

A satellite image of a hurricane, showing a distinct eye and spiral cloud bands over a vast expanse of the ocean. The text is overlaid on the center of the image.

Hurricanes and Climate

Kerry Emanuel

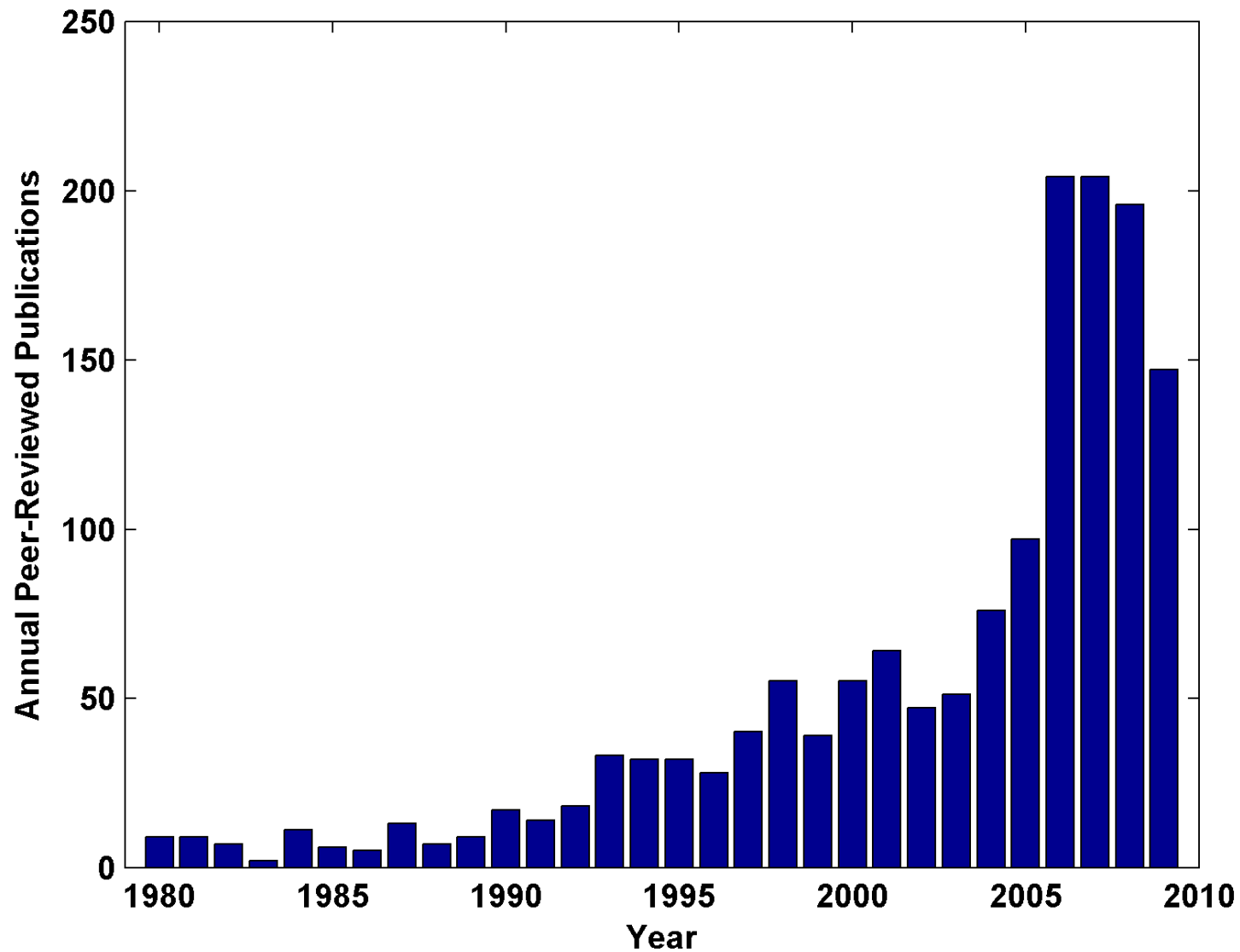
Program in Atmospheres, Oceans, and
Climate

MIT

Program

A satellite view of Earth's atmosphere and clouds, showing a large-scale weather system with a distinct eye and spiral structure, likely a tropical cyclone or hurricane. The image is used as a background for the slide.

- **Potential Intensity**
- **Role of potential intensity in storm intensity**
- **Role of potential intensity in storm frequency**
- **Records of tropical cyclone activity**
- **Outflow temperature**



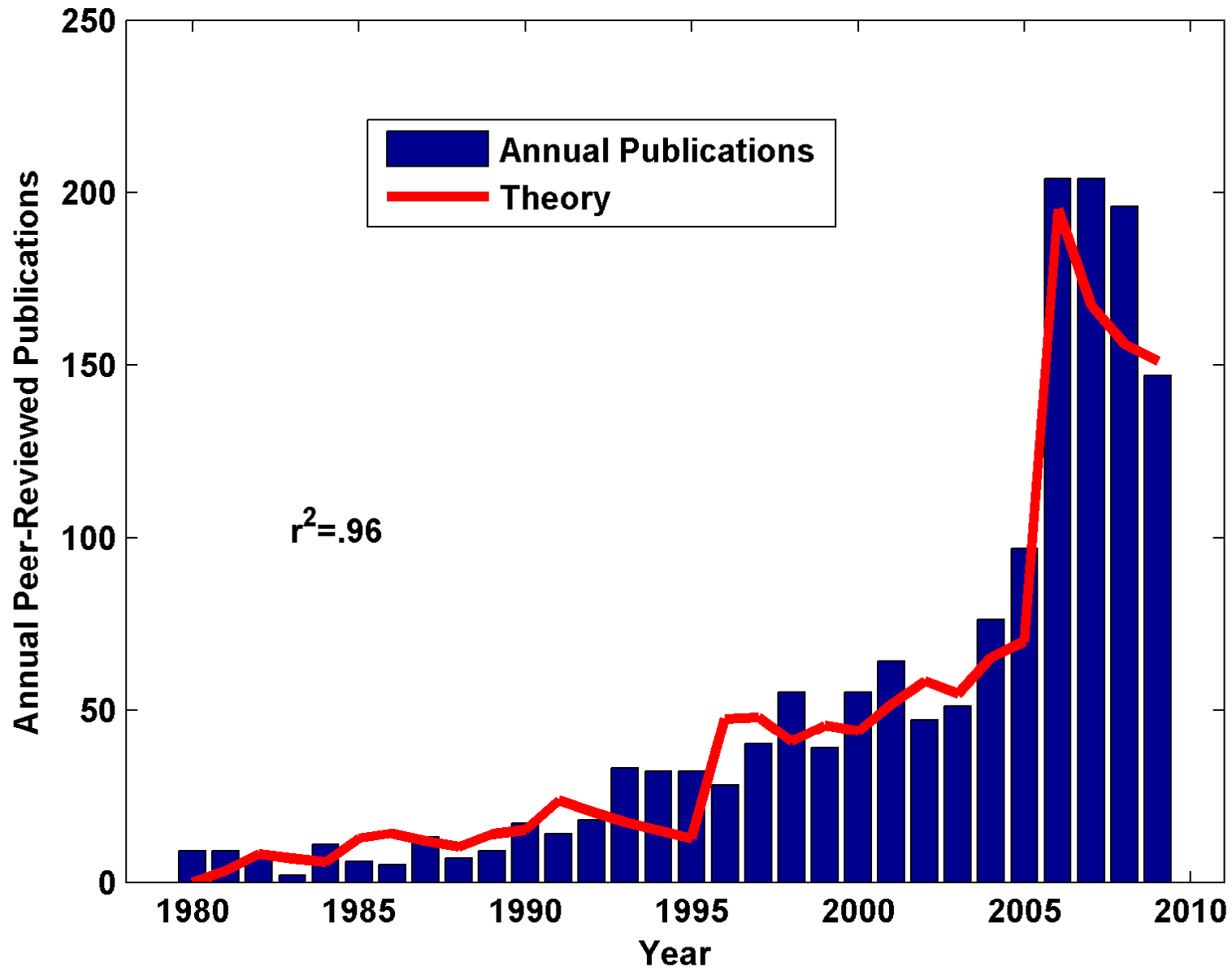
Annual Number of Peer-Reviewed Articles with "Hurricane" or "Tropical Cyclone" in their Titles, according to *Meteorological and Geostrophysical Abstracts*

Theory:

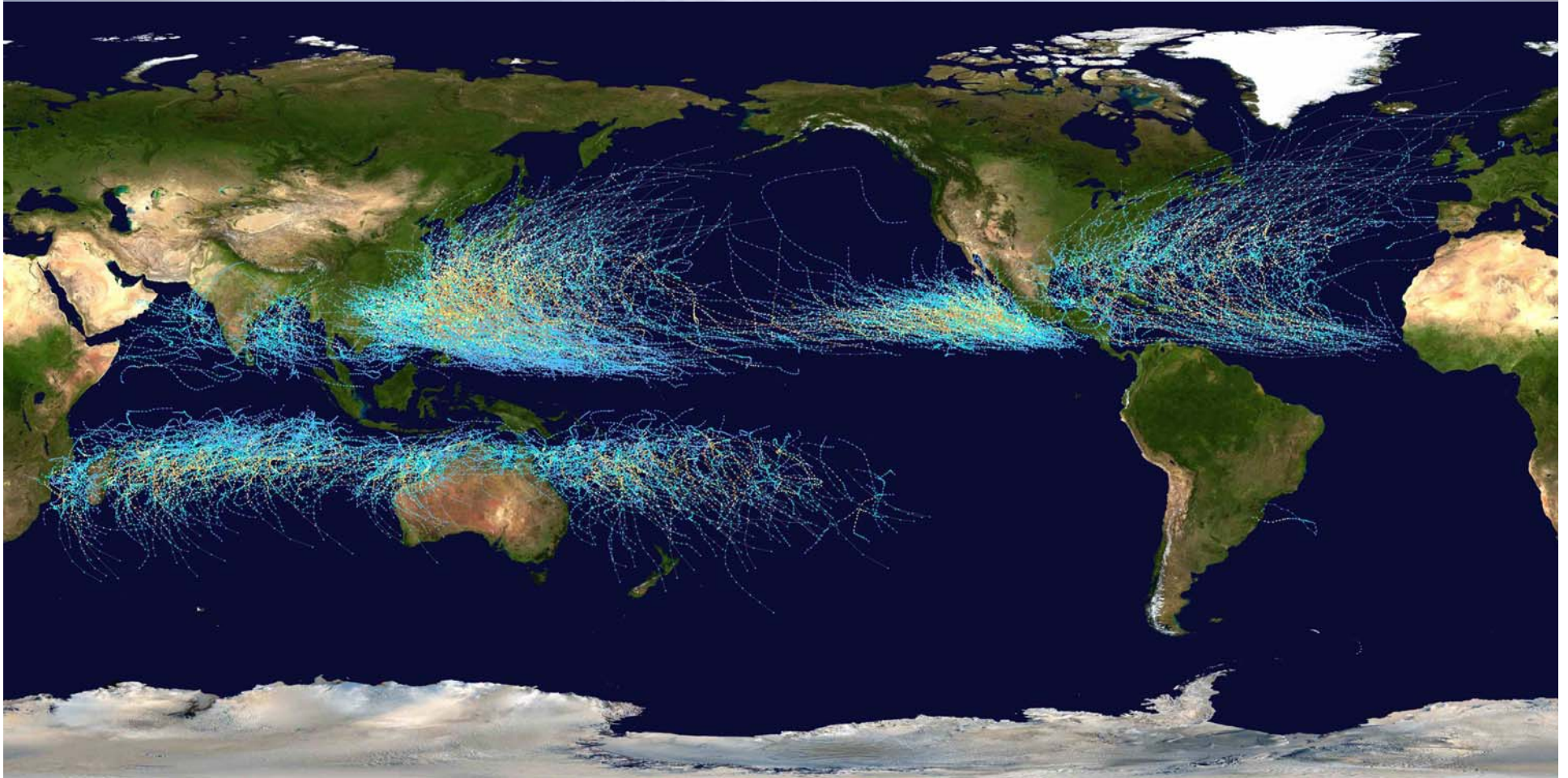
$$\frac{\partial PRP}{\partial t} = \overset{\text{Interest Stimulation}}{\downarrow} 0.08 \left(N_{Atl} - 6 \right)^{5/2} - \underset{\uparrow \text{Scientist Attention Span}}{\frac{PRP}{6 \text{ years}}}$$

PRP = Annual peer reviewed publications

N_{Atl} = Number of Atlantic TCs per year

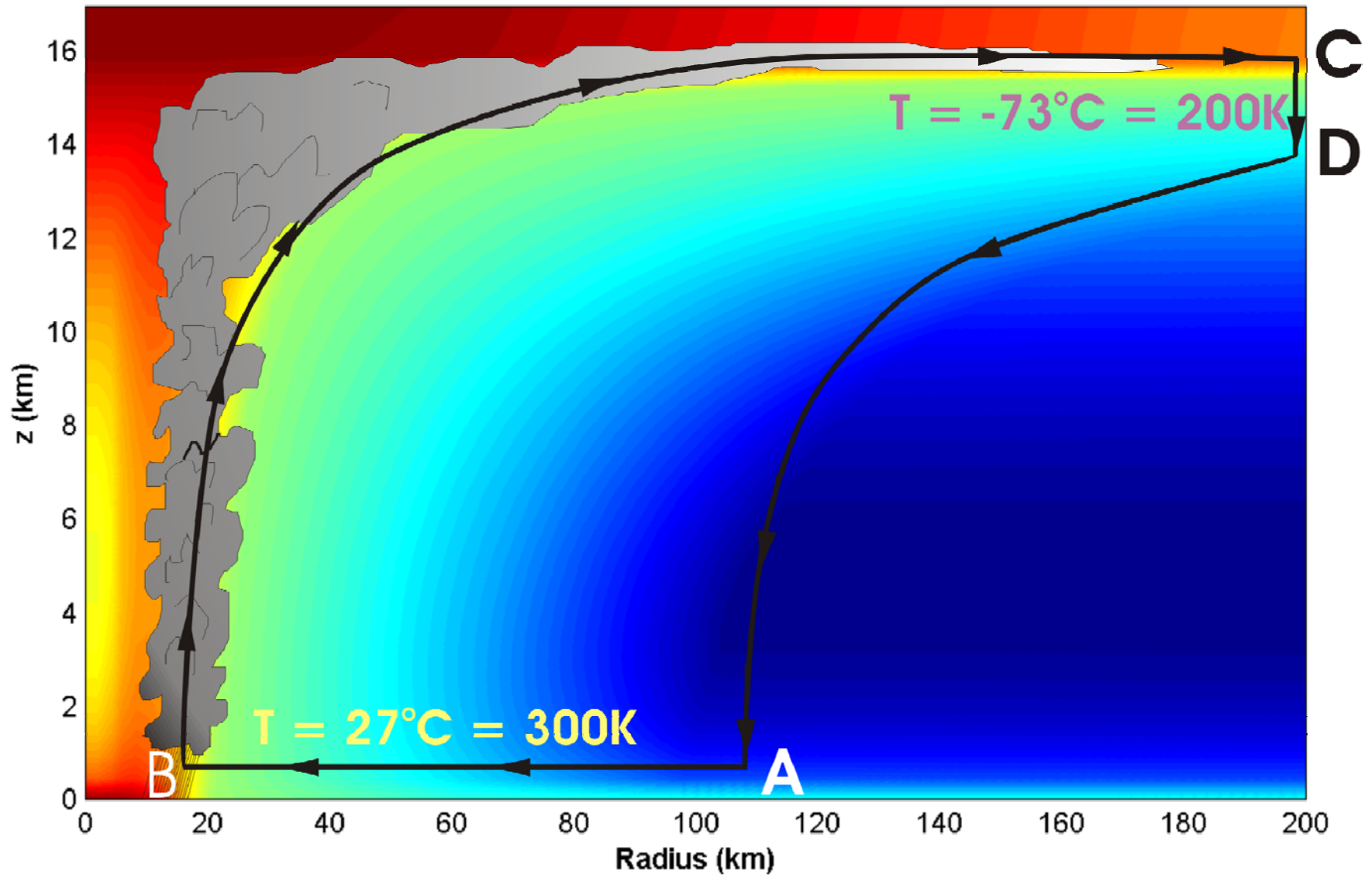


Tracks of all tropical cyclones, 1985-2005




Source: Wikipedia

Energy Production



Total rate of heat input to hurricane:

$$\dot{Q} = 2\pi \int_0^{r_0} \rho \left[C_k |\mathbf{V}| (k_0^* - k) + C_D |\mathbf{V}|^3 \right] r dr$$



Surface enthalpy flux **Dissipative heating**

In steady state, energy production is used to balance frictional dissipation:

$$D = 2\pi \int_0^{r_0} \rho \left[C_D |\mathbf{V}|^3 \right] r dr$$

Plug into Carnot equation:

$$\int_0^{r_0} \rho \left[C_D |\mathbf{V}|^3 \right] r dr = \frac{T_s - T_o}{T_o} \int_0^{r_0} \rho \left[C_k |\mathbf{V}| (k_0^* - k) \right] r dr$$

If integrals dominated by values of integrands near radius of maximum winds,

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

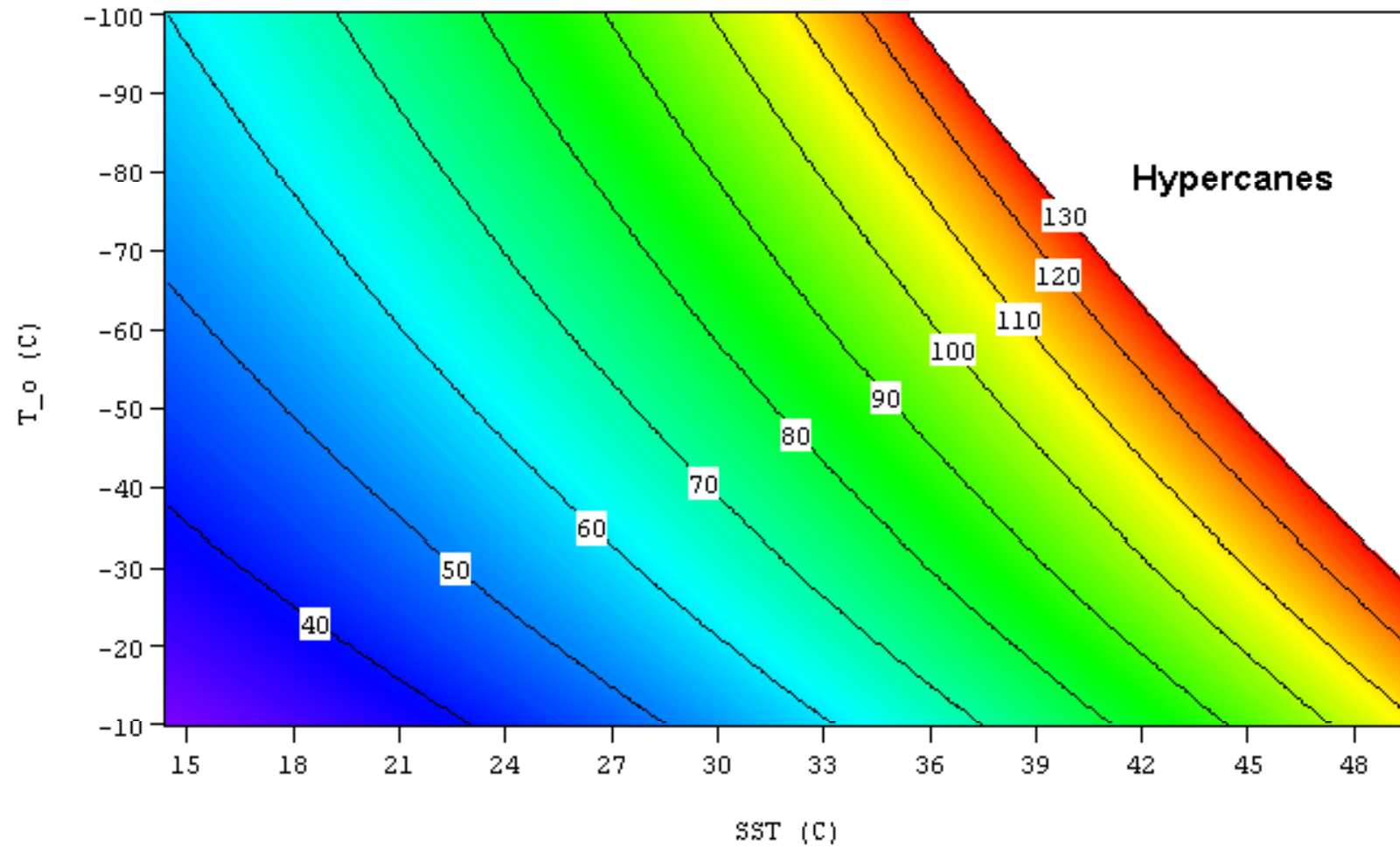
Note: This equation can be derived exactly from the governing equations

Theoretical Upper Bound on Hurricane Maximum Wind Speed:

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

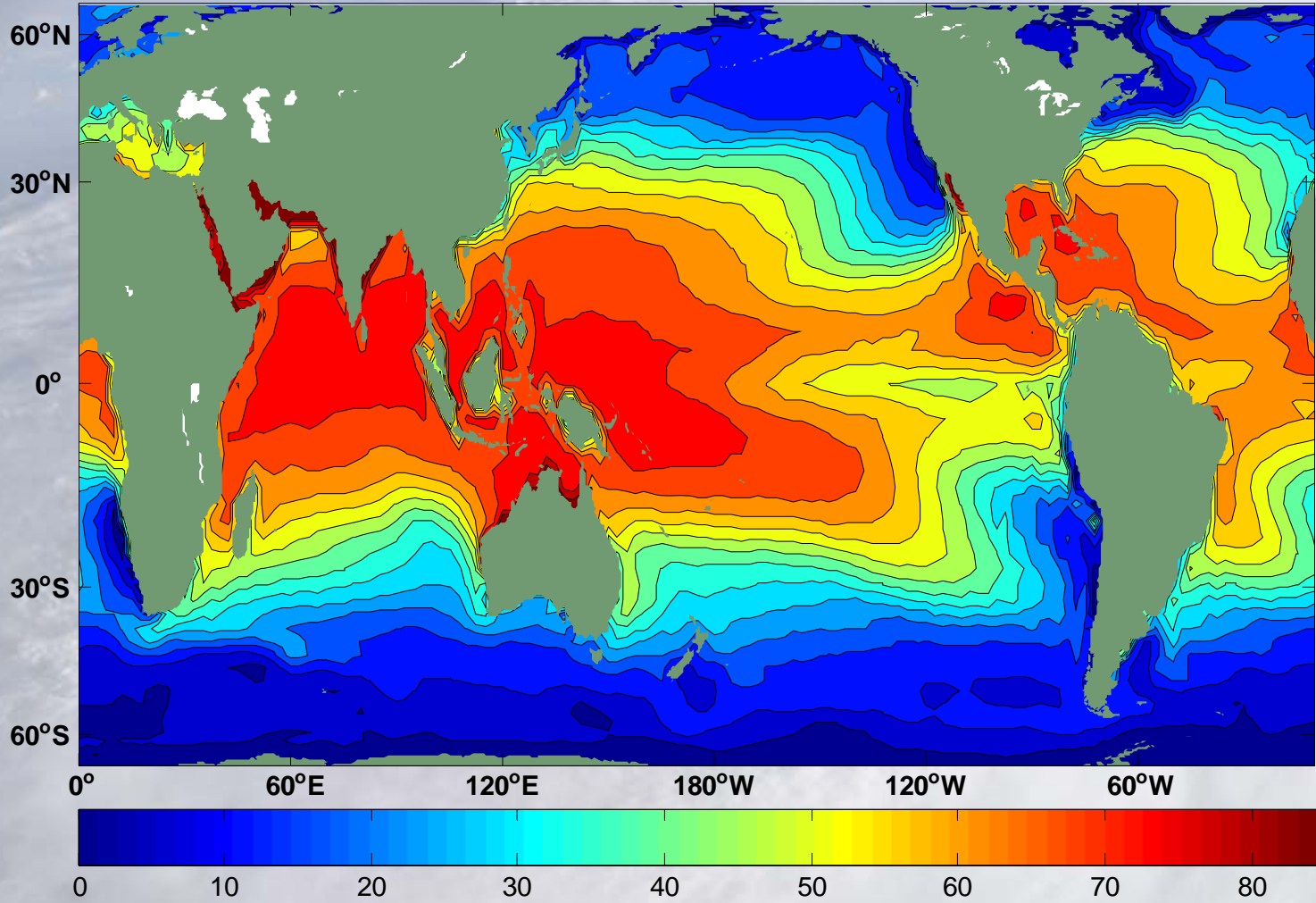
Surface temperature
 Ratio of exchange coefficients of enthalpy and momentum
 Outflow temperature
 Air-sea enthalpy disequilibrium

Maximum Wind Speed (m/s)



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

Annual Maximum Potential Intensity (m/s)



Condition of convective neutrality:

$$s_b = s^* \text{ of free troposphere}$$

Also, s^* of free troposphere is approximately spatially uniform (WTG approximation)

$$|V_{pot}|^2 \cong \frac{C_k}{C_D} \frac{T_s - T_o}{T_o} T_s \left(s_0^* - s^* \right)$$

approximately constant

What matters, apparently, is the SST (s_0^*) relative to the tropospheric temperature (s^*)

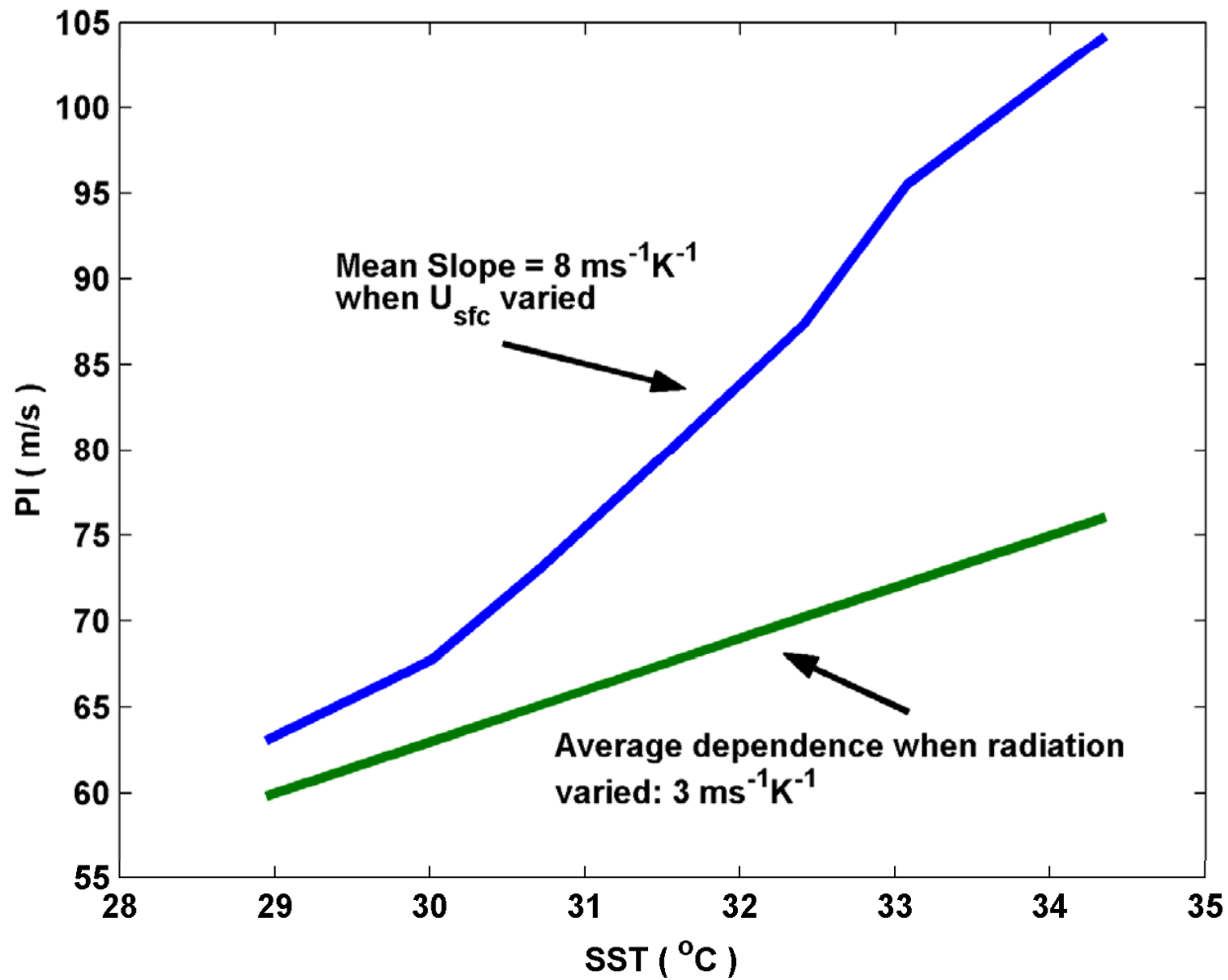
Combine expression for potential intensity, V_{max} , with energy balance of ocean mixed layer:

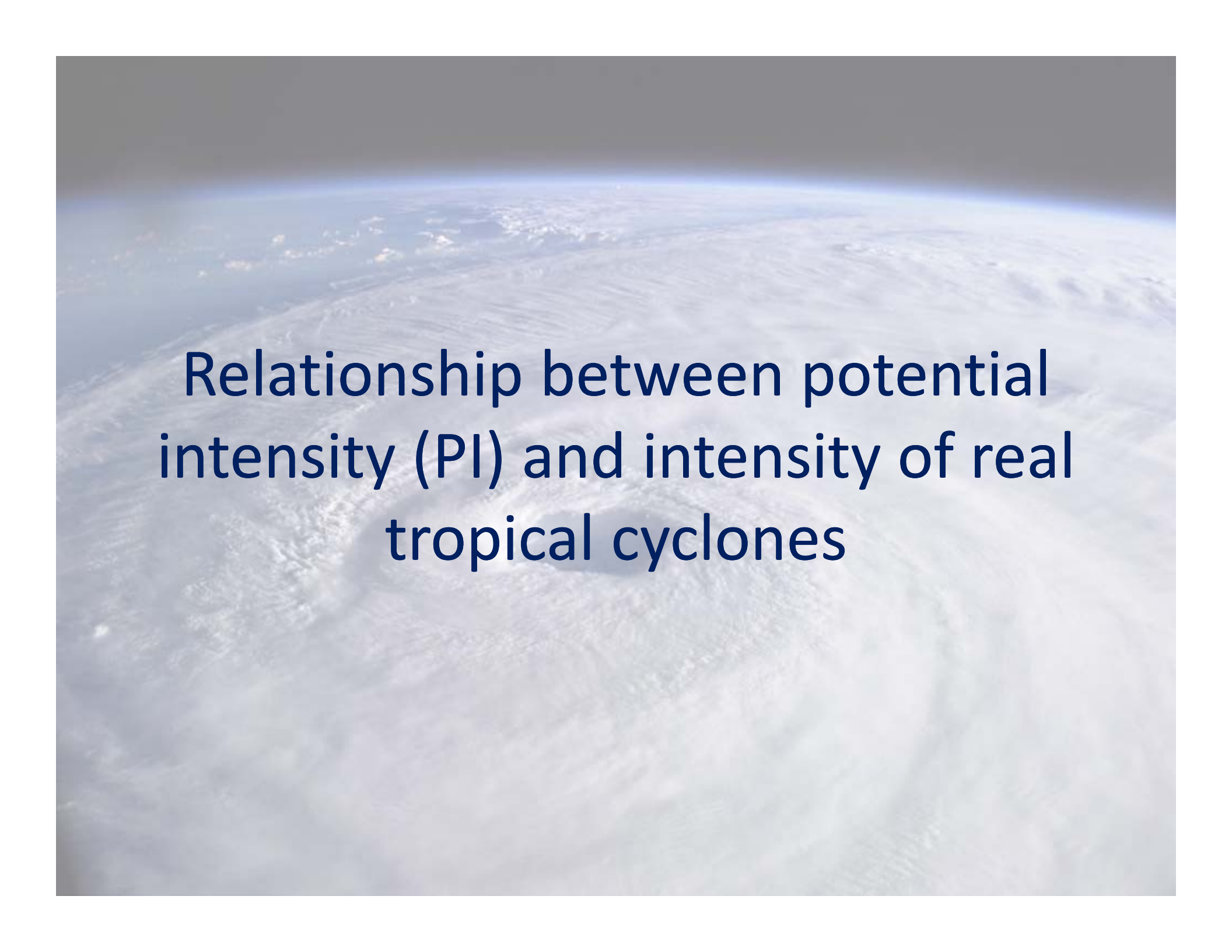
$$V_{max}^2 = \frac{\frac{T_s - T_o}{T_o} \frac{F_{rad} - d \nabla \cdot \mathbf{F}_{ocean}}{C_D \rho |V_s|}}$$

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

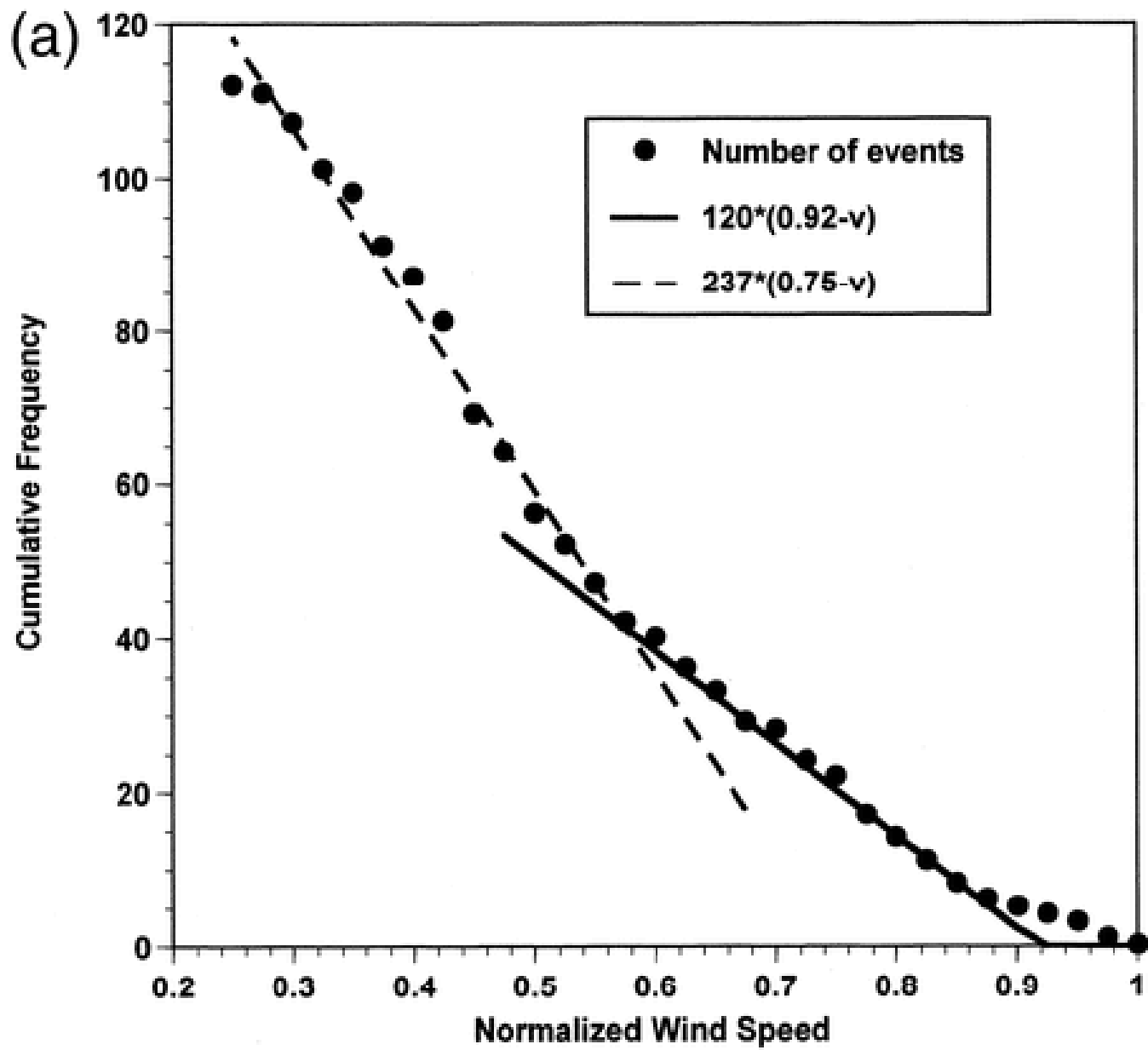
Valid on time scales > thermal equilibration time of ocean mixed layer (~ 2 years)

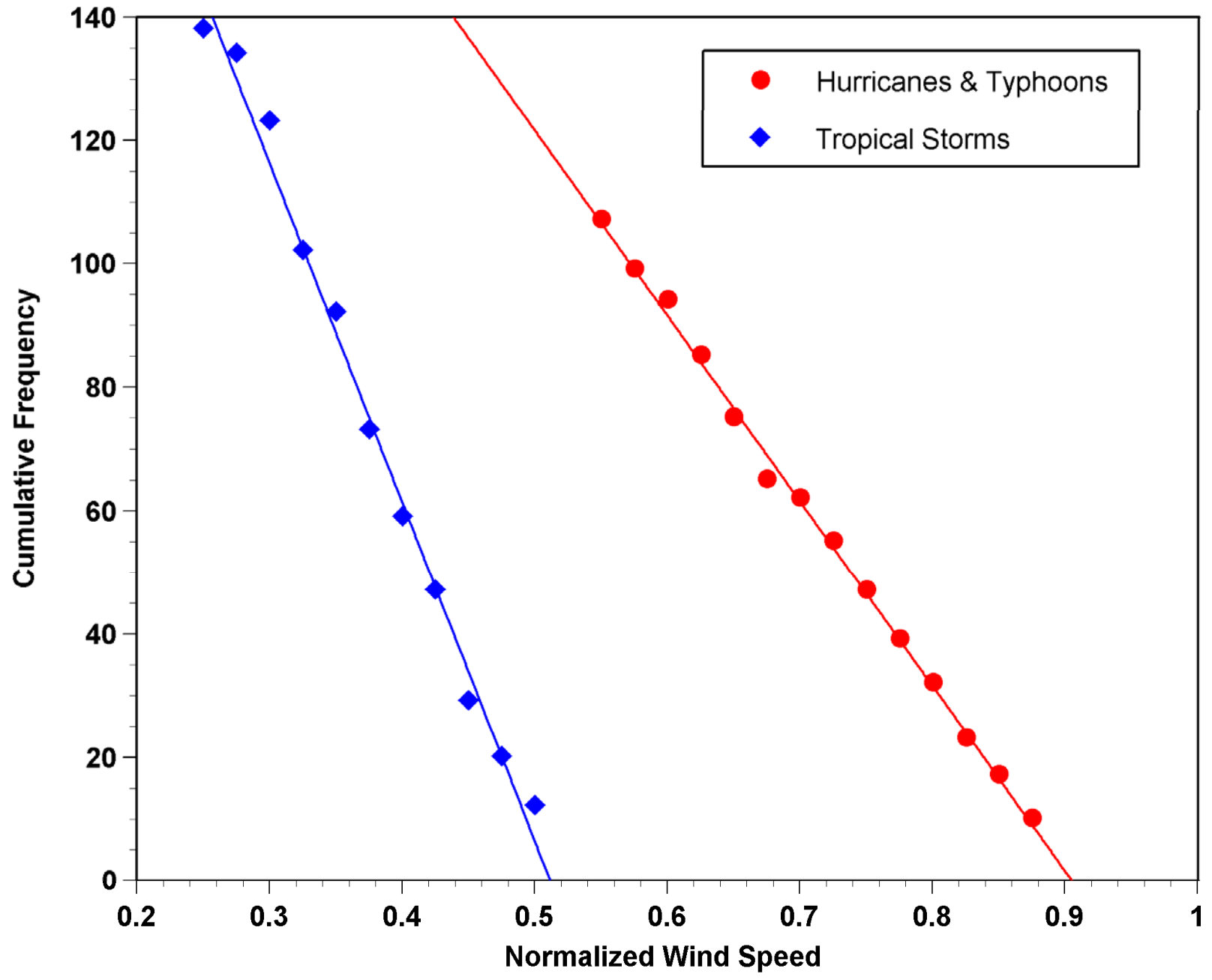
Dependence on Sea Surface Temperature (SST):



A satellite image of Earth's atmosphere, showing a large-scale view of cloud patterns and a tropical cyclone. The image is centered on a tropical cyclone, which appears as a large, swirling cloud mass with a distinct eye and spiral structure. The surrounding atmosphere is filled with various cloud formations, including large-scale wave patterns and smaller-scale convective clouds. The Earth's surface is visible at the bottom of the frame, showing the curvature of the planet and the blue color of the oceans. The text is overlaid on the image in a dark blue, sans-serif font.

**Relationship between potential
intensity (PI) and intensity of real
tropical cyclones**





Empirical Evidence for the Importance of Potential Intensity to TC Genesis: A Genesis Potential Index (GPI)

Base choice of predictors on physics, intuition, past experience

- 850 hPa absolute vorticity (η)
- 850 – 250 hPa shear (S)
- Potential intensity (PI)
- Non-dimensional subsaturation of the middle troposphere:

$$\chi \equiv \frac{S^* - S_{600}}{S_0^* - S^*}$$

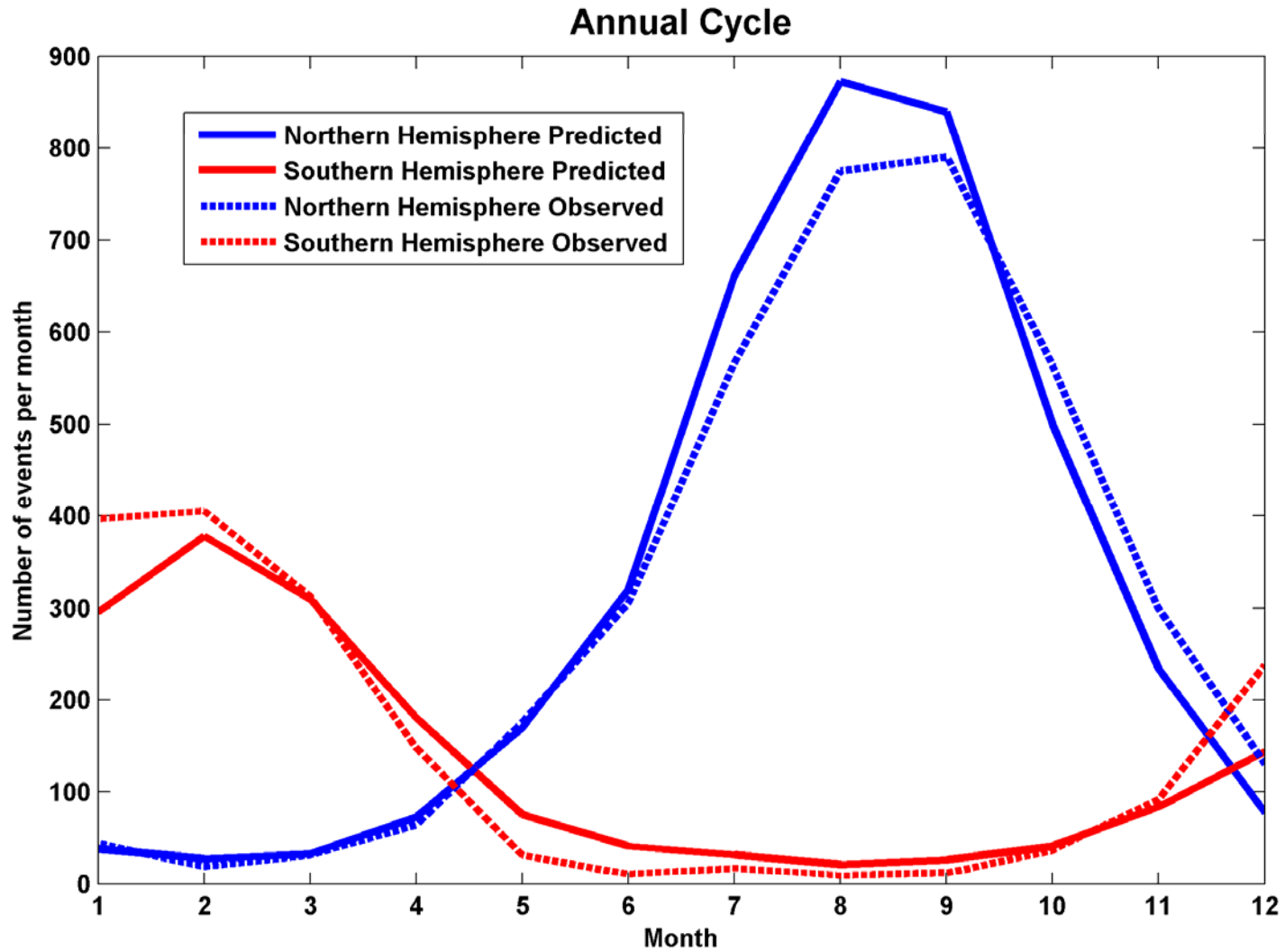
New Genesis Potential Index:

$$GPI \equiv \frac{|\eta|^3 \left(PI - 35 \text{ms}^{-1} \right)^2}{\chi \left(20 \text{ms}^{-1} + S \right)^4}$$

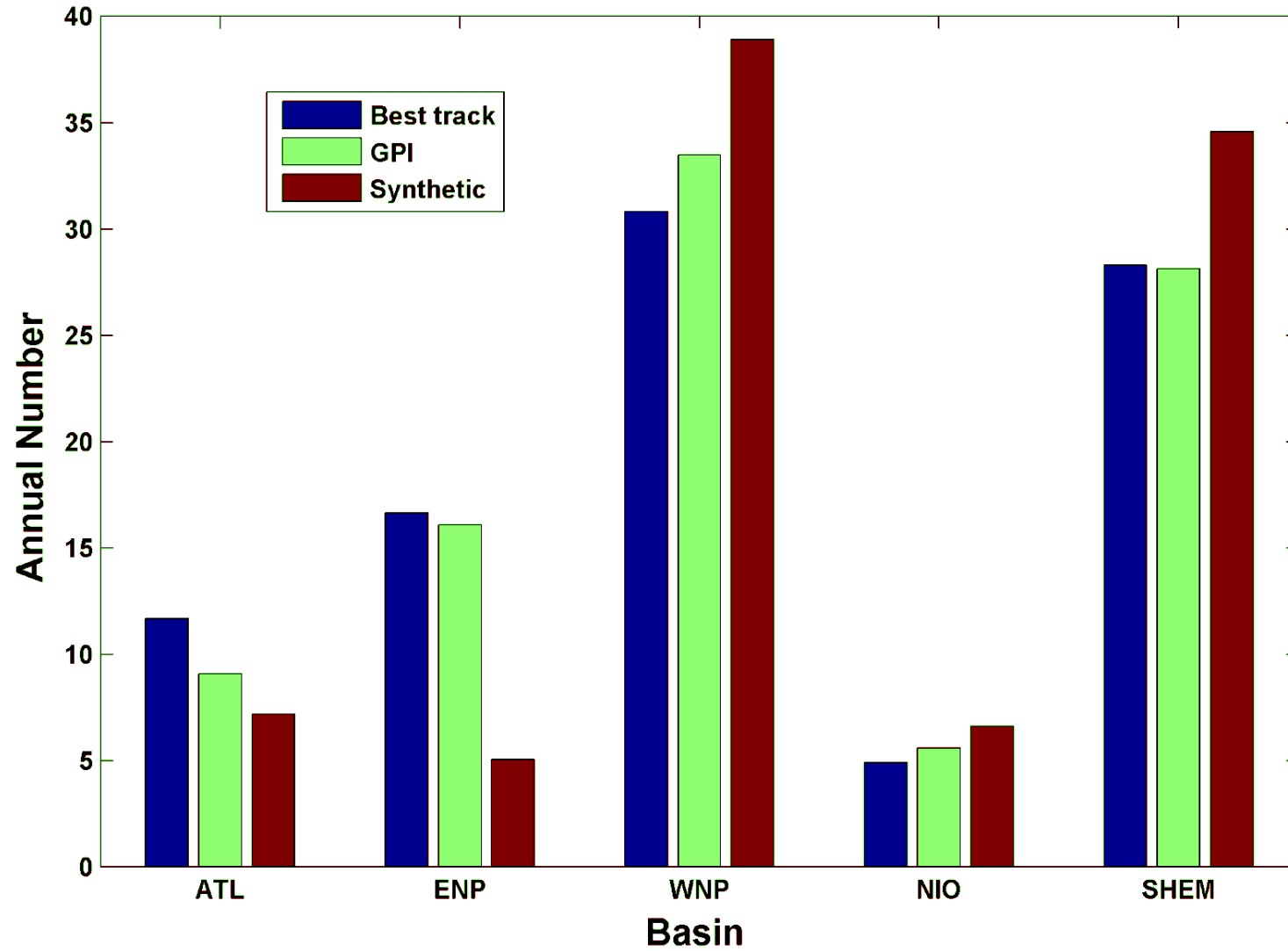
- 850 hPa absolute vorticity (η)
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Performance



Basin Frequencies



TC Activity Metric:

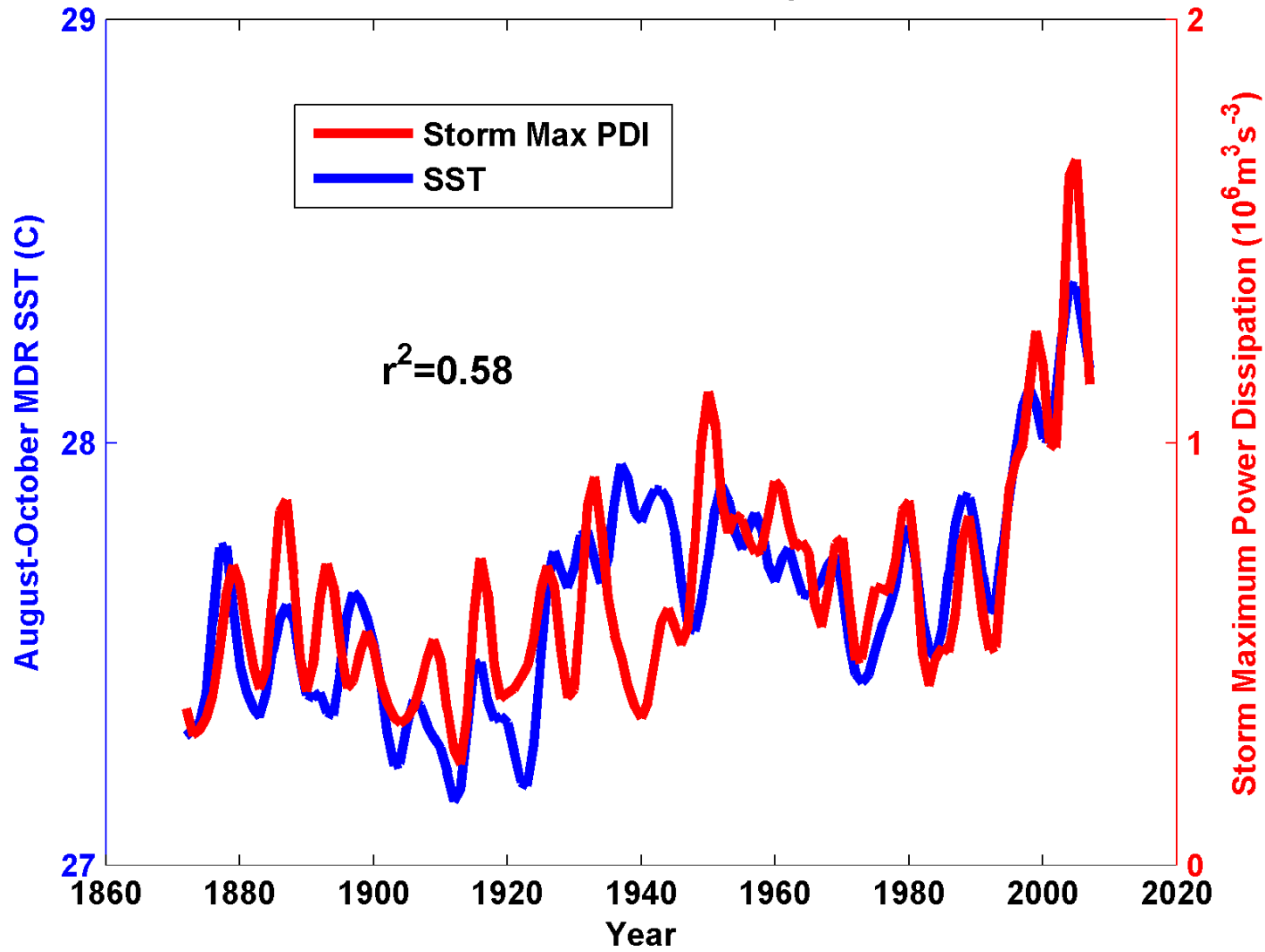
Hurricane Power (Power Dissipation Index)

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

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

High Correlation between North Atlantic TC Power Dissipation and MDR SST Continues

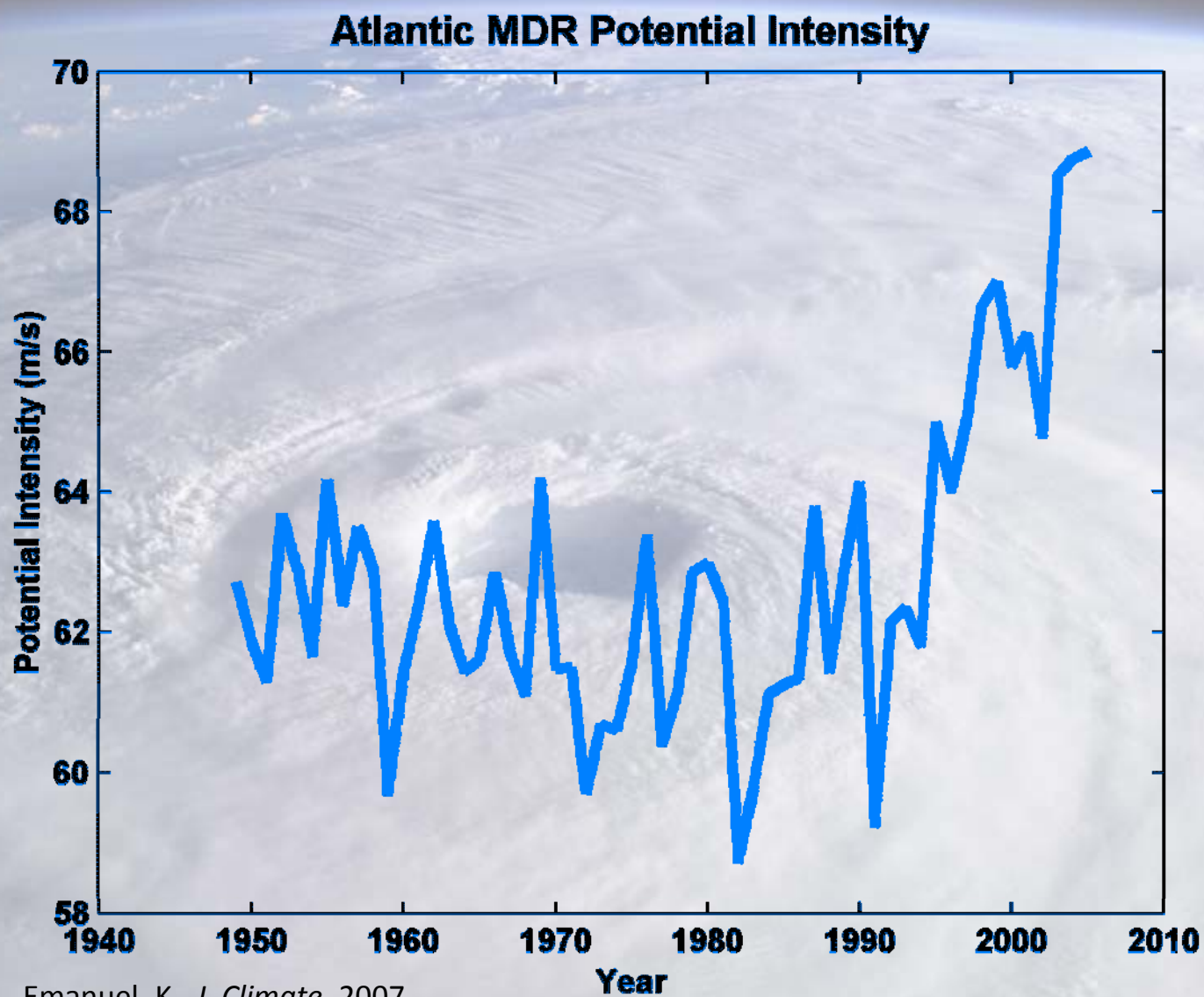
North Atlantic Storm Maximum Power Dissipation vs. SST, 1949-2009



An aerial photograph of a tropical cyclone, showing a well-defined eye and spiral cloud bands over a vast expanse of the ocean. The text is overlaid on the center of the image.

Tropical cyclone power dissipation has nearly tripled since the 1980s, though there has been an increase of only 0.5° C in sea surface temperature

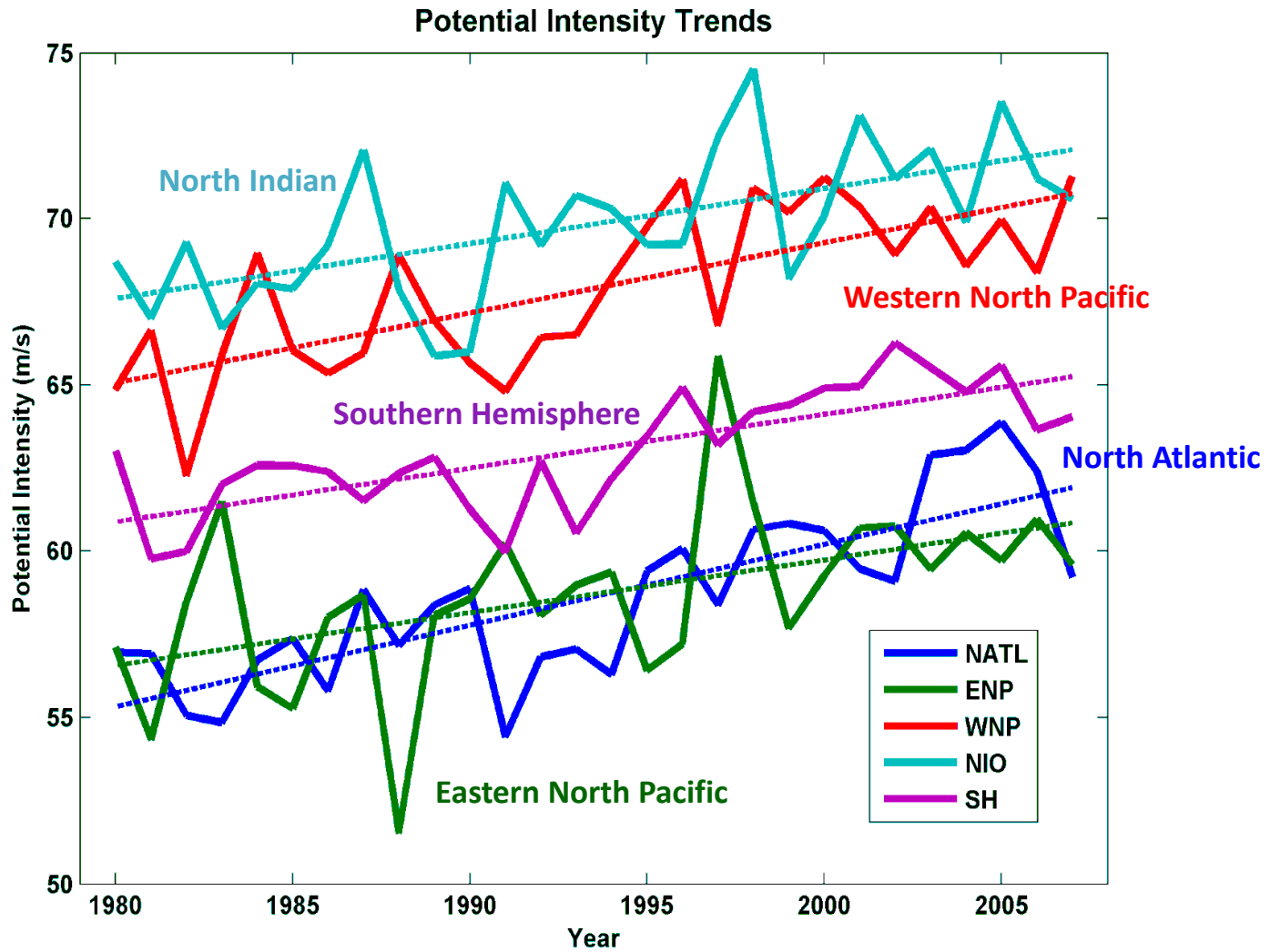
Observed Tropical Atlantic Potential Intensity



Emanuel, K., *J. Climate*, 2007

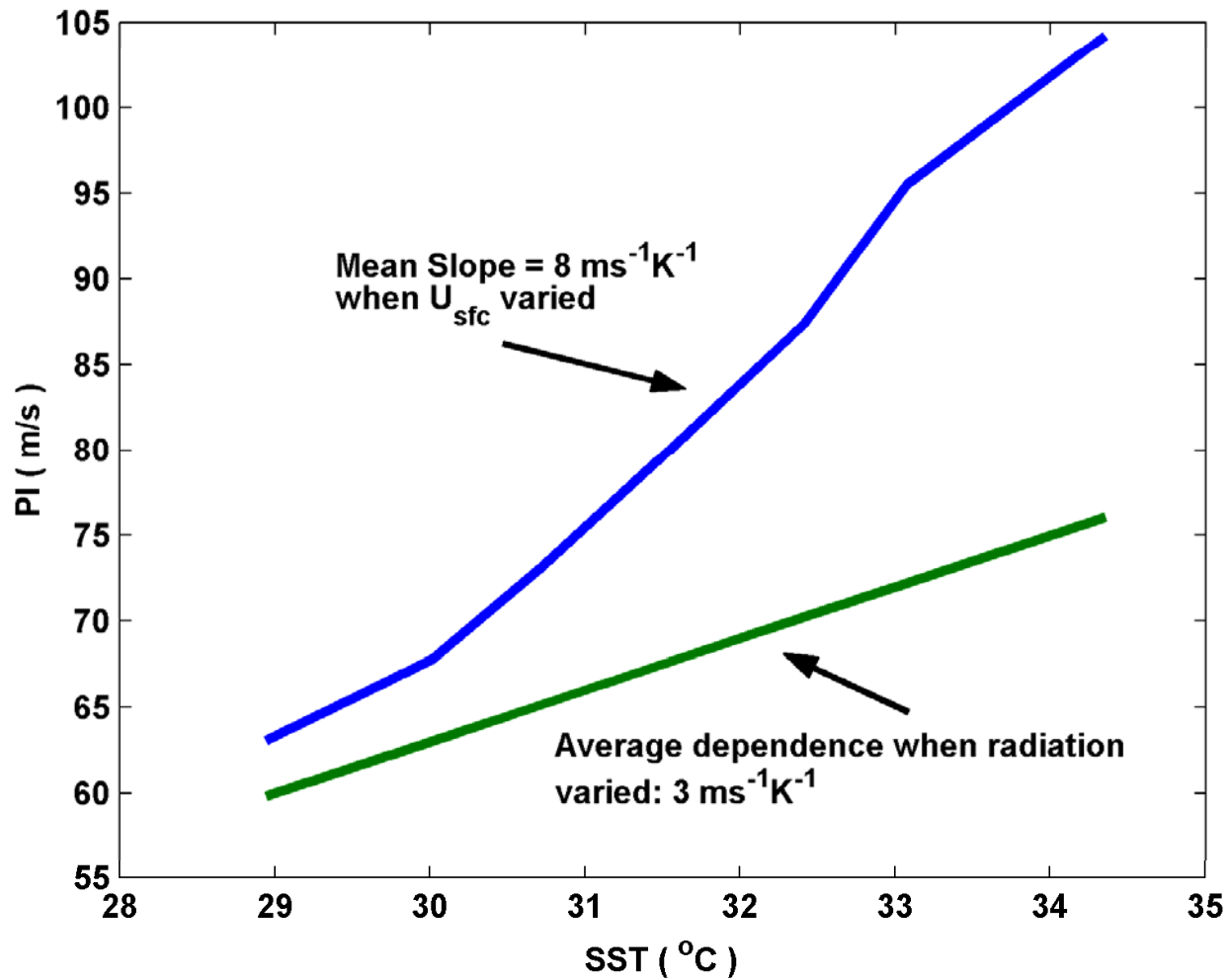
Data Sources: NCAR/NCEP re-analysis with pre-1979 bias correction, UKMO/HADSST1


Potential Intensity, 1980-2008



From NCAR/NCEP reanalysis data

Dependence on Sea Surface Temperature (SST):

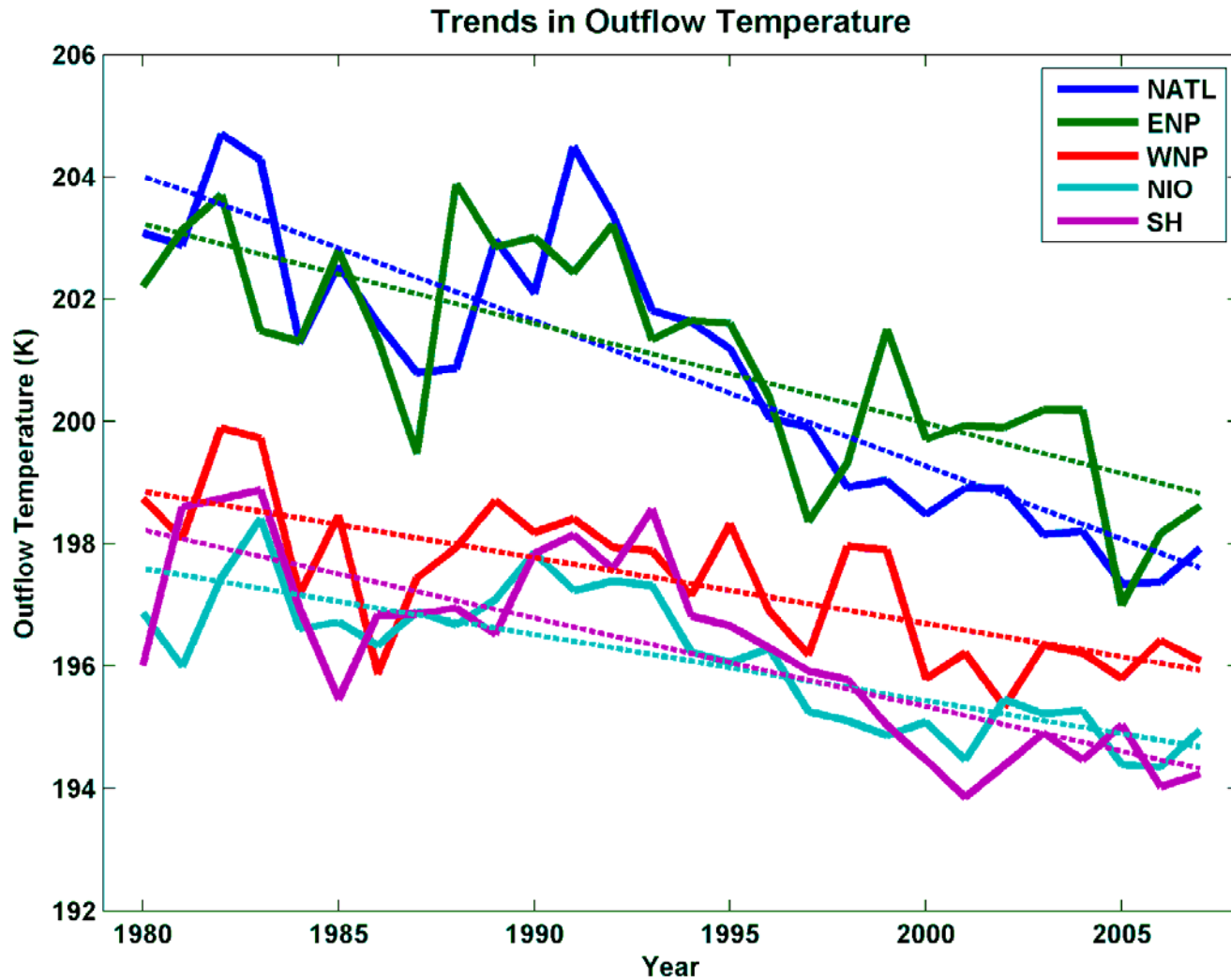


A satellite image of Earth's ocean surface, showing a large, dark, swirling cyclone or storm system in the center. The surrounding ocean is a light blue color, and the horizon is visible at the top of the image.

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

Stay Tuned for Next Talk!

Trends in outflow temperature



From NCAR/NCEP reanalysis data