Assessing Storm Surge Risk at New York City

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Massachusetts Institute of Technology

Program

- Brief Review of Tropical Cyclones
- Why historical statistics are inadequate for assessing long-term surge risk in NYC
- Physically based method for estimating surge risk

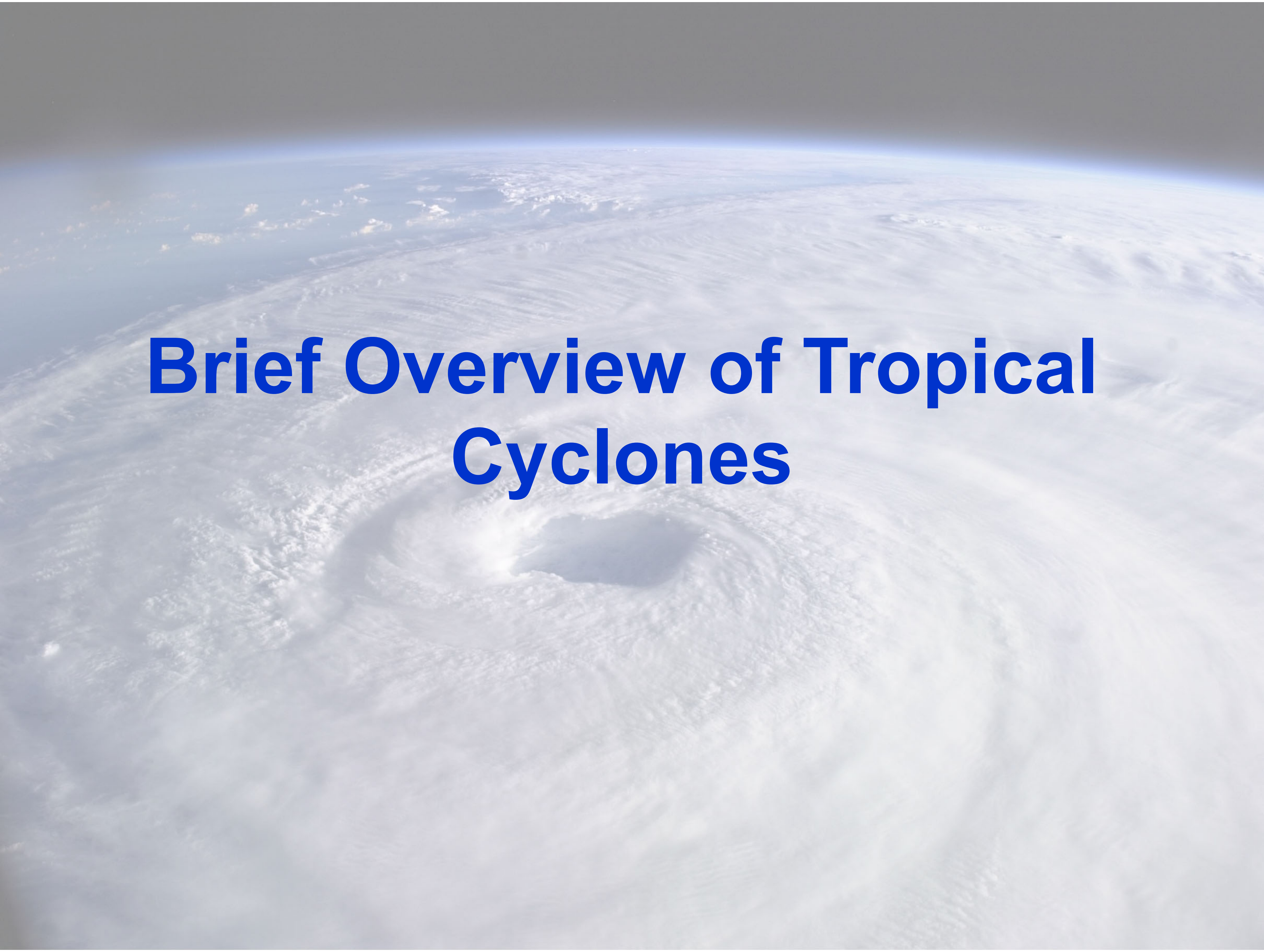
More Information about this Talk:

Physically based assessment of hurricane surge threat under climate change

Ning Lin, Kerry Emanuel, Michael Oppenheimer
& Erik Vanmarcke

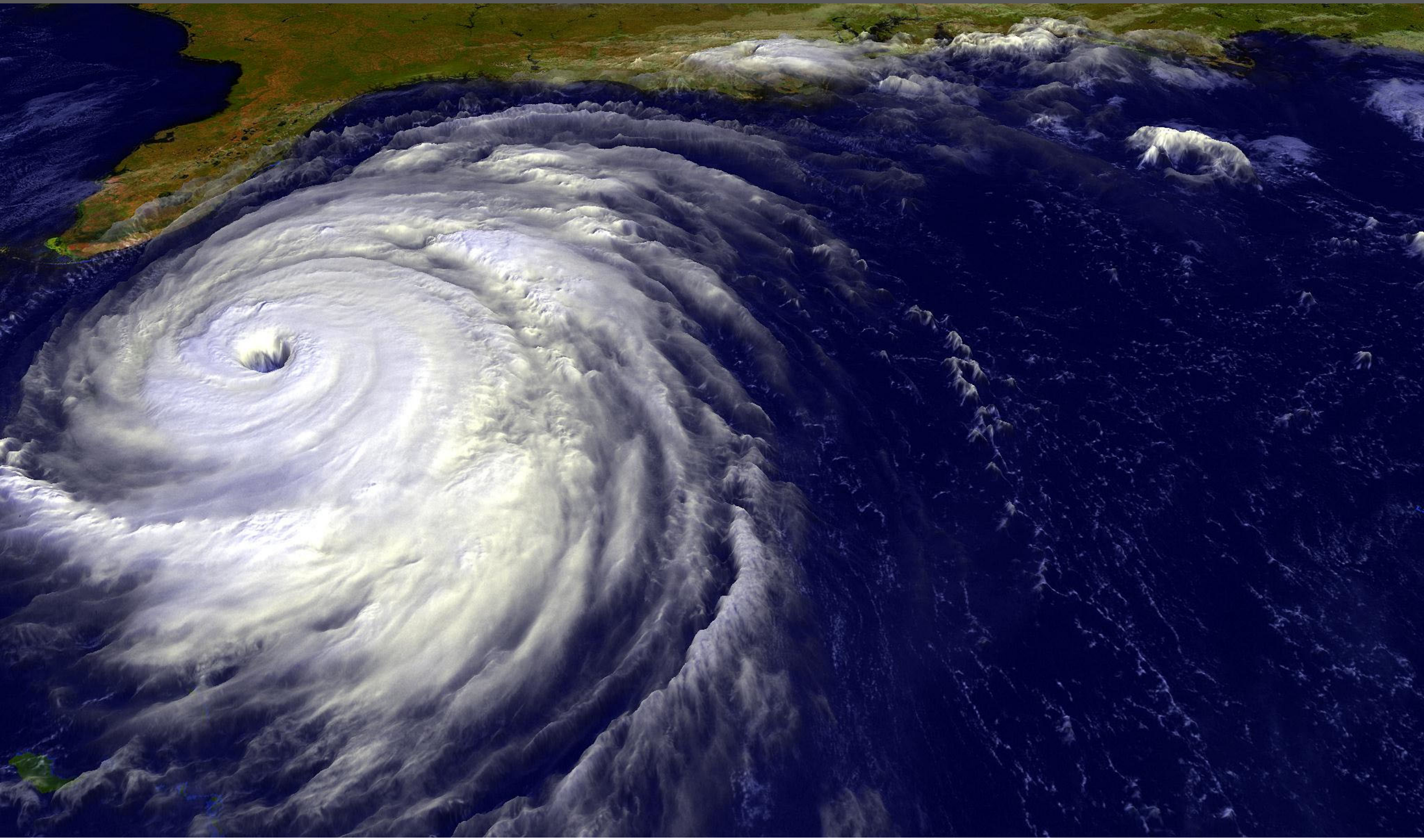
Nature Climate Change, **2**, 462–467 (February, 2012)
doi:10.1038/nclimate1389

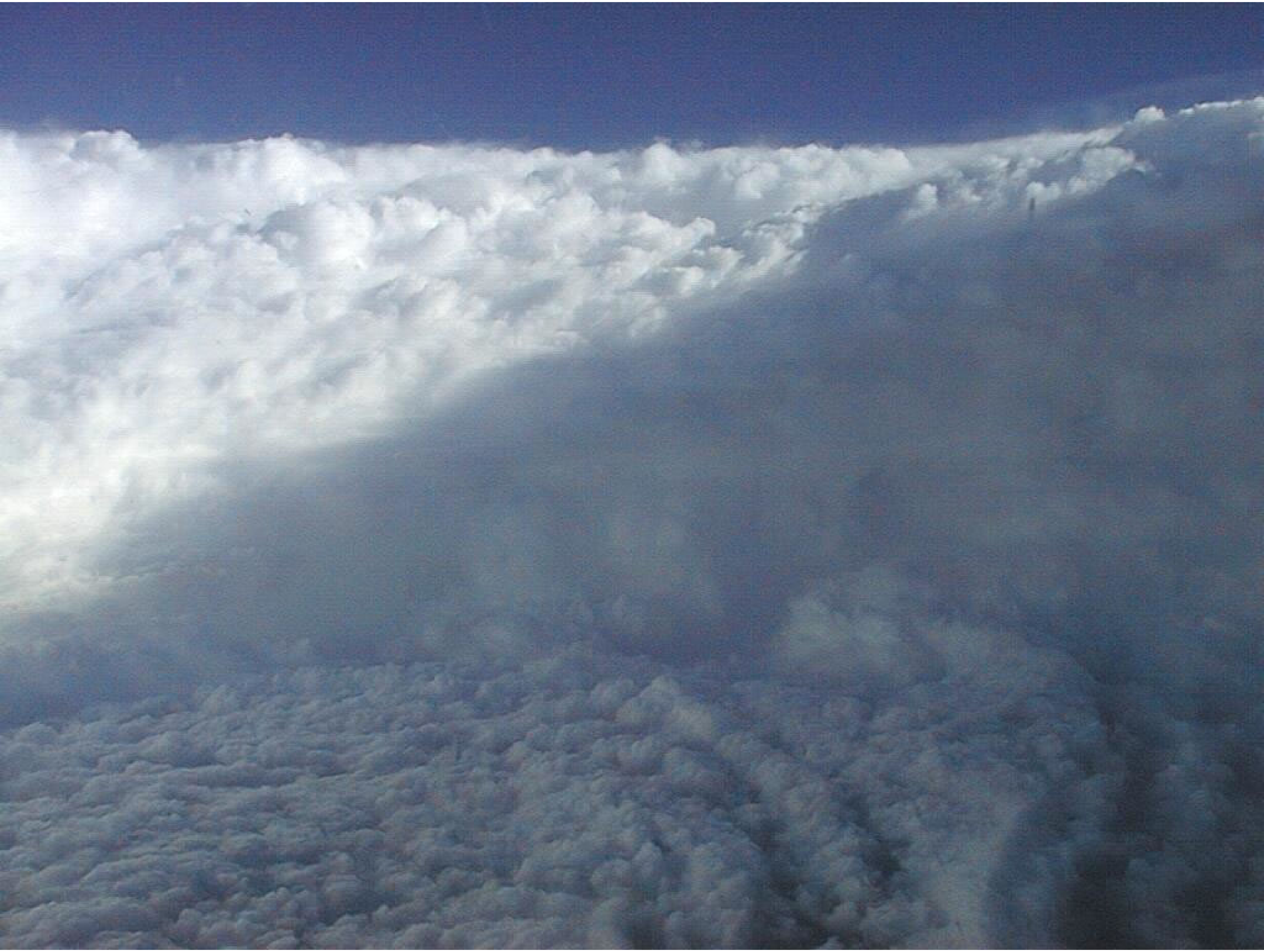
"***The combined effects of storm climatology change and a 1m SLR may cause the present NYC 100-yr surge flooding to occur every 3–20 yr and the present 500-yr flooding to occur every 25–240 yr by the end of the century"***



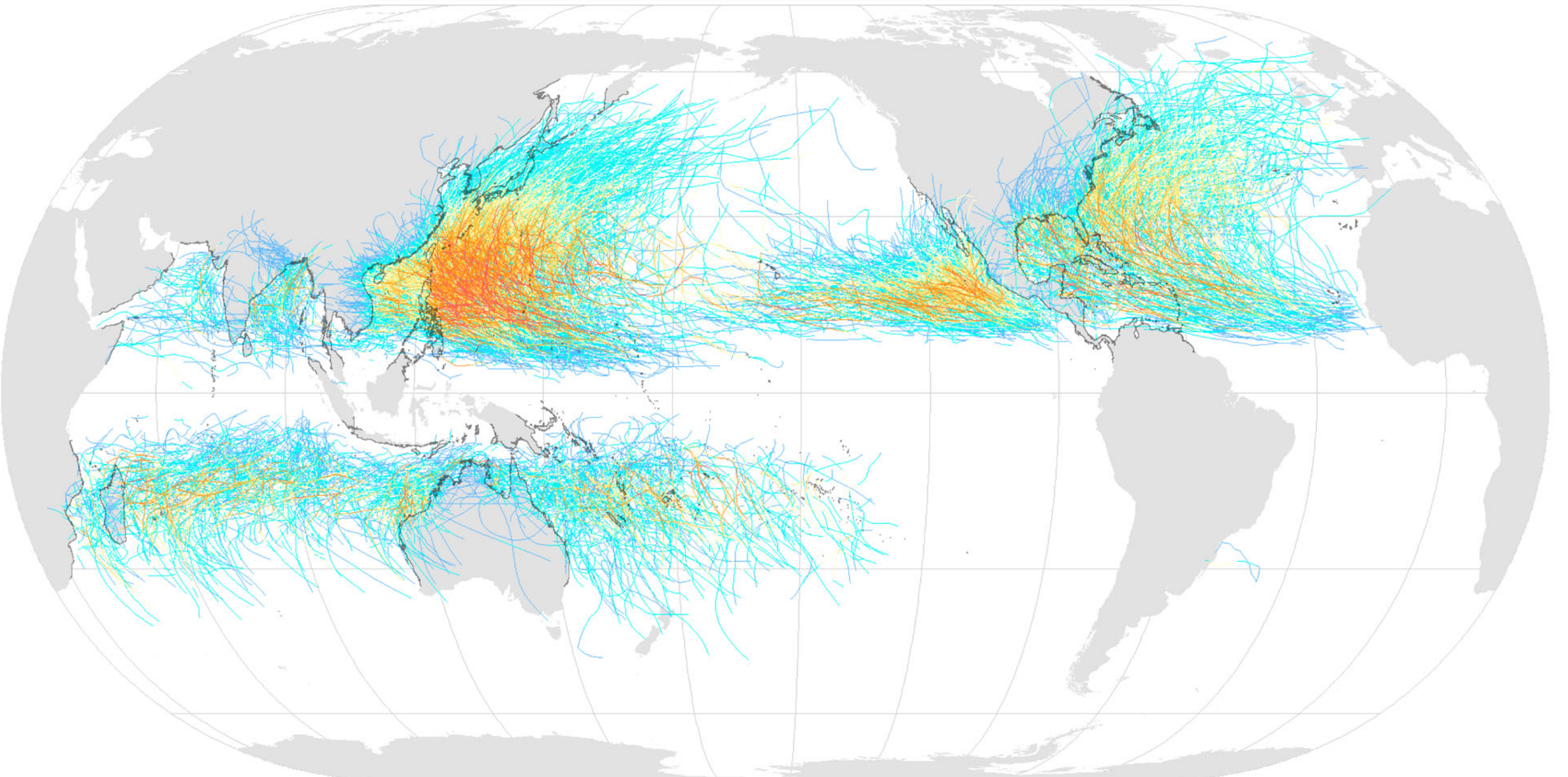
Brief Overview of Tropical Cyclones

The View from Space



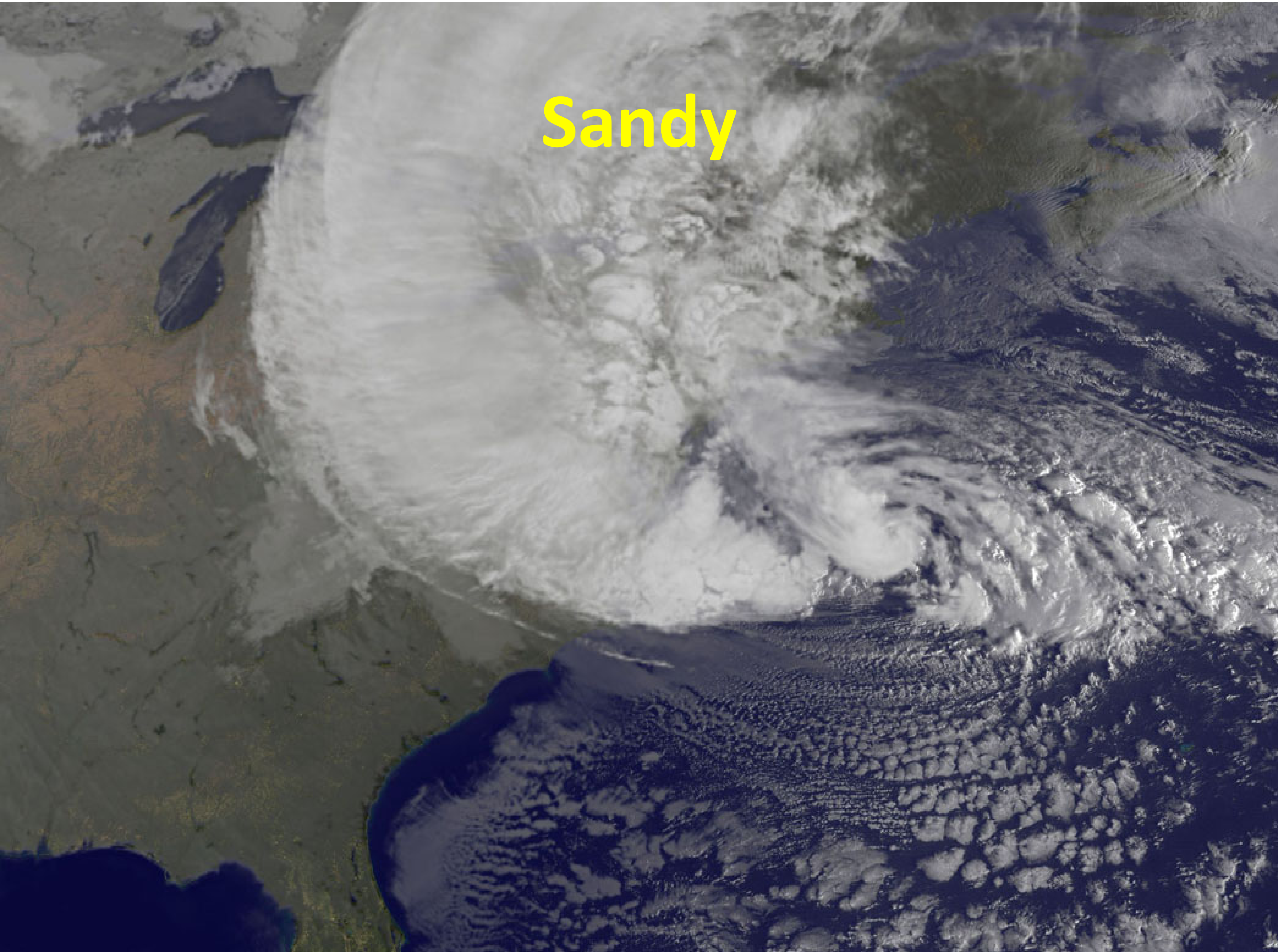


Tropical Cyclones, 1945–2006



Saffir-Simpson Hurricane Scale:

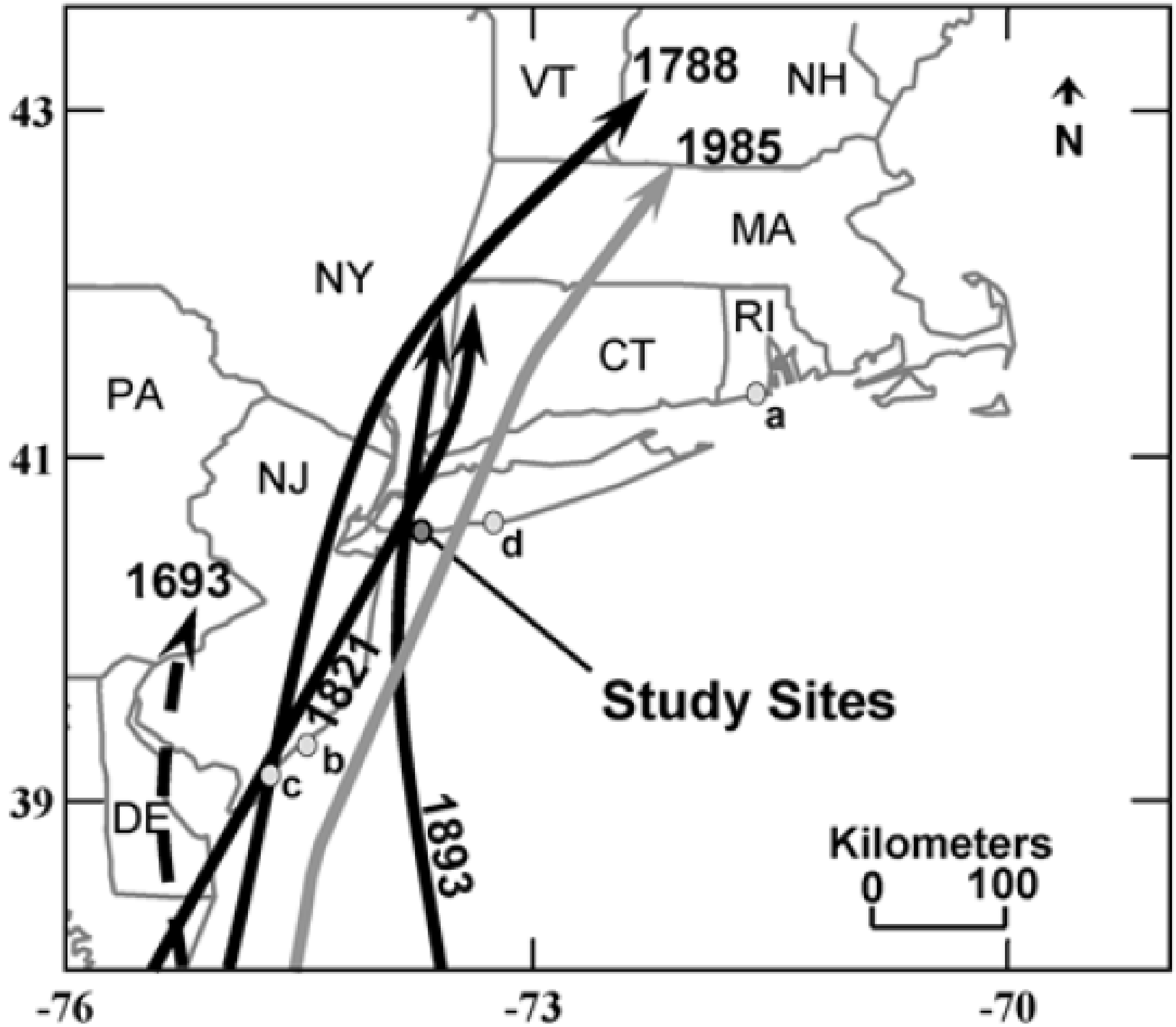
tropical depression | tropical storm | hurricane category 1 | hurricane category 2 | hurricane category 3 | hurricane category 4 | hurricane category 5


Sandy

Limitations of a strictly statistical approach U.S. Hurricanes in General

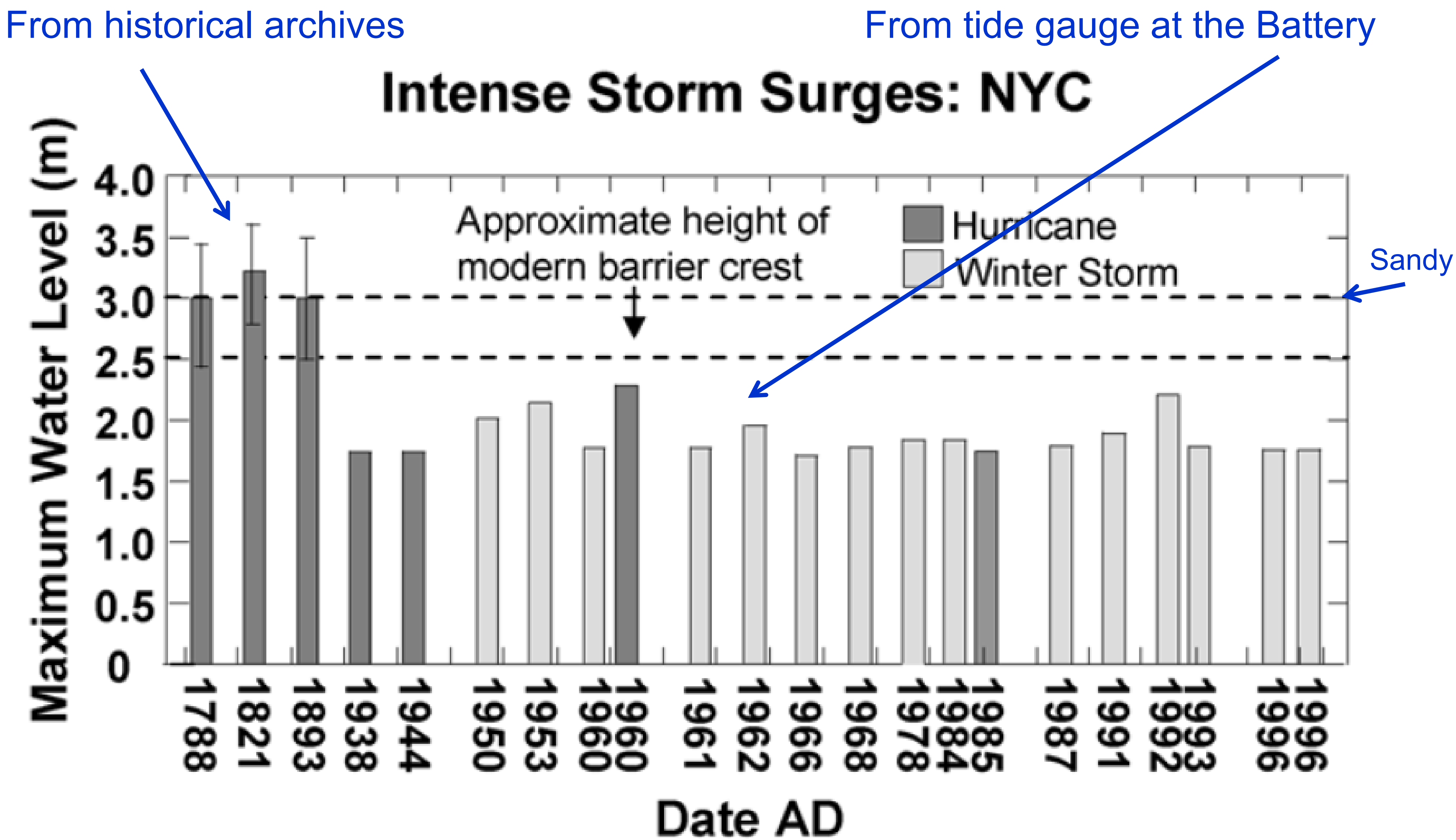
- >50% of all normalized damage caused by **top 8 events**, all category 3, 4 and 5
- **>90%** of all damage caused by storms of category **3** and greater
- Category 3,4 and 5 events are only 13% of total landfalling events; only 30 since 1870
- ∴ ***Landfalling storm statistics are inadequate for assessing hurricane risk***

Historical Surge Events Affecting New York City



Tracks of historical hurricanes affecting NYC and western Long Island

Source: Scileppi and Donnelly, 2007: *Geochem., Geophys., Geosys*., **8**

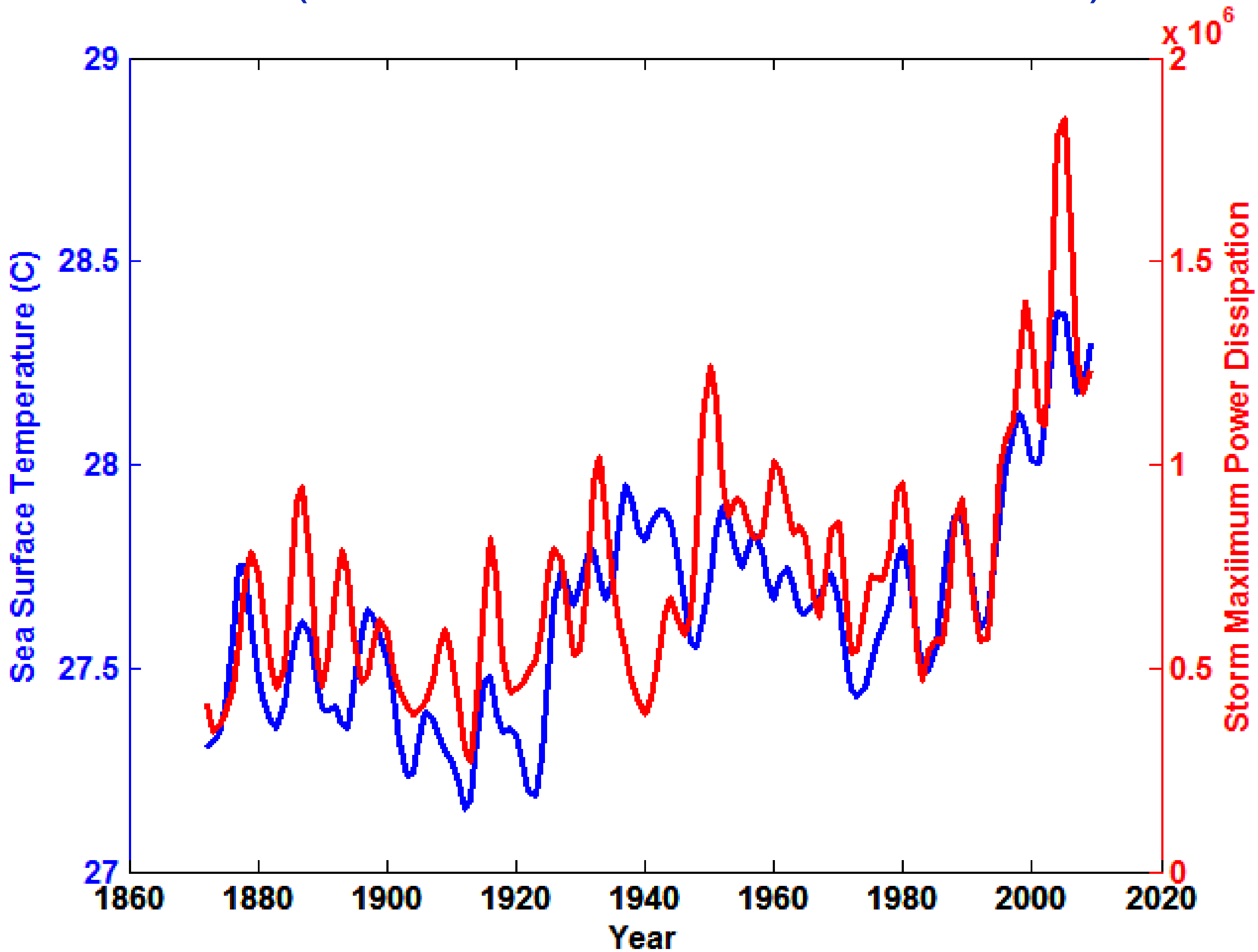


Source: Scileppi and Donnelly, 2007: *Geochem., Geophys., Geosys.*, **8**

Additional Problem: Nonstationarity of climate

Atlantic Sea Surface Temperatures and Storm Max Power Dissipation

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



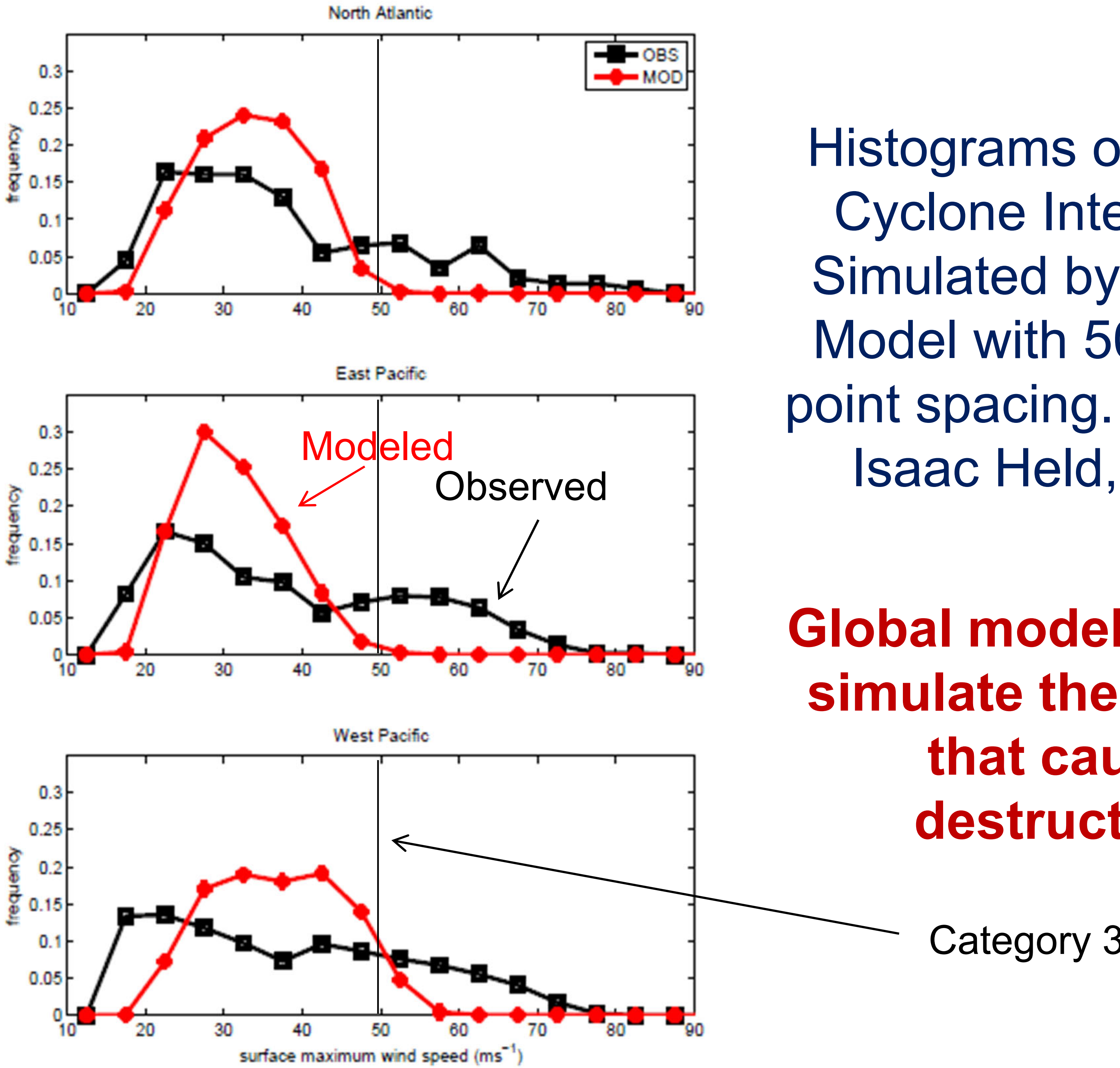
Years included: 1870-2011

Data Sources: Hurricanes: NOAA/TPC; Sea Surface Temperatures: UKMO/HADSST1

Bringing Physics to Bear: Risk Assessment by Direct Numerical Simulation of Hurricanes

The Problem

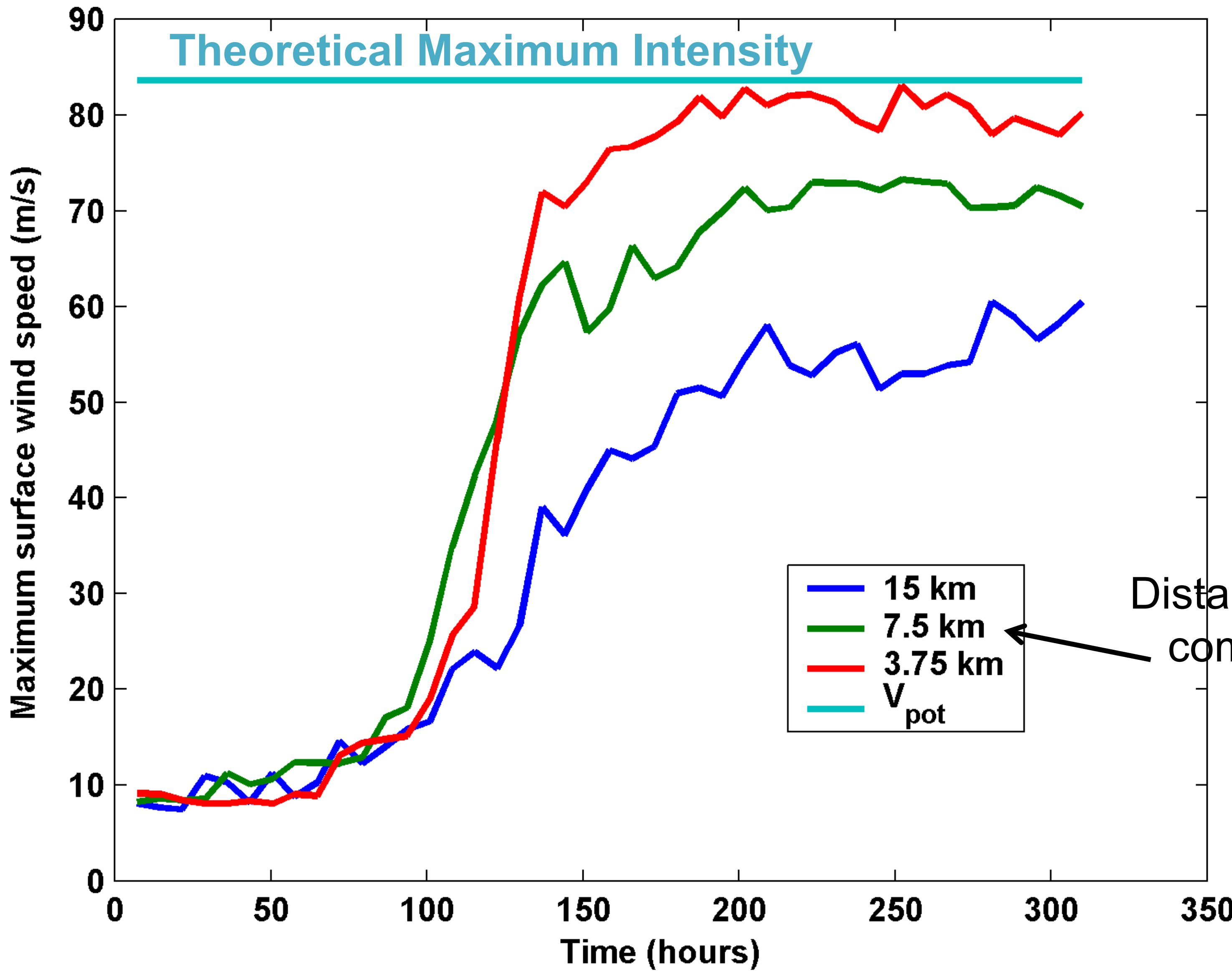
- **The hurricane eyewall is an intense, circular *front*, attaining scales of ~ 1 km or less**
- **At the same time, the storm's circulation extends to ~1000 km and is embedded in much larger scale flows**



Histograms of Tropical Cyclone Intensity as Simulated by a Global Model with 50 km grid point spacing. (Courtesy Isaac Held, GFDL)

Global models do not simulate the storms that cause destruction

Numerical convergence in an axisymmetric, nonhydrostatic model (Rotunno and Emanuel, 1987)



Distance between computational nodes

How to deal with this?

- **Option 1: Brute force and obstinacy**

How to deal with this?

- Option 1: Brute force and obstinacy
- **Option 2: Applied math and modest resources**

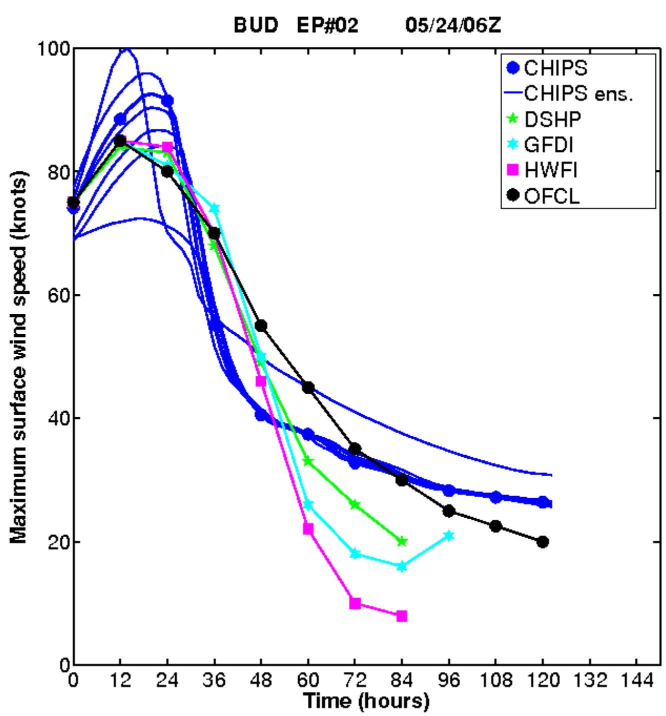
Time-dependent, axisymmetric model phrased in R space

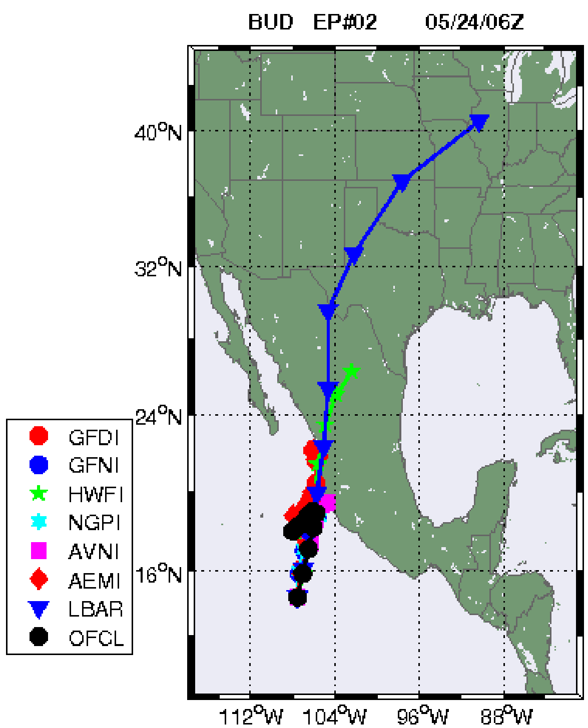
$$M = rV + \frac{1}{2} f r^2 \qquad \frac{1}{2} f R^2 \equiv M \qquad f \equiv 2\Omega \sin\theta$$

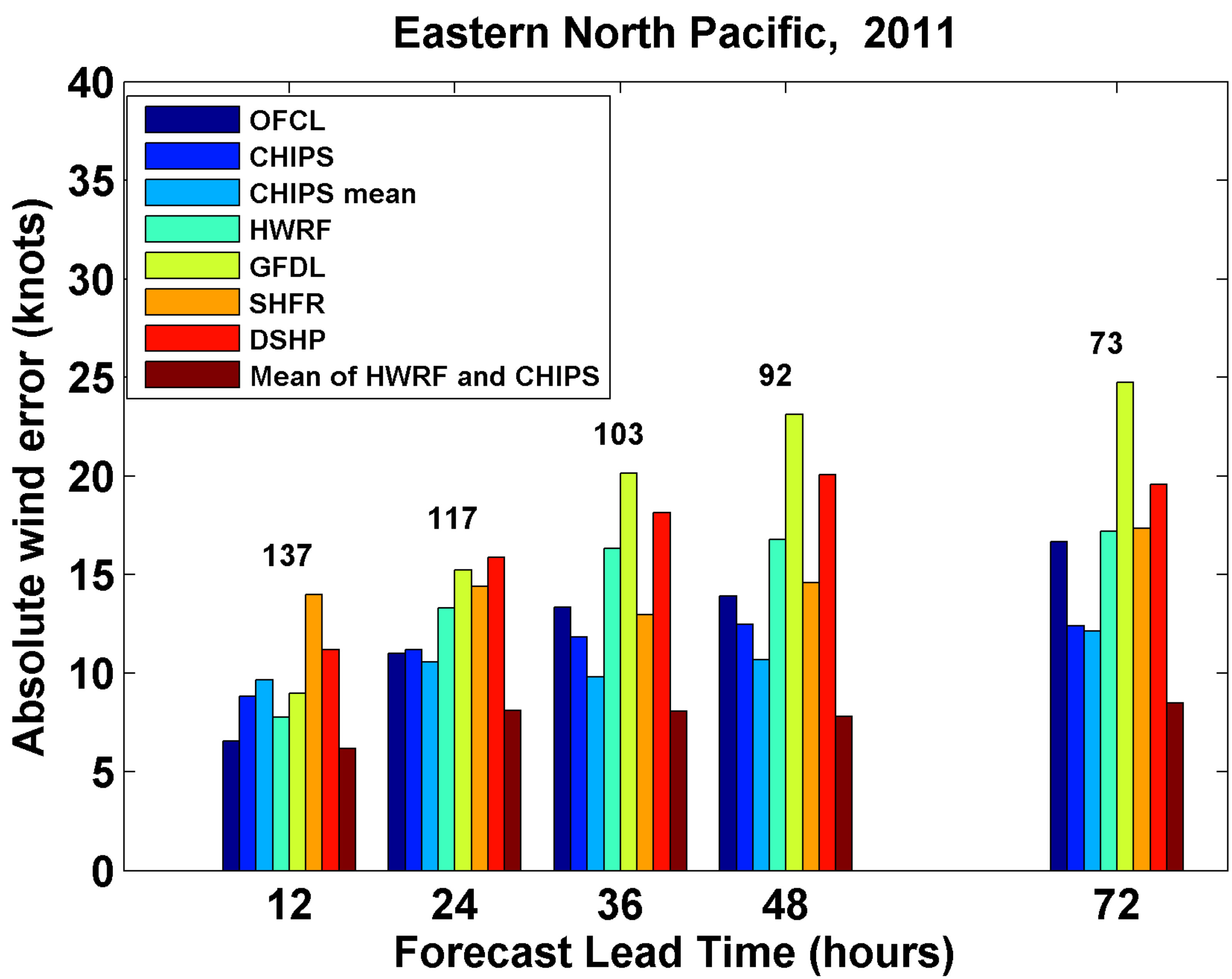
- **Hydrostatic and gradient balance above PBL**
- **Moist adiabatic lapse rates on M surfaces above PBL**
- **Boundary layer quasi-equilibrium convection**
- **Deformation-based radial diffusion**
- **Coupled to simple 1-D ocean model**
- **Environmental wind shear effects parameterized**

Originally Developed as a Student Laboratory Tool, Later Adapted as a Hurricane Intensity Forecasting Model

(http://wind.mit.edu/~emanuel/storm.html)






Eastern North Pacific, 2011
Absolute wind error (knots)
Forecast Lead Time (hours)
OFCL
CHIPS
CHIPS mean
HWRF
GFDL
SHFR
DSHP
Mean of HWRF and CHIPS
137
117
103
92
73
0
5
10
15
20
25
30
35
40
12
24
36
48
72

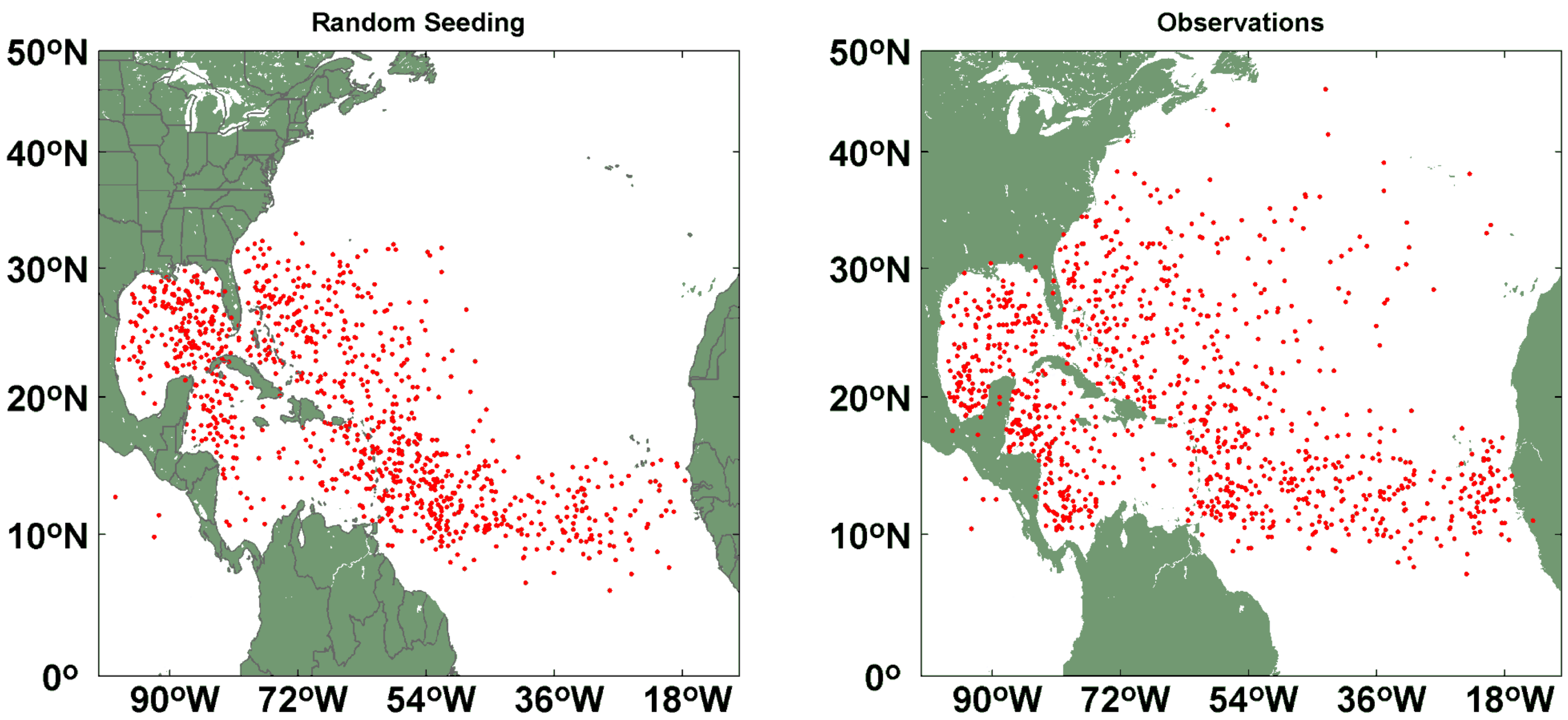
How Can We Use This Model to Help Assess Hurricane Wind and Rain Risk in Current and Future Climates?

Risk Assessment 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, plus a correction for beta drift
- **Step 3**: Run the CHIPS model 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

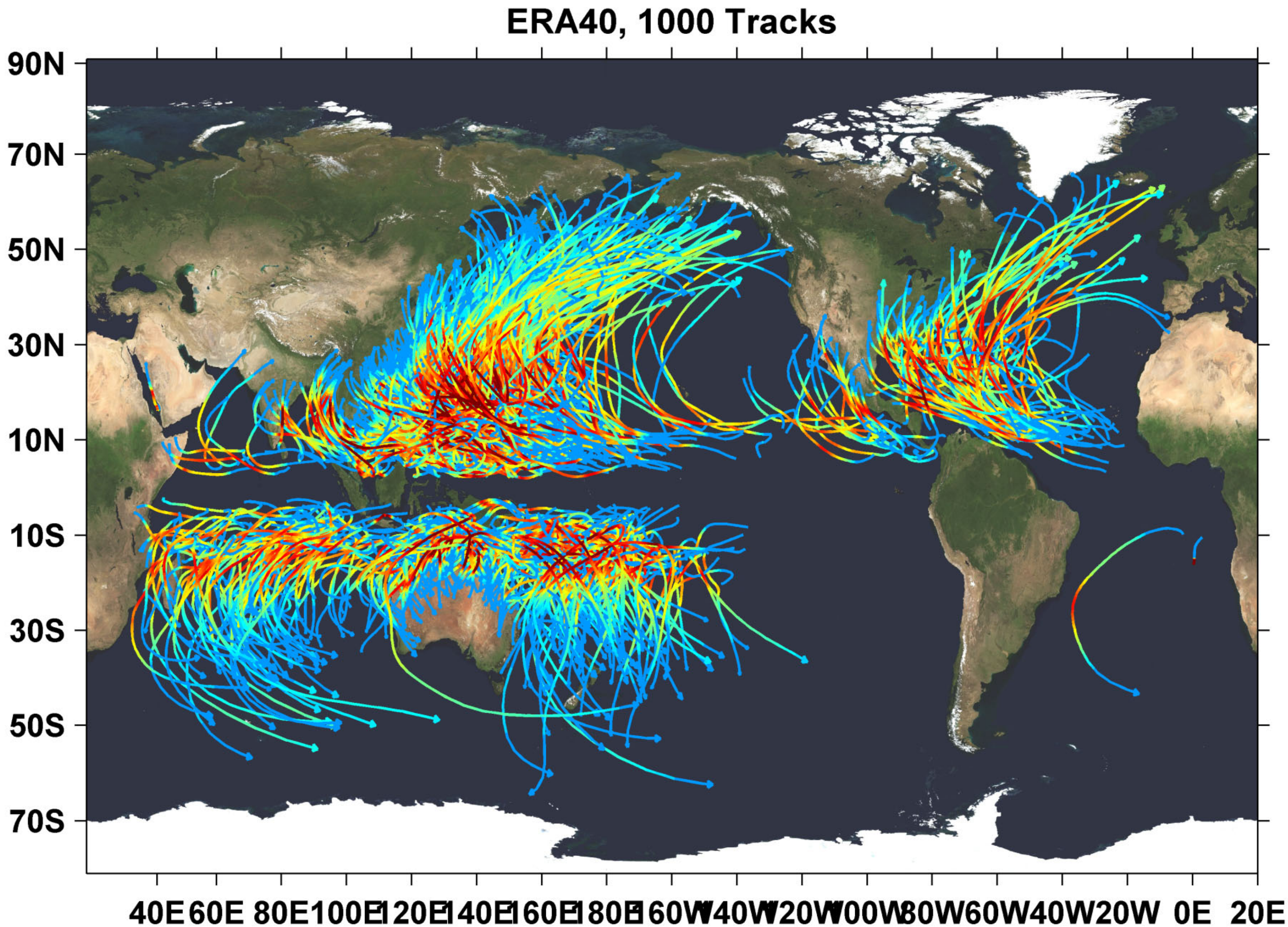
Details: Emanuel et al., *Bull. Amer. Meteor. Soc*, 2008

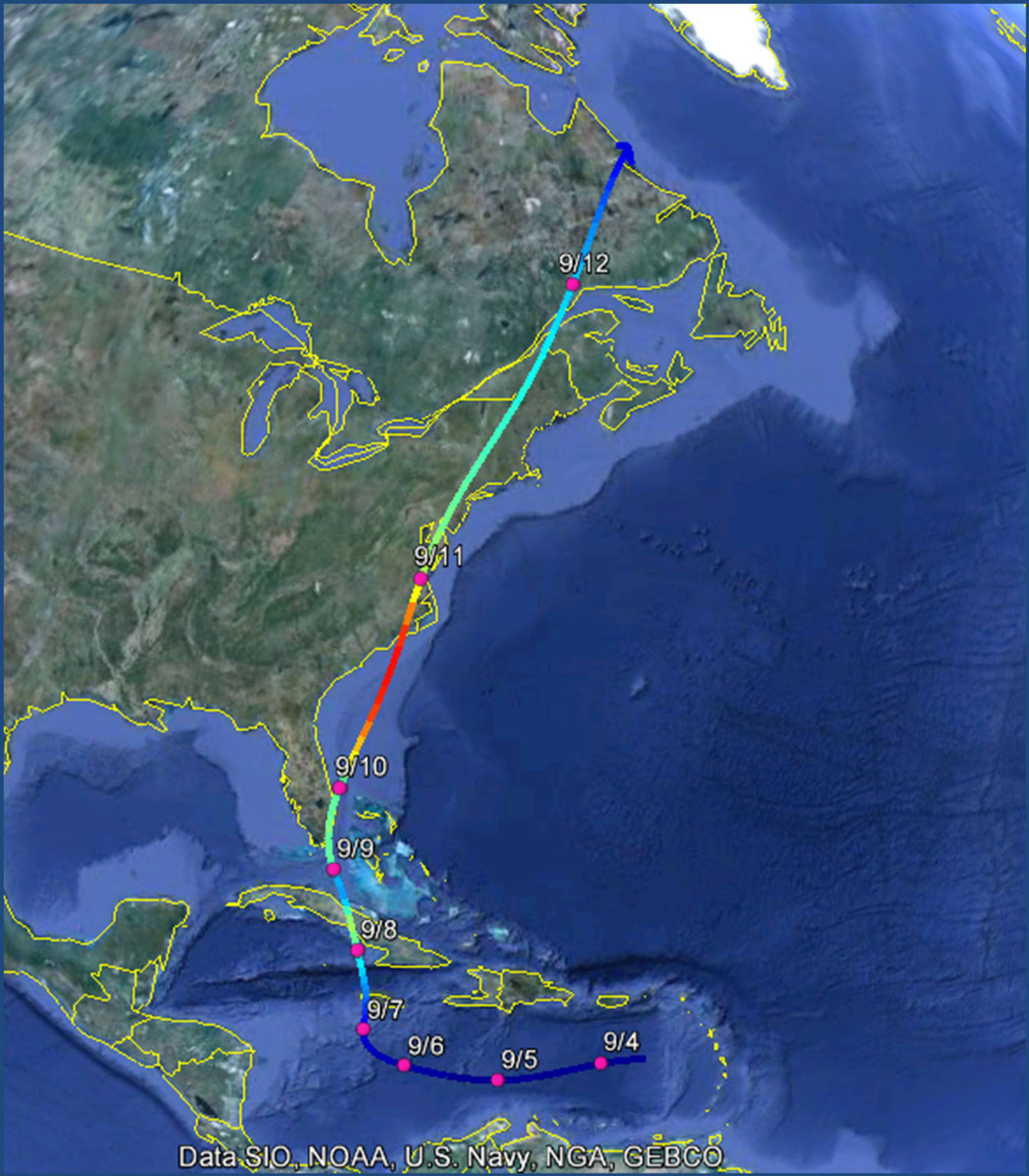
Comparison of Random Seeding Genesis Locations with Observations



Calibration

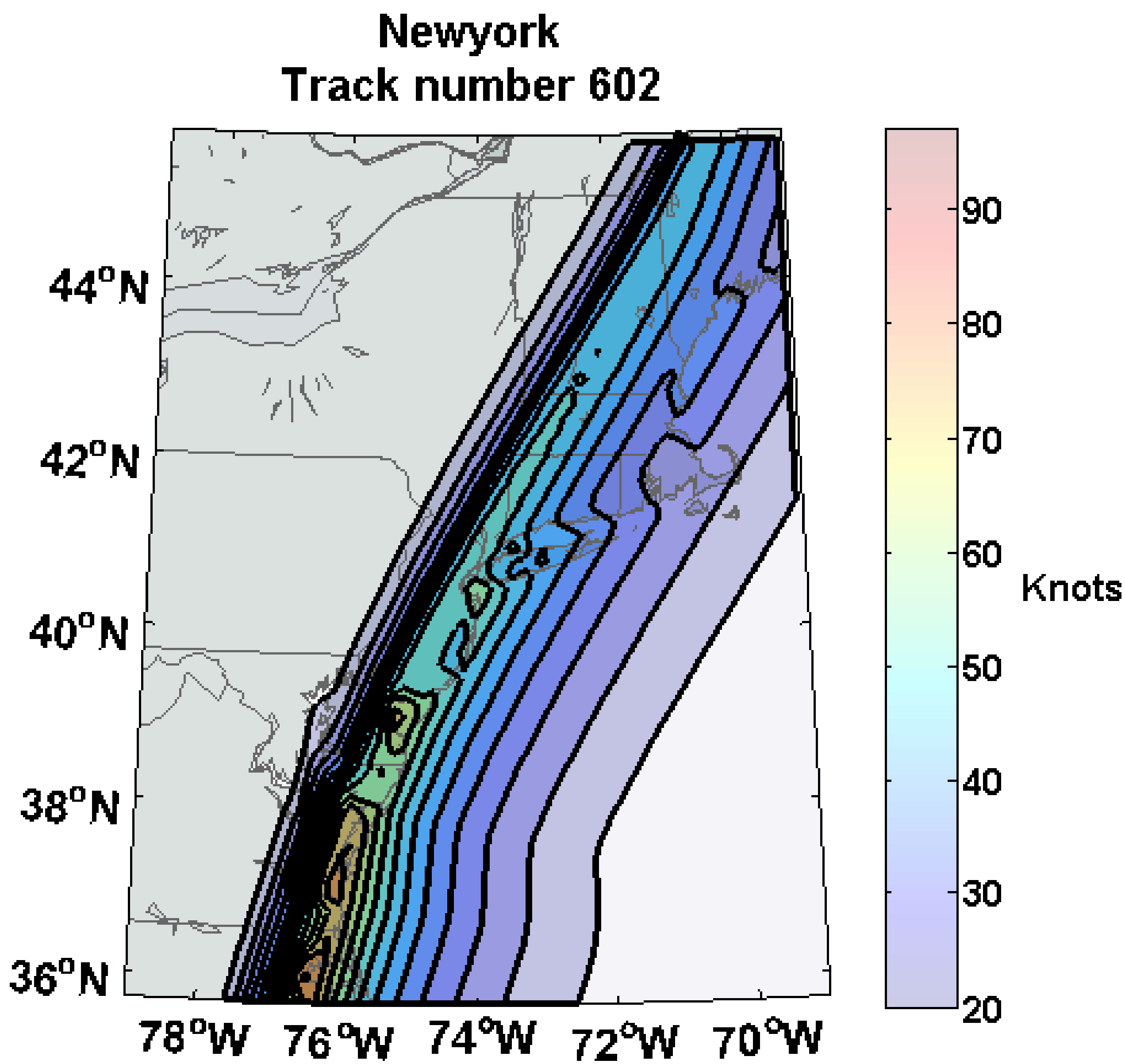
- **Absolute genesis frequency calibrated to globe during the period 1980-2005**


ERA40, 1000 Tracks
90N
70N
50N
30N
10N
10S
30S
50S
70S
40E 60E 80E 100E 120E 140E 160E 180E 160W 140W 120W 100W 80W 60W 40W 20W 0E 20E

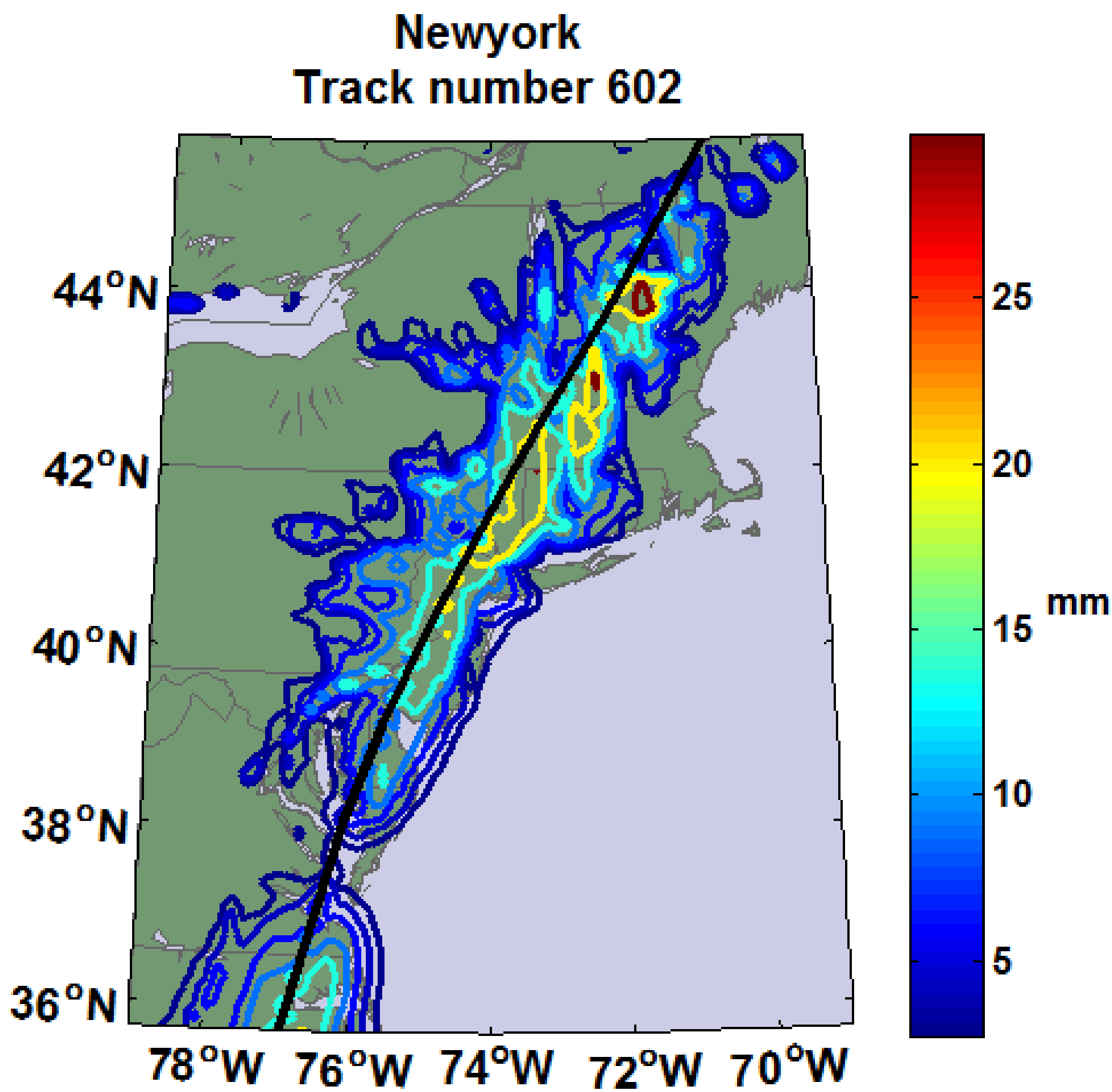


Example: Hurricane affecting New York City

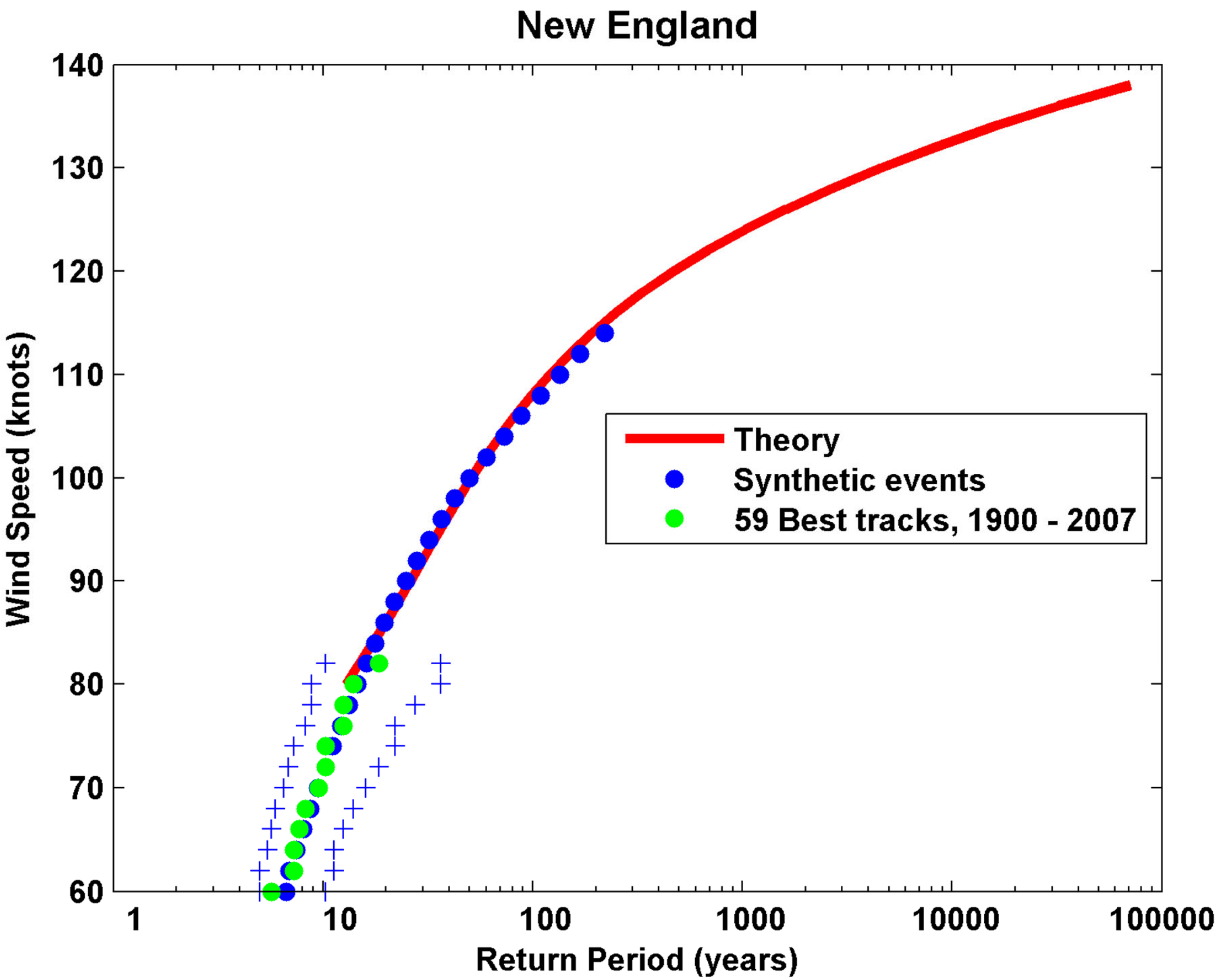
Wind Swath


Newyork
Track number 602
44°N
42°N
40°N
38°N
36°N
78°W
76°W
74°W
72°W
70°W
90
80
70
60
50
40
30
20
Knots

Accumulated Rainfall (mm)



Return Periods



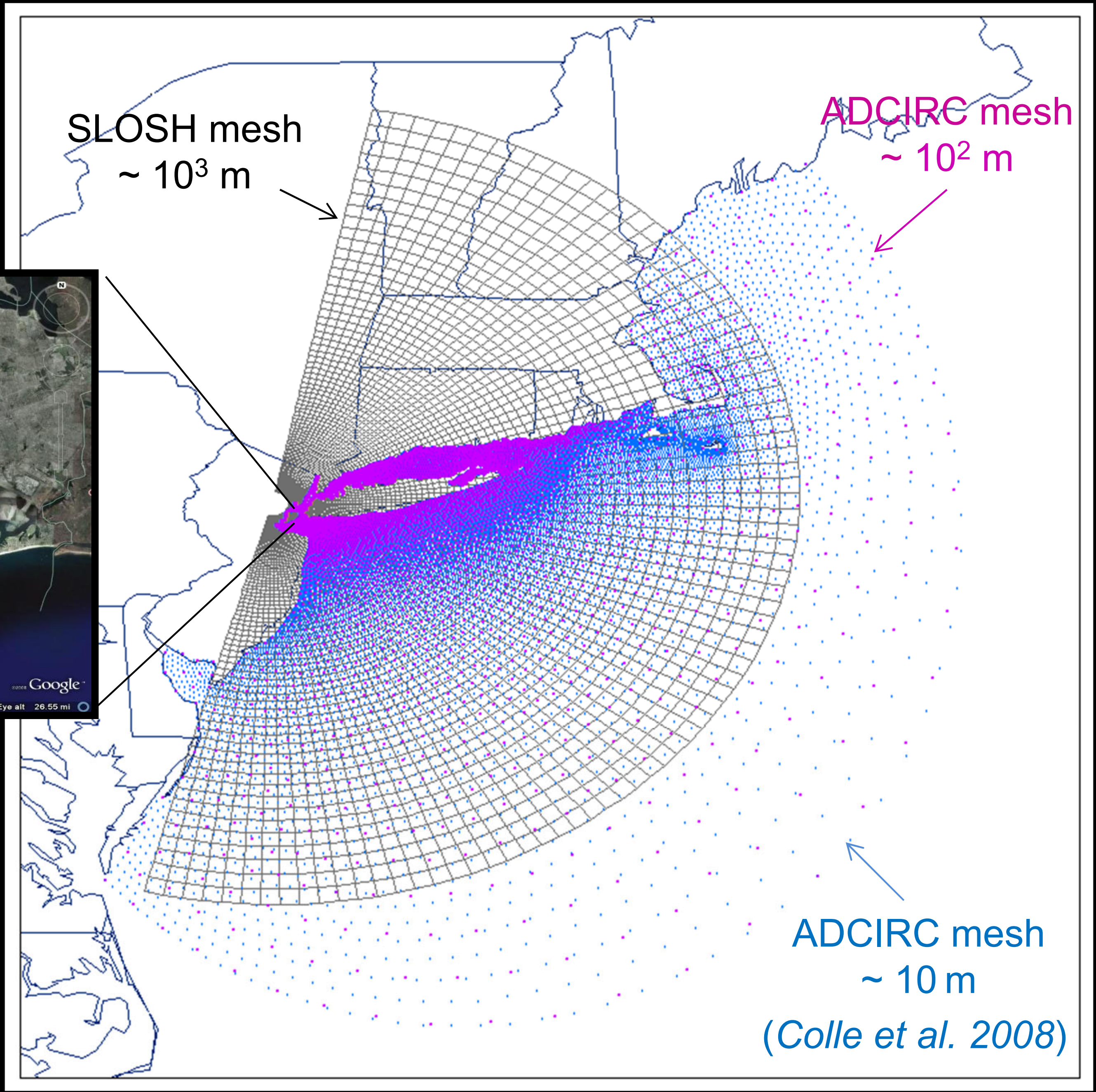
Coupling large hurricane event sets to surge models (with Ning Lin)

- Couple synthetic tropical cyclone events (Emanuel et al., BAMS, 2008) to surge models
  - SLOSH
  - ADCIRC (fine mesh)
  - ADCIRC (coarse mesh)
- Generate probability distributions of surge at desired locations

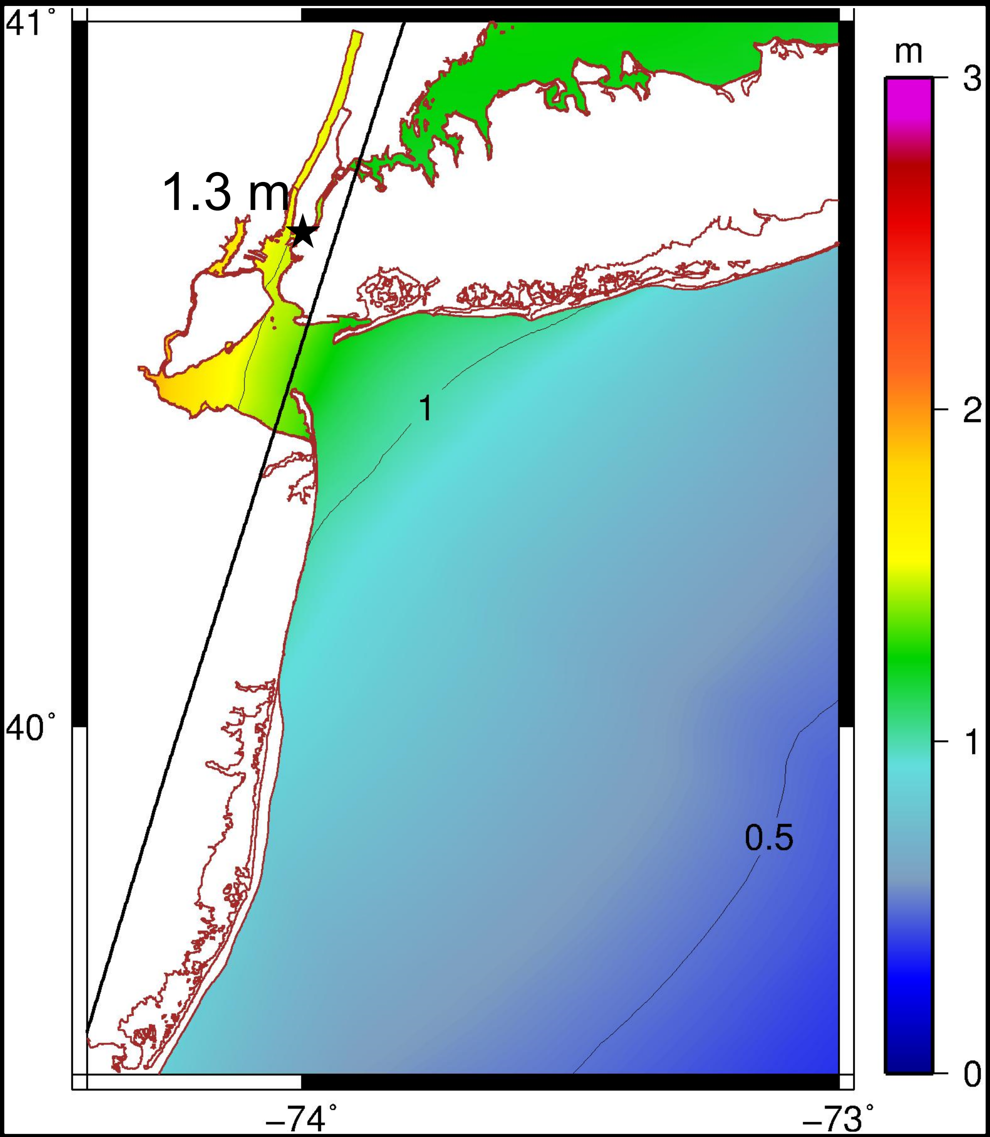
Storm Surge Simulation

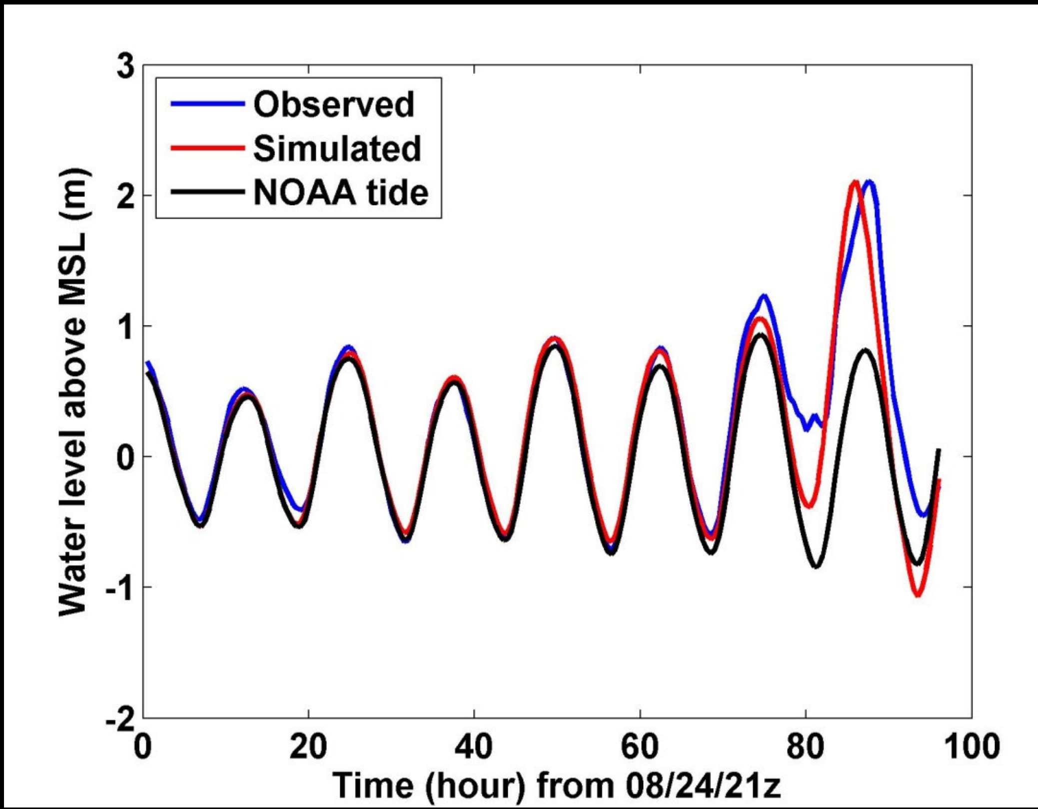
SLOSH model
(*Jelesnianski et al. 1992*)

ADCIRC model
(*Luettich et al. 1992*)



Hurricane Irene (2011) Hindcast

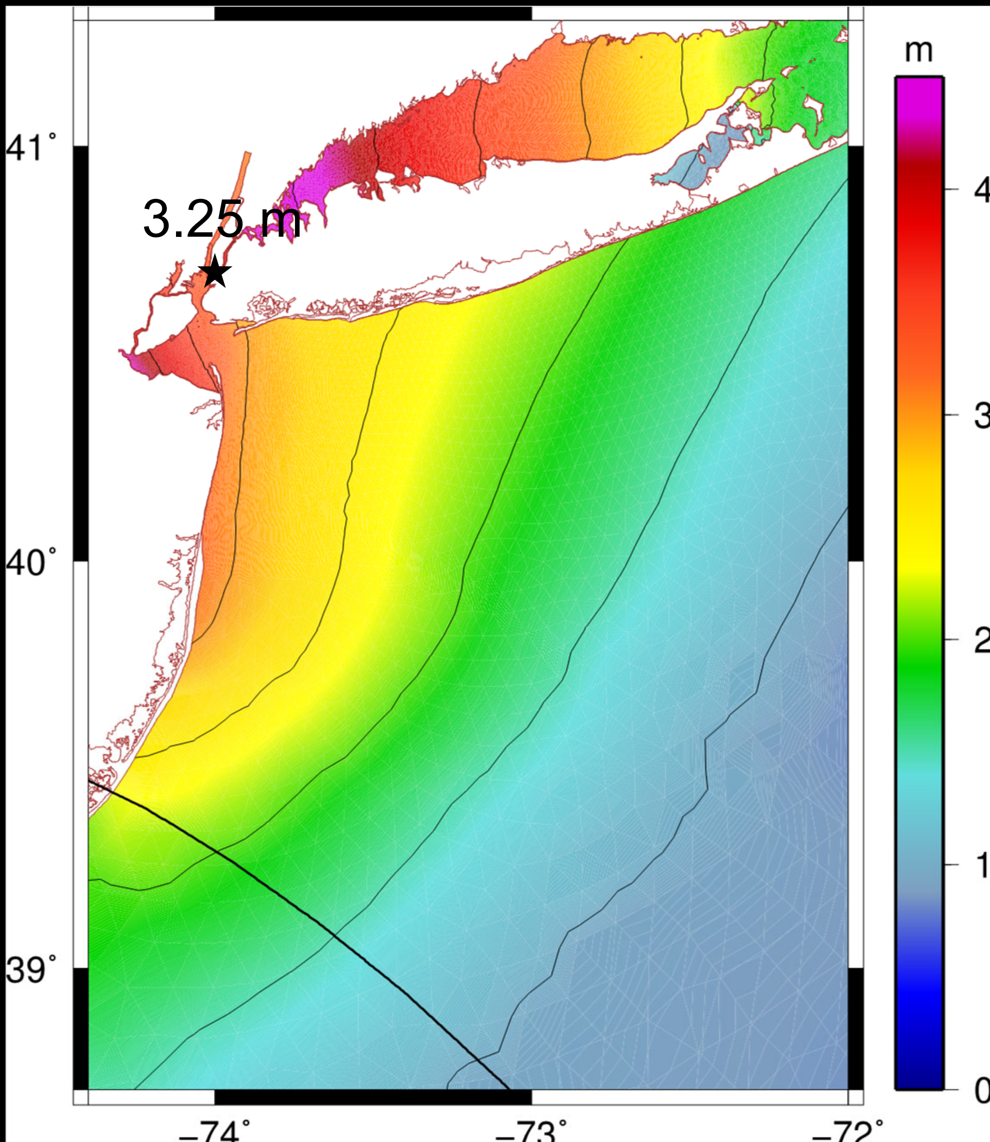




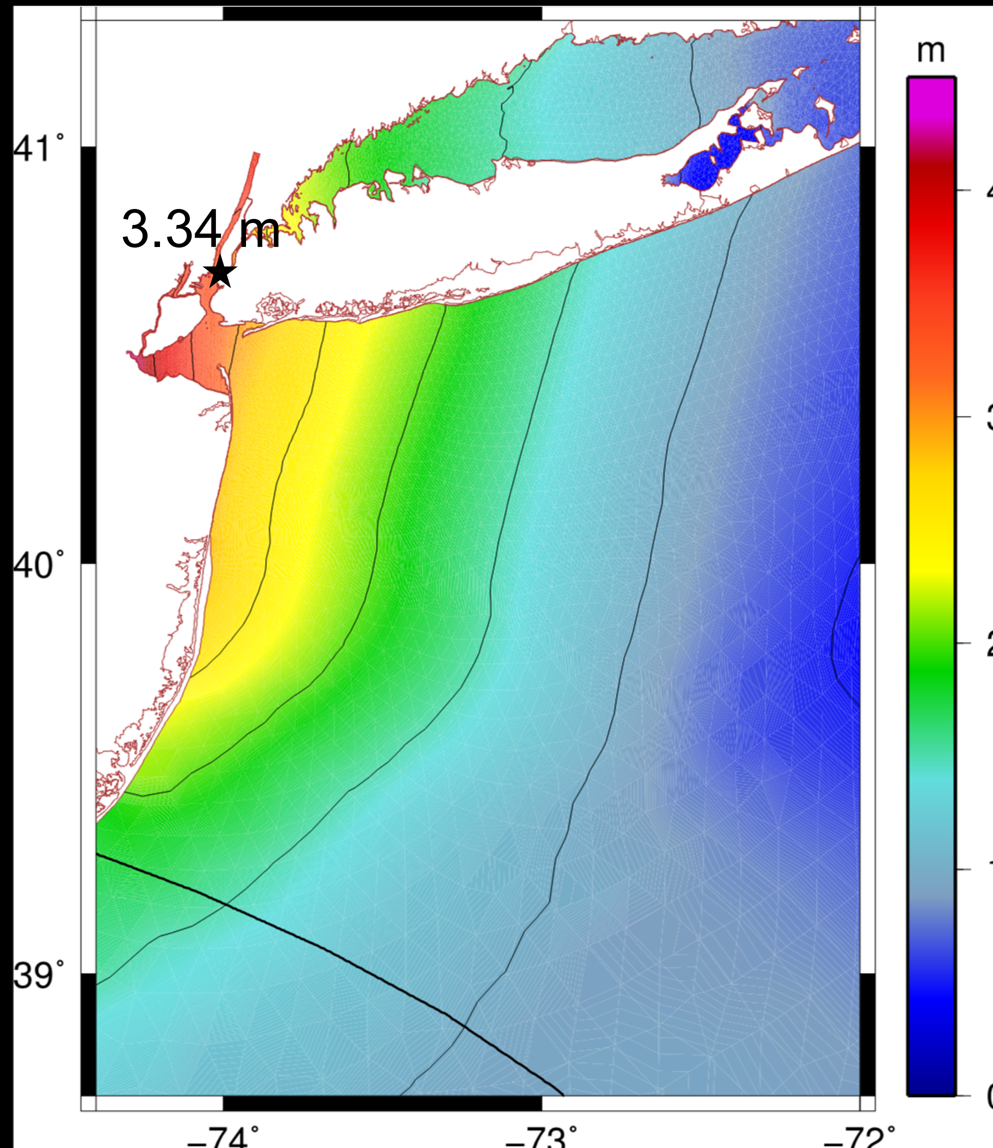
V_m = 17 m/s, P_c = 977 mb

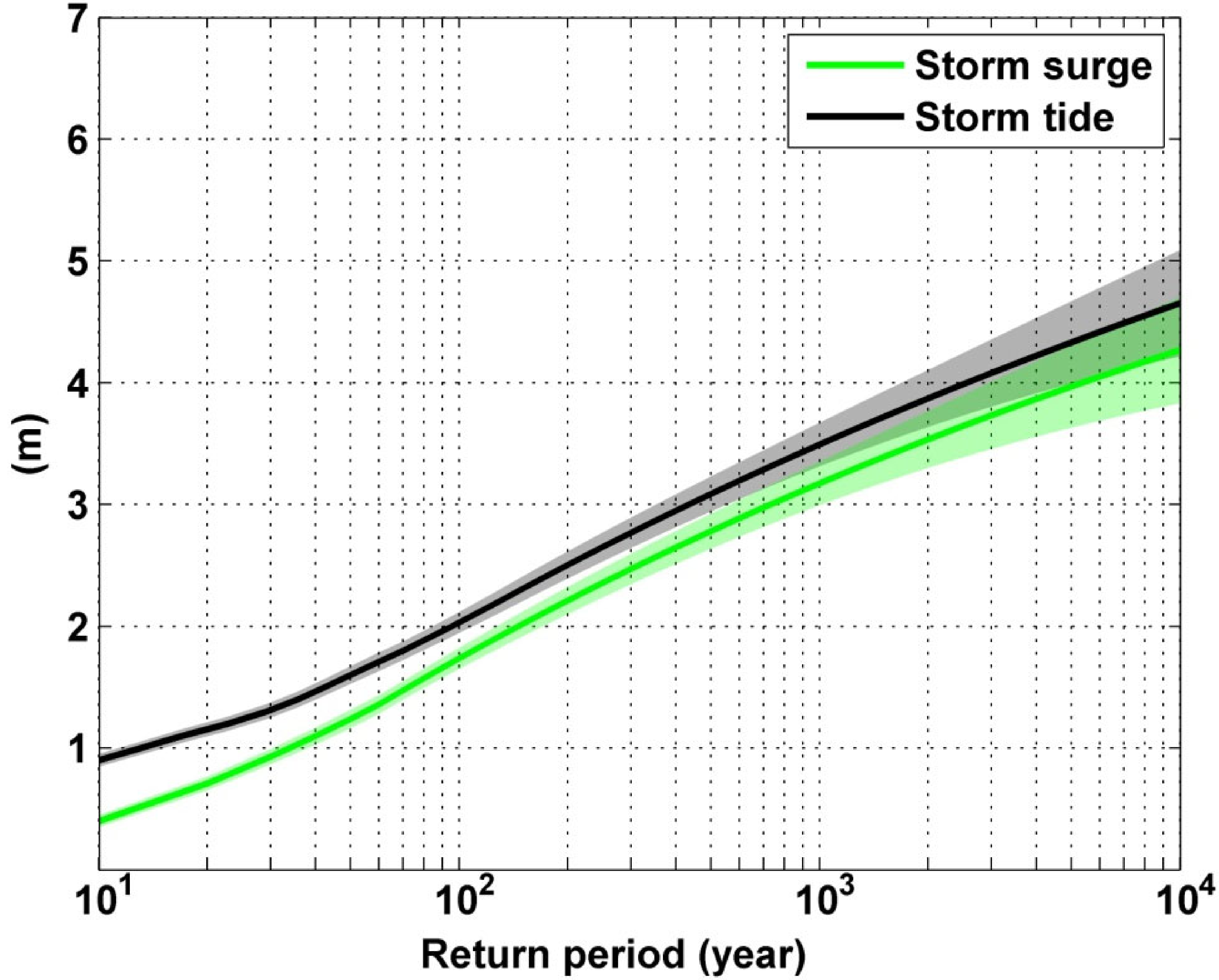
R_m = 83 km, U_t = 12 m/s, ds = 9 km

Hurricane Sandy (2012) Hindcast



HWRF Forecast at 2012102818z

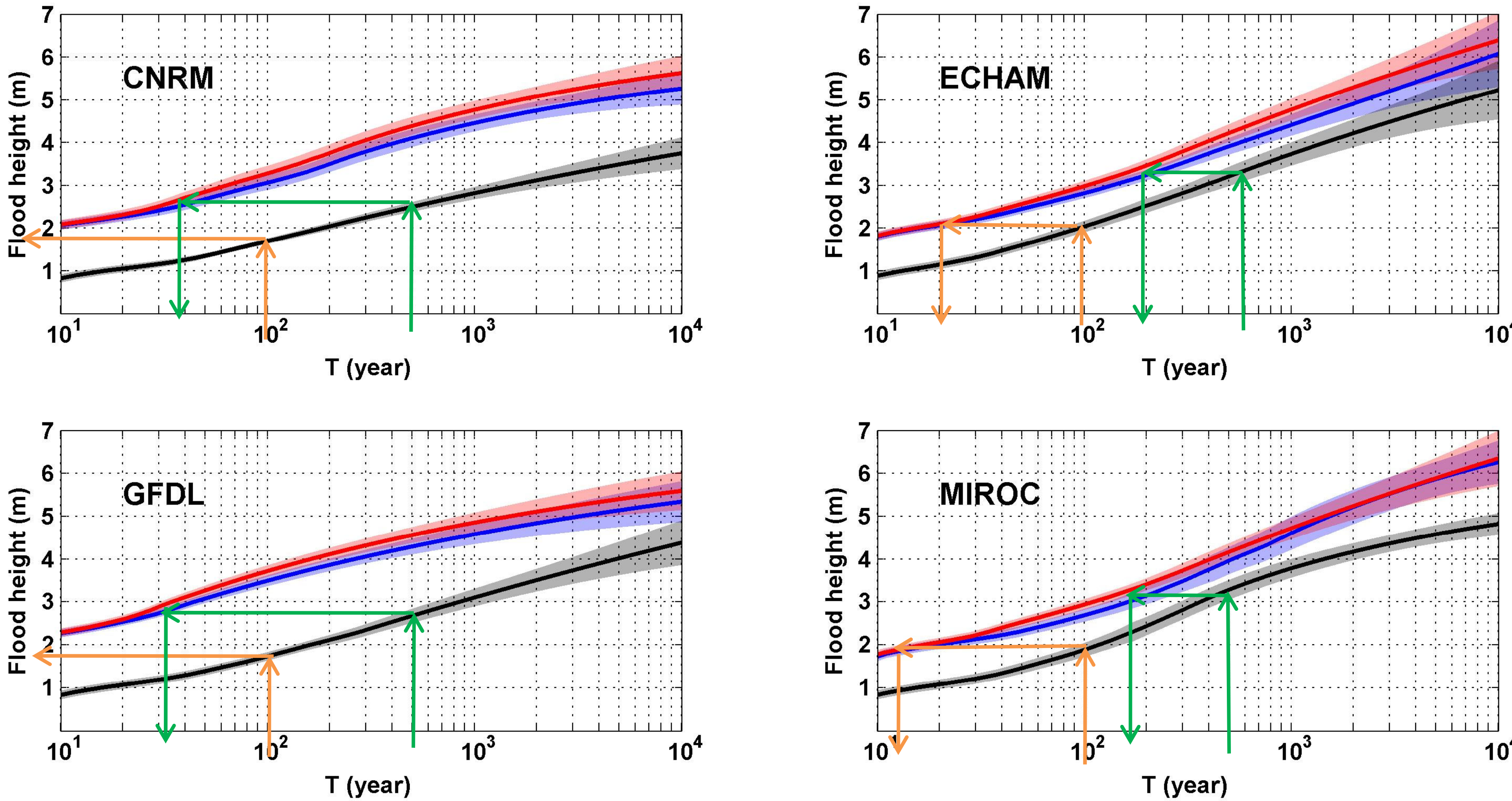



Storm surge
Storm tide
(m)
Return period (year)
7
6
5
4
3
2
1
10^1
10^2
10^3
10^4

Looking Ahead

GCM flood height return level

(assuming SLR of 1 m for the future climate)



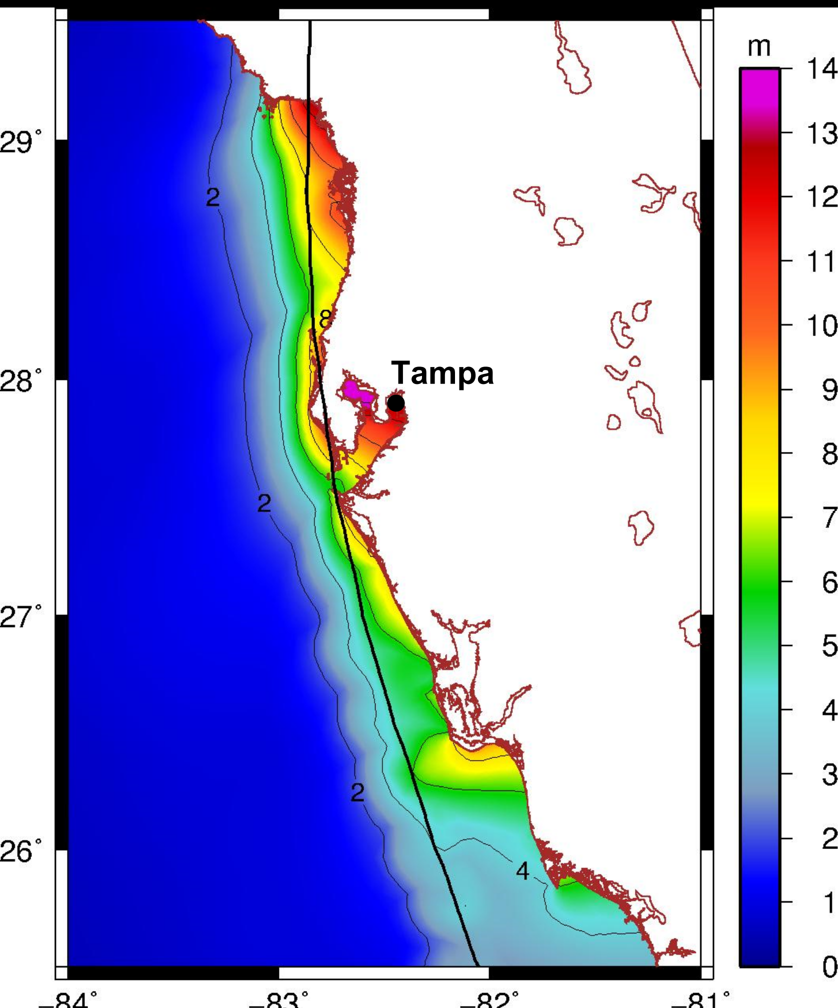
Black: Current climate (1981-2000)

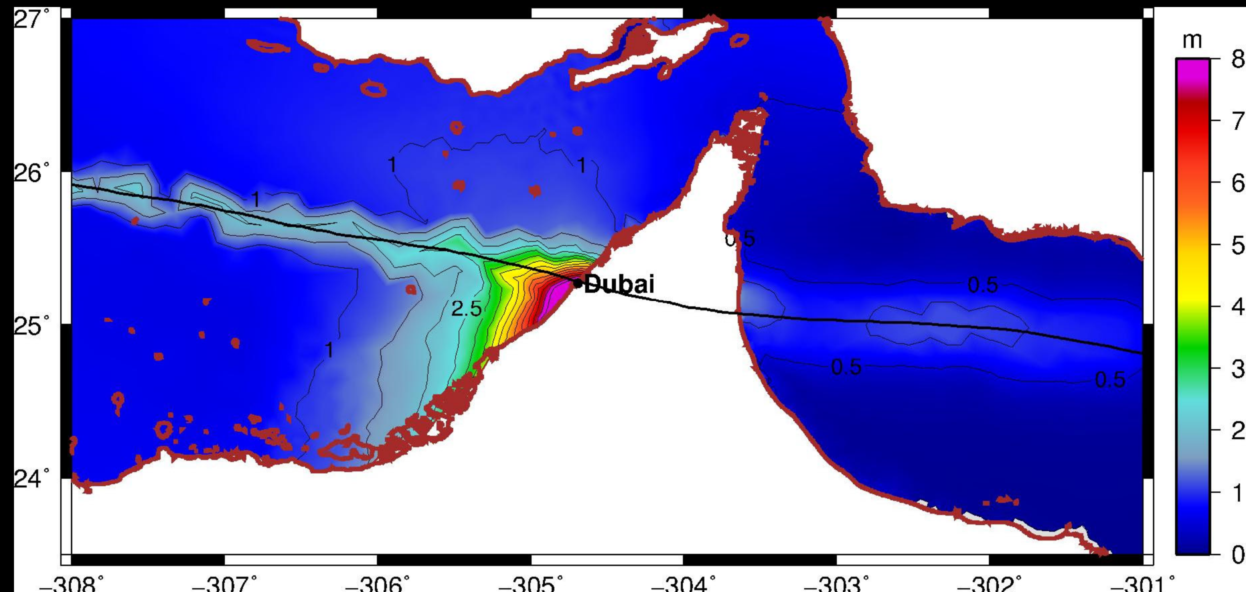
Blue: A1B future climate (2081-2100)

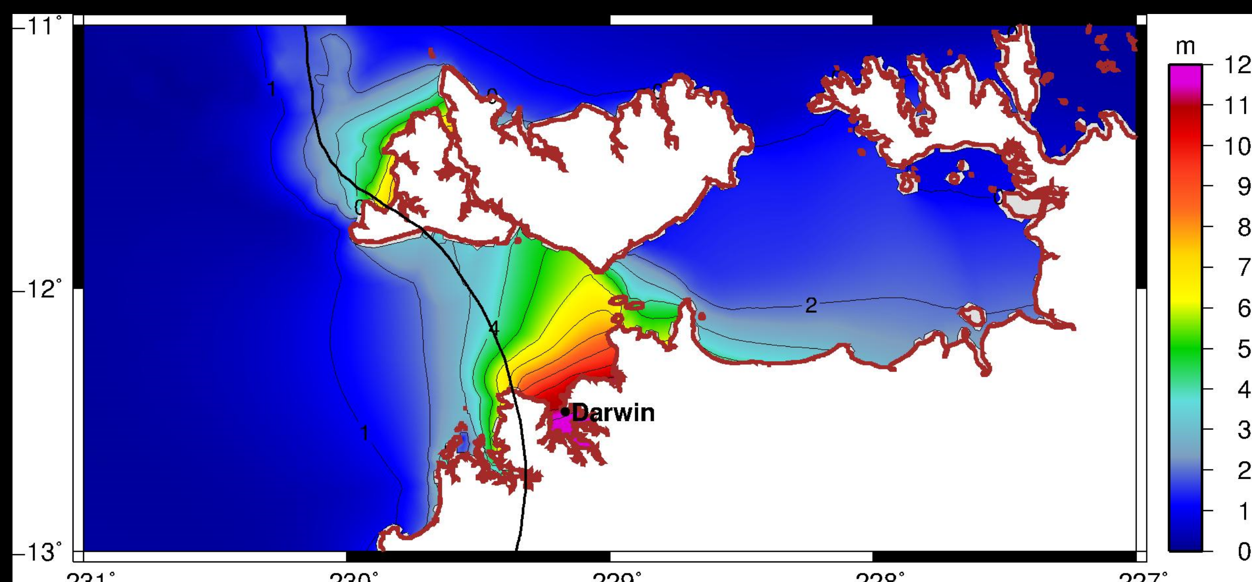
Red: A1B future climate (2081-2100) with R_0 increased by 10% and R_m increased by 21%

Lin et al. (2012)

Black Swan Tropical Cyclones







Summary

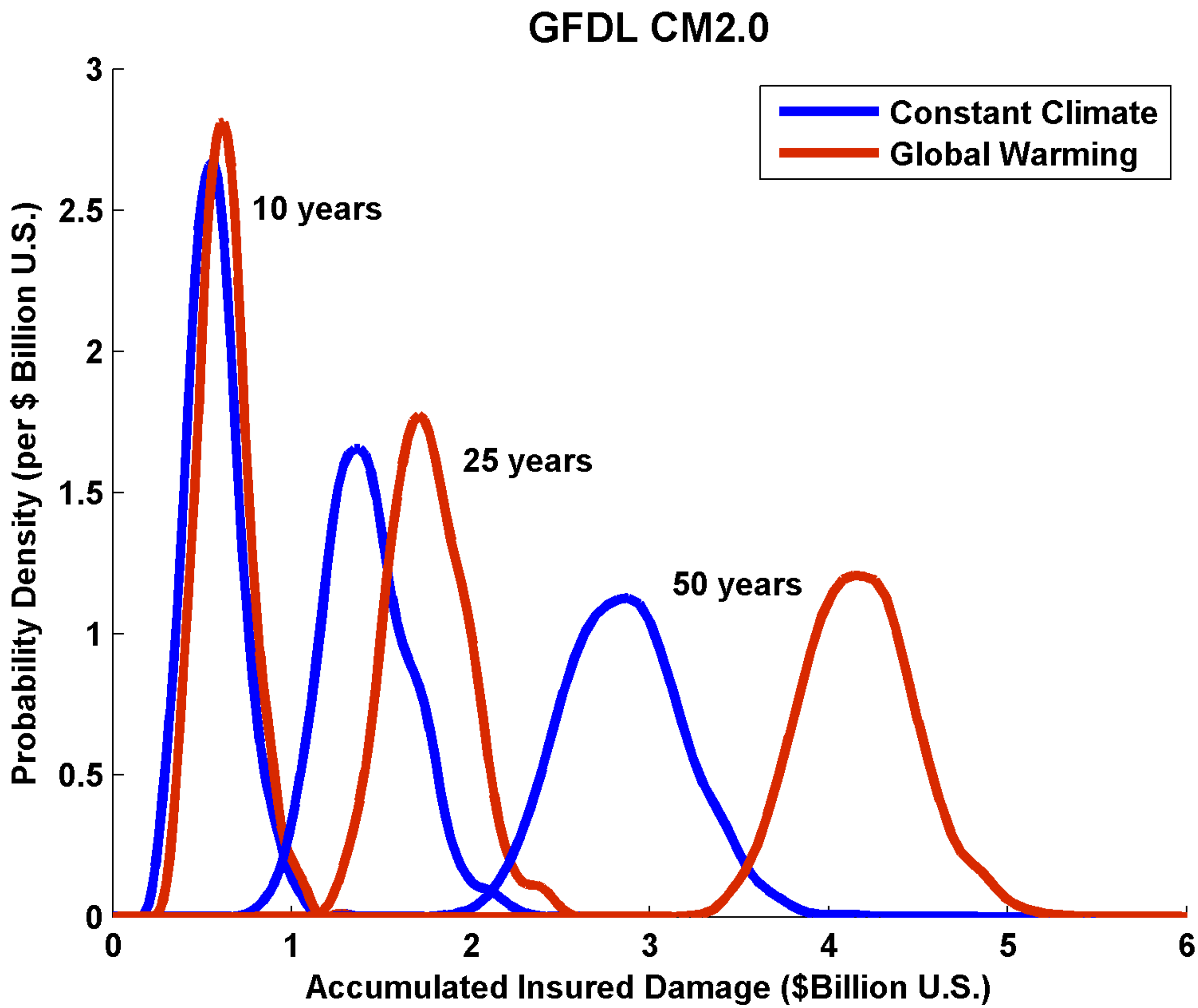
- Historical records are in general too short to permit accurate estimates of surge risk
- Climate change also compromises estimates based strictly on historical records

- Simple but high resolution coupled tropical cyclone model can be used to ‘downscale” tropical cyclone activity and associated surges from global climate data sets

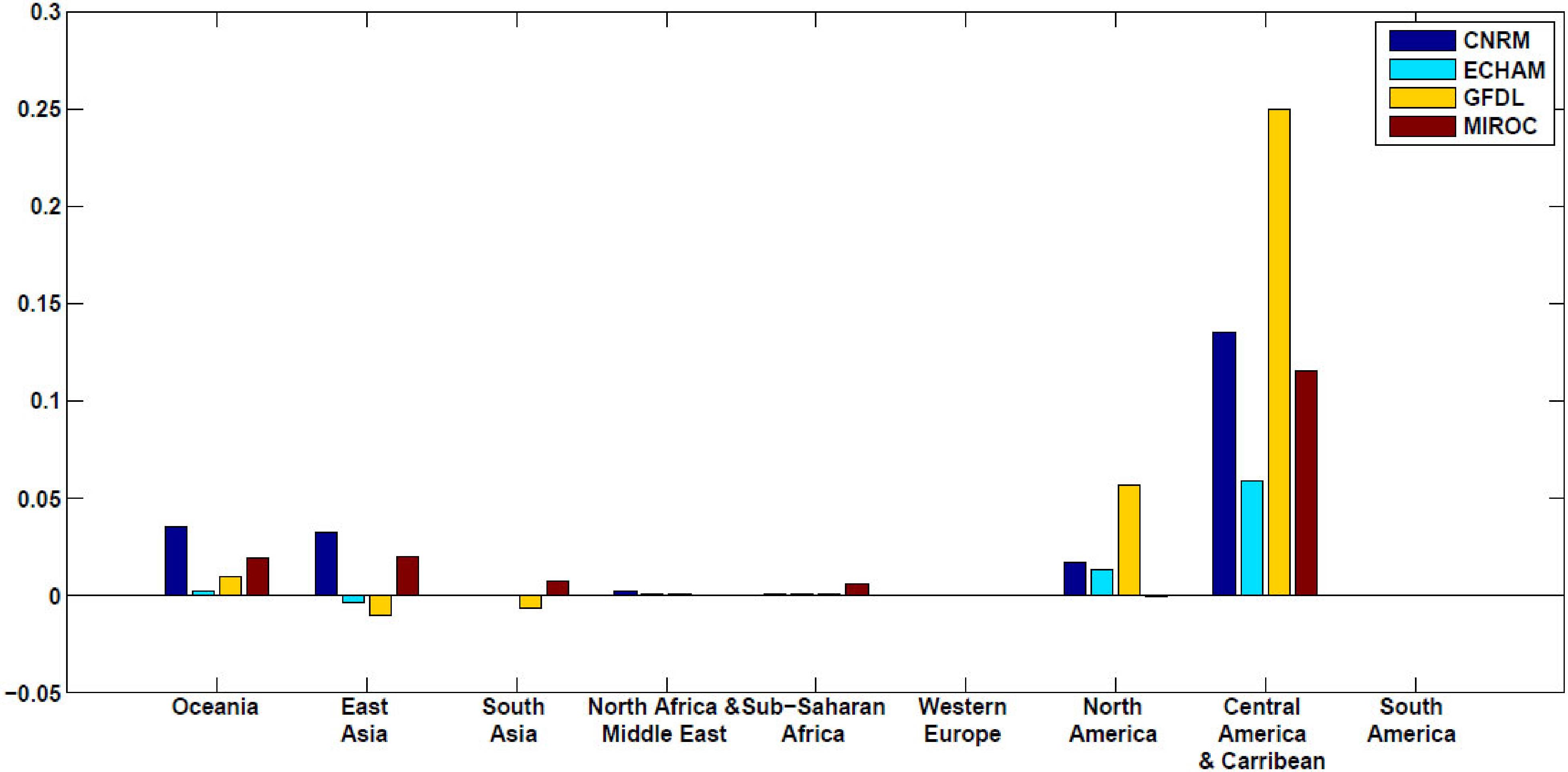
- Studies based on this downscaling suggest some sensitivity of tropical cyclones to climate state, and possibly important changes in tropical activity over the next century

- The 500 year flooding event in New York City is expected to occur every 25-240 years as a result of sea level rise and increased incidence of intense tropical cyclones
- New York City is also susceptible to winter storm- and hybrid storm-induced surges. More work needs to be done to estimate risks from such events

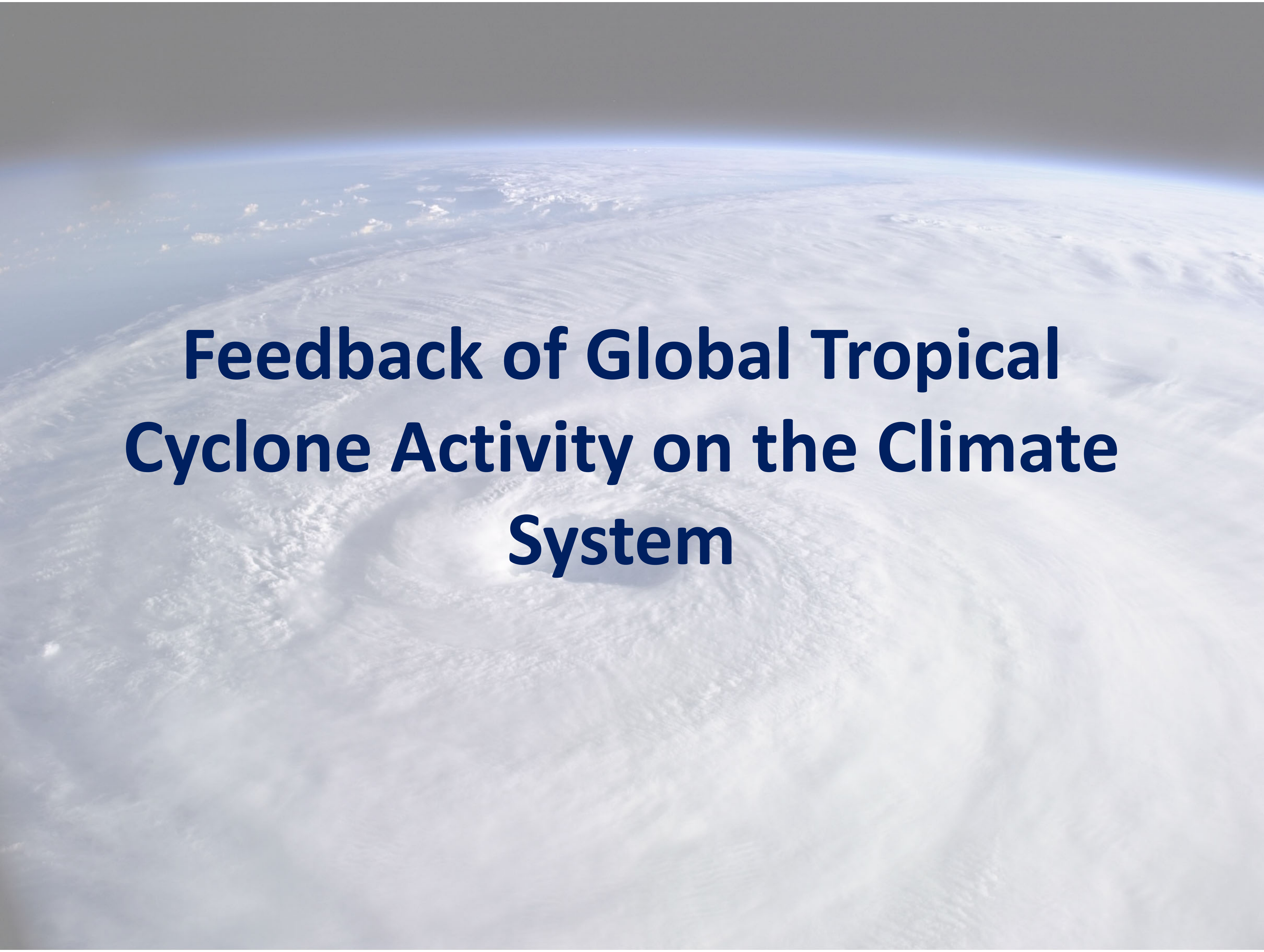
Projections of U.S. Insured Damage



Emanuel, K. A., 2012, *Weather, Climate, and Society*

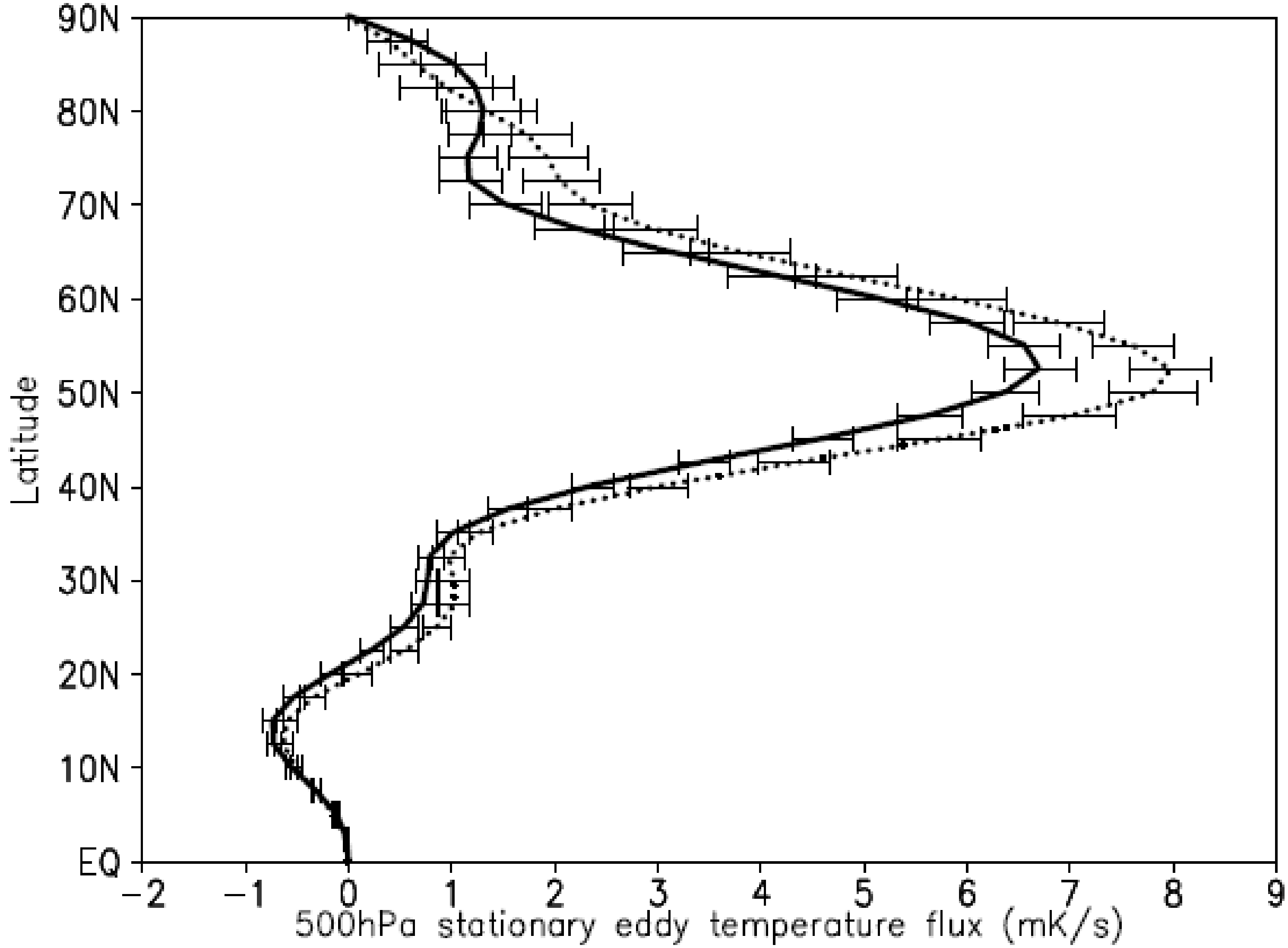


Climate change impacts on tropical cyclone damage divided by GDP by region in 2100. The ratio of damage to GDP is highest in the Caribbean–Central American region but North America, Oceania and East Asia all have above-average ratios.



Feedback of Global Tropical Cyclone Activity on the Climate System

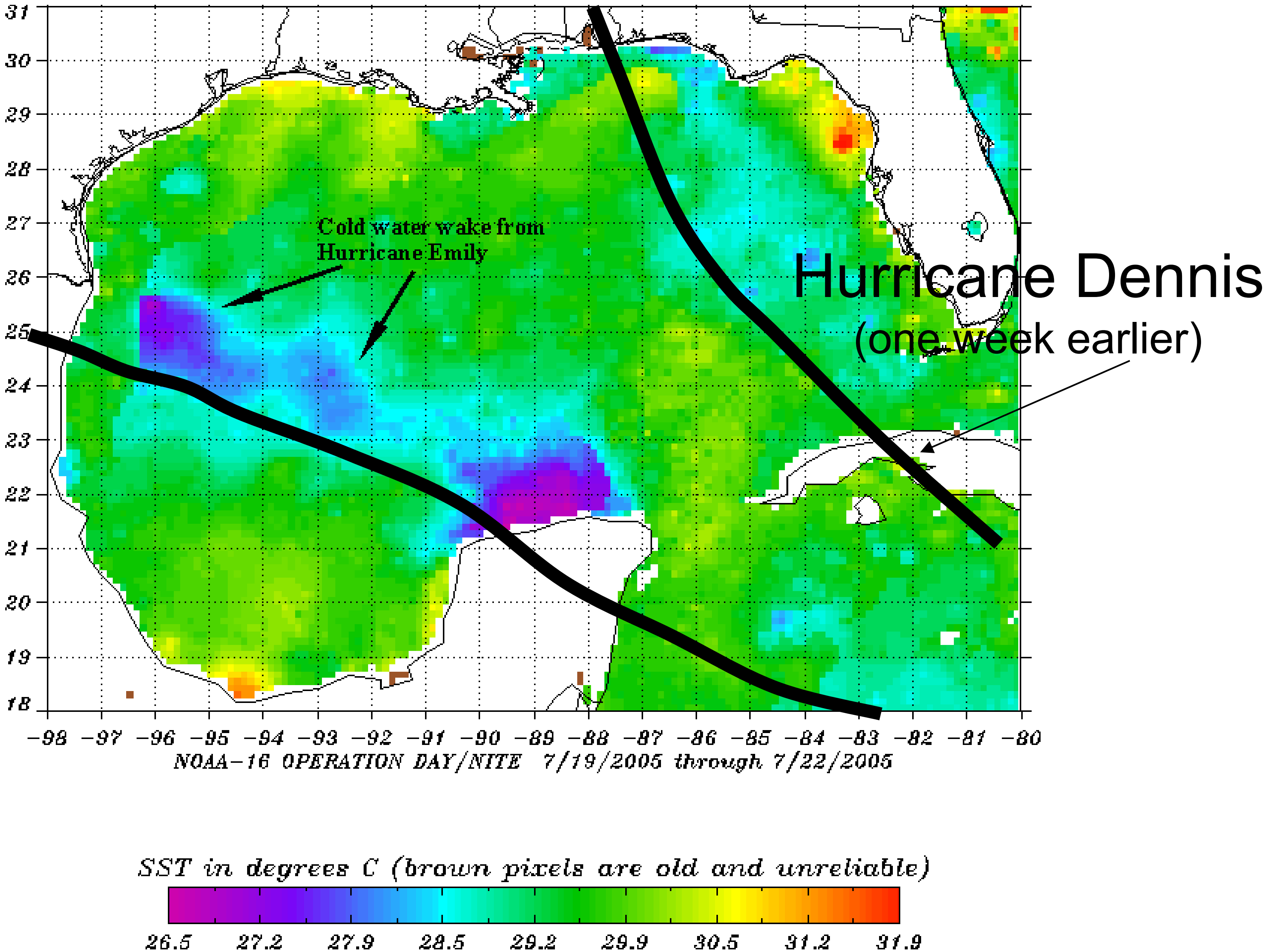
Hart, 2010



500hPa zonal mean meridional temperature flux (mK/s) of the stationary eddies for January through March. The dotted (solid) curve represents the composite mean of the winters following inactive (active) northern hemisphere TC seasons. Error bars represent the standard error of the mean for datasets of size varying from N=9 to 13. Flux calculated using NCAR/NCEP reanalysis for the period 1960-2008

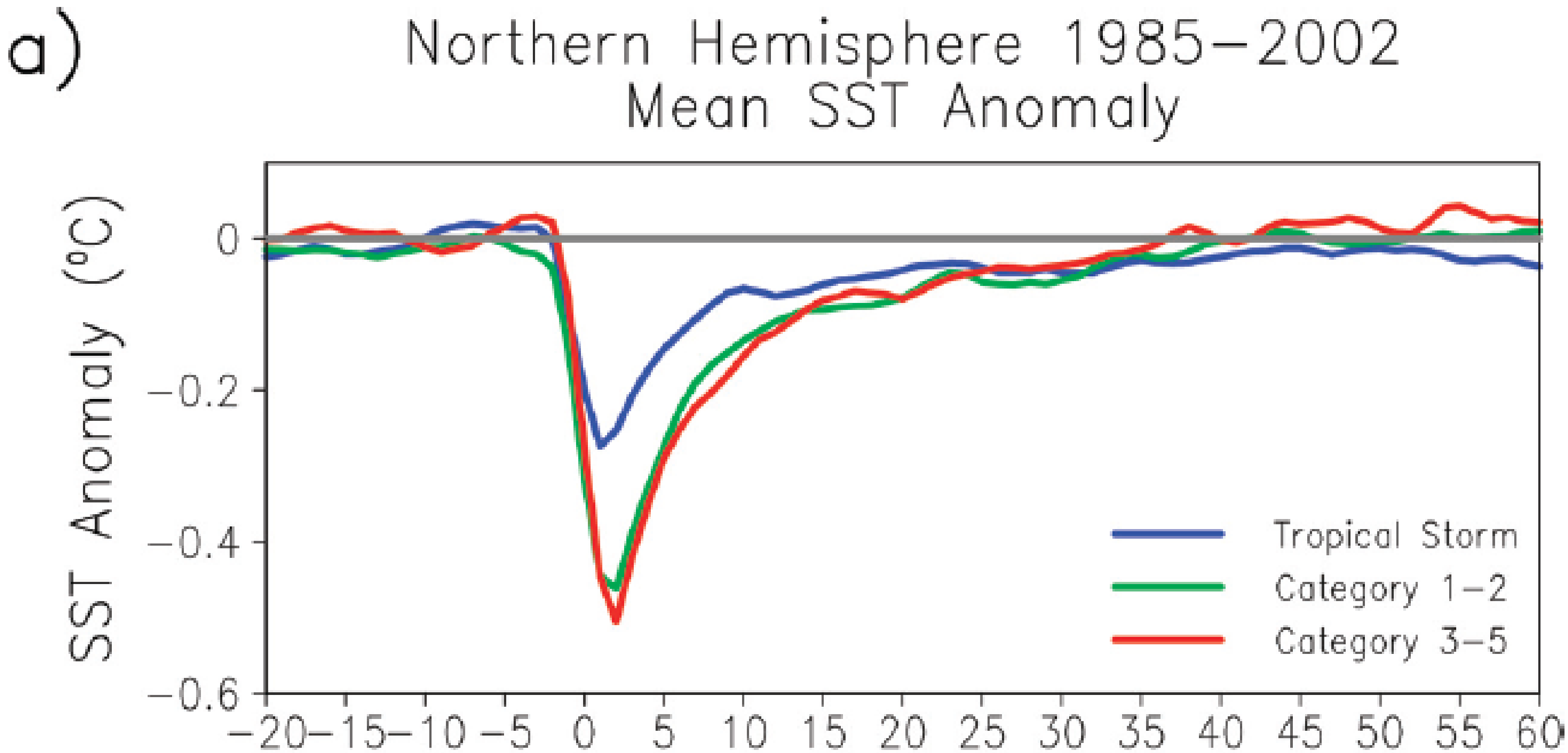
The wake of Hurricane Emily (July 2005)

Sea Surface Temperature in the Wakes of Hurricanes



Source: Rob Korty, CalTech

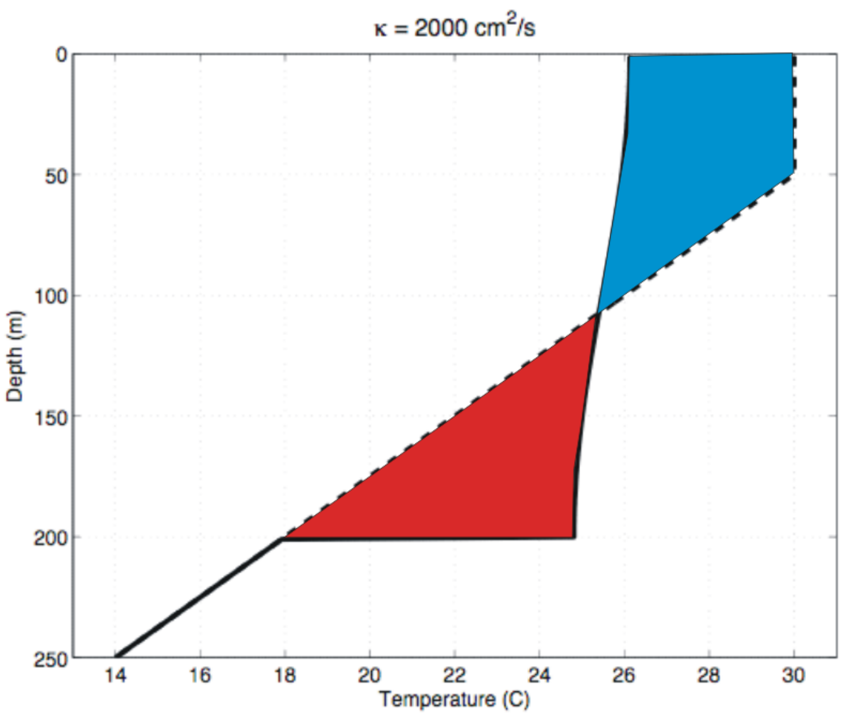
Wake Recovery



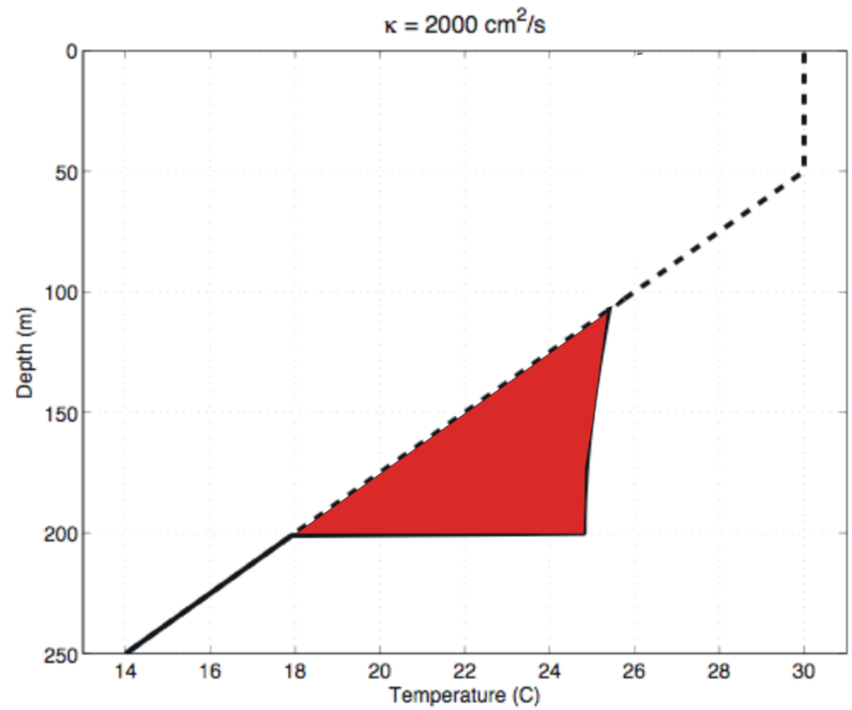
Hart, Maue, and Watson, *Mon. Wea. Rev.*, 2007

Direct mixing by tropical cyclones

Stage 1:
Enthalpy-conserving mixing



Stage 2:
Wake recovery

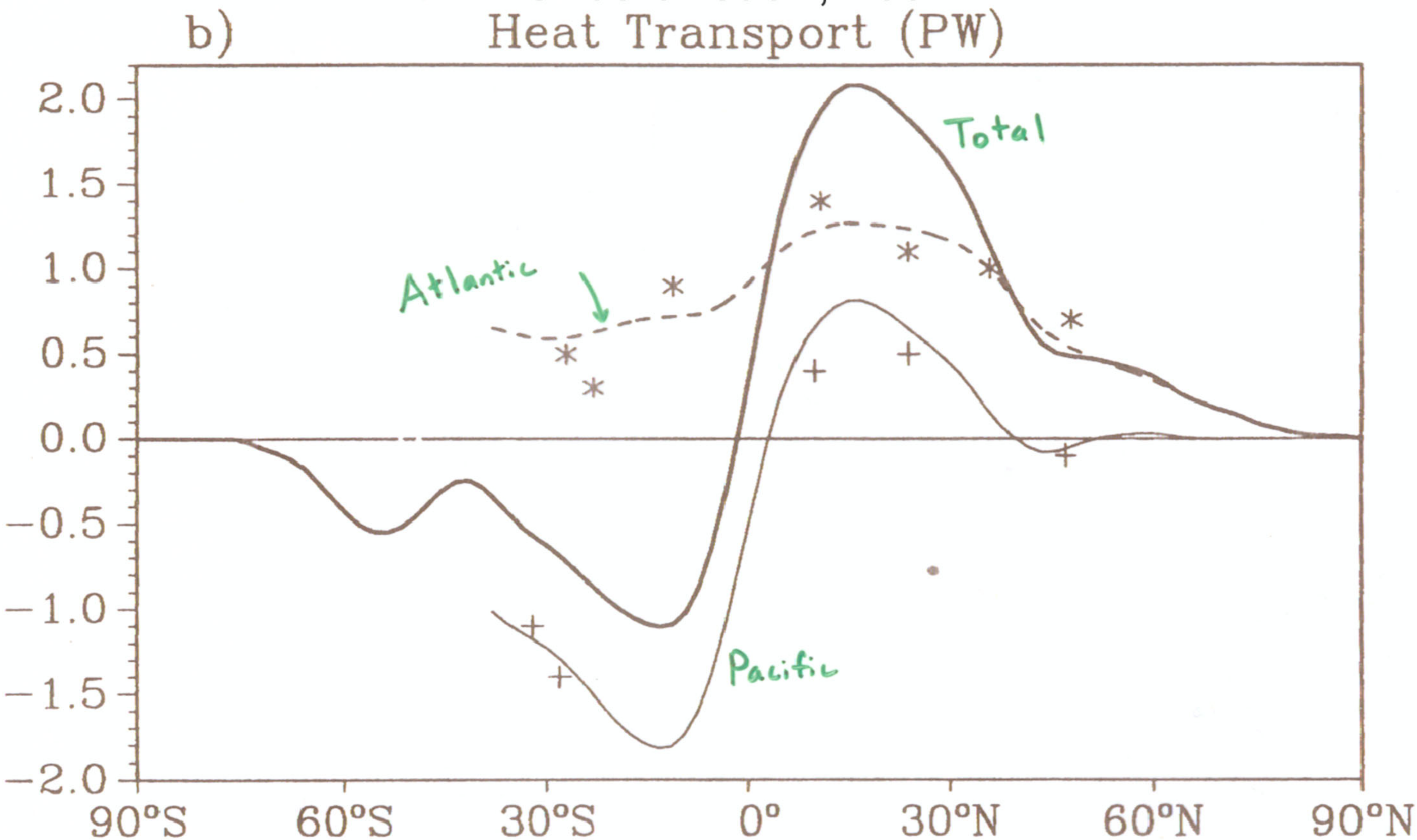


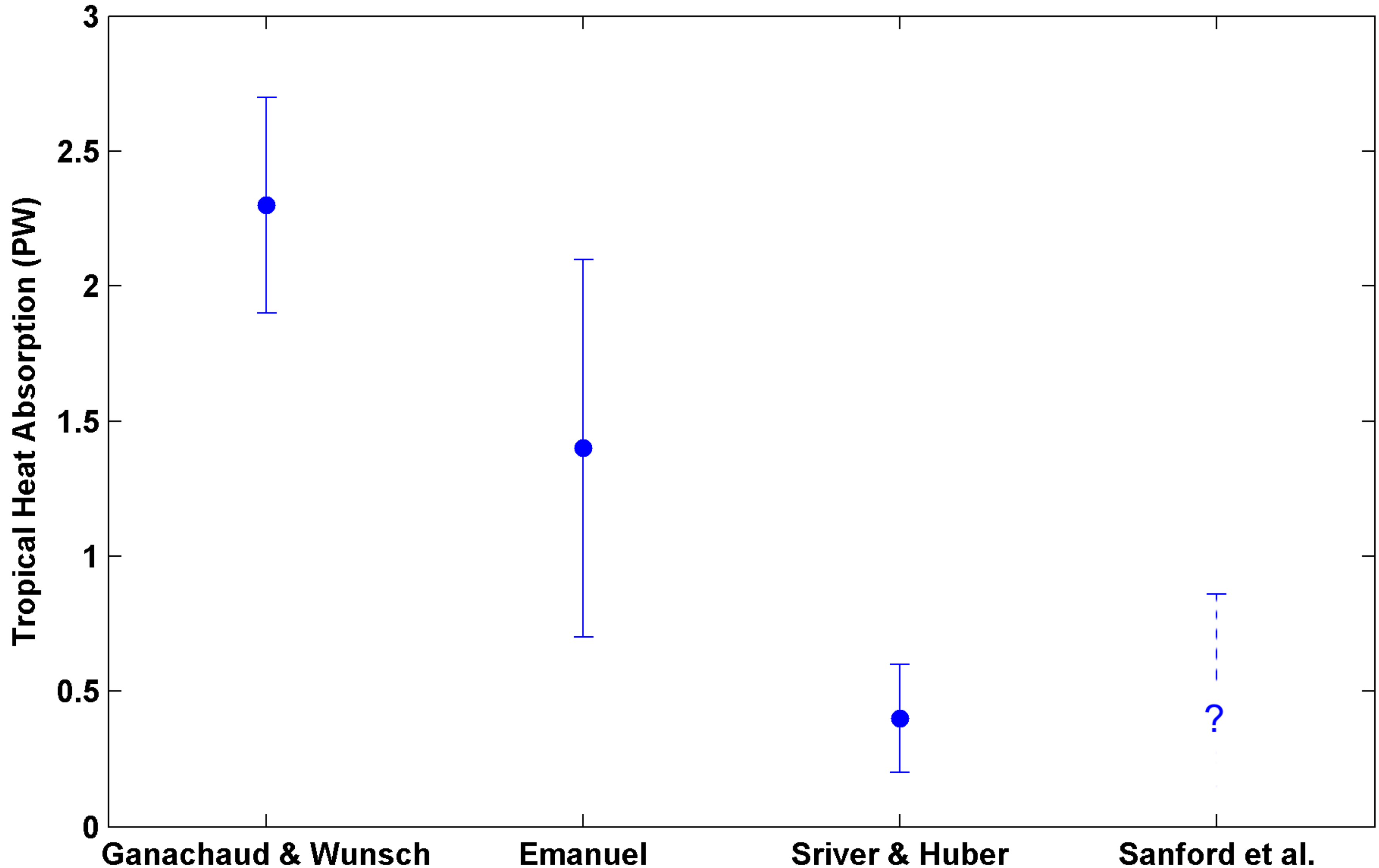
Emanuel (2001) estimated global rate of heat input as 1.4 X 10^{15} Watts

Source: Rob Korty, CalTech

TC Mixing May Induce Much or Most of the Observed Poleward Heat Flux by the Oceans

Trenberth et al., 2001

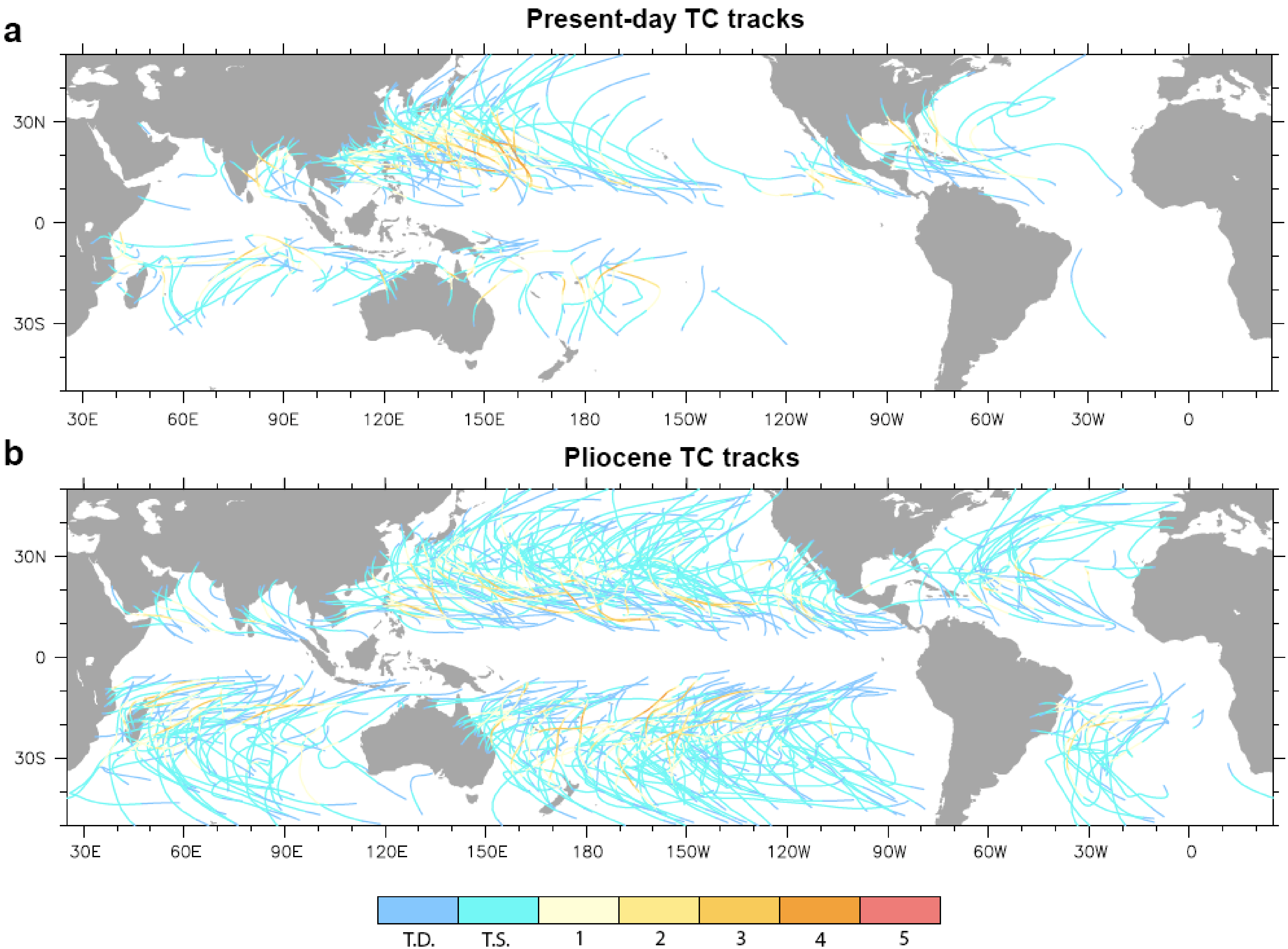




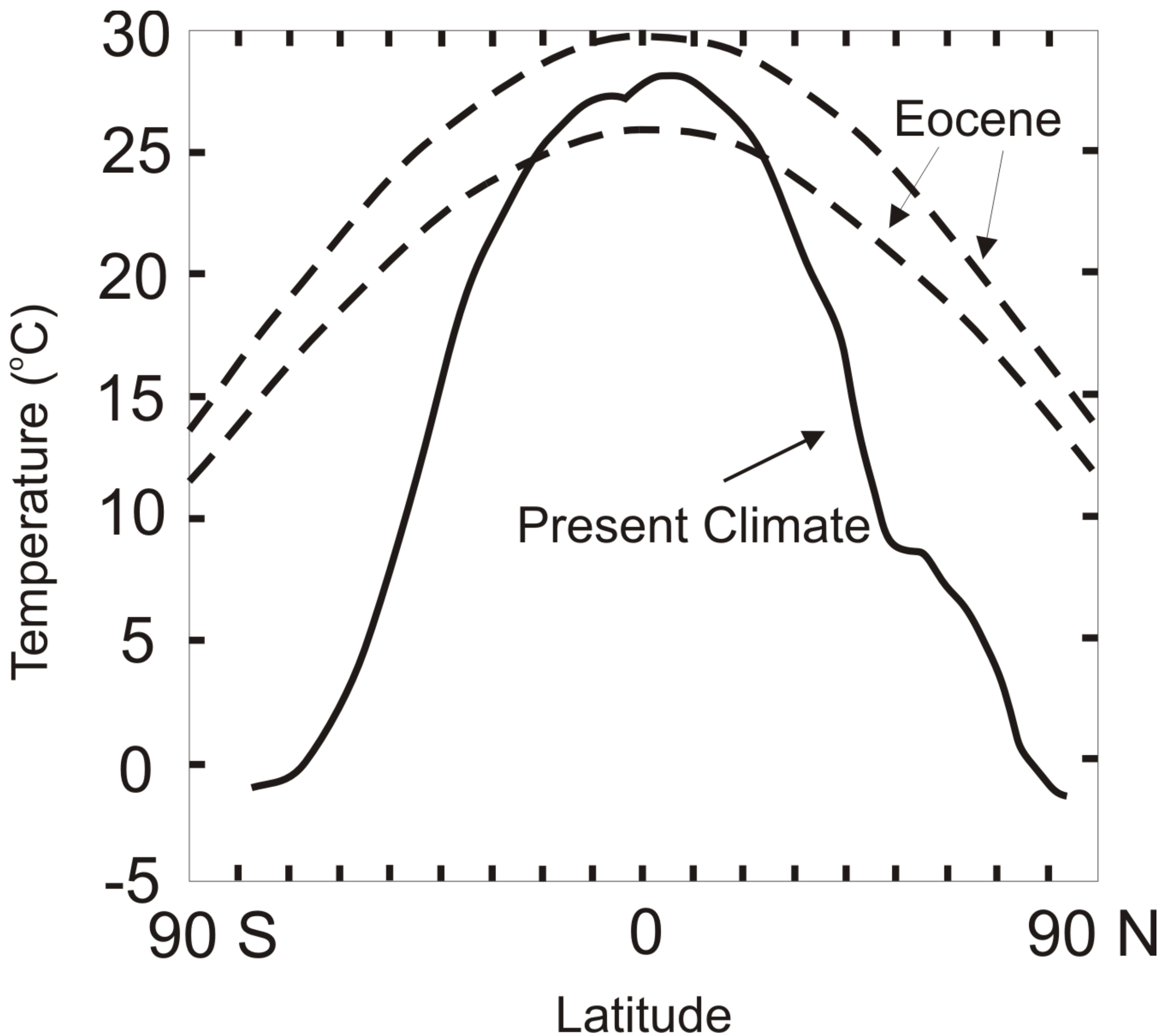
Estimate of total heat uptake by tropical oceans

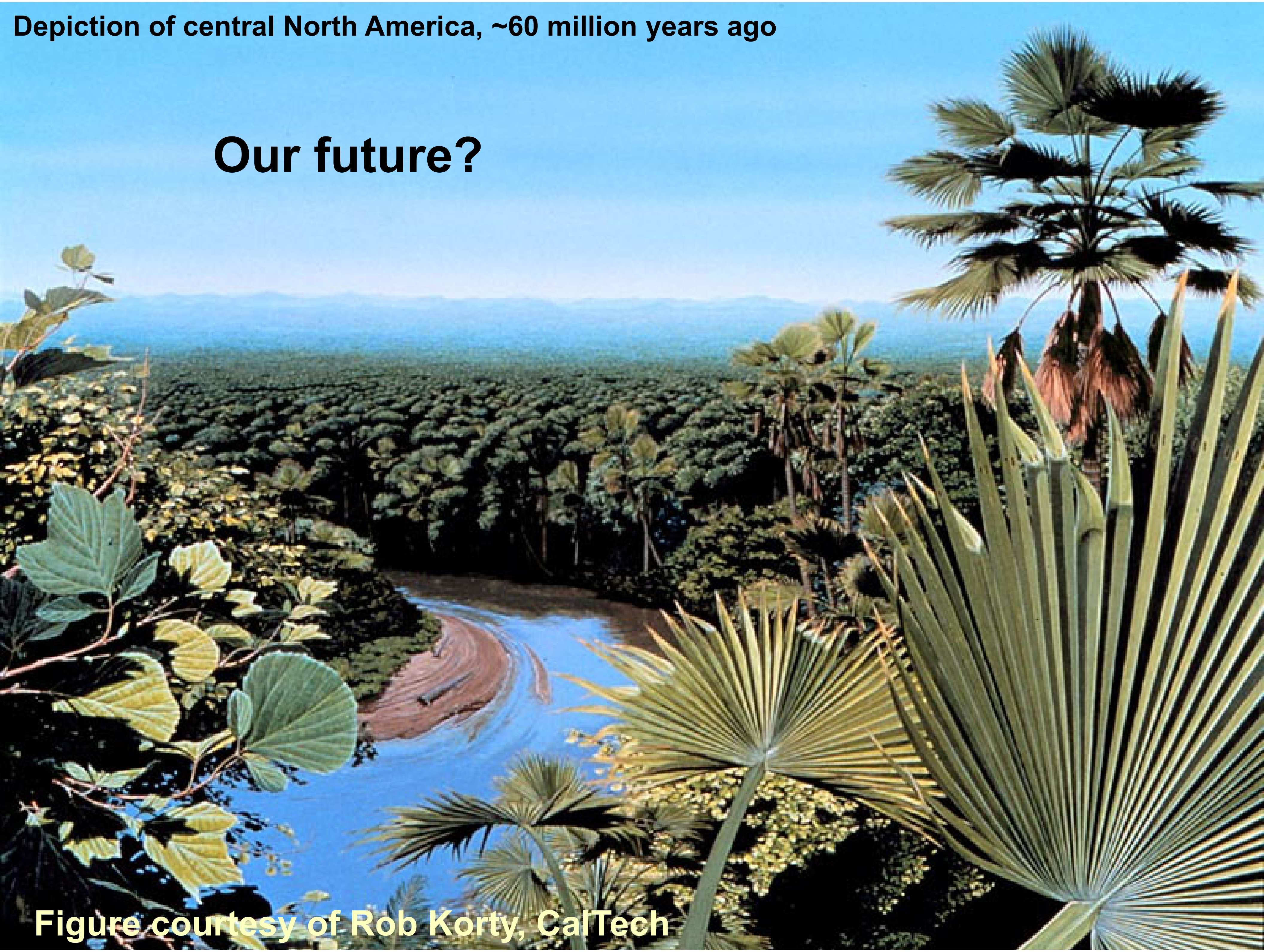
Estimate from satellite-derived wake recoveries

Extrapolation from detailed ocean measurements of one storm

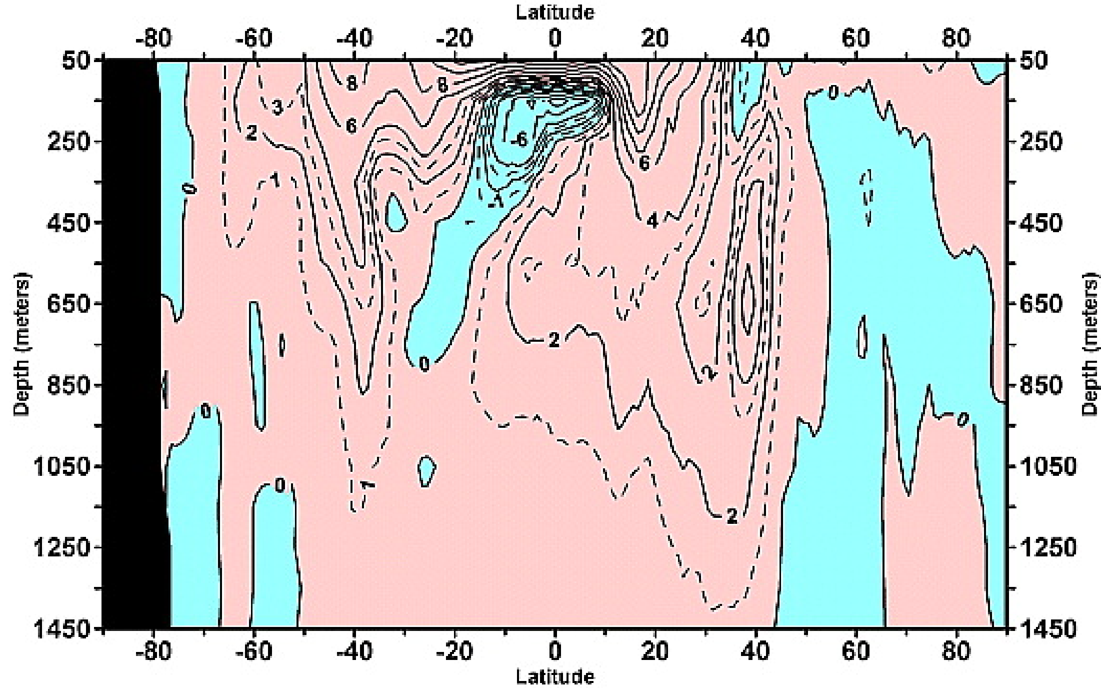

a
Present-day TC tracks
b
Pliocene TC tracks
30N
0
30S
30E
60E
90E
120E
150E
180
150W
120W
90W
60W
30W
0
T.D.
T.S.
1
2
3
4
5

TC-Mixing may be Crucial for High-Latitude Warmth and Low-Latitude Moderation During Warm Climates, such as that of the Eocene

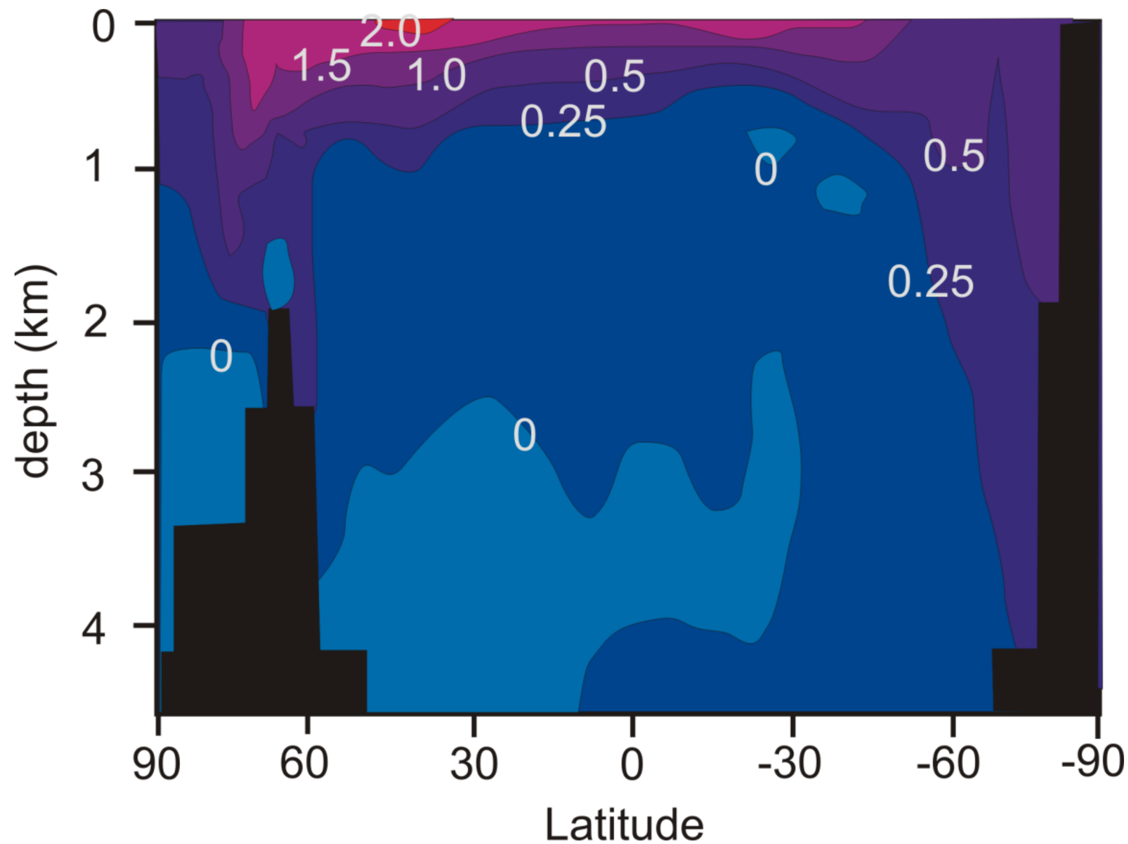



Depiction of central North America, ~60 million years ago
Our future?
Figure courtesy of Rob Korty, CalTech

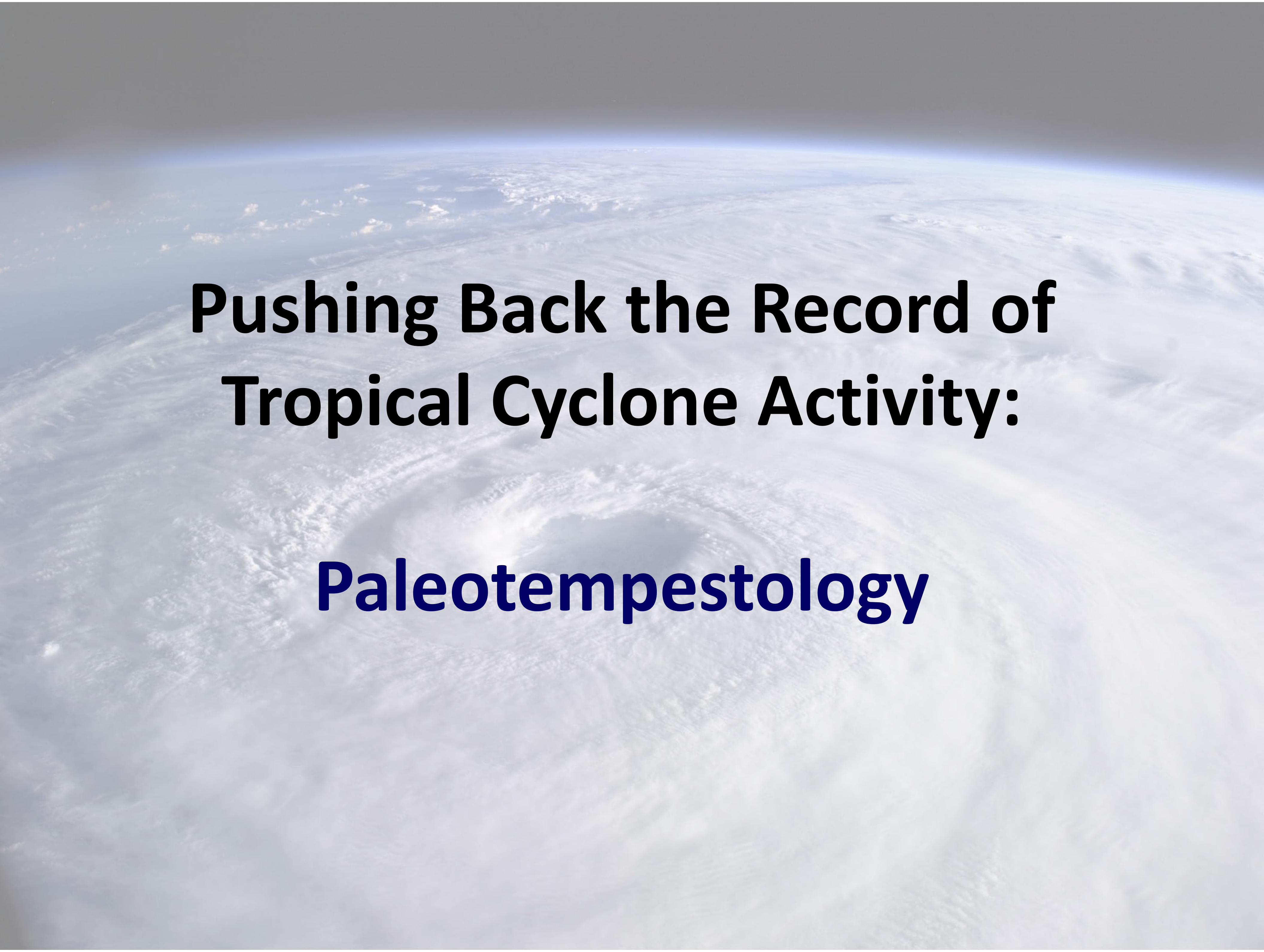
Linear trend (1955–2003) of the zonally integrated heat content of the world ocean by one-degree latitude belts for 100-m thick layers. Source: Levitus et al., 2005



TC-Mixing may explain difference between observed and modeled ocean warming



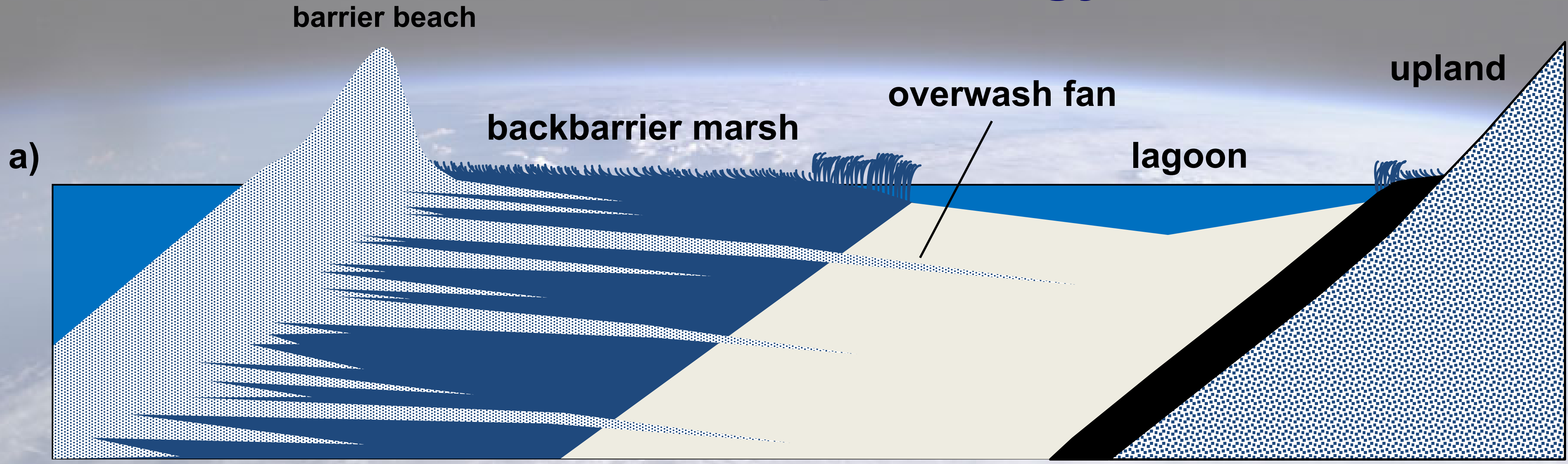
Zonally averaged temperature trend due to global warming in a coupled climate model. Source: Manabe et al, 1991

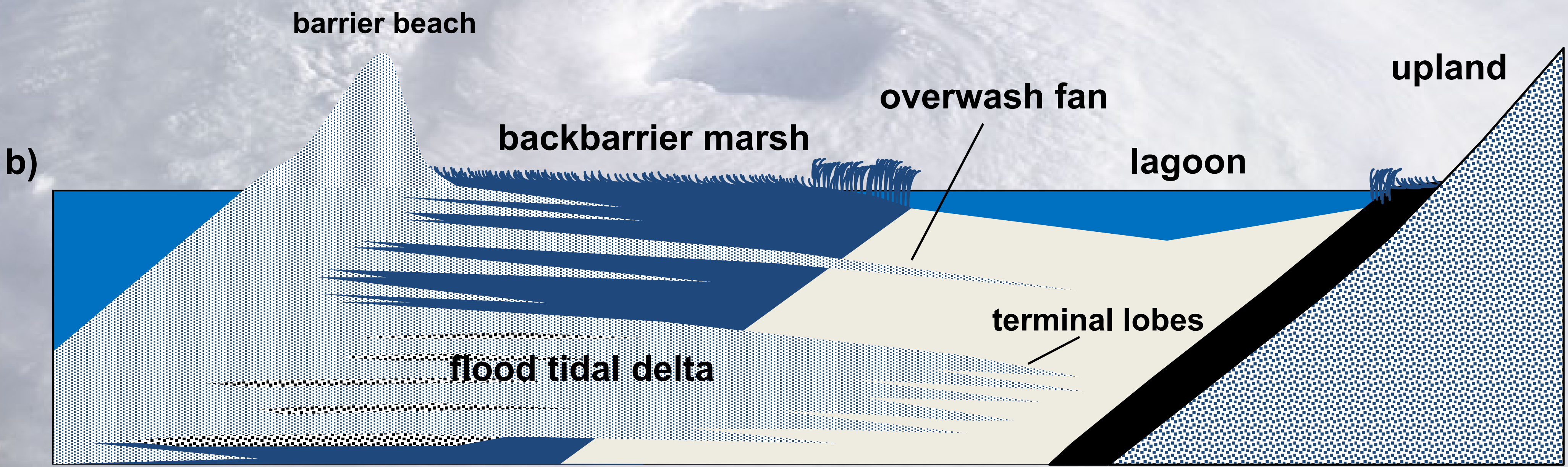


Pushing Back the Record of Tropical Cyclone Activity:

Paleotempestology

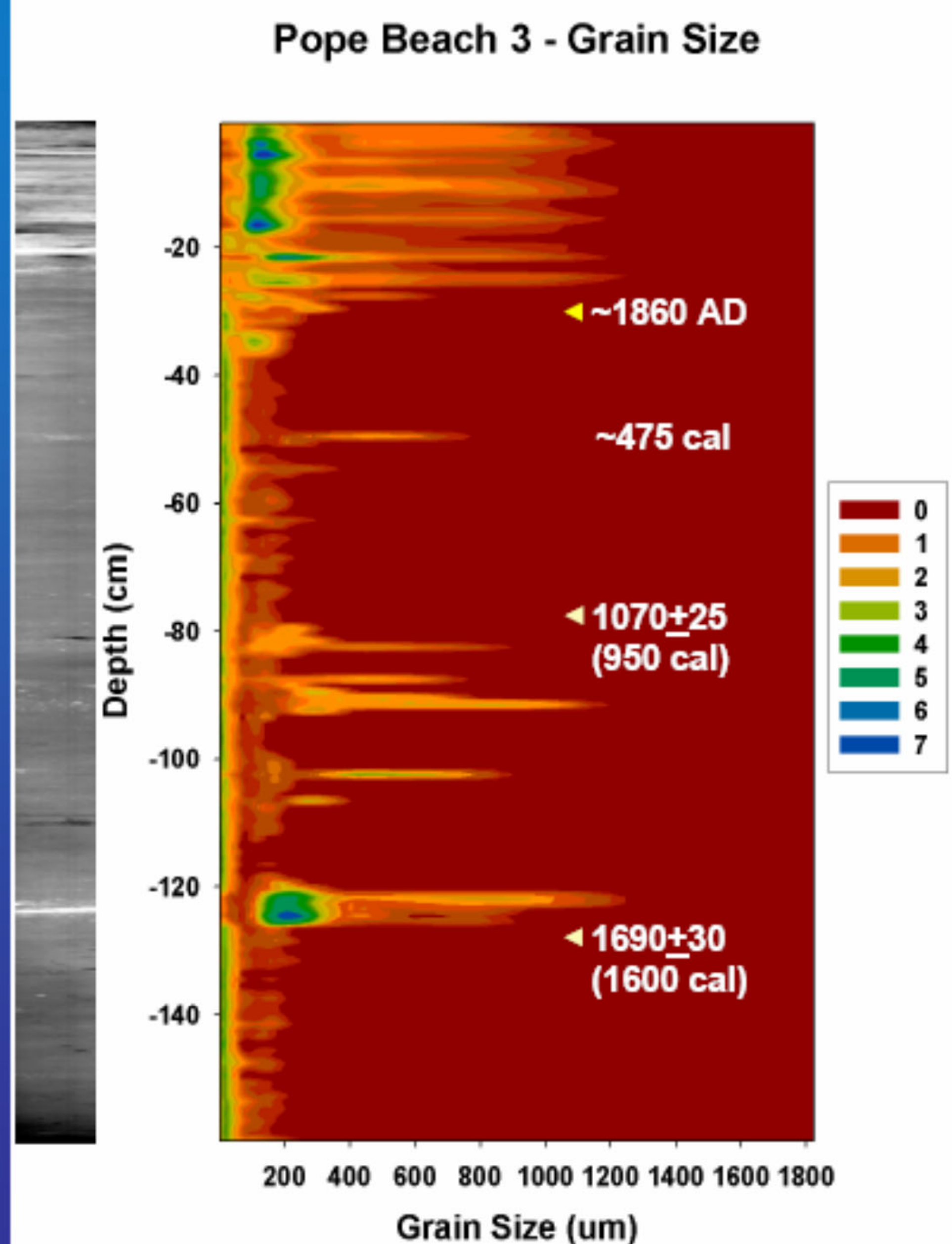
Paleotempestology



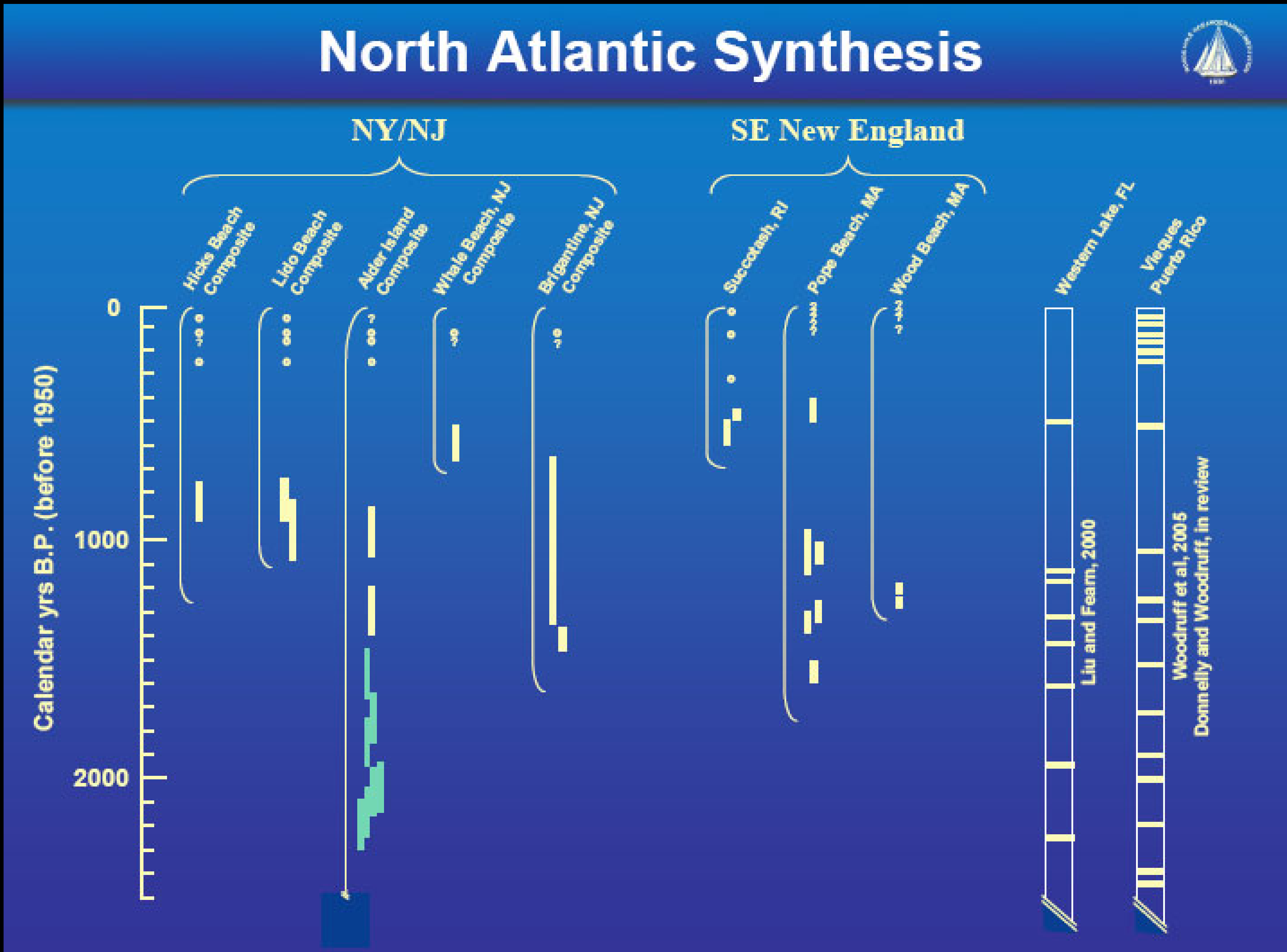


Source: Jeff Donnelly, WHOI

Pope Beach Marsh, Fairhaven, MA



Source: Jeff Donnelly, Jon Woodruff, Phil Lane; WHOI



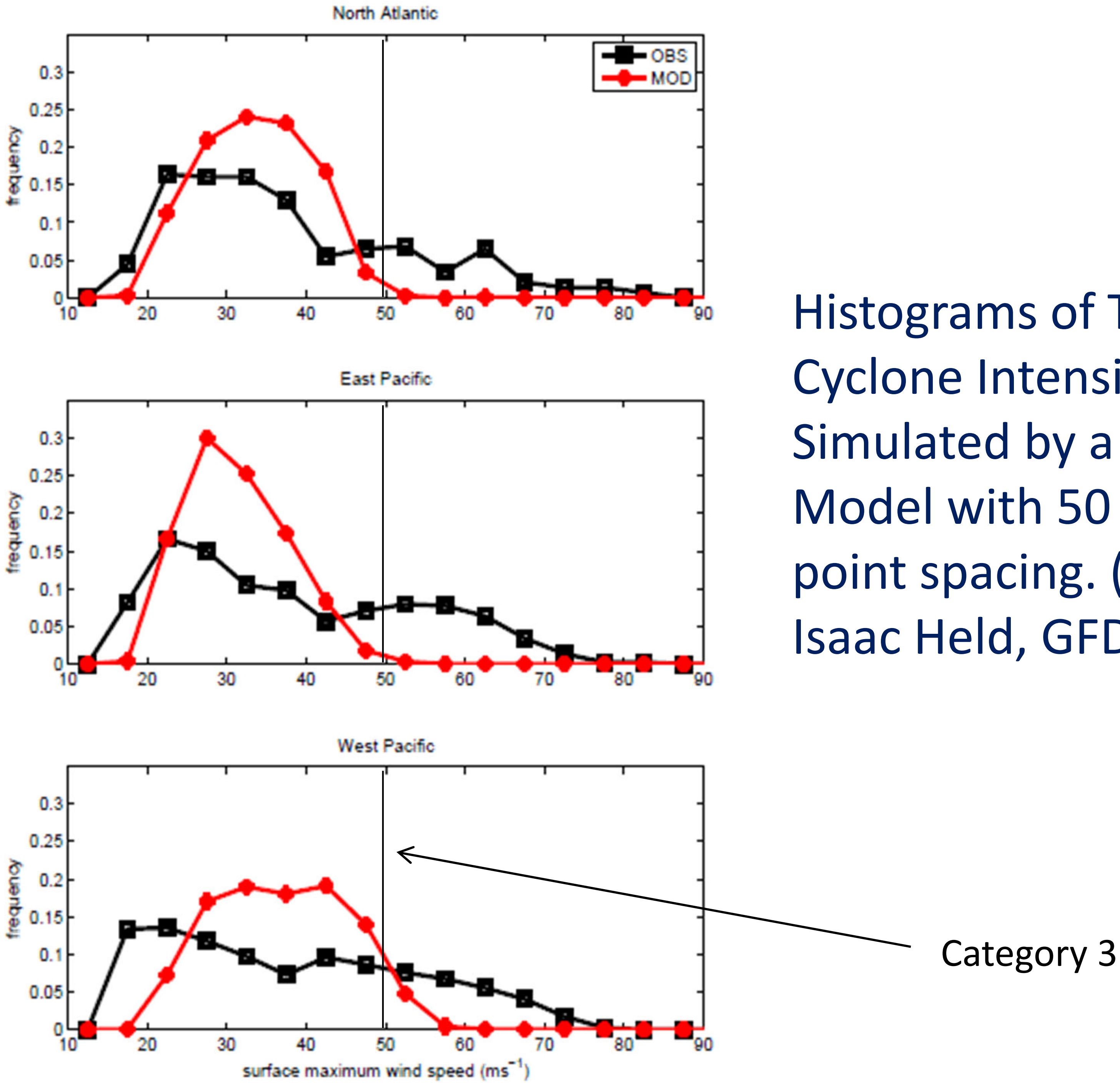
Source: Jeff Donnelly, Jon Woodruff, Phil Lane; WHOI

Inferences from Modeling

The Problem:

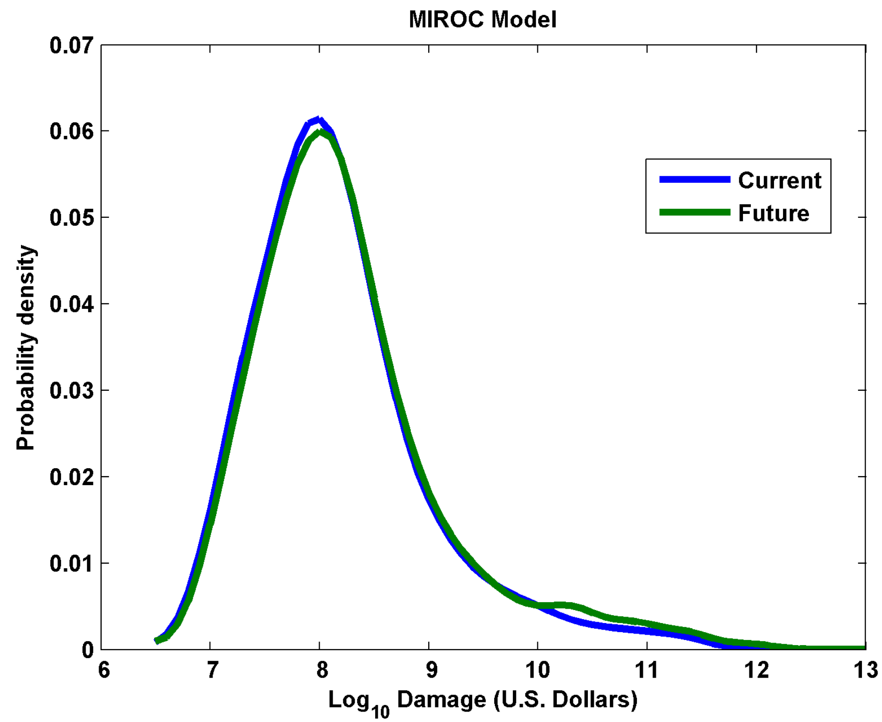
- **Global models are far too coarse to simulate high intensity tropical cyclones**

- **Embedding regional models within global models introduces problems stemming from incompatibility of models, and even regional models are usually too coarse**

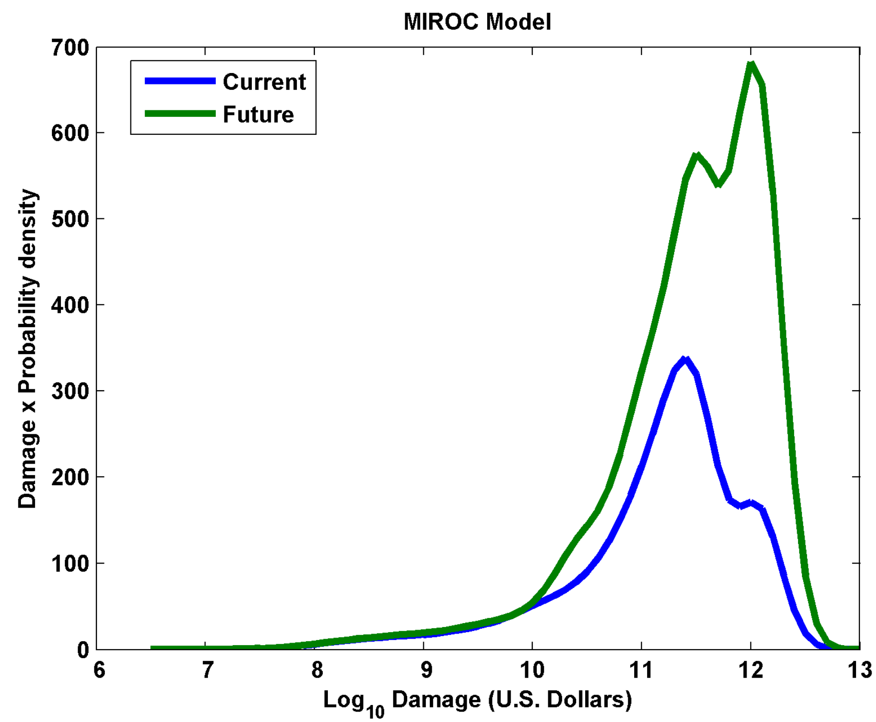


Histograms of Tropical Cyclone Intensity as Simulated by a Global Model with 50 km grid point spacing. (Courtesy Isaac Held, GFDL)

Probability Density of TC Damage, U.S. East Coast

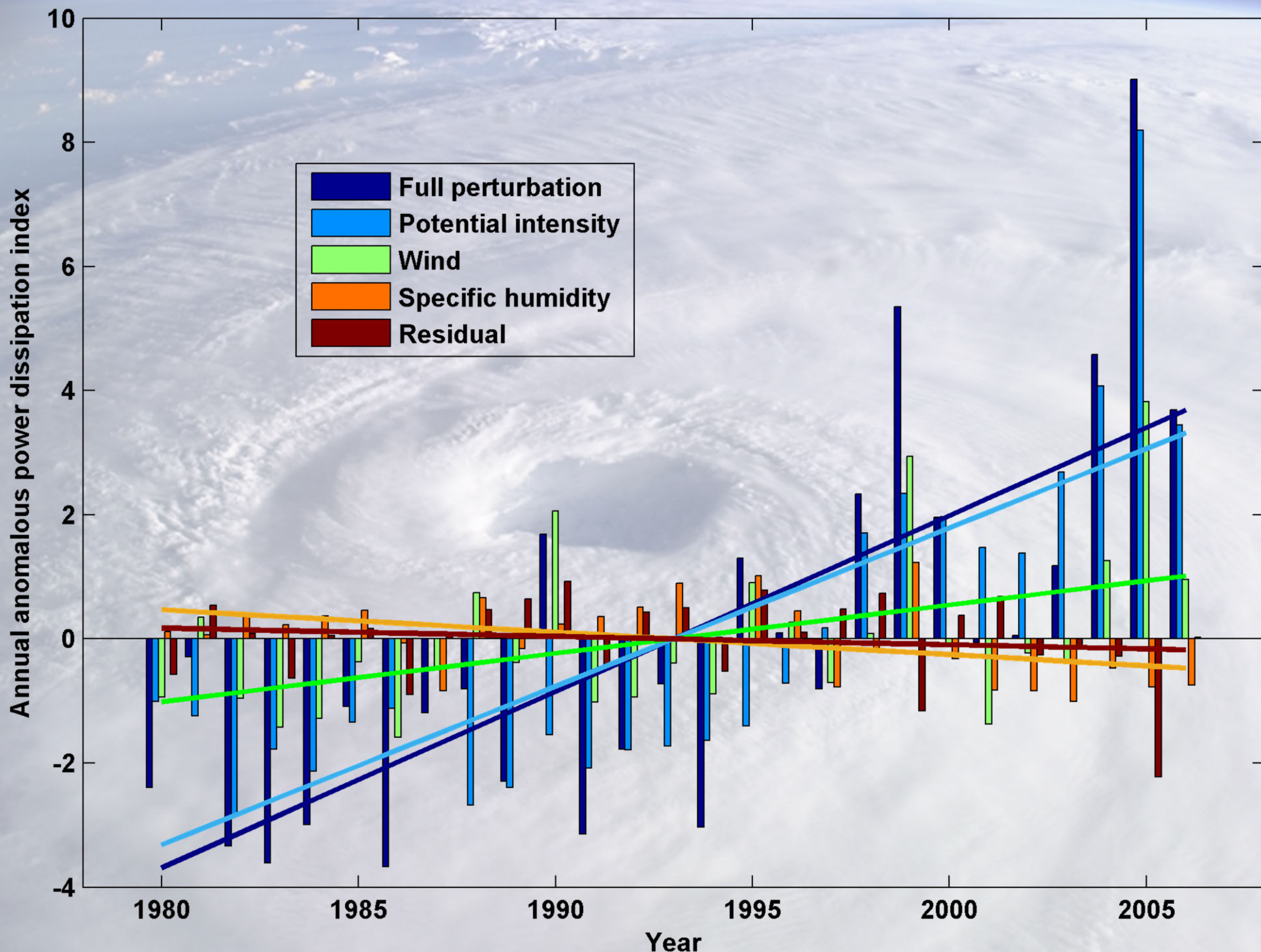


Damage Multiplied by Probability Density of TC Damage, U.S. East Coast

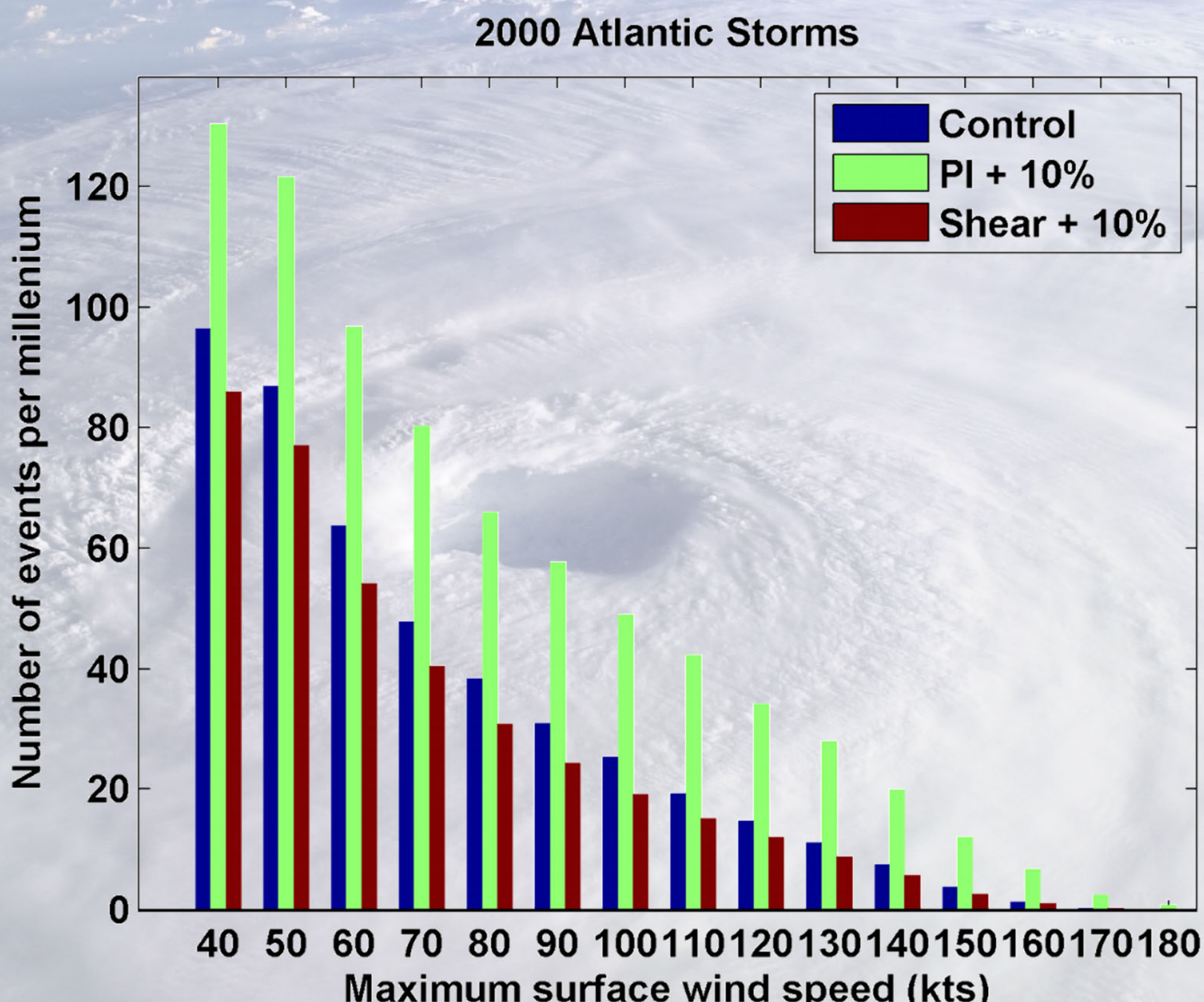


To the extent that they simulate tropical cyclones at all, global models simulate storms that are largely irrelevant to society and to the climate system itself, given that ocean stirring effects are heavily weighted towards the most intense storms

Decomposition of PDI Trends



Sensitivity to Shear and Potential Intensity



Hydrostatic Compensation (following Holloway and Neelin)

Perturbations to moist adiabatic troposphere:

$$\frac{\partial \phi'}{\partial p} = -\alpha' = -\left(\frac{\partial \alpha}{\partial p}\right)_p s^*{}' = -\left(\frac{\partial T}{\partial p}\right)_{s^*{}'} s_b{}'$$

$$\rightarrow \phi_T{}' = \left(T_s - T_T\right) s_b{}'$$

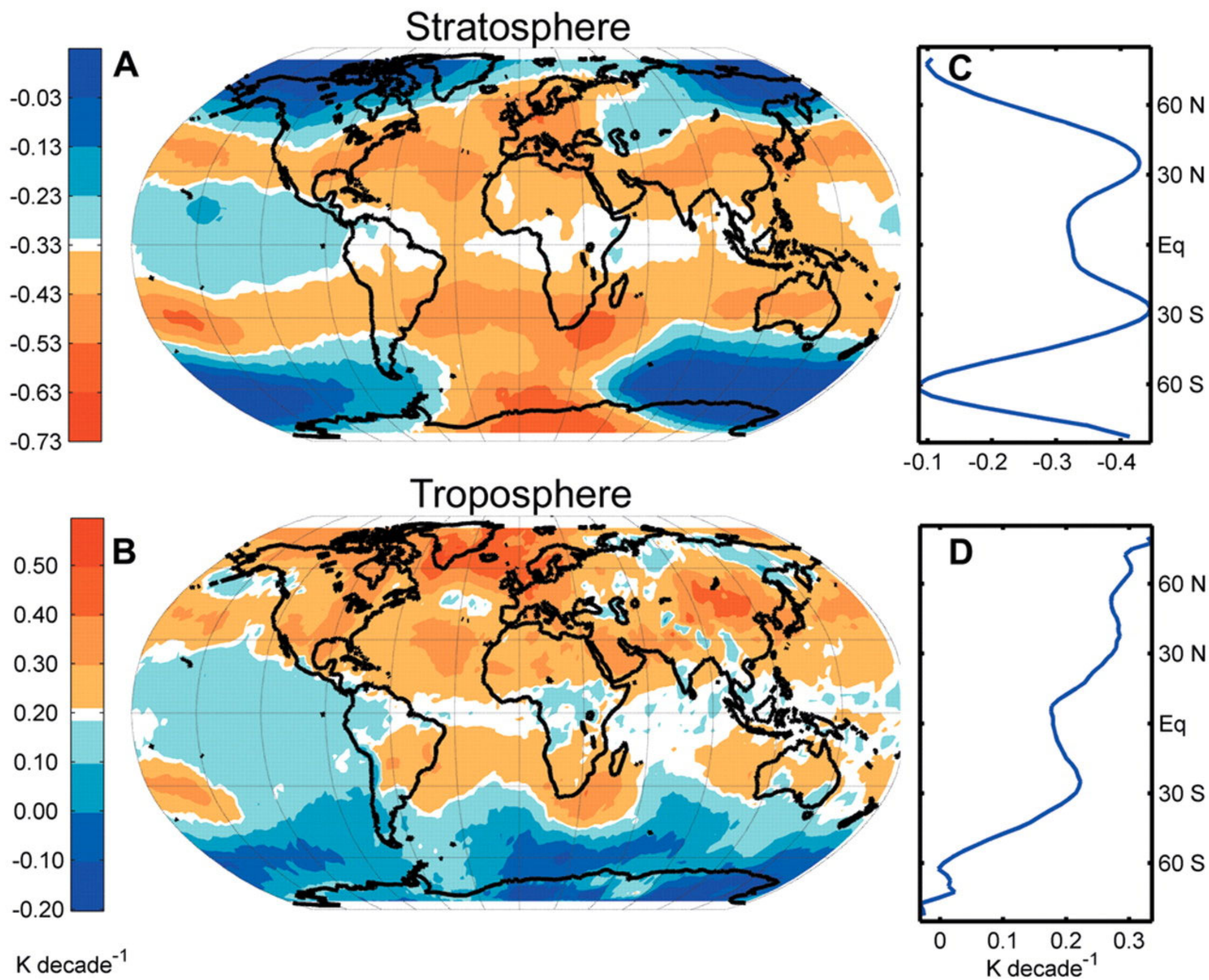
Stratospheric compensation:

$$RT_T{}' = -\frac{\partial \phi'}{\partial \ln(p)} \cong -\frac{\phi_T{}'}{\Delta \ln(p)} = -\frac{\left(T_s - T_T\right) s_b{}'}{\Delta \ln(p)}$$

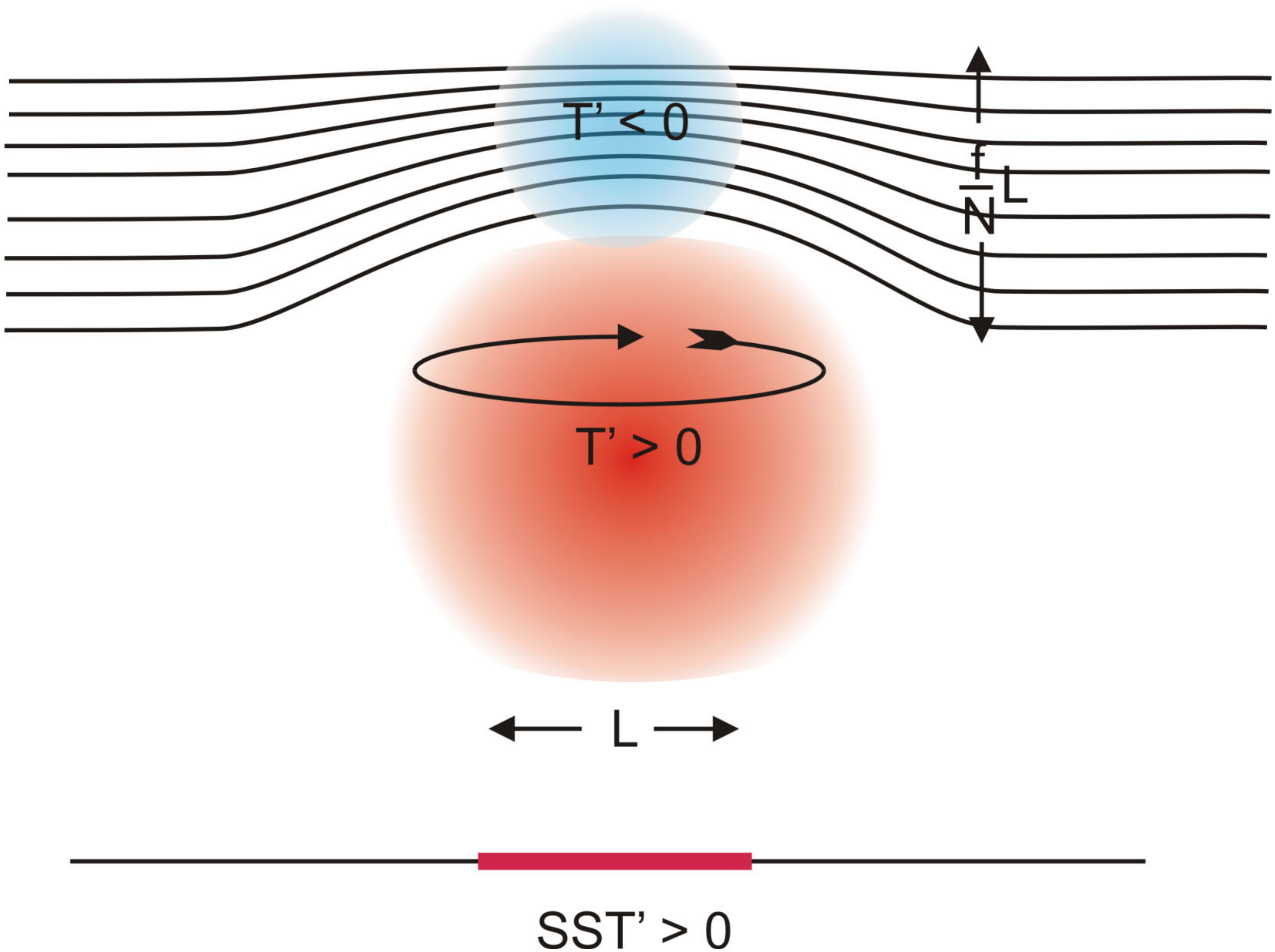
For typical values of the parameters

$$T_T' \simeq -T_s'$$

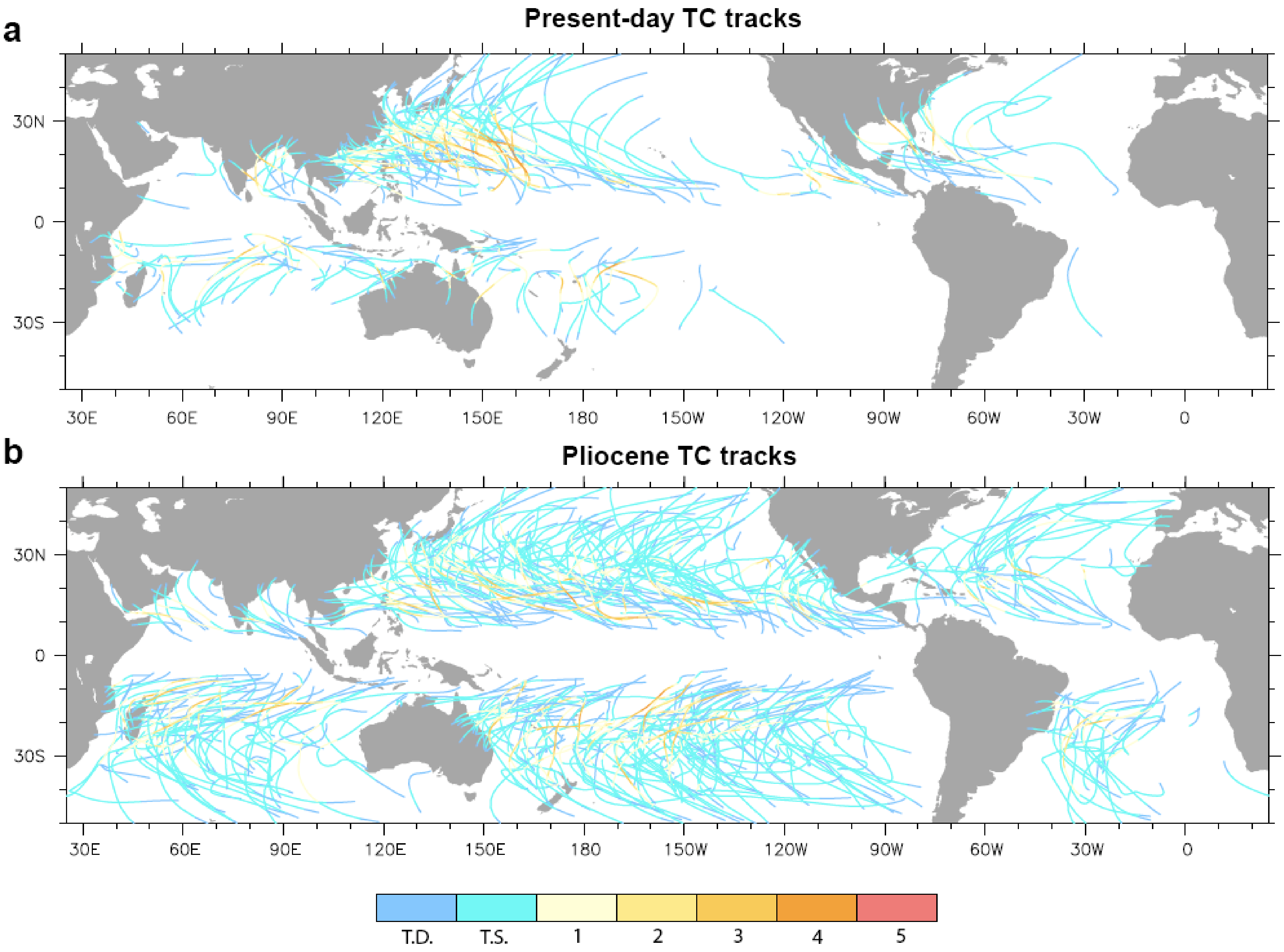
Ozone may not explain spatial pattern of cooling (Fu and Wallace, *Science*, 2006)



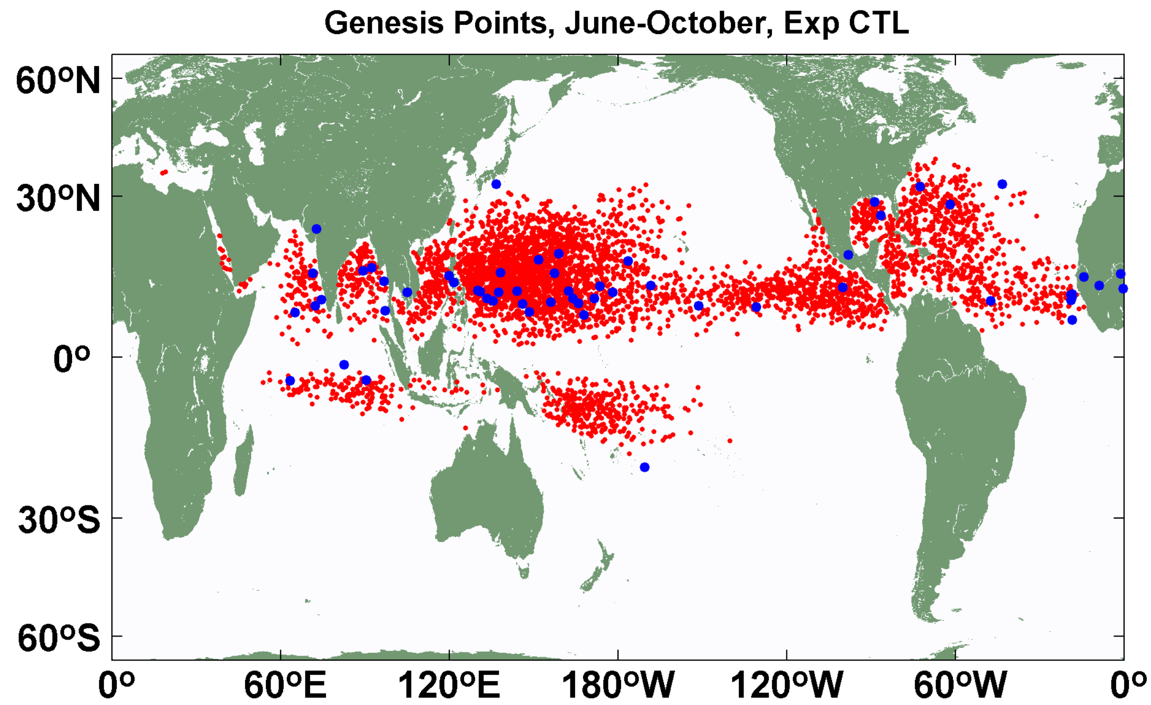
Stratospheric Compensation

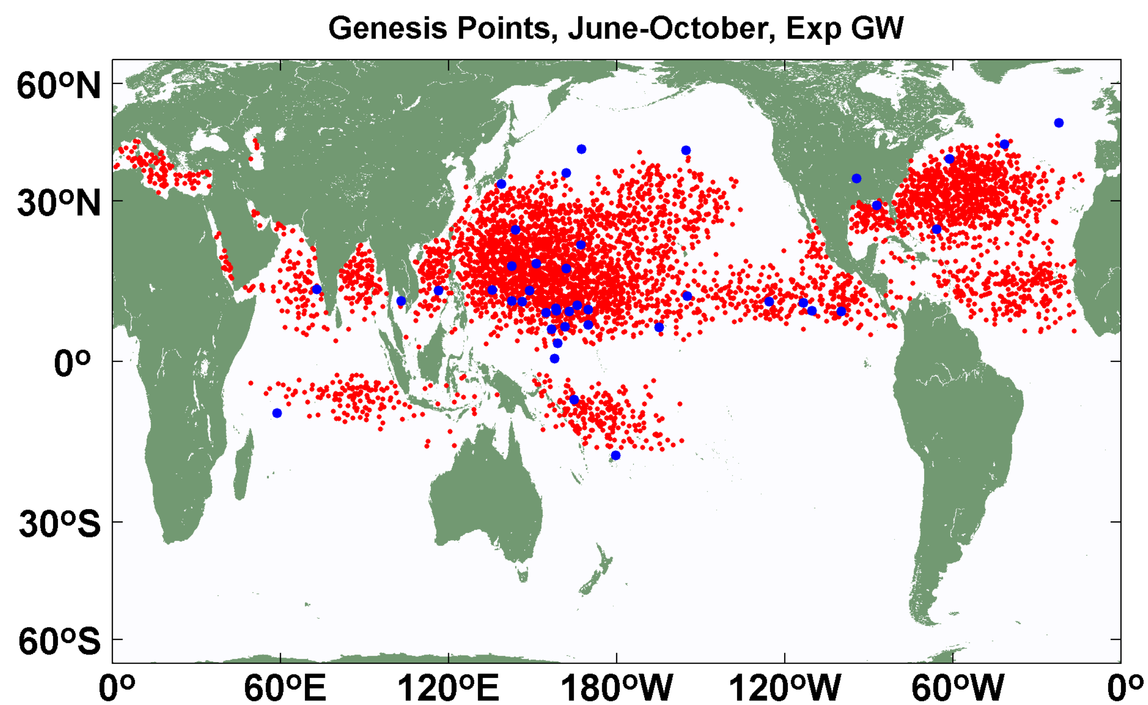


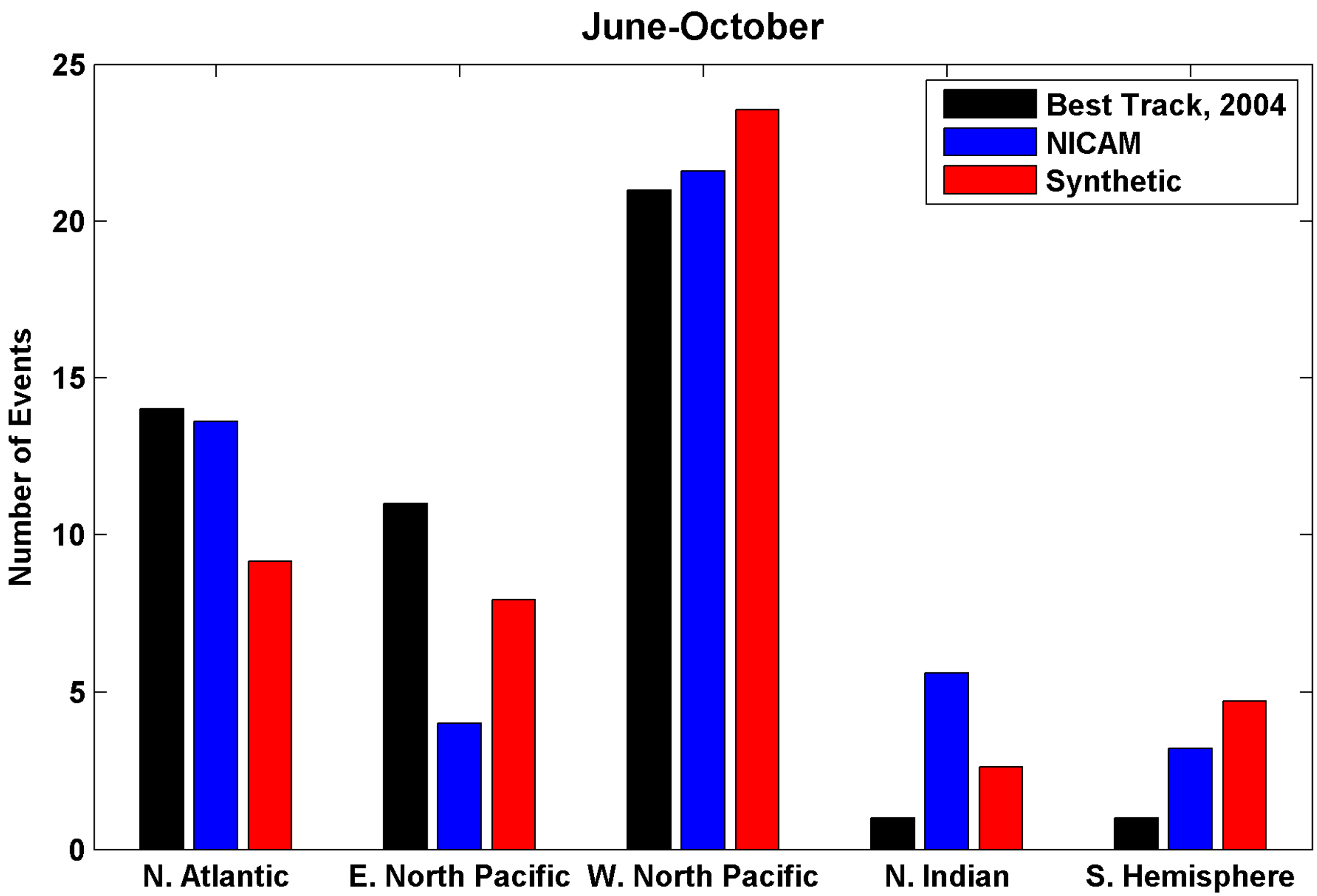
Application to the Climate of the Pliocene



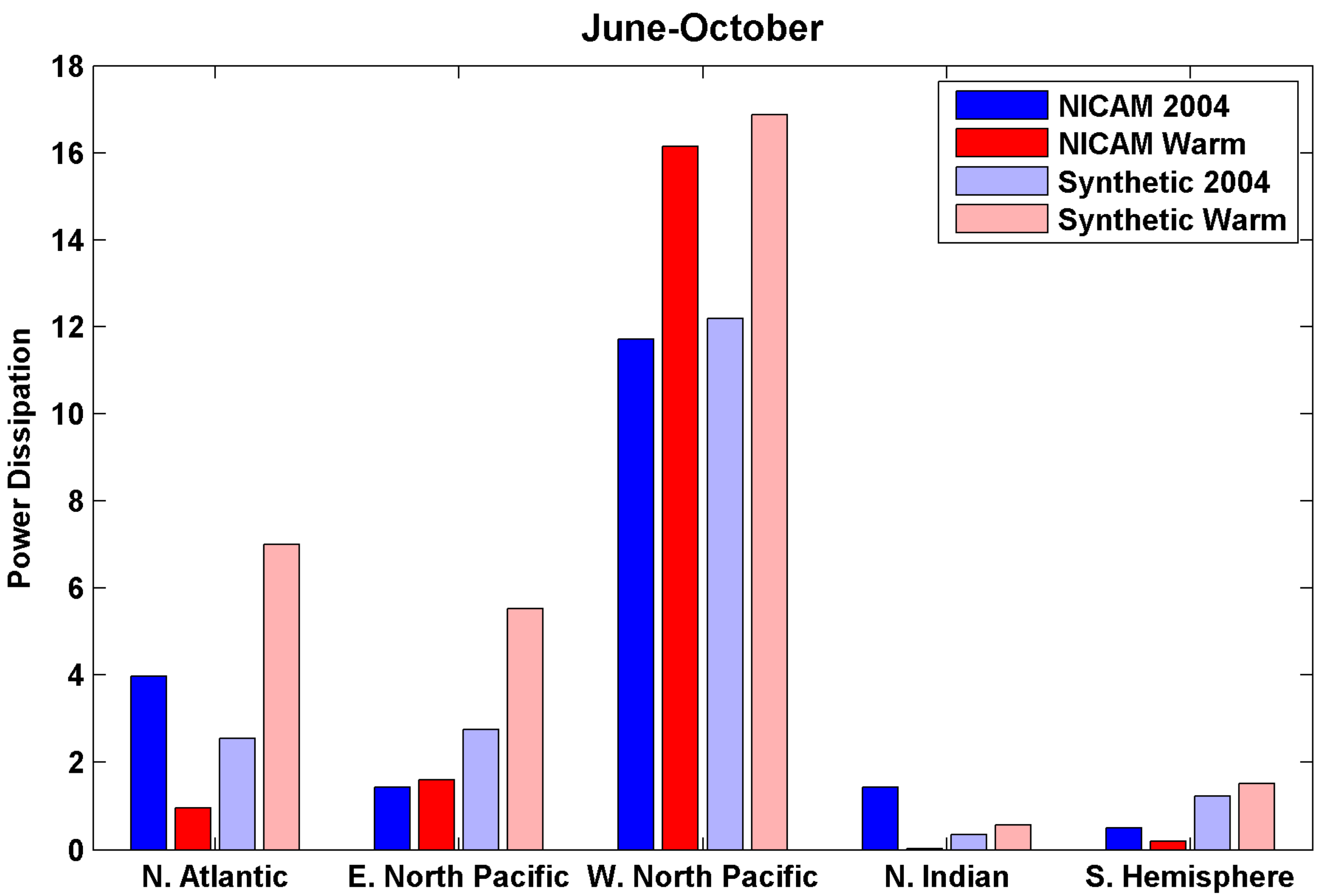
Explicit (blue dots) and downscaled (red dots) genesis points for June-October for Control (top) and Global Warming (bottom) experiments using the 14-km resolution NICAM model. Collaborative work with K. Oouchi.



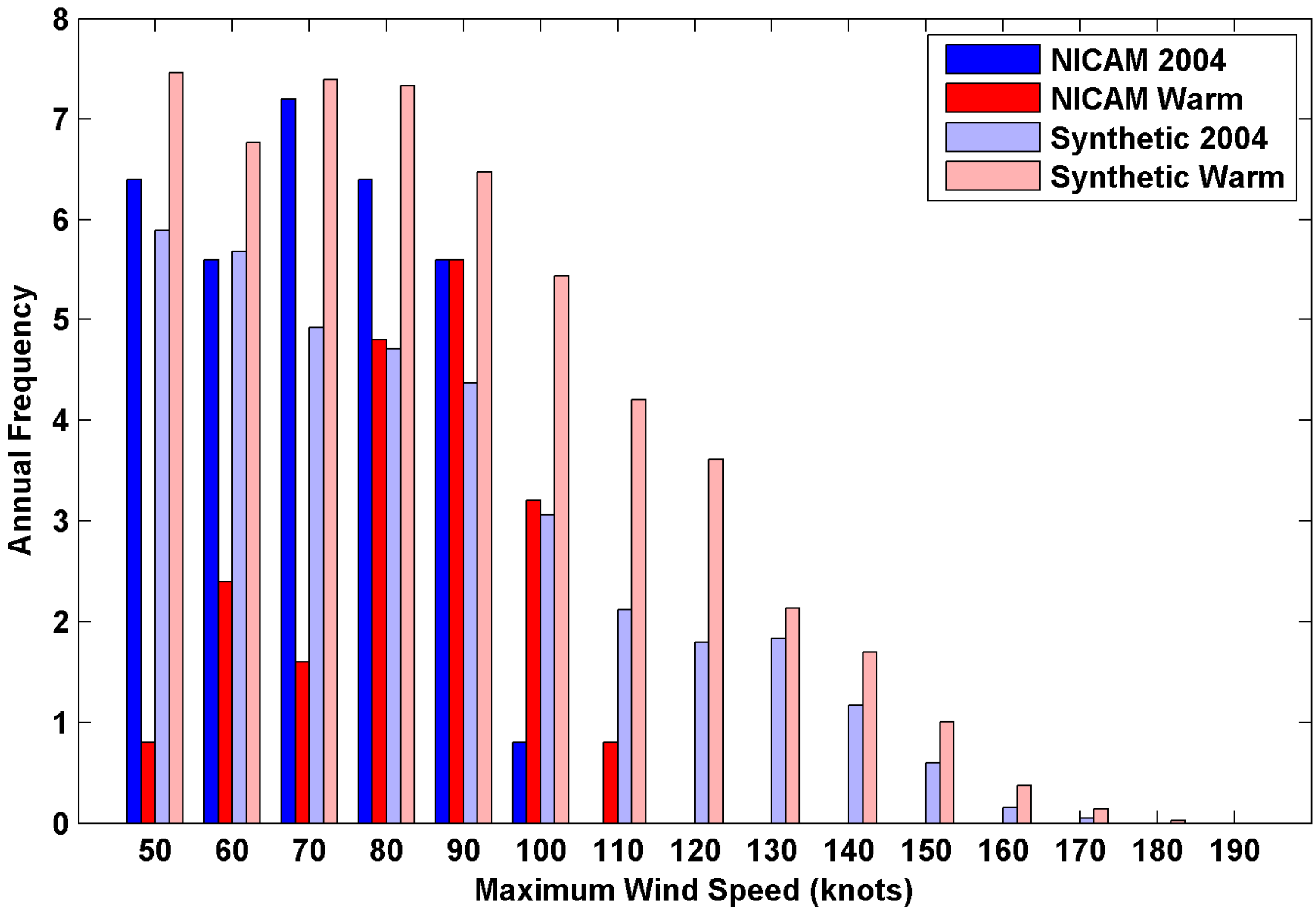



June-October
Number of Events
25
20
15
10
5
0
Best Track, 2004
NICAM
Synthetic
N. Atlantic
E. North Pacific
W. North Pacific
N. Indian
S. Hemisphere

Change in Power Dissipation with Global Warming

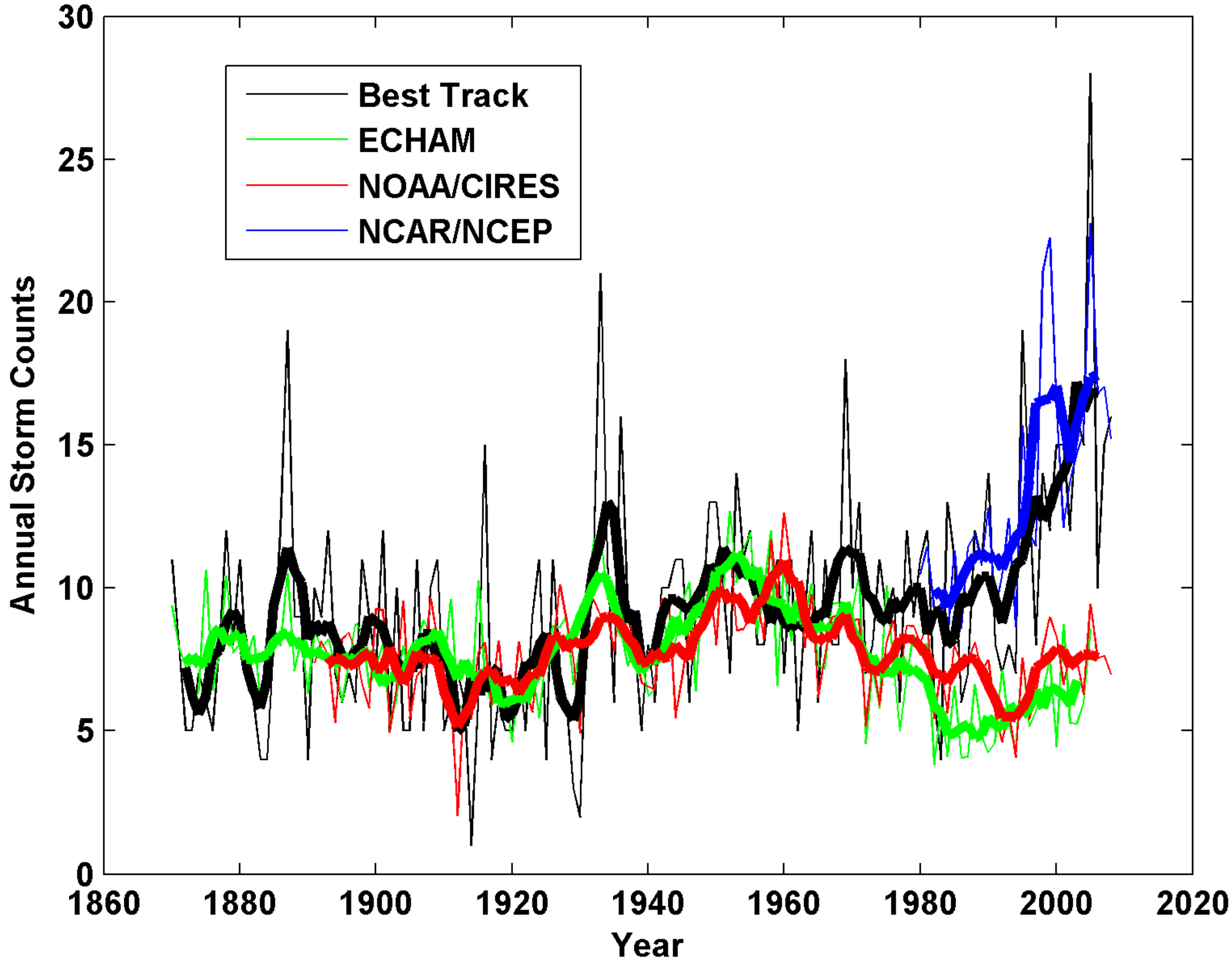


Probability Density by Storm Lifetime Peak Wind Speed, Explicit and Downscaled Events



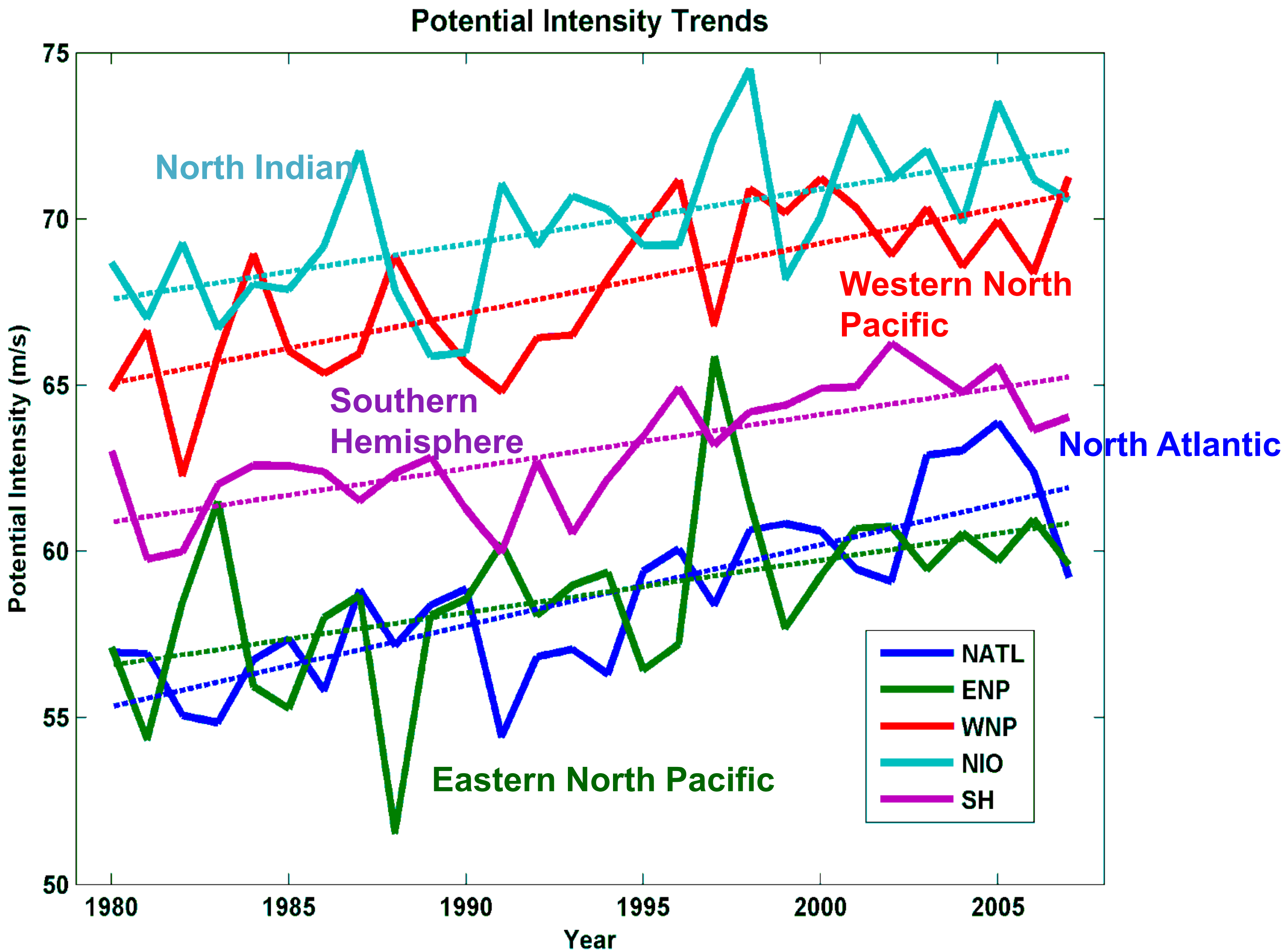
The Importance of Potential Intensity for Genesis and for Storm Intensity

Application to Re-analyses and AGCMs



Annual Atlantic tropical cyclone counts: Unadjusted best-track data (black); and downscaled from the NCAR/NCEP reanalysis, 1980-2008 (blue), the ECHAM 5 simulation, 1870-2005 (green), and the NOAA/CIRES reanalysis, 1891-2008 (red). Thin lines show annual values, thick lines show 5-year running means

Interpretation of Recent Trends in Potential Intensity



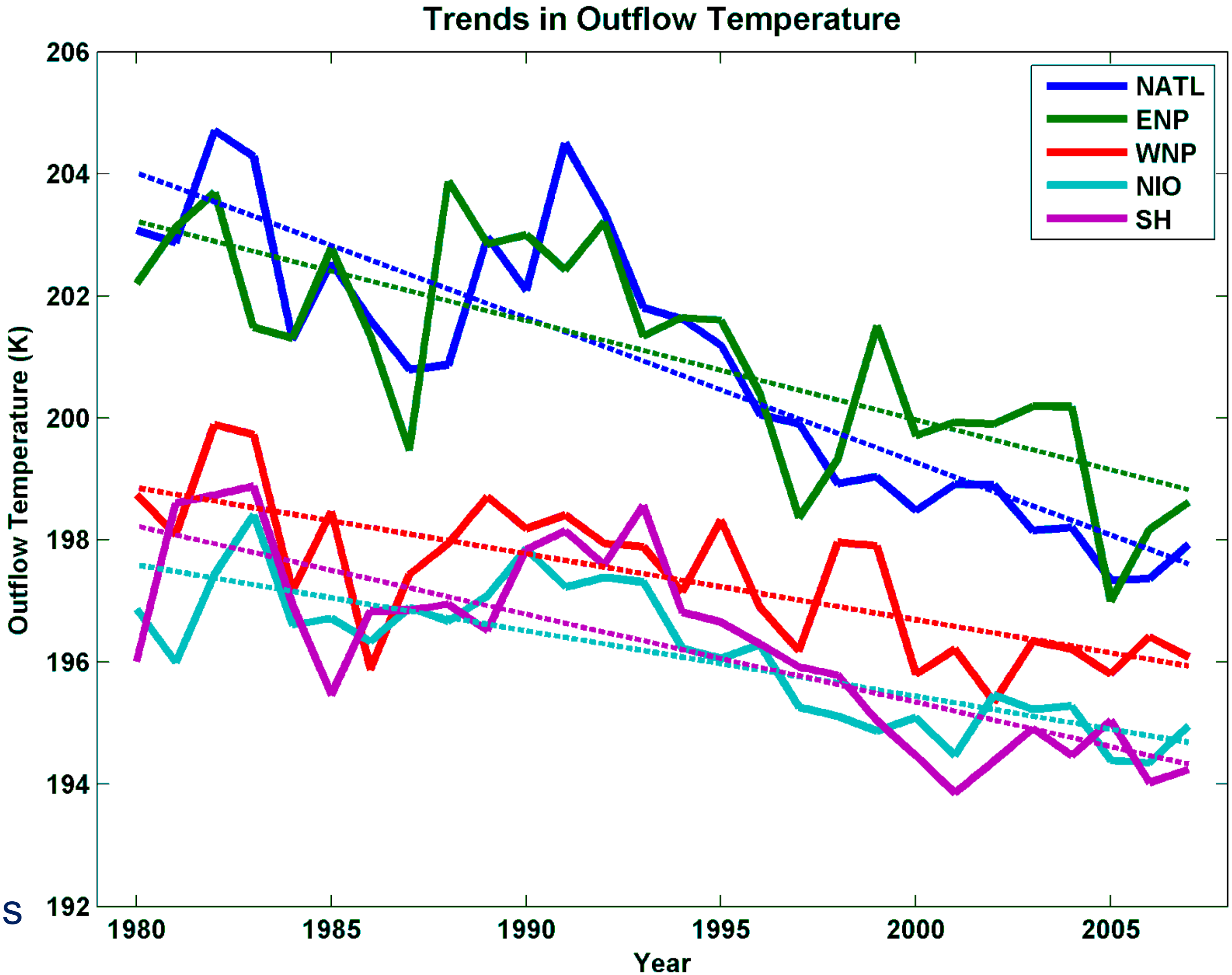
From NCAR/NCEP reanalysis data, 1980-2008

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?

Surface wind speeds have not changed much since 1980. Key variable: Outflow temperature, which in general decreases with:

- Increasing SST
- Decreasing temperature of lower stratosphere and/or troposphere transition layer

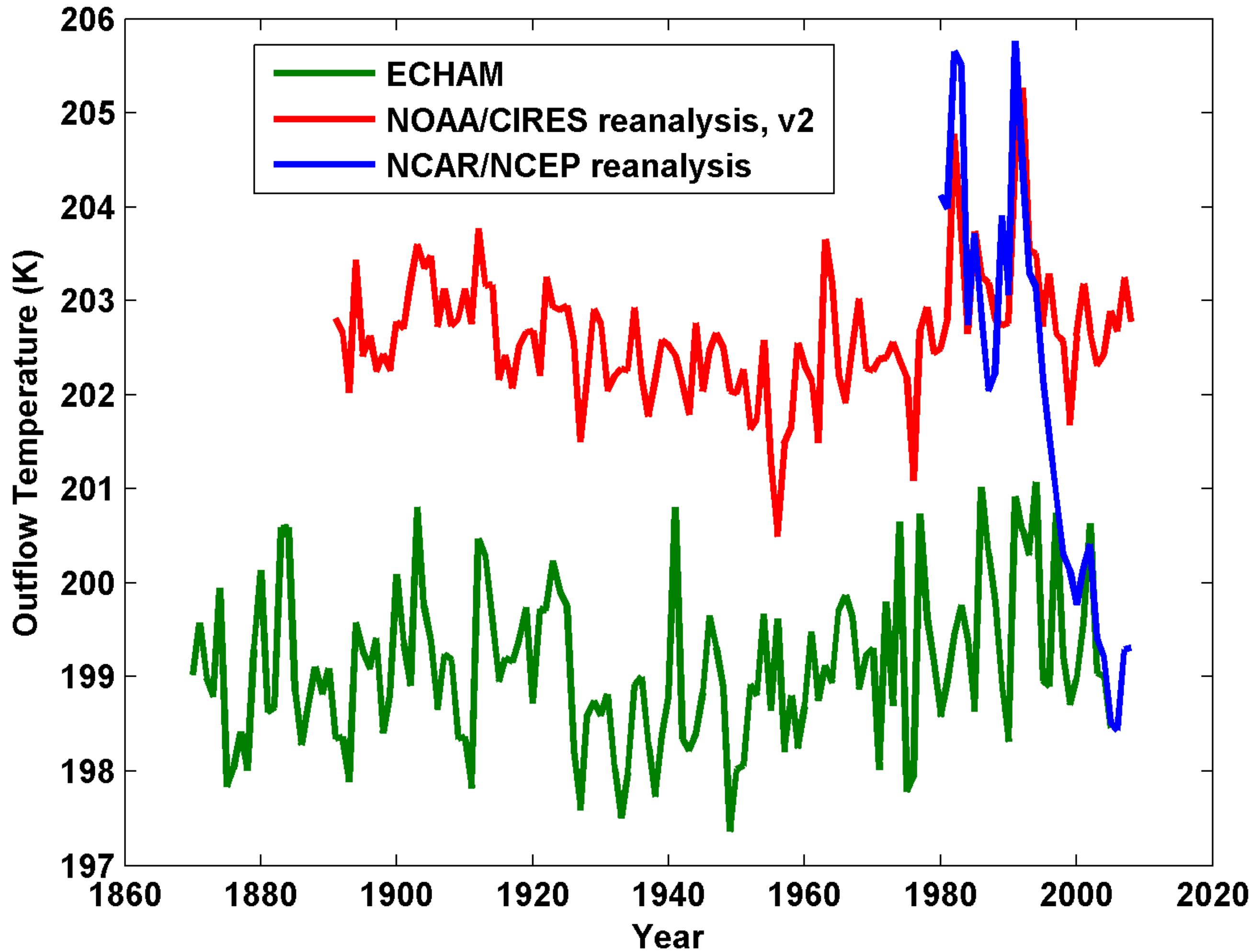
Importance of Trends in Outflow Temperature



From
NCEP
Reanalysis

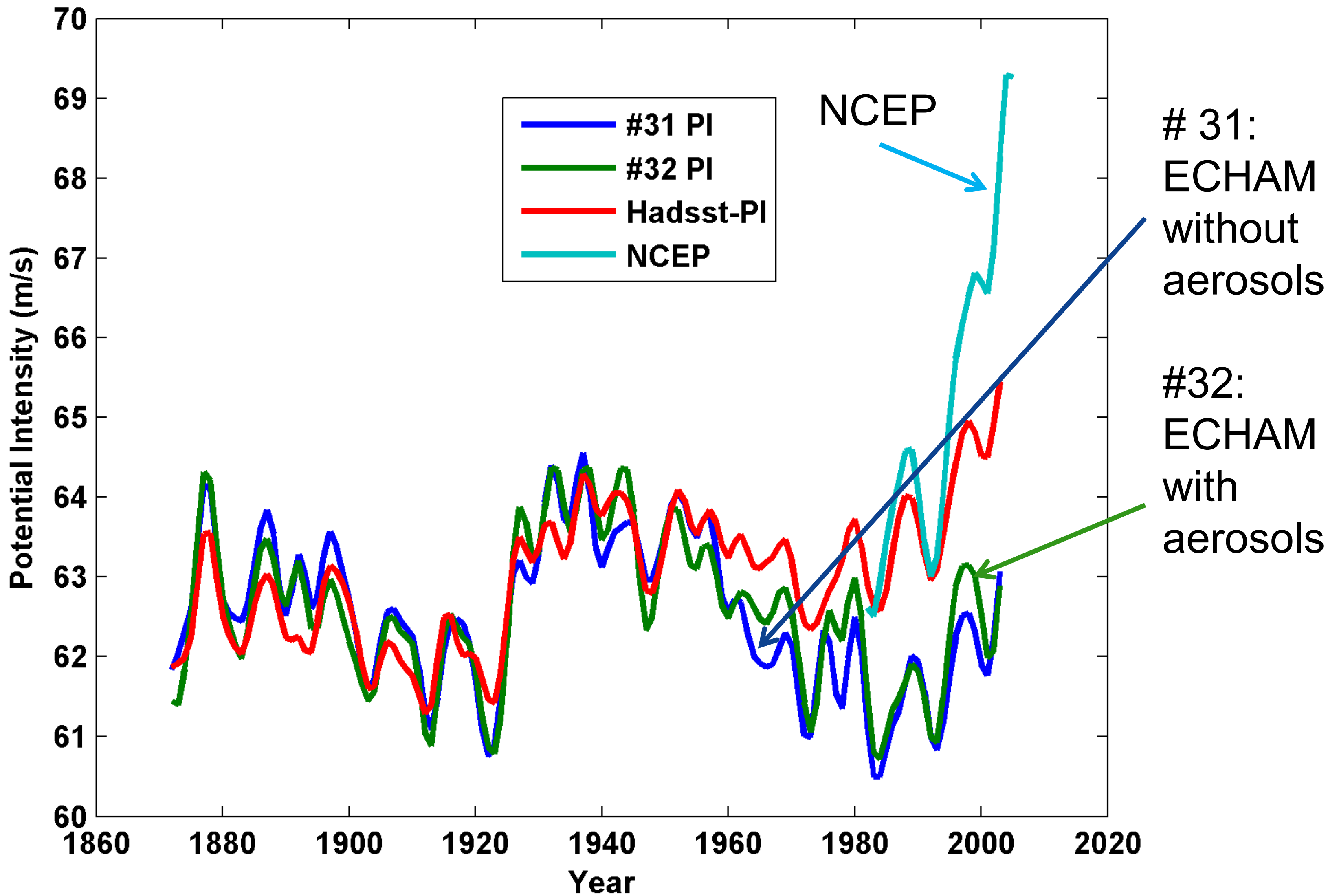
Do Climate Models Capture Lower Stratospheric Cooling?

AGCMs, *driven by observed SSTs*, do not get the cooling!

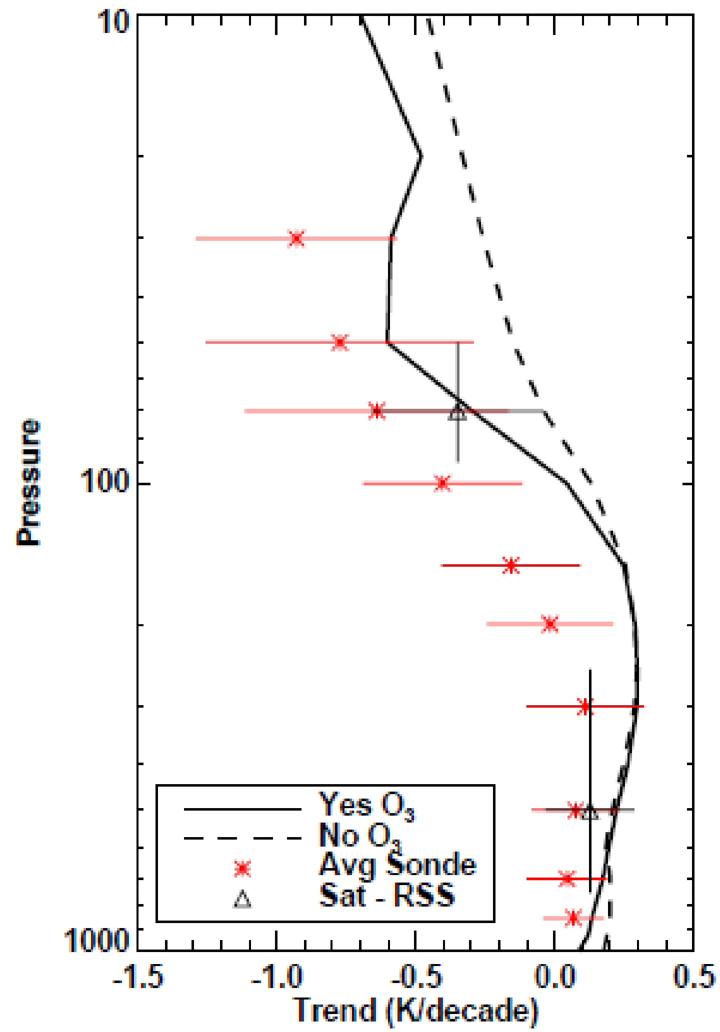


August-October outflow temperatures averaged over the Atlantic MDR from the ECHAM 5 simulation (green), the NOAA/CIRES 20th Century reanalysis, version 2 (red) and the NCAR/NCEP reanalysis (blue)

As a result, they miss the recent increase in potential intensity



1979-1999 Temperature Trends, 30S-30N. Red: Radiosondes; Solid Black: Mean of Models with Ozone; Dashed Black: Mean of Models without Ozone (Cordero and Forster, 2006)

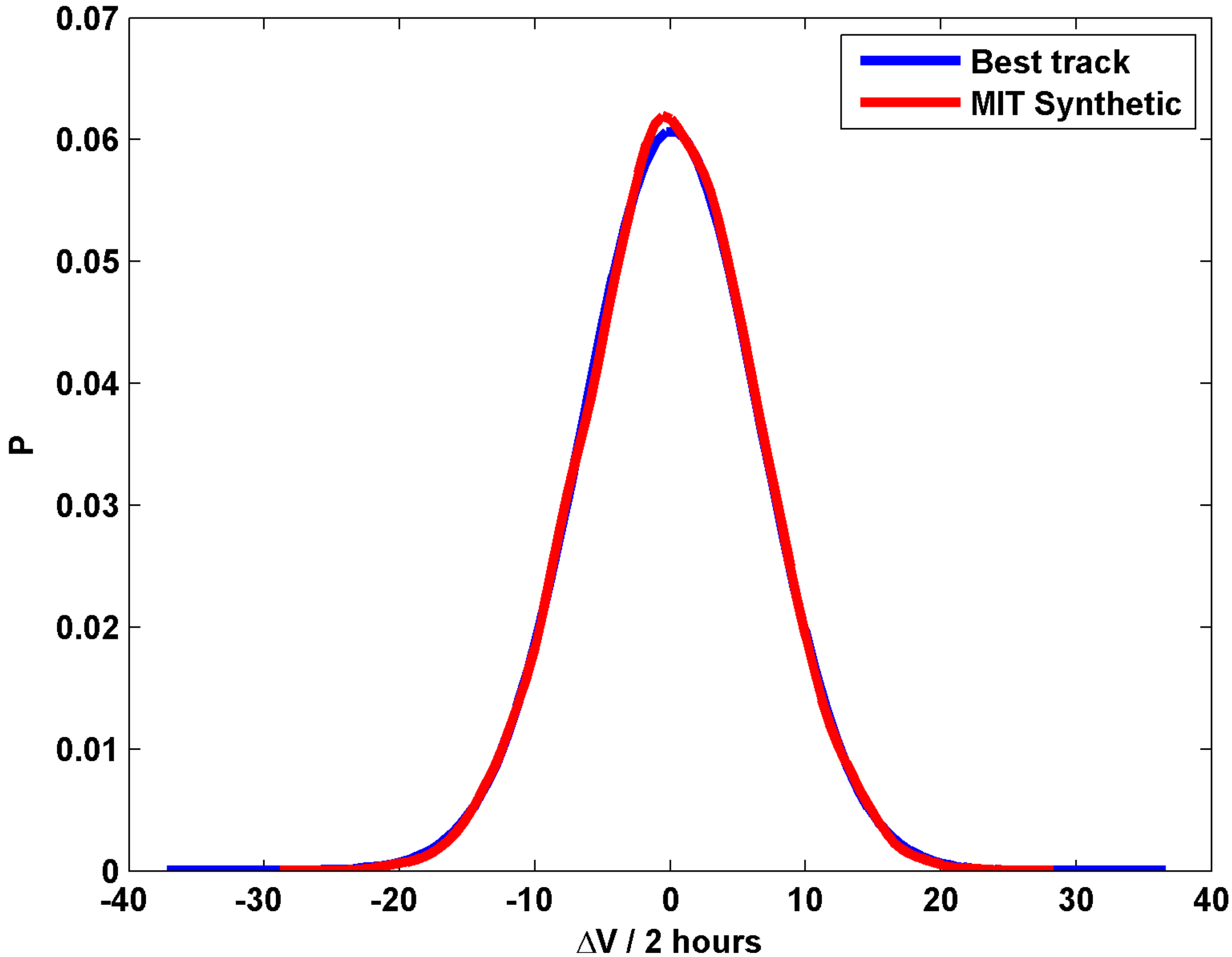


Combine expression for potential intensity, V_{max}, with energy balance of ocean mixed layer:

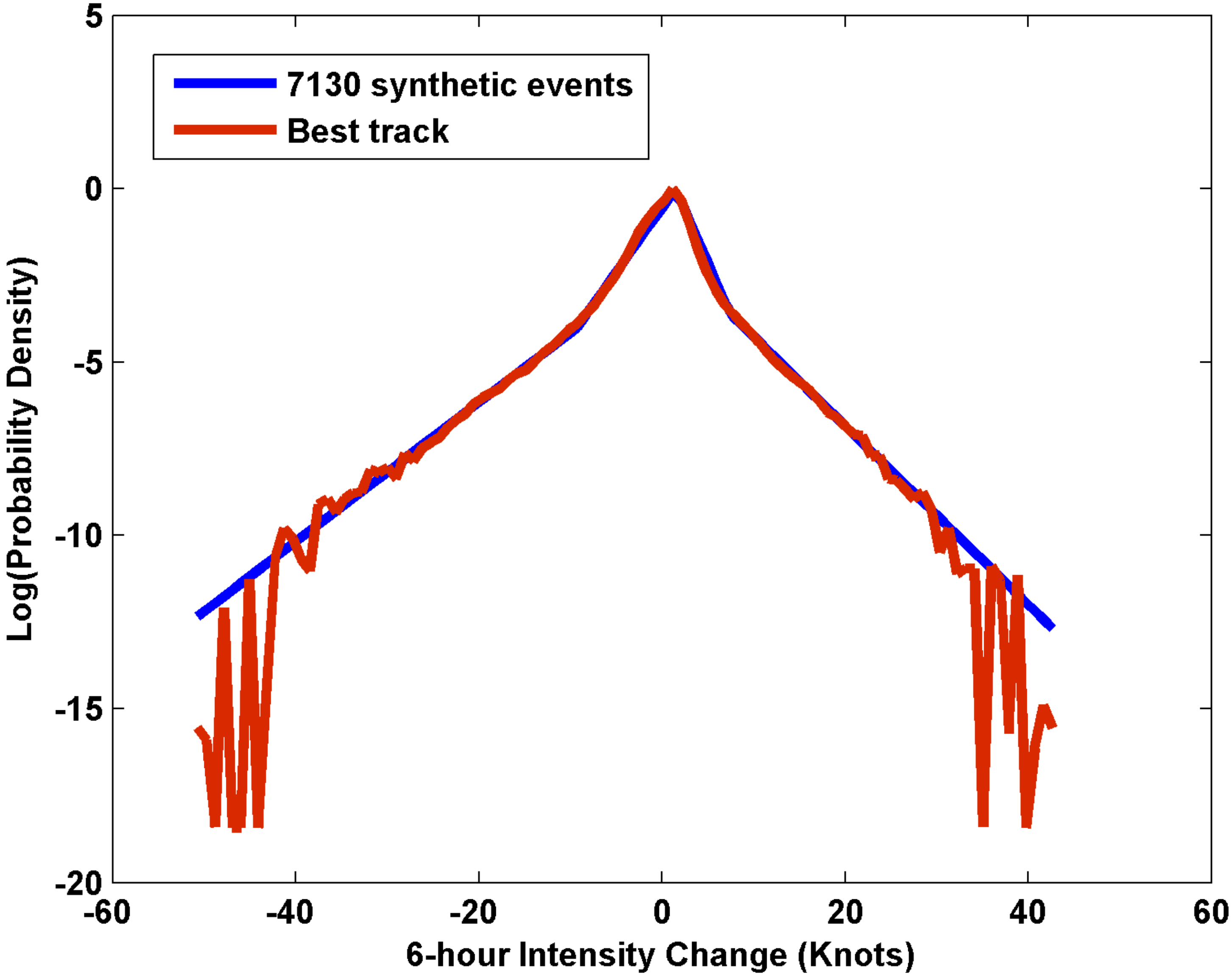
$$V_{max}^2 = \frac{T_s - T_o}{T_o} \, \frac{F_{rad} - d\nabla \bullet \mathbf{F}_{\mathbf{ocean}}}{C_D \rho \, |\mathbf{V}_\mathbf{s}|}$$

- SST (T_s)
- Outflow T (T_o)
- Net surface radiative flux (F_{rad})
- Ocean mixed layer depth (d)
- Mixed layer heat flux ($\mathbf{F}_{\mathbf{ocean}}$)
- Drag coefficient (C_D)
- Mean surface wind speed ($\mathbf{V}_\mathbf{s}$)

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

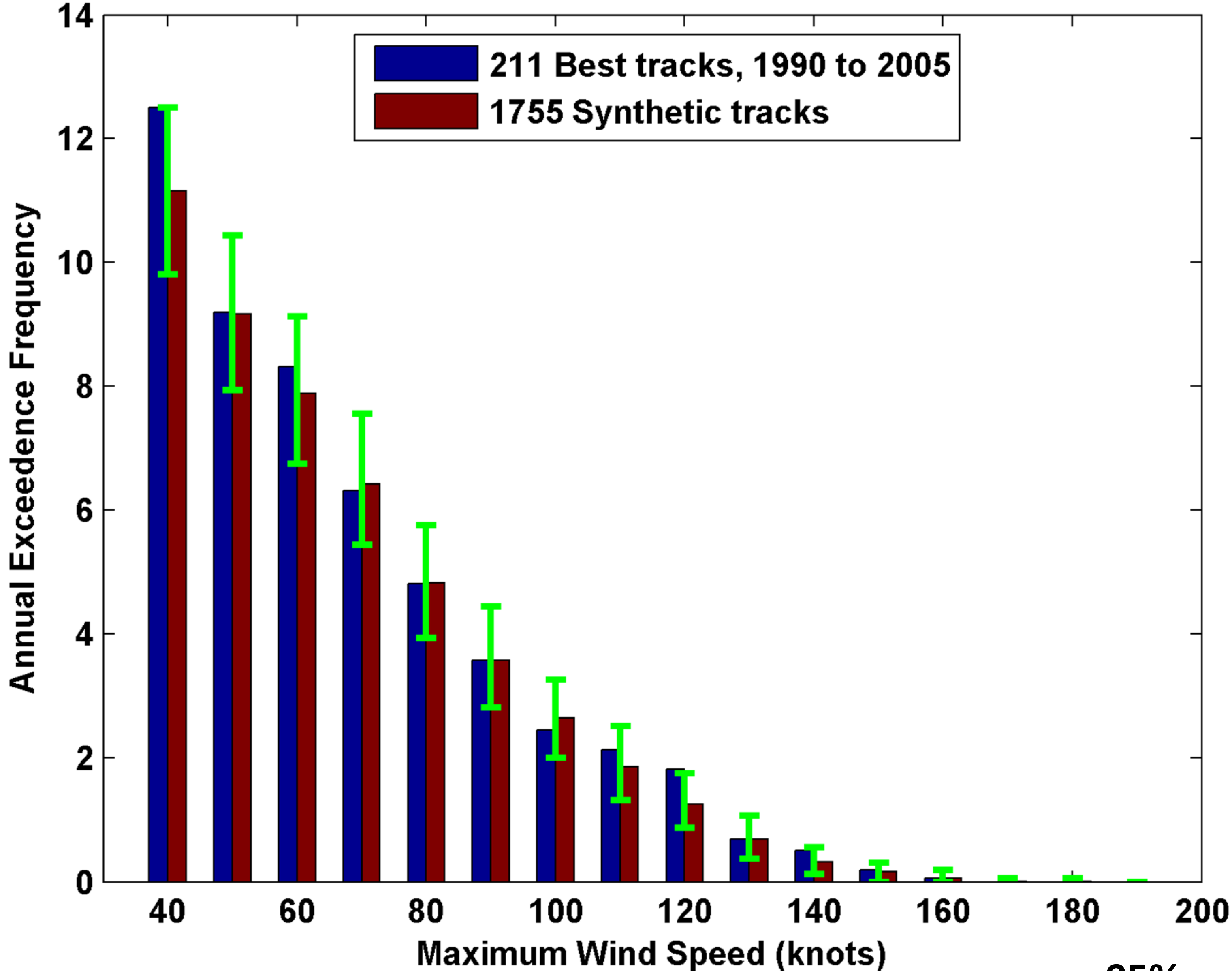


Probability densities of 2-hour intensity change



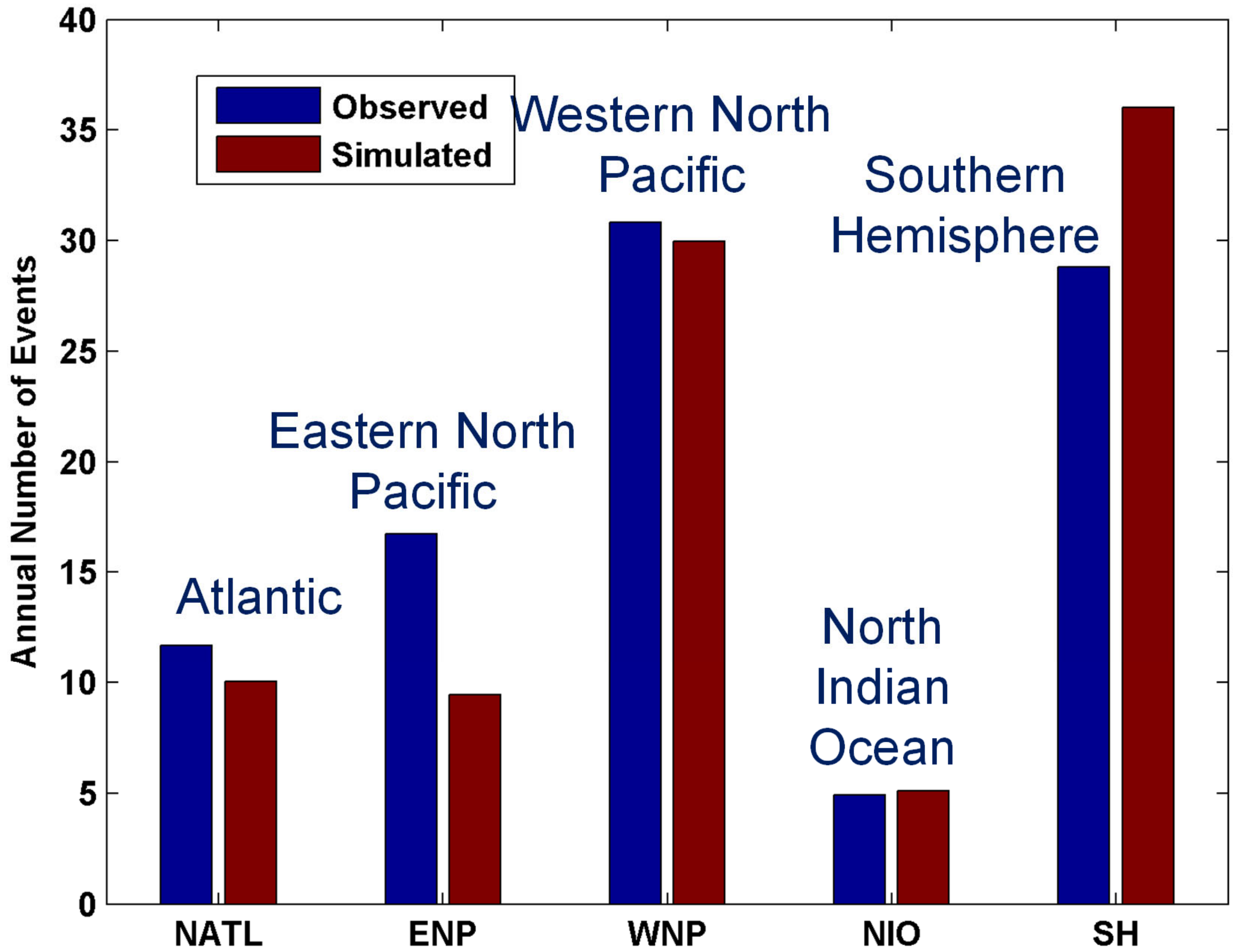
Log of the probability density of 6-hour intensity change

Cumulative Distribution of Storm Lifetime Peak Wind Speed, with Sample of 1755 Synthetic Tracks

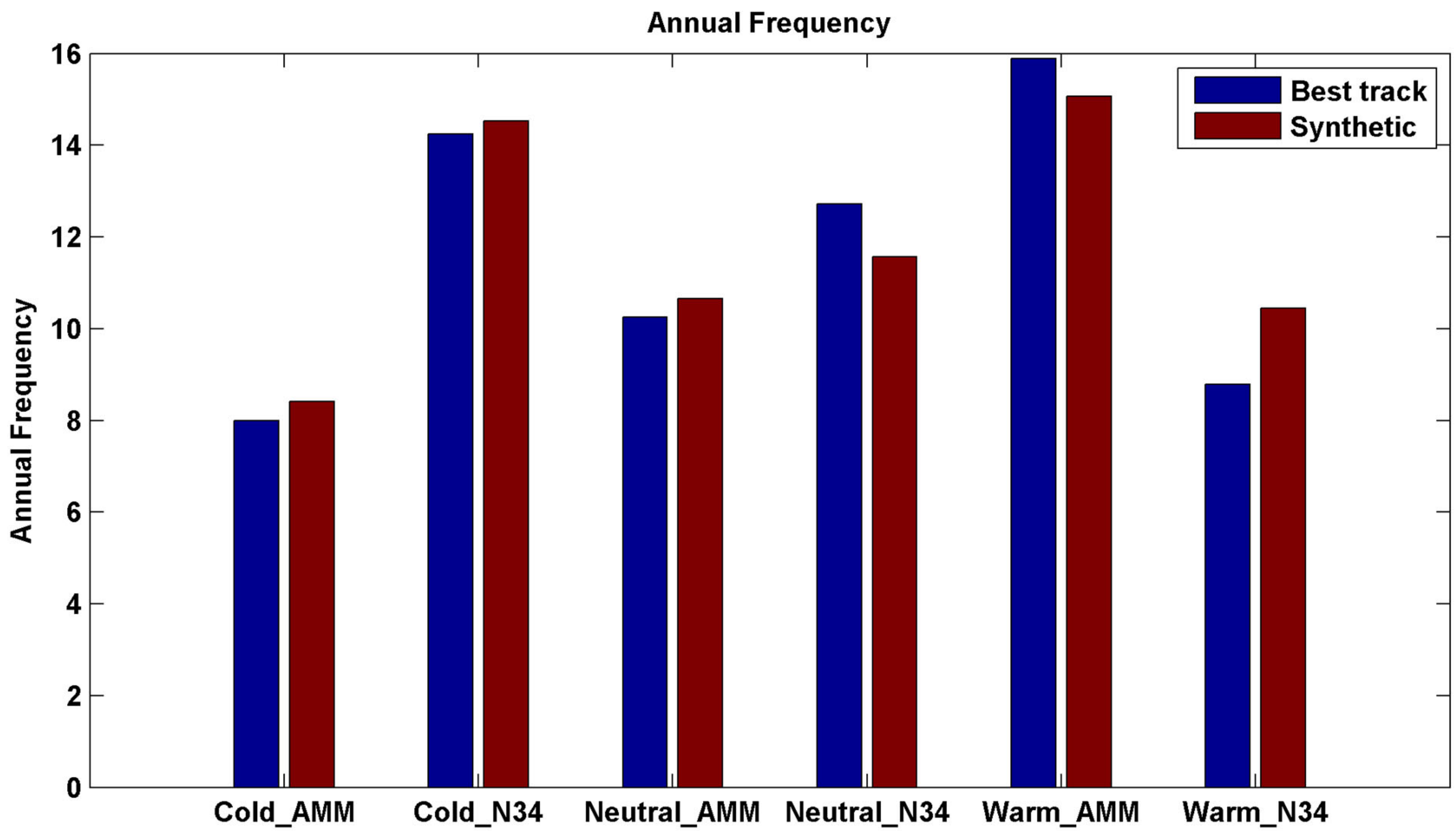


95% confidence bounds

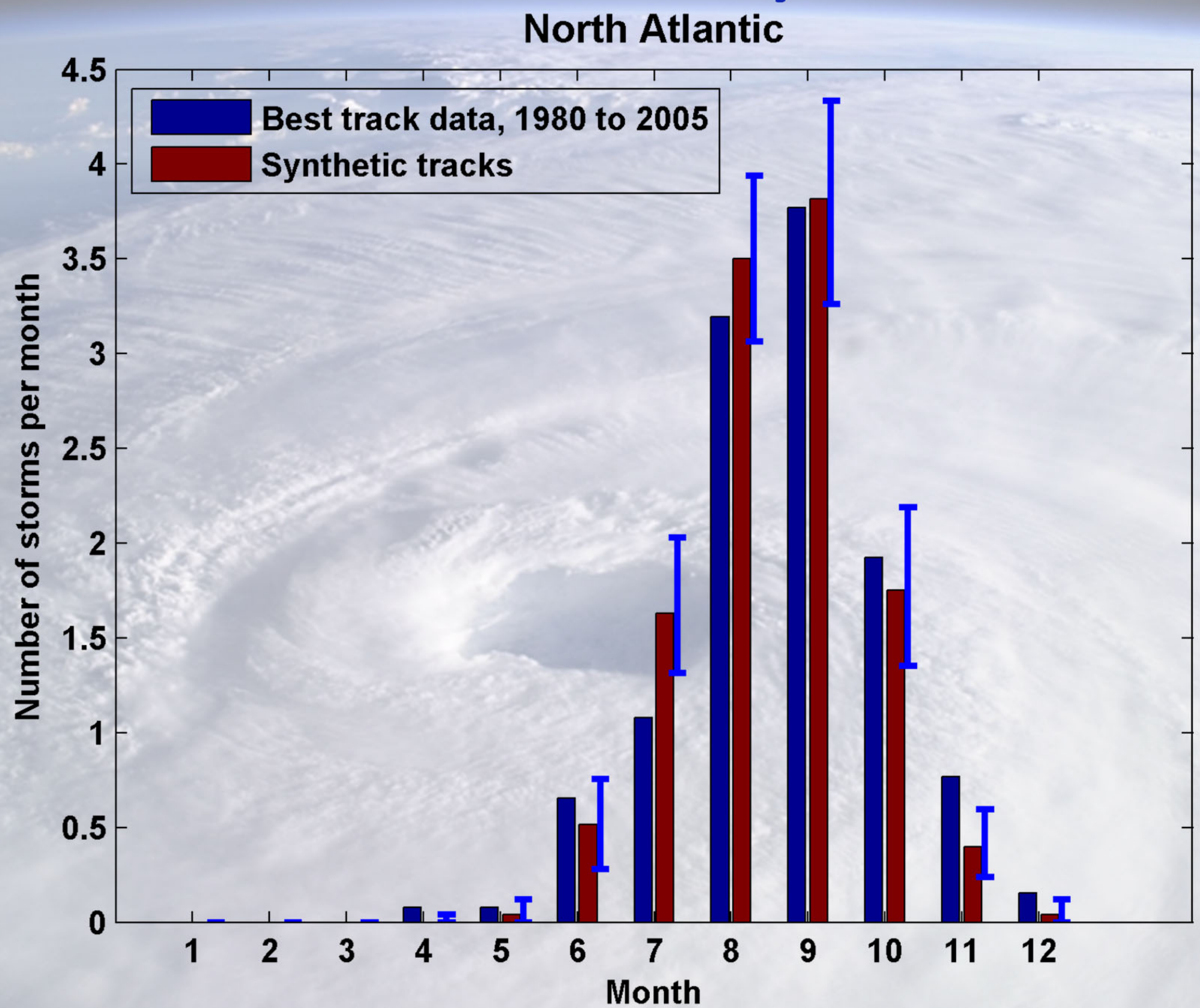
Genesis rates



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



Seasonal Cycles



Atlantic