

An aerial photograph of a hurricane, showing the central eye surrounded by a dense ring of clouds, with multiple spiral bands of clouds extending outwards over the dark blue ocean. The text "Hurricanes and Climate" is overlaid in yellow.

Hurricanes and Climate

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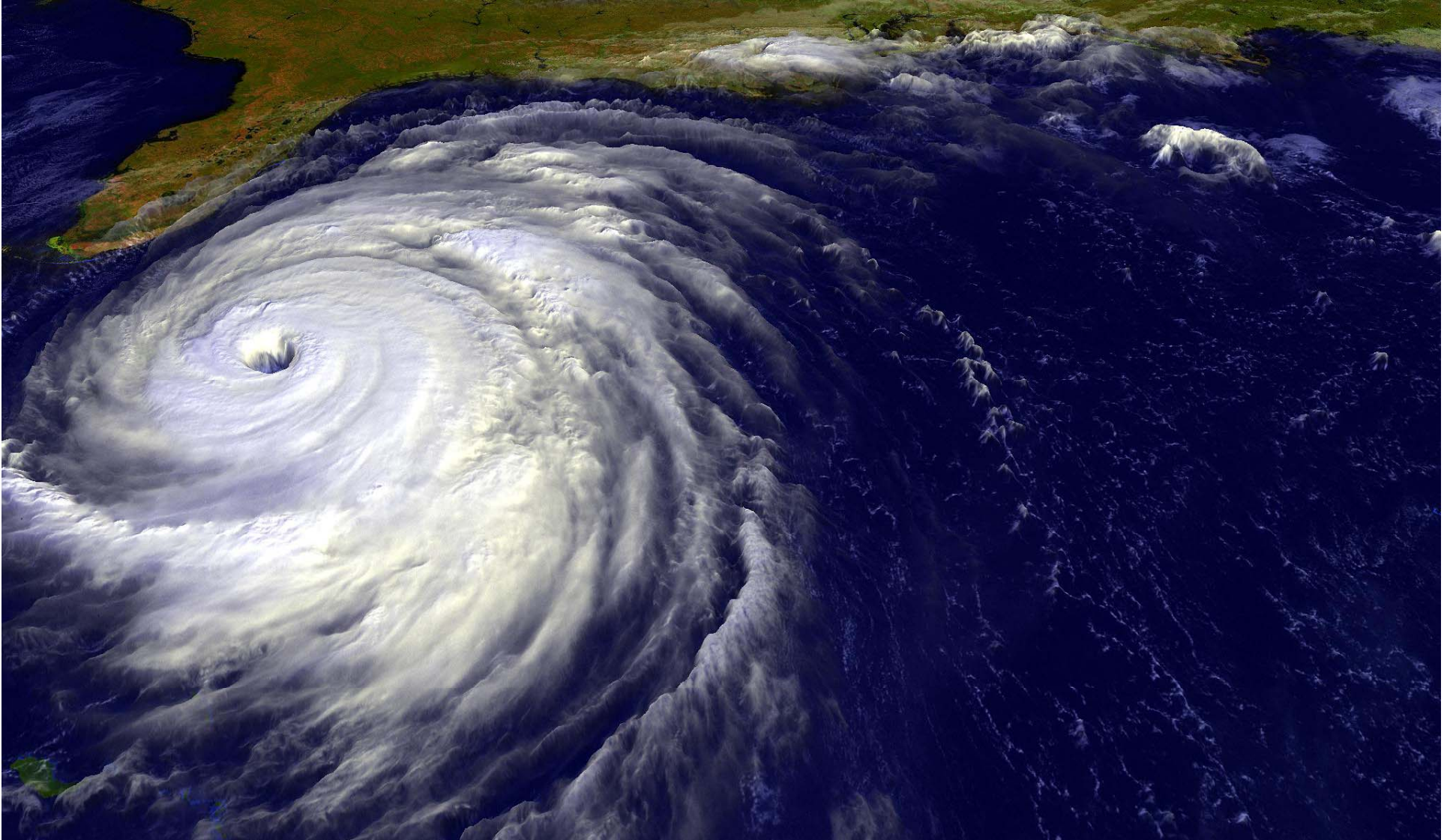
Issues

- **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?**

A satellite image of a tropical cyclone, showing a distinct eye and spiral cloud bands over a dark ocean. The cyclone is centered in the lower-left quadrant of the frame. The surrounding clouds are dense and white, contrasting with the dark blue of the ocean. The horizon of the Earth is visible at the top of the image, showing a thin blue line against a black sky.

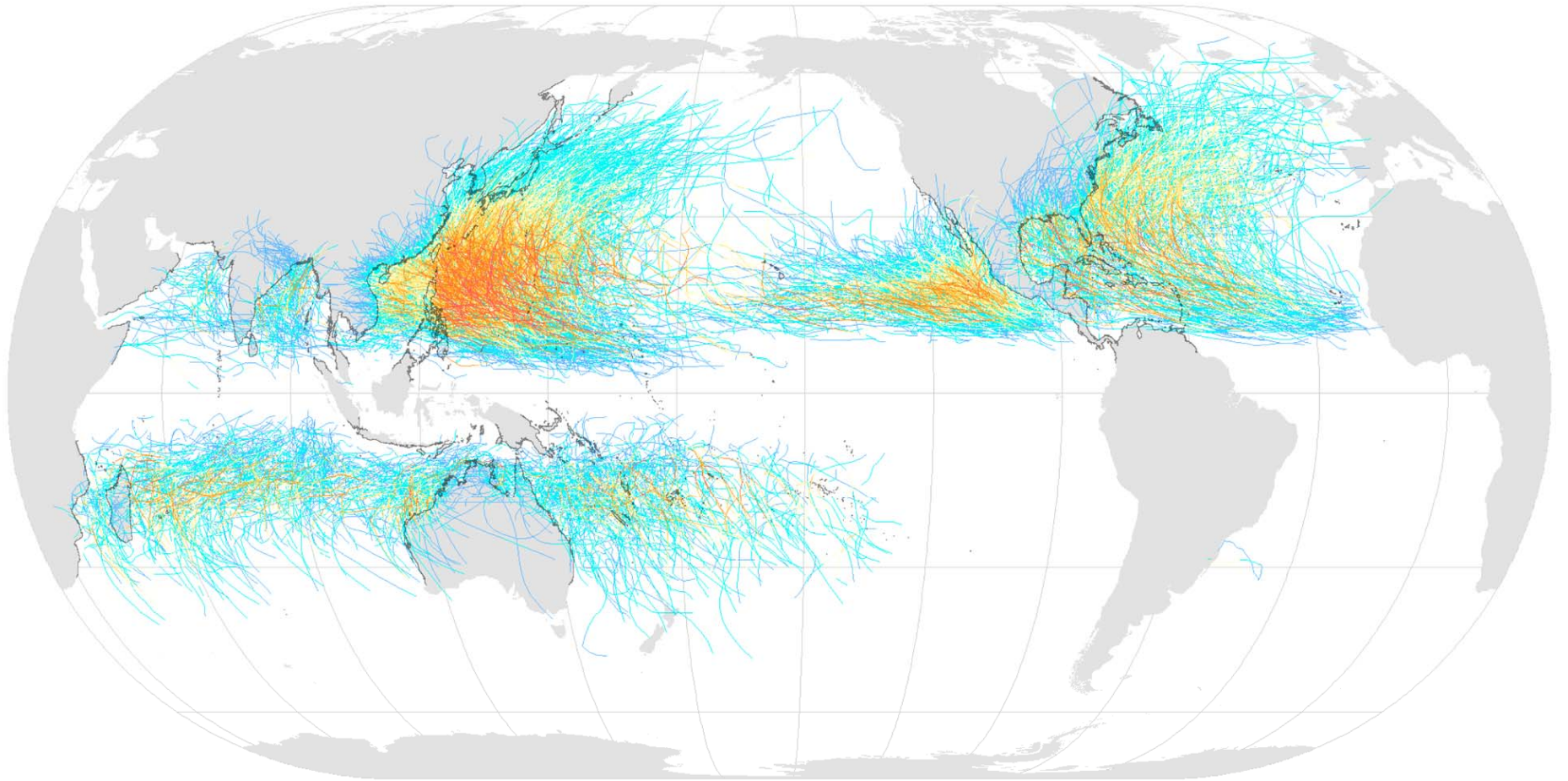
Brief Overview of Tropical Cyclones

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

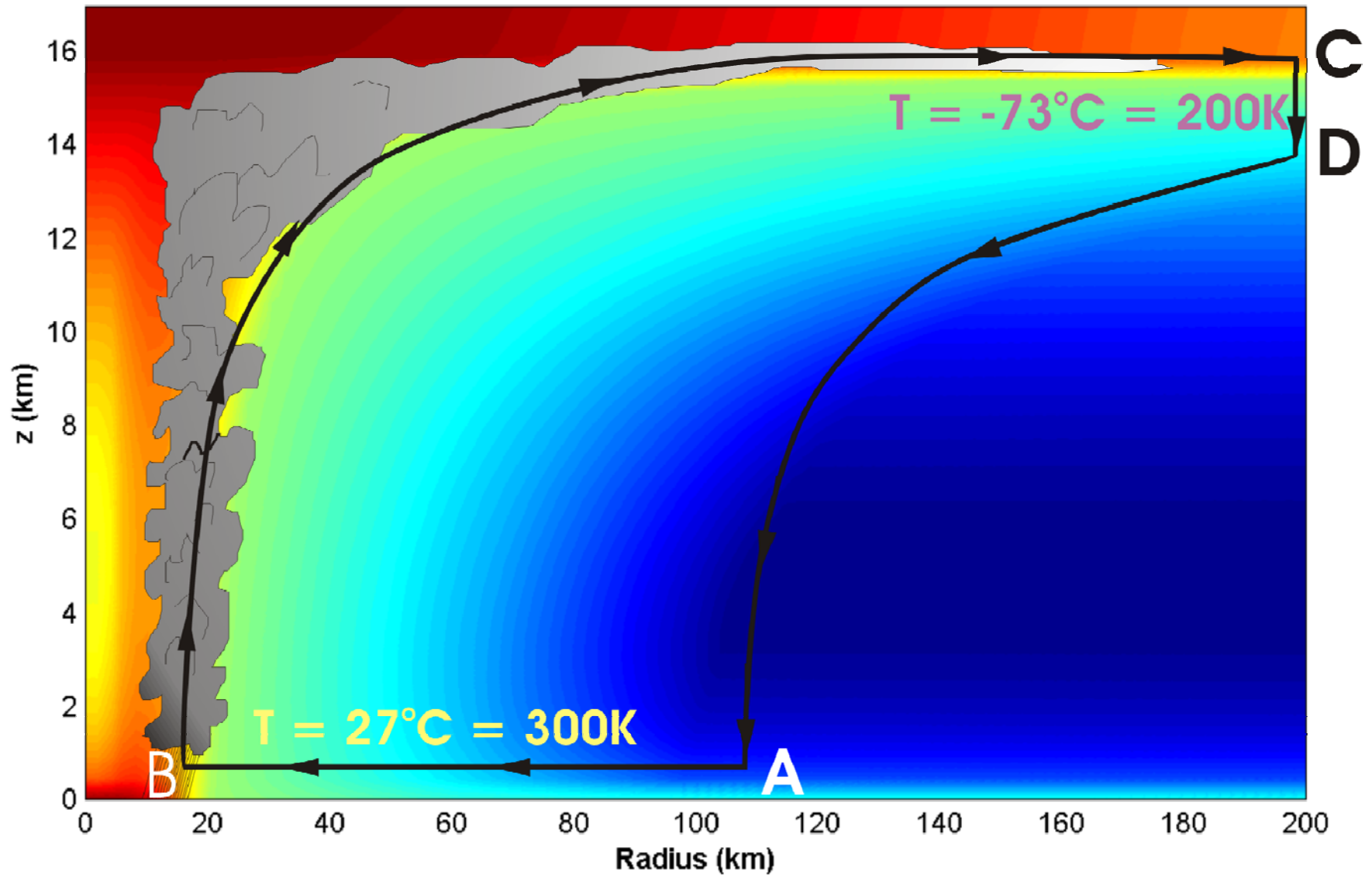
hurricane
category 4

hurricane
category 5

An aerial satellite photograph of a mature hurricane. The hurricane features a well-defined eye in the center, surrounded by a dense ring of clouds known as the eye wall. Multiple spiral bands of clouds extend outwards from the center, creating a characteristic swirling pattern. The surrounding ocean surface is visible between the cloud bands. The text "Physics of Mature Hurricanes" is overlaid in the center of the image.

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:

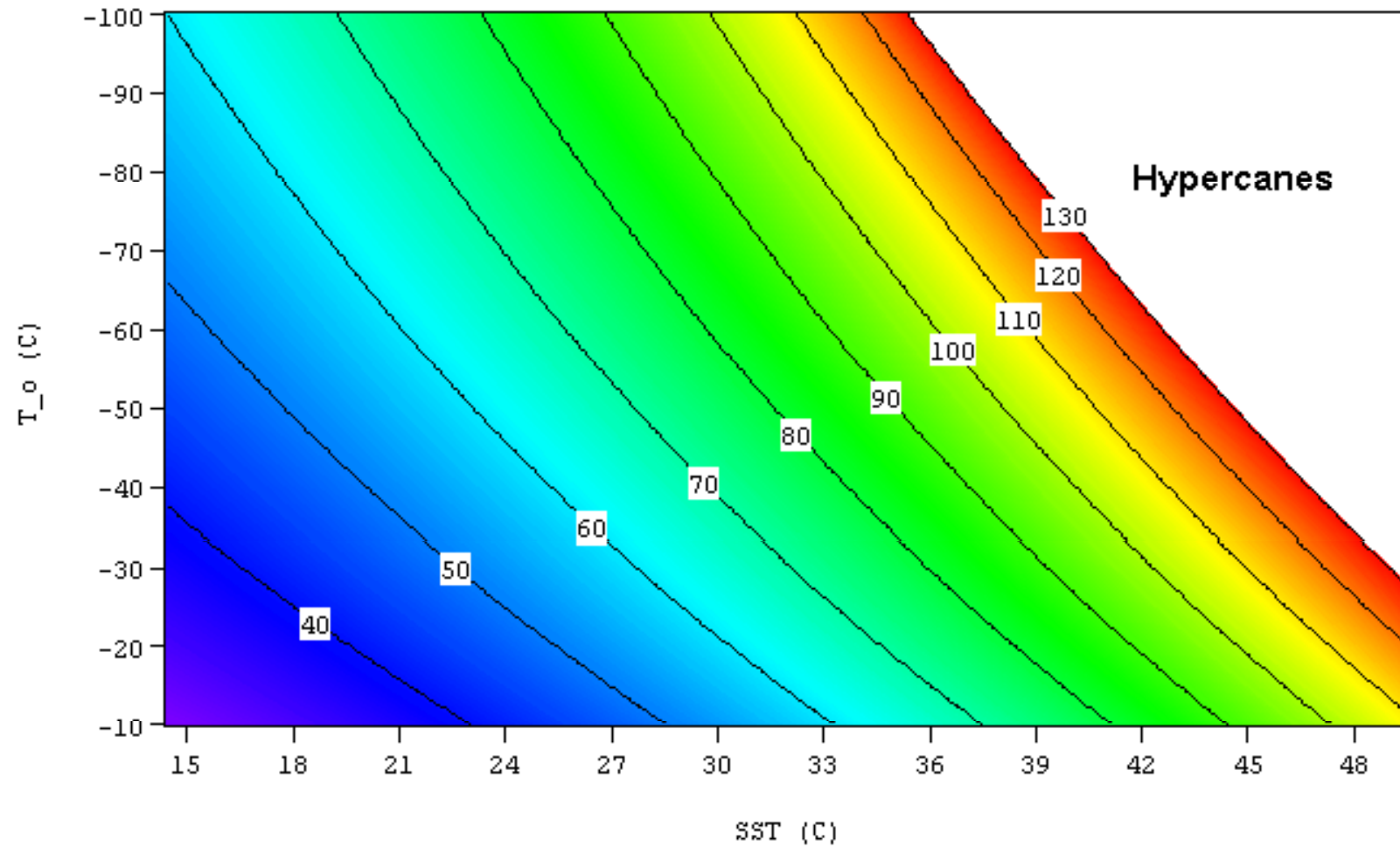
$$P = \frac{T_s - T_o}{T_s} \dot{Q}$$

Theoretical Upper Bound on Hurricane Maximum Wind Speed:

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

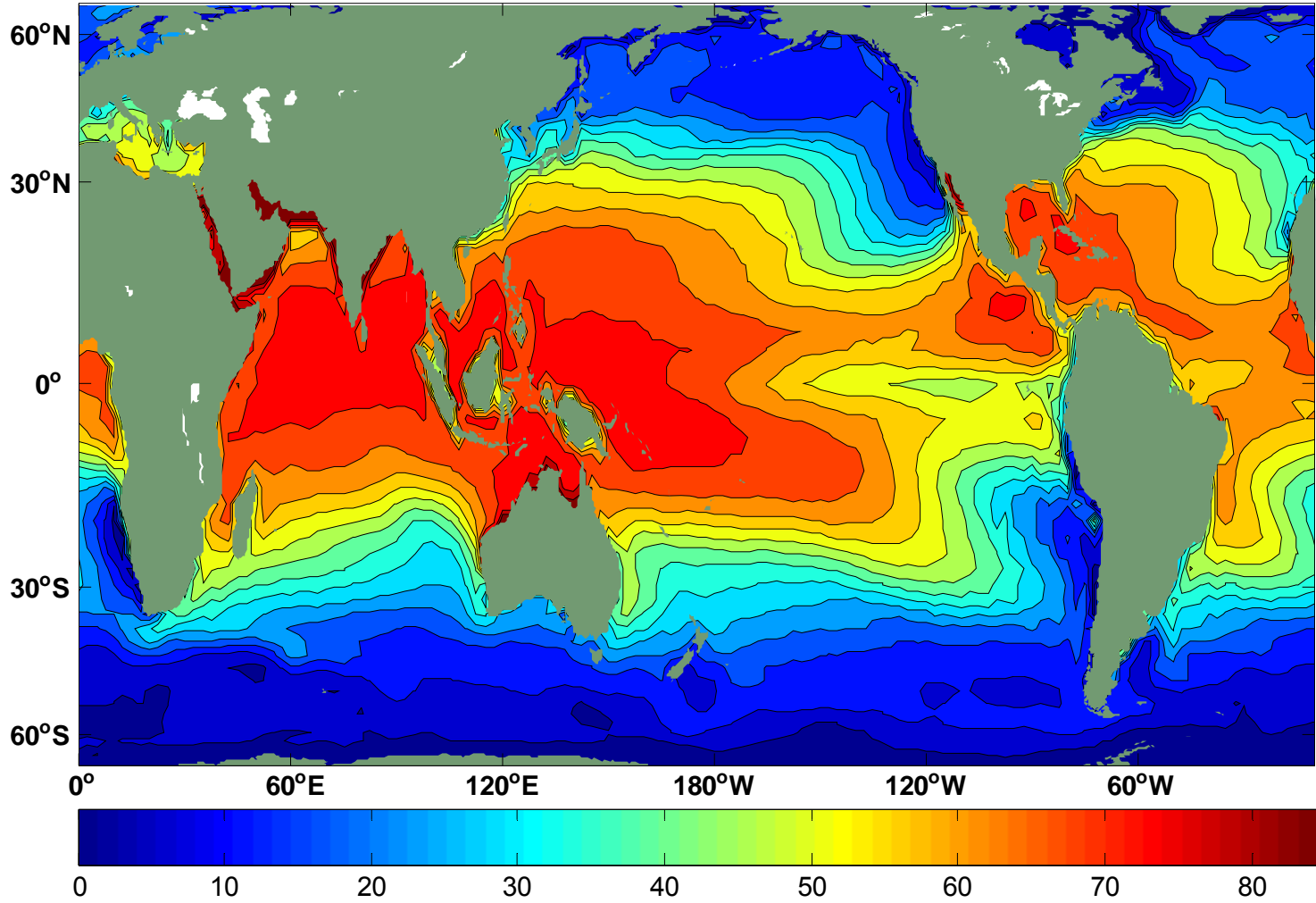
Surface temperature
 Ratio of exchange coefficients of enthalpy and momentum
 Outflow temperature
 Air-sea enthalpy disequilibrium

Maximum Wind Speed (m/s)

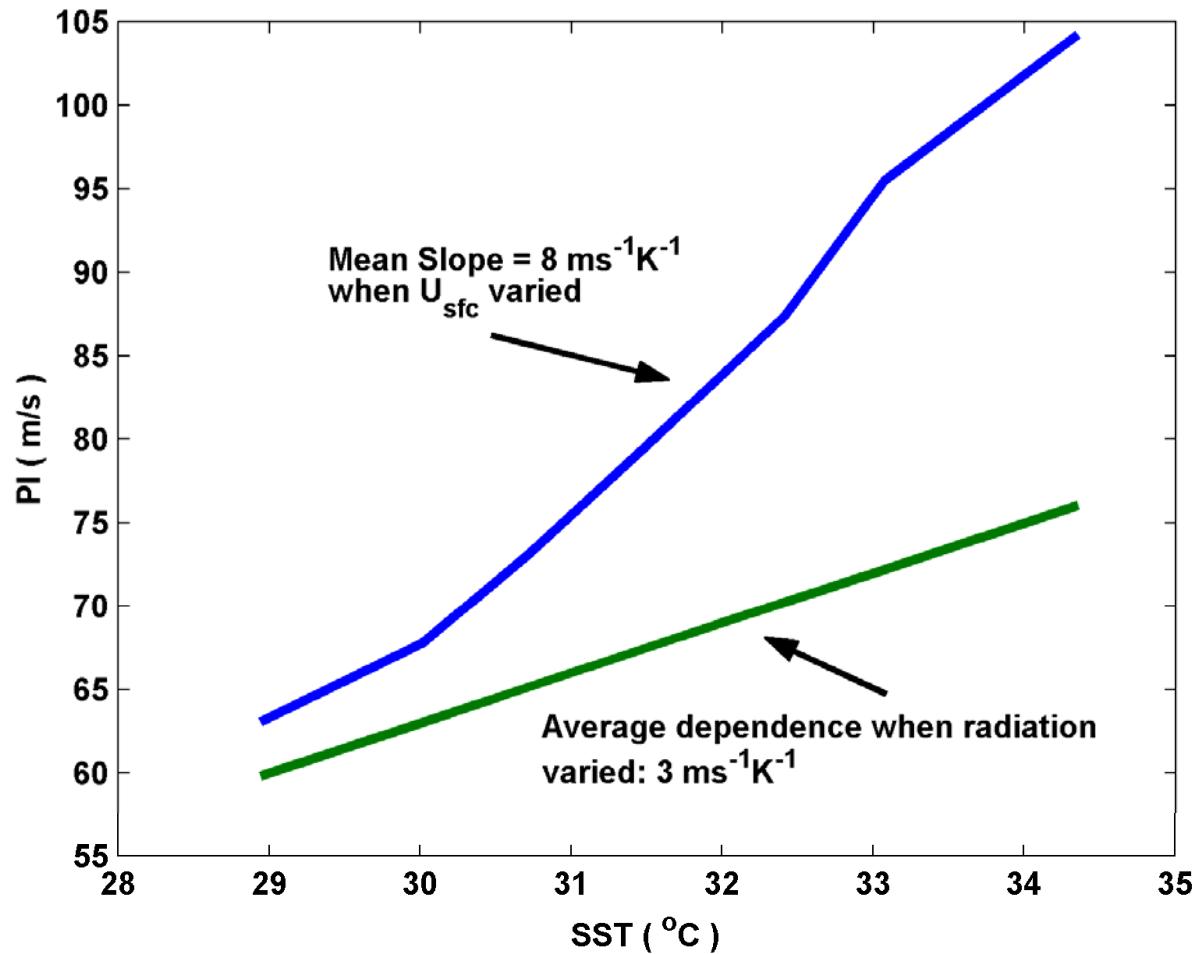


$$\mathcal{R} = 0.75 \quad C_k/C_D = 1.2$$

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 CO₂ content (green)

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

$$V_{max}^2 = \frac{\frac{\text{SST} \quad \text{Outflow T} \quad \text{Net surface radiative flux}}{T_s - T_o} \frac{F_{rad}}{\text{Ocean mixed layer depth}} - \text{Mixed layer heat flux}}{T_o \frac{C_D \rho |V_s|}{\text{Drag coefficient} \quad \text{Mean surface wind speed}}}$$

The equation is annotated with green text and arrows:

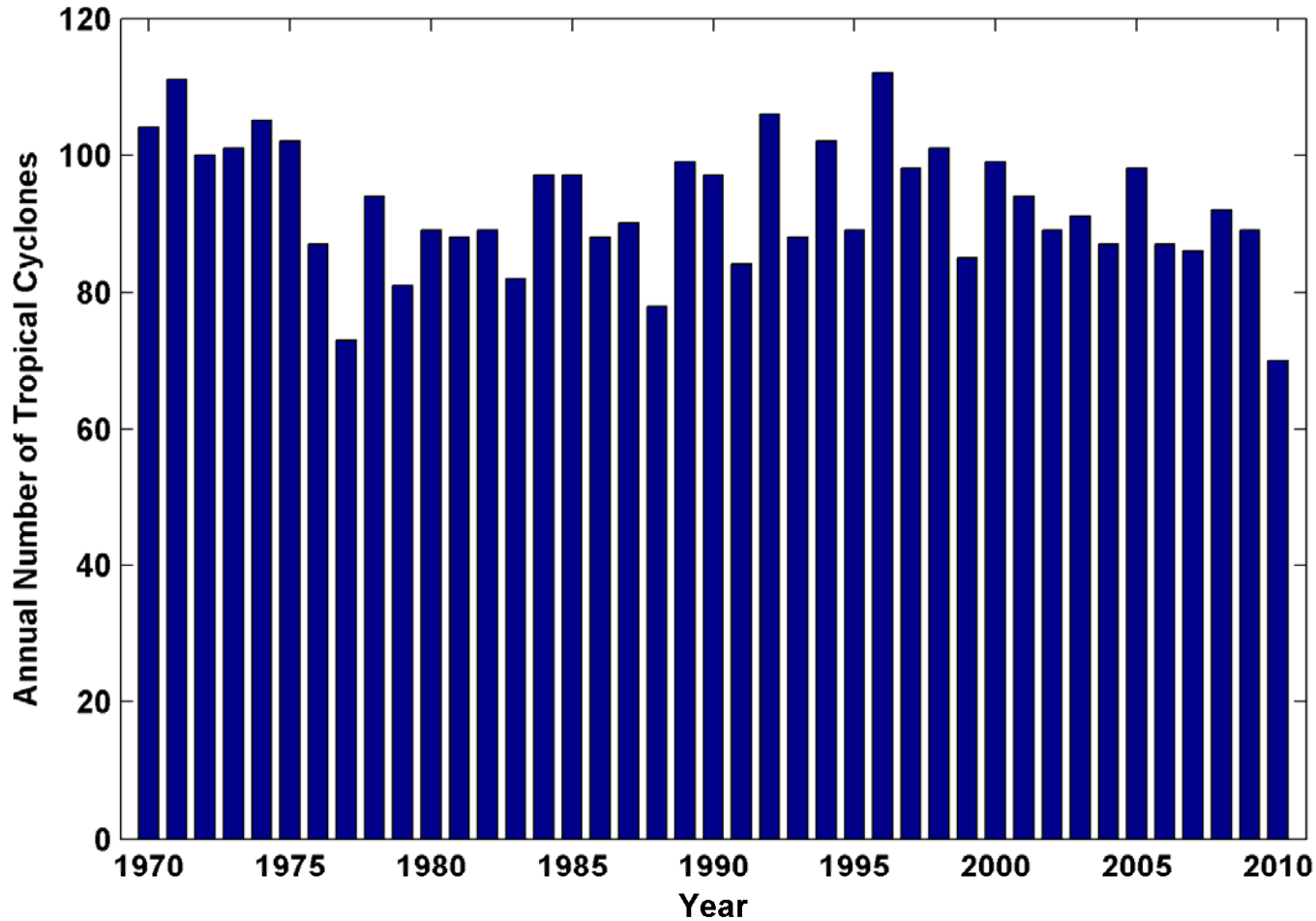
- SST** points to T_s .
- Outflow T** points to T_o .
- Net surface radiative flux** points to F_{rad} .
- Ocean mixed layer depth** points to d .
- Mixed layer heat flux** points to $\nabla \cdot \mathbf{F}_{ocean}$.
- Drag coefficient** points to C_D .
- Mean surface wind speed** points to $|V_s|$.

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

An aerial photograph of a tropical cyclone, showing a dark, dense eye at the center surrounded by a thick, swirling ring of white and grey clouds. The surrounding ocean is visible in shades of blue and grey, with some smaller, less defined cloud structures scattered across the surface. The overall scene is captured from a high altitude, providing a clear view of the storm's structure.

The Genesis Puzzle

No Obvious Trend in Global Hurricane Frequency, 1970-2010



Data Sources: NOAA/TPC and NAVY/JTWC

A satellite image of Earth showing a vast expanse of white and grey cloud patterns over the ocean. The clouds are organized into large-scale, swirling structures, likely representing tropical cyclones or weather systems. The horizon is visible at the top, showing the curvature of the Earth and the blue of the sky.

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



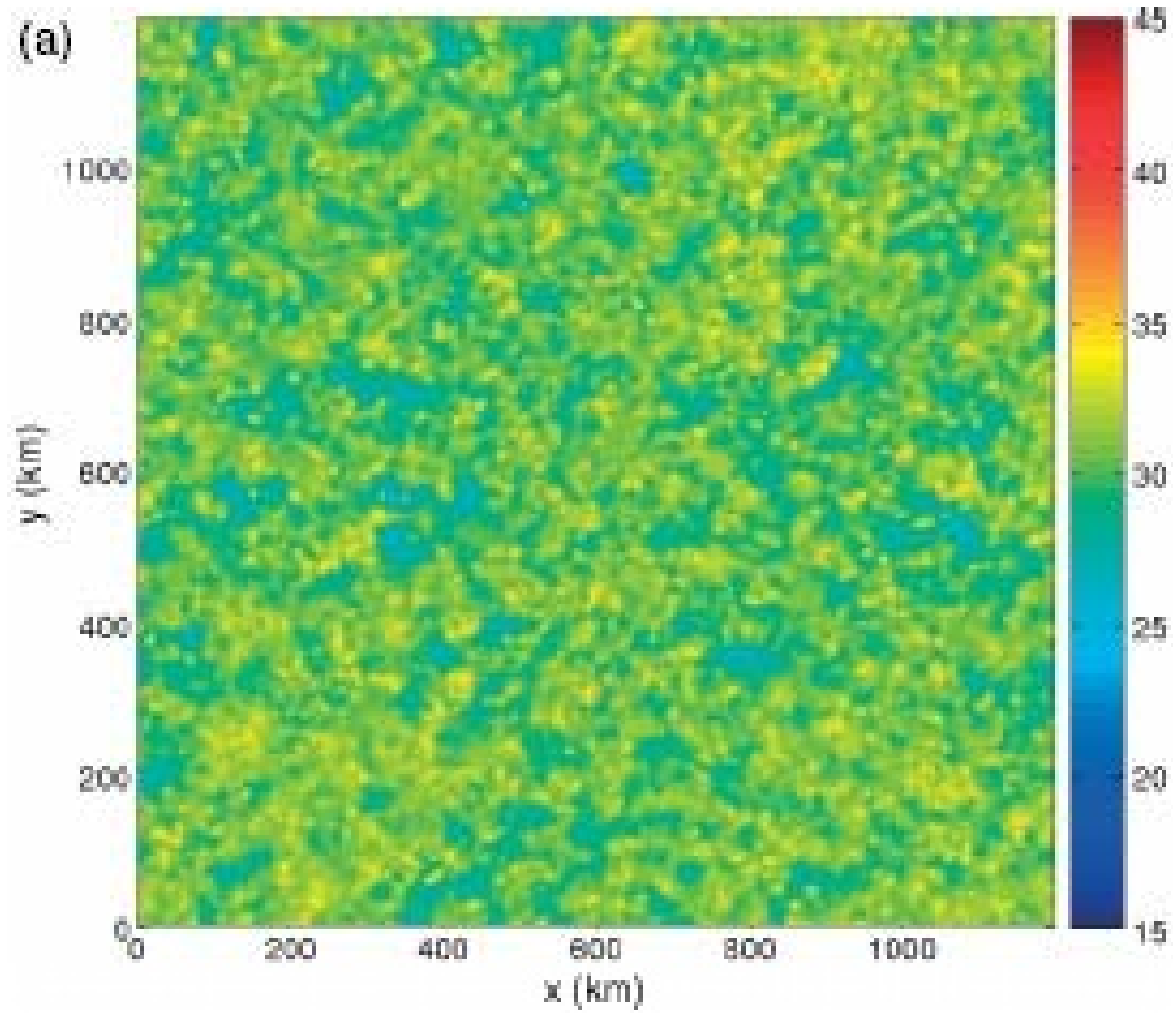
Monsoonal Thunderstorms, Bangladesh and India July 1985

A satellite view of Earth's atmosphere, showing a vast expanse of white and grey clouds swirling in a circular pattern. The horizon is visible at the top, with a thin blue line representing the Earth's surface. The sky transitions from a pale blue near the horizon to a darker blue at the top.

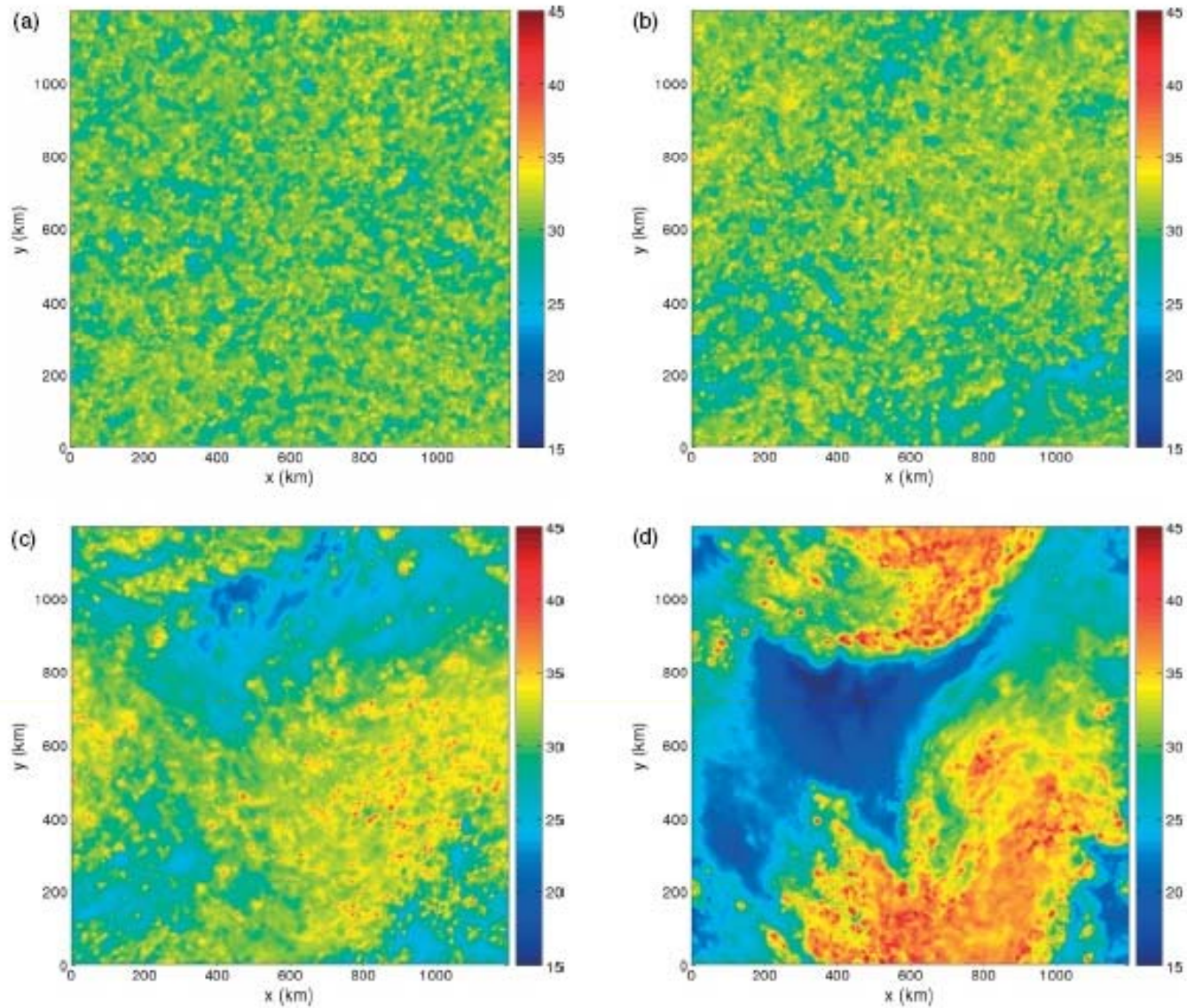
**Simplest Statistical Equilibrium
State:**

Radiative-Convective Equilibrium

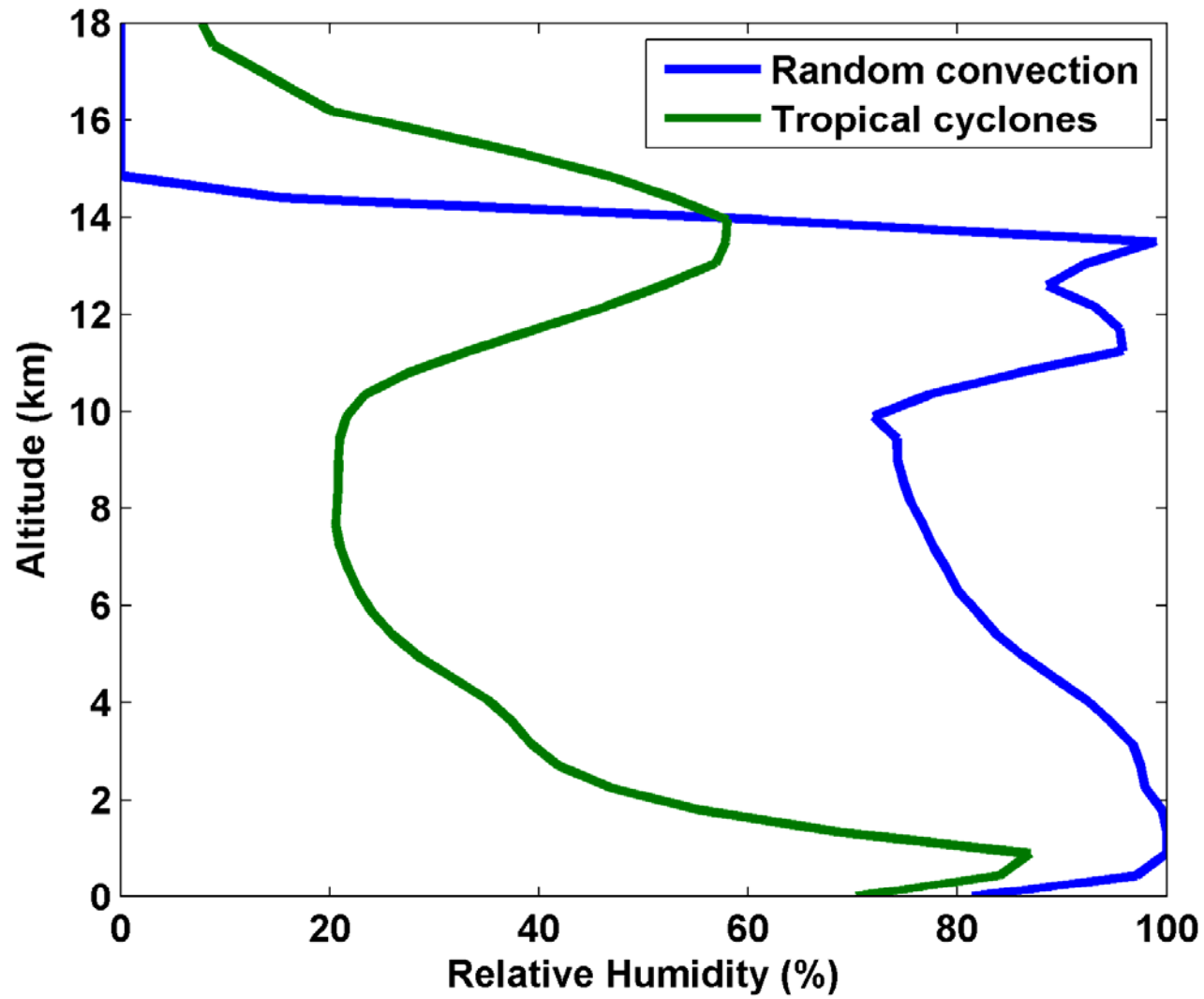
Vertically integrated water vapor at 4 days (Nolan et al., QJRMS, 2007)



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

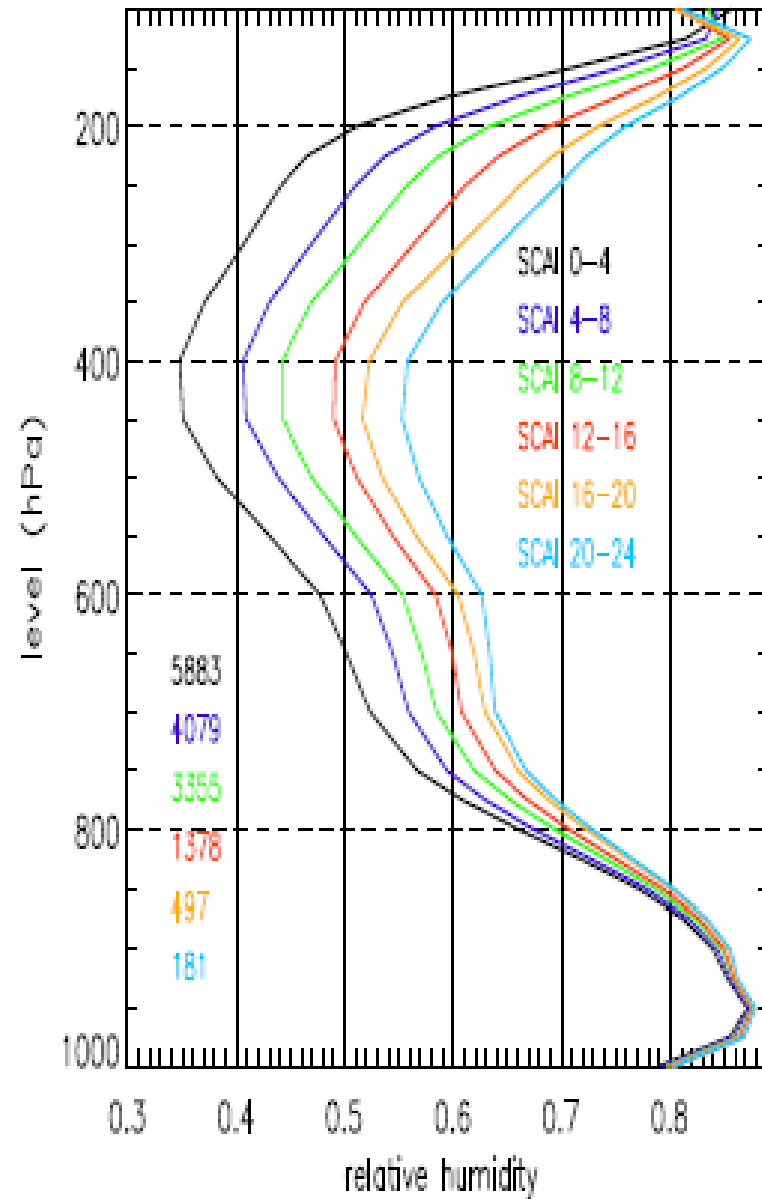


Nolan et al., QJRMS, 2007



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

Courtesy Isabelle Tobin, Sandrine Bony, and Remy Roca

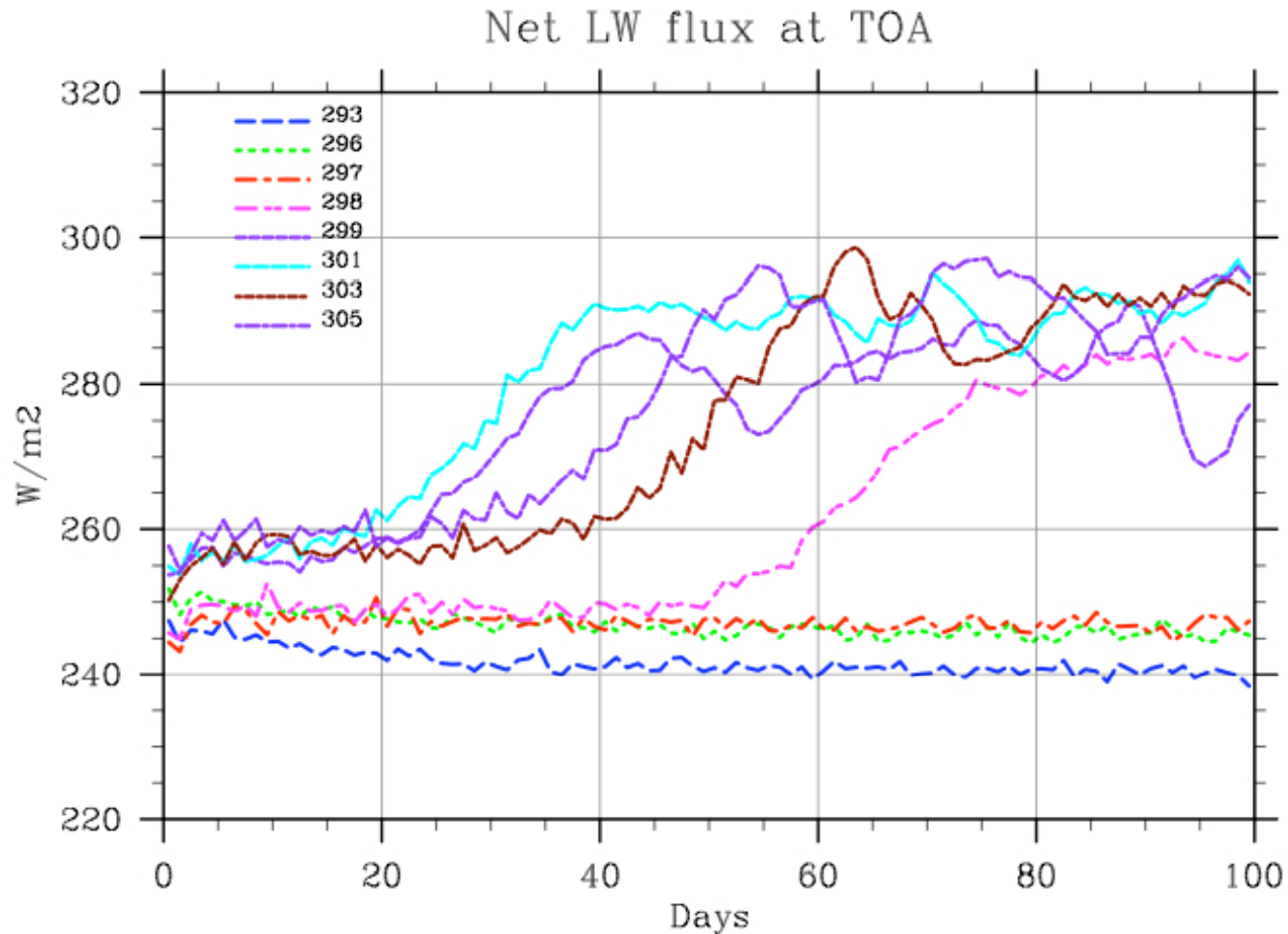


Empirical Necessary Conditions for Self-Aggregation (after Held et al., 1993; Bretherton et al., 2005; Nolan et al.; 2007)

- 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

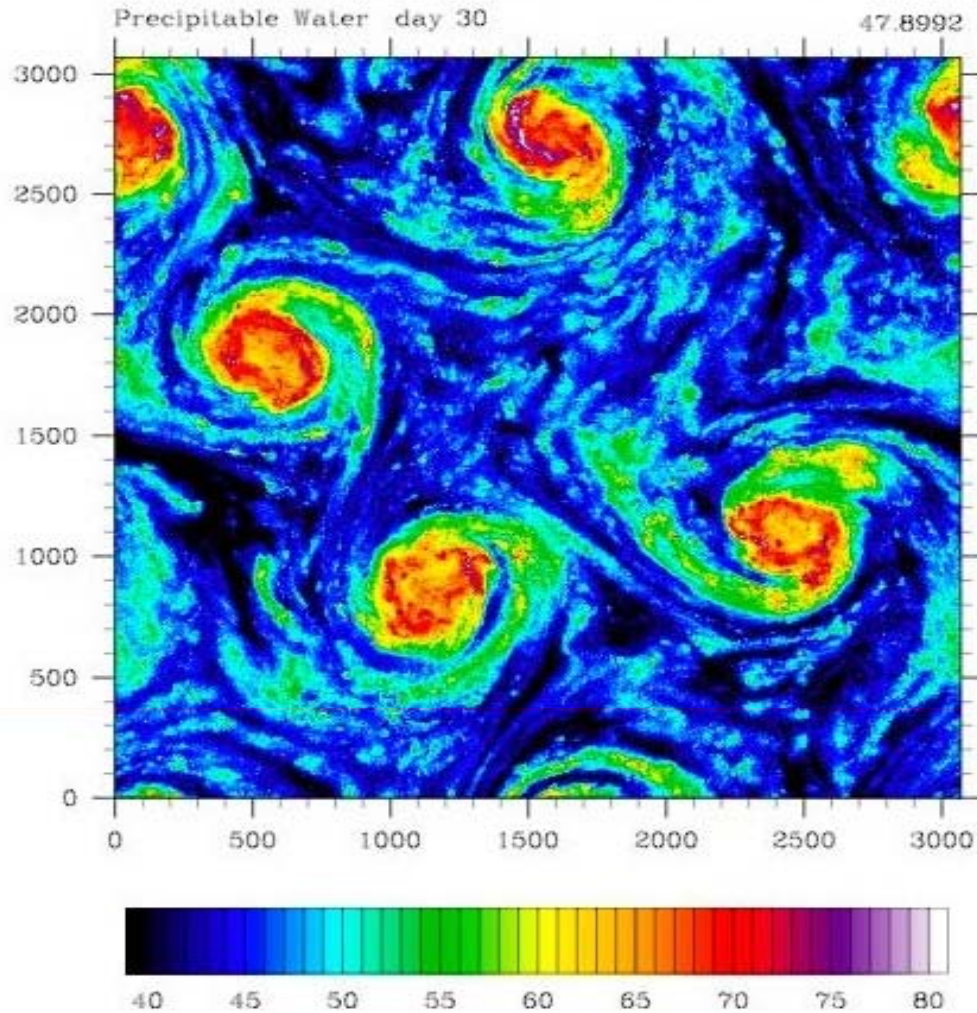
Self-Aggregation is Temperature-Dependent

(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 $\sim \frac{f^2}{V_{pot}^2}$
- Intensity $\sim V_{pot}$
- Power Dissipation $\sim V_{pot} f^2$

Hypothesis

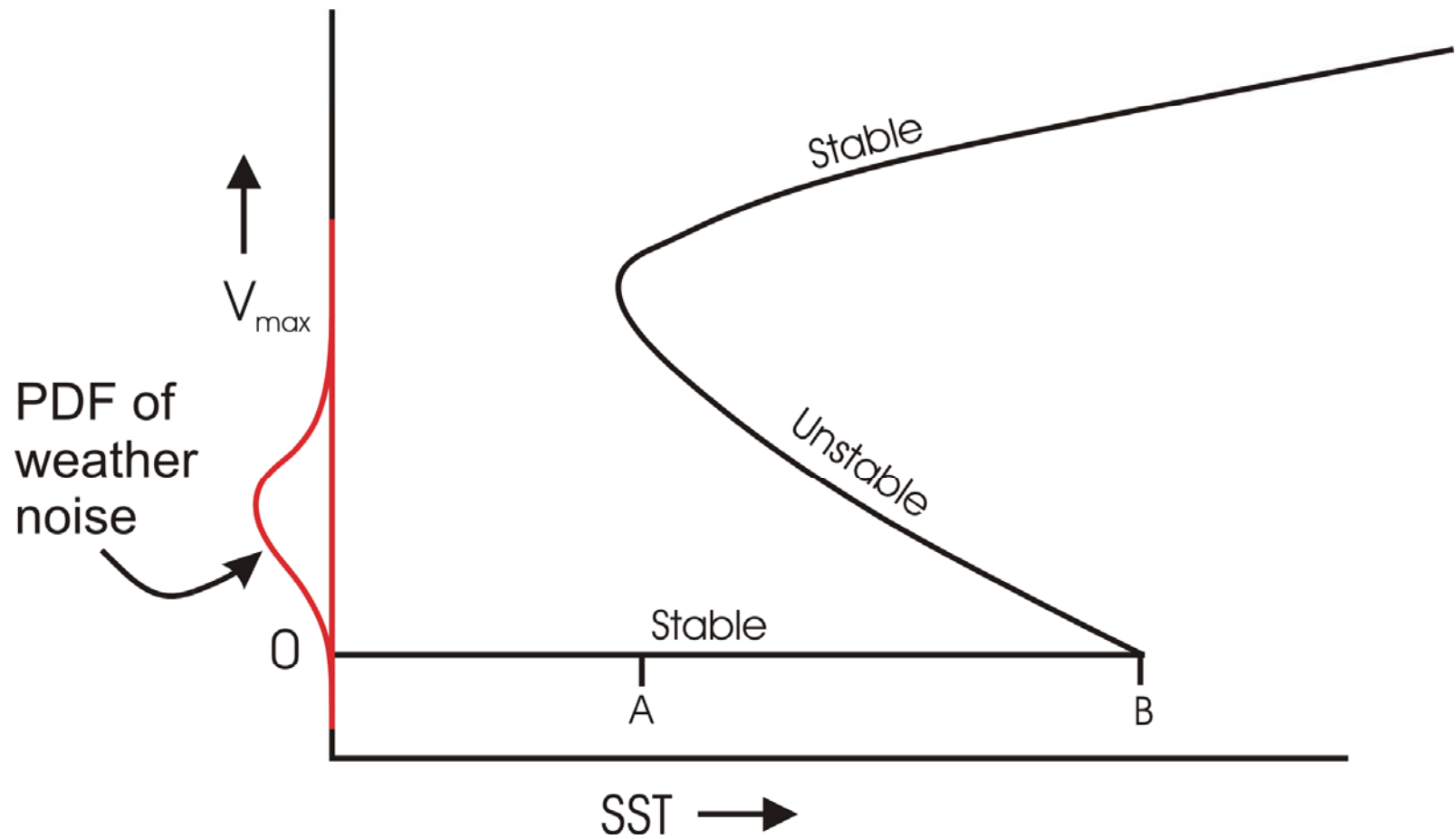
- At high temperature, convection self-aggregates
- →Horizontally averaged humidity drops dramatically
- →Reduced greenhouse effect cools system
- →Convection disaggregates
- →Humidity increases, system warms
- →System wants to be near phase transition to aggregated state

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



A satellite image of a hurricane over the ocean. The hurricane is a large, circular storm system with a dark, well-defined eye in the center. The surrounding clouds are dense and spiral outwards. The ocean surface is visible as a lighter blue area. The text "Hurricanes and Climate: Some Empirical Results" is overlaid in the center of the image in a bold, blue font.

Hurricanes and Climate: Some Empirical Results

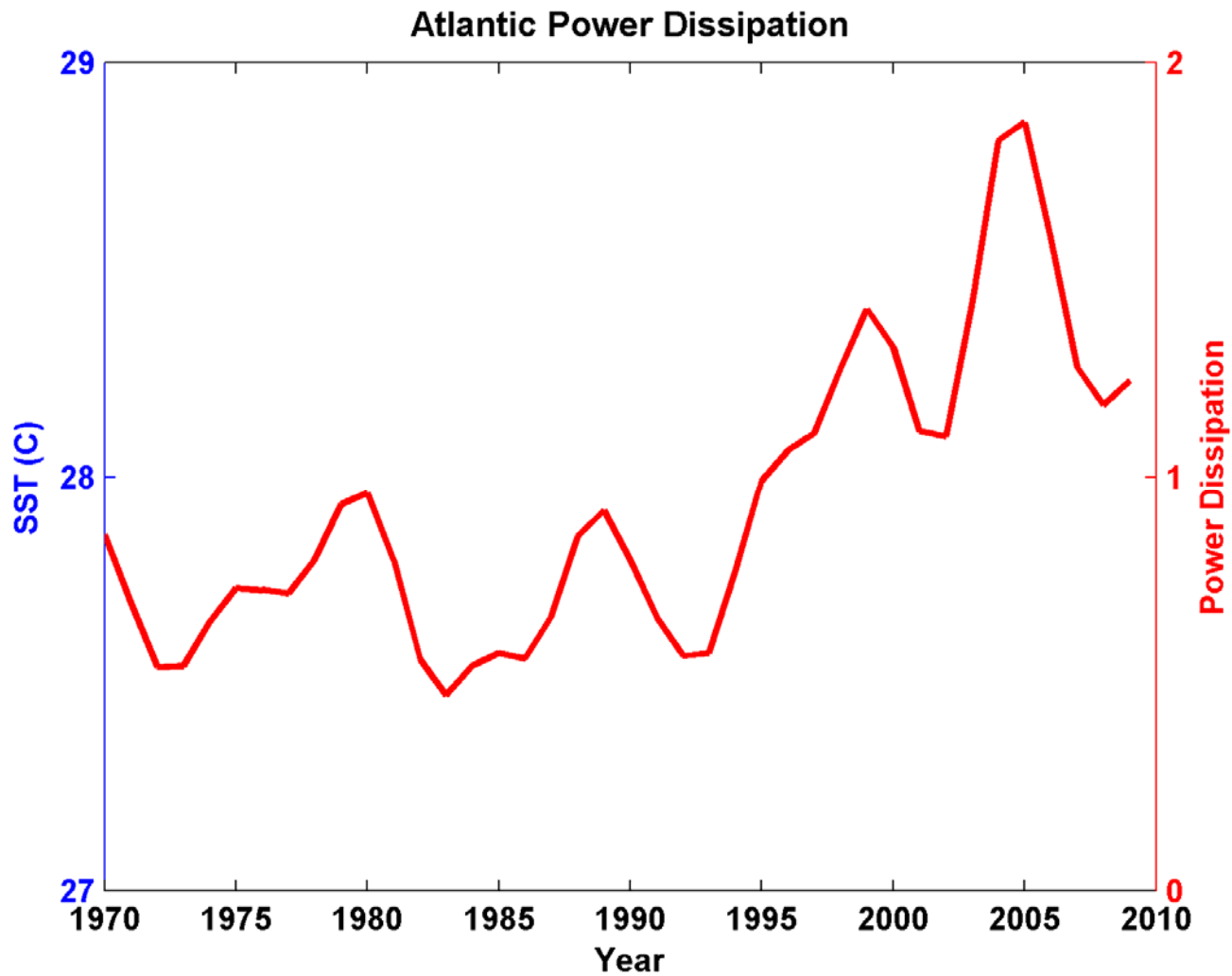
Intensity Metric:

Hurricane Power (Power Dissipation Index)

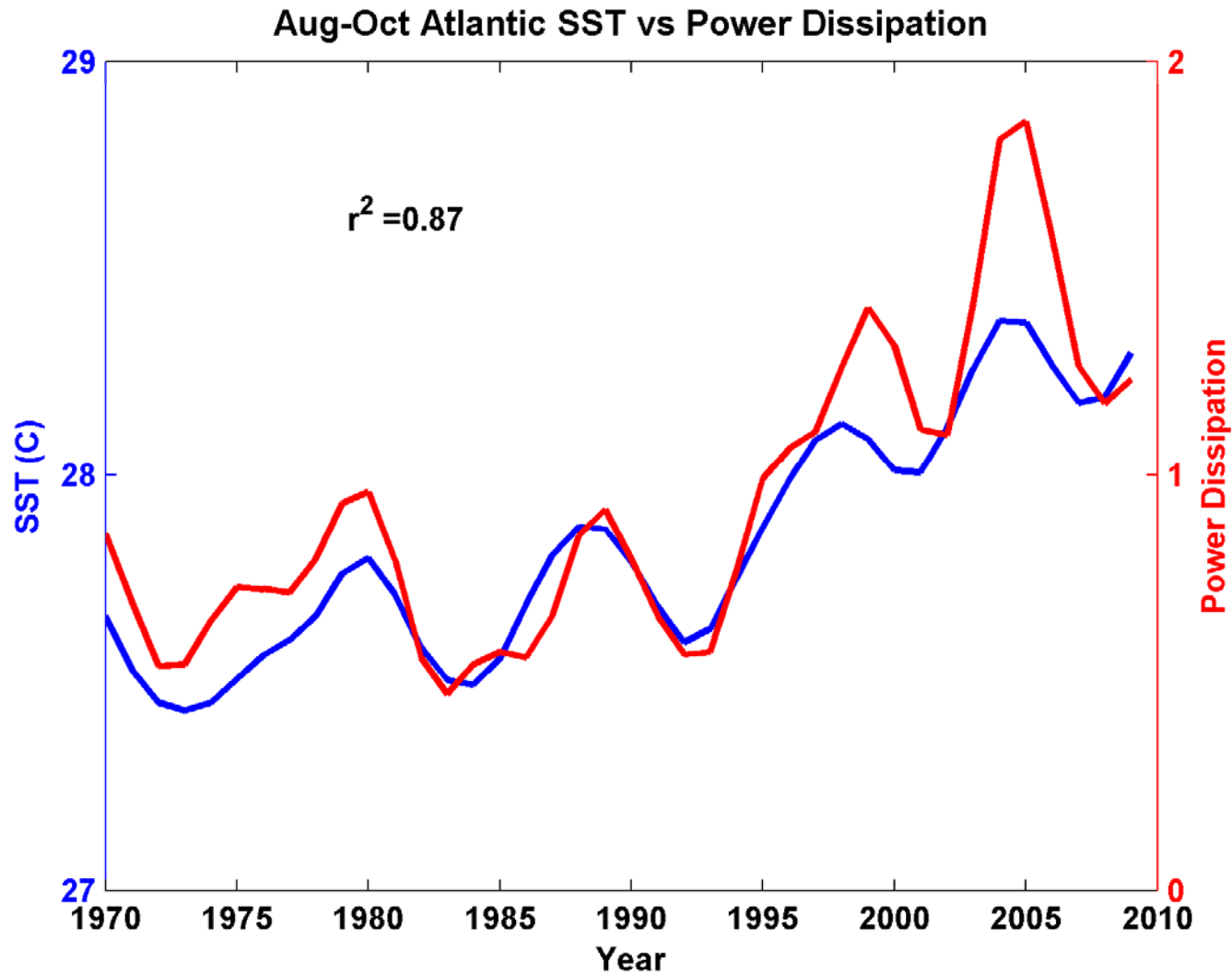
$$PDI \equiv \int_0^{\tau} V_{max}^3 dt$$

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

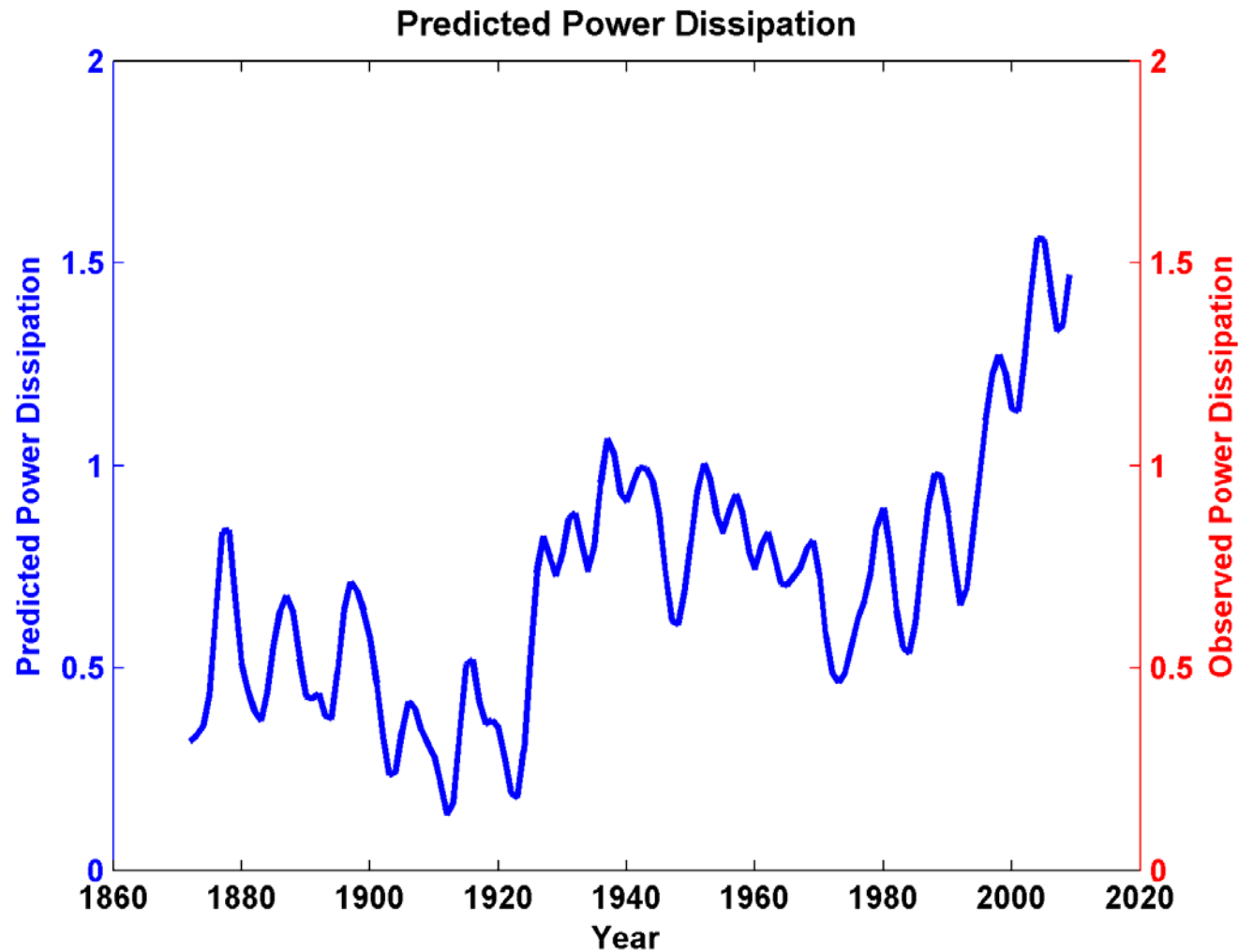
Atlantic Tropical Cyclone Power Dissipation during an era of high quality measurements, 1970-2011 (smoothed with 1-3-4-3-1 filter)



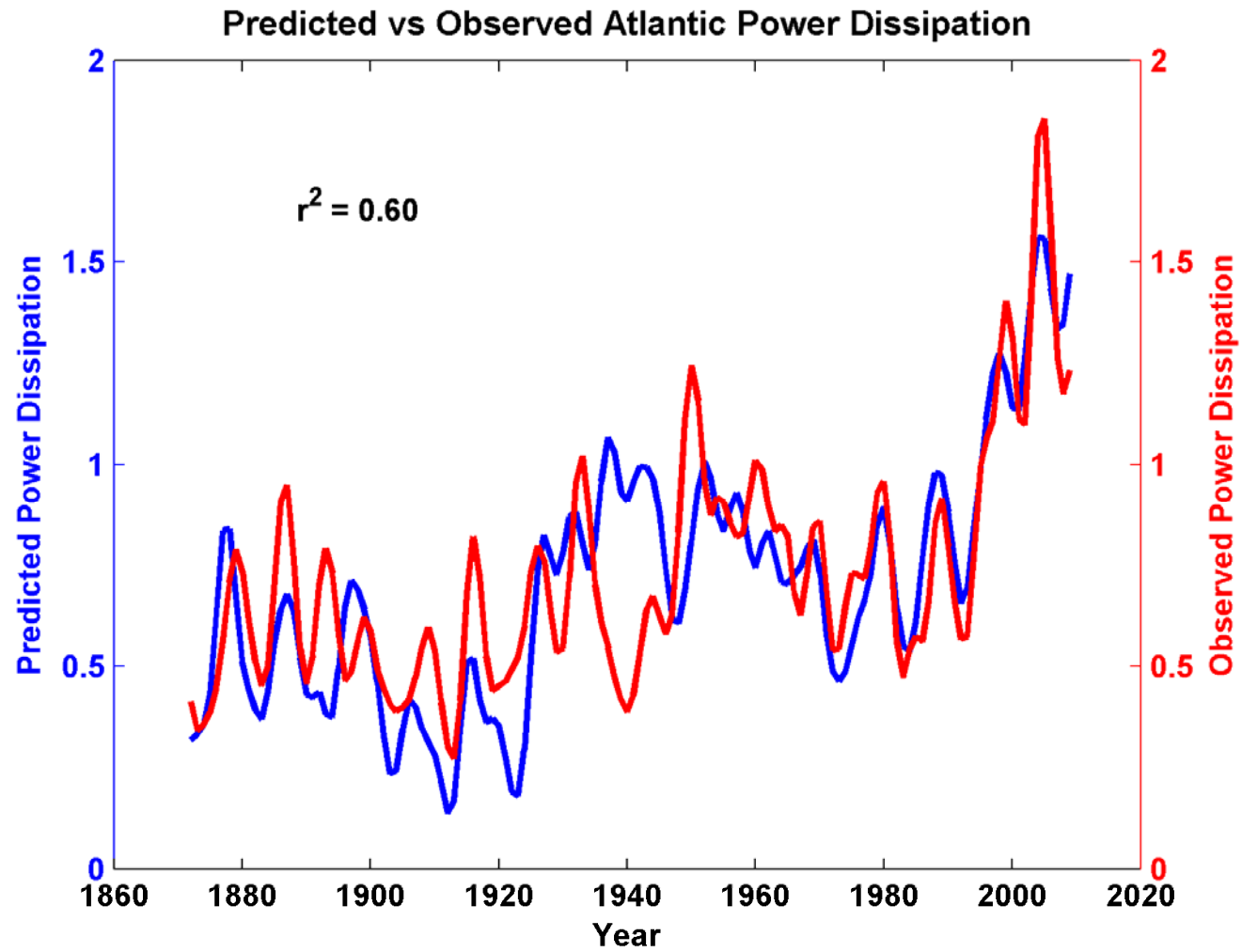
Atlantic Tropical Cyclone Power Dissipation and Sea Surface Temperature during an era of high quality measurements, 1970-2011 (smoothed with 1-3-4-3-1 filter)

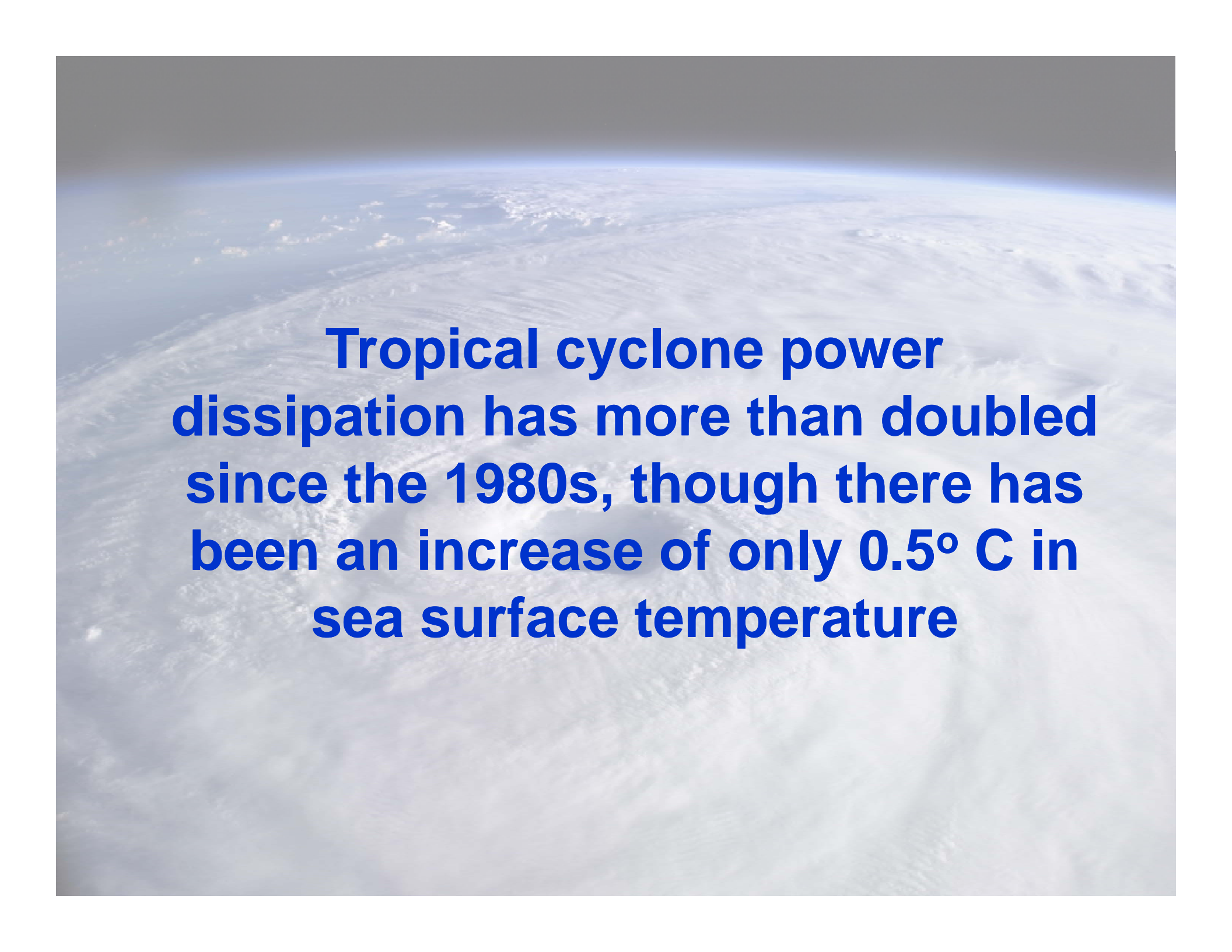


Use Linear Regression to Predict Power Dissipation back to 1870 based on SST:



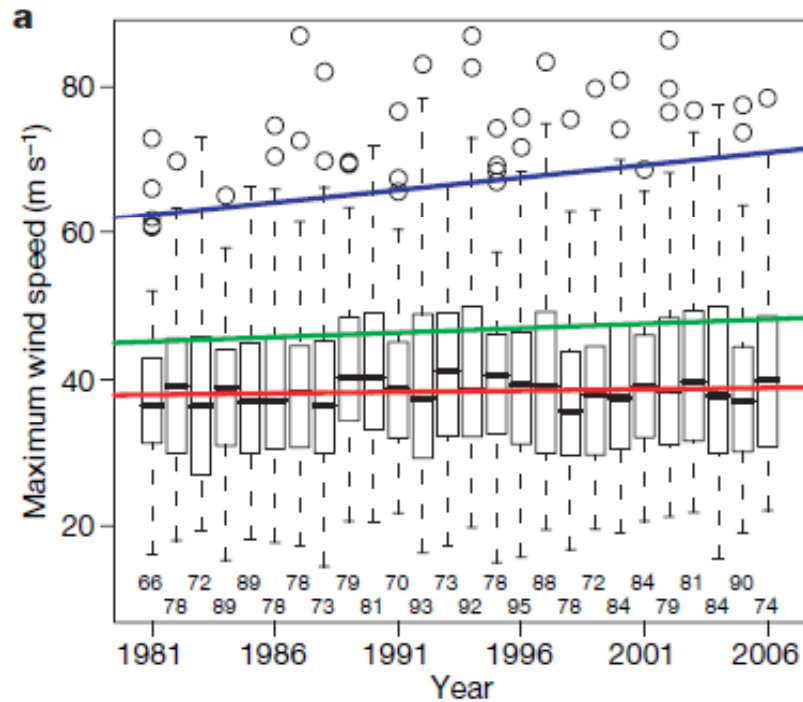
Now Compare to Observed Power Dissipation



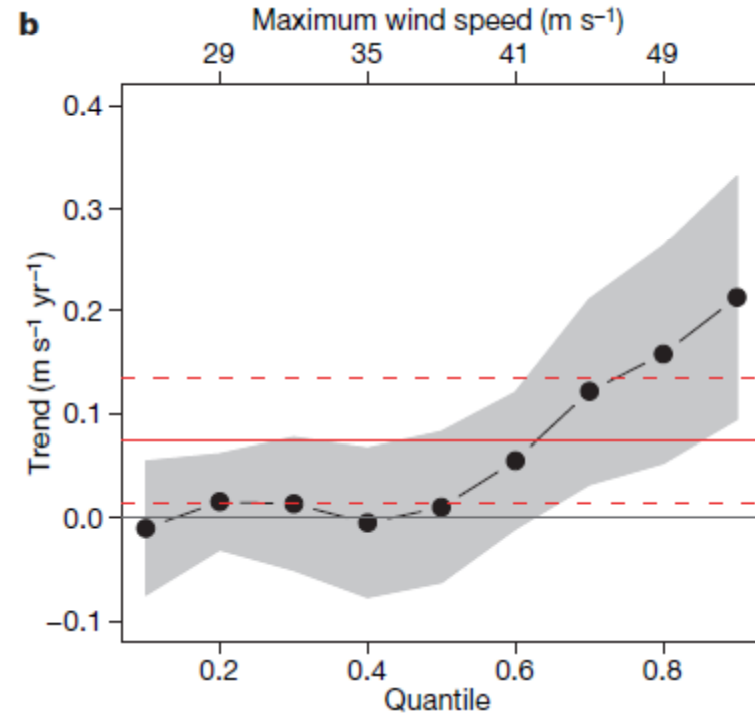
A satellite image of Earth's oceans, showing a large tropical cyclone with a distinct eye and spiral cloud bands. The text is overlaid in the center of the image.

**Tropical cyclone power
dissipation has more than doubled
since the 1980s, though there has
been an increase of only 0.5° 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



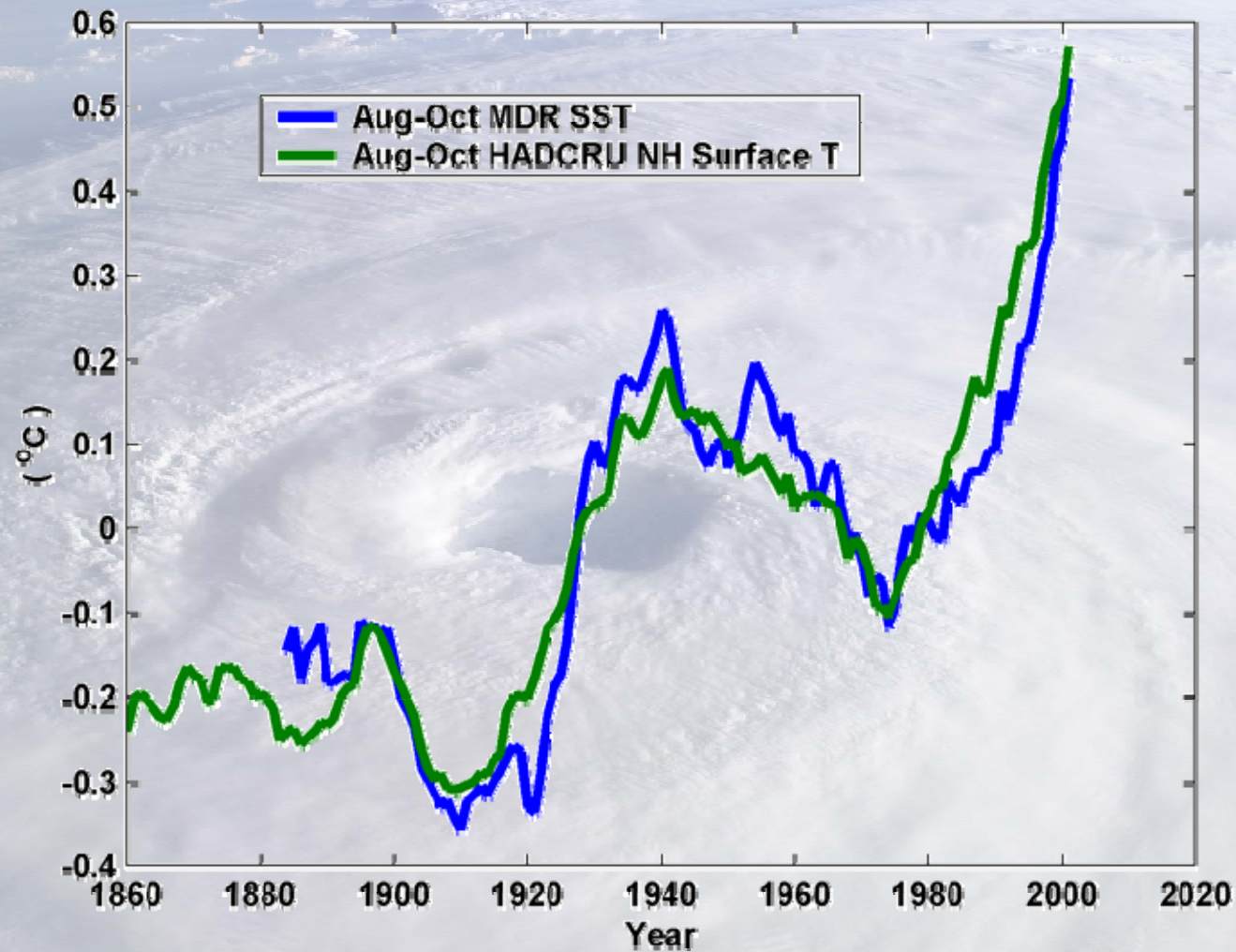
Trends in global satellite-derived tropical cyclone maximum wind speeds by quantile, from 0.1 to 0.9 in increments of 0.1.

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

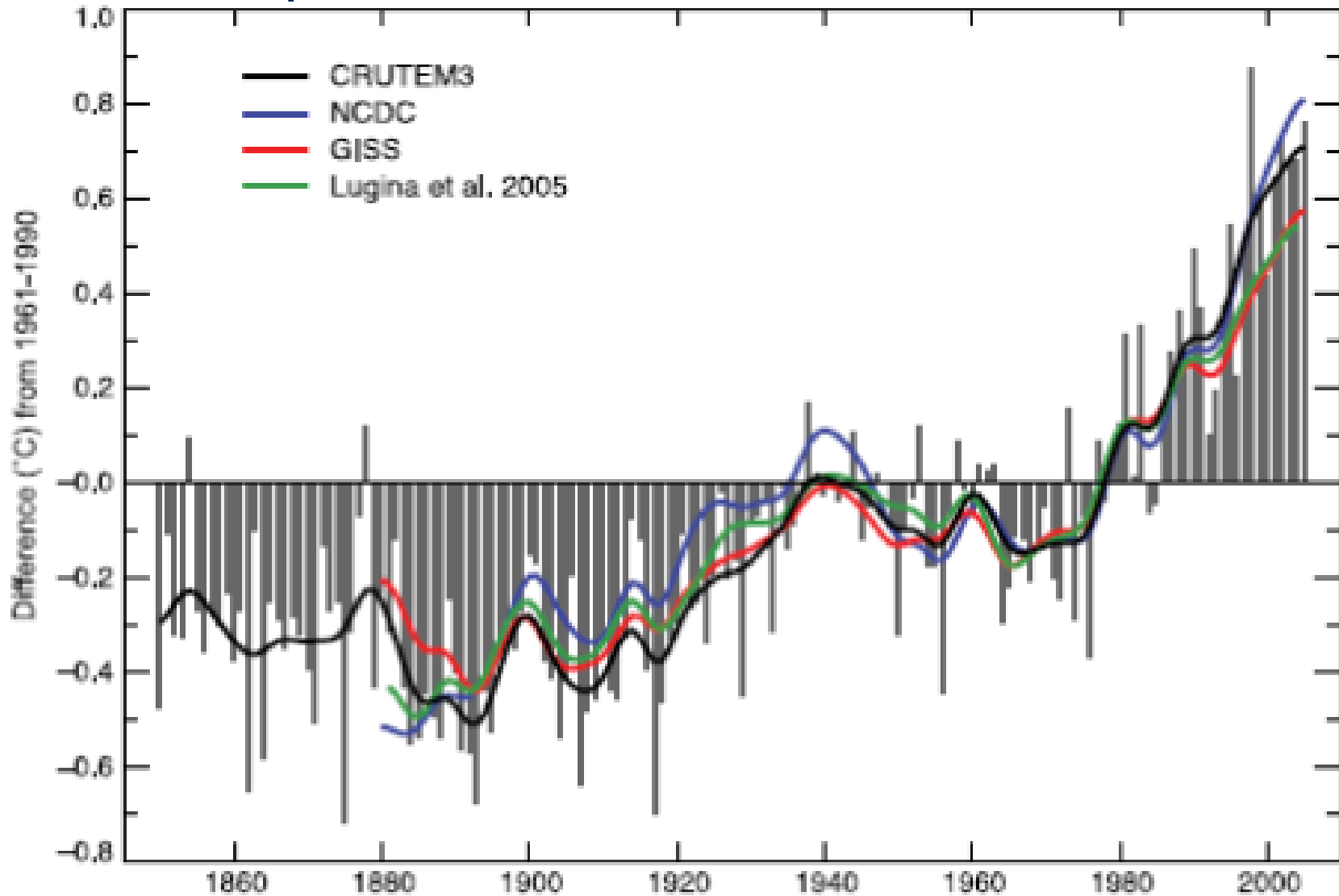
A satellite image of the tropical Atlantic Ocean. The image shows a large, well-defined cyclone or hurricane in the lower-left quadrant, with a dark eye and a bright, swirling cloud structure. The rest of the ocean surface is covered in a dense layer of white clouds, with some darker patches indicating different cloud heights or temperatures. The horizon of the Earth is visible at the top of the image, showing a thin blue line against a dark background.

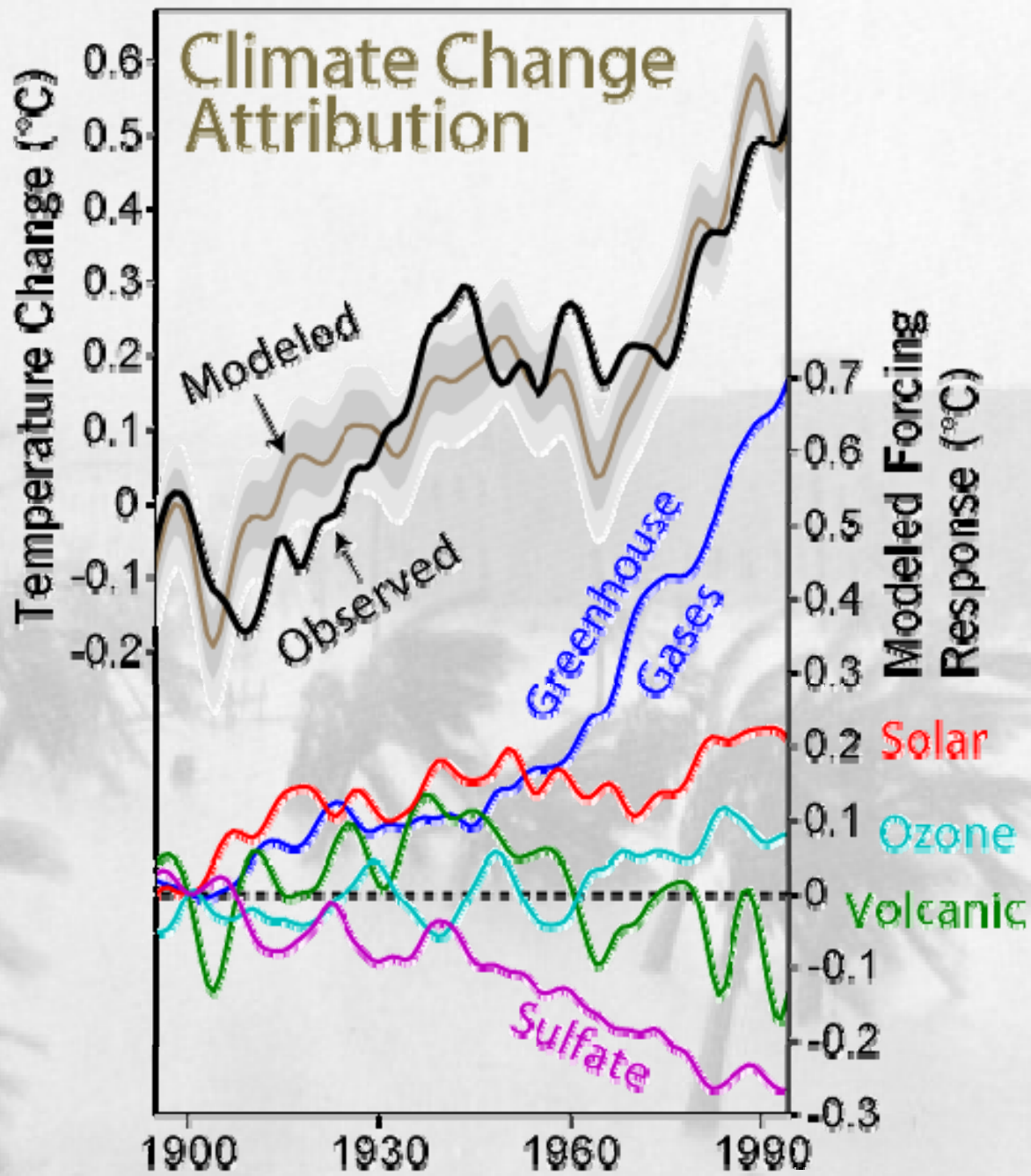
**What is Causing Changes in
Tropical Atlantic Sea Surface
Temperature?**

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

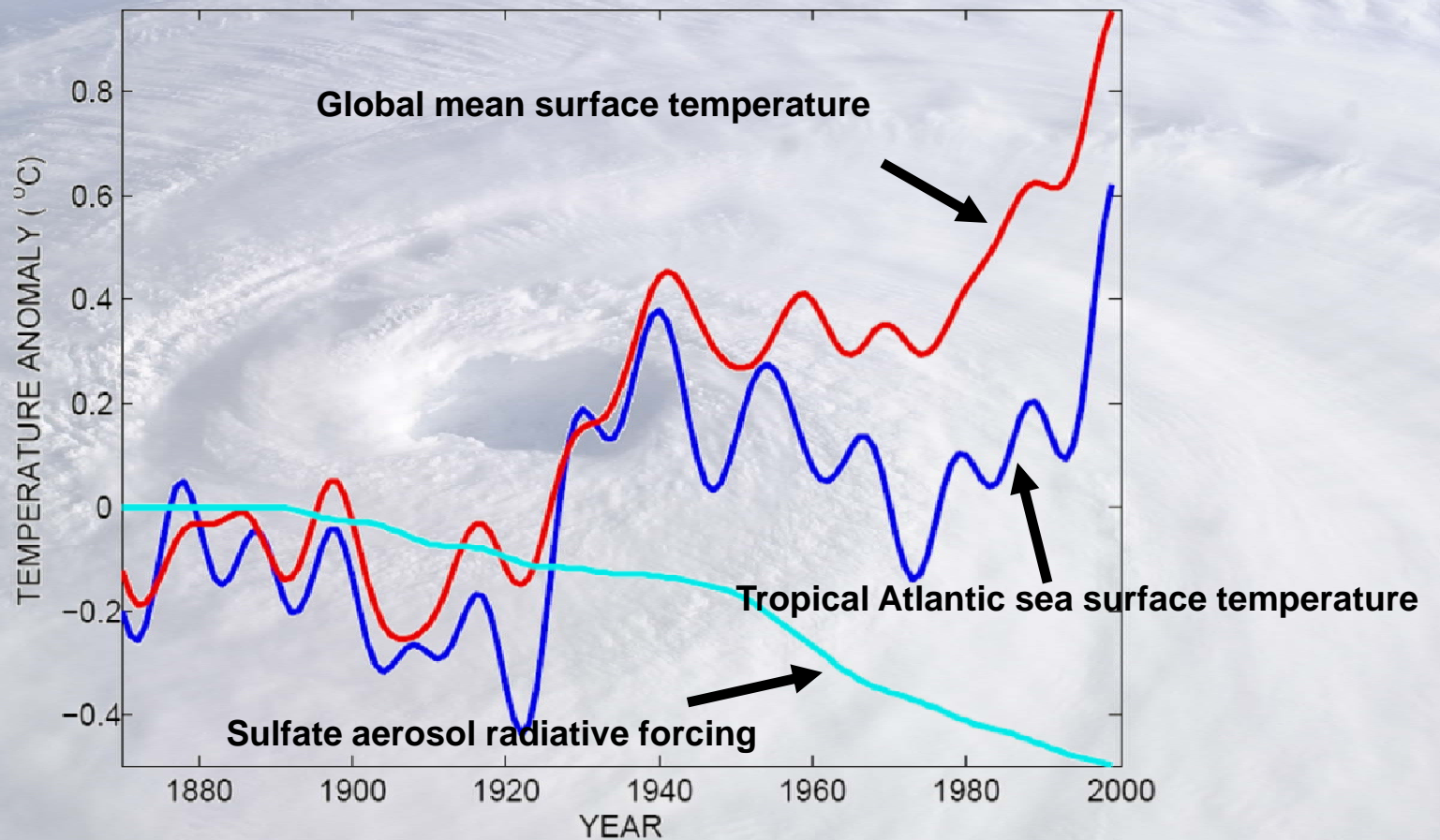


Estimates of Global Mean Surface Temperature from the Instrumental Record



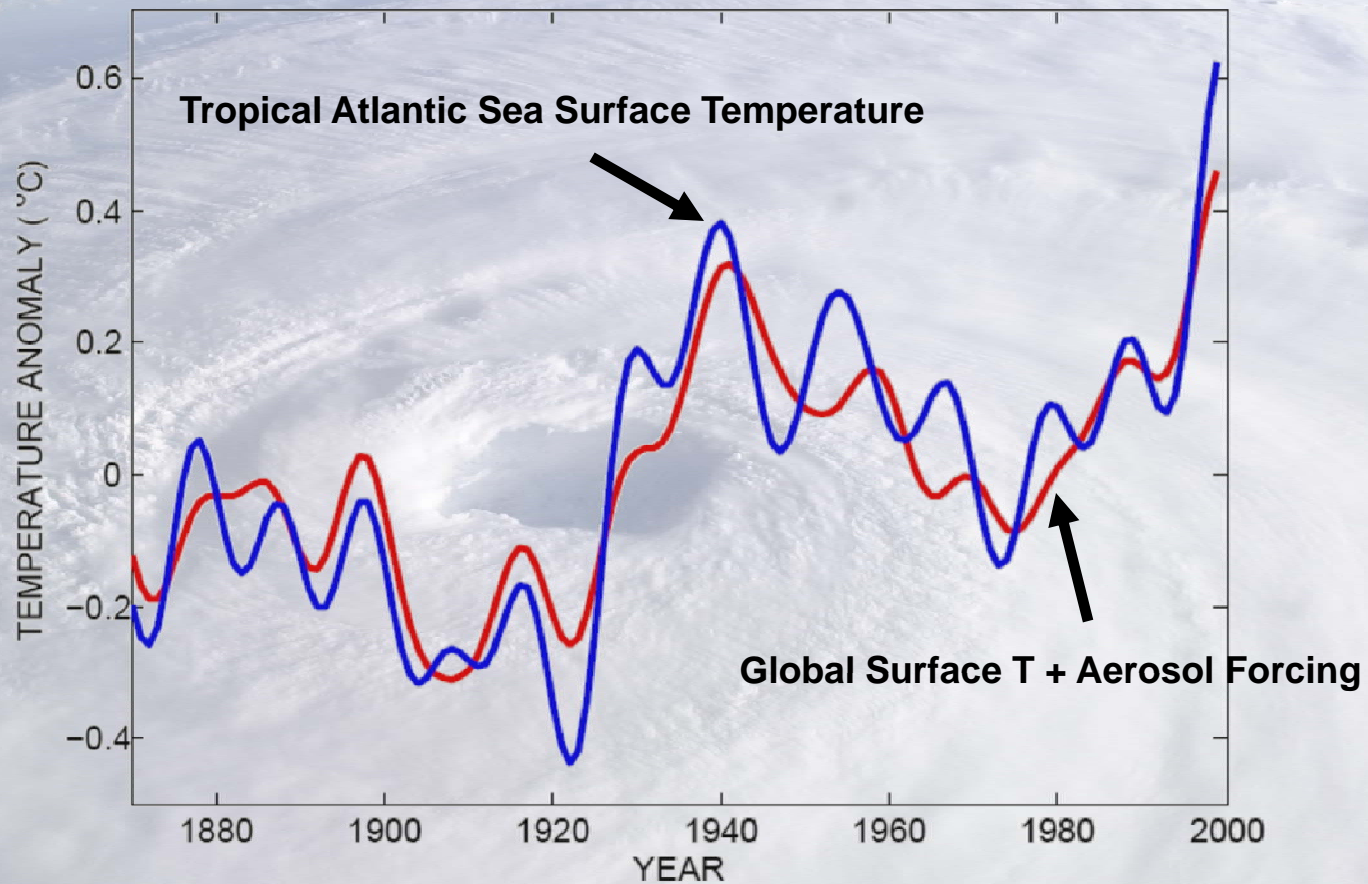


Tropical Atlantic SST(blue), Global Mean Surface Temperature (red), Aerosol Forcing (aqua)



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)

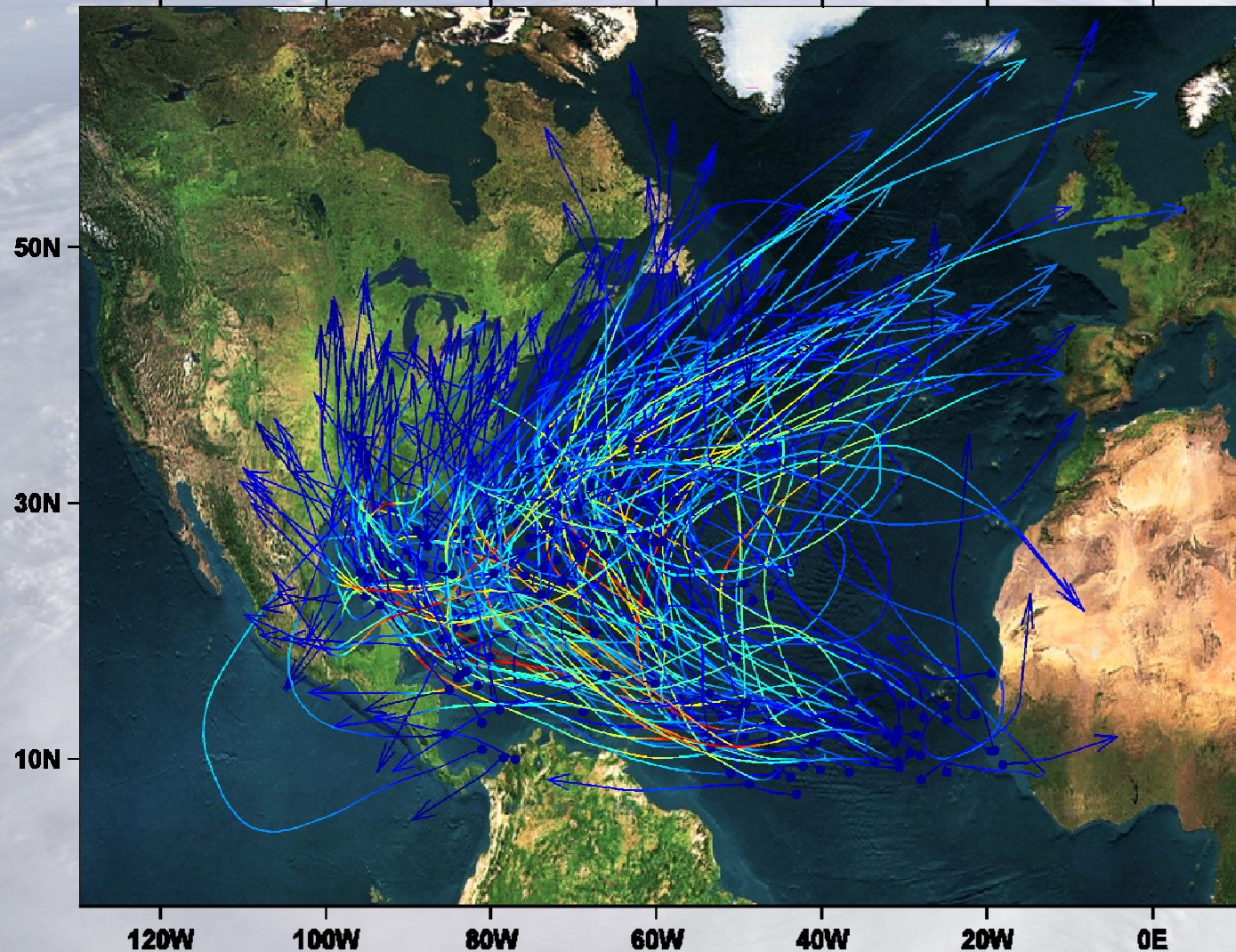


Mann, M. E., and K. A. Emanuel, 2006. Atlantic hurricane trends linked to climate change. EOS, 87, 233-244.

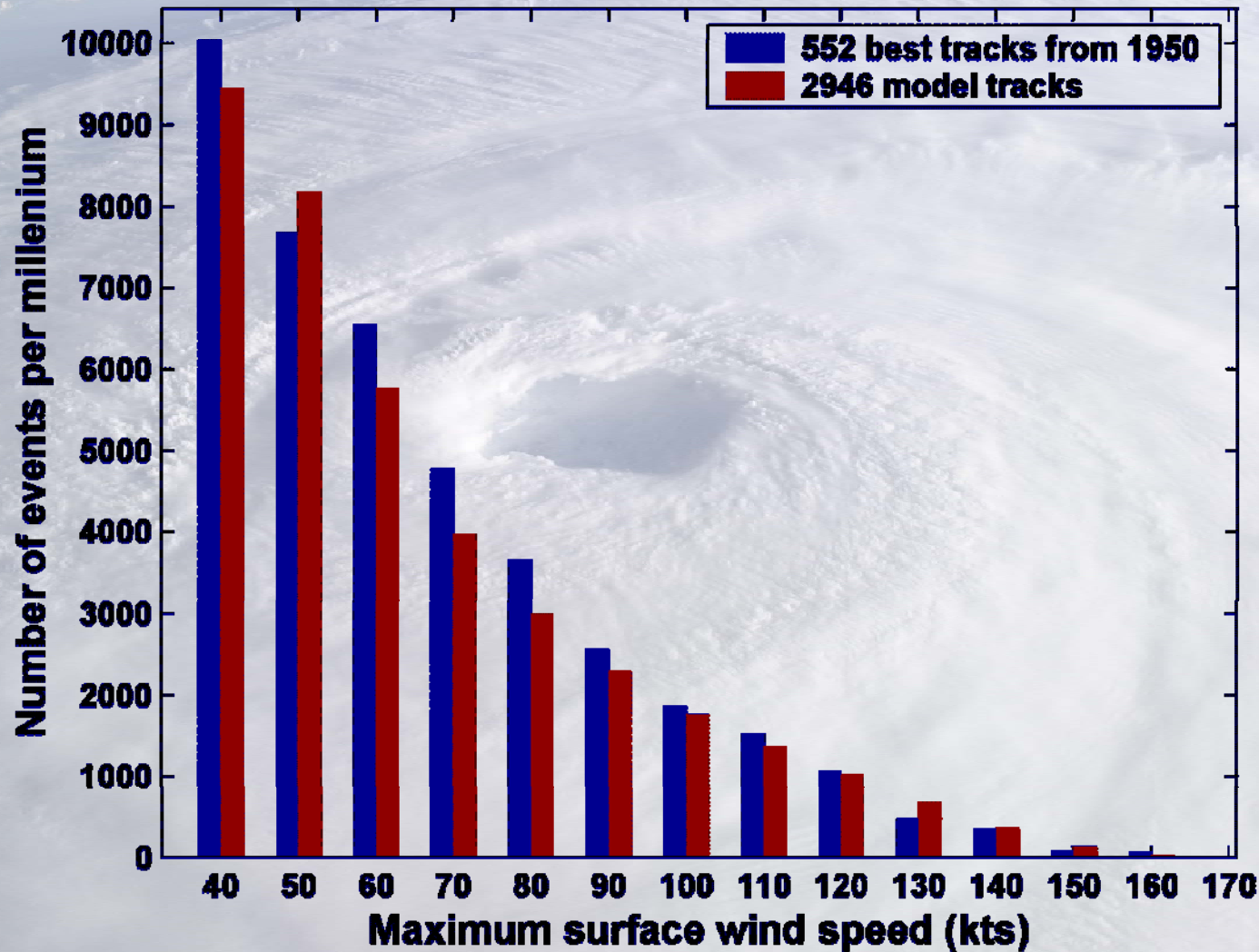
Our Approach to Downscaling Tropical Cyclones from Climate Models

- **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.

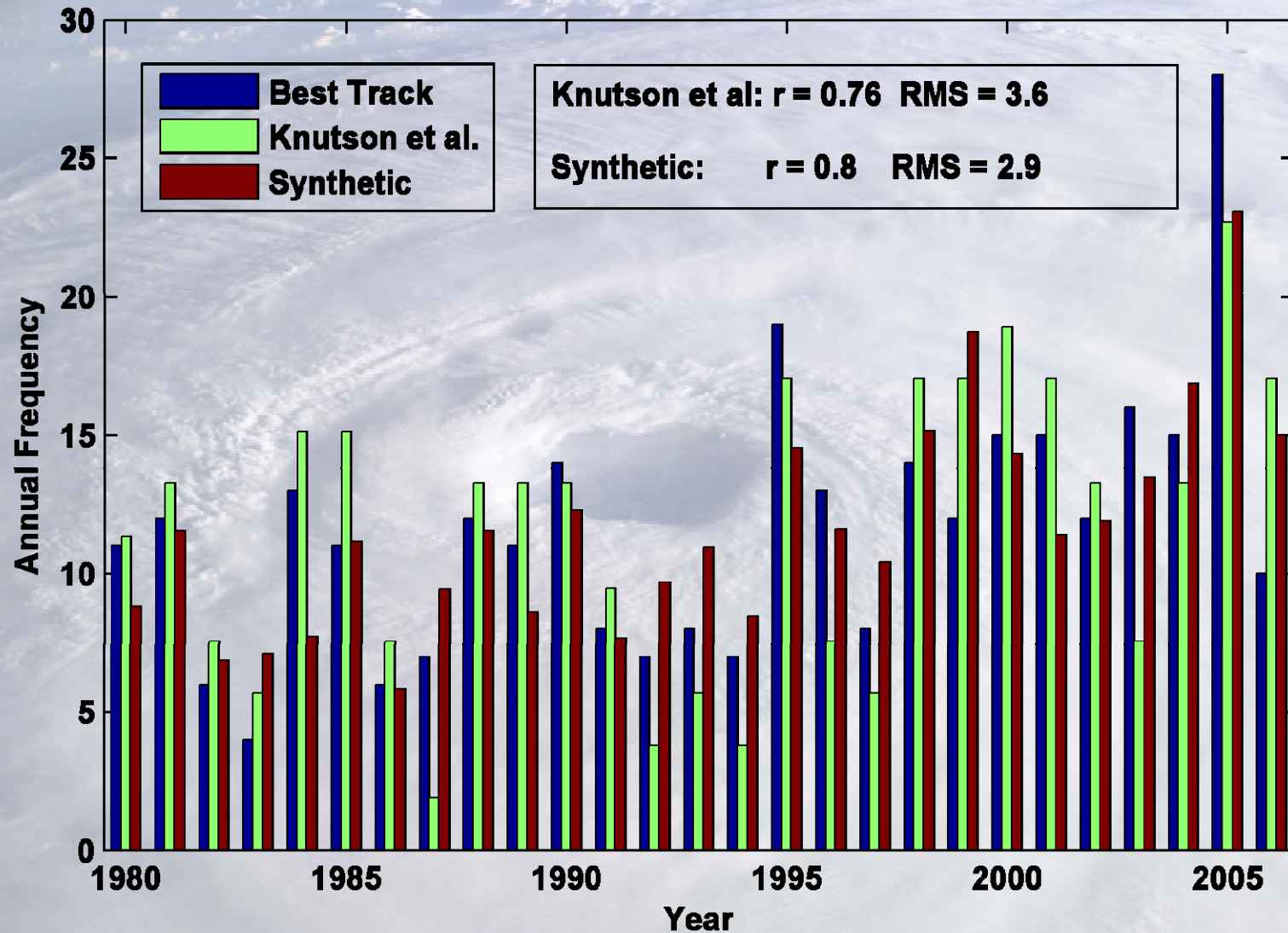
New Downscaling Technique: 200 Synthetic U.S. Landfalling tracks (color coded by S-S Scale)



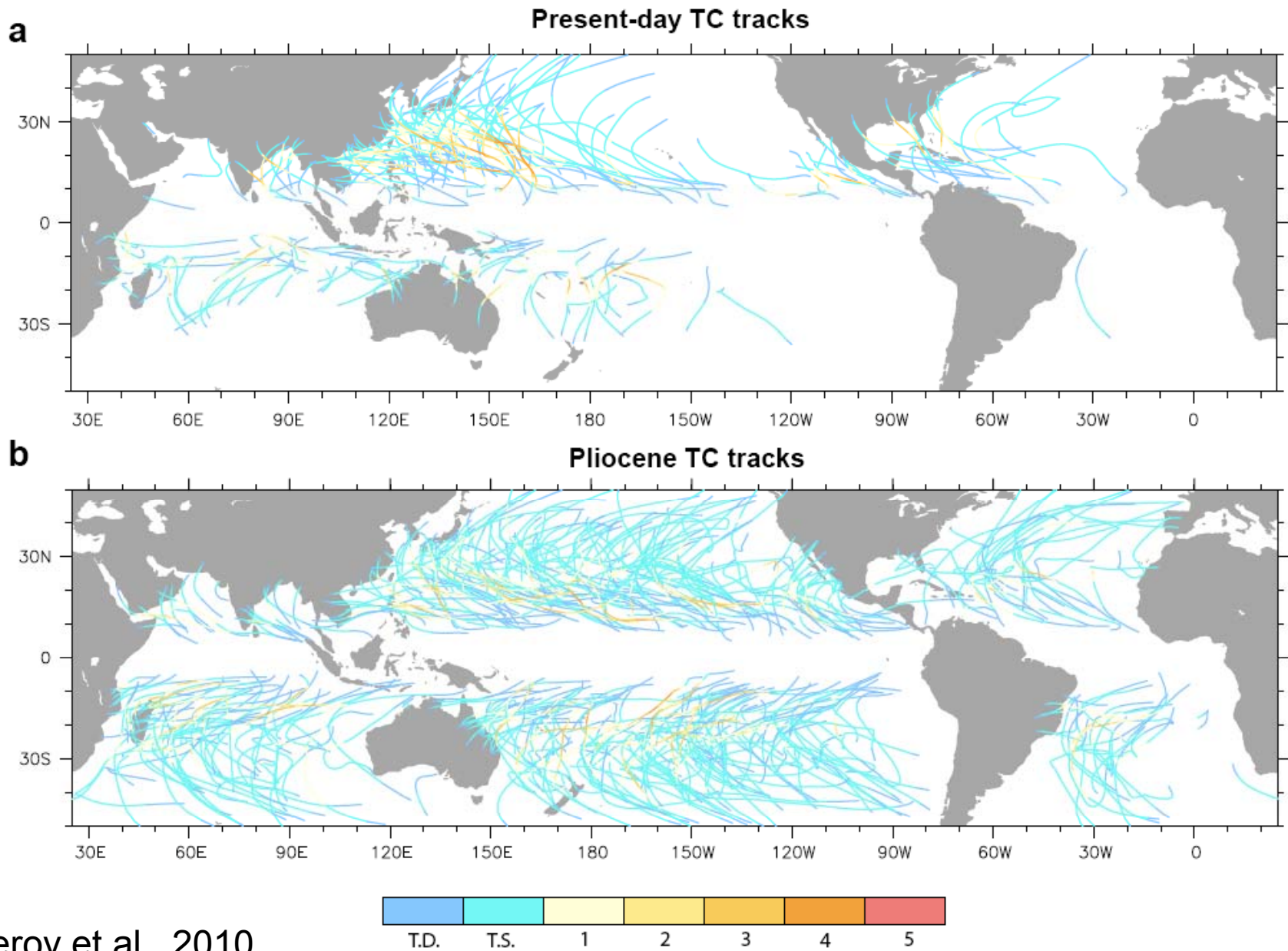
Cumulative Distribution of Storm Lifetime Peak Wind Speed, with Sample of 2946 Synthetic Tracks



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

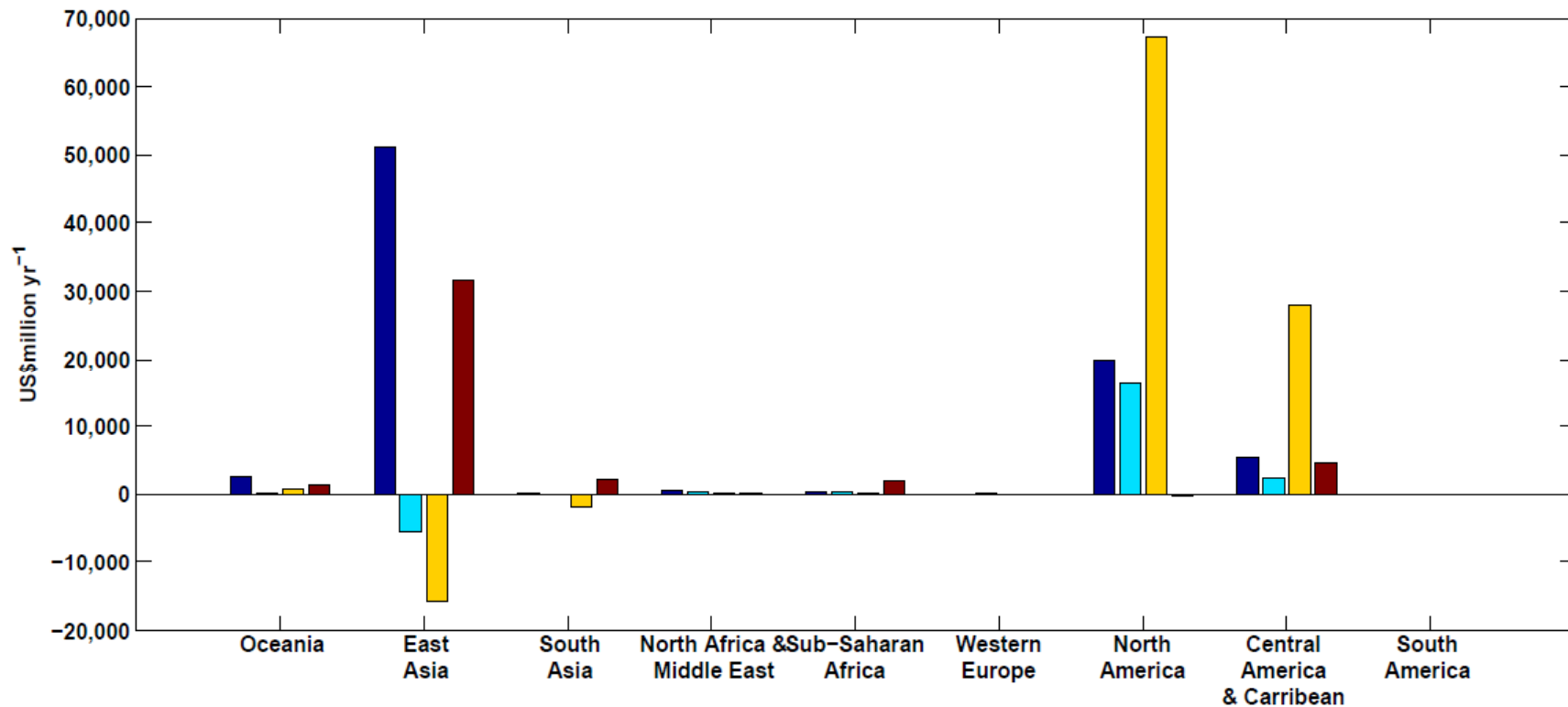


Application to Other Climates



Federov et al., 2010

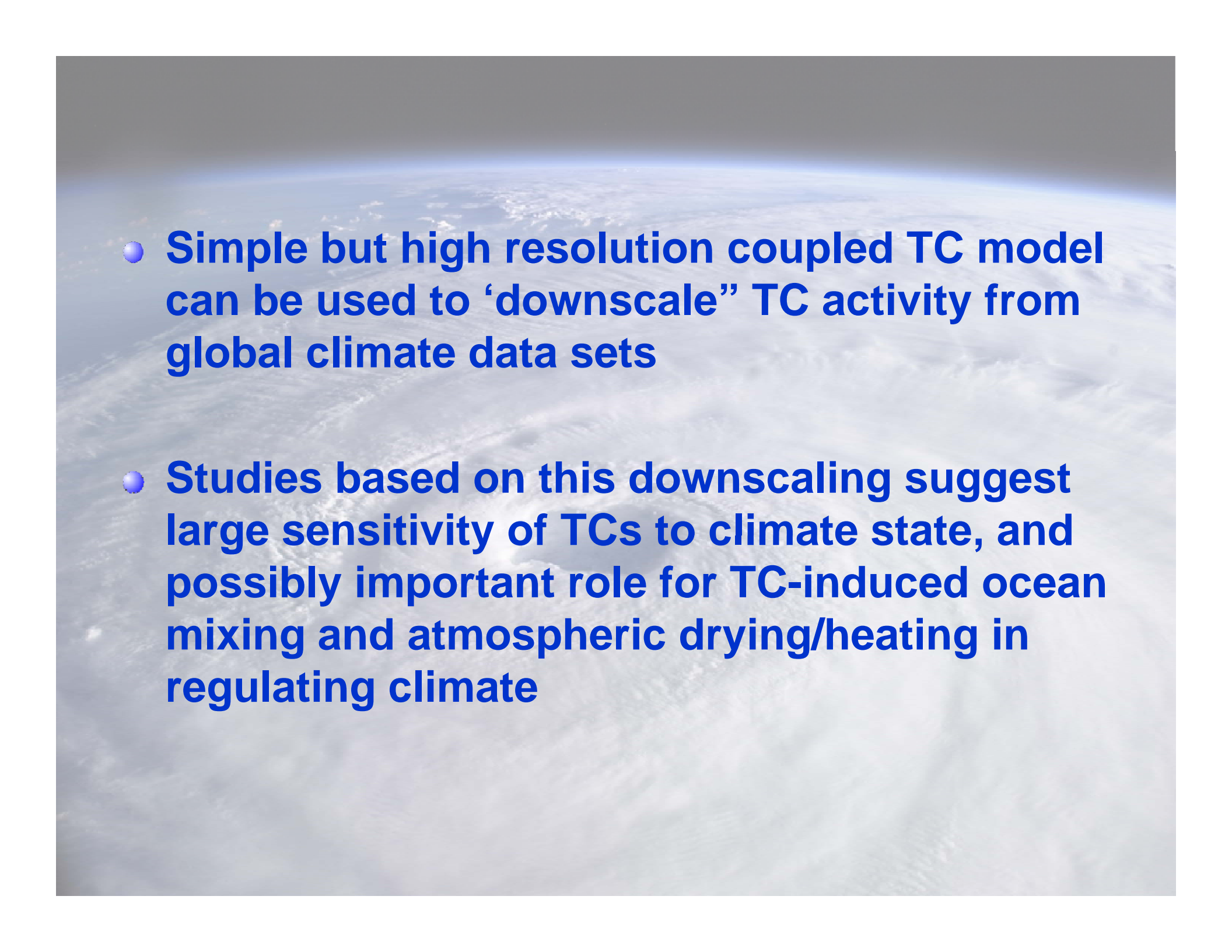
Mendelsohn et al., 2012



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**

- 
- An aerial photograph of Earth's surface, showing a vast expanse of white clouds over a blue ocean. The perspective is from a high altitude, looking down at the planet's surface. The clouds are dense and cover most of the visible area, with some darker patches of water visible between them. The horizon is visible at the top of the image, showing a thin blue line of the atmosphere against a lighter sky.
- **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**