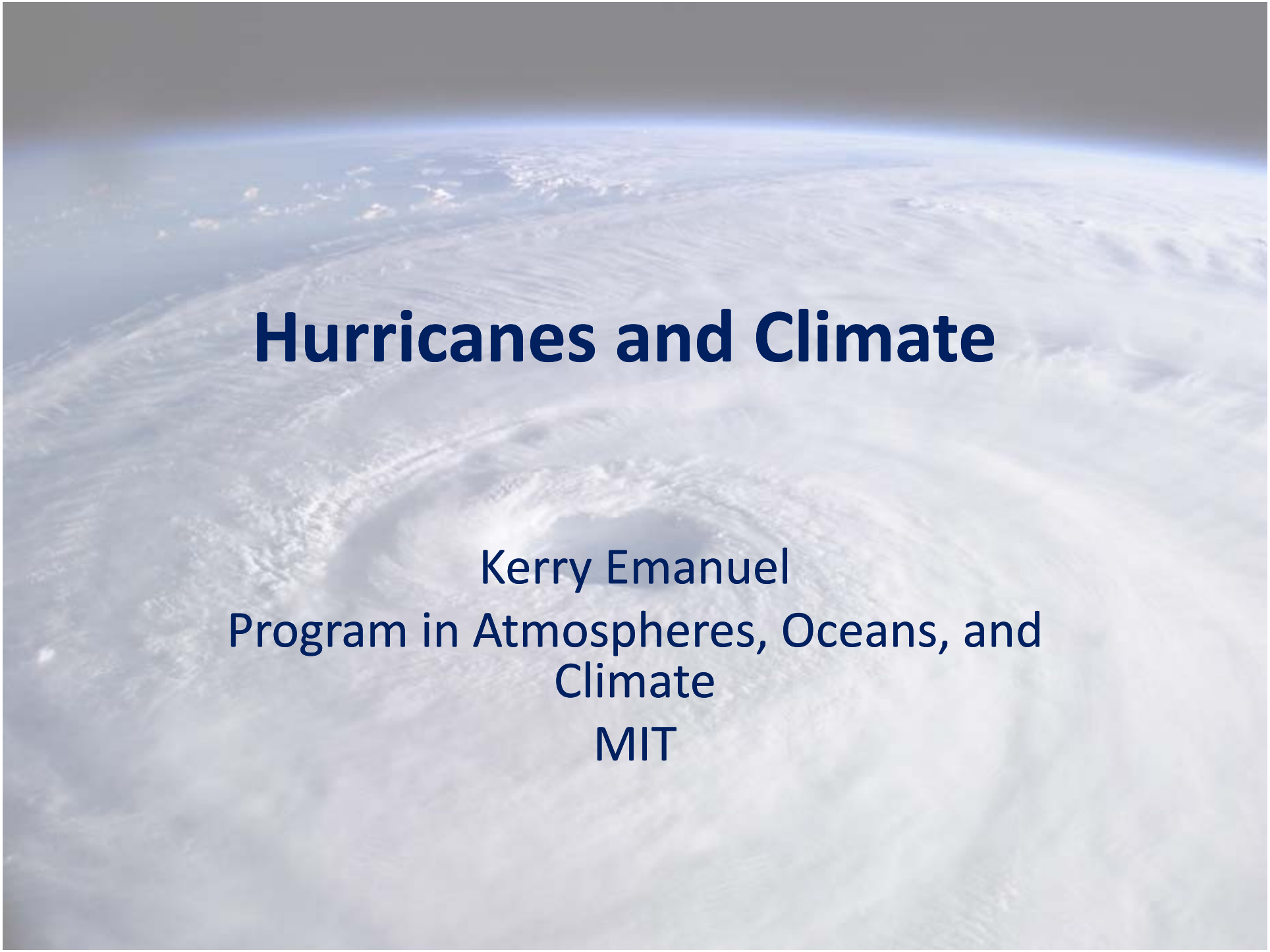
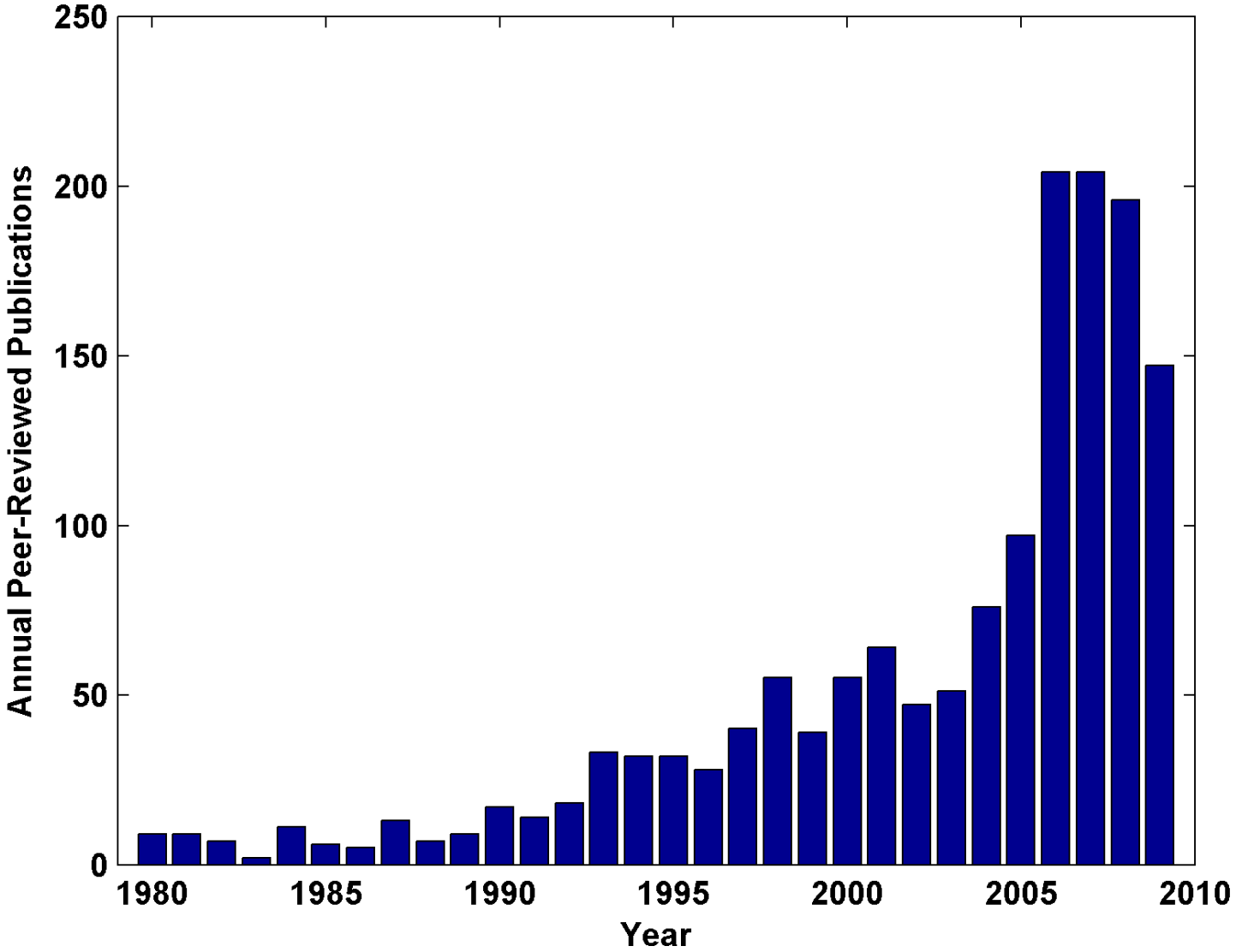


Hurricanes and Climate

Kerry Emanuel
Program in Atmospheres, Oceans, and Climate
MIT

Program

- **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 Geoastrophysical Abstracts*

Theory:

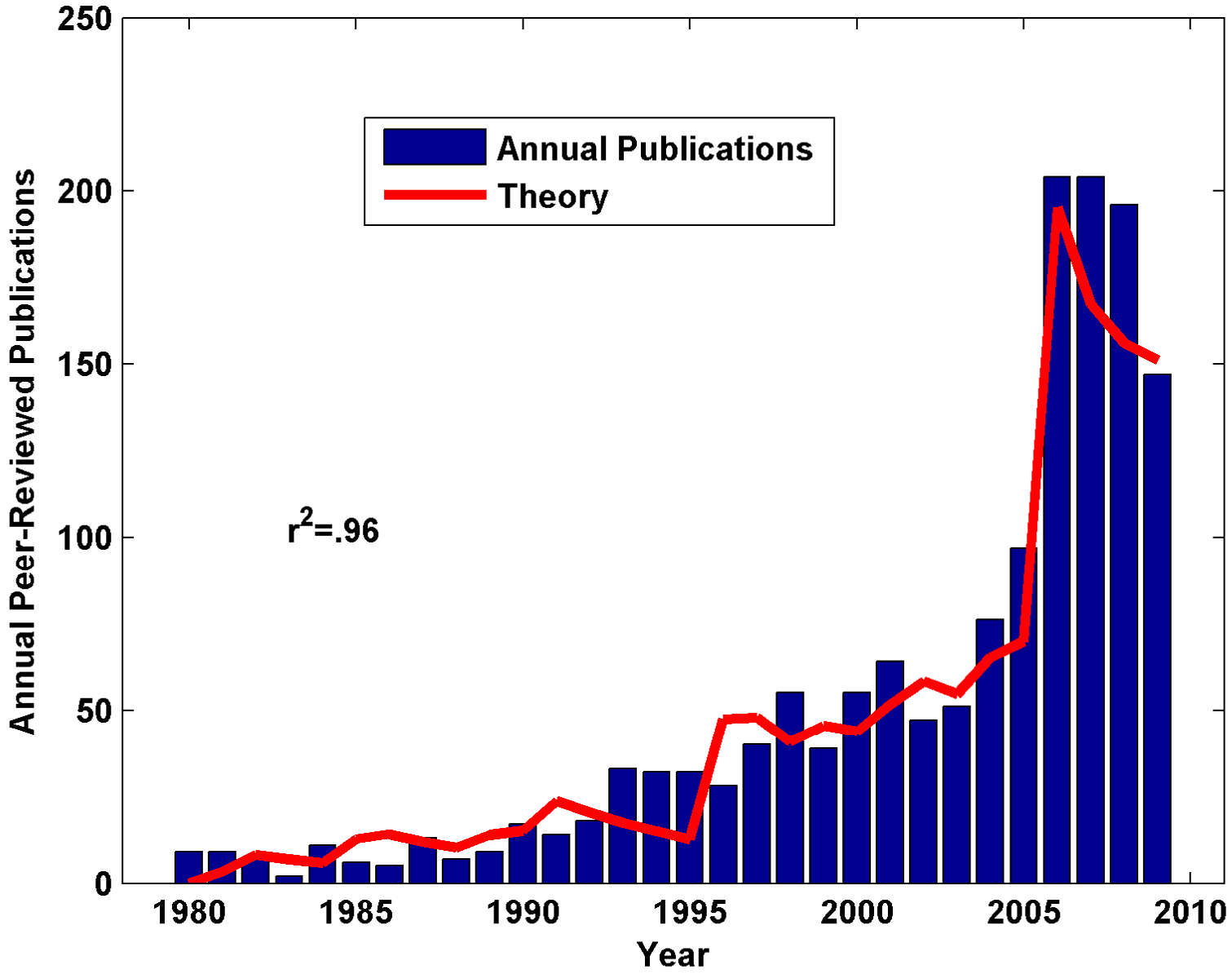
Interest Stimulation

$$\frac{\partial PRP}{\partial t} = 0.08\left(N_{Atl} - 6\right)^{5/2} - \frac{PRP}{6\ years}$$

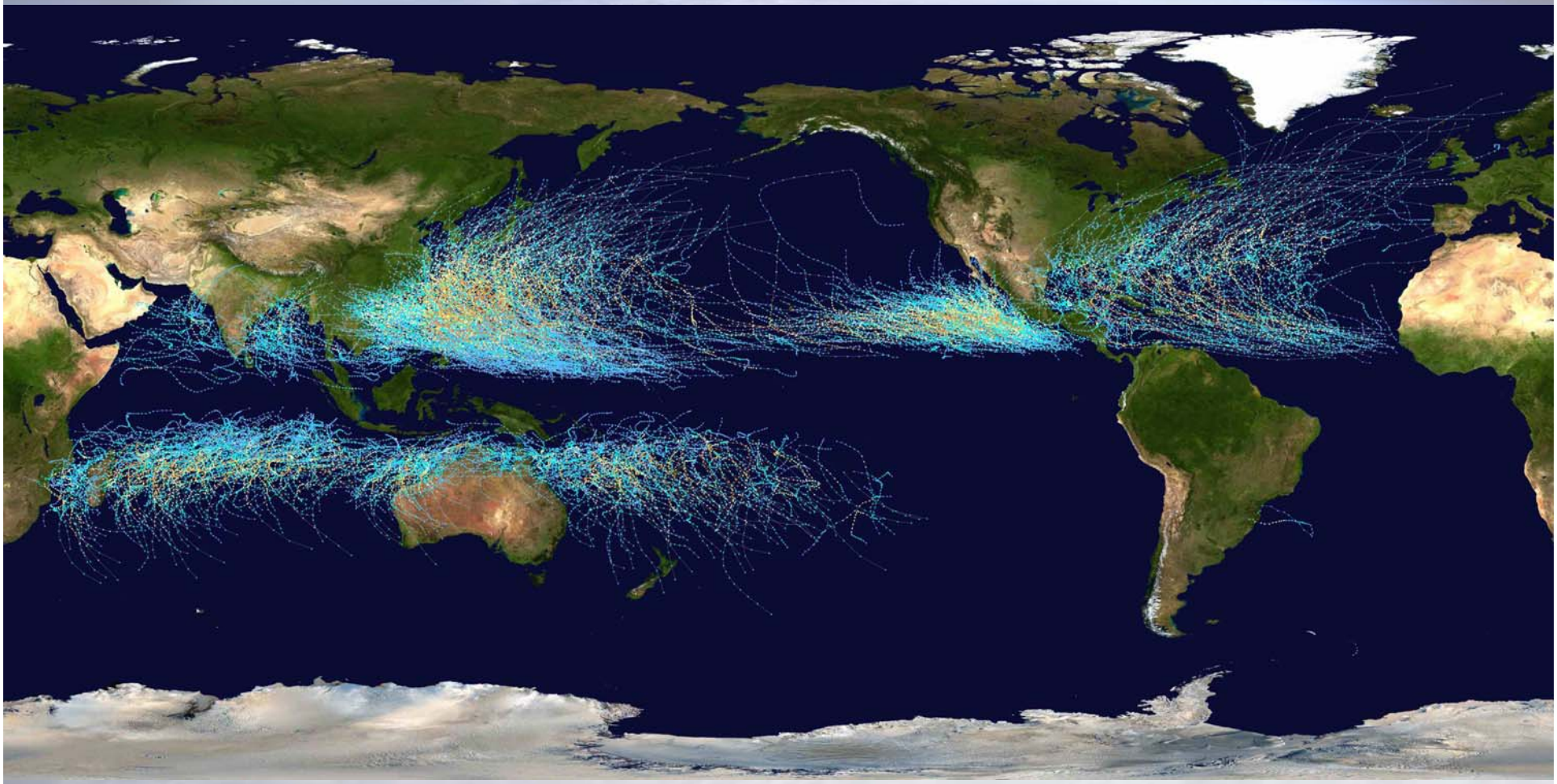
Scientist Attention Span

$$PRP = Annual\ \ peer\ reviewed\ \ publications$$

$$N_{Atl} = Number\ of\ \ Atlantic\ TCs\ \ per\ \ year$$

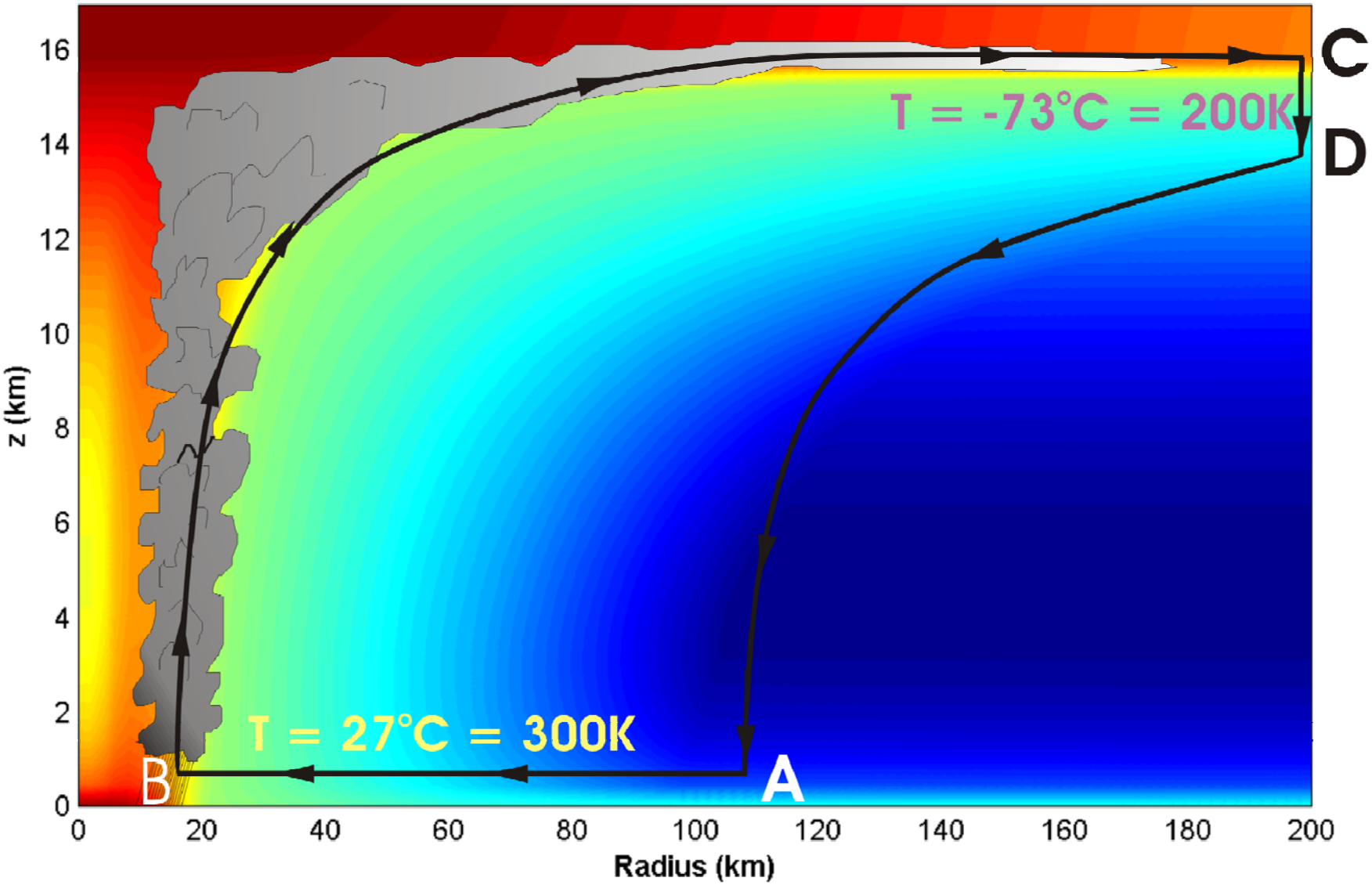

Annual Publications
Theory
r^2=.96
Annual Peer-Reviewed Publications
Year
0
50
100
150
200
250
1980
1985
1990
1995
2000
2005
2010

Tracks of all tropical cyclones, 1985-2005



Source: Wikipedia

Energy Production



Total rate of heat input to hurricane:

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

Surface enthalpy flux

Dissipative heating

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

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

Plug into Carnot equation:

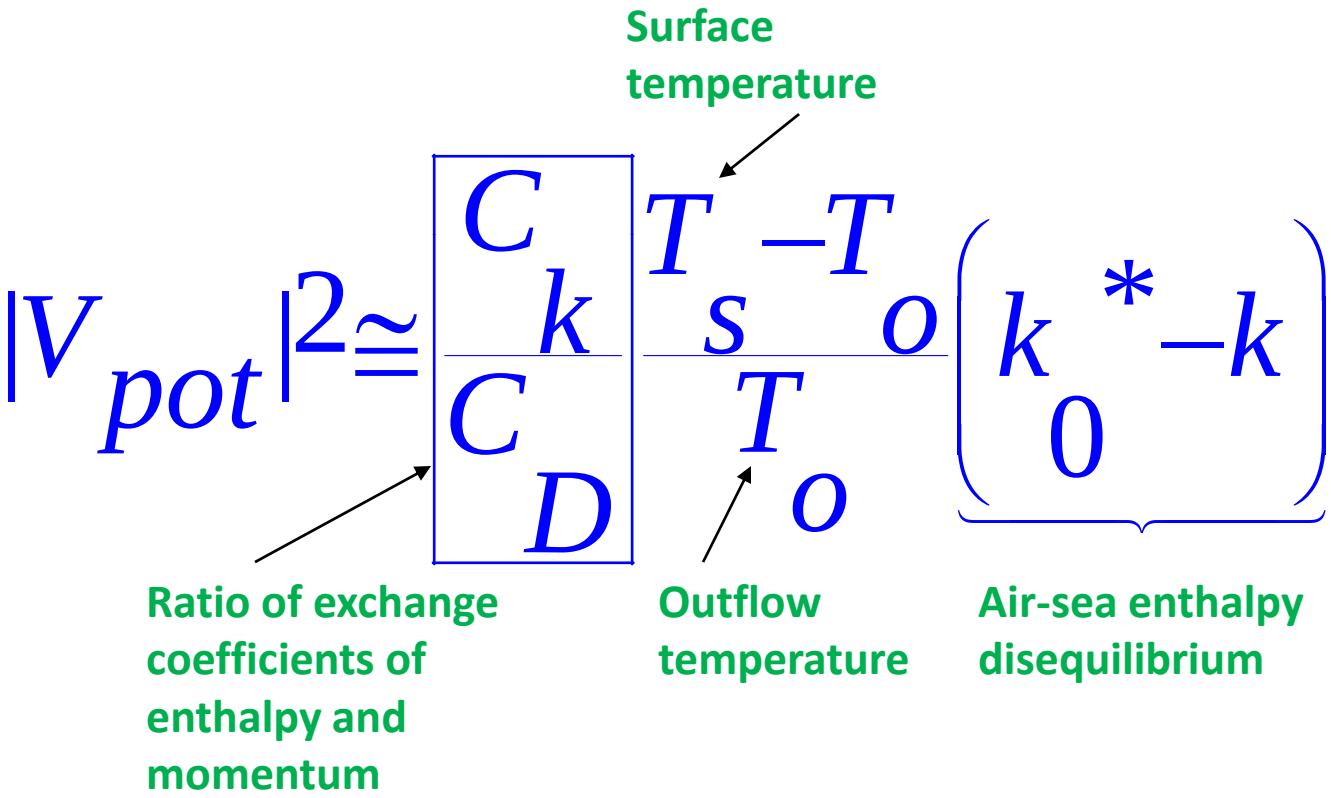
$$\int_0^{r_0} \rho\left[C_D \,|\, \mathbf{V} \,|^3\right] r dr = \frac{T_s - T_o}{T_o} \int_0^{r_0} \rho\left[C_k \,|\, \mathbf{V} \,|\left(k_0^* - k\right)\right] r dr$$

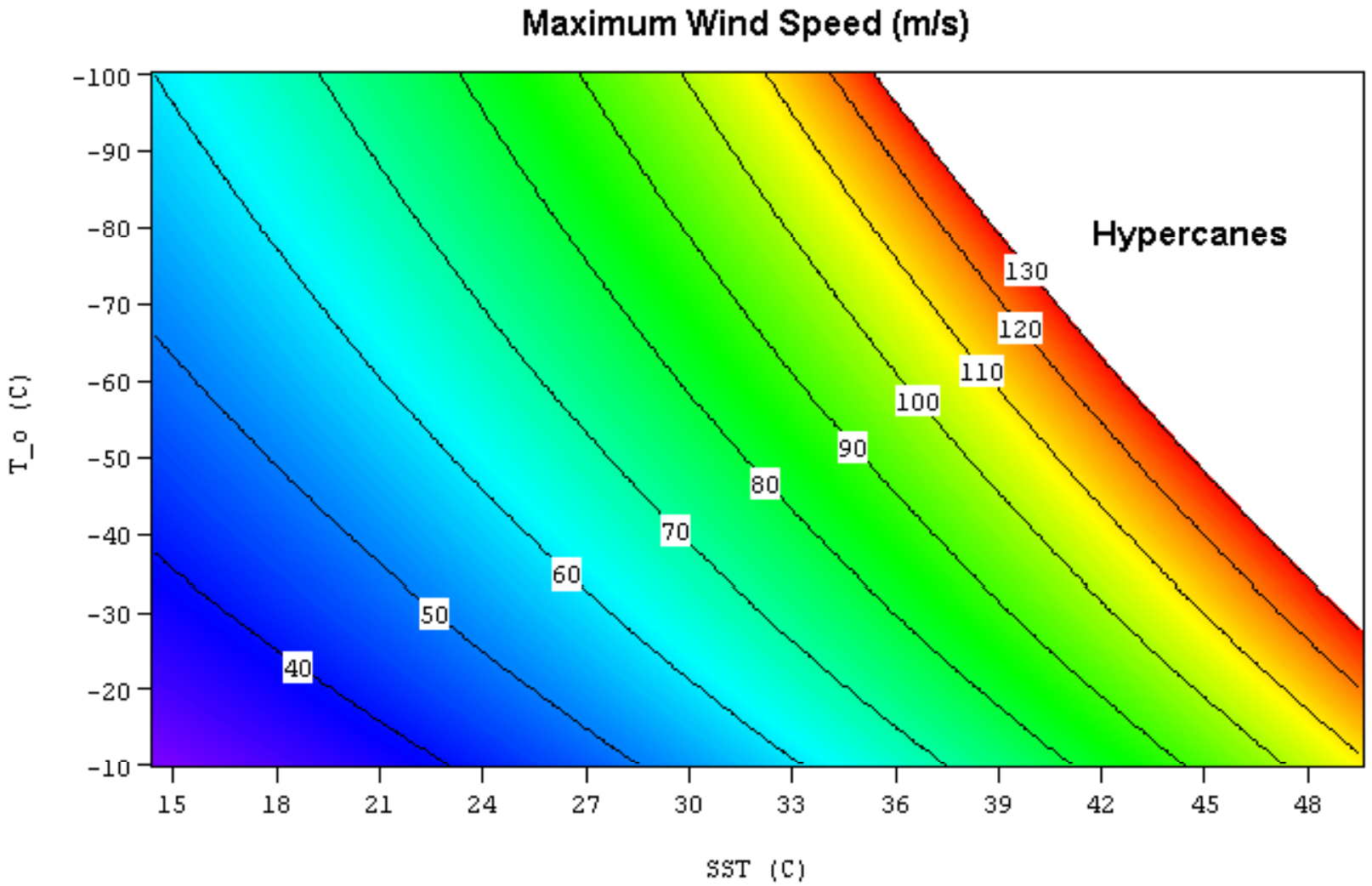
If integrals dominated by values of integrands near radius of maximum winds,

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

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

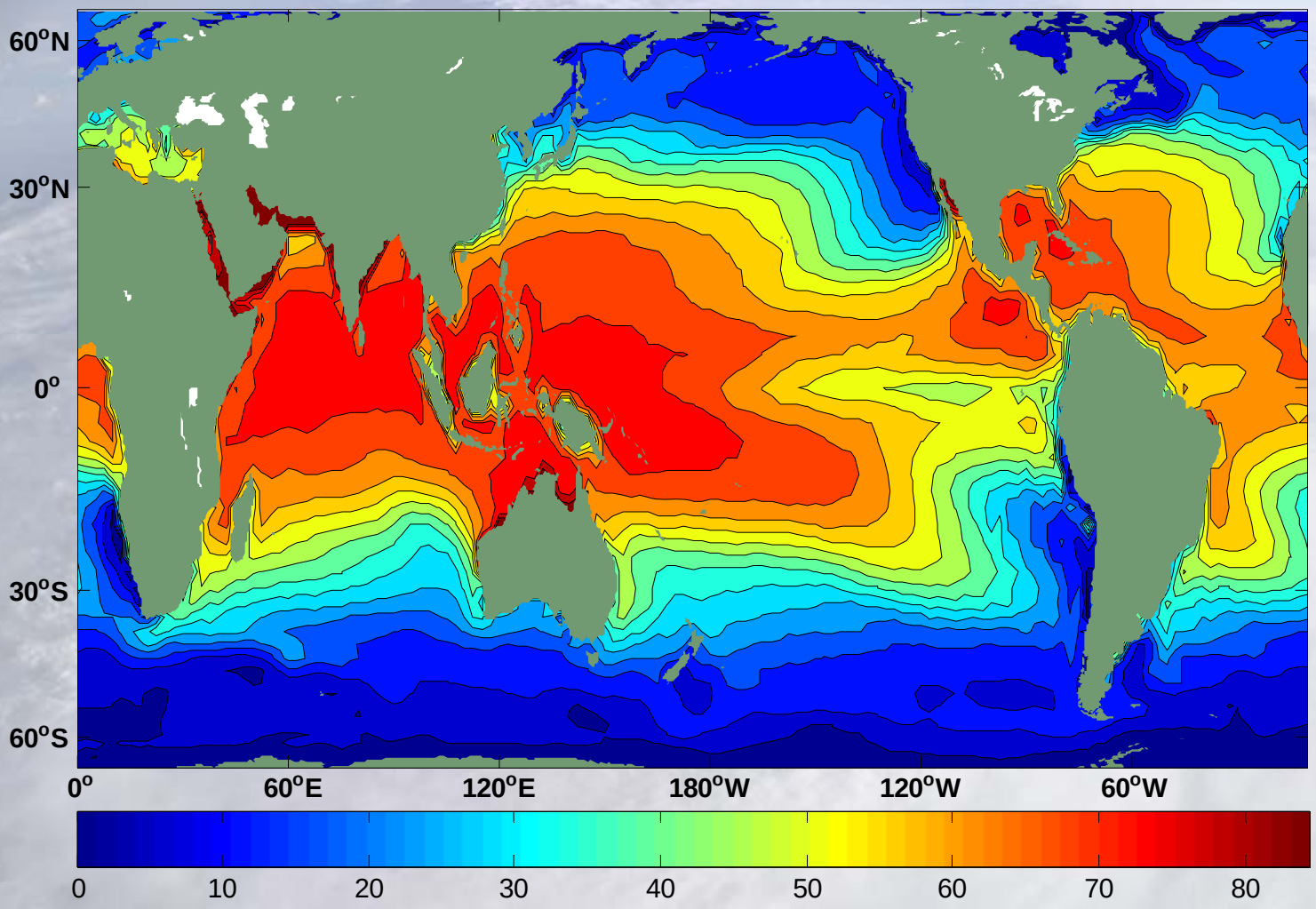
Theoretical Upper Bound on Hurricane Maximum Wind Speed:





χ = 0.75 C_k/C_D = 1.2

Annual Maximum Potential Intensity (m/s)



Condition of convective neutrality:

s_b = s* of free troposphere

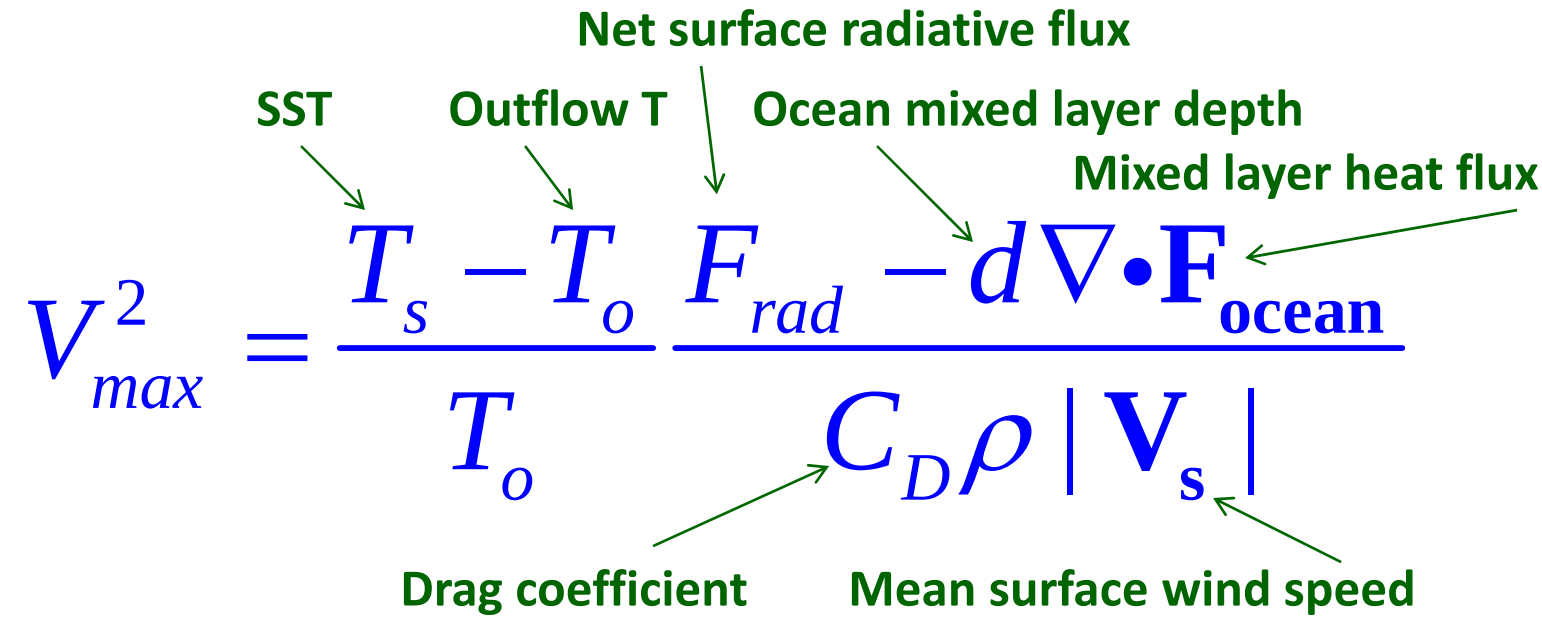
Also, s* of free troposphere is approximately spatially uniform (WTG approximation)

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

approximately constant

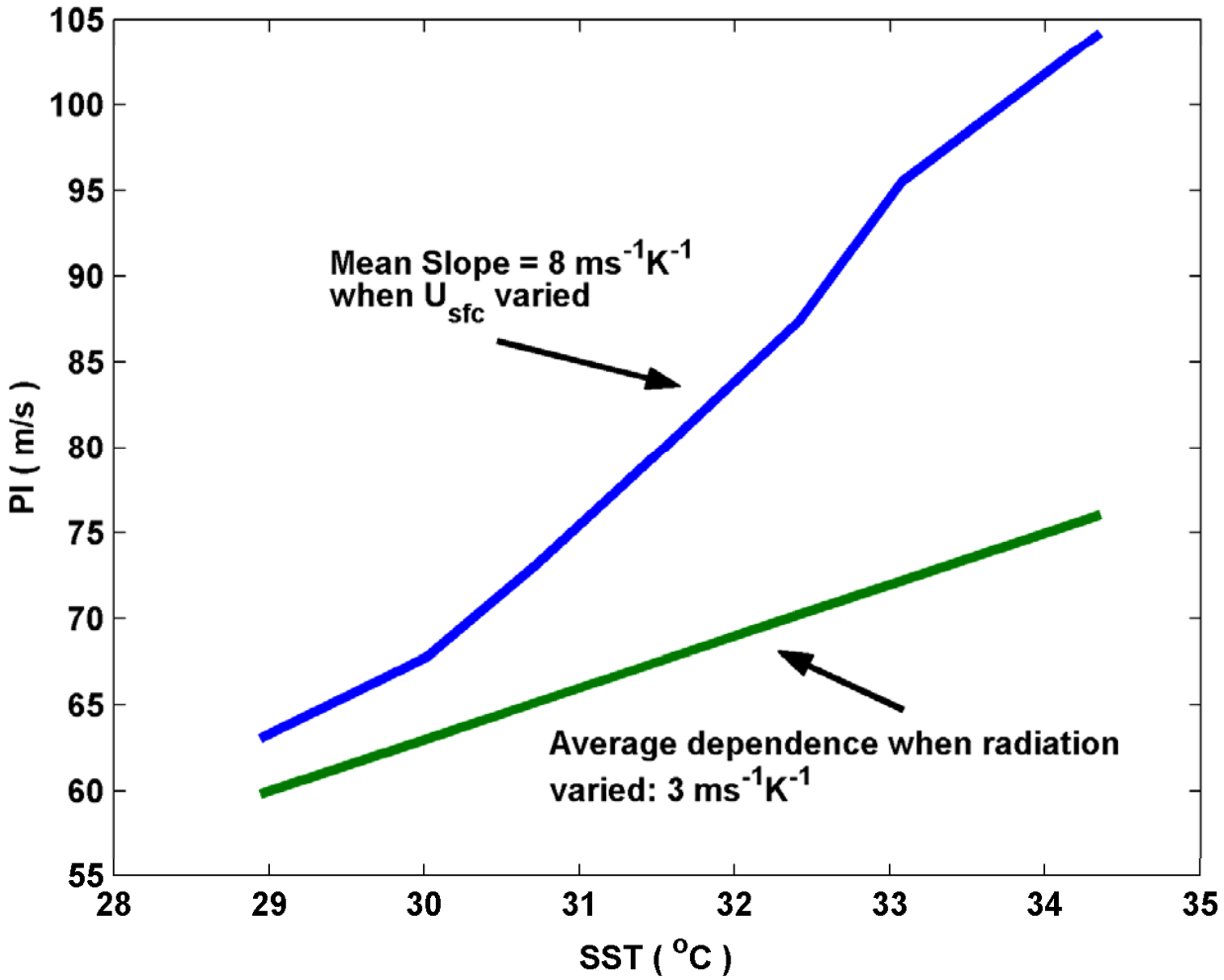
What matters, apparently, is the SST (s_0*) relative to the tropospheric temperature (s*)

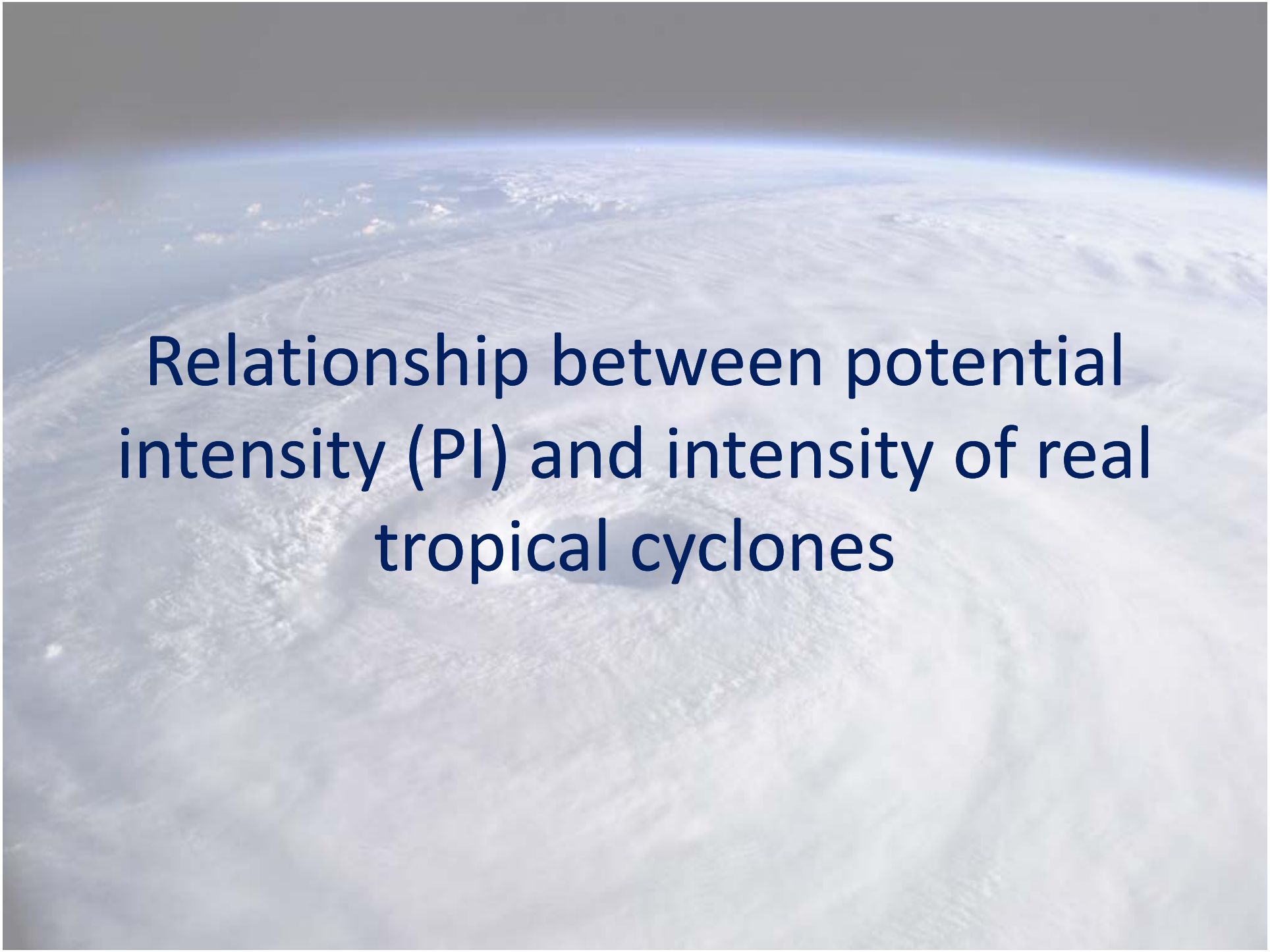
Combine expression for potential intensity, V_{max}, with energy balance of ocean mixed layer:



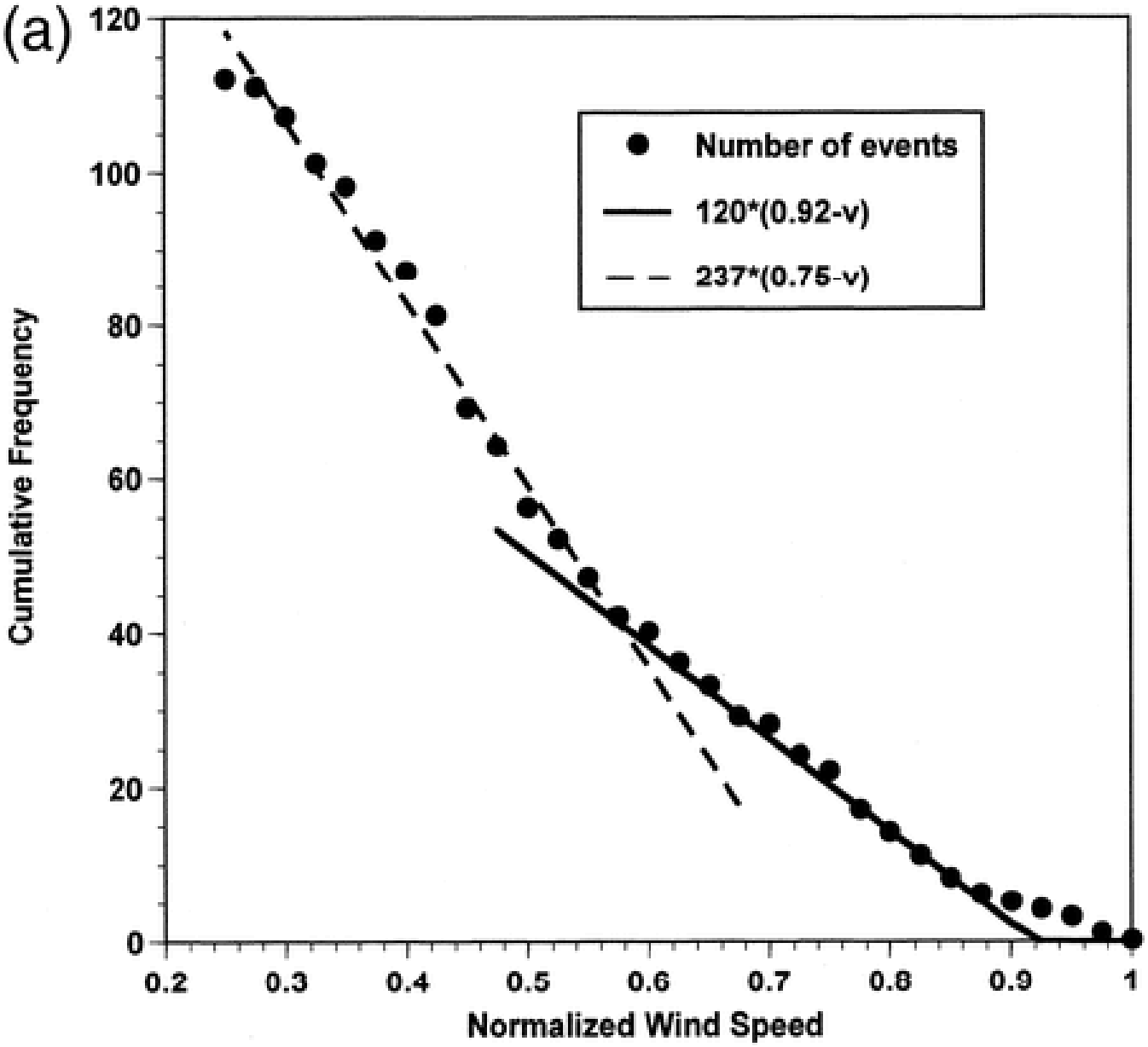
Valid on time scales > thermal equilibration time of ocean mixed layer (~ 2 years)

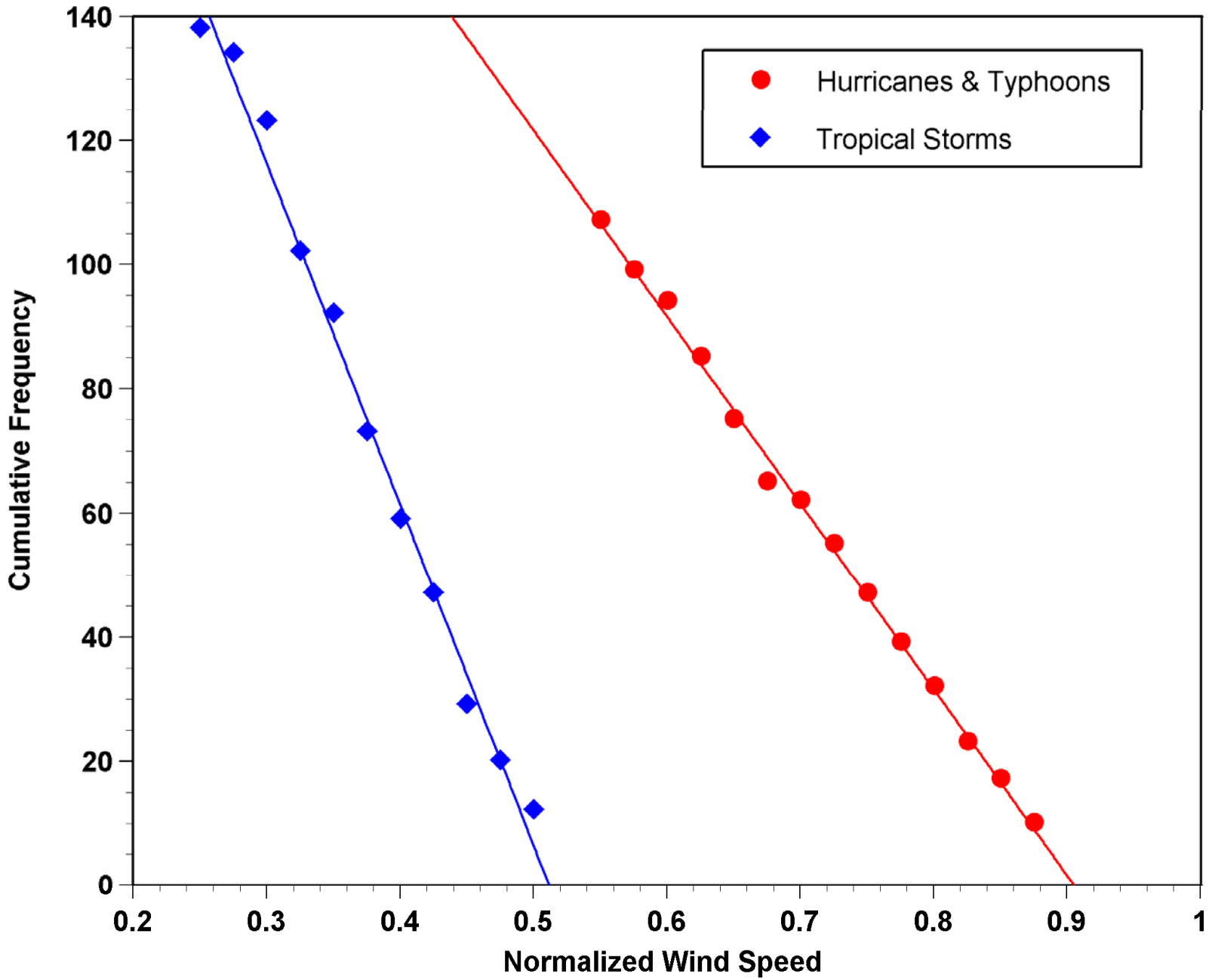
Dependence on Sea Surface Temperature (SST):





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


(a)
Number of events
120*(0.92-v)
237*(0.75-v)
Cumulative Frequency
Normalized Wind Speed
0
20
40
60
80
100
120
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1


Hurricanes & Typhoons
Tropical Storms
Cumulative Frequency
Normalized Wind Speed
0
20
40
60
80
100
120
140
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

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:

$$\chi \equiv \frac{s^* - s_{600}}{s_0^* - s^*}$$

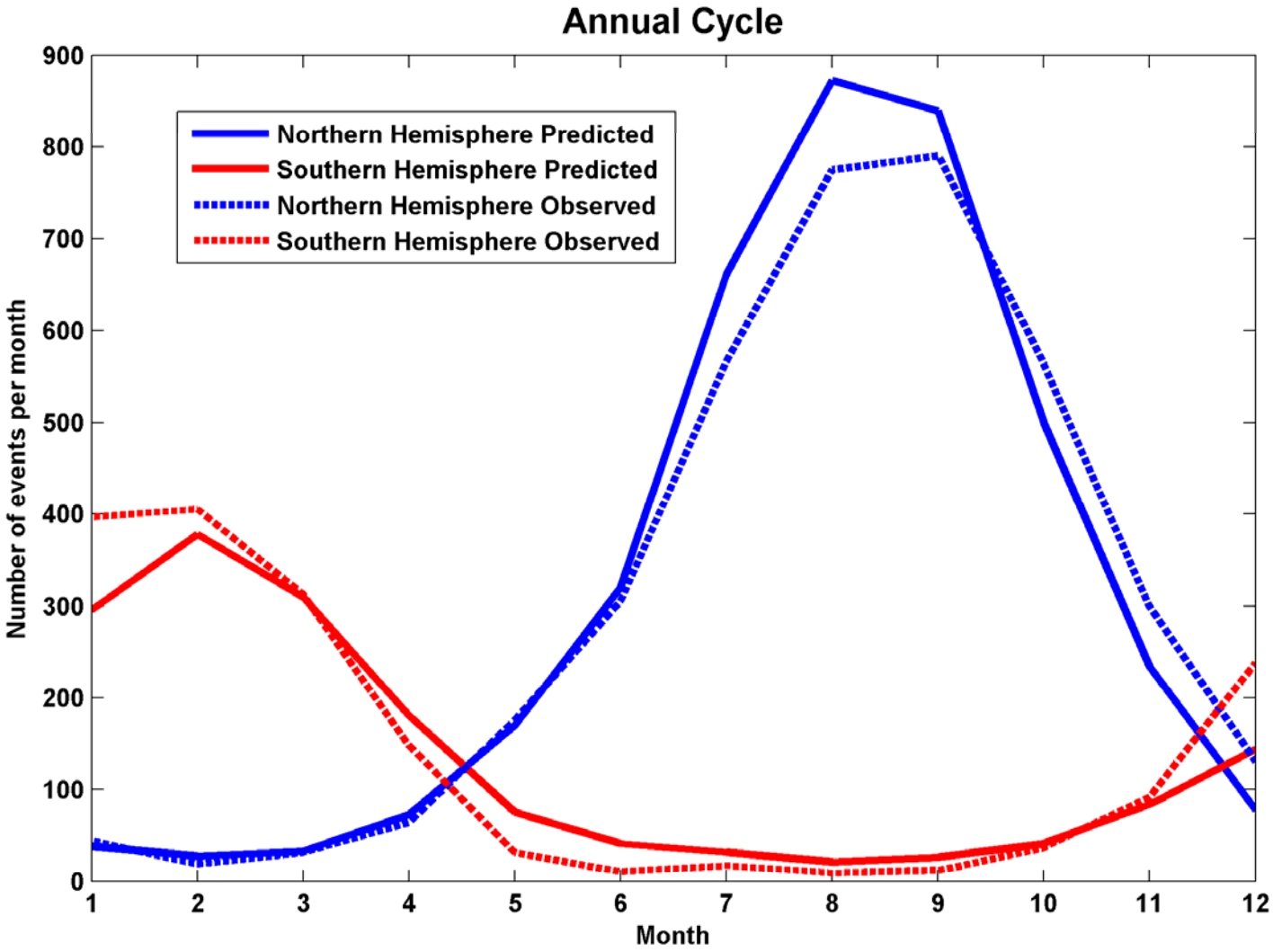
New Genesis Potential Index:

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

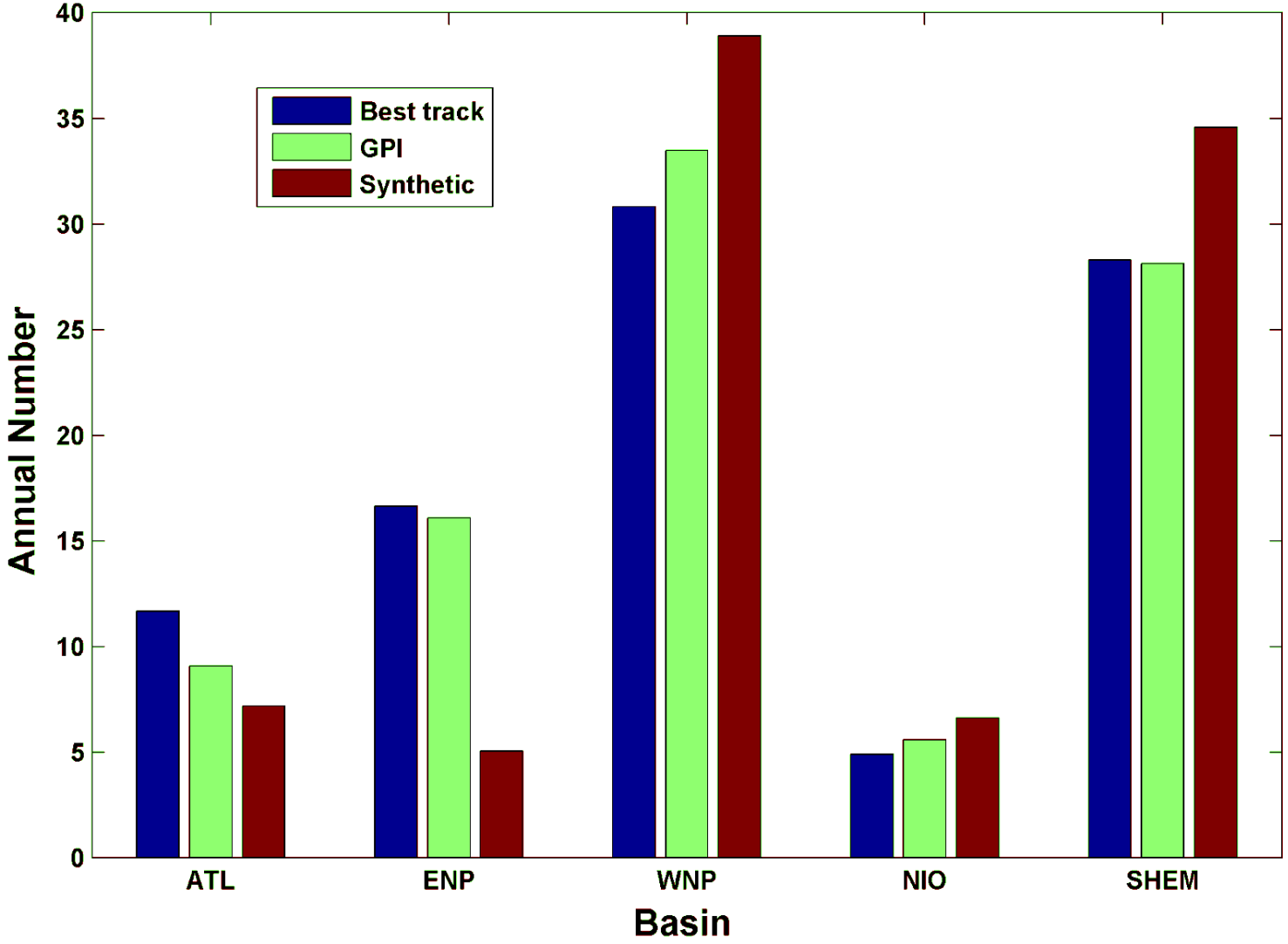
- 850 hPa absolute vorticity (η)
- 850 – 250 hPa shear (S)
- Potential intensity (PI)
- Non-dimensional subsaturation of the middle troposphere:

$$\chi \equiv \frac{s^* - s_{600}}{s_0^* - s^*}$$

Performance



Basin Frequencies



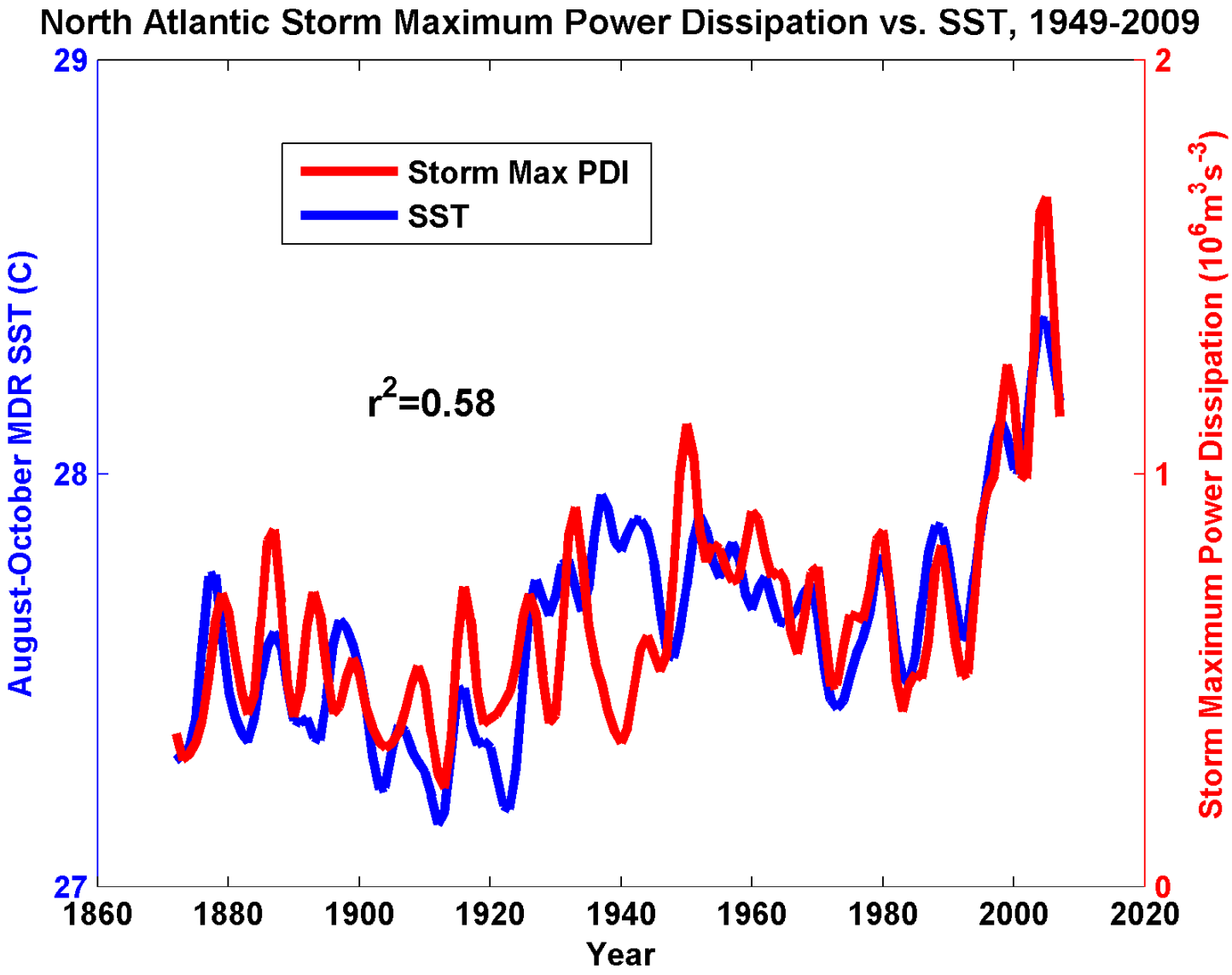
TC Activity Metric:

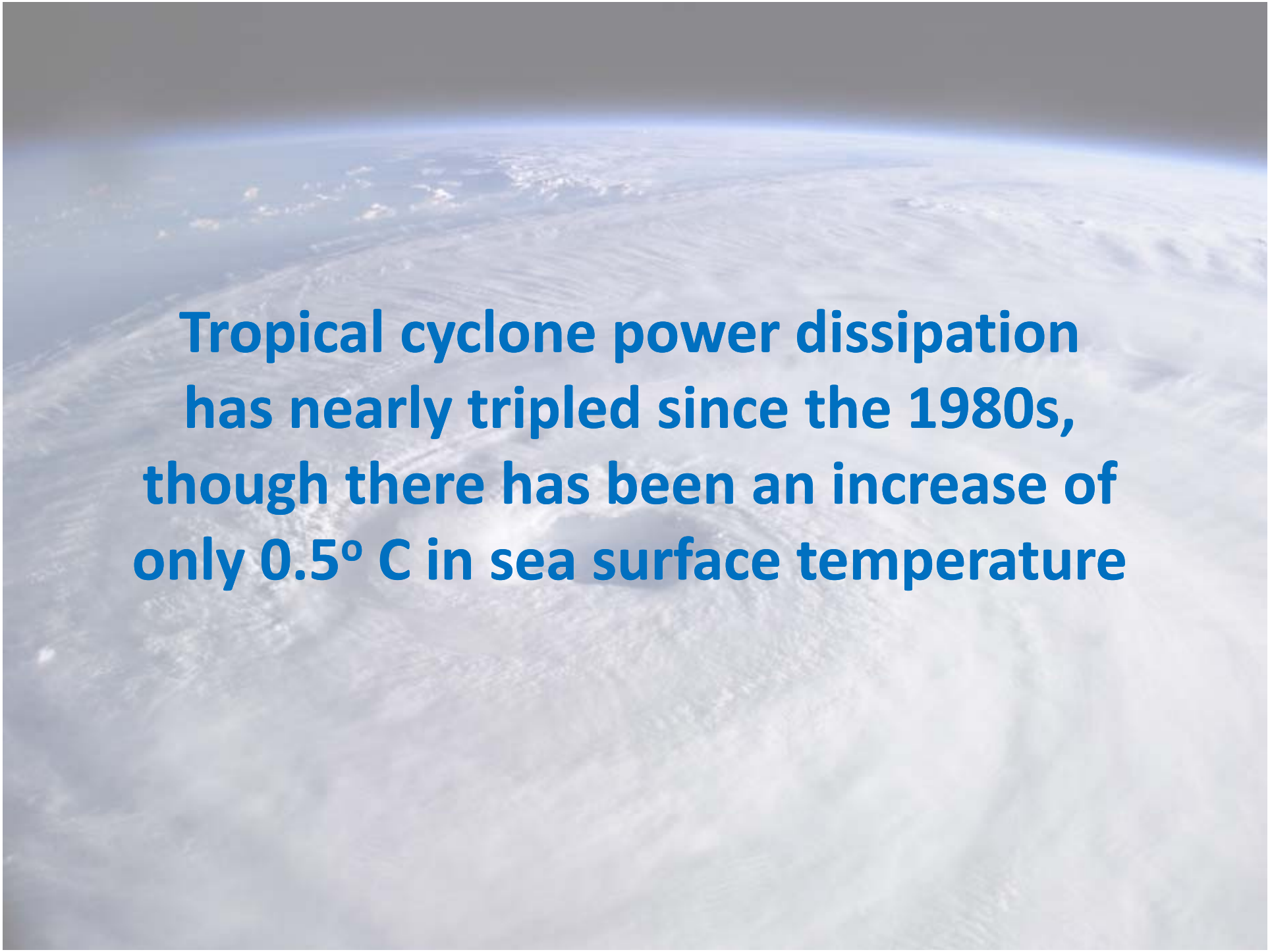
Hurricane Power
(Power Dissipation Index)

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

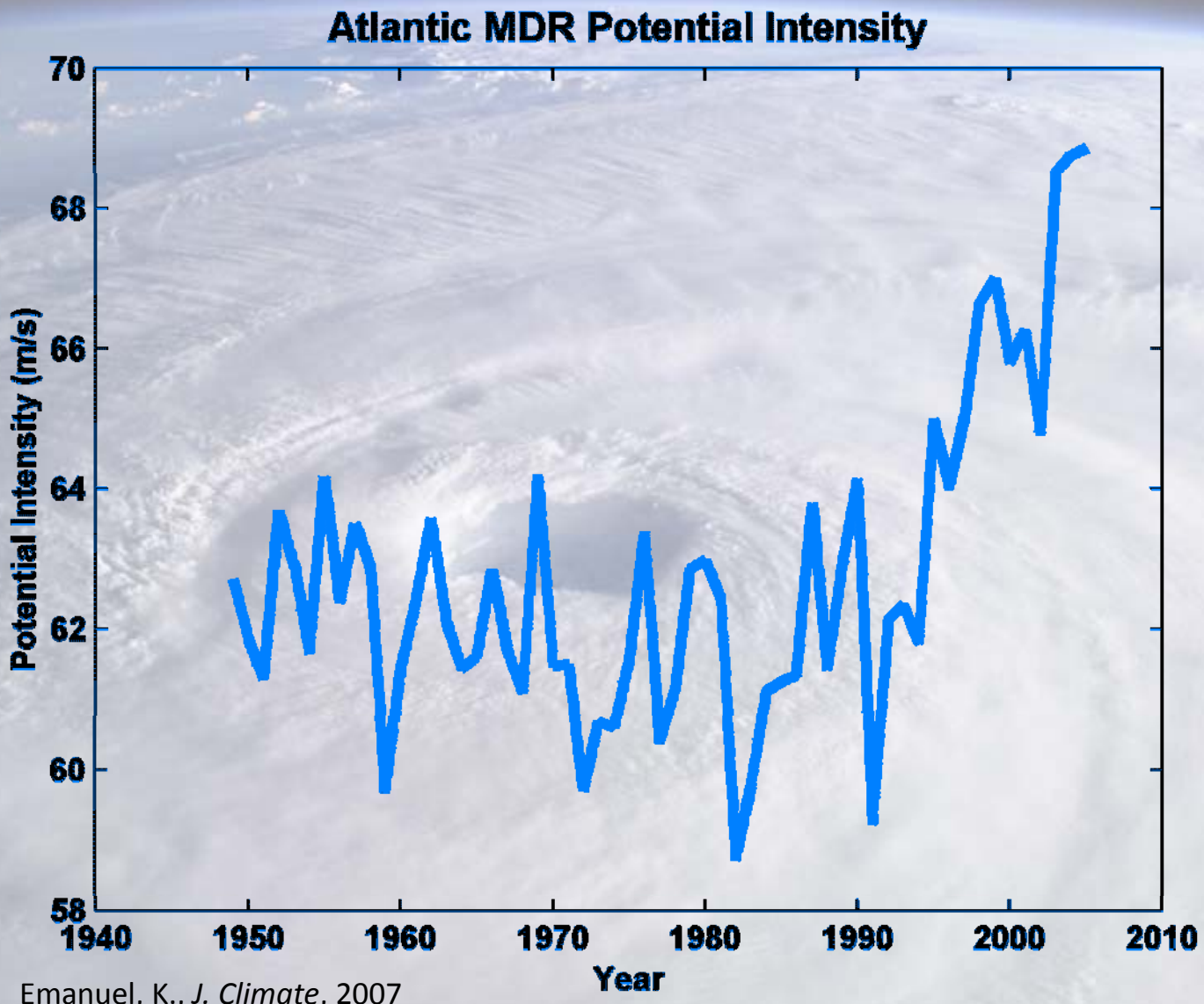
A measure of the total frictional dissipation of kinetic energy in the hurricane boundary layer over the lifetime of the storm

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




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

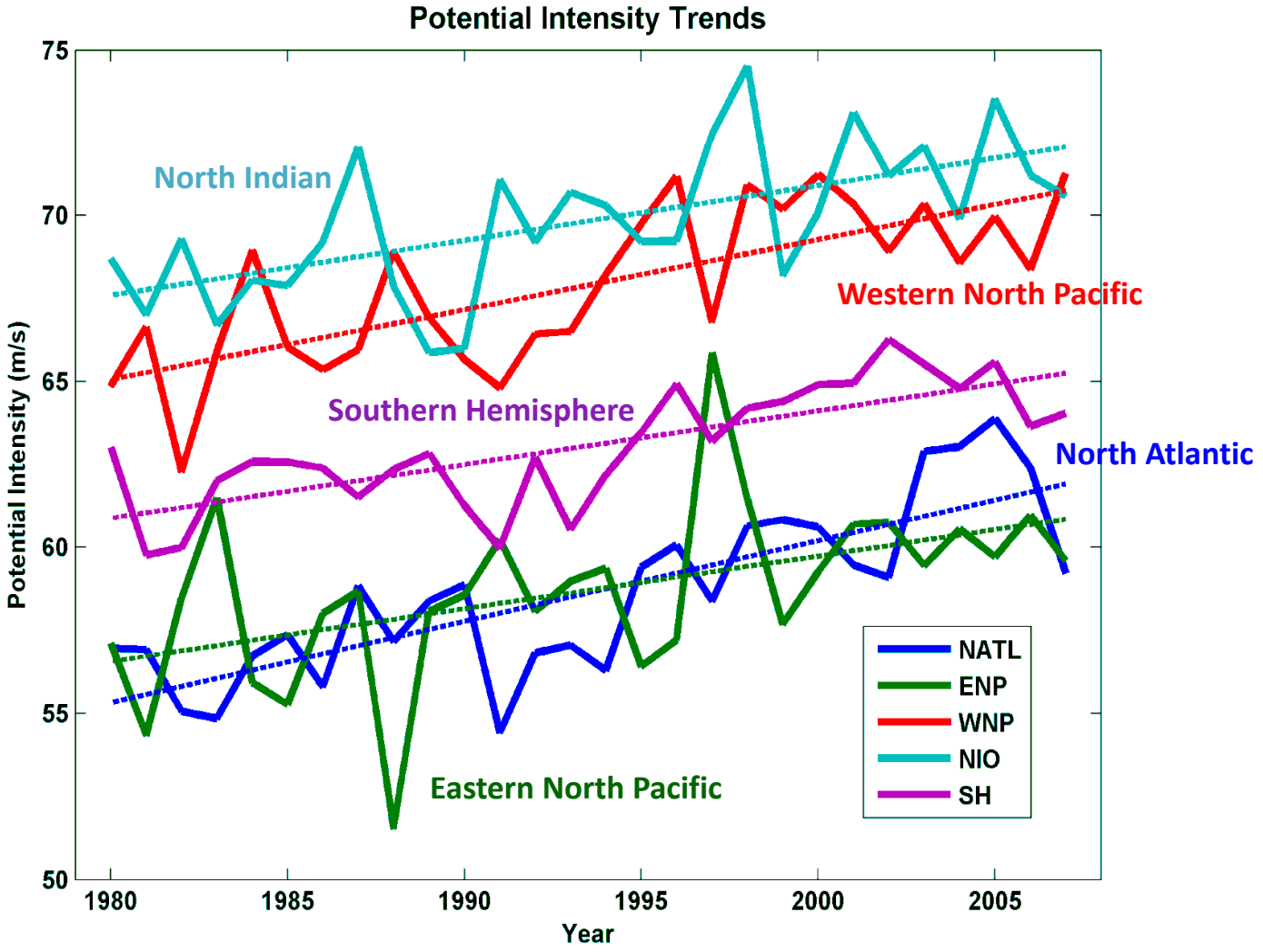
Observed Tropical Atlantic Potential Intensity



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

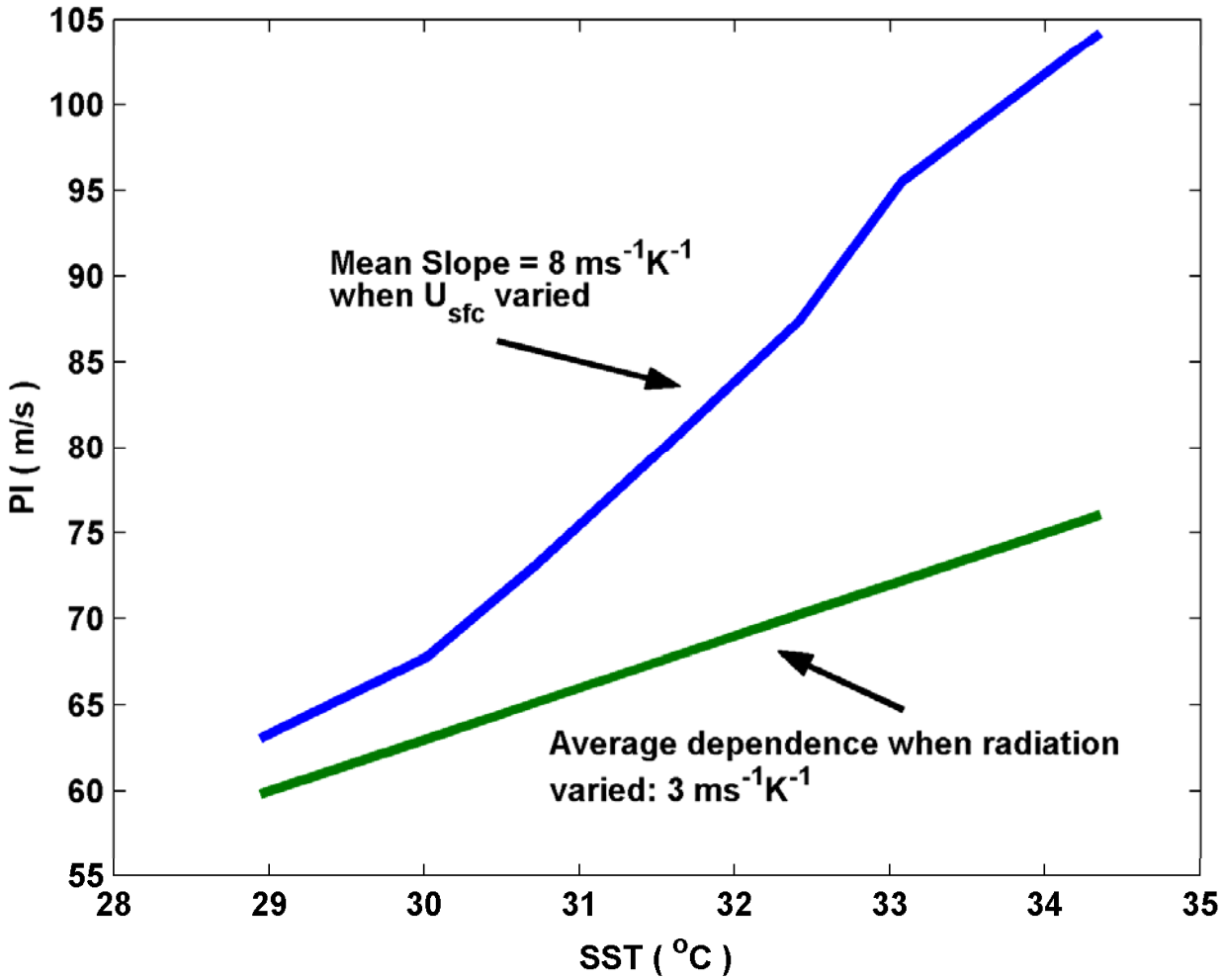
Data Sources: NCAR/NCEP re-analysis with pre-1979 bias correction, UKMO/HADSST1

Potential Intensity, 1980-2008



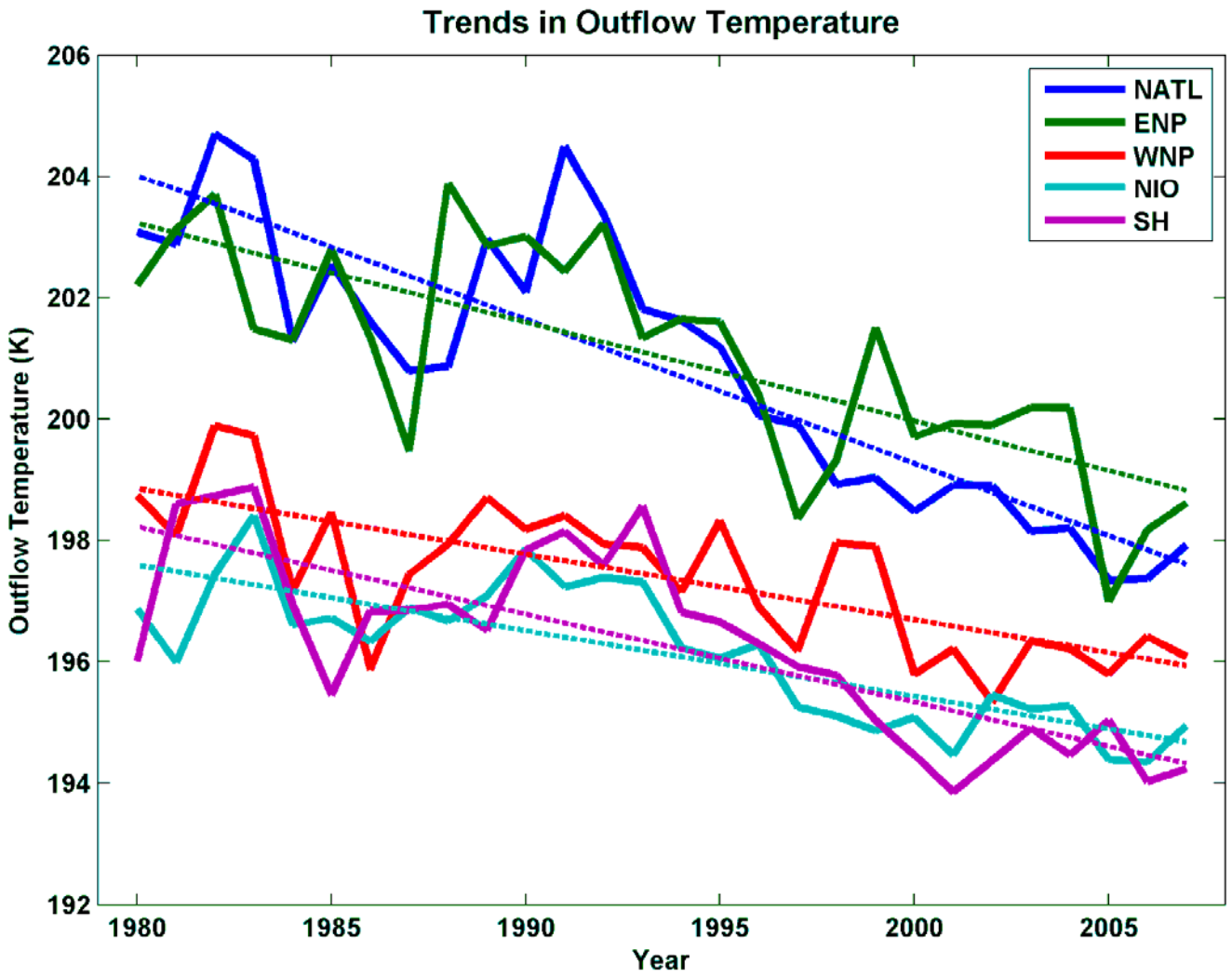
From NCAR/NCEP reanalysis data

Dependence on Sea Surface Temperature (SST):




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?
Stay Tuned for Next Talk!

Trends in outflow temperature



From NCAR/NCEP reanalysis data