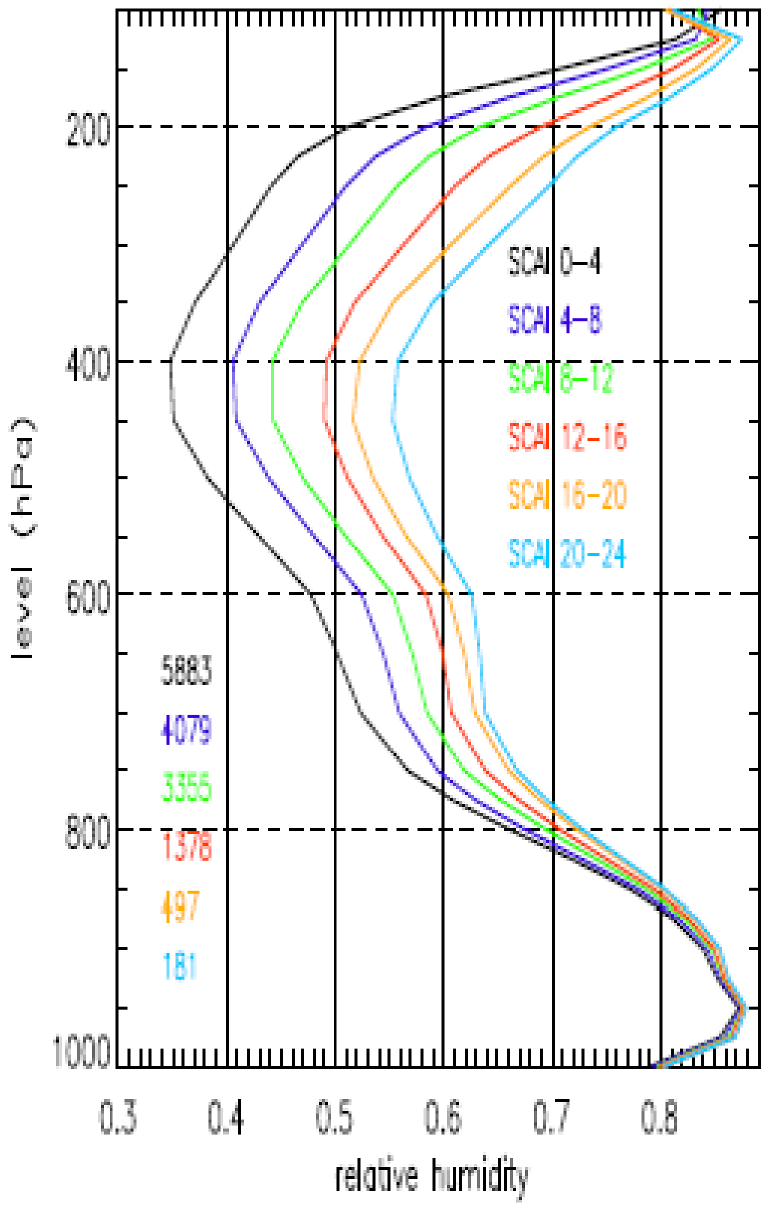


Nolan et al., QJRMS, 2007



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

Courtesy Isabelle Tobin, Sandrine Bony, and Remy Roca

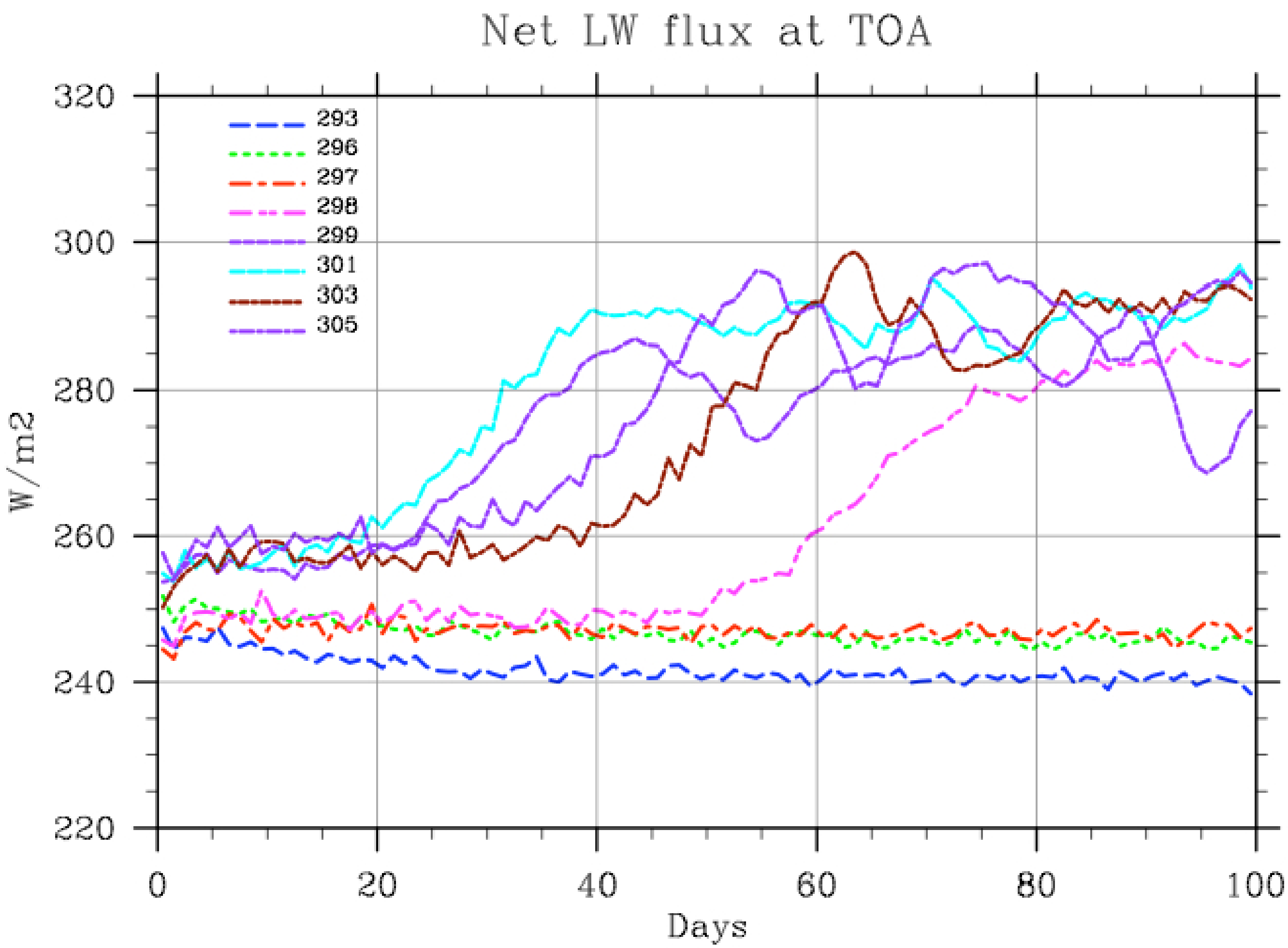


Empirical Necessary Conditions for Self-Aggregation
(after Held et al., 1993; Bretherton et al., 2005; Nolan et al.; 2007)

- 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

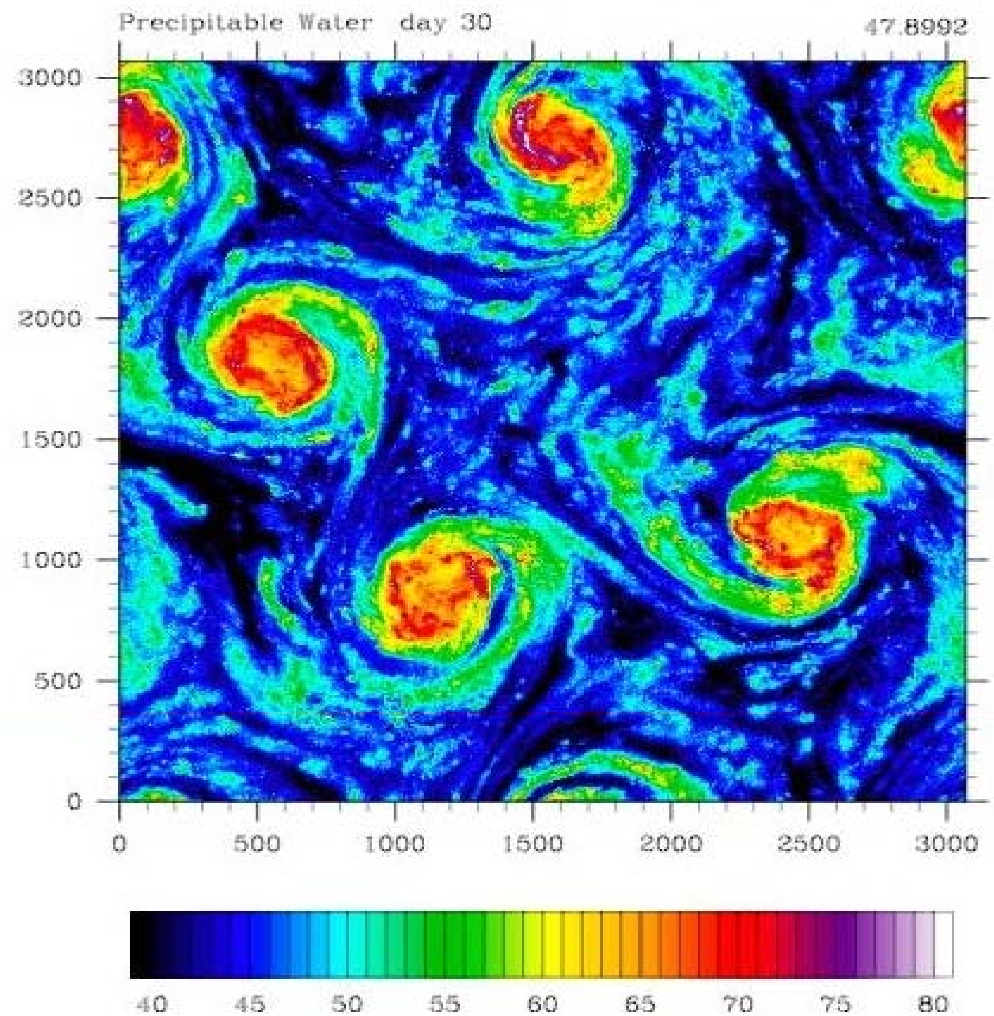
Self-Aggregation is Temperature-Dependent

(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

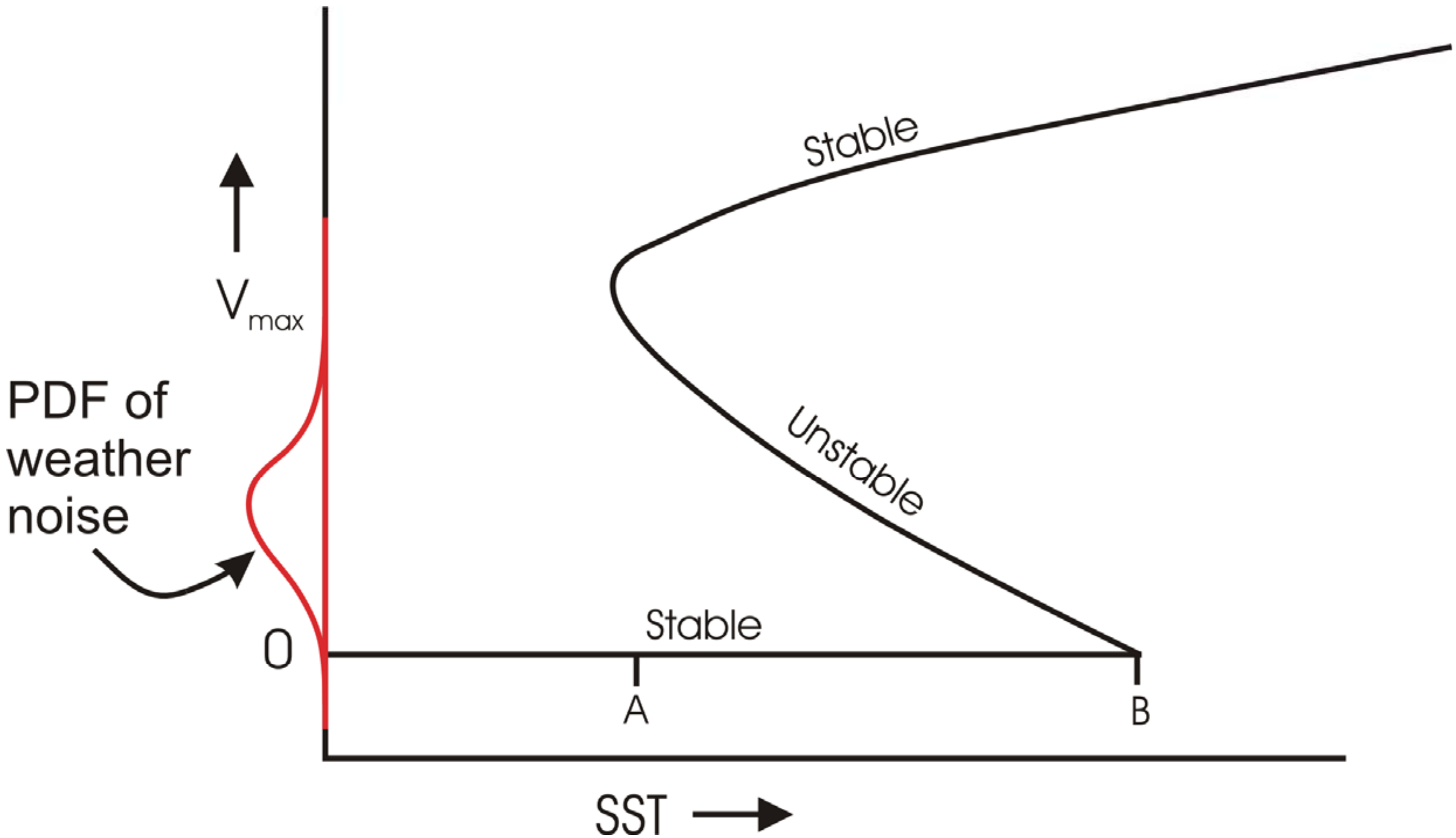
- At high temperature, convection self-aggregates
- →Horizontally averaged humidity drops dramatically
- →Reduced greenhouse effect cools system
- →Convection disaggregates
- →Humidity increases, system warms
- →System wants to be near phase transition to aggregated state

Recipe for Self-Organized Criticality

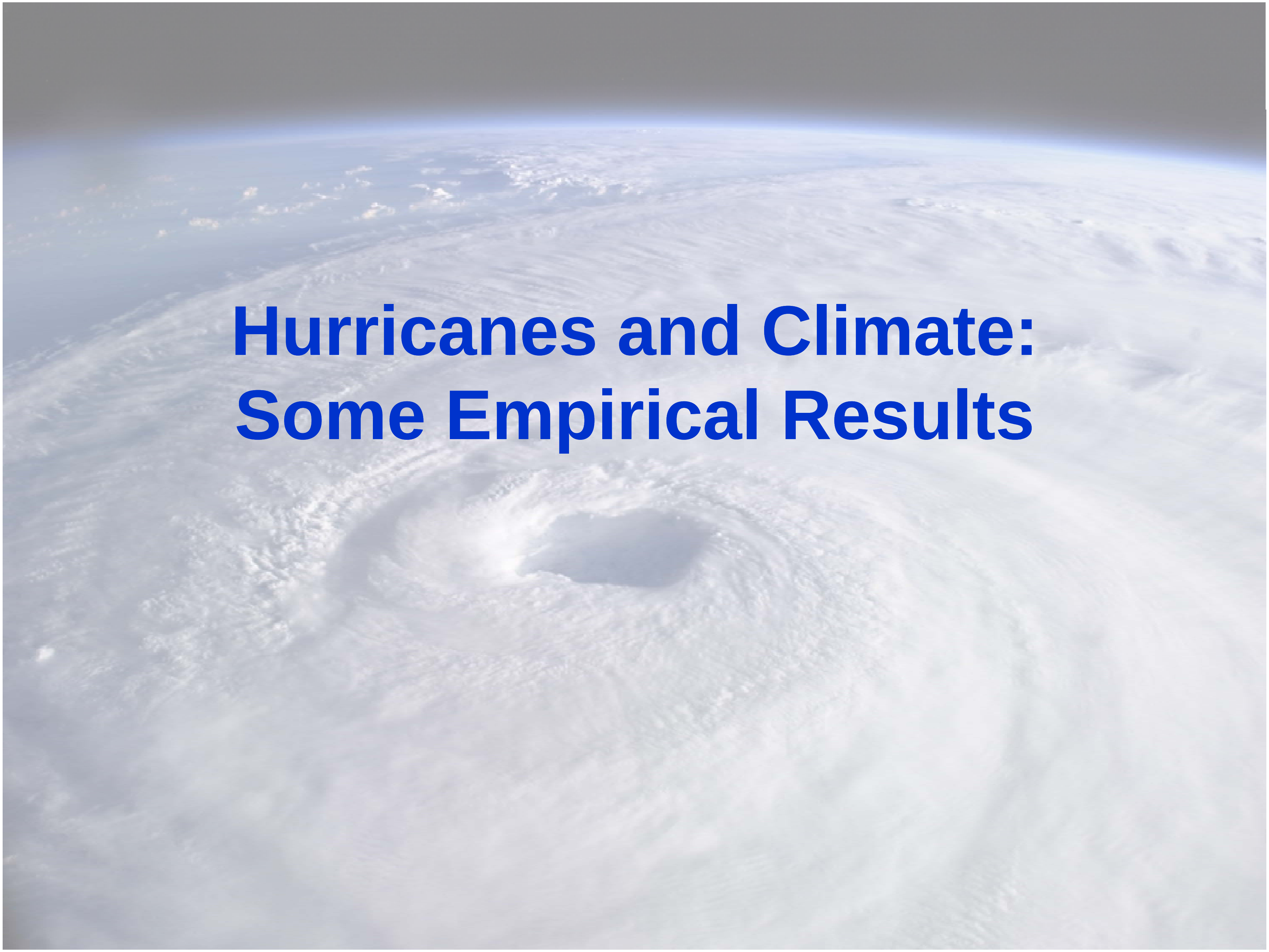
(First proposed by David Neelin, but by different mechanism)

- 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



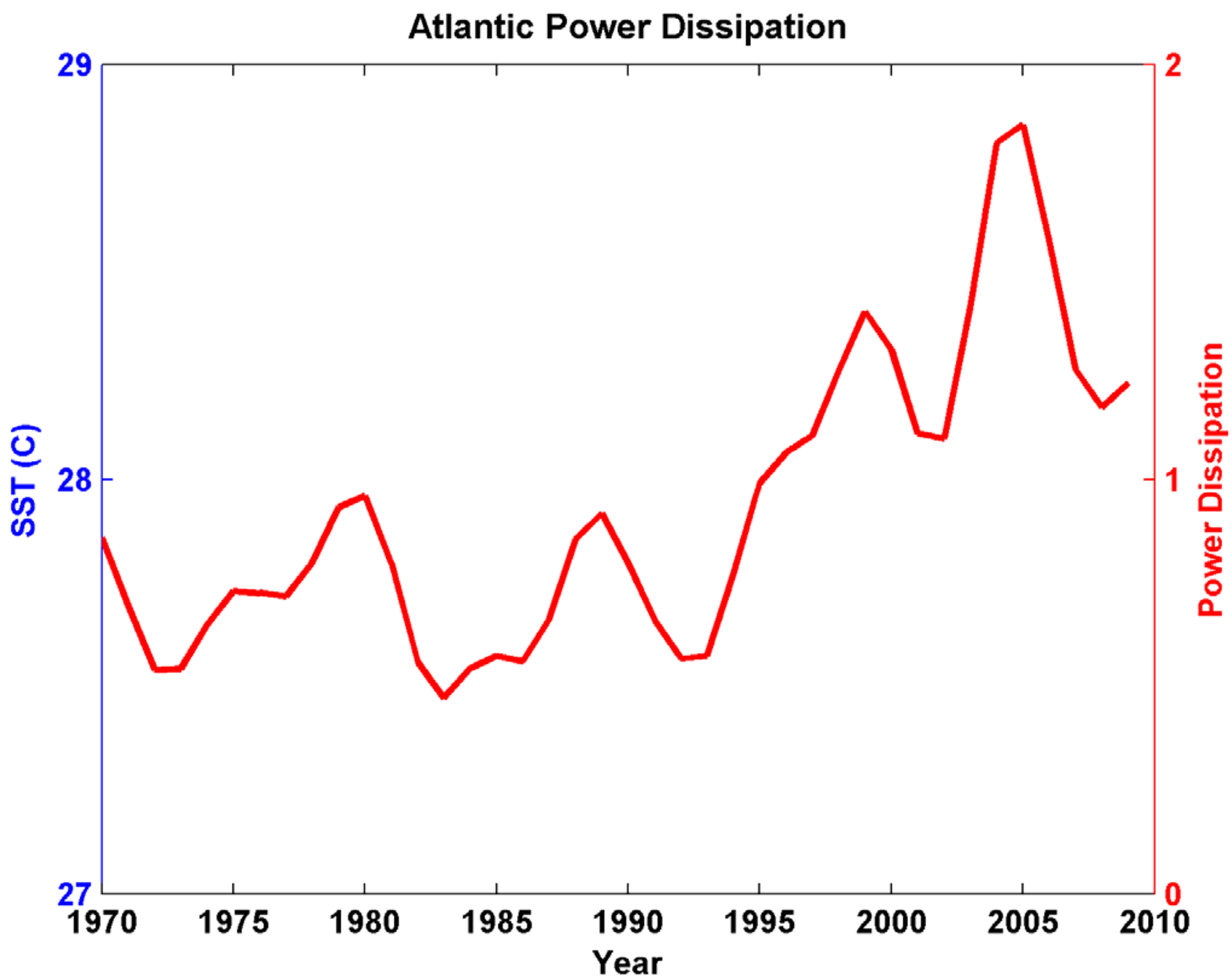
Intensity Metric:

Hurricane Power (Power Dissipation Index)

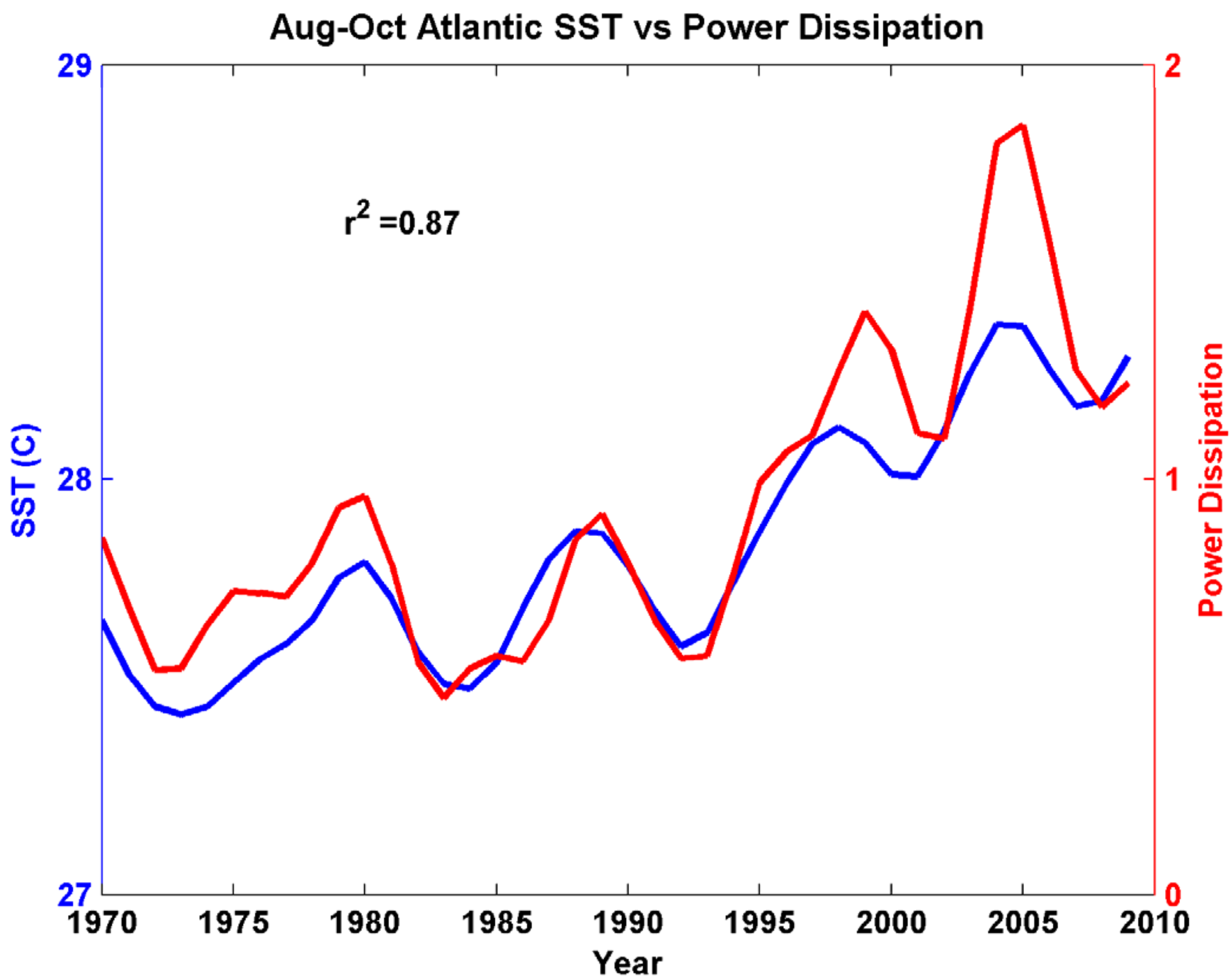
$$PDI \equiv \int_0^{\tau} V_{max}^3 \, dt$$

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

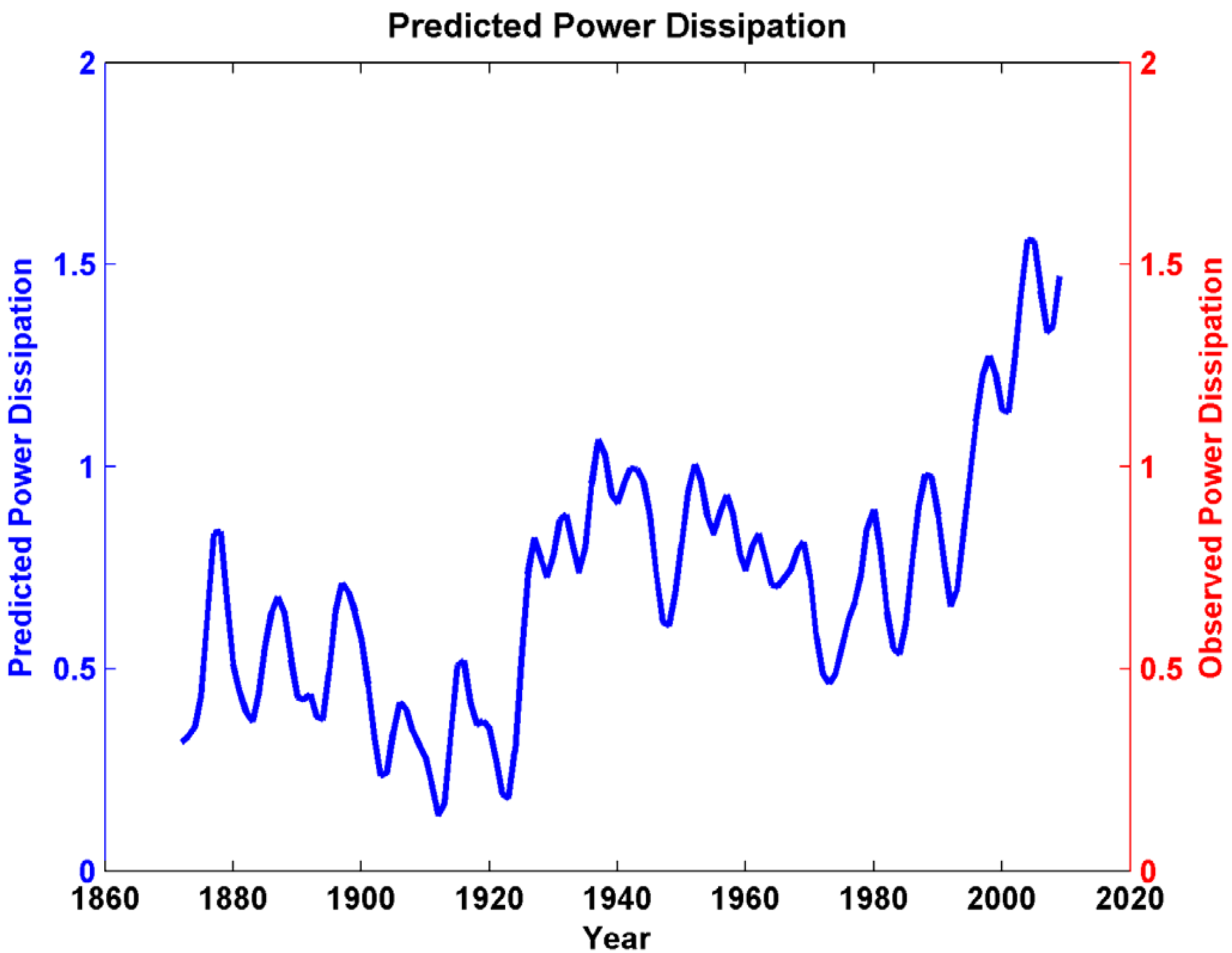
Atlantic Tropical Cyclone Power Dissipation during an era of high quality measurements, 1970-2011 (smoothed with 1-3-4-3-1 filter)



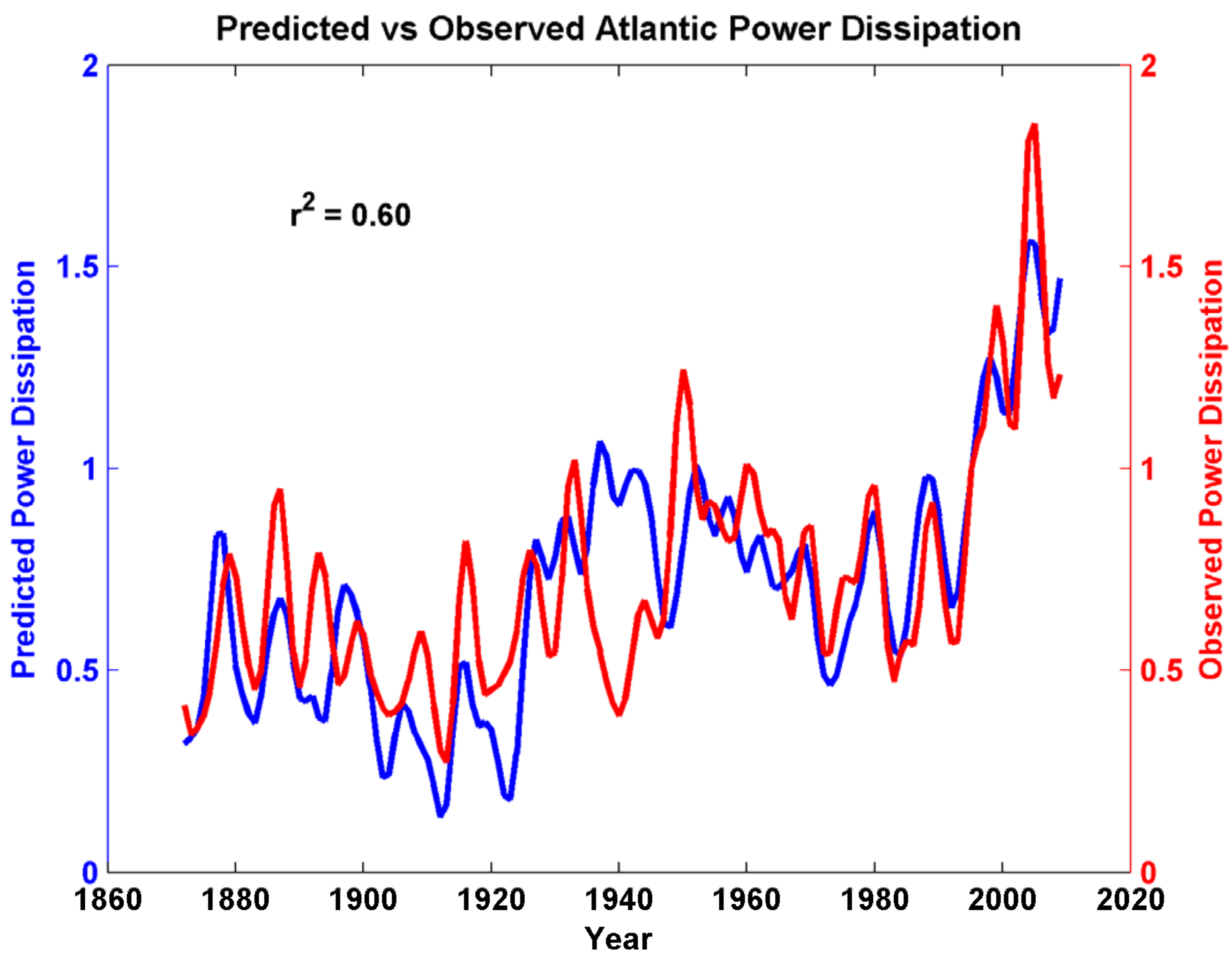
Atlantic Tropical Cyclone Power Dissipation and Sea Surface Temperature during an era of high quality measurements, 1970-2011 (smoothed with 1-3-4-3-1 filter)



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

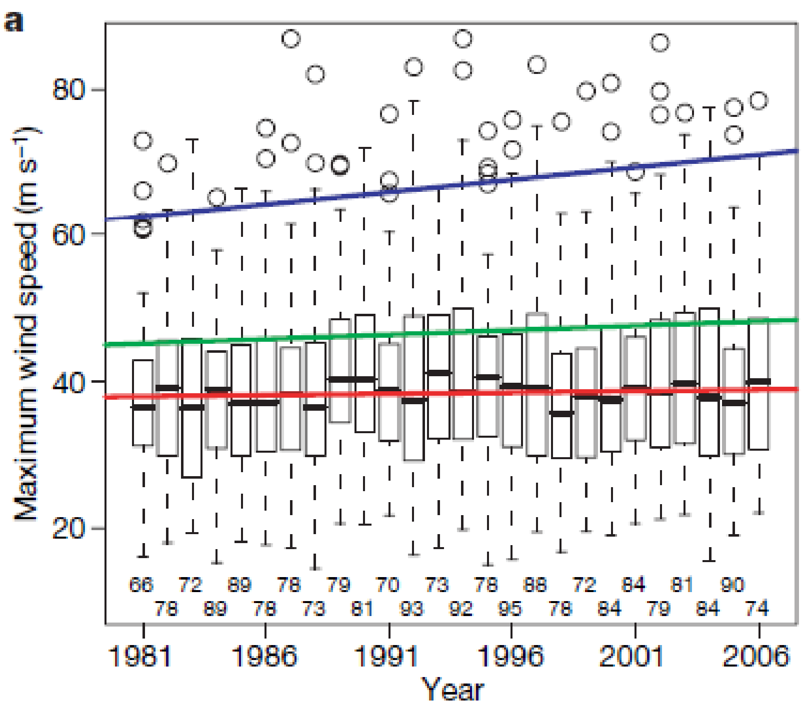


Now Compare to Observed Power Dissipation

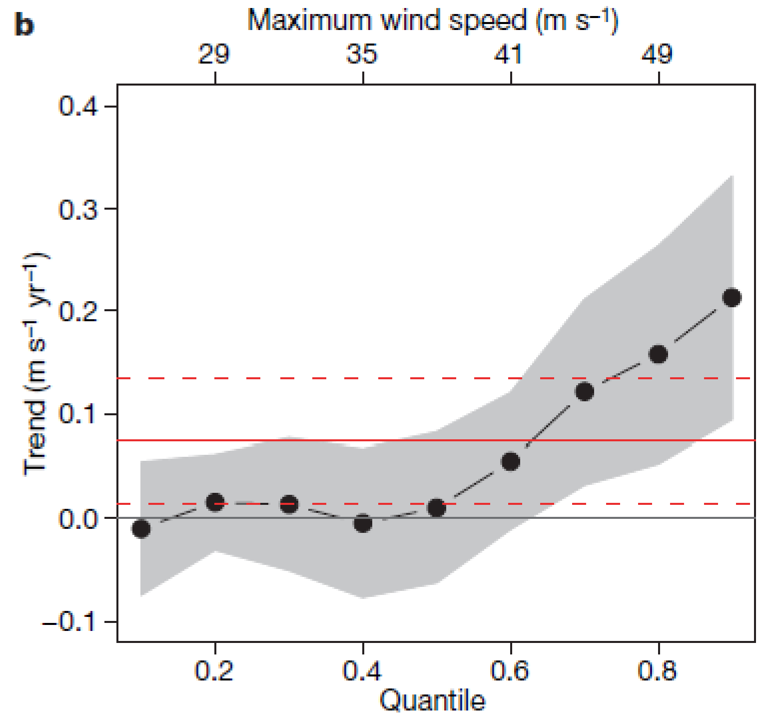


Tropical cyclone power dissipation has more than doubled since the 1980s, though there has been an increase of only 0.5^{o} C in sea surface temperature

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



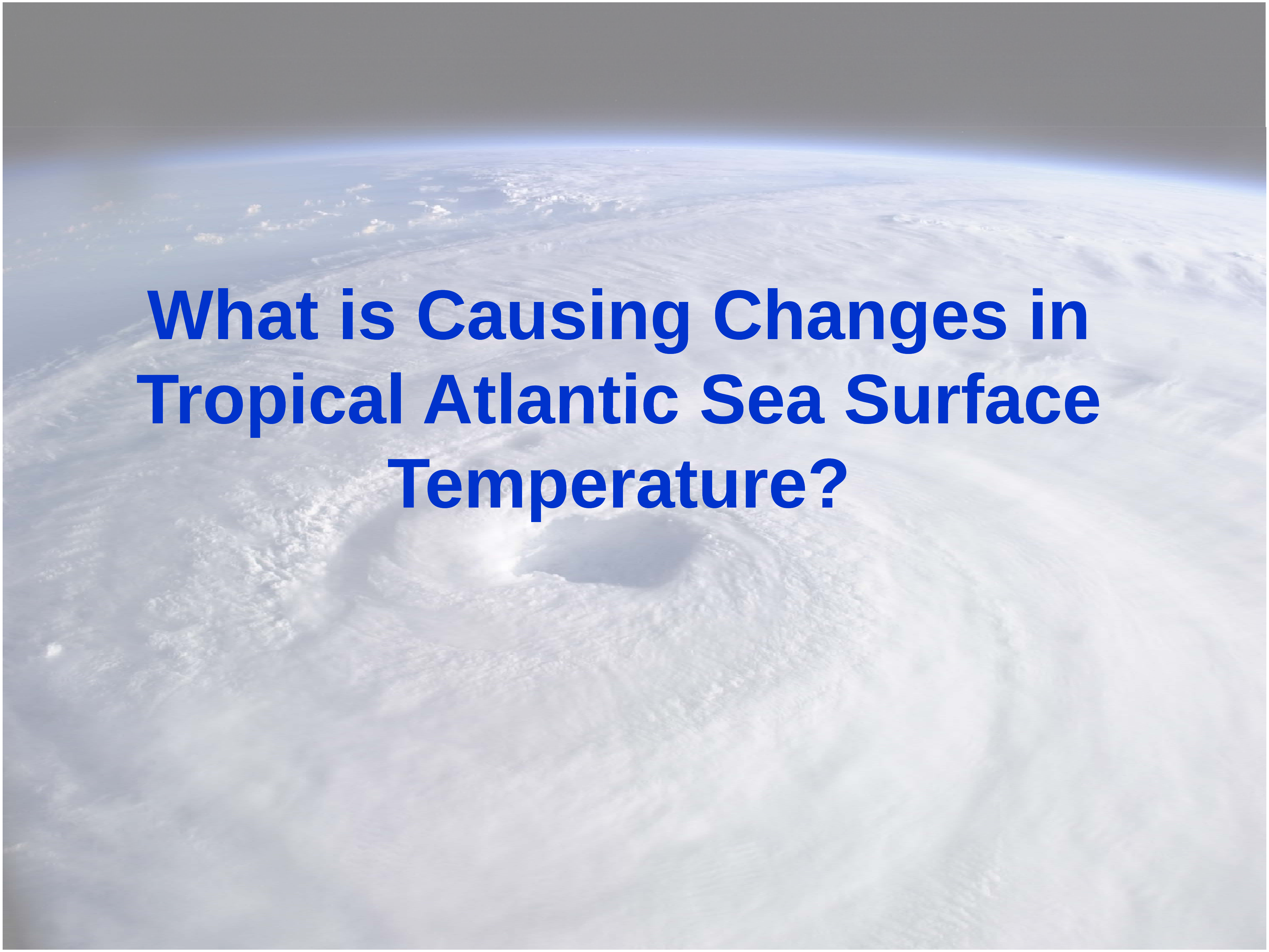
Box plots by year. Trend lines are shown for the median, 0.75 quantile, and 1.5 times the interquartile range



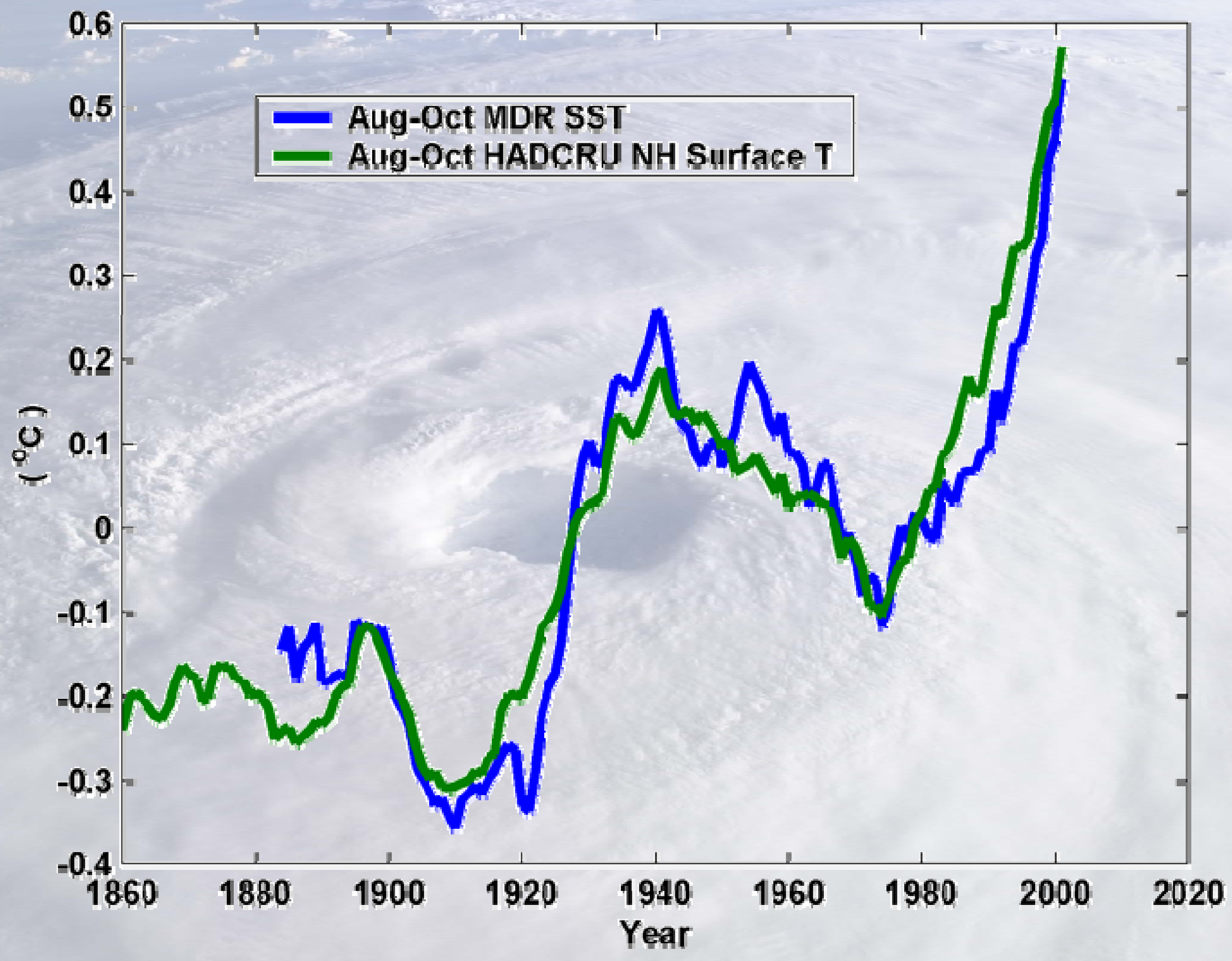
Trends in global satellite-derived tropical cyclone maximum wind speeds by quantile, from 0.1 to 0.9 in increments of 0.1.

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

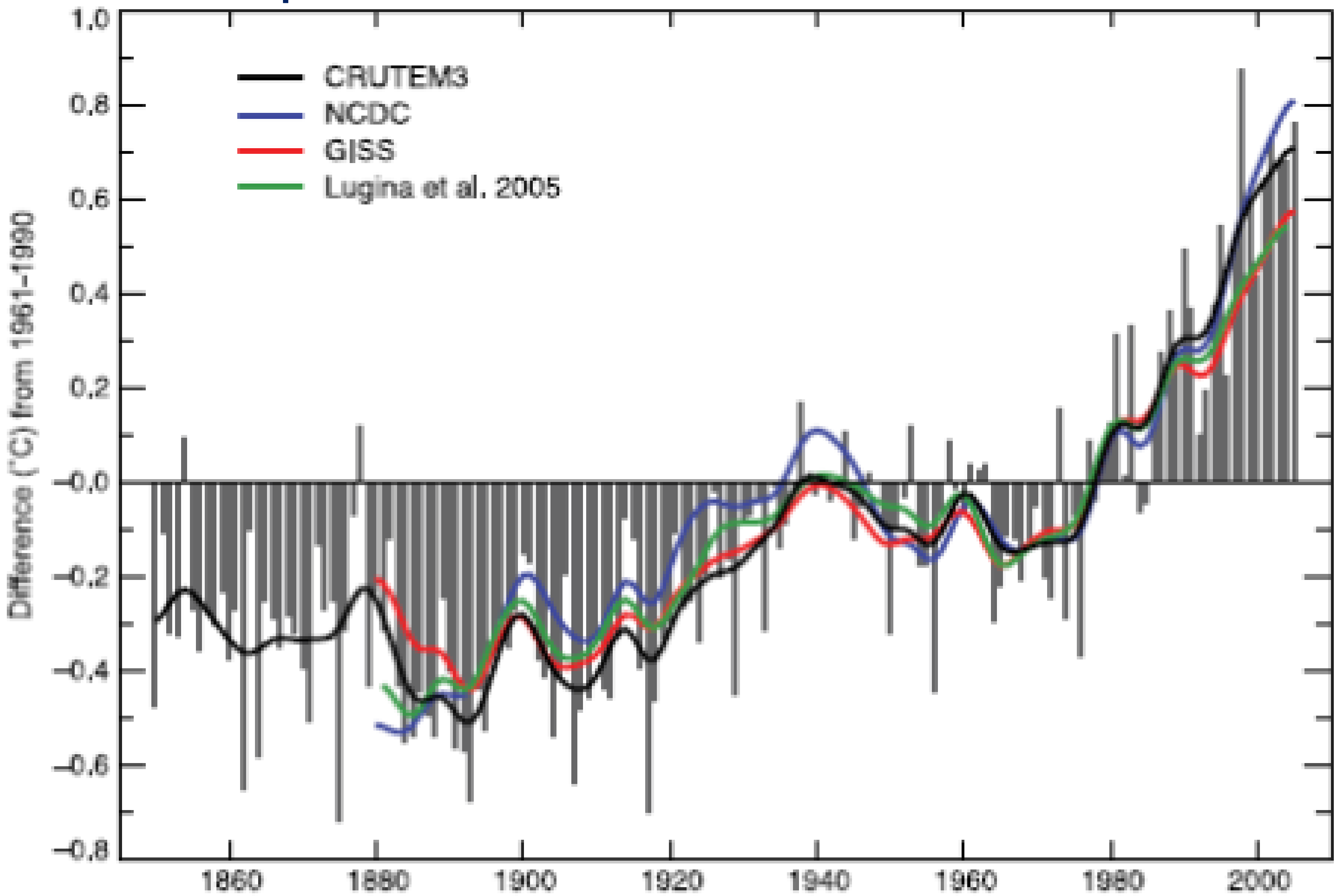
What is Causing Changes in Tropical Atlantic Sea Surface Temperature?

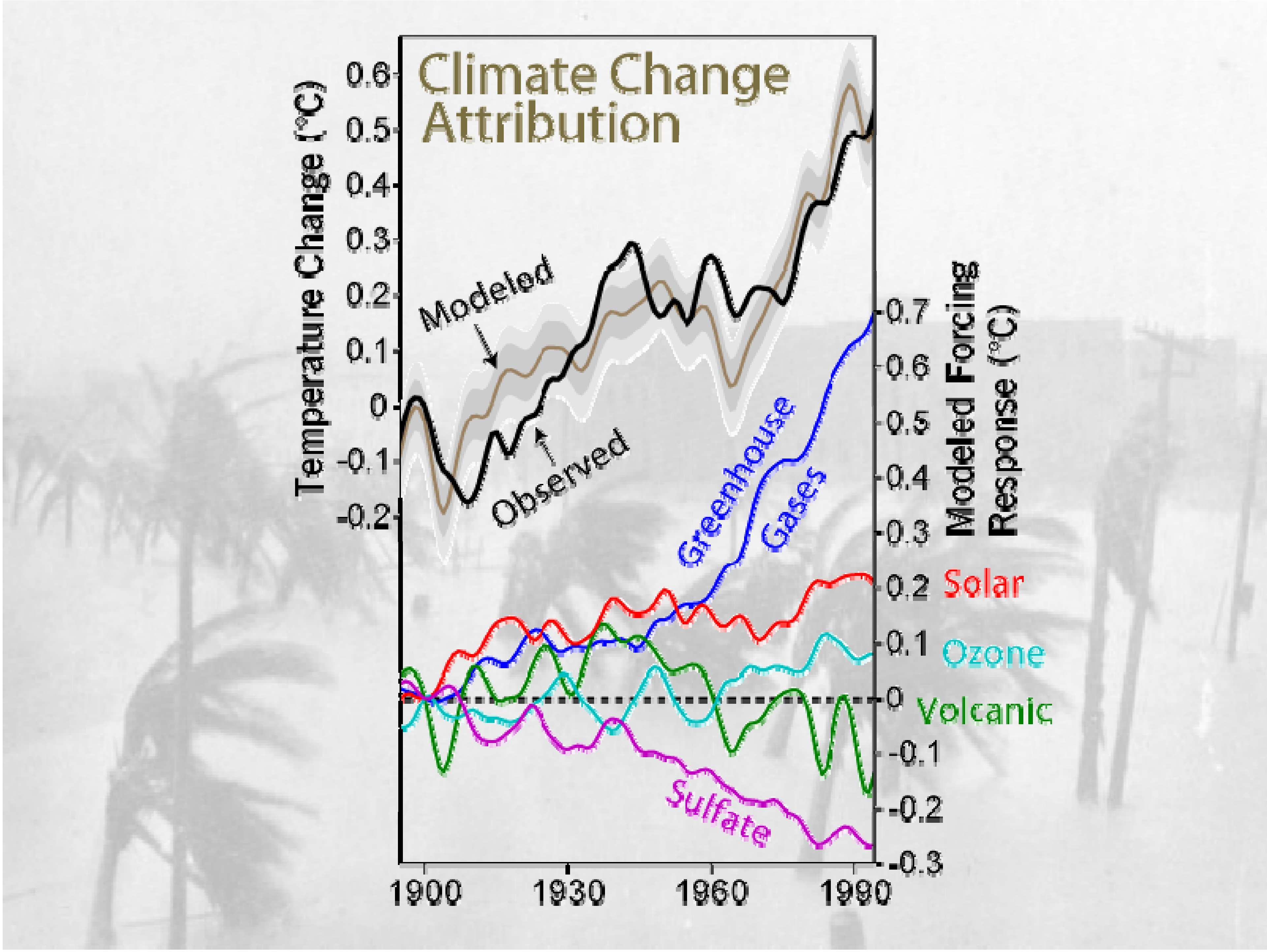


10-year Running Average of Aug-Oct Northern Hemisphere Surface Temp and Hurricane Region Ocean Temp



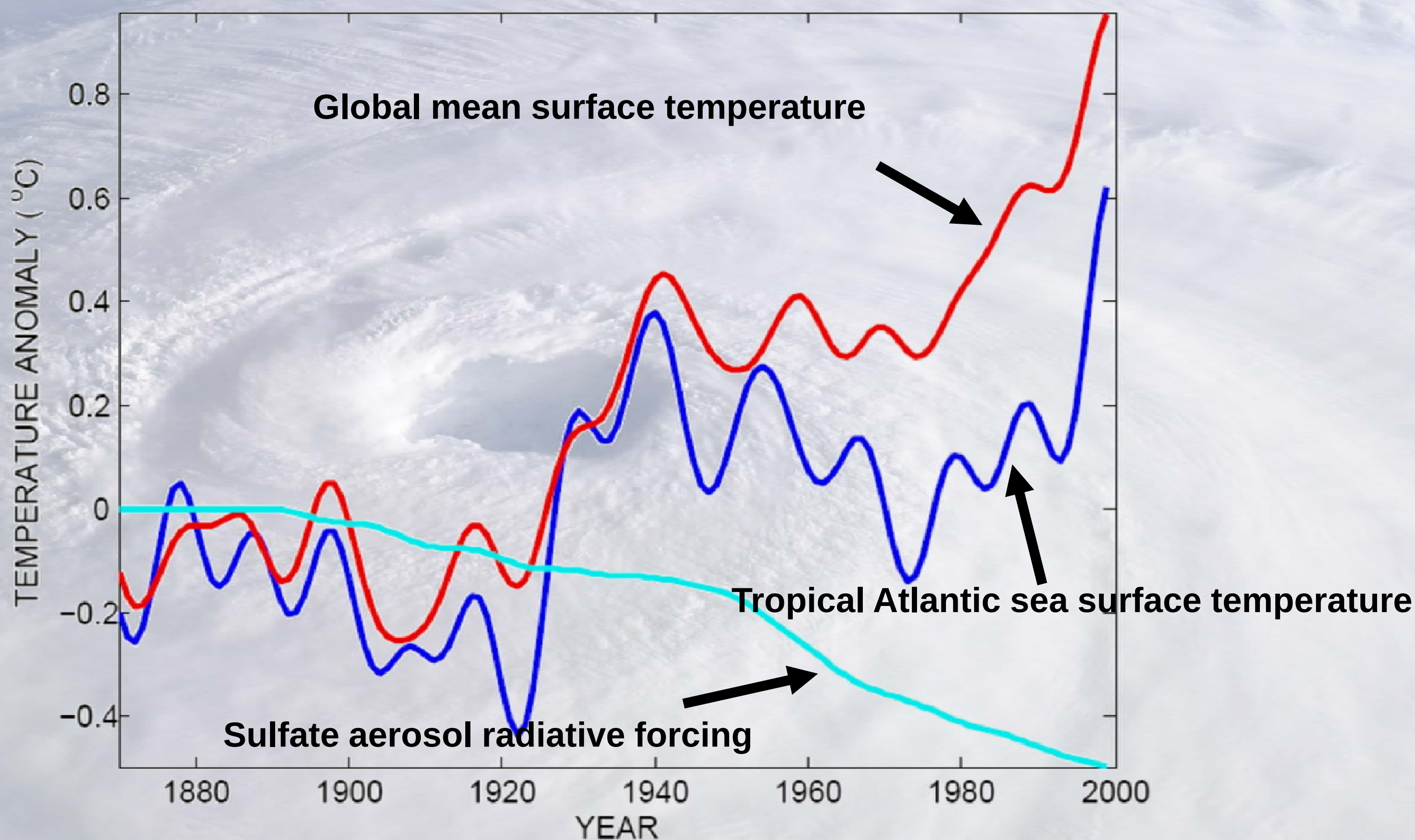
Estimates of Global Mean Surface Temperature from the Instrumental Record





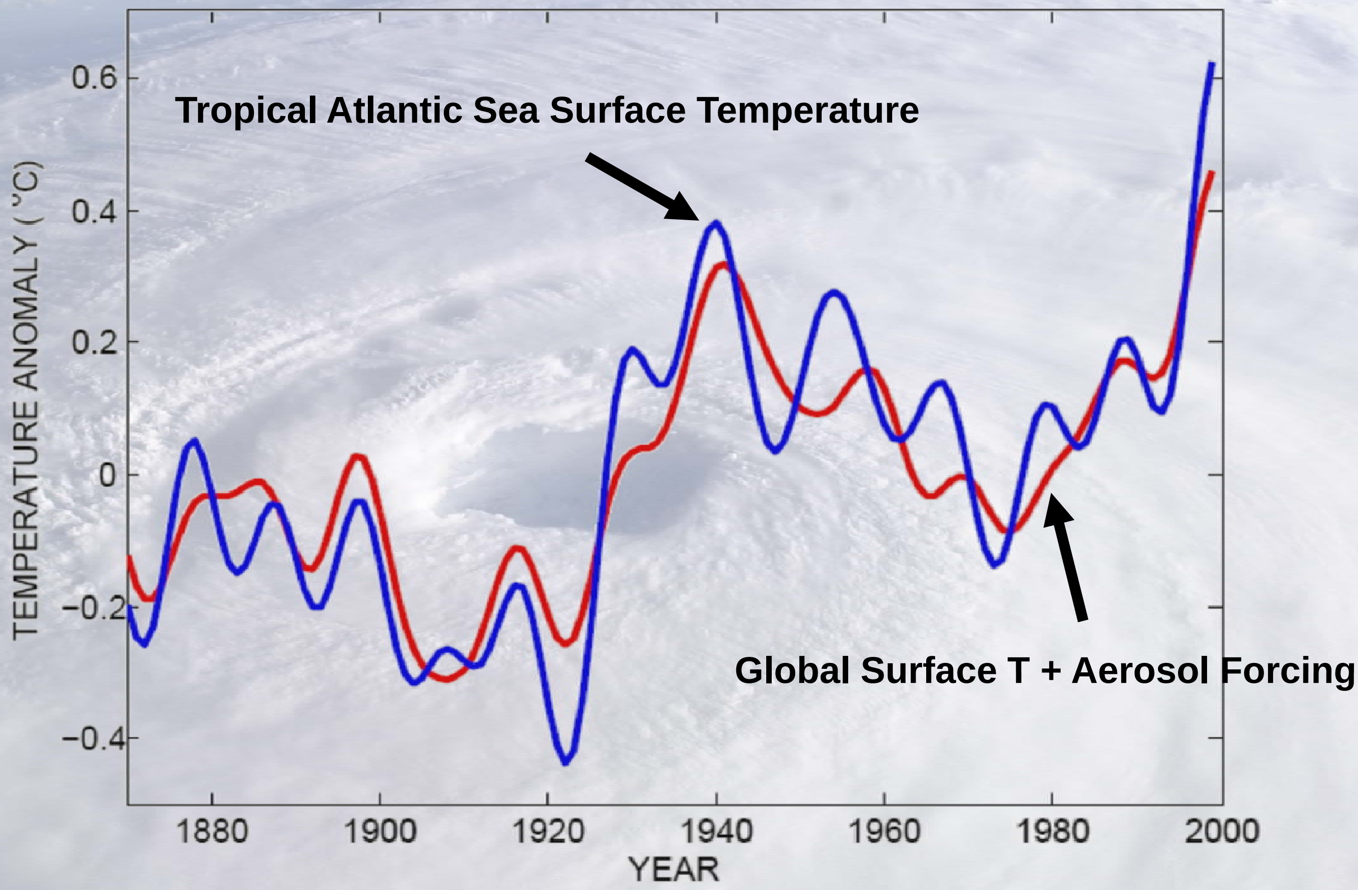
Climate Change Attribution
Temperature Change (°C)
Modeled Forcing Response (°C)
Modeled
Observed
Greenhouse Gases
Solar
Ozone
Volcanic
Sulfate
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
1900
1930
1960
1990

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

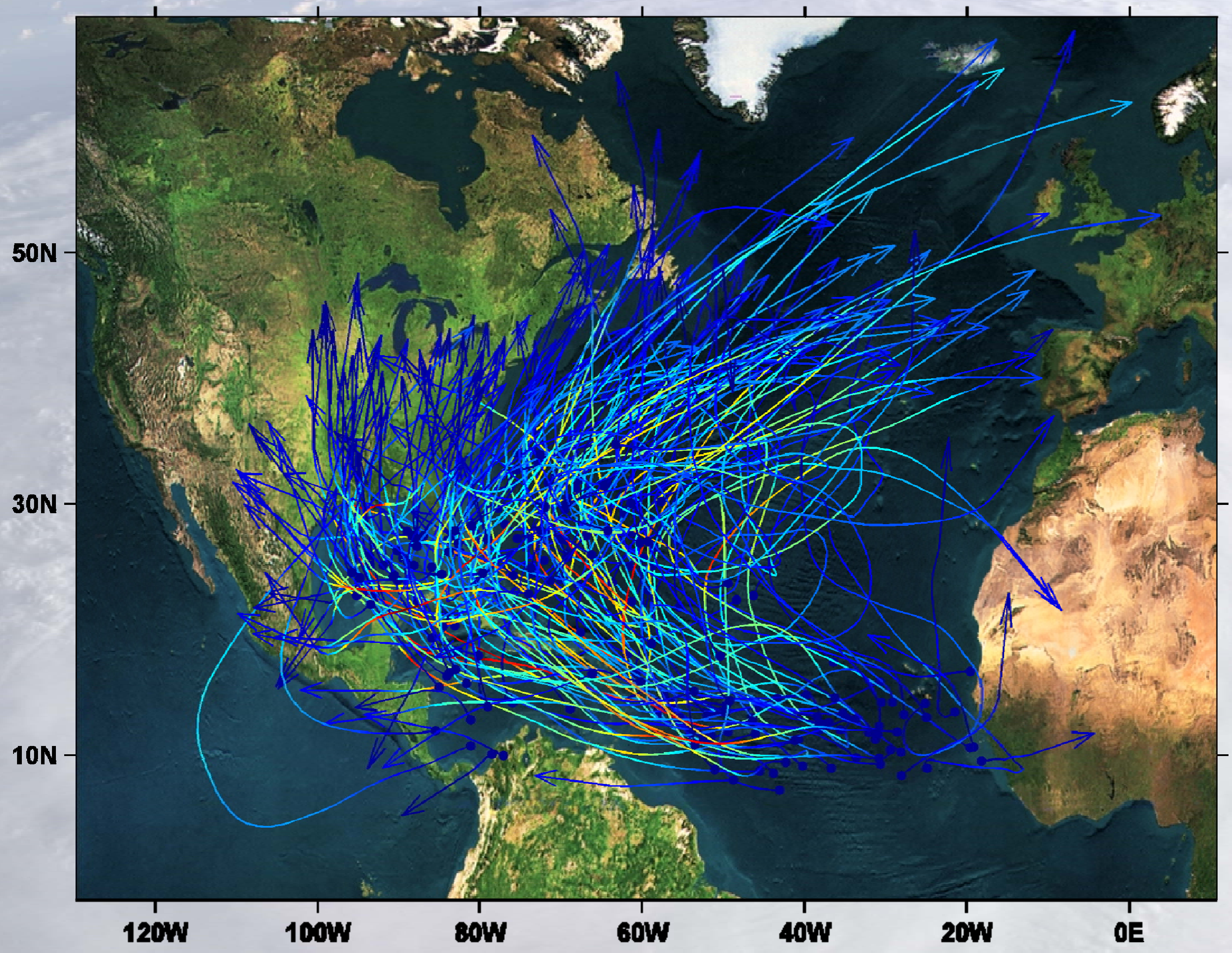
- **Step 1**: Seed each ocean basin with a very large number of weak, randomly located vortices

- **Step 2**: Vortices are assumed to move with the large scale atmospheric flow in which they are embedded

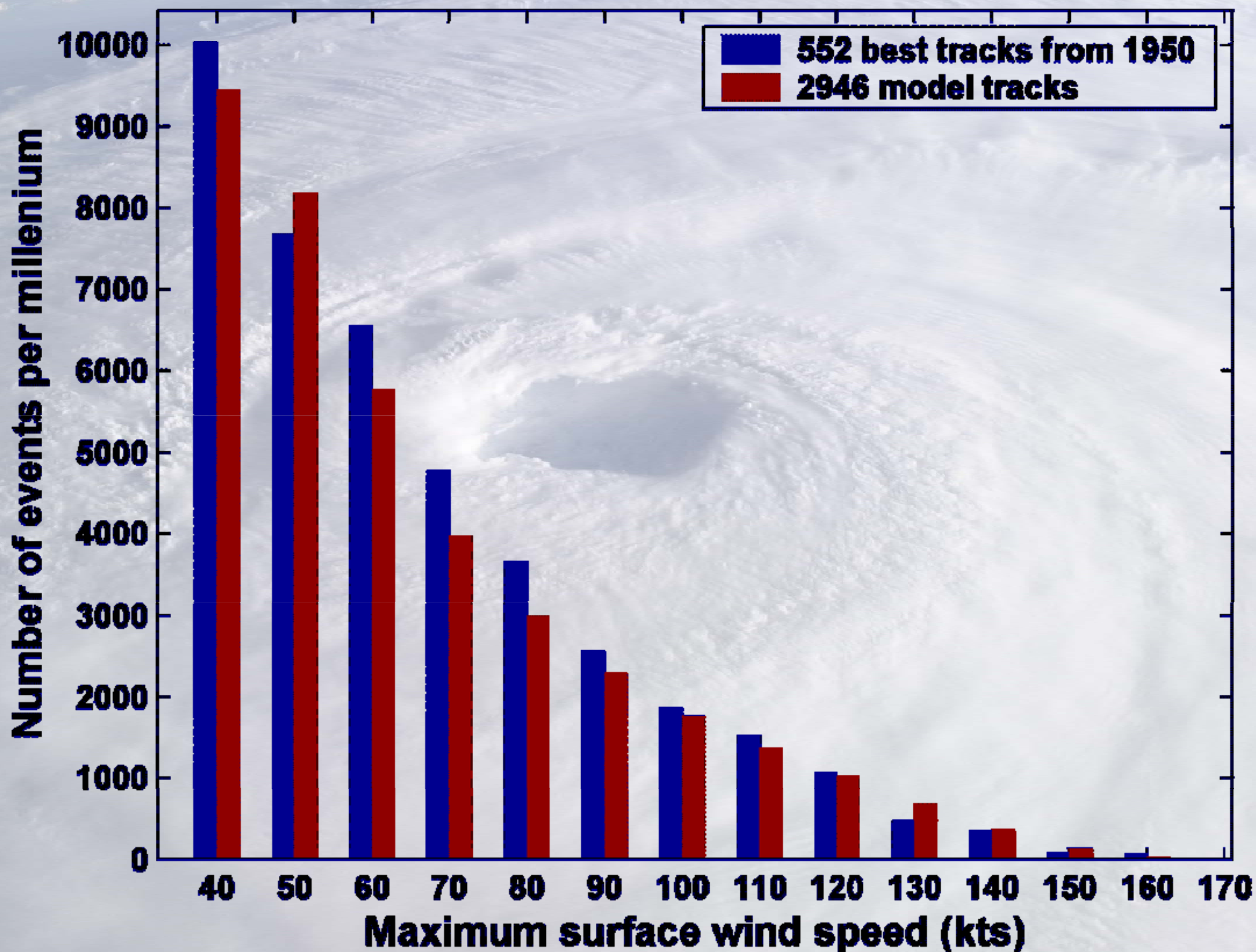
- **Step 3**: Run a coupled, ocean-atmosphere computer model for each vortex, and note how many achieve at least tropical storm strength; discard others

- **Step 4:** Using the small fraction of surviving events, determine storm statistics.

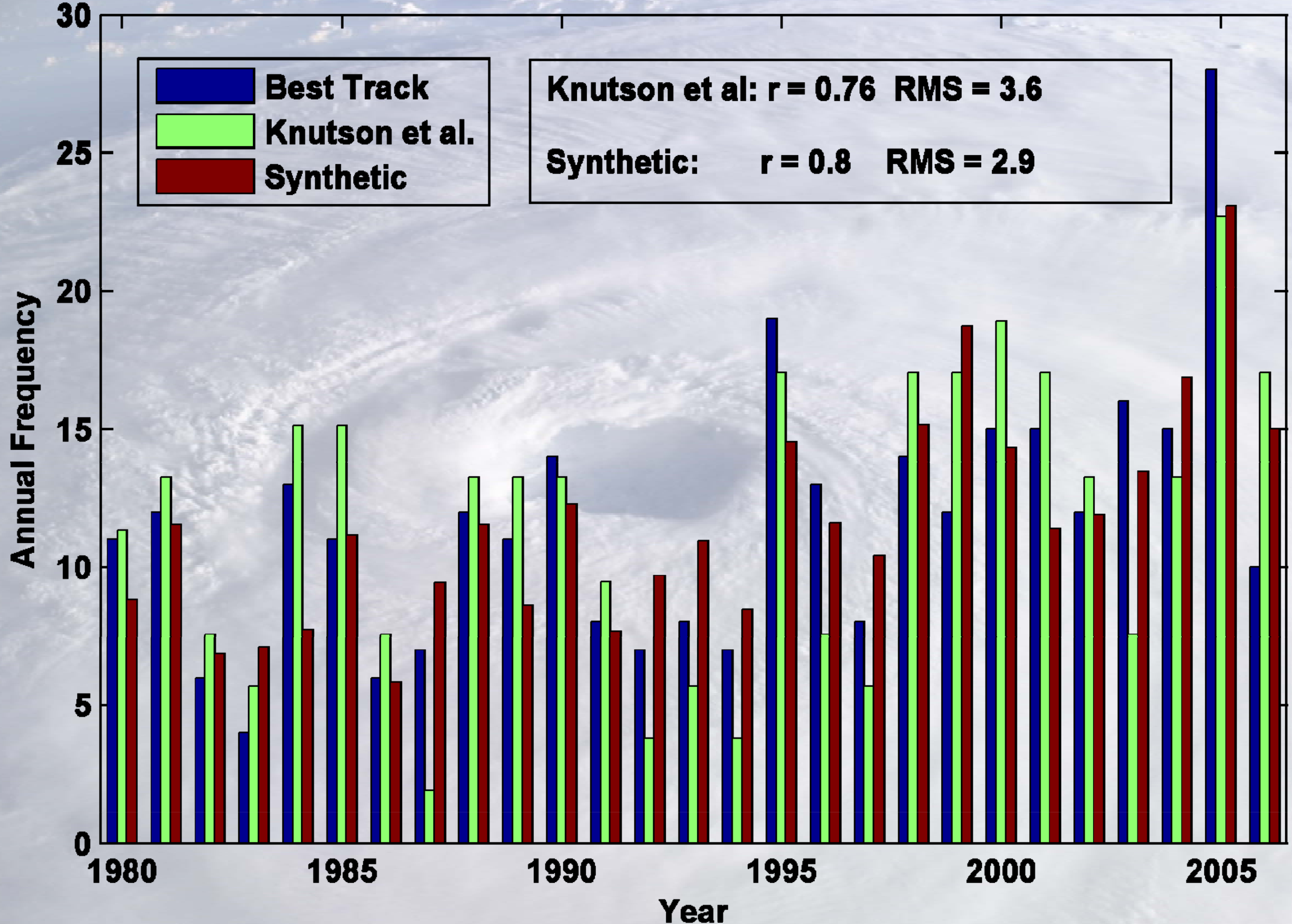
New Downscaling Technique: 200 Synthetic U.S. Landfalling tracks (color coded by S-S Scale)



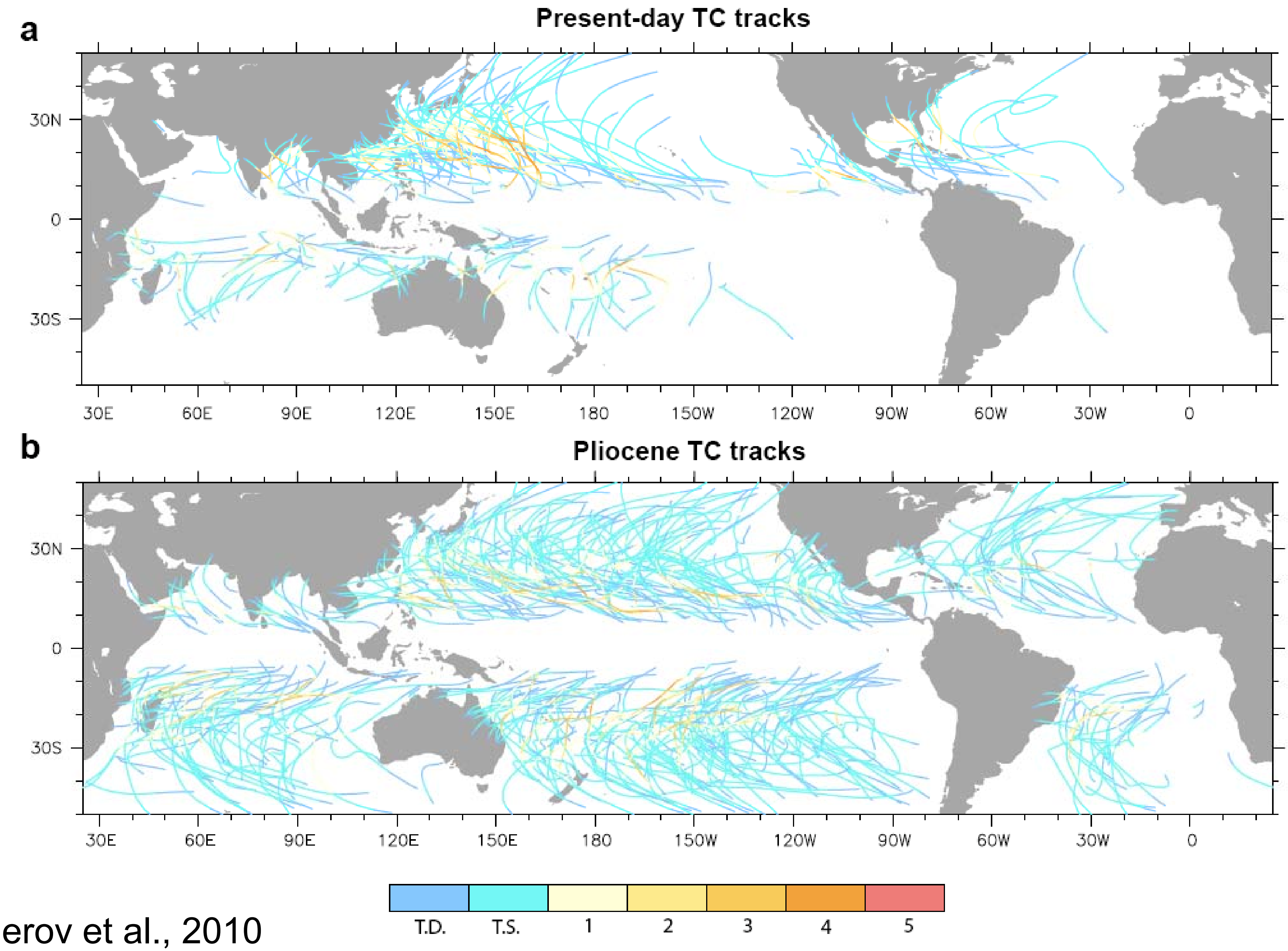
Cumulative Distribution of Storm Lifetime Peak Wind Speed, with Sample of 2946 Synthetic Tracks



Year by Year Comparison with Best Track and with Knutson et al., 2007

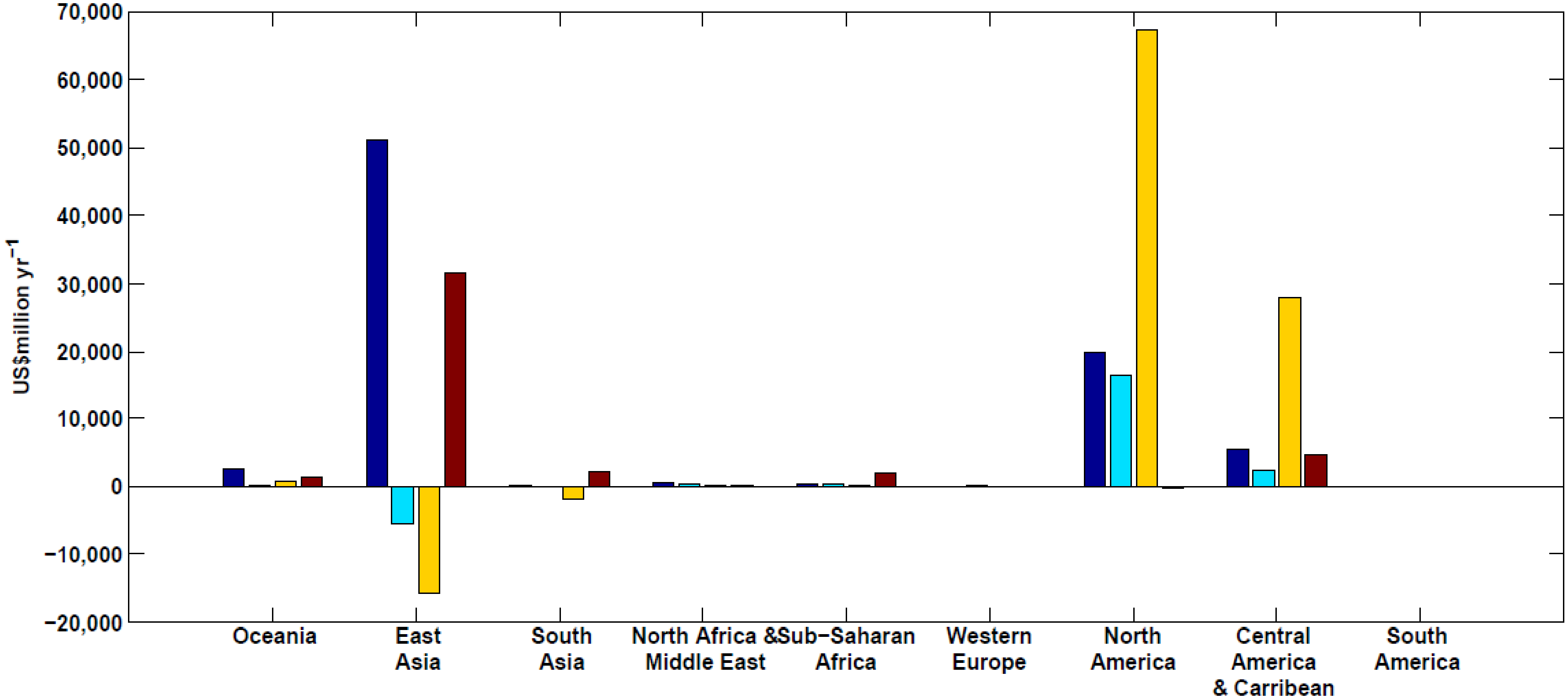


Application to Other Climates



Federov et al., 2010

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.

Summary

- Potential intensity is an important (but not the only) control on tropical cyclone activity, including frequency and intensity

- On time scales long enough for the ocean mixed layer to be in thermal equilibrium, potential intensity is controlled largely by surface radiation, surface wind speed, ocean heat fluxes, and outflow temperature

- **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 role for TC-induced ocean mixing and atmospheric drying/heating in regulating climate**