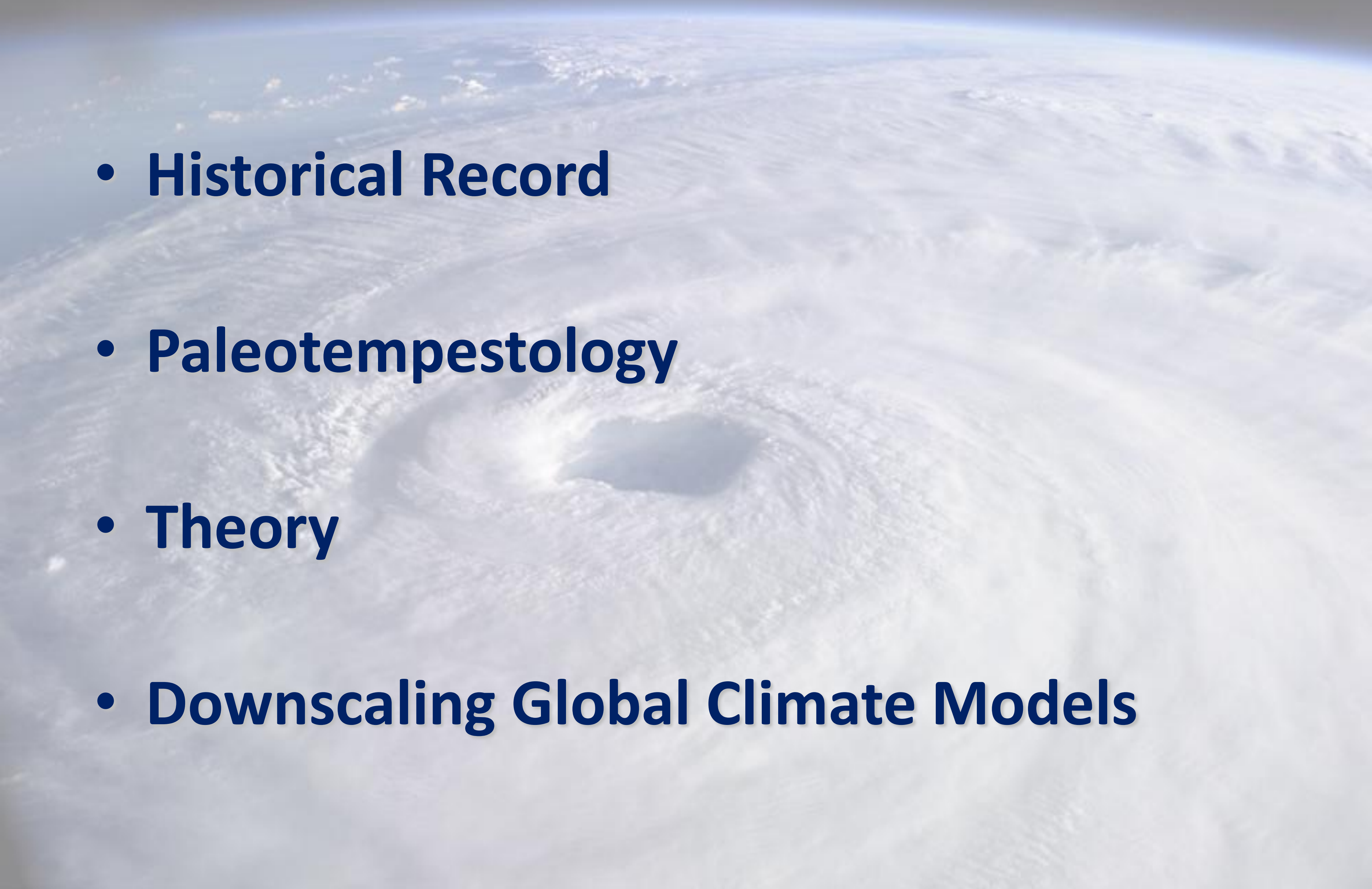
Is Global Warming Affecting Hurricanes, and Will it Do So in the Future?

Kerry Emanuel

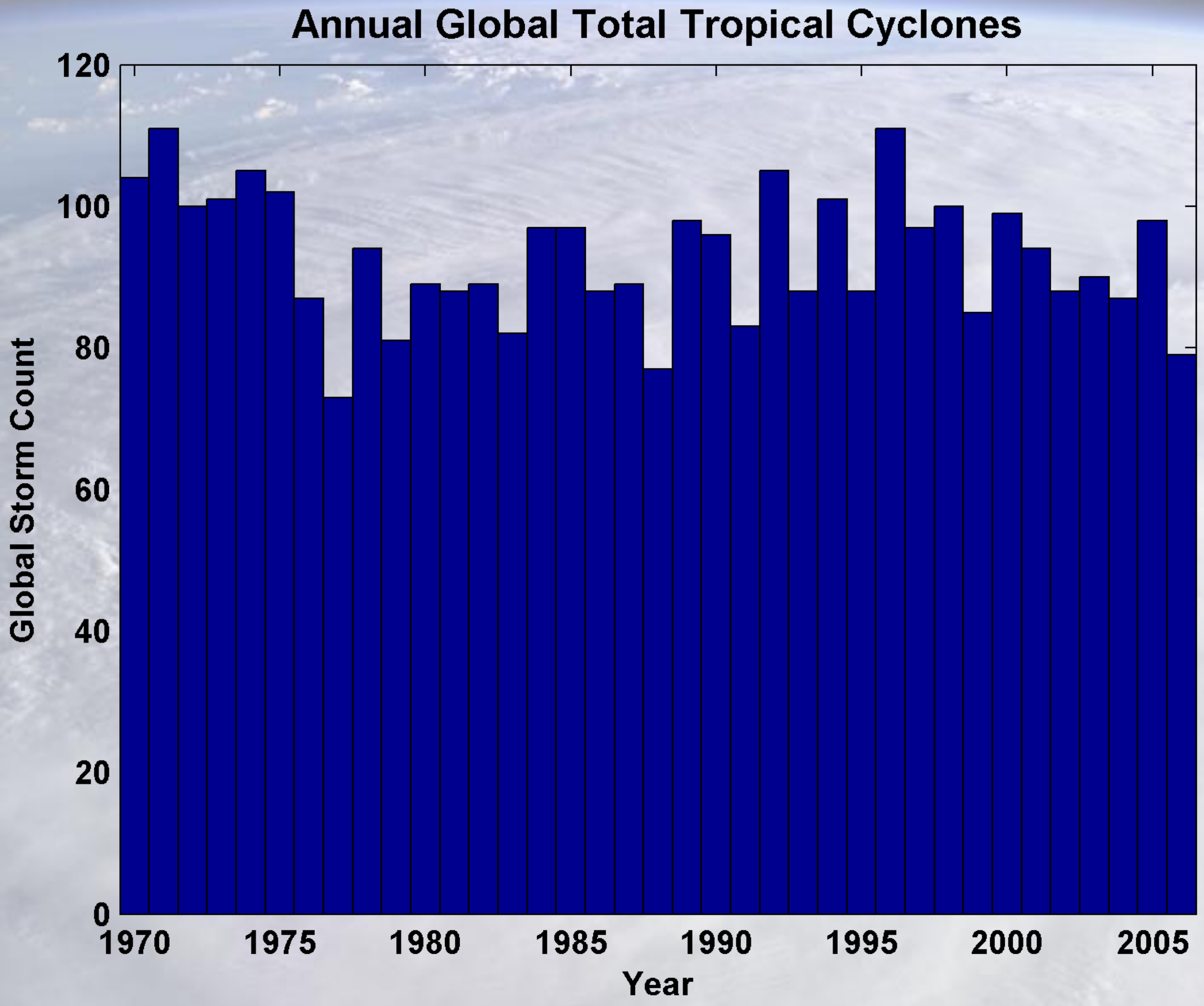
Massachusetts Institute of Technology

The Evidence



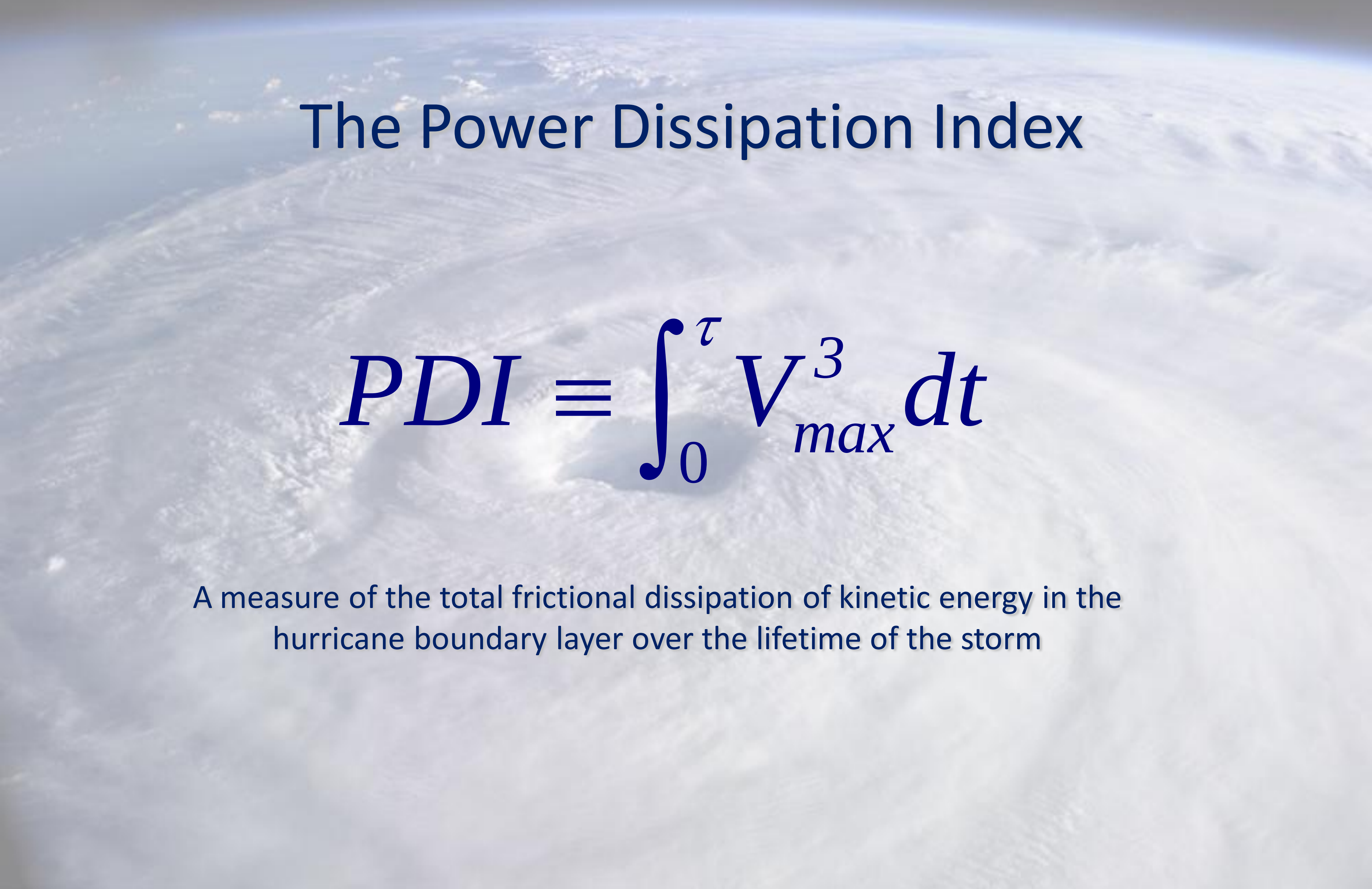
- Historical Record
- Paleotempestology
- Theory
- Downscaling Global Climate Models

No Obvious Trend in Global TC Frequency, 1970-2006



Data Sources: NOAA/TPC and NAVY/JTWC

Better Intensity Metric:



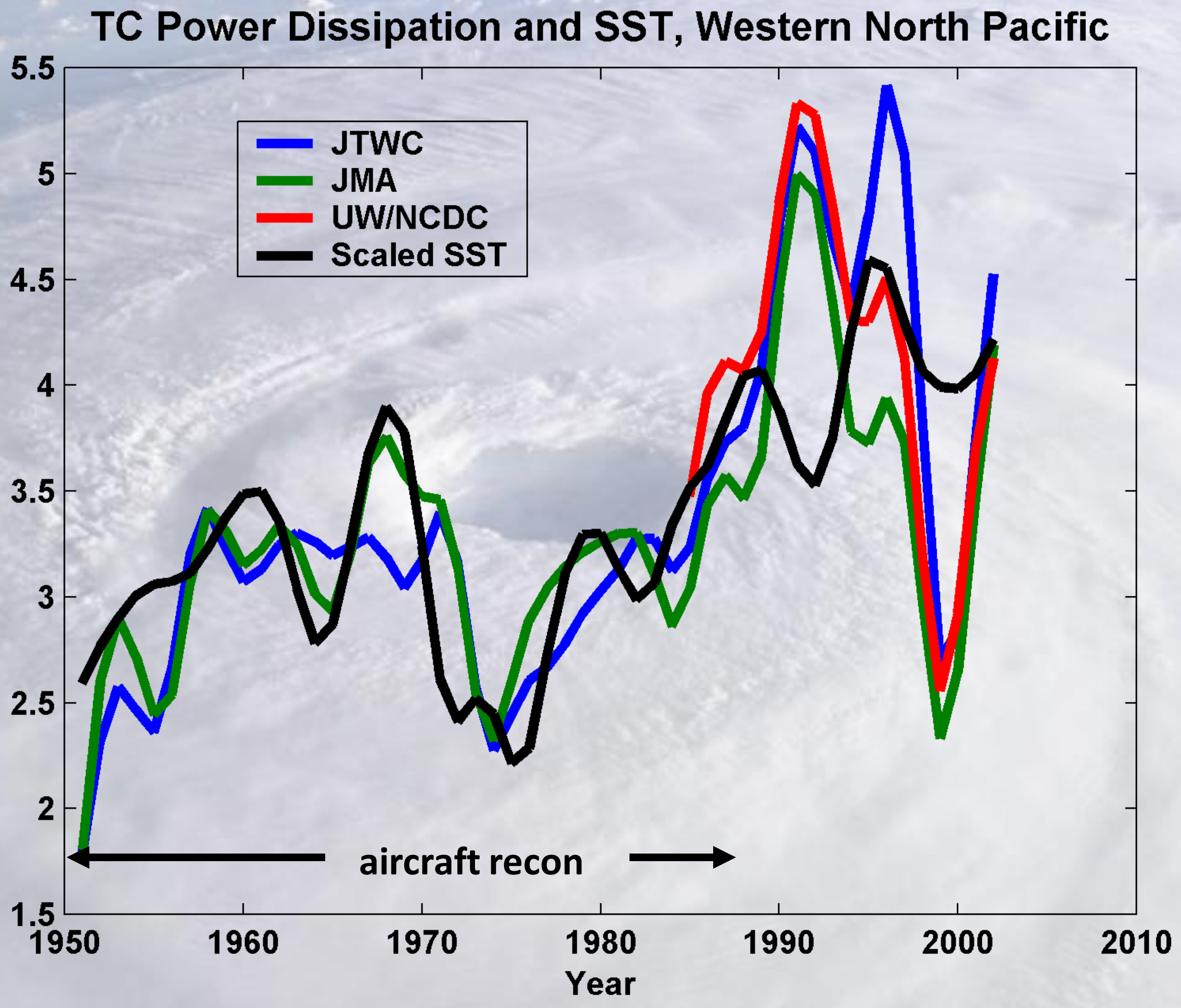
The Power Dissipation Index

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

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

Power Dissipation Based on 3 Data Sets for the Western North Pacific

(smoothed with a 1-3-4-3-1 filter)

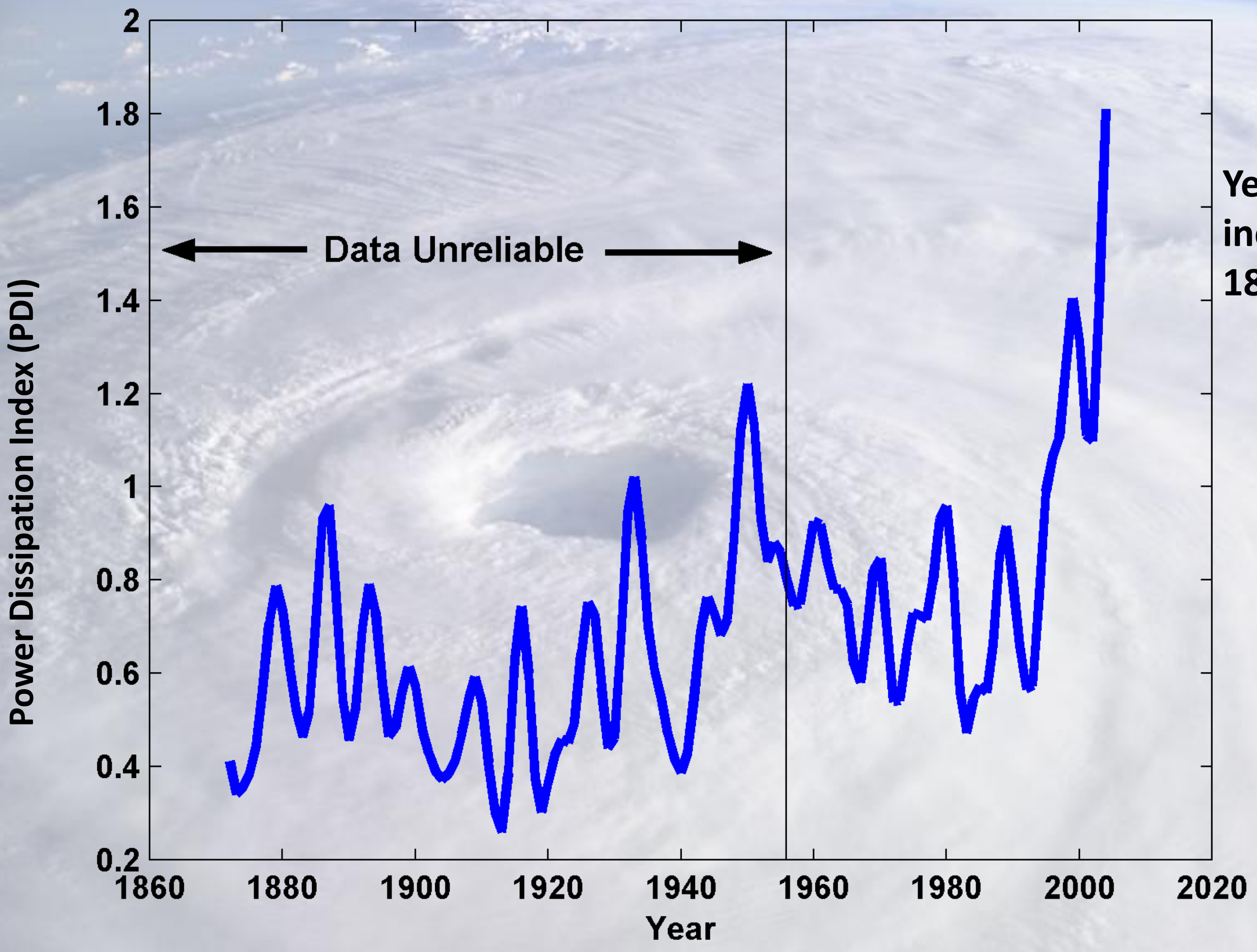


Years included: 1949-2004

Data Sources: NAVY/JTWC, Japan Meteorological Agency, UKMO/HADSST1, Jim Kossin, U. Wisconsin

Atlantic Storm Maximum Power Dissipation

(Smoothed with a 1-3-4-3-1 filter)

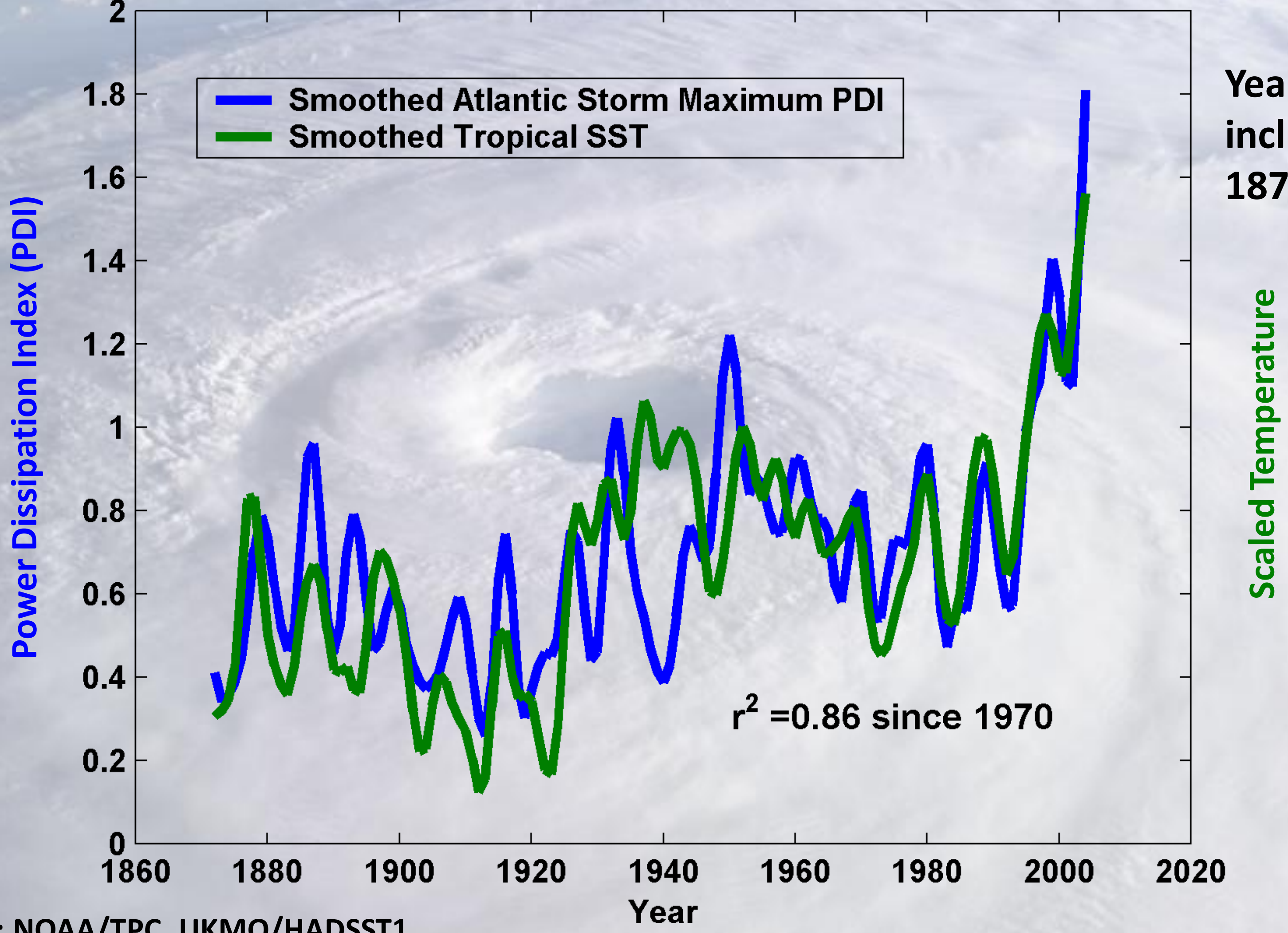


Years included: 1870-2006

Data Source: NOAA/TPC

Atlantic Sea Surface Temperatures and Storm Max Power Dissipation

(Smoothed with a 1-3-4-3-1 filter)

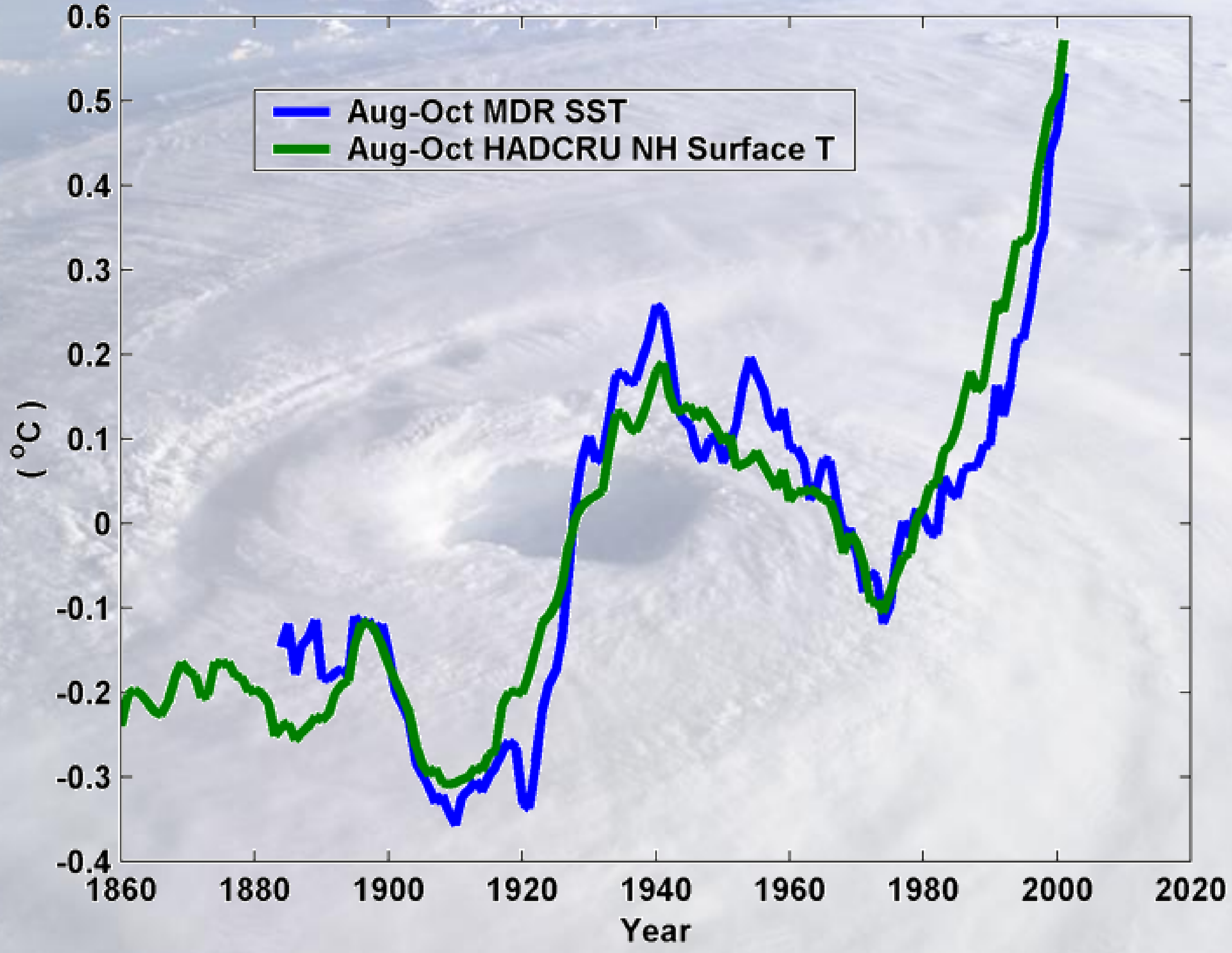


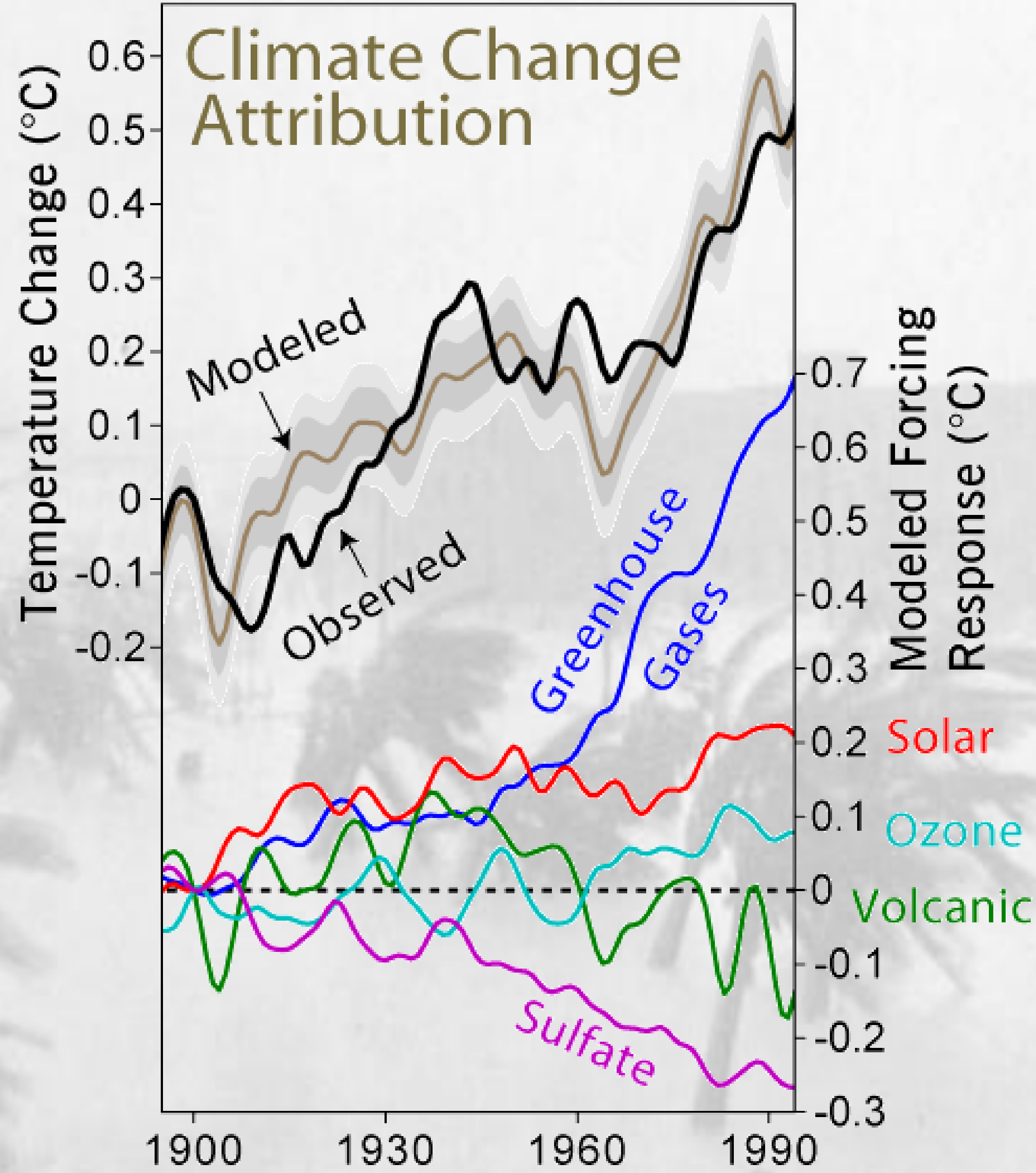
Years
included:
1870-2006

Data Sources: NOAA/TPC, UKMO/HADSST1

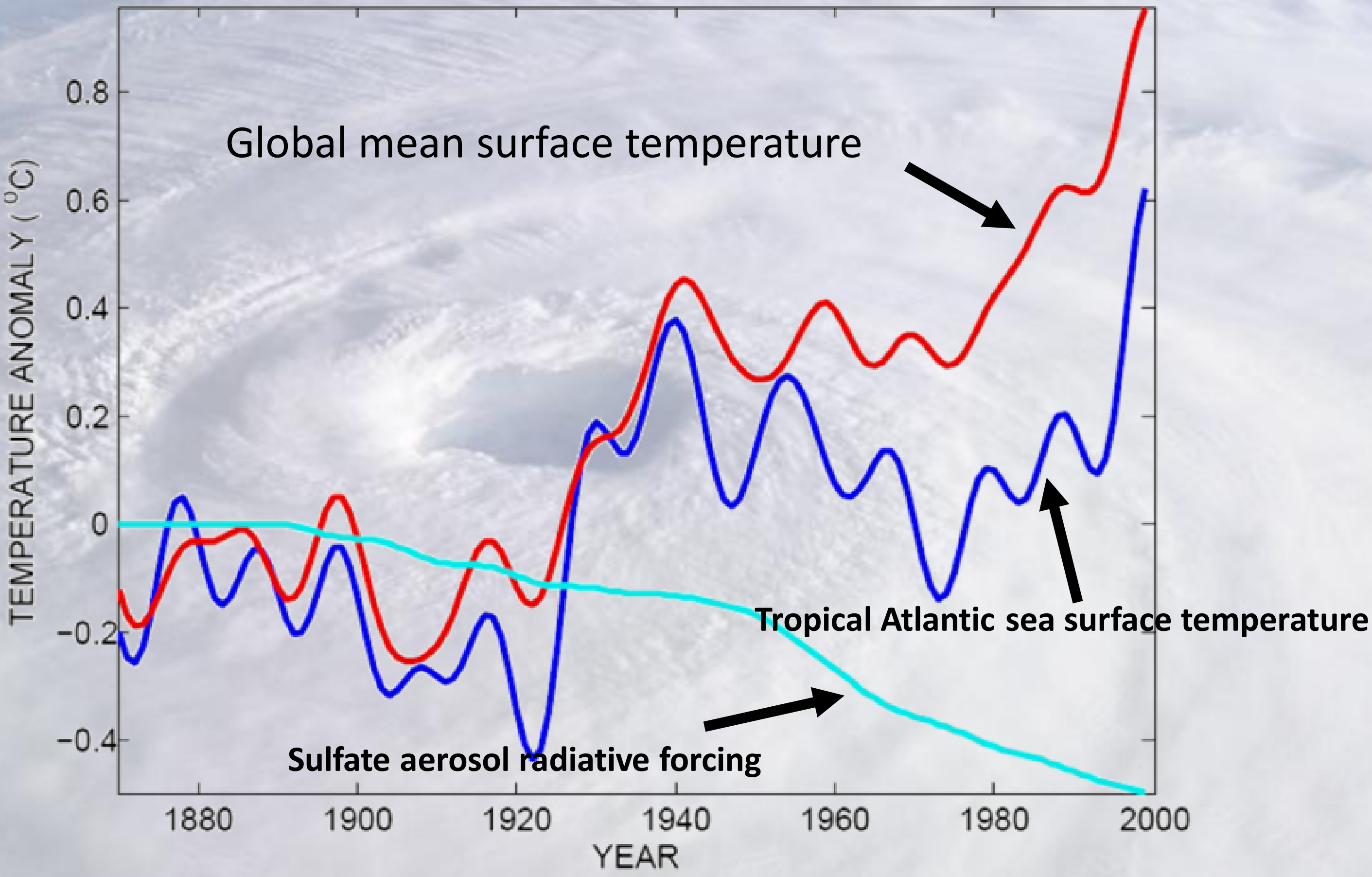
What is Causing Changes in Tropical Atlantic Sea Surface Temperature?

10-year Running Average of Aug-Oct NH Surface T and MDR SST




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
Greenhouse Gases
Solar
Ozone
Volcanic
Sulfate
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
1900
1930
1960
1990

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



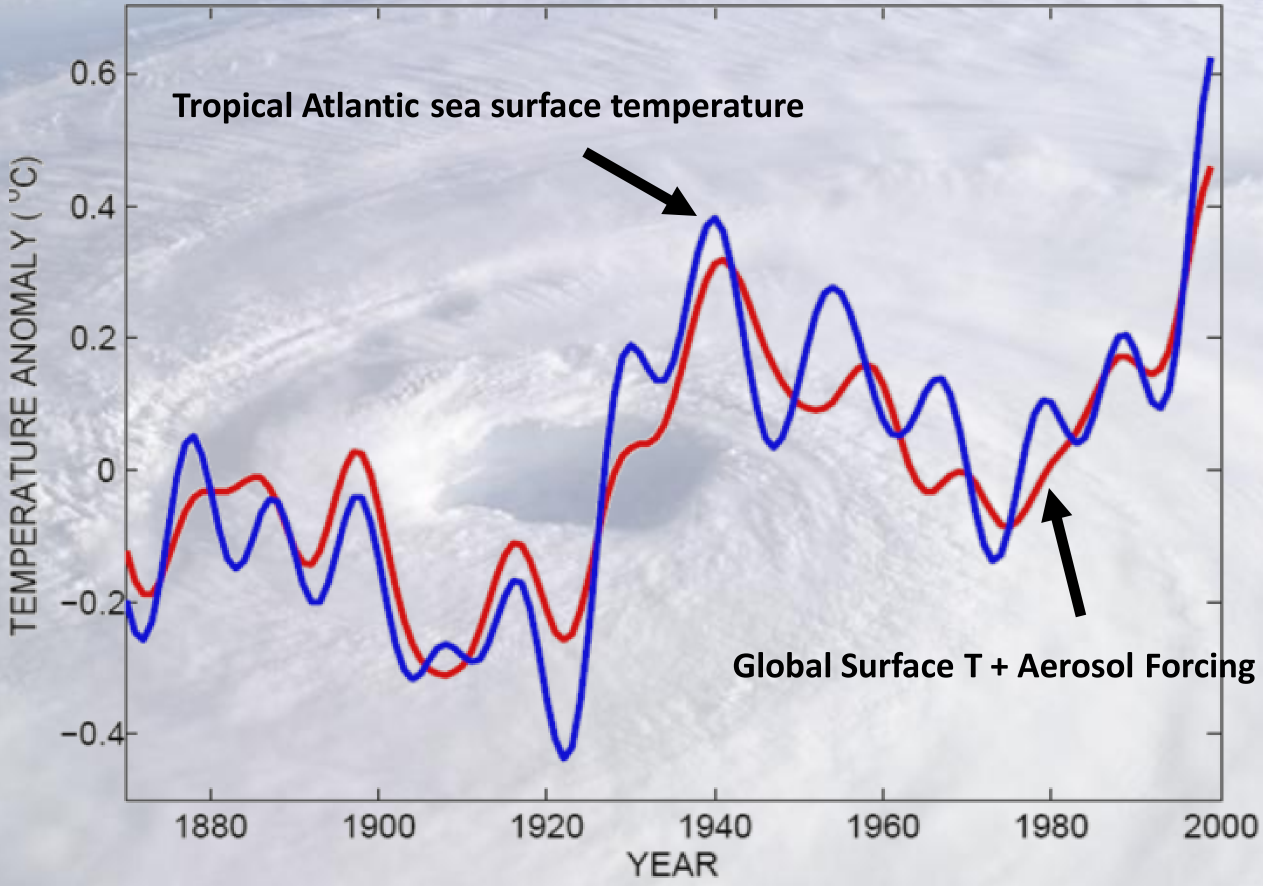
Global mean surface temperature

Tropical Atlantic sea surface temperature

Sulfate aerosol radiative forcing

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

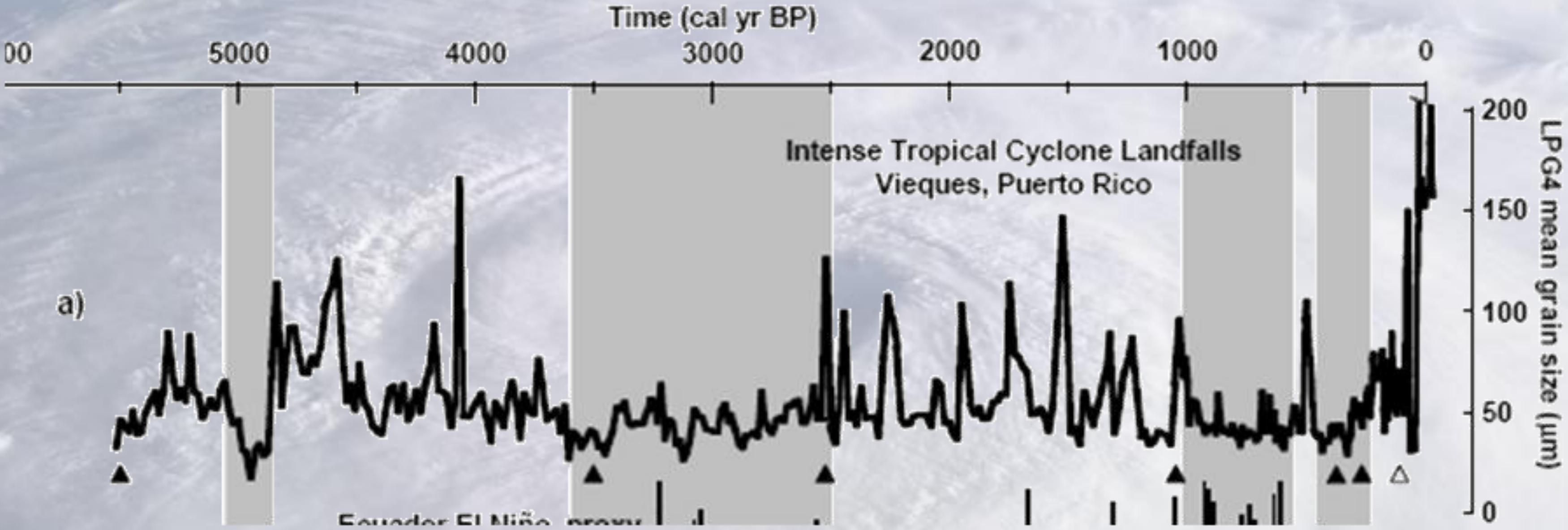
Best Fit Linear Combination of Global Warming and Aerosol Forcing (red) versus Tropical Atlantic SST (blue)



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

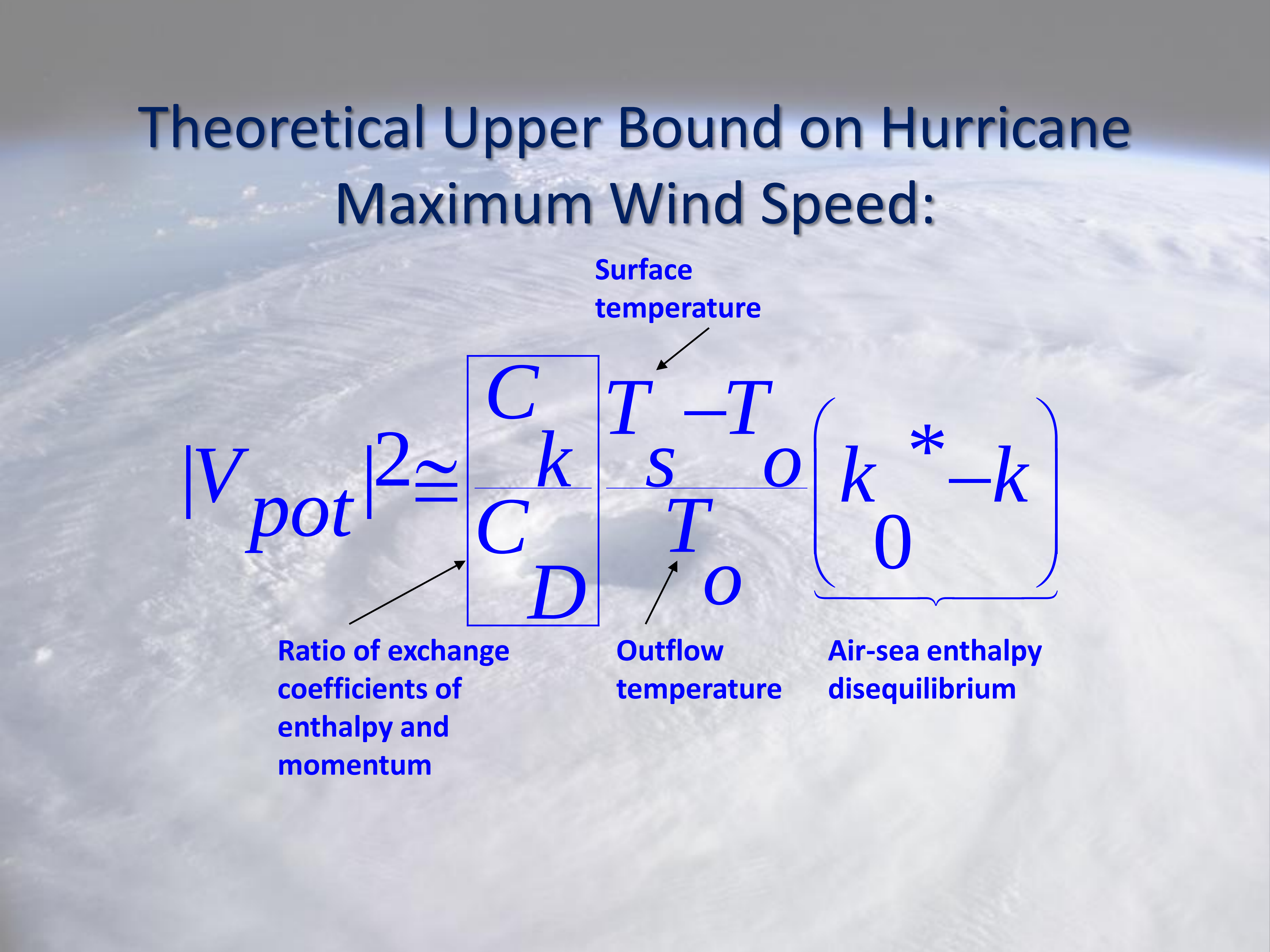
Paleotempestology

Donnelly and Woodruff (2006)



Physics

Theoretical Upper Bound on Hurricane Maximum Wind Speed:



Surface temperature

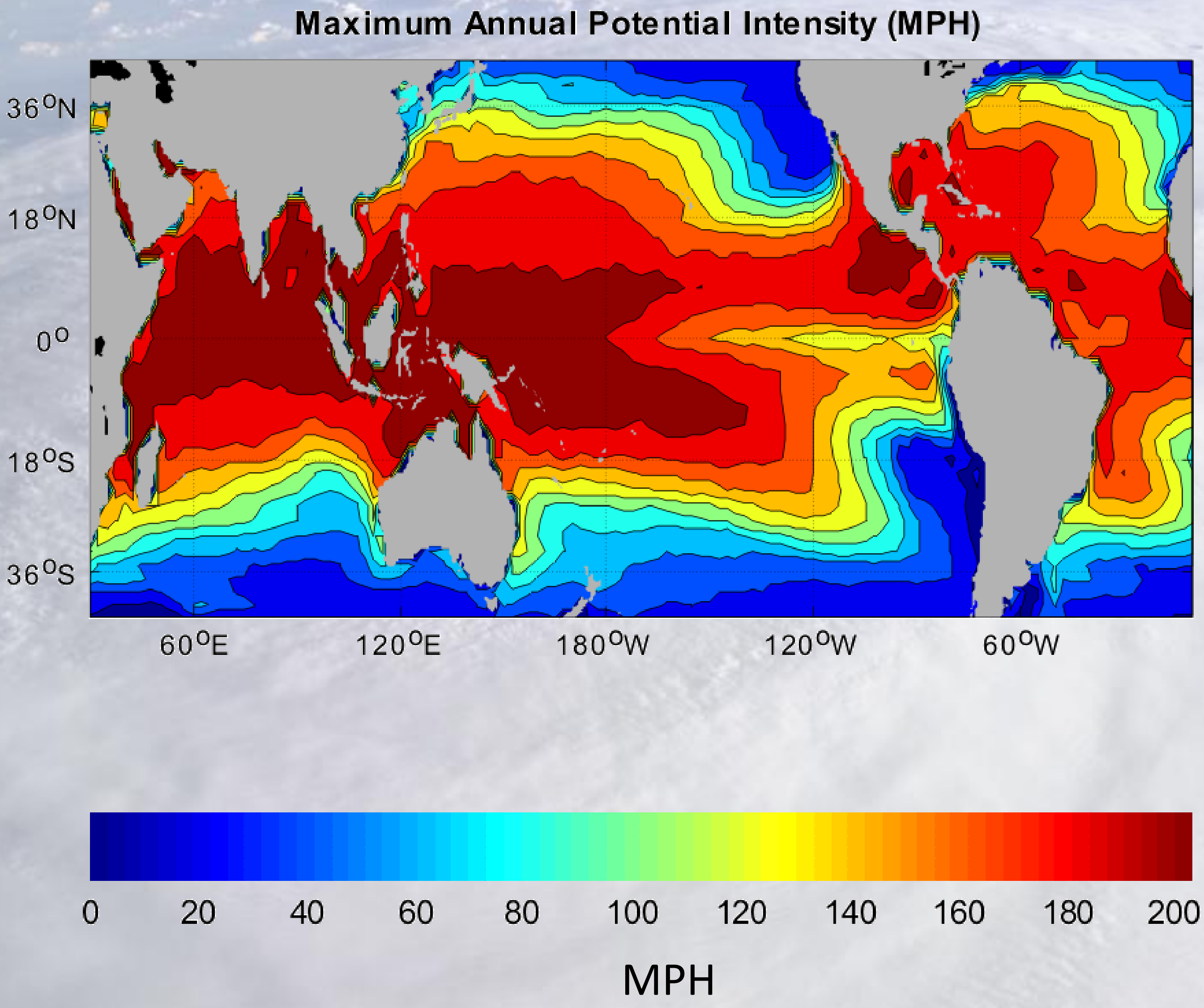
$$|V_{pot}|^2 \cong \boxed{\frac{C_k}{C_D}} \frac{T_s - T_o}{T_o} \underbrace{\left(k_0^* - k\right)}$$

Ratio of exchange coefficients of enthalpy and momentum

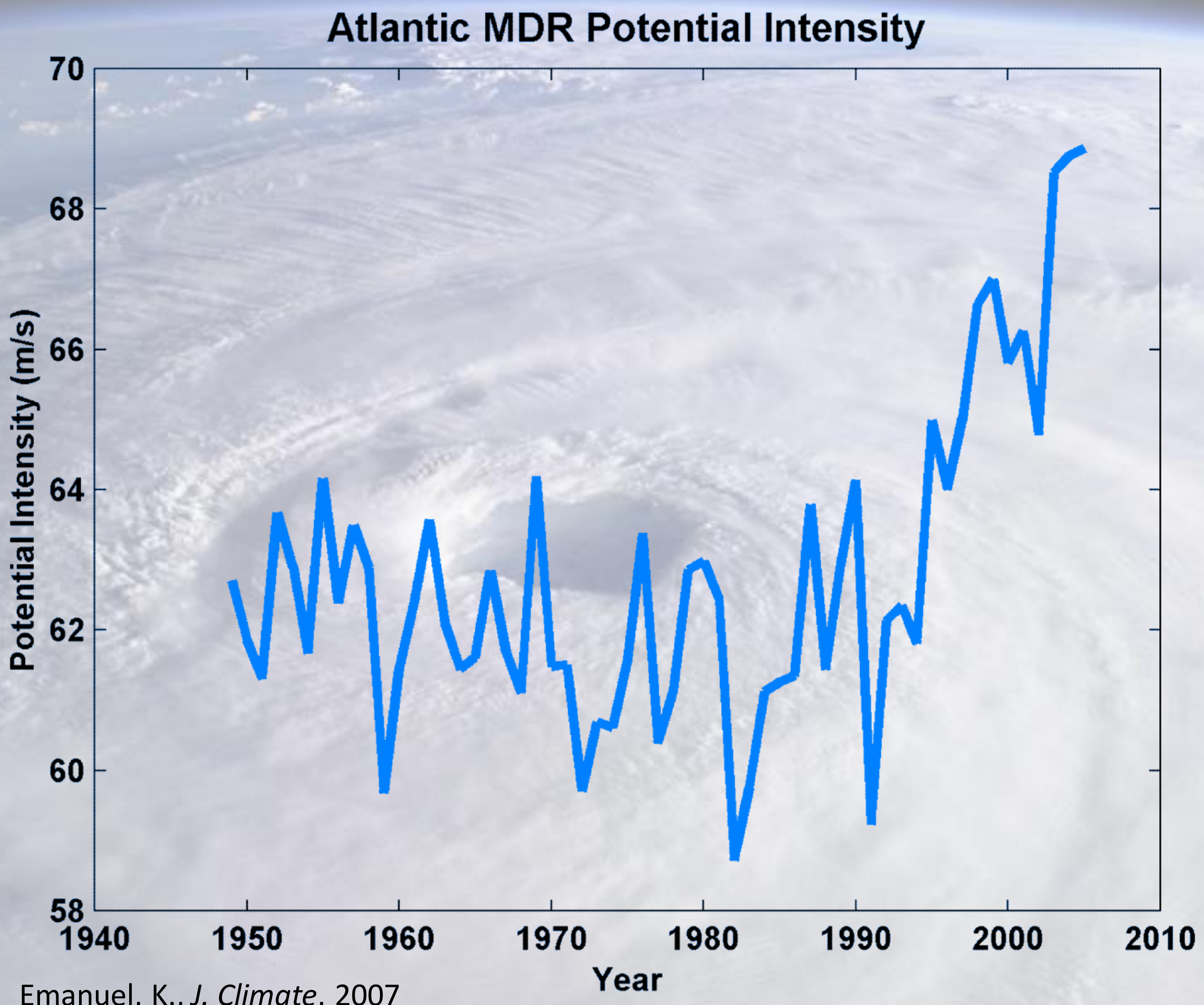
Outflow temperature

Air-sea enthalpy disequilibrium

Heat Engine Theory Predicts Maximum Hurricane Winds



Observed Tropical Atlantic Potential Intensity



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

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

Downscaling from Global Climate Models

Our Approach

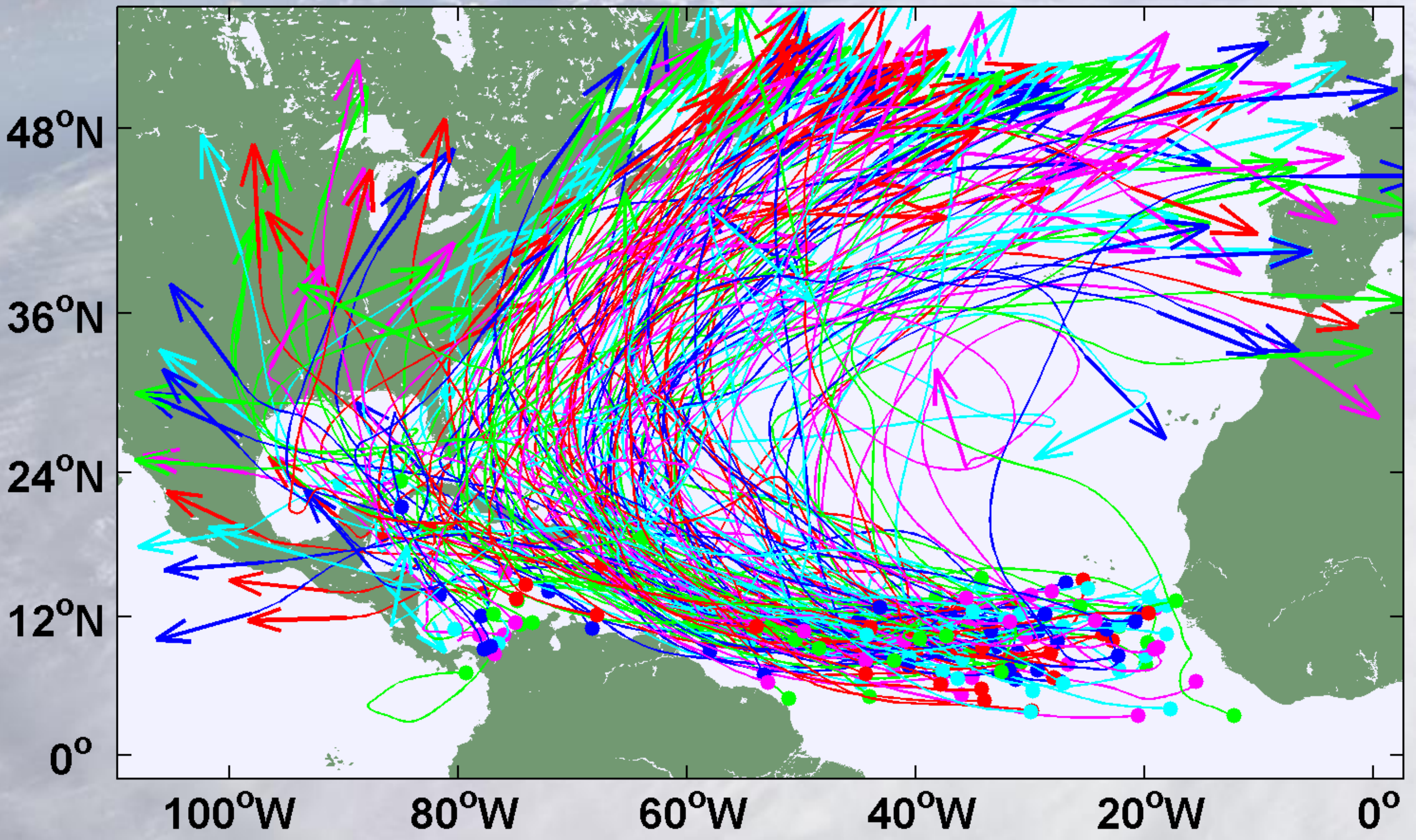
- **Step 1**: Seed each ocean basin with a very large number of weak, randomly located cyclones

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

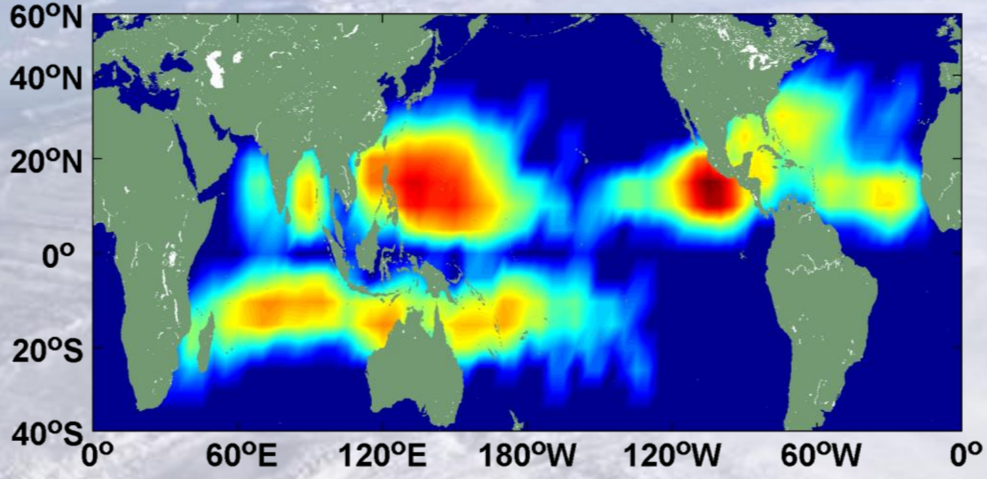
- **Step 3**: Run a coupled, ocean-atmosphere computer model (CHIPS) for each cyclone, and note how many achieve at least tropical storm strength

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

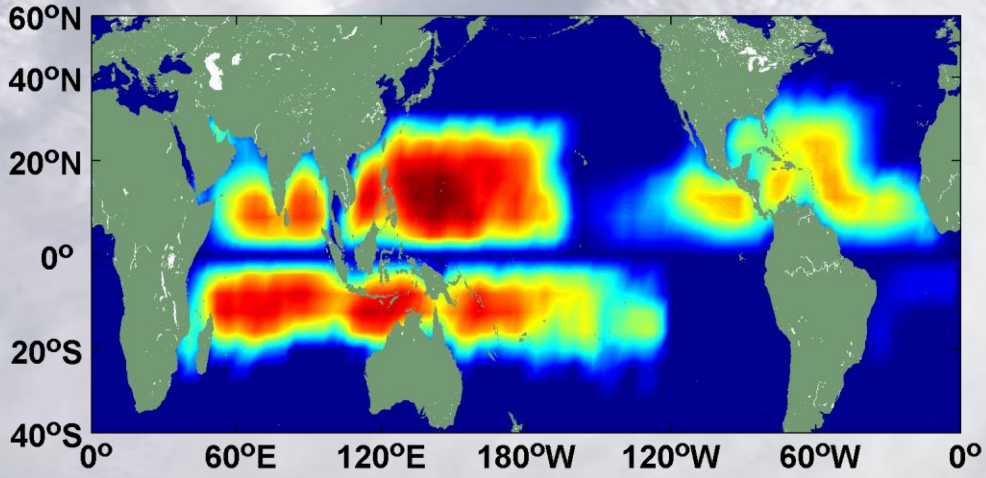
Example: 200 Synthetic Tracks



Present Climate: Spatial Distribution of Genesis Points



Observed

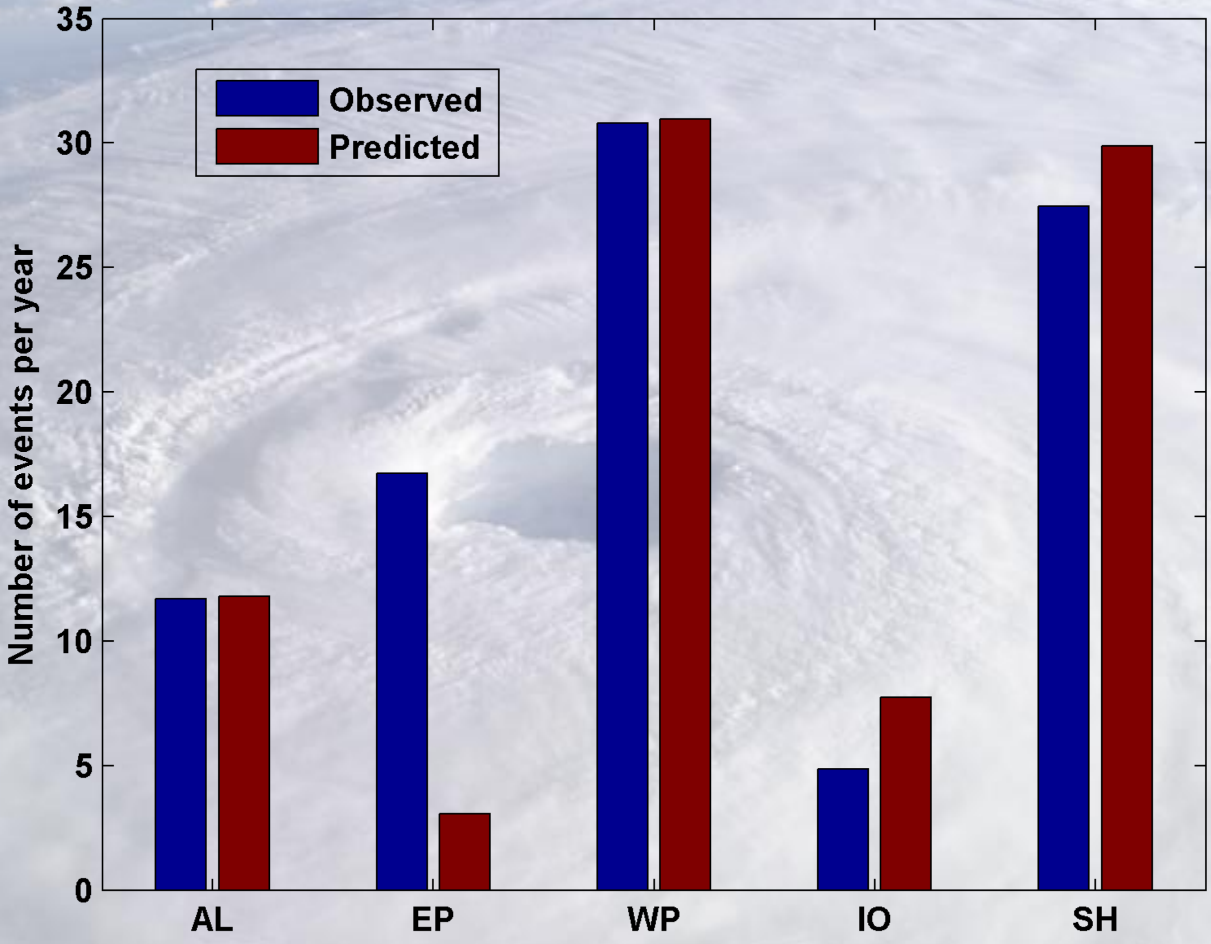


Synthetic

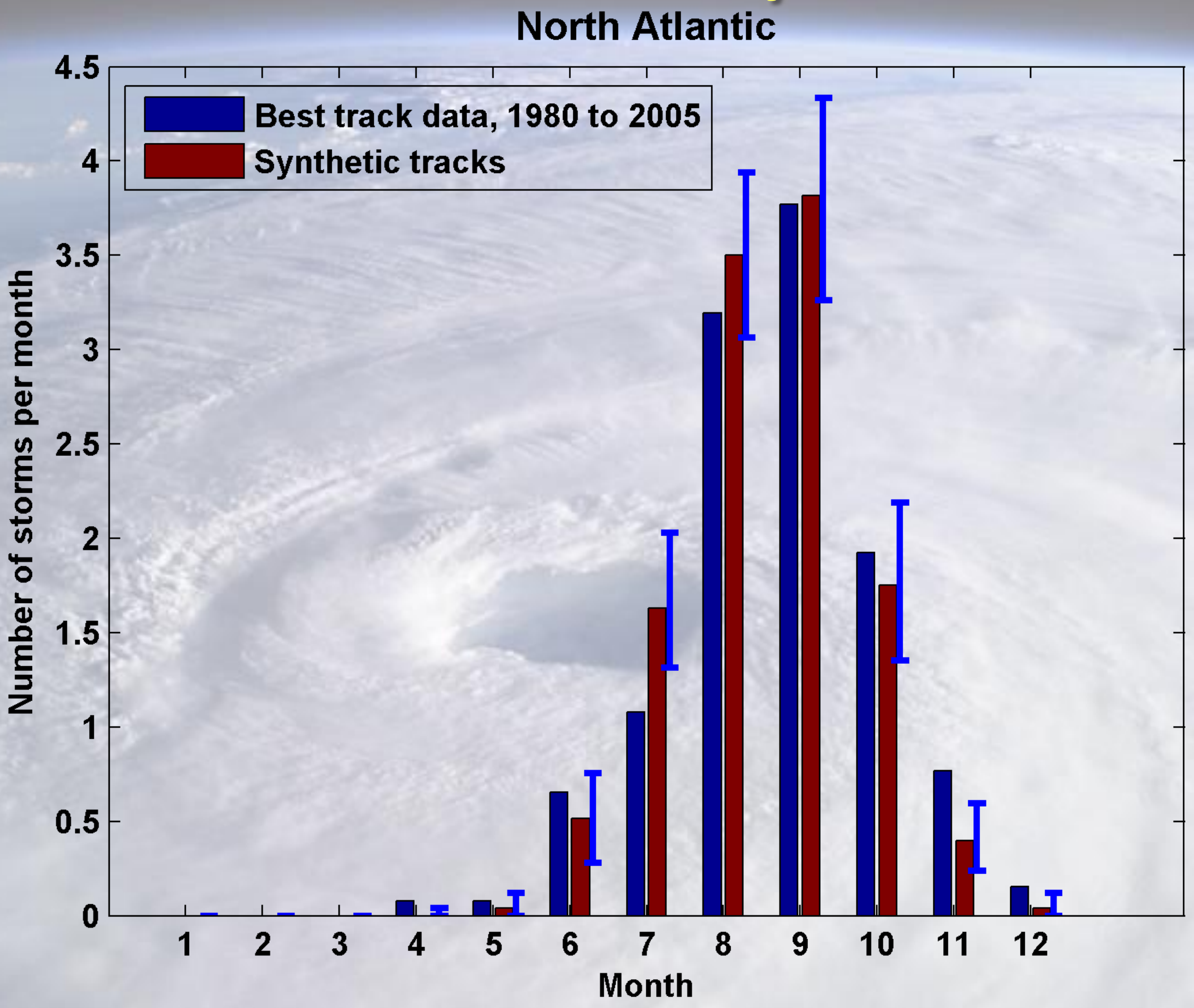
Calibration

- **Absolute genesis frequency calibrated to North Atlantic during the period 1980-2005**

Genesis Rates

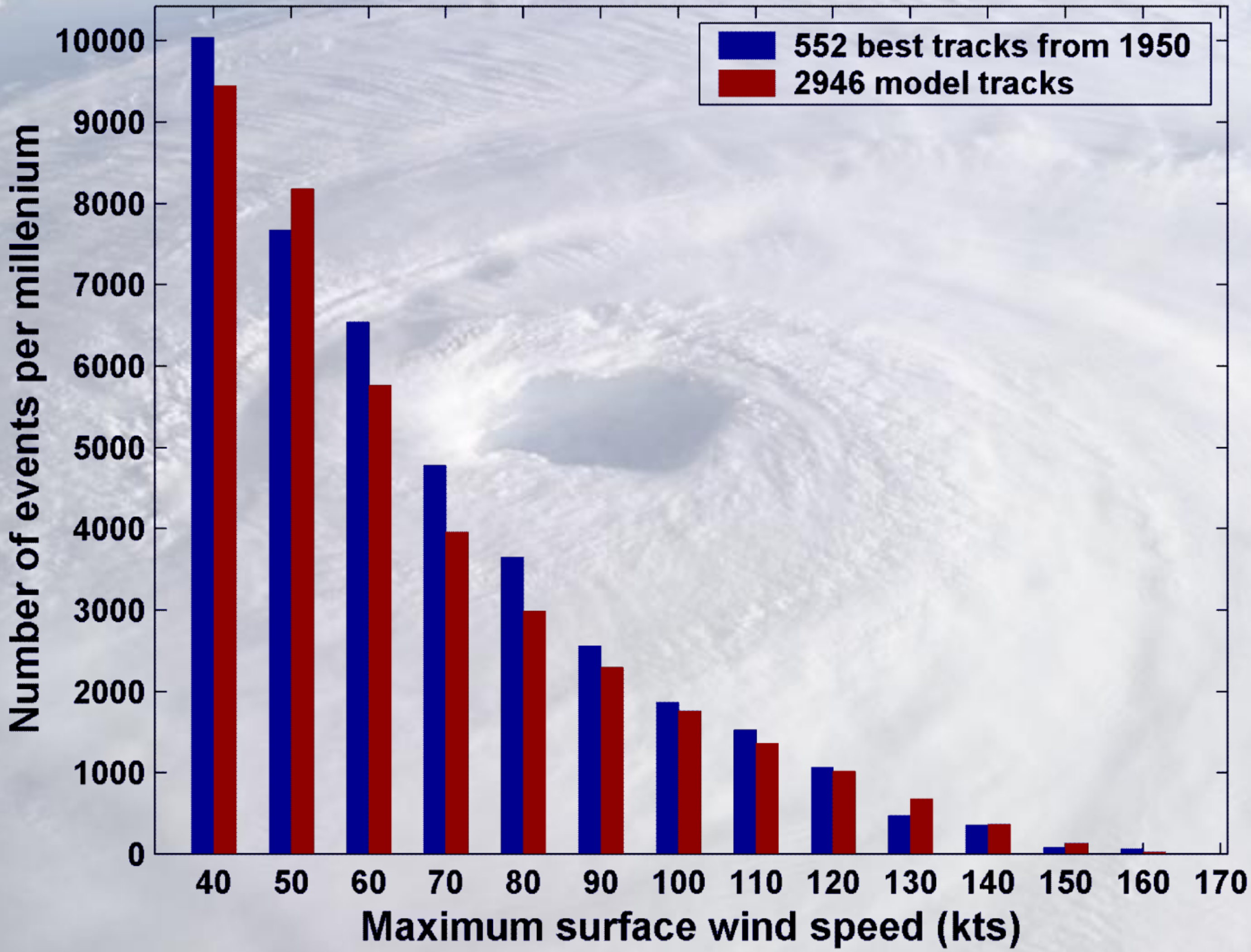


Seasonal Cycles

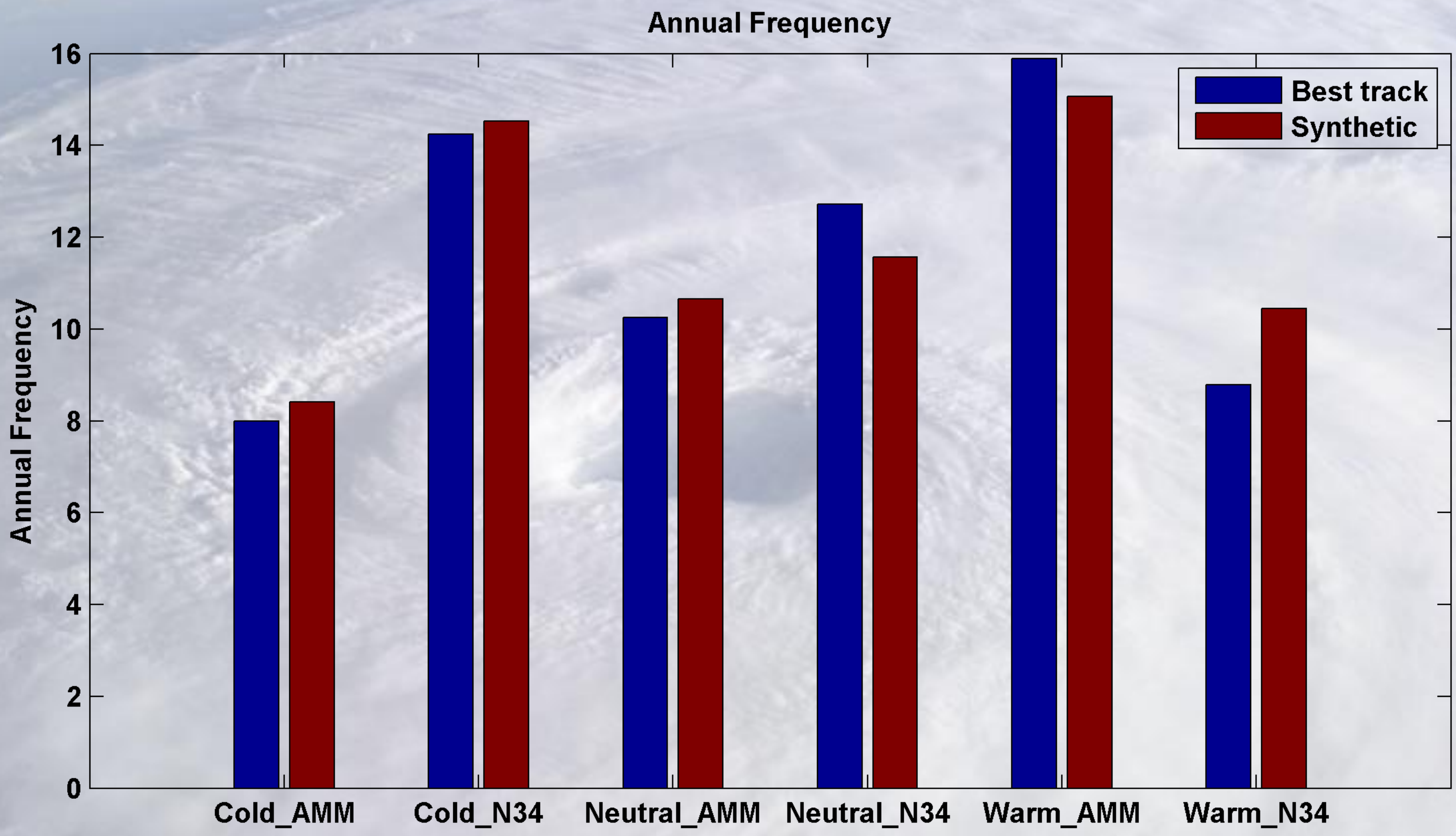


Atlantic

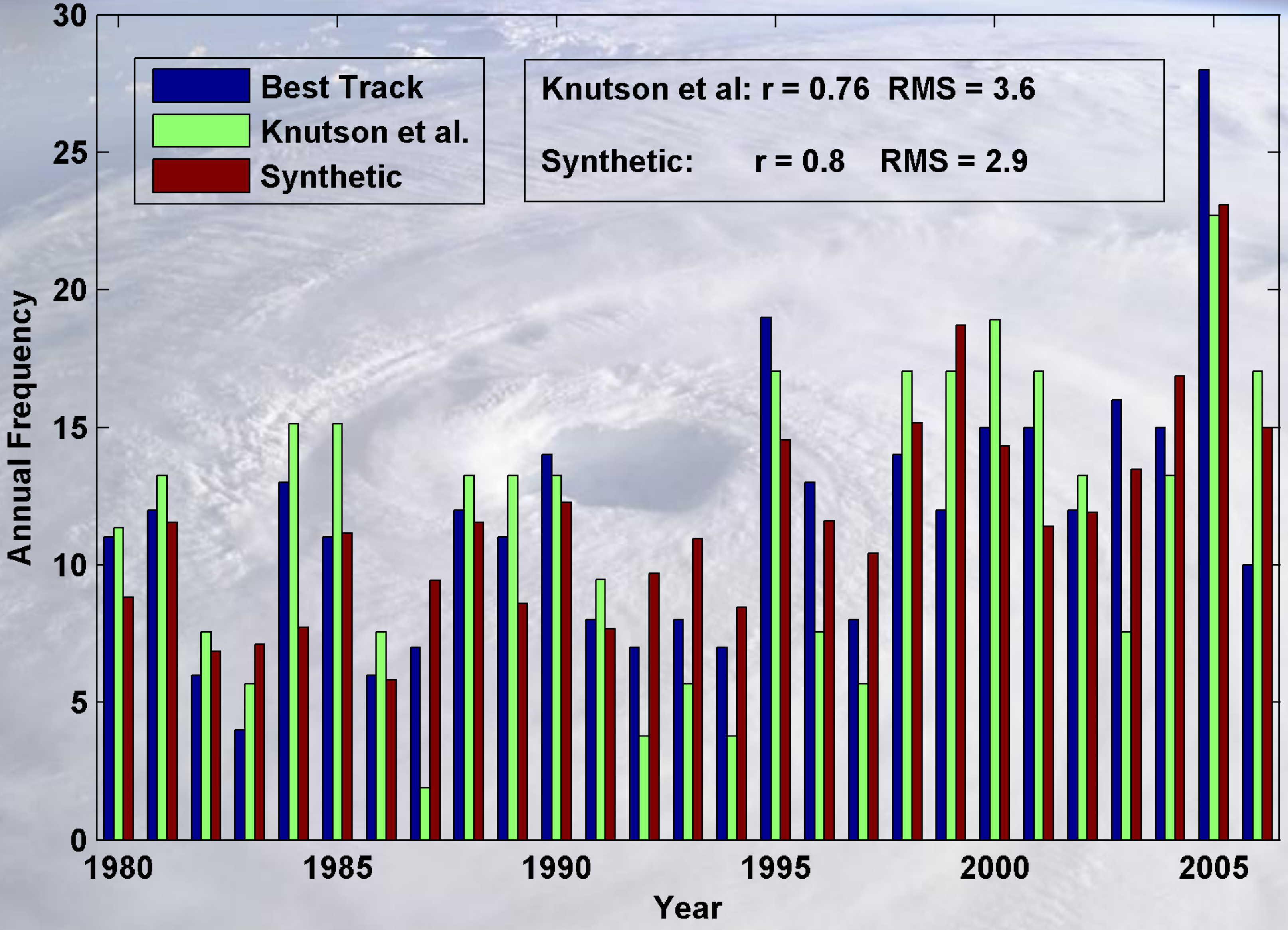
Cumulative Distribution of Storm Lifetime Peak Wind Speed, with Sample of 2946 Synthetic Tracks



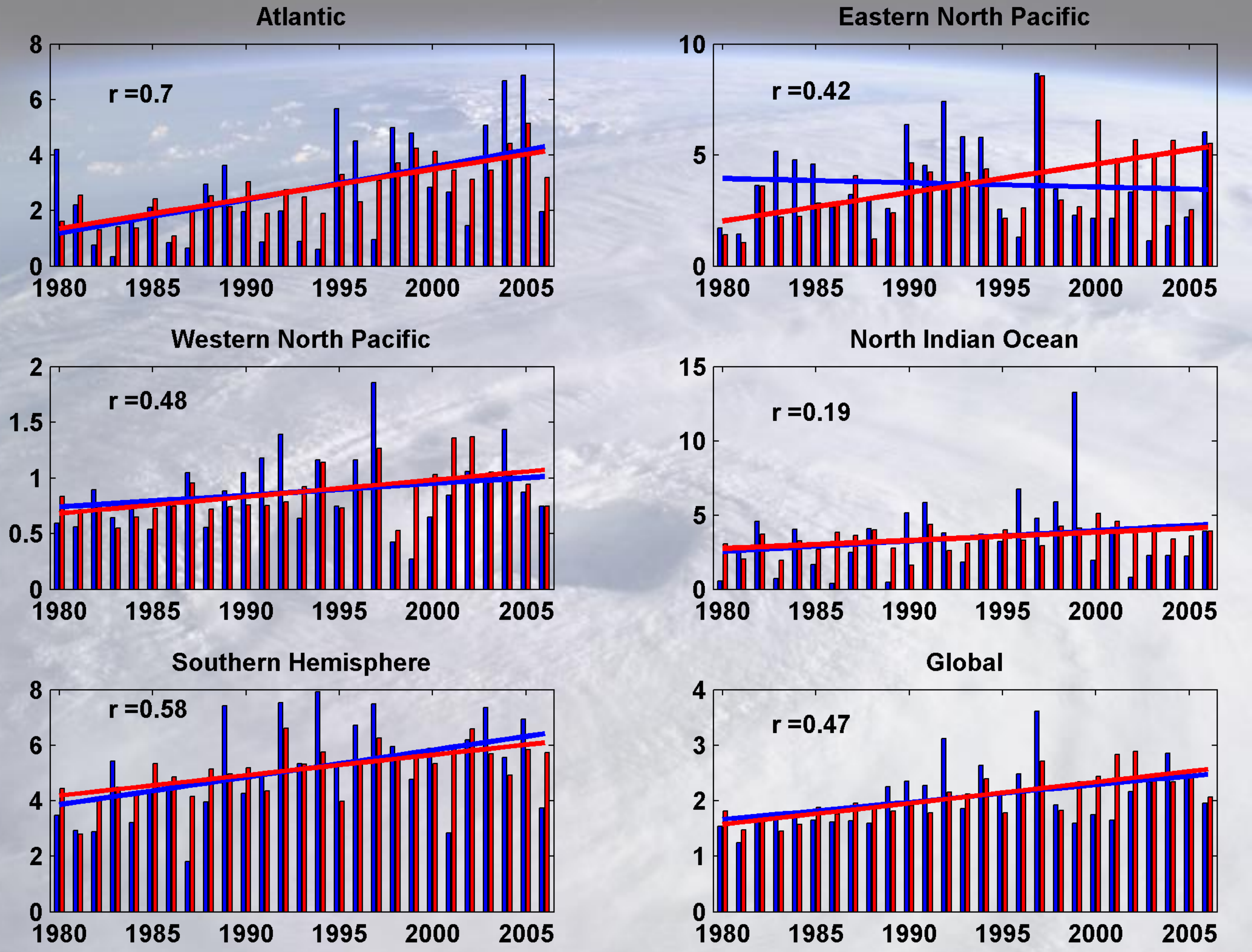
Captures effects of regional climate phenomena (e.g. ENSO, AMM)



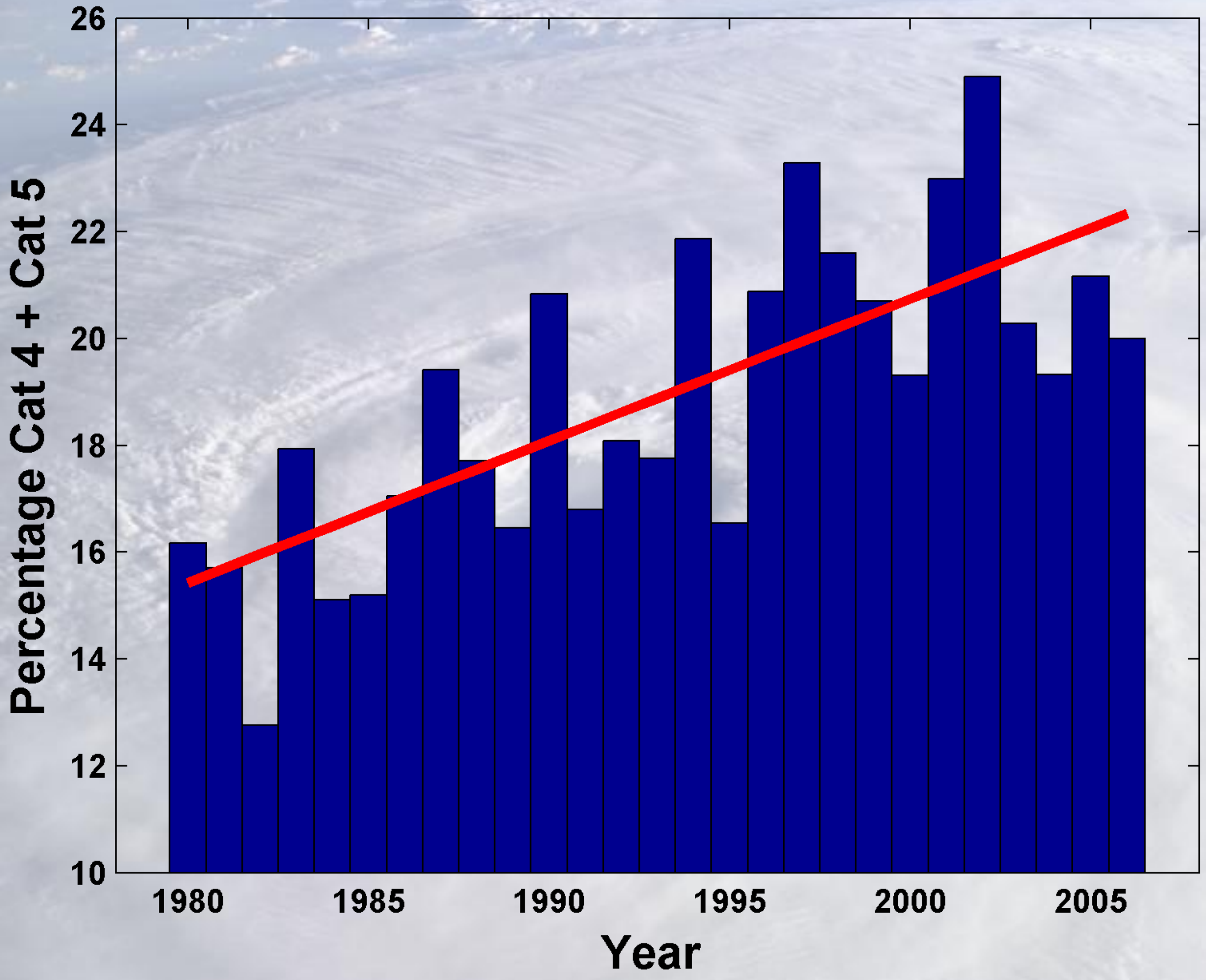
Year by Year Comparison with Best Track and with Knutson et al., 2007



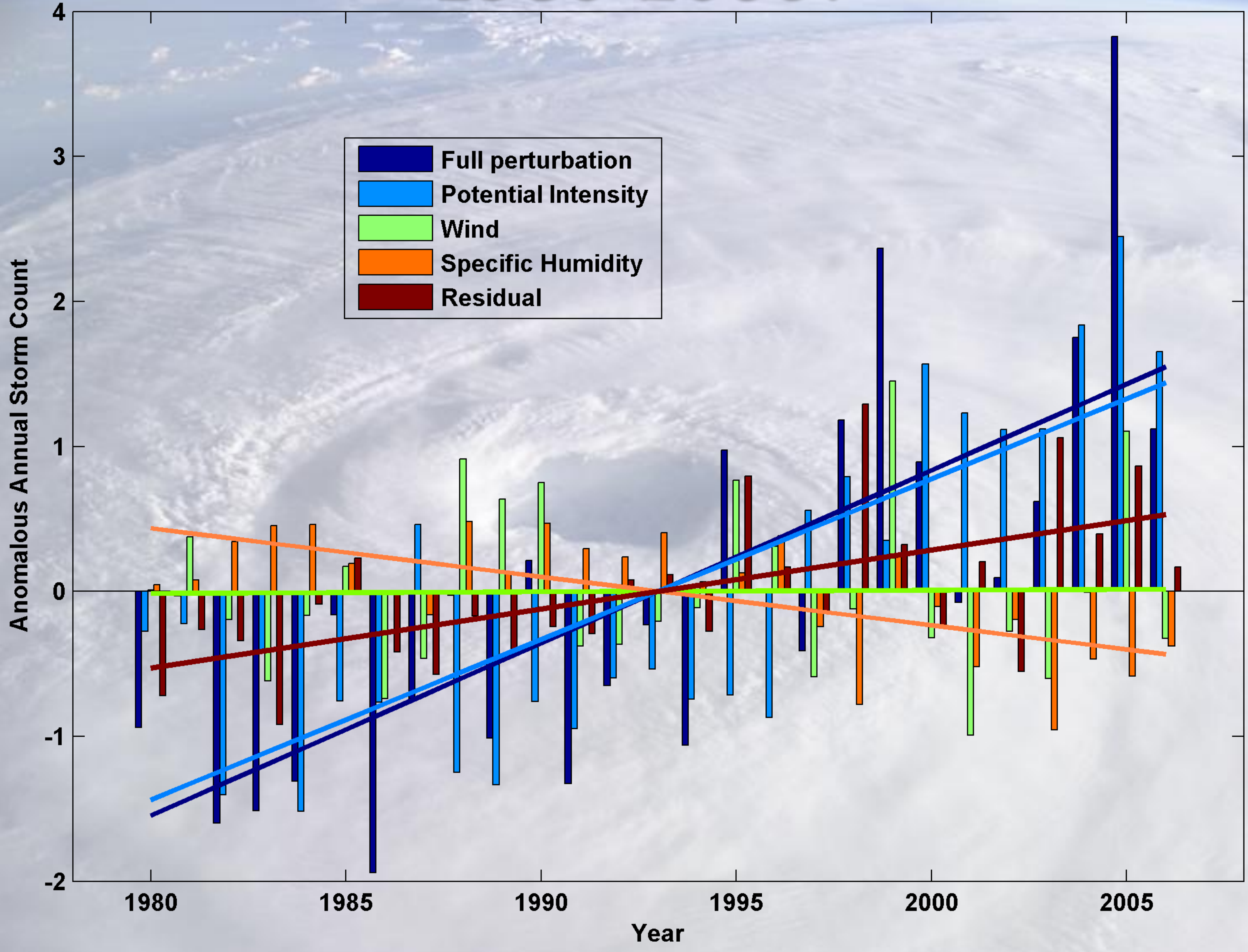
Simulated vs. Observed Power Dissipation Trends, 1980-2006



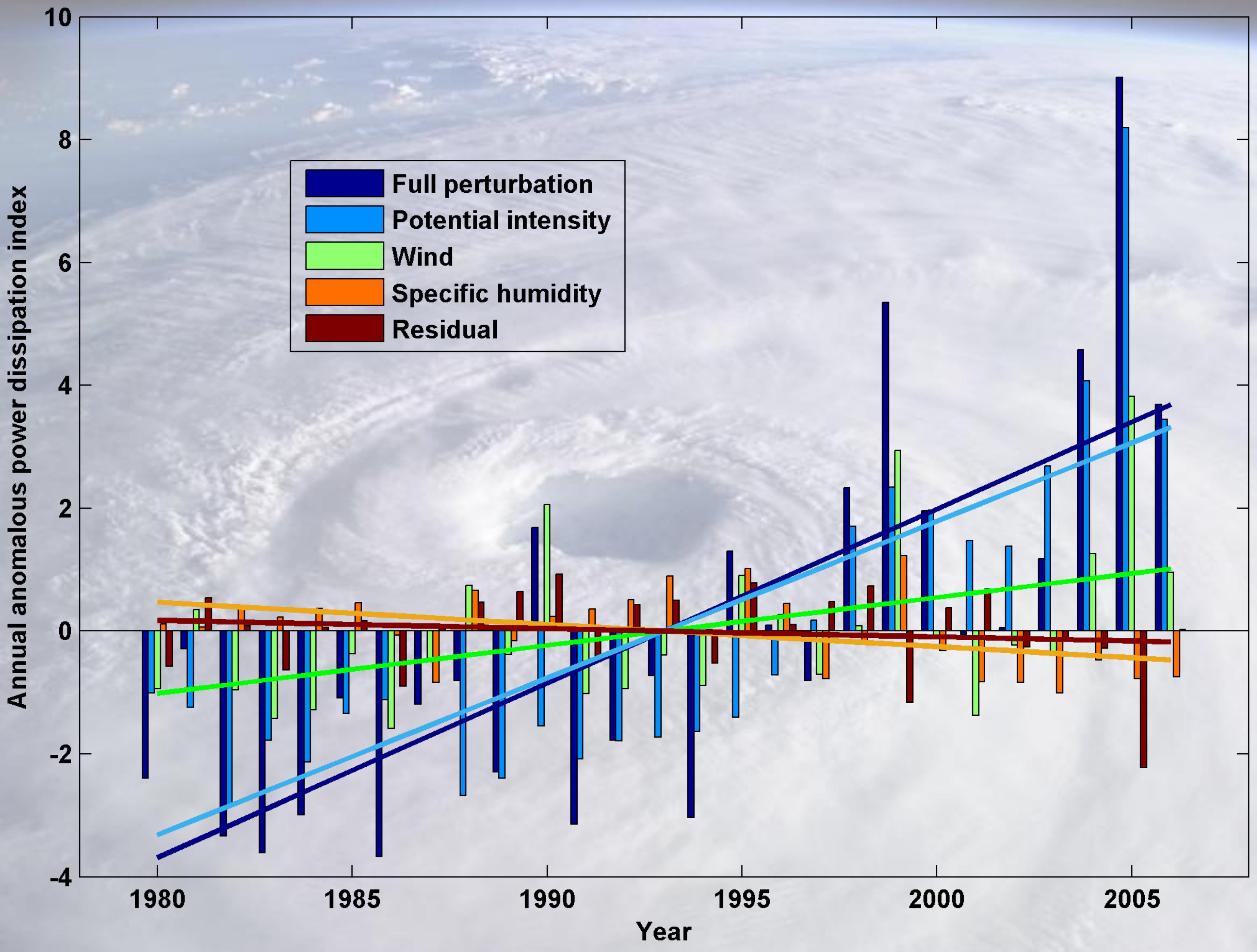
Global Percentage of Cat 4 & Cat 5 Storms



What Caused Changes in the Atlantic, 1980-2006?

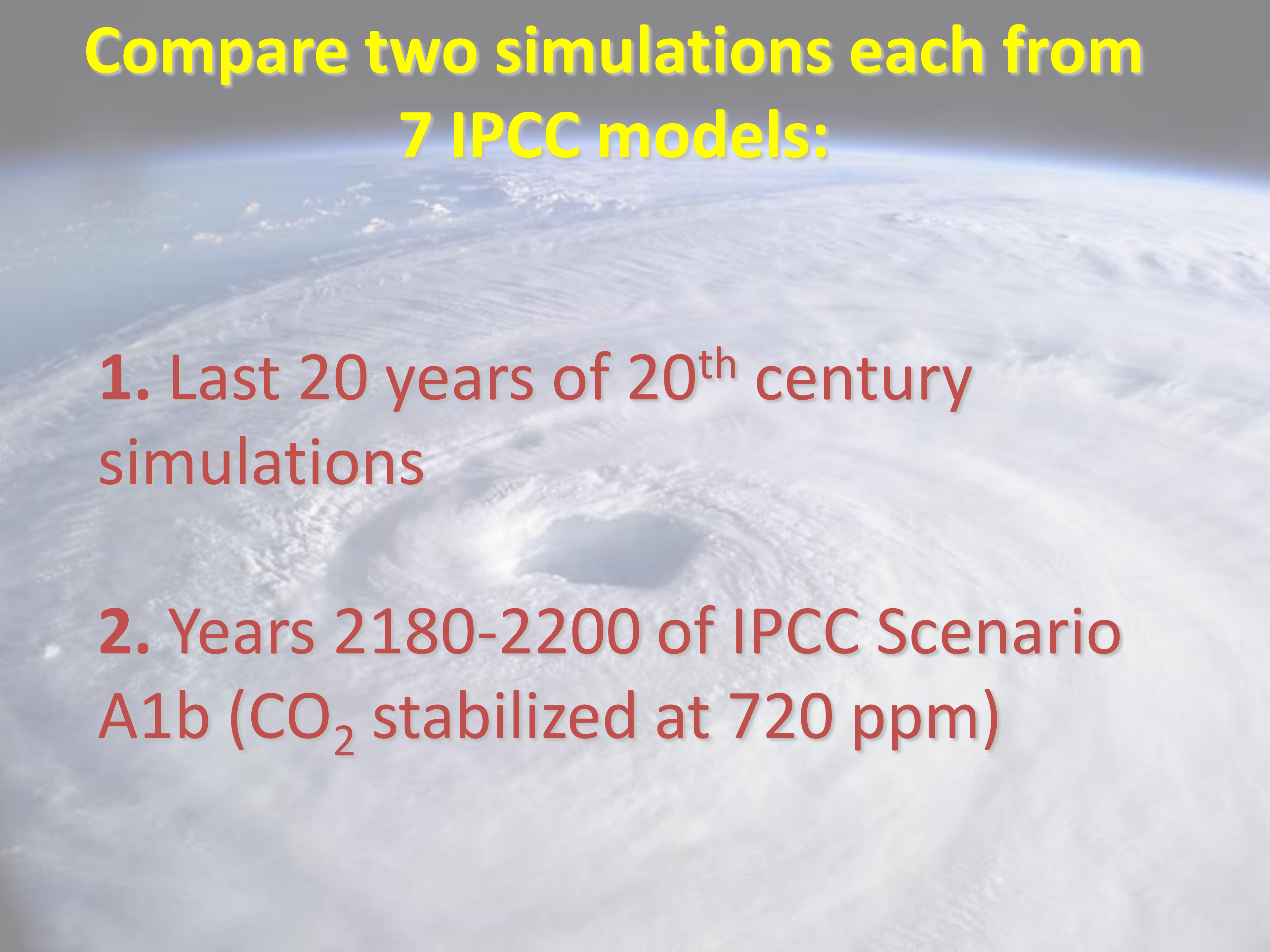


Power Dissipation



Now Use Daily Output from IPCC Models to Derive Wind Statistics, Thermodynamic State Needed by Synthetic Track Technique

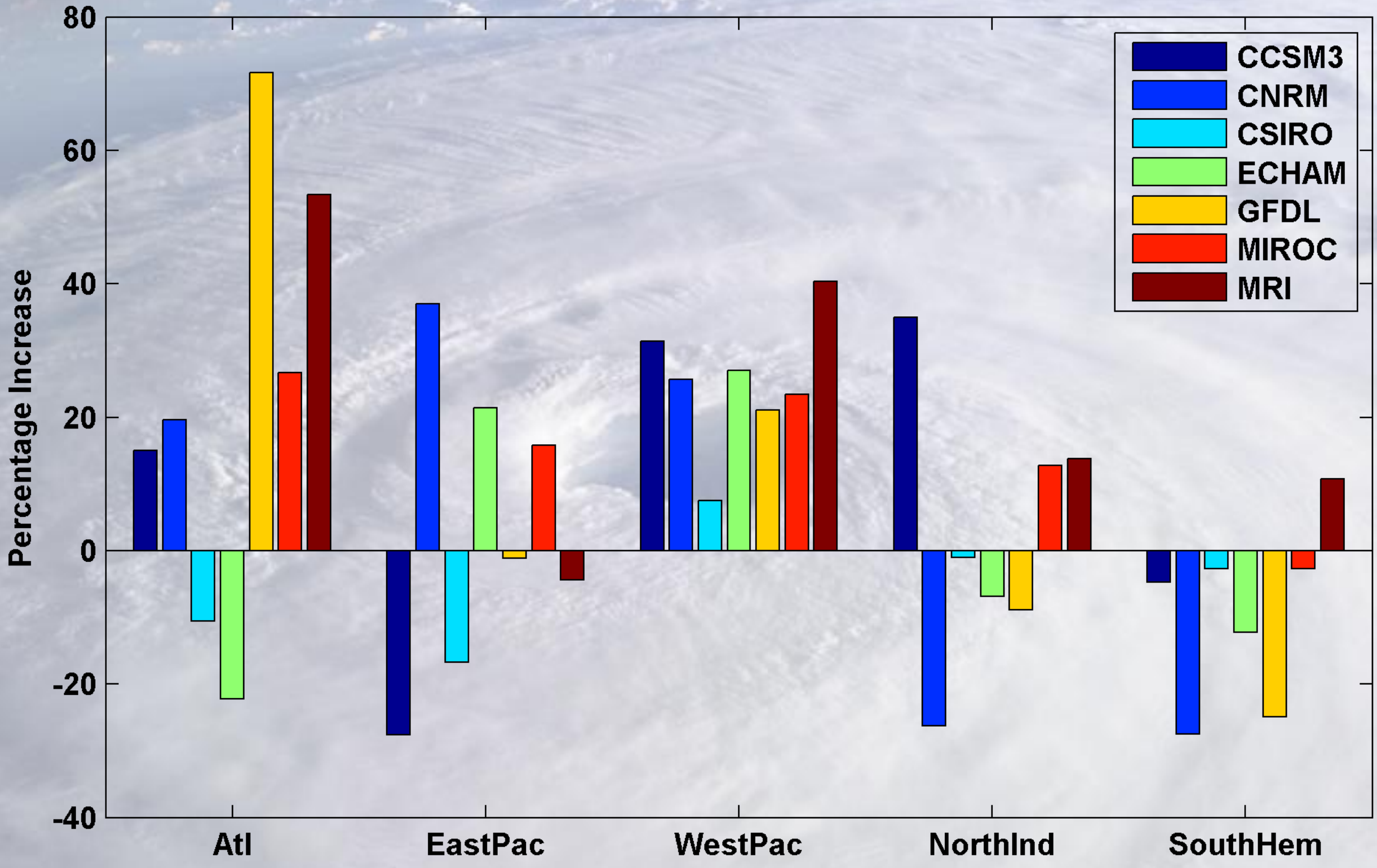
Compare two simulations each from 7 IPCC models:



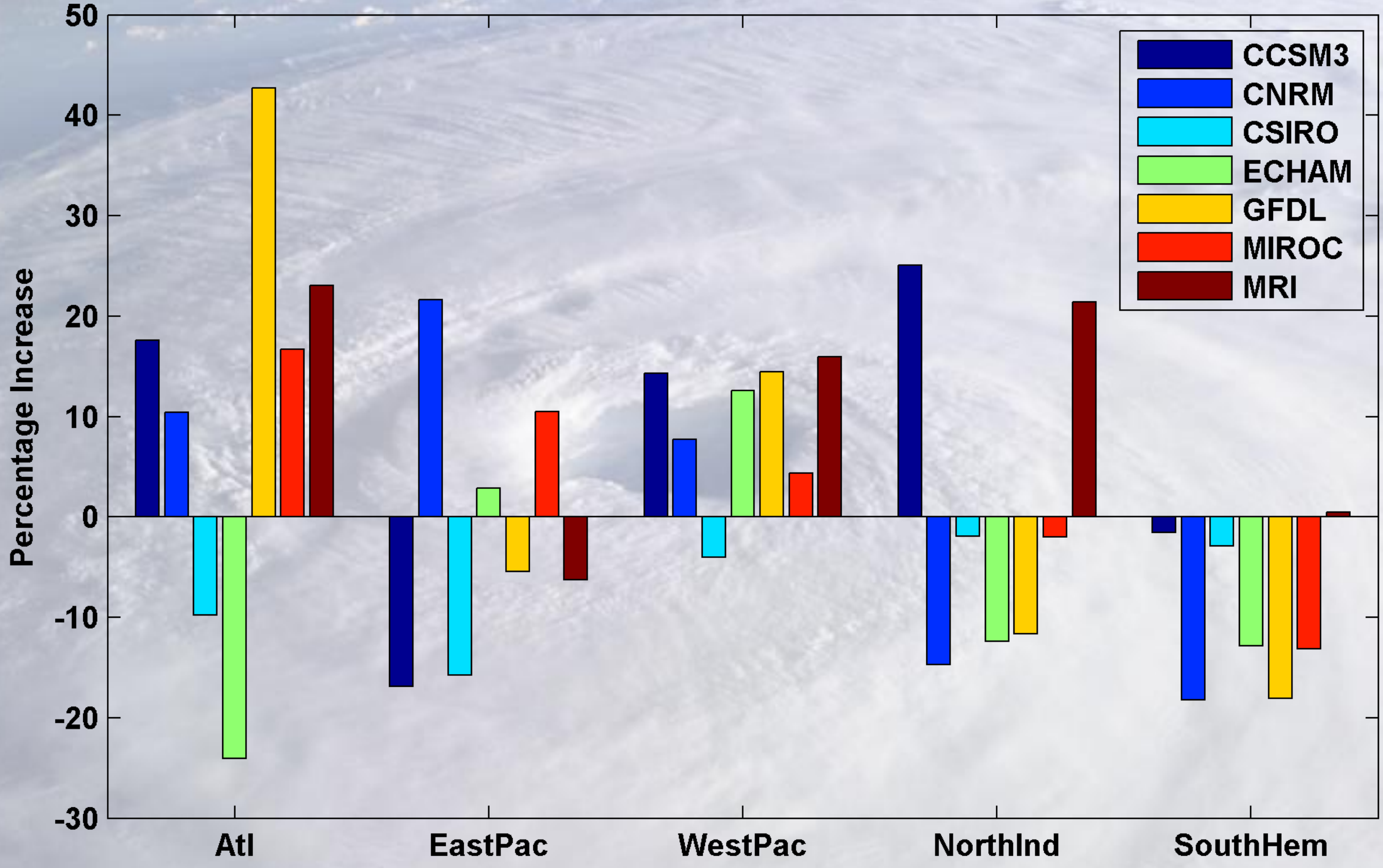
1. Last 20 years of 20th century simulations

2. Years 2180-2200 of IPCC Scenario A1b (CO_2 stabilized at 720 ppm)

Basin-Wide Percentage Change in Power Dissipation

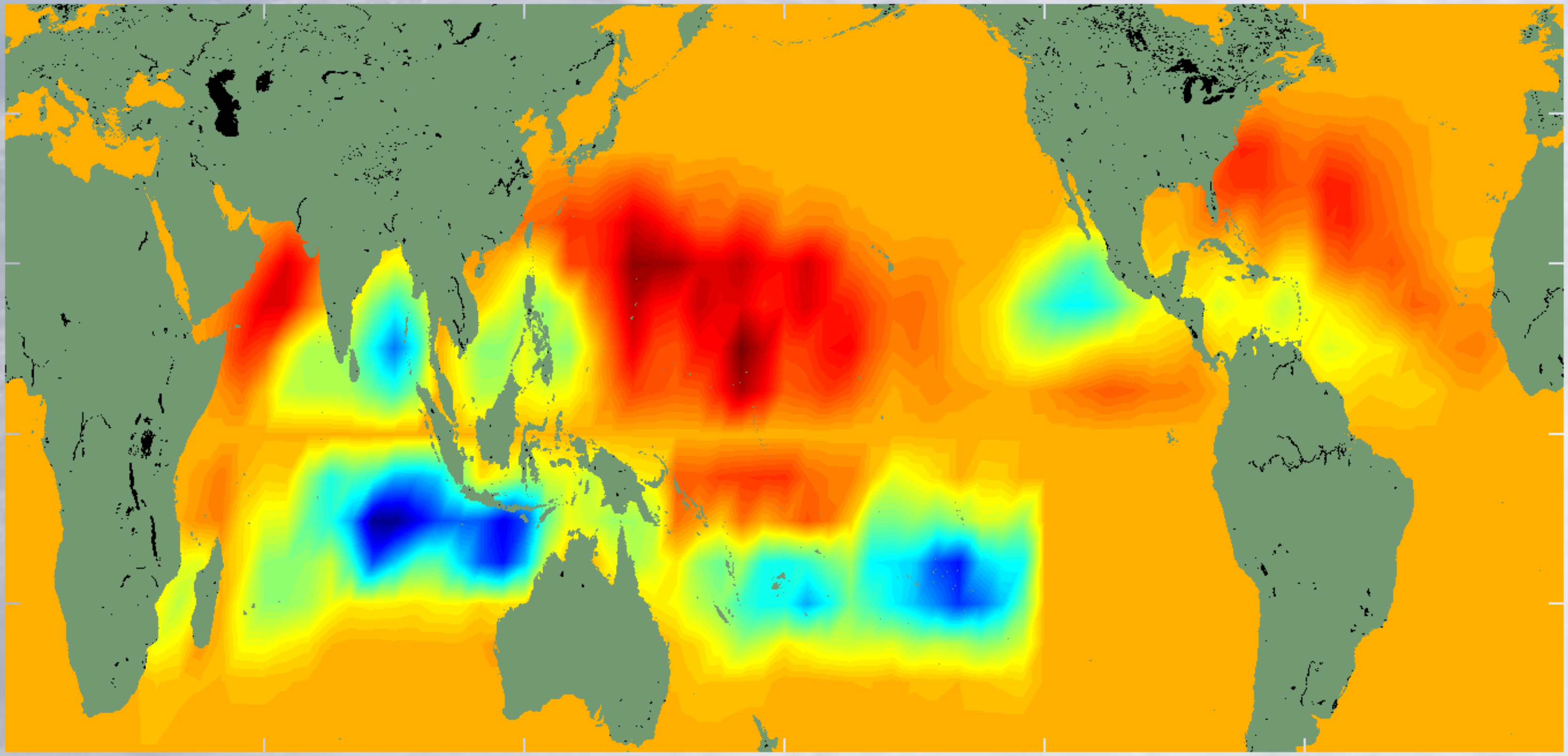


Basin-Wide Percentage Change in Storm Frequency



7 Model Consensus Change in Storm Frequency

7-Model Consensus Change in Genesis Density

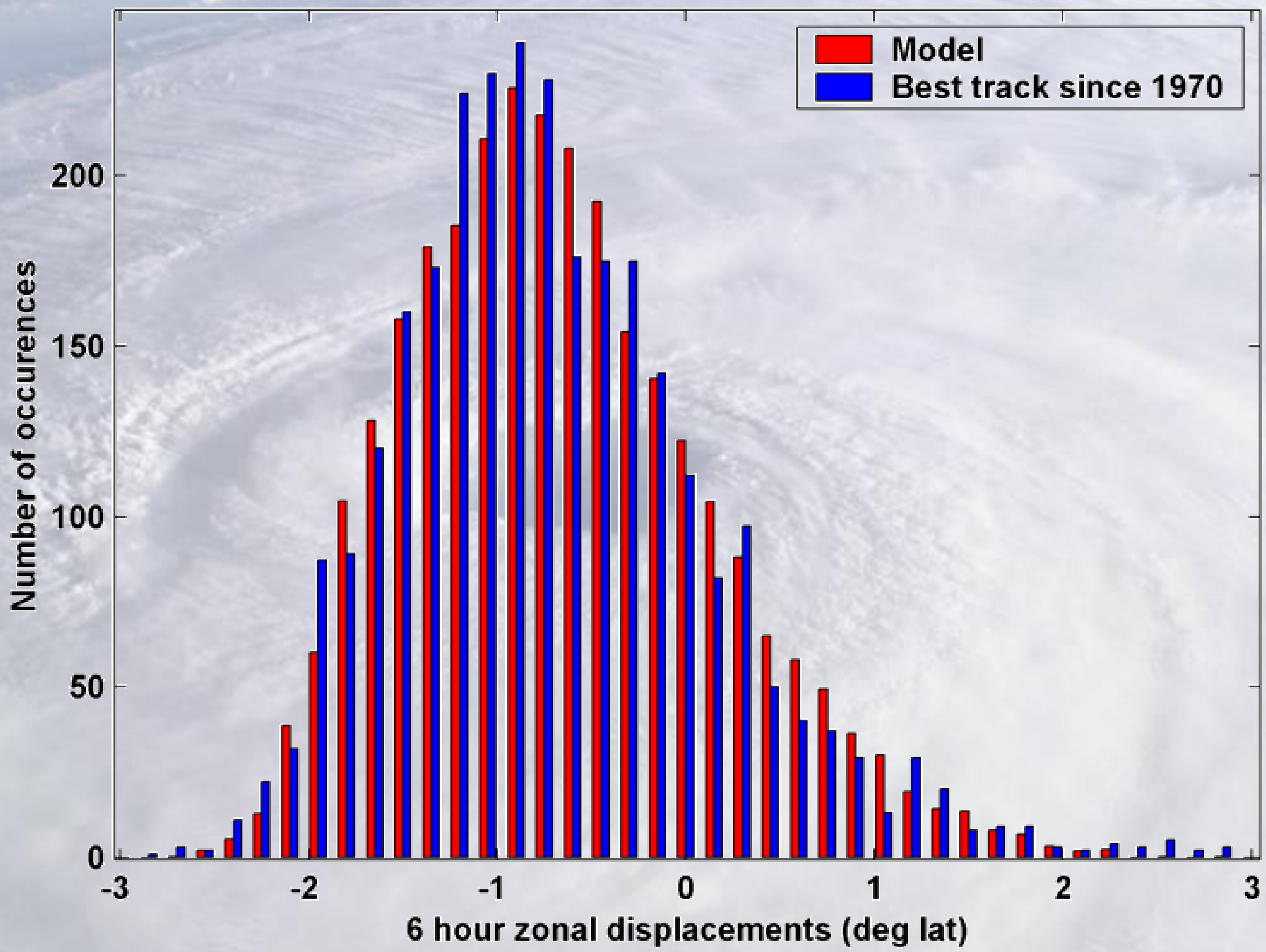


Some Concluding Thoughts:

- **Globally, the frequency of tropical cyclones shows no trend, but power dissipation has been increasing over the past 25 years**
- **Atlantic hurricane frequency and power dissipation are increasing, probably as a result of global warming**
- **Future projections yield mixed results on affect of global warming on hurricane activity**

Spare Slides

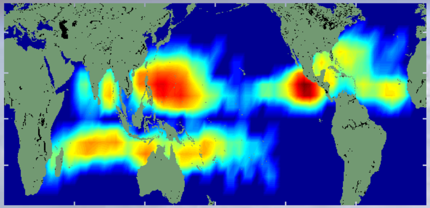
6-hour zonal displacements in region bounded by 10° and 30° N latitude, and 80° and 30° W longitude, using only post-1970 hurricane data



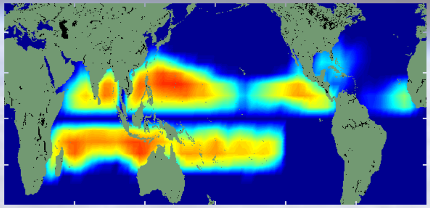
Model	**Institution**	**Atmospheric Resolution**	**Designation in this paper**	**Potential Intensity Multiplicative Factor**
Community Climate System Model, 3.0	National Center for Atmospheric Research	T85, 26 levels	**CCSM3**	1.2
CNRM-CM3	Centre National de Recherches Météorologiques, Météo-France	T63, 45 levels	**CNRM**	1.15
CSIRO-Mk3.0	Scientific and Research Organization	T63, 18 levels	**CSIRO**	1.2
ECHAM5	Max Planck Institution	T63, 31 levels	**ECHAM**	0.92
GFDL-CM2.0	NOAA Geophysical Fluid Dynamics Laboratory	2.5^{o} X 2.5^{o} , 24 levels	**GFDL**	1.04
MIROC3.2	CCSR/NIES/FRCGC, *Japan*	T42, 20 levels	**MIRO**	1.07
mri_cgcm2.3.2a	Meteorological Research Institute,	T42, 30 levels	**MRI**	0.97

Genesis Distributions

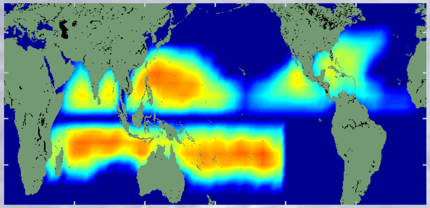
Best Track



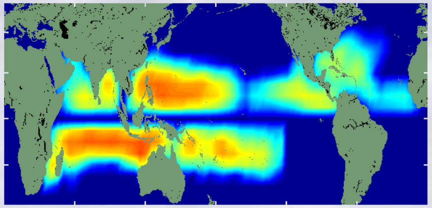
CCSM3



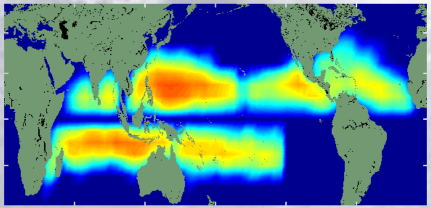
CNRM



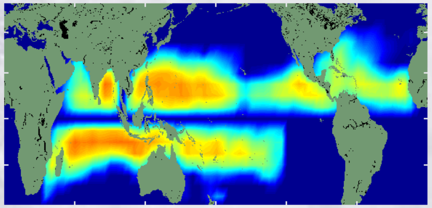
CSIRO



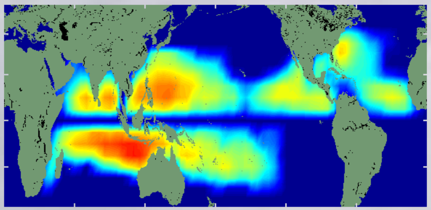
ECHAM



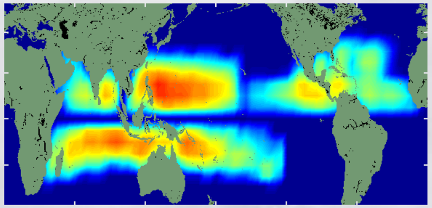
GFDL



MIROC



MRI



Why does frequency decrease?

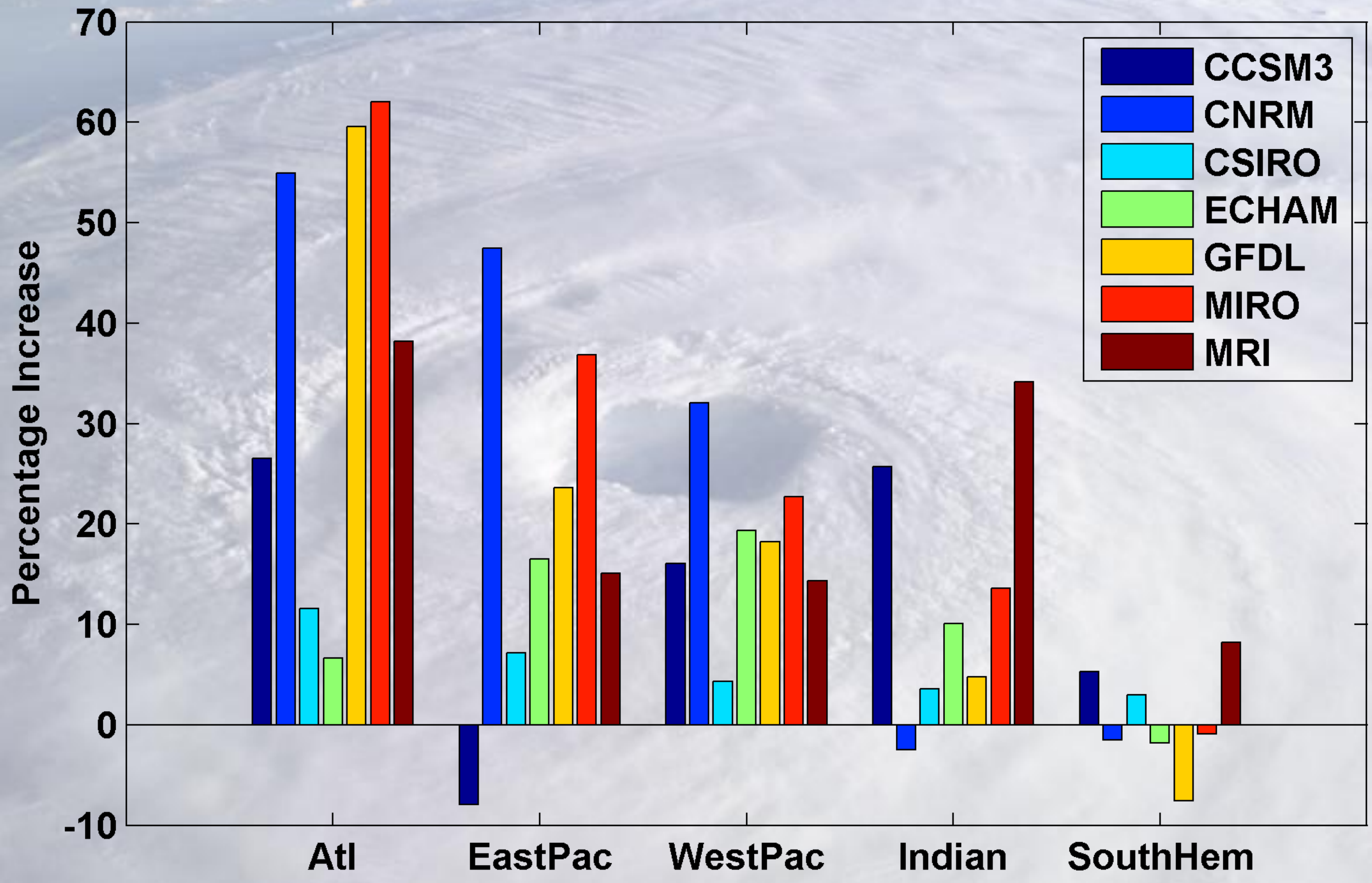
Critical control parameter in CHIPS:

$$\chi_m \equiv \frac{s_m - s_b}{s_0^* - s_b},$$

$$s_m - s_b \cong s_m - s^* = \frac{L_v q^*}{T}(\mathcal{H} - 1) - R_v \mathcal{H} q^* \ln \mathcal{H},$$

Entropy difference between boundary layer and middle troposphere *increases* with temperature at constant relative humidity

Change in Frequency when T held constant in χ_m



Synthetic Track Generation, Using Synthetic Wind Time Series

- Postulate that TCs move with vertically averaged environmental flow plus a “beta drift” correction (Beta and Advection Model, or “BAMS”)

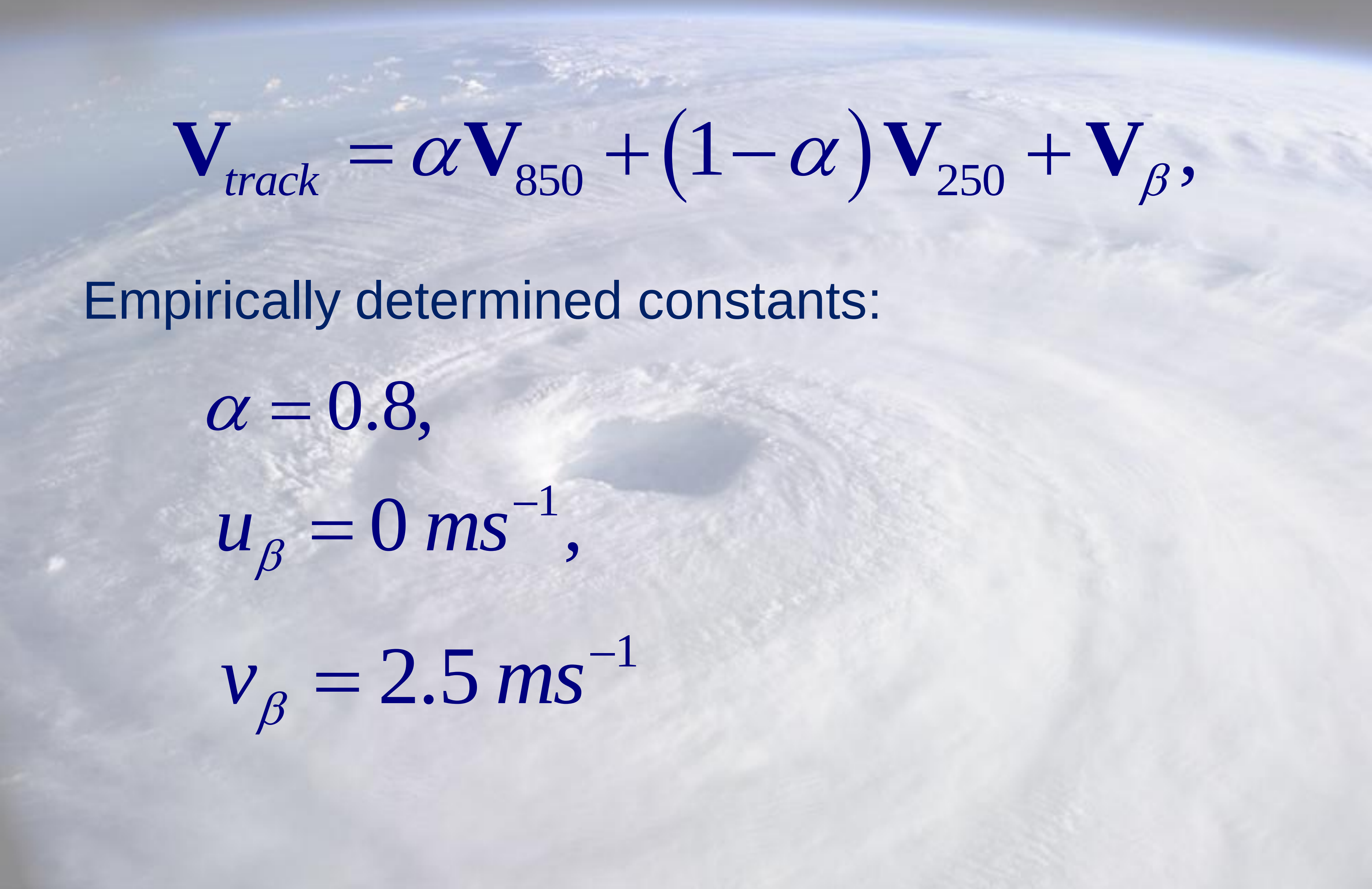
- Approximate “vertically averaged” by weighted mean of 850 and 250 hPa flow

Synthetic wind time series

- Monthly mean, variances and co-variances from NCEP re-analysis data

- Synthetic time series constrained to have the correct mean, variance, co-variances and an power series ω^{-3}

Track:



$$\mathbf{V}_{track} = \alpha \mathbf{V}_{850} + (1-\alpha)\mathbf{V}_{250} + \mathbf{V}_{\beta},$$

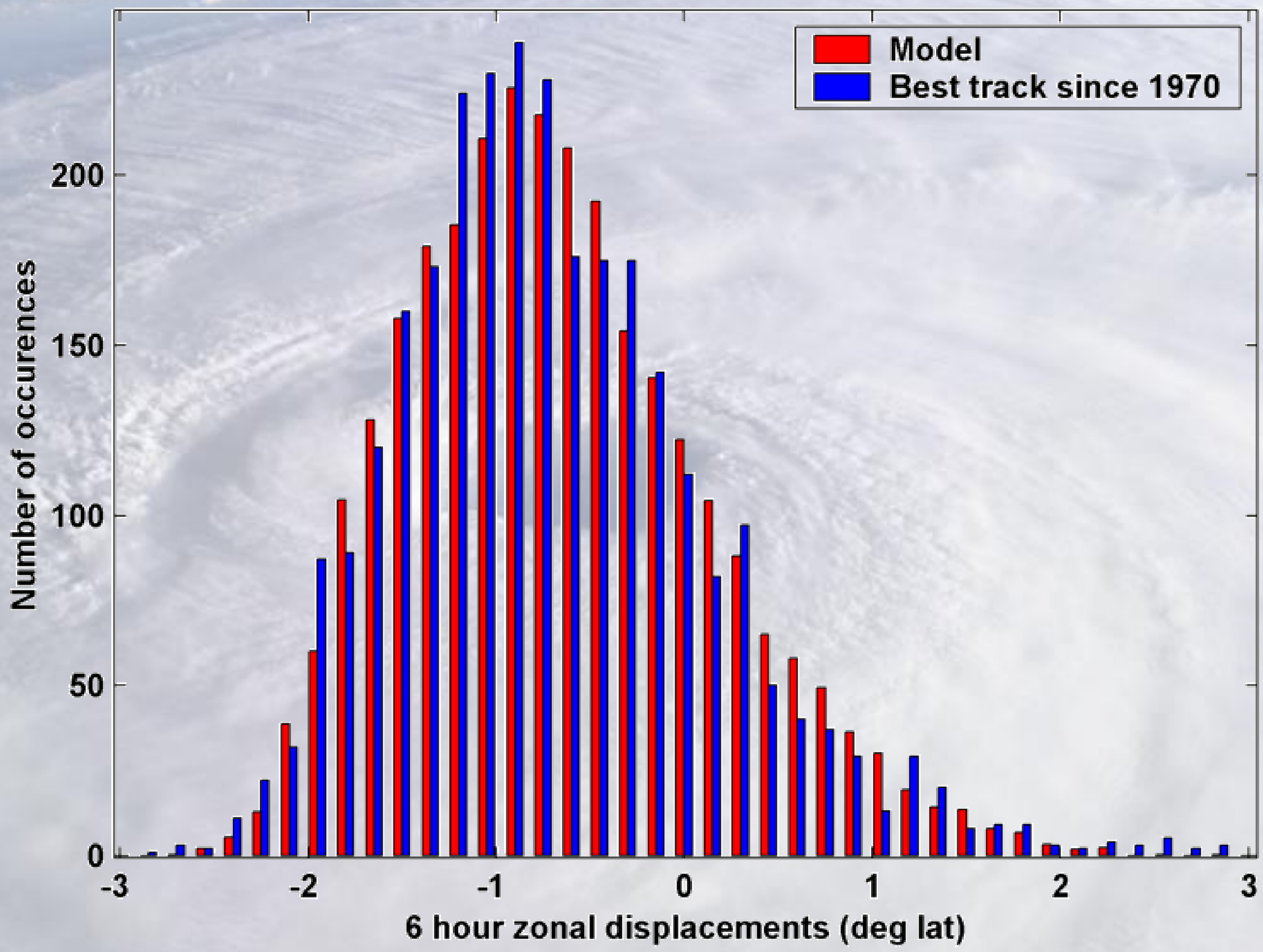
Empirically determined constants:

$$\alpha = 0.8,$$

$$u_{\beta} = 0\, ms^{-1},$$

$$v_{\beta} = 2.5\, ms^{-1}$$

6-hour zonal displacements in region bounded by 10° and 30° N latitude, and 80° and 30° W longitude, using only post-1970 hurricane data



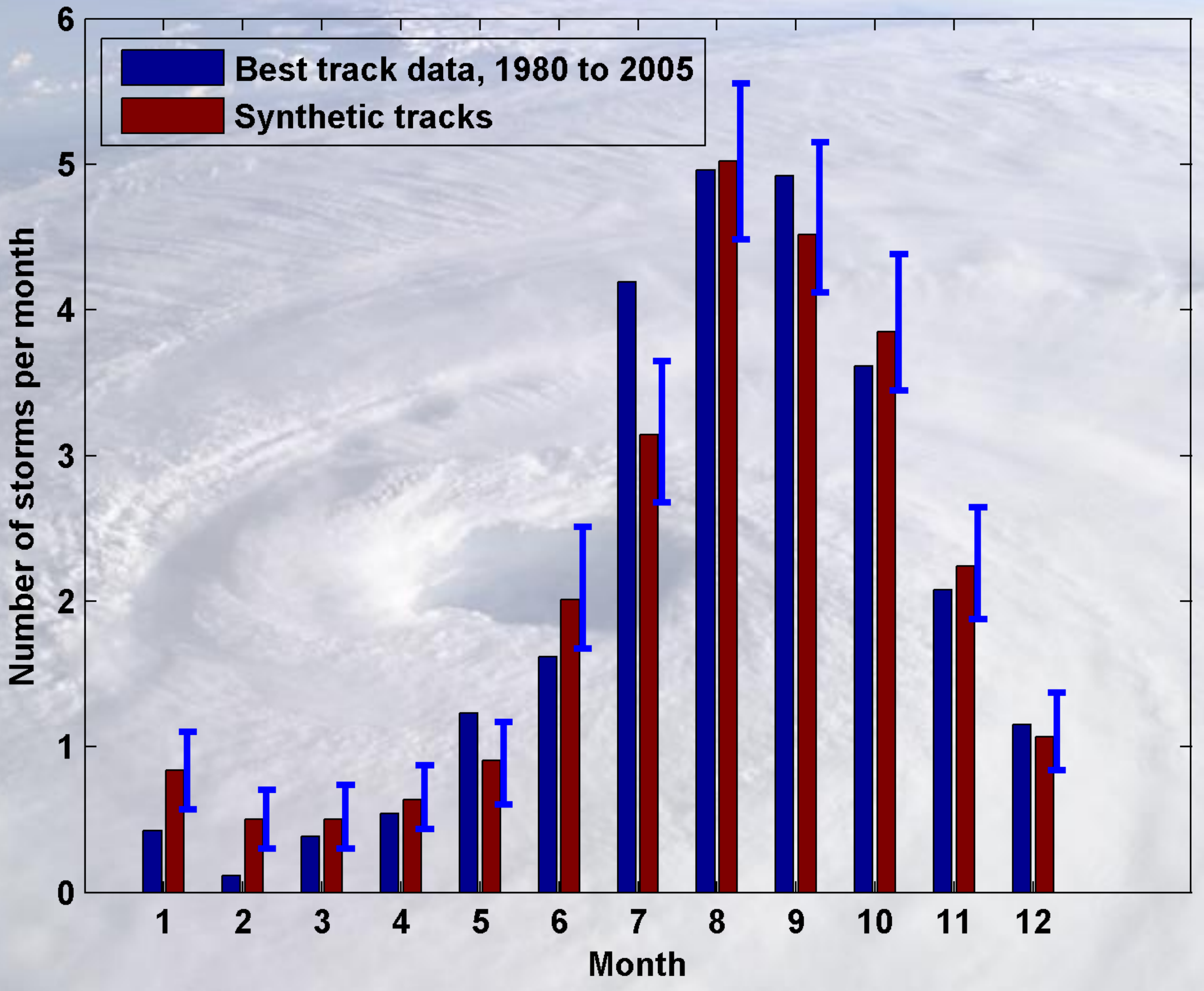
250 hPa zonal wind modeled as Fourier series in time with random phase:

$$u_{250}(x,y,\tau,t)=\bar{u}_{250}(x,y,\tau)+\sqrt{\overline{u'^{2}_{250}(x,y,\tau)}F_1(t)}$$

$$F_1\equiv\sqrt{\frac{2}{\sum\limits_{n=1}^{N}n^{-3}}}\sum_{n=1}^{N}n^{-3/2}\sin\left(2\pi\left({}^{nt}\!/_{T}+X_{1n}\right)\right)$$

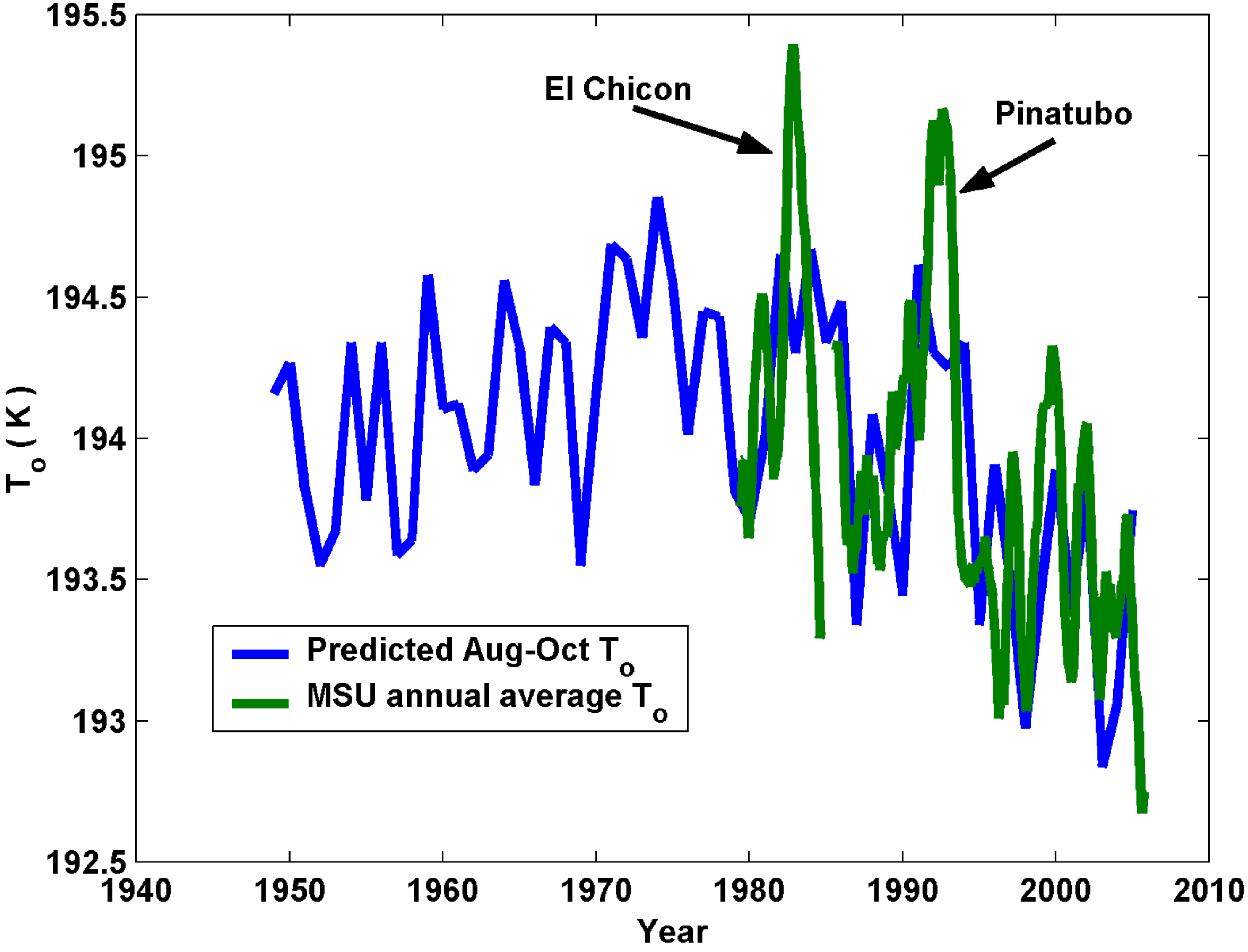
where T is a time scale corresponding to the period of the lowest frequency wave in the series, N is the total number of waves retained, and X_{1n} is, for each n, a random number between 0 and 1.

Seasonal Cycles

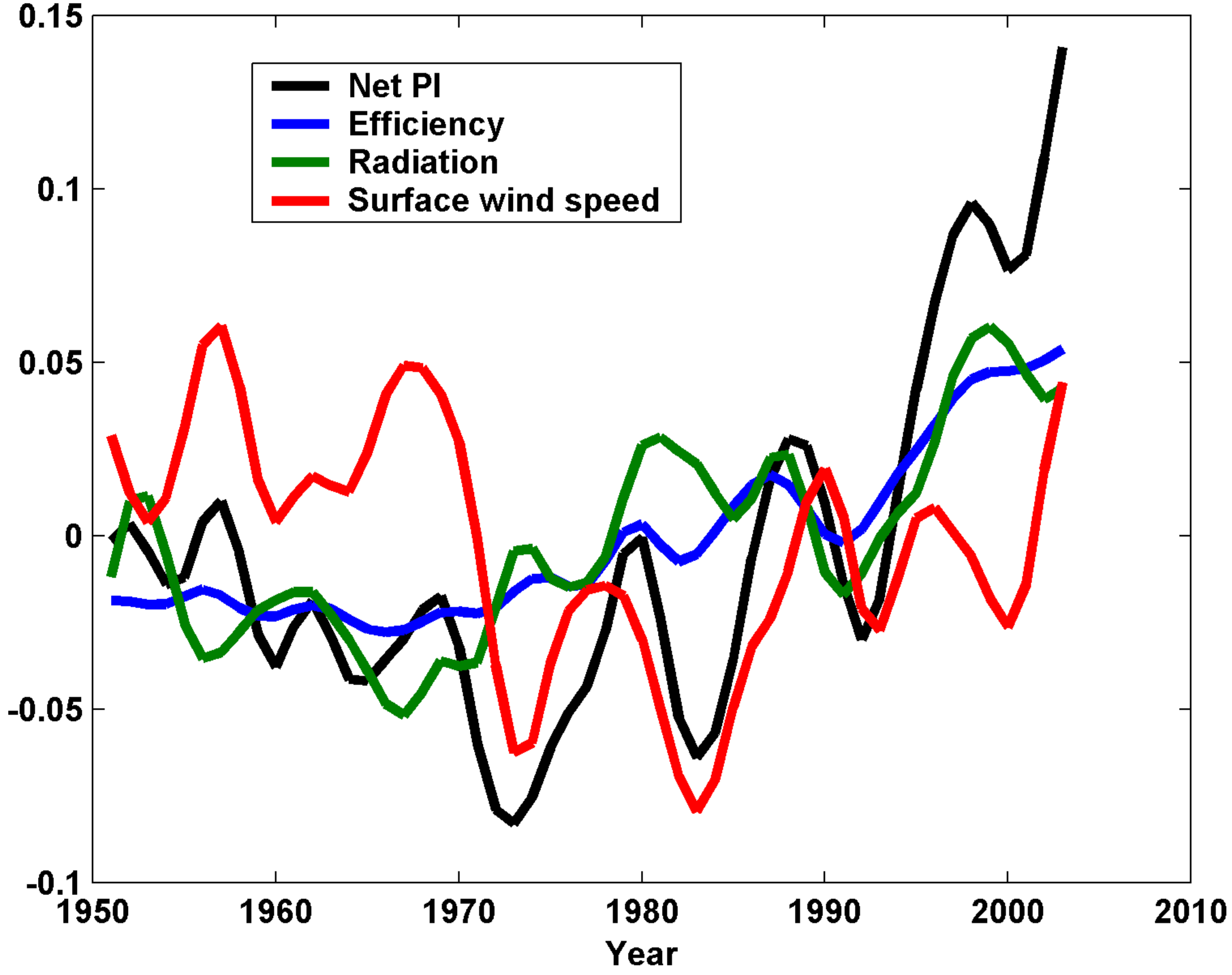


Western North Pacific

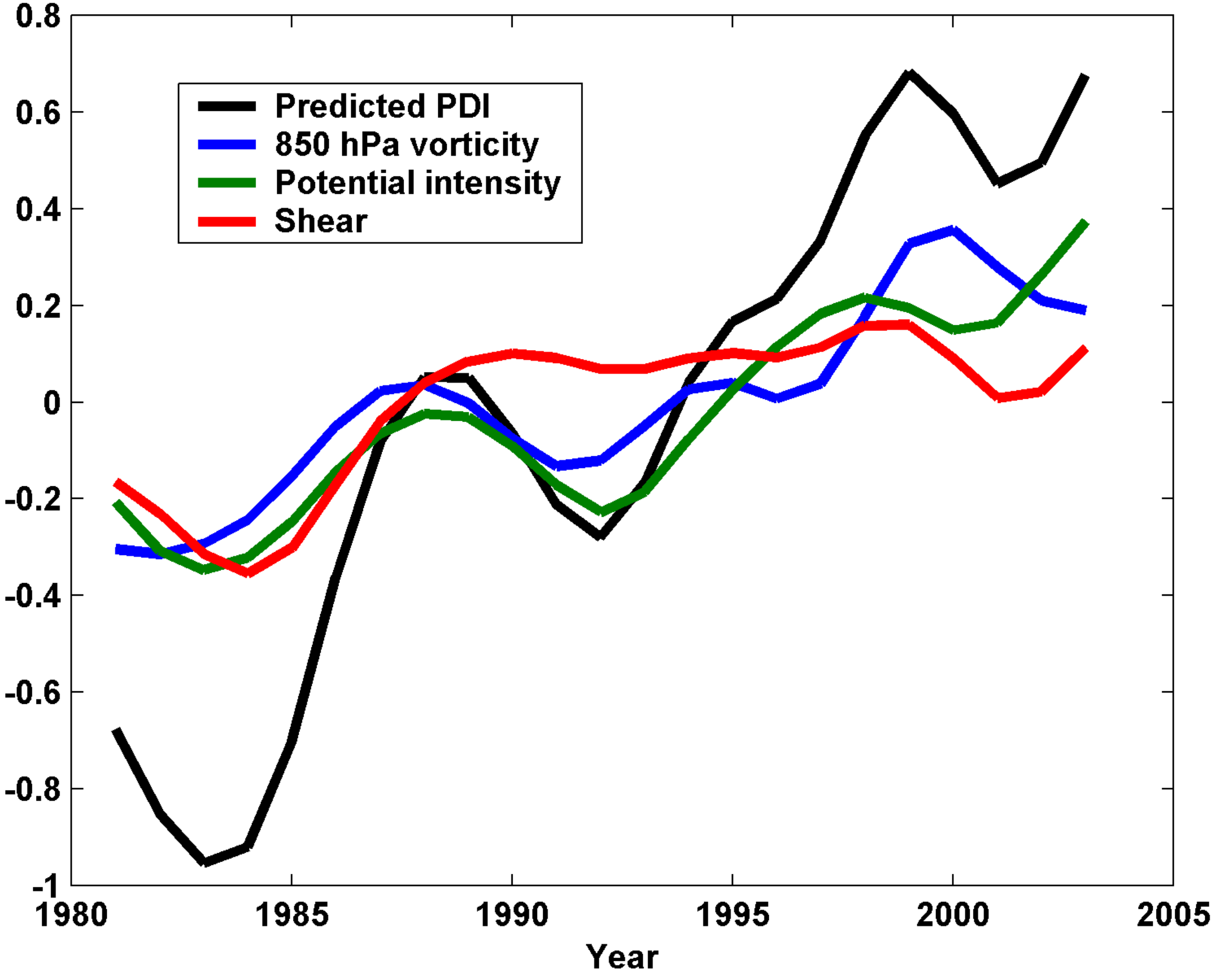
MDR Lower Stratospheric Temperature



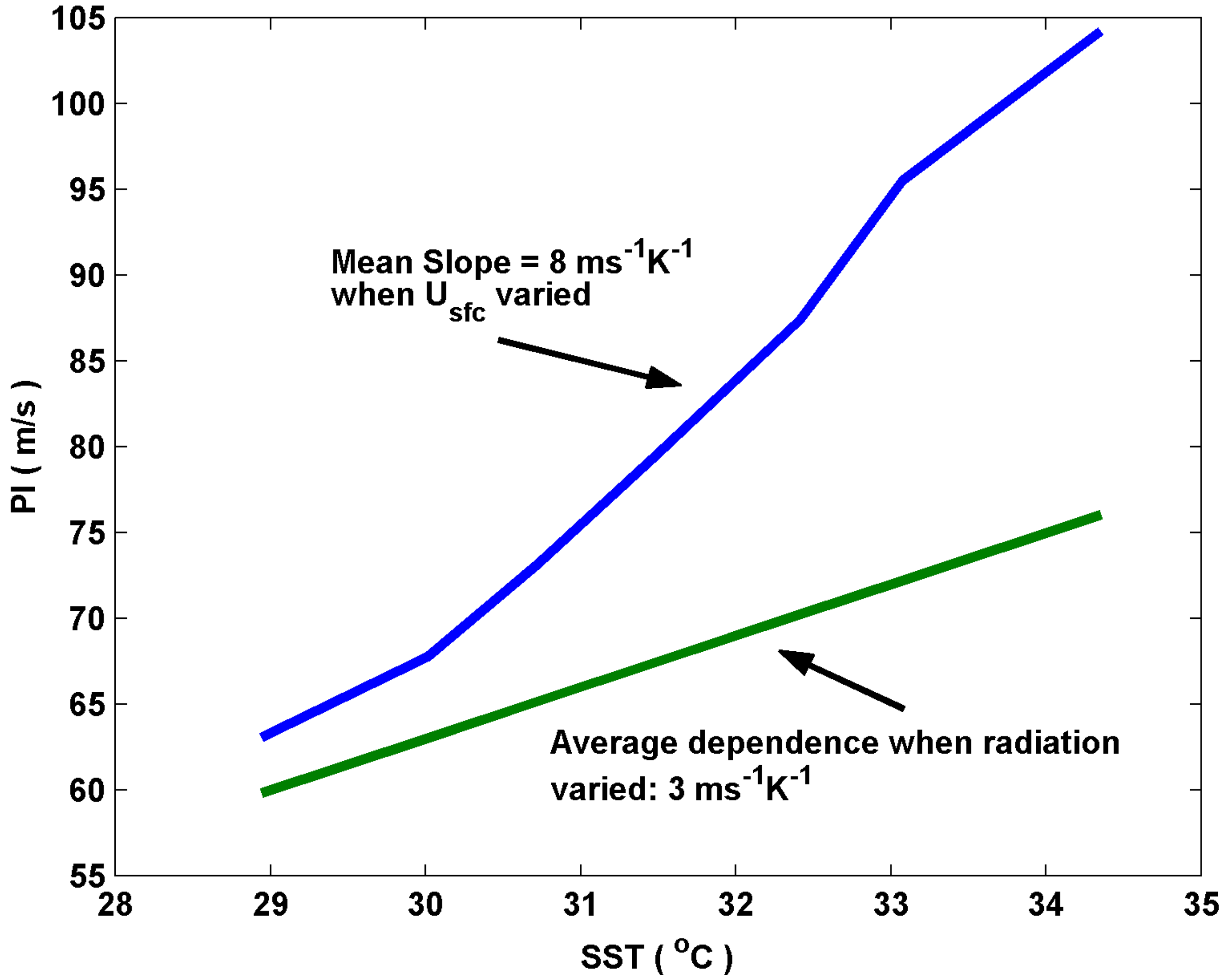
Contributions to North Atlantic Potential Intensity



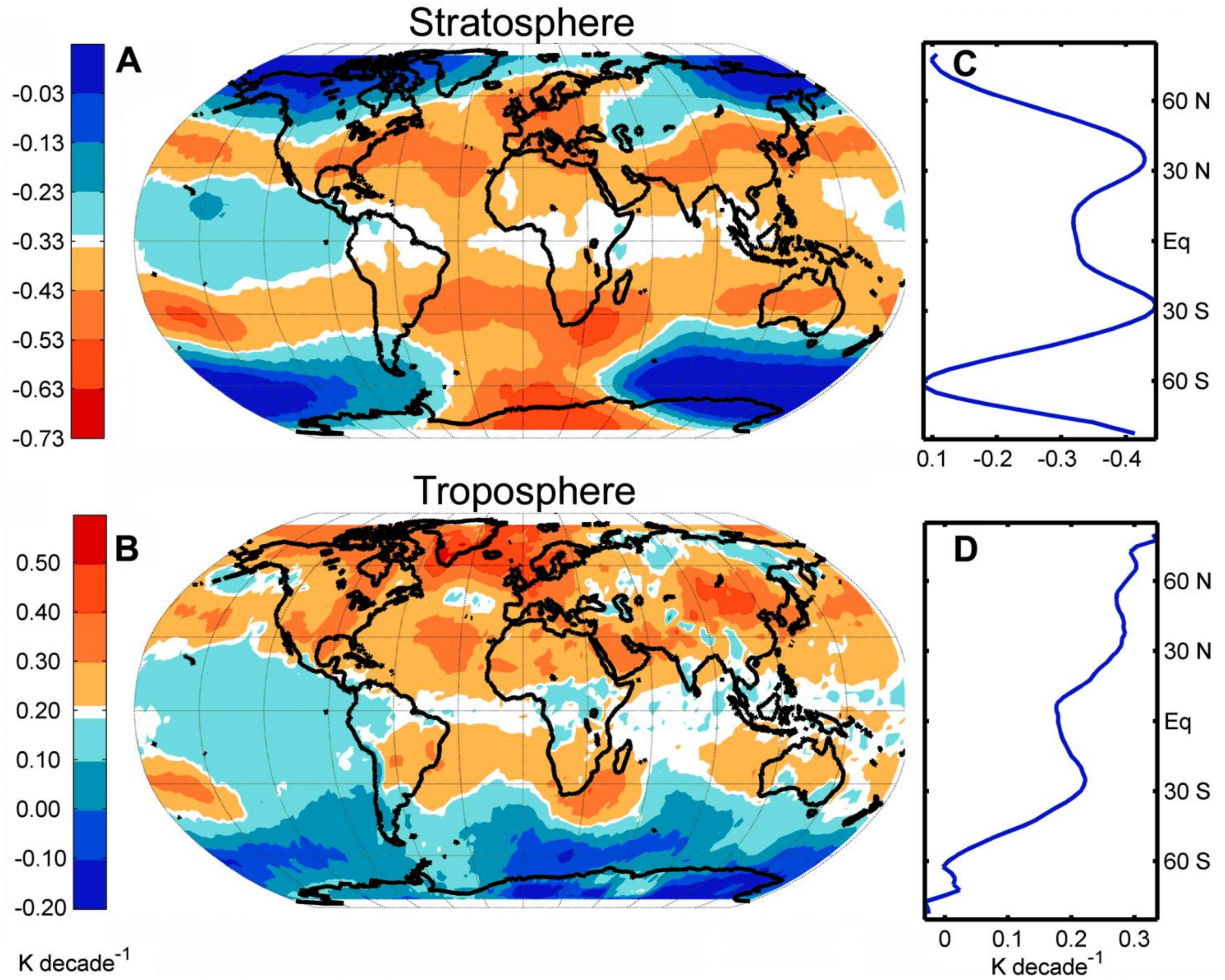
Contributions to North Atlantic Hurricane Power Dissipation:



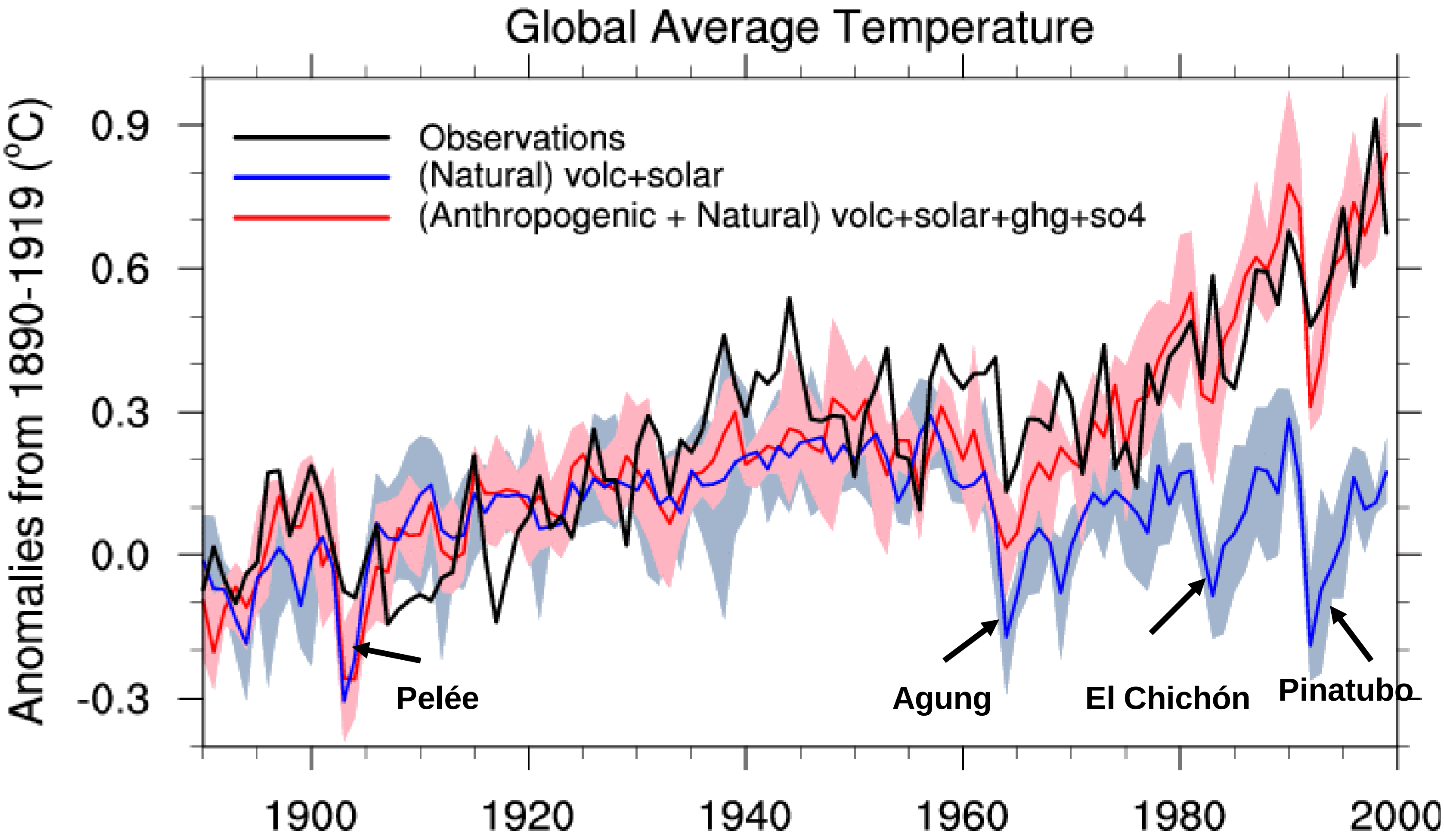
Enhanced Apparent Dependence on Sea Surface Temperature



Global Atmospheric Temperature Trend Patterns (1979-2005)



Fu, Johanson, Wallace (*2006, Science, in press*)


Global Average Temperature
Observations
(Natural) volc+solar
(Anthropogenic + Natural) volc+solar+ghg+so4
Anomalies from 1890-1919 (°C)
0.9
0.6
0.3
0.0
-0.3
1900
1920
1940
1960
1980
2000
Pelée
Agung
El Chichón
Pinatubo

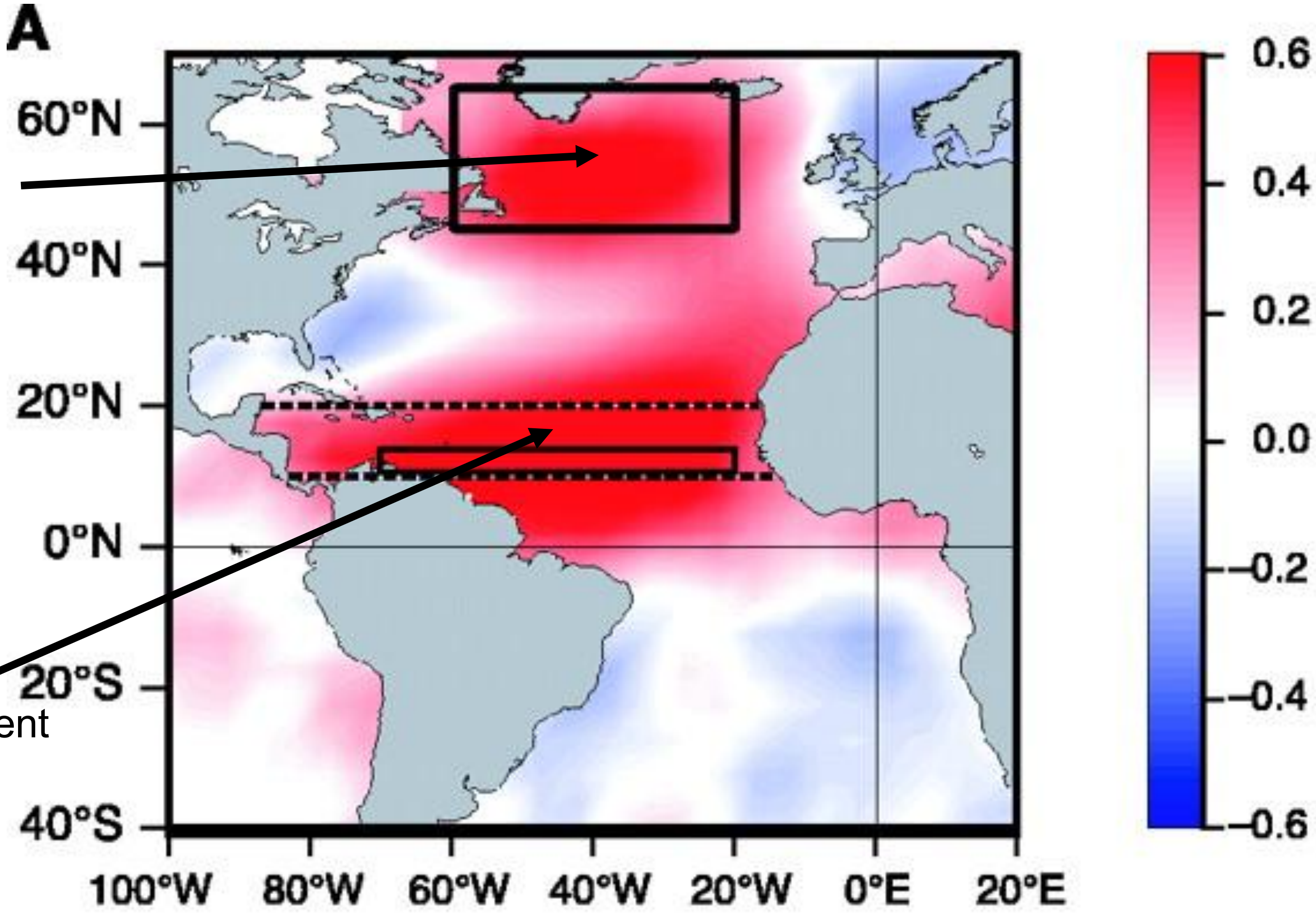
Scientific Basis of the “Natural Cycles” Story

The Atlantic Multi-Decadal Oscillation (AMO)

NOAA’s take on Atlantic Hurricane Variability:

- *“ Research indicates that the effect of global climate change on hurricanes, if any, is relatively small, whereas the fluctuations of activity associated with multidecadal changes in ocean temperatures is very large”*
  - – NOAA talking points Q&A

Third rotated EOF of the non-ENSO residual 1856-1991 de-trended SST data. From Goldenberg et al., 2001, adapted from Enfield et al., 1999, *J. Climate*

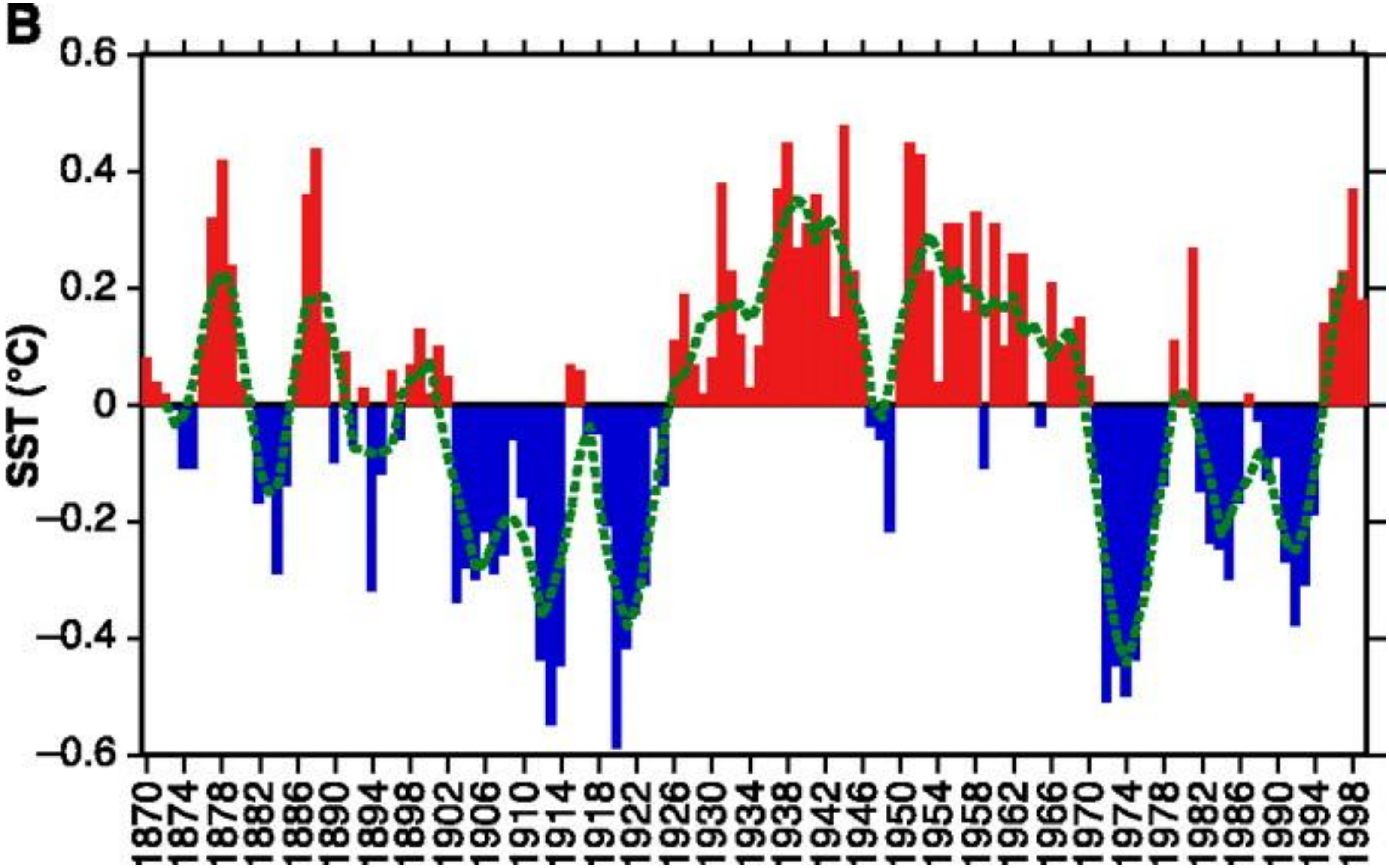


High-latitude North Atlantic

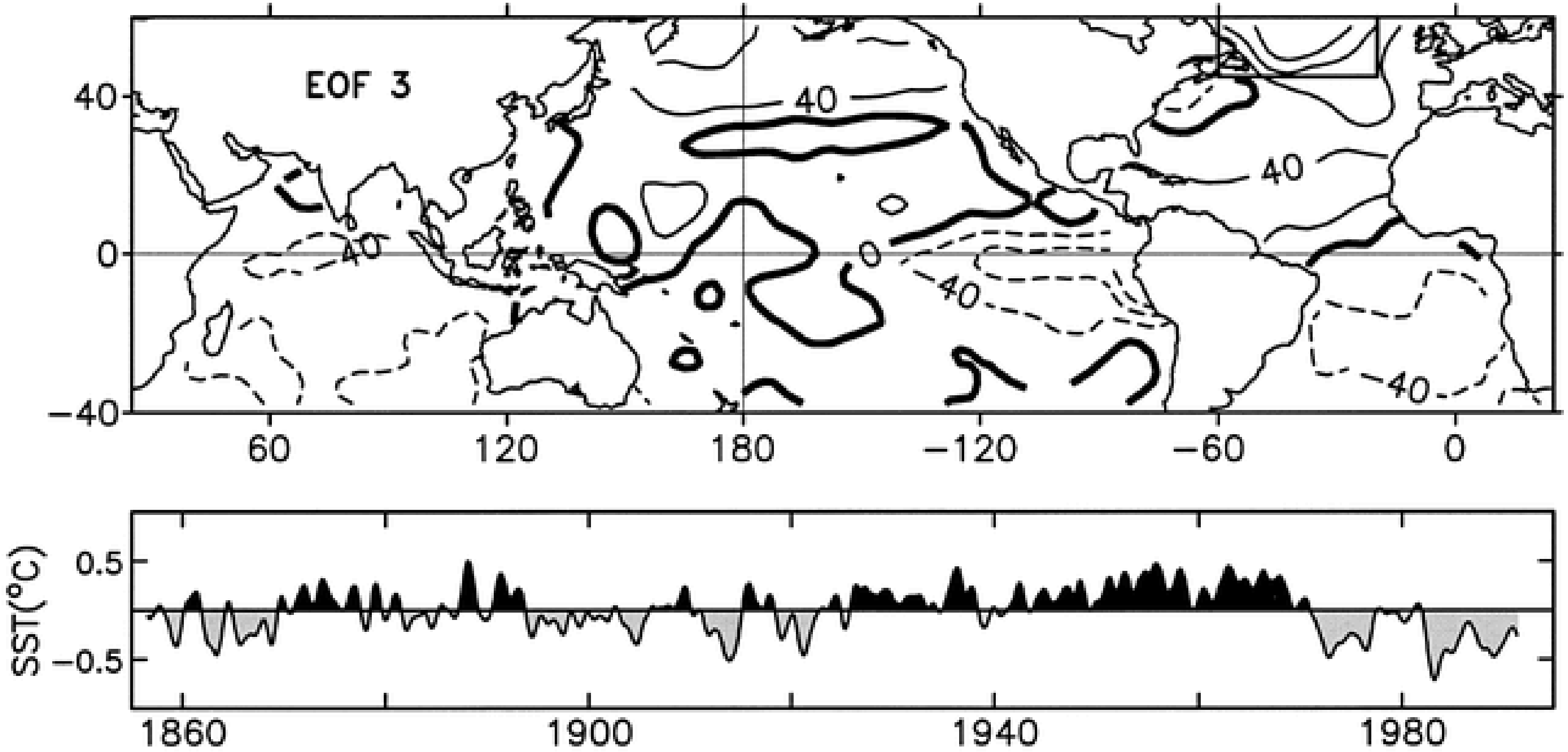
“Main development region”

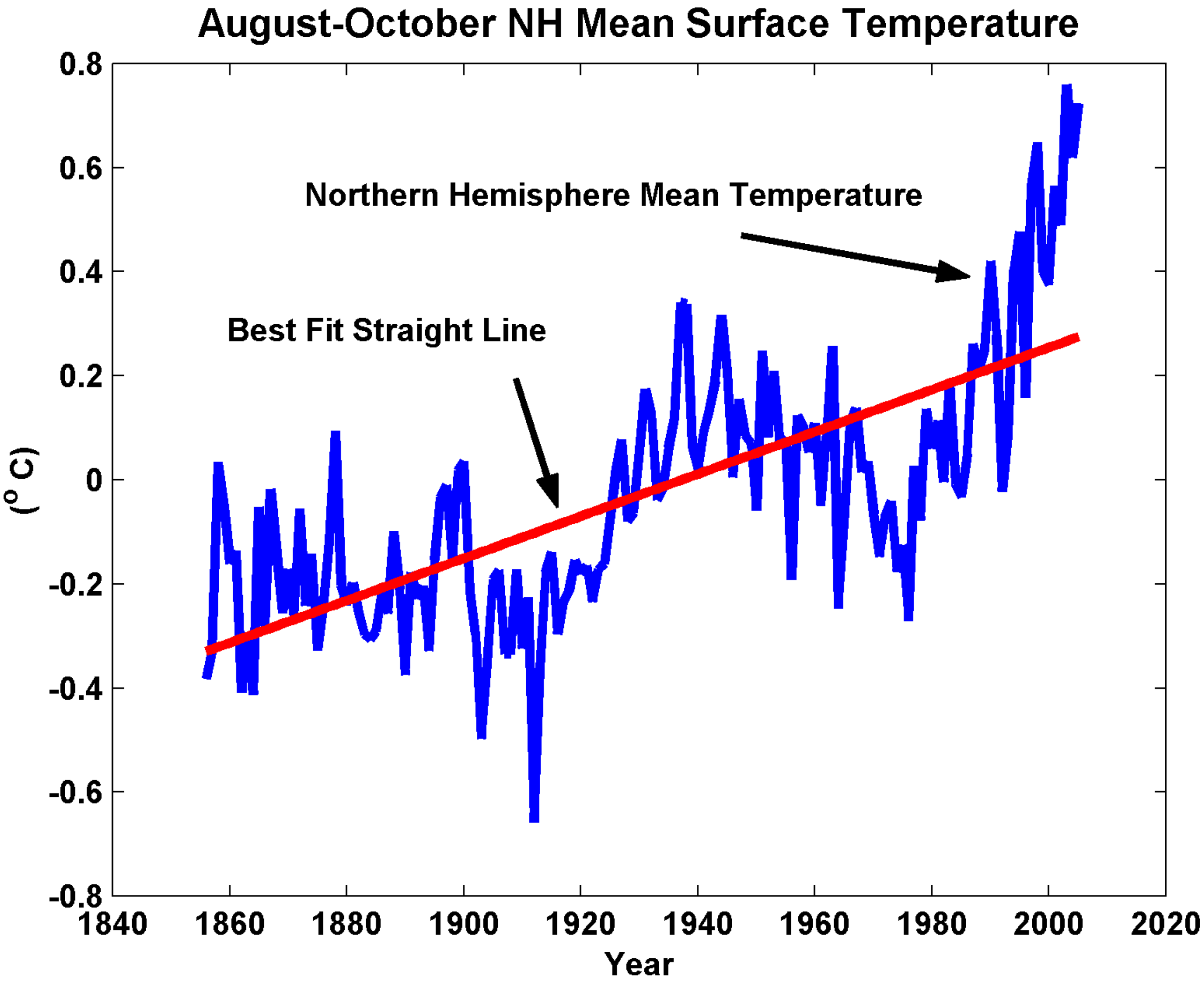
S. B. Goldenberg et al., Science 293, 474 -479 (2001)

Variation with time of amplitude of third rotated EOF of the non-ENSO residual 1856-1991 de-trended SST data



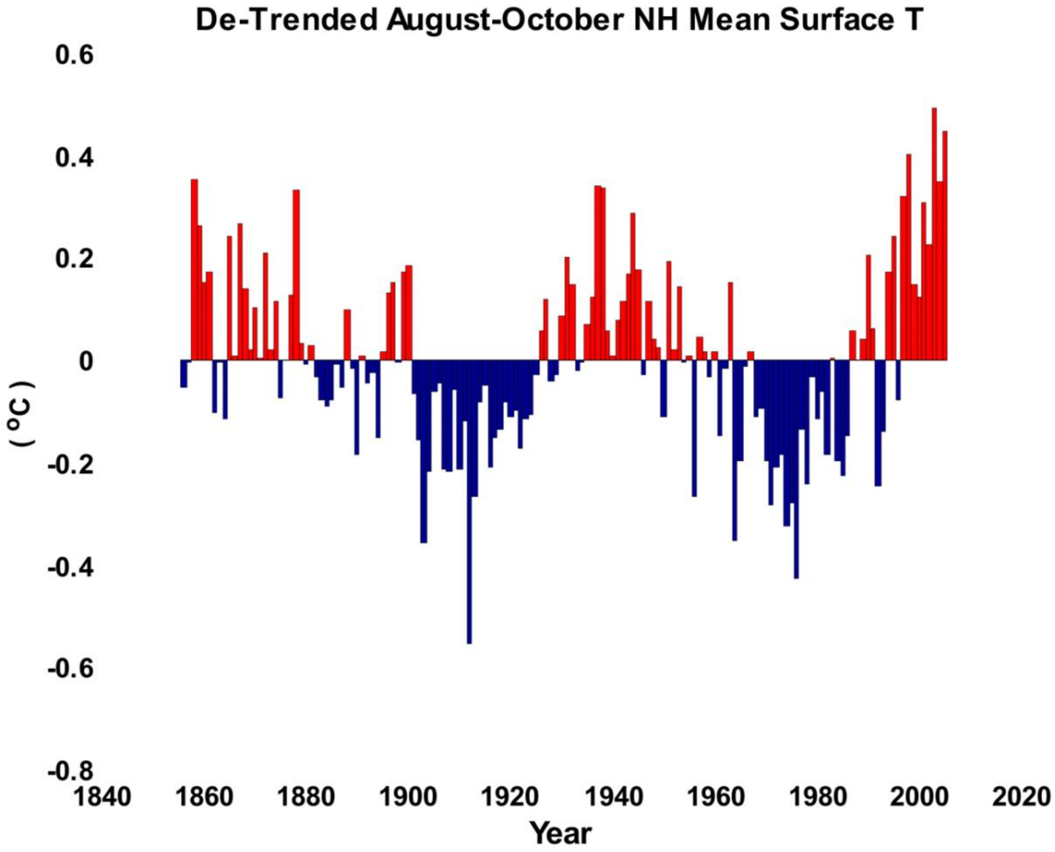
Same, but showing global distribution. From Enfield et al., 1999



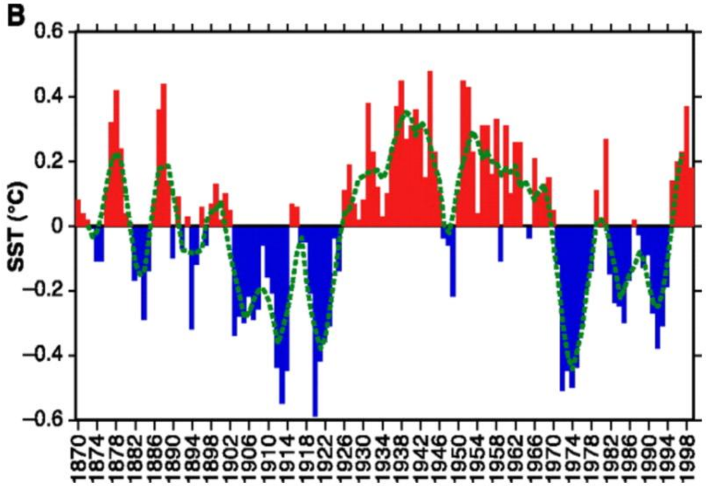


Source: Hadley Centre Global Surface Temperature Data

De-trended Aug-Oct NH surface T



Goldenberg et al. AMO index



Sulfate Aerosol Forcing (Kiehl et al., *JGR*, 2000)

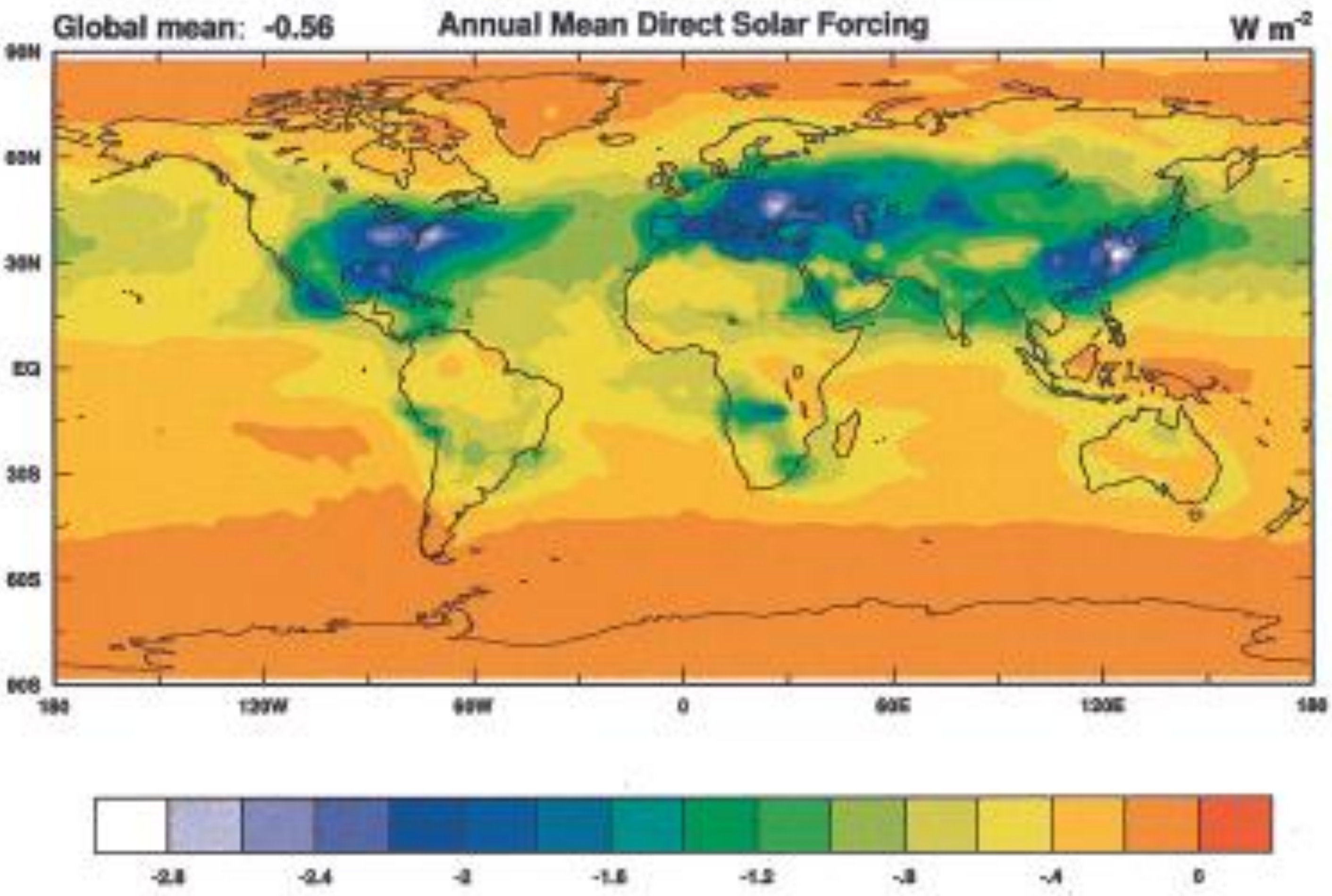
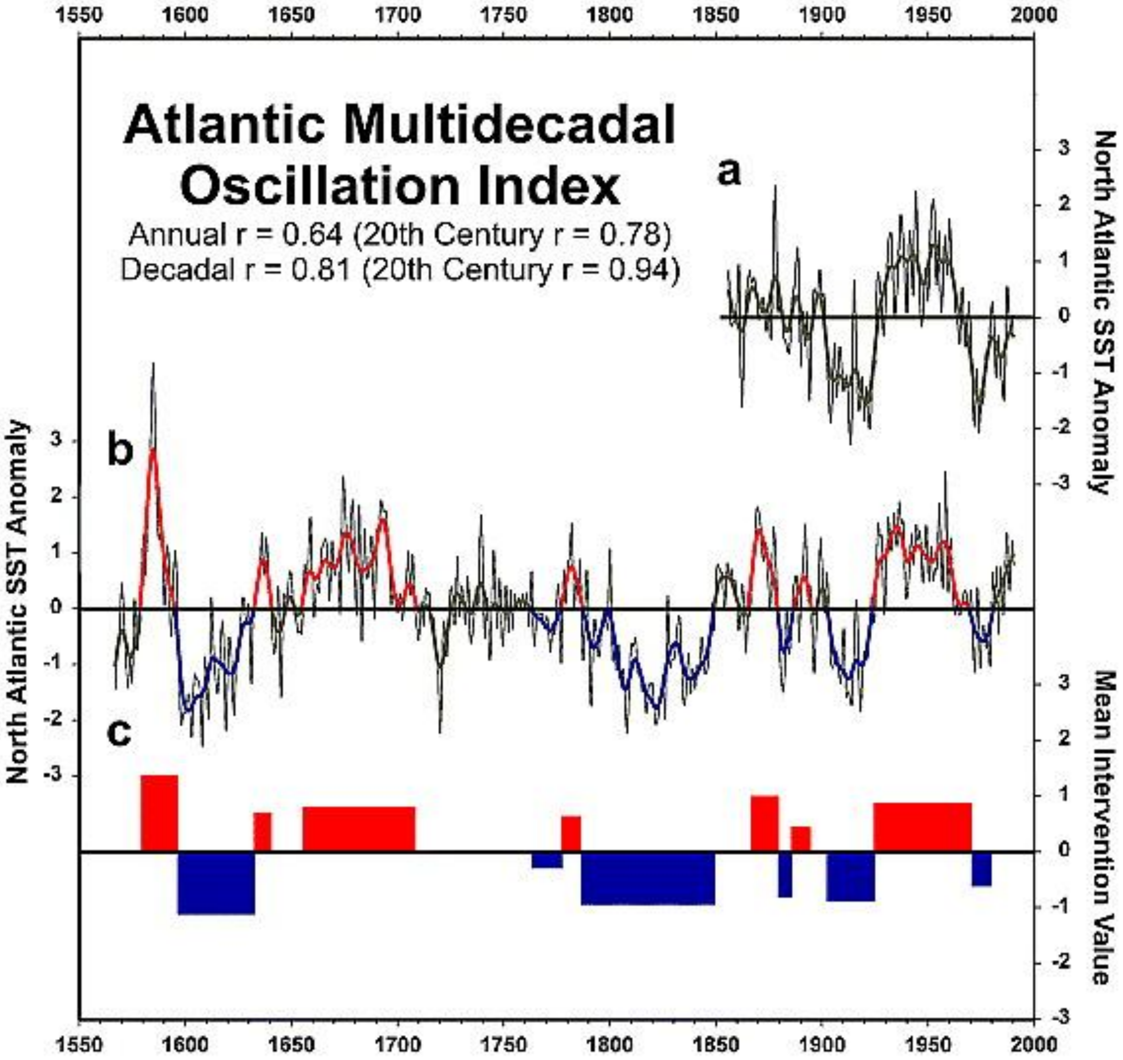


Plate 3. Geographic distribution of the annual mean direct forcing (W m^{-2}) due to anthropogenic sulfate aerosols.

Gray et al., Geo. Res. Lett., 2004: PCA's of tree rings from 12 trees in Europe and North America…curve fit amplitudes of first 5 PCs to instrumental record of de-trended North Atlantic SSTs



Knight et al., 2005: 1400 year simulation with coupled global model (HADCM3): Multi-decadal fluctuations in thermohaline strength, associated with North Atlantic SST variations of ~0.1 C