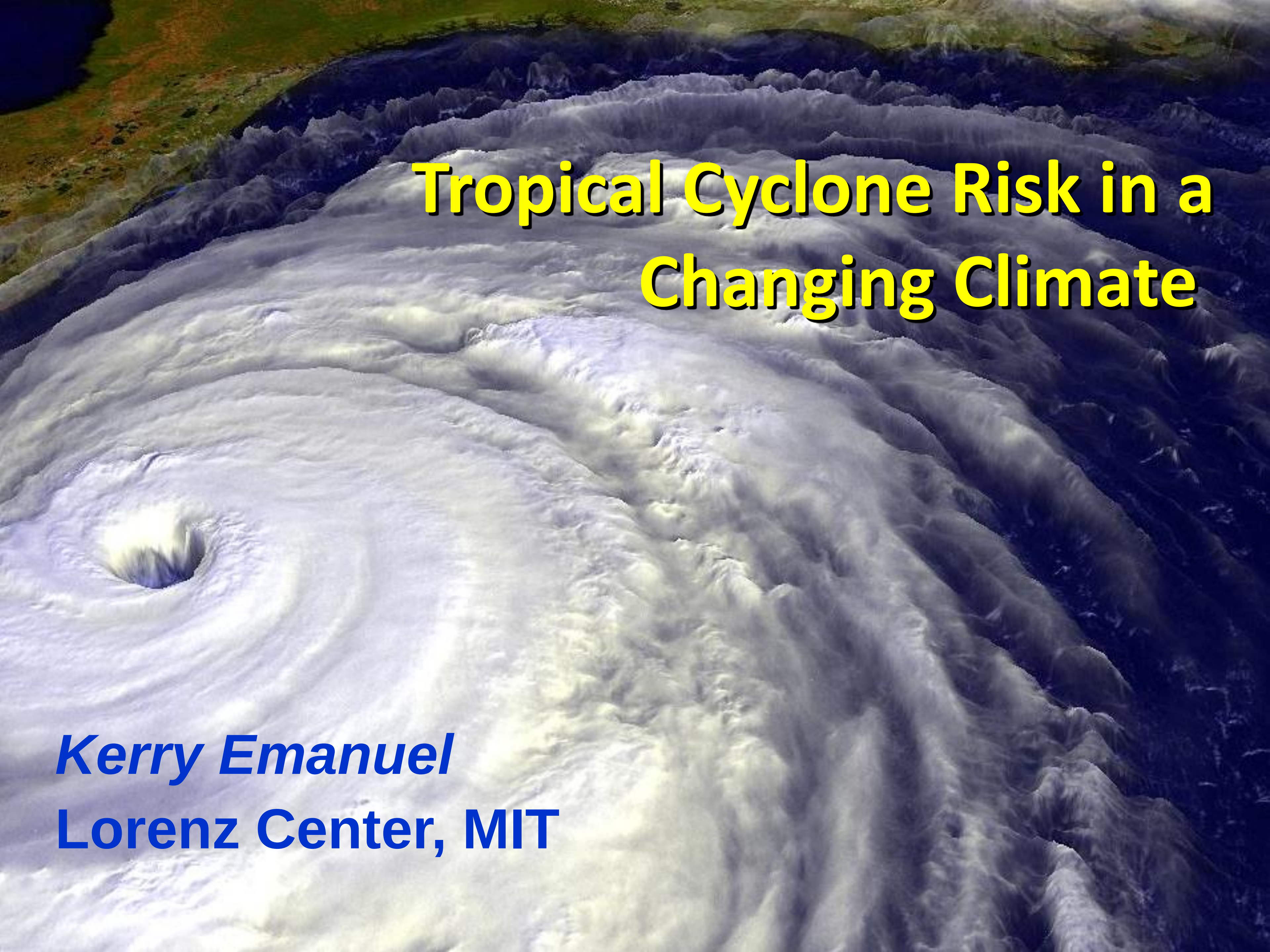


Tropical Cyclone Risk in a Changing Climate

Kerry Emanuel
Lorenz Center, MIT

Hurricane Risks:

- Wind

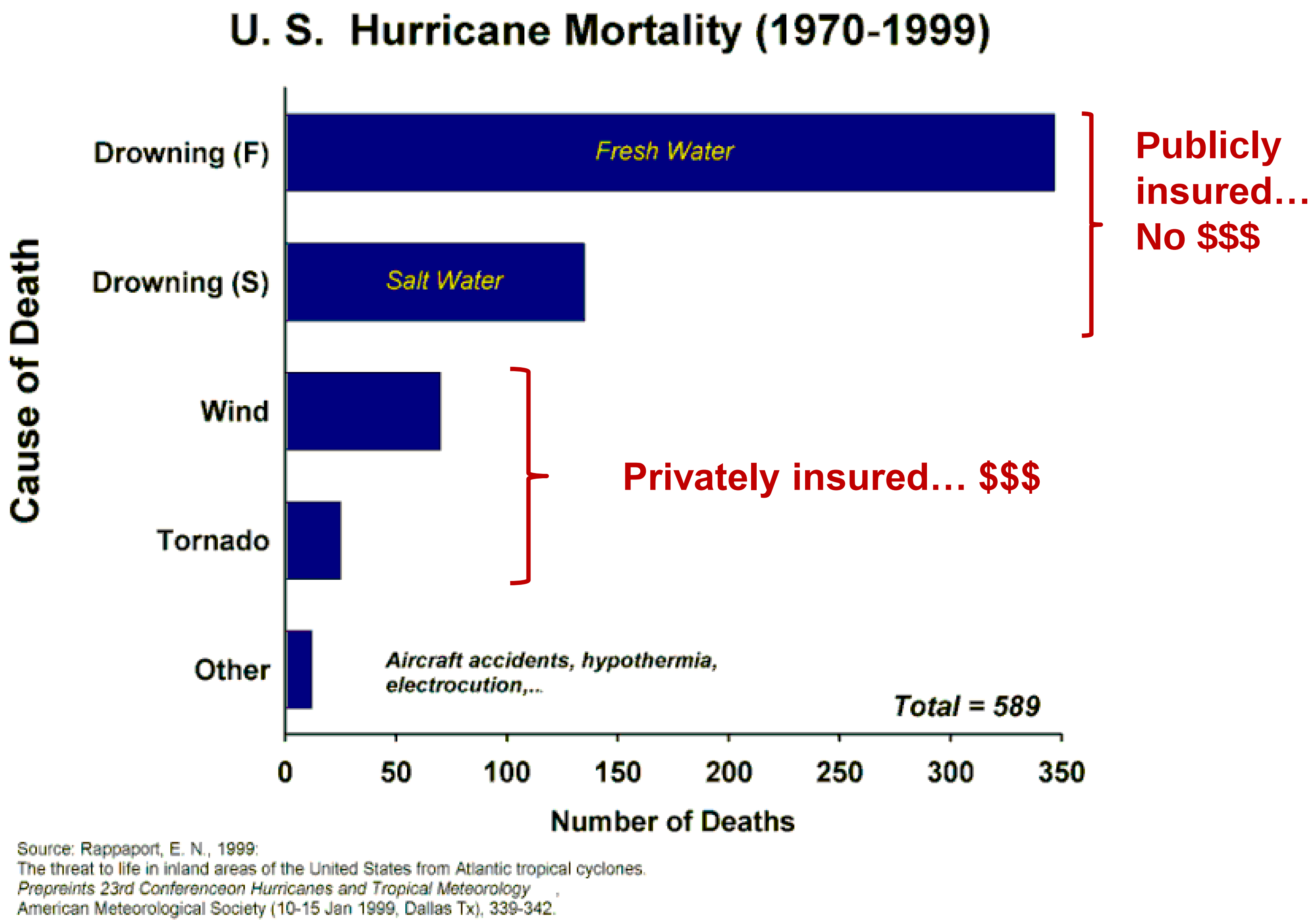
- Rain

- Storm Surge

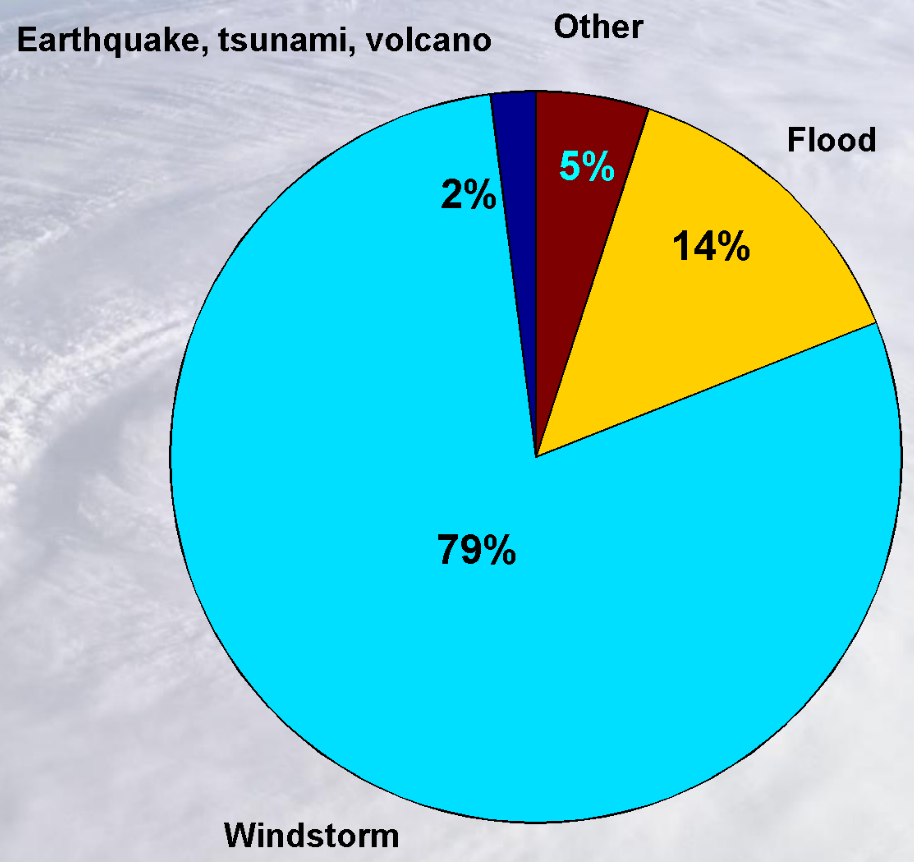
The Global Hurricane Hazard

- About 10,000 deaths per year since 1971
- $700 Billion 2015 U.S. Dollars in Damages Annually since 1971
- Global population exposed to hurricane hazards has tripled since 1970

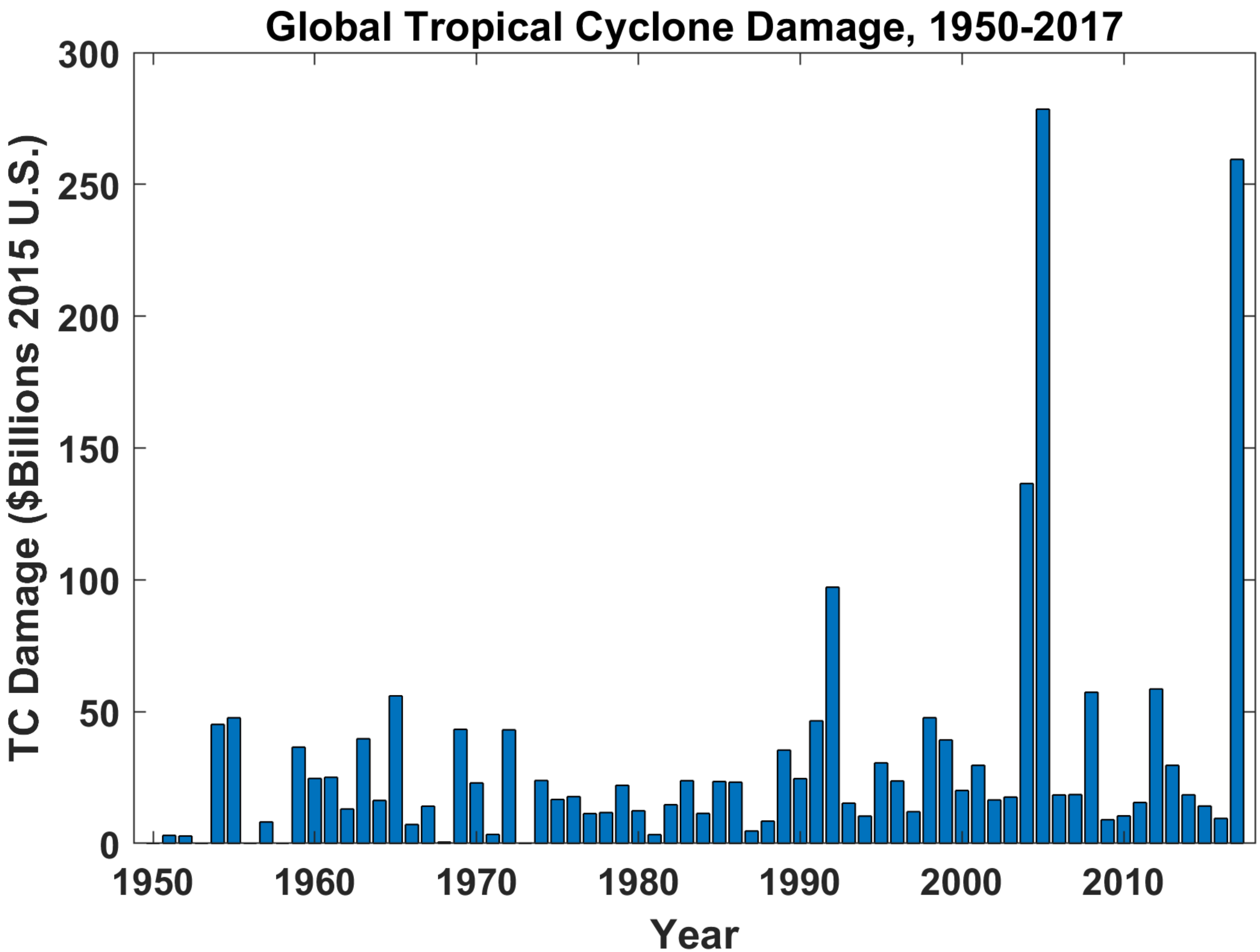
EM-DAT, 2016: The OFDA/CRED International Disaster Database
http://www.emdat.be/.


U. S. Hurricane Mortality (1970-1999)
Cause of Death
Drowning (F)
Fresh Water
Drowning (S)
Salt Water
Wind
Tornado
Other
Aircraft accidents, hypothermia, electrocution,...
Total = 589
0
50
100
150
200
250
300
350
Number of Deaths
Publicly insured… No $$$
Privately insured… $$$
Source: Rappaport, E. N., 1999:
The threat to life in inland areas of the United States from Atlantic tropical cyclones.
Prepreints 23rd Conferenceon Hurricanes and Tropical Meteorology,
American Meteorological Society (10-15 Jan 1999, Dallas Tx), 339-342.

Windstorms Account for Bulk of Insured Losses Worldwide



Percentage Distribution of Global Insured Losses, 2006 (Munich Re)



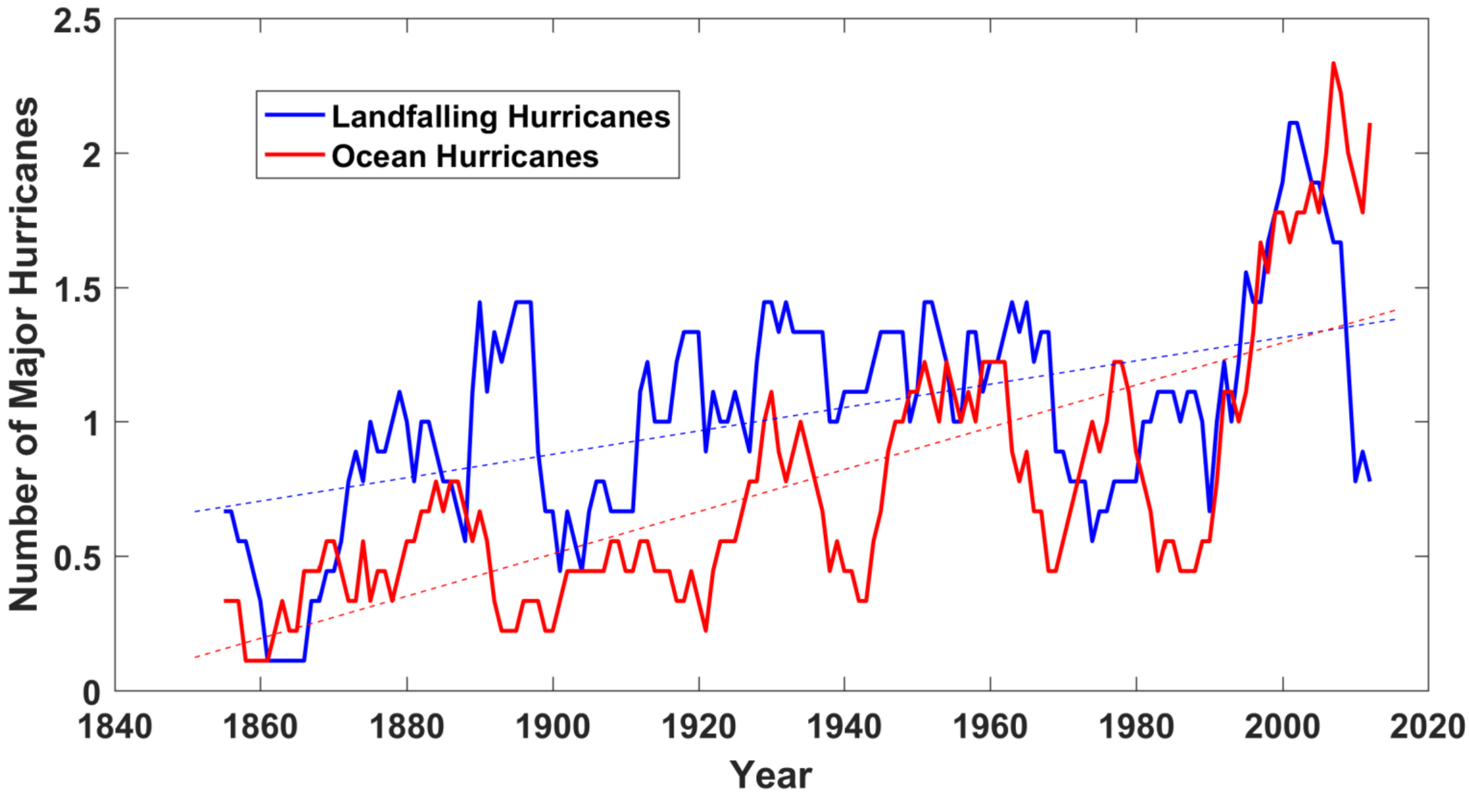
EM-DAT, 2018: The OFDA/CRED International Disaster Database
http://www.emdat.be/. GDP correction from Federal Reserve Bank

Is Hurricane Risk Changing?

Historical Records

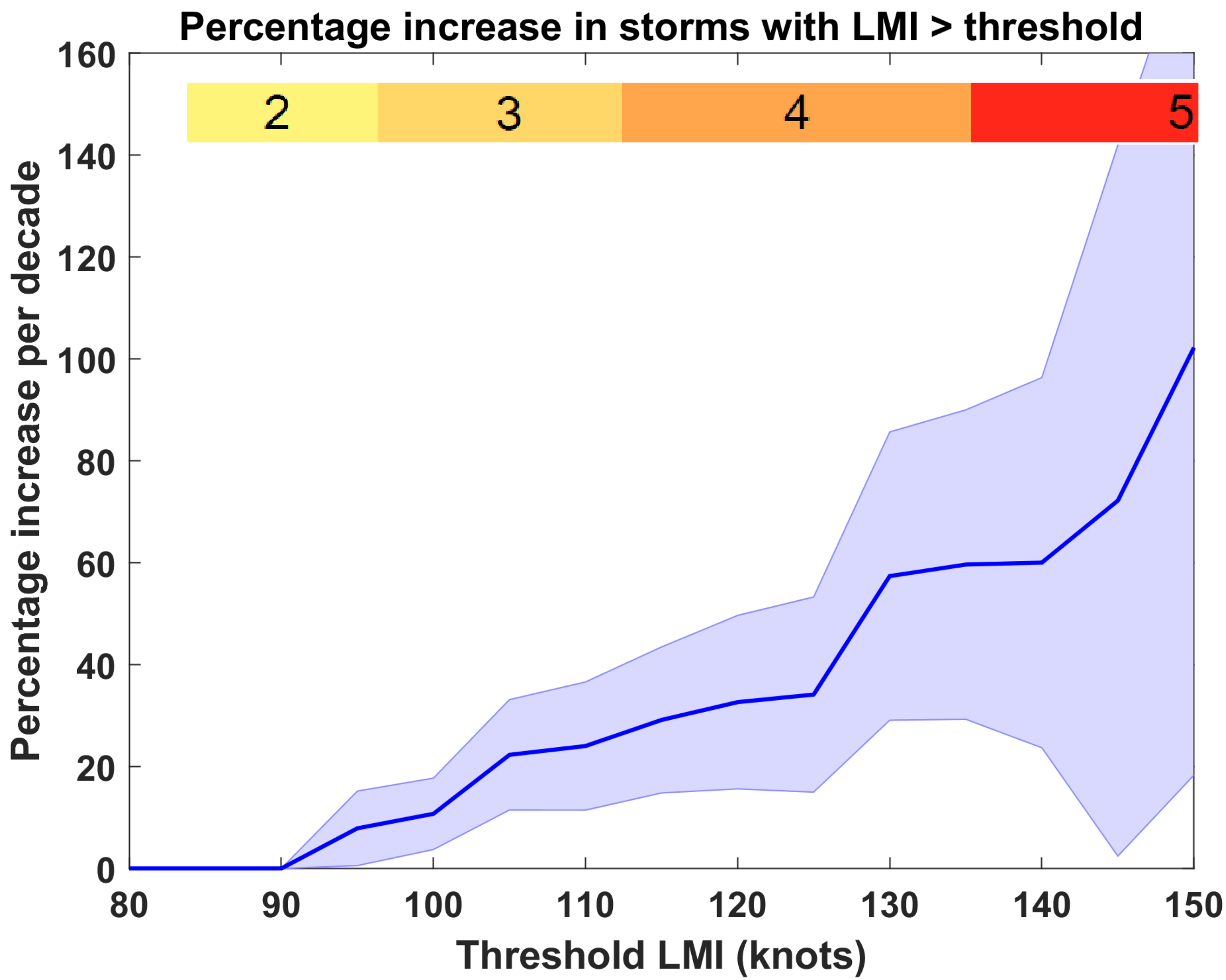
- Pre-1943: Anecdotal accounts from coastal cities and ships
- 1943: Introduction of routine aircraft reconnaissance in Atlantic, western North Pacific
- 1958: Inertial navigation permits direct measurement of wind speed at flight level
- 1970: Complete global detection by satellites
- 1978: Introduction of satellite scatterometry
- 1987: Termination of airborne reconnaissance in western North Pacific
- 2017: Introduction of CYGNSS scatterometry

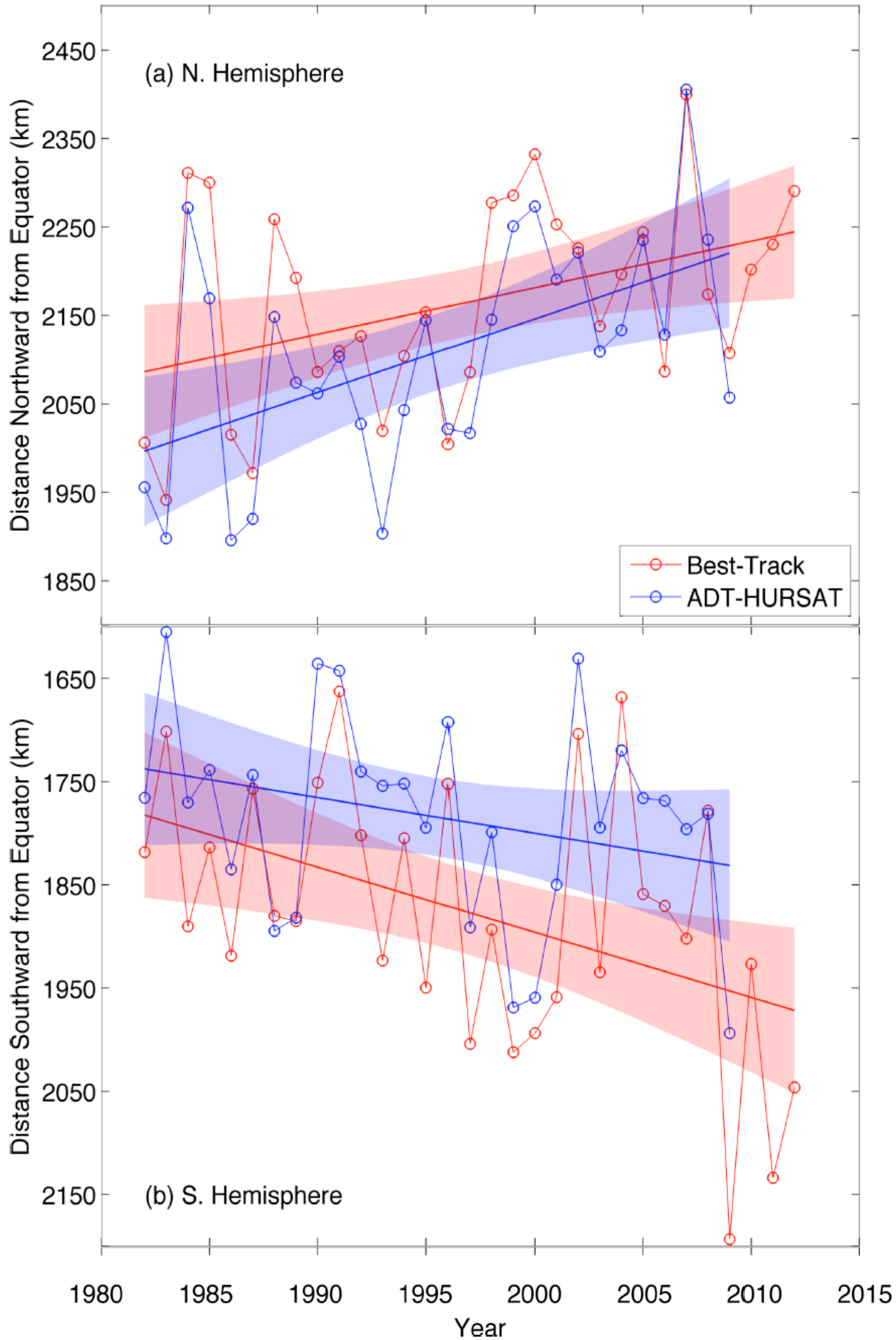
Historical Records:
Prior to 1970, Many Storms Were Missed



Major hurricanes in the North Atlantic, 1851-2016, smoothed using a 10-year running average. Shown in blue are storms that either passed through the chain of Lesser Antilles or made landfall in the continental U.S.; all other major hurricanes are shown in red. The dashed lines show the best fit trend lines for each data set.

Trends in Global TC Frequency Over Threshold Intensities, from Historical TC Data, 1980-2016. Trends Shown Only When $p < 0.05$.



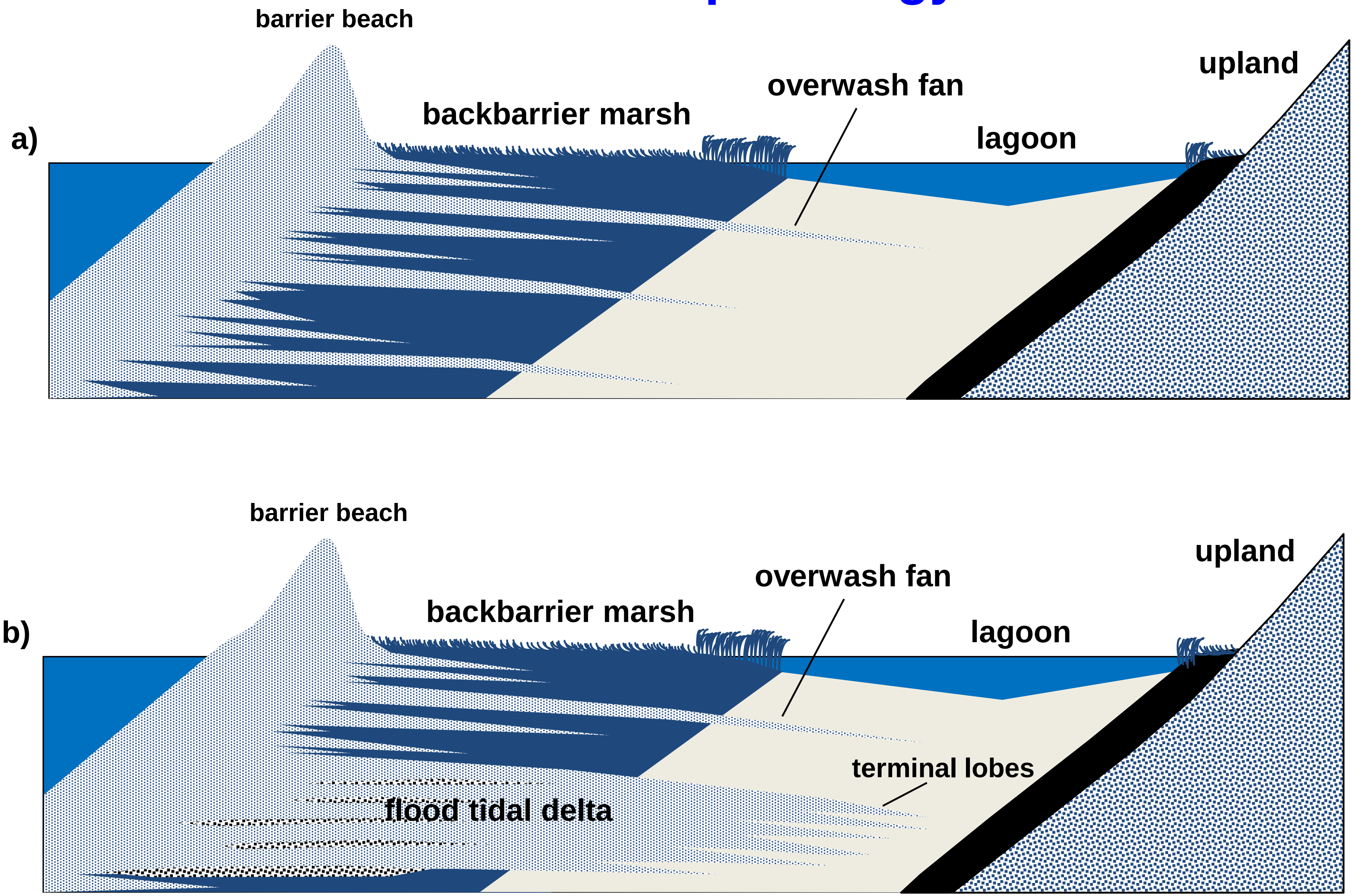


Hurricanes are reaching peak intensity at higher latitudes

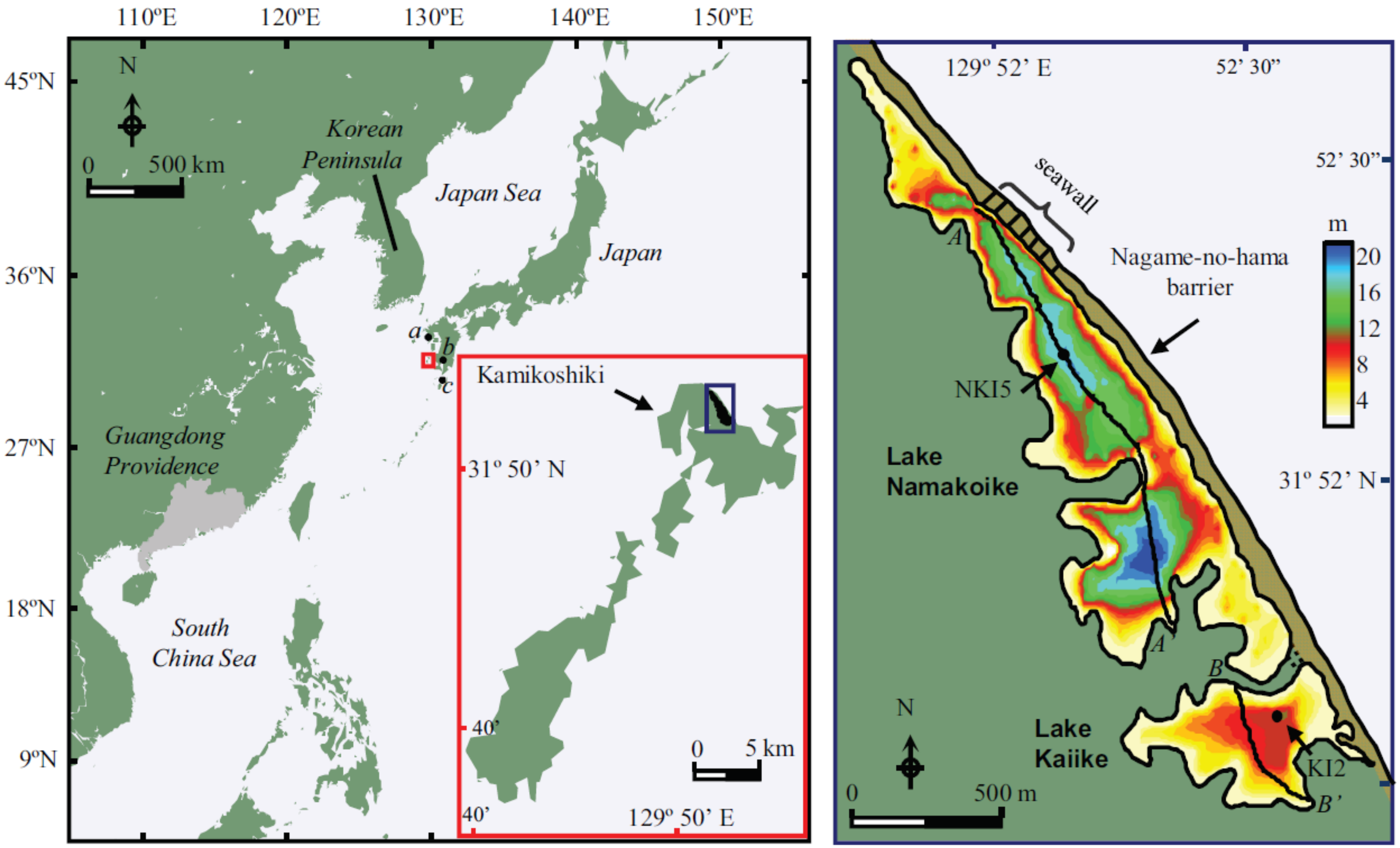
Time series of the latitudes at which tropical cyclones reach maximum intensity.

From *Kossin et al. (2014)*

Paleotempestology

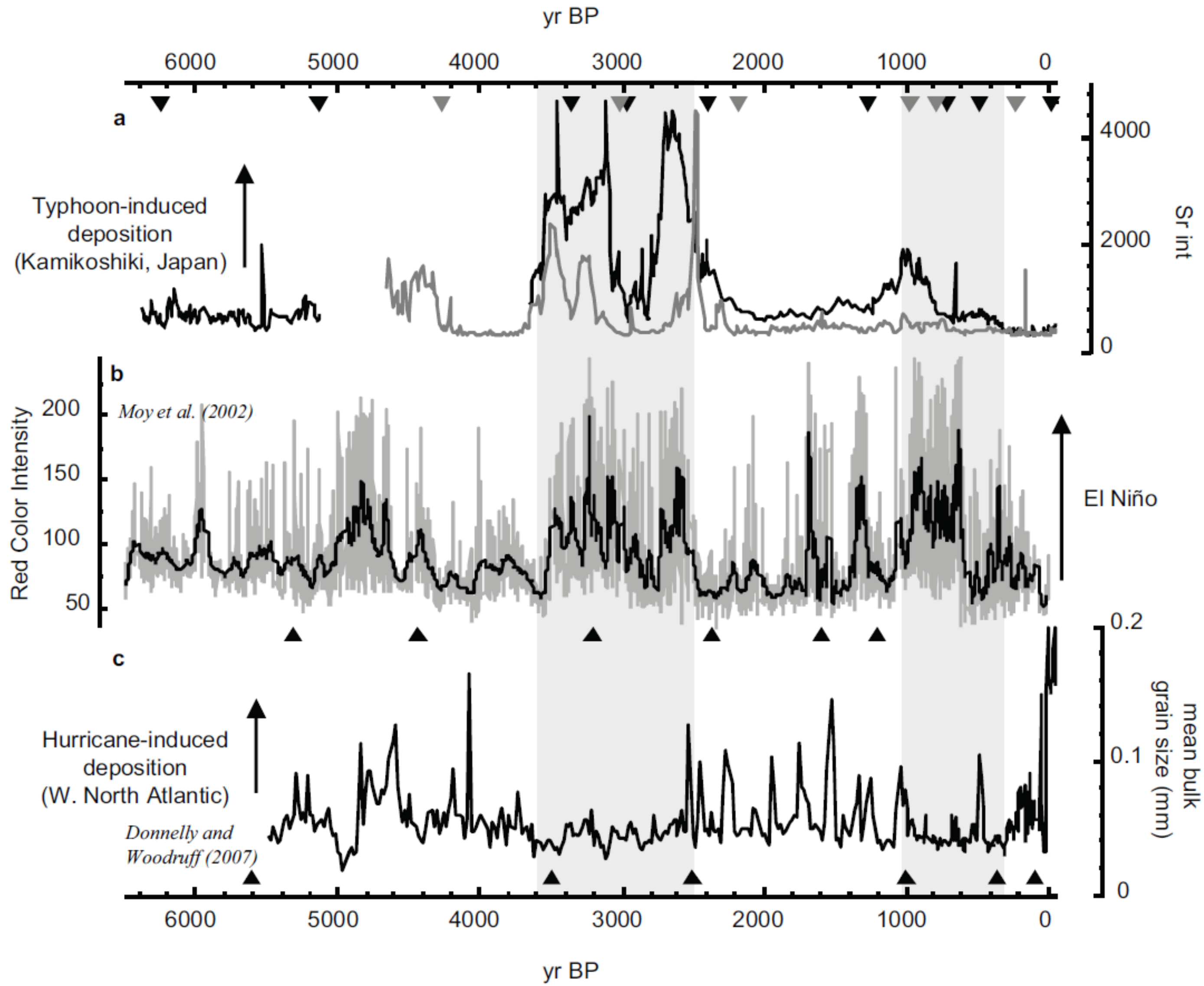


Source: Jeff Donnelly, WHOI



Map of the western North Pacific showing study area (open red square). The locations of Nagasaki, Kagoshima Bay, and Tanegashima are identified by a, b, and c, respectively.

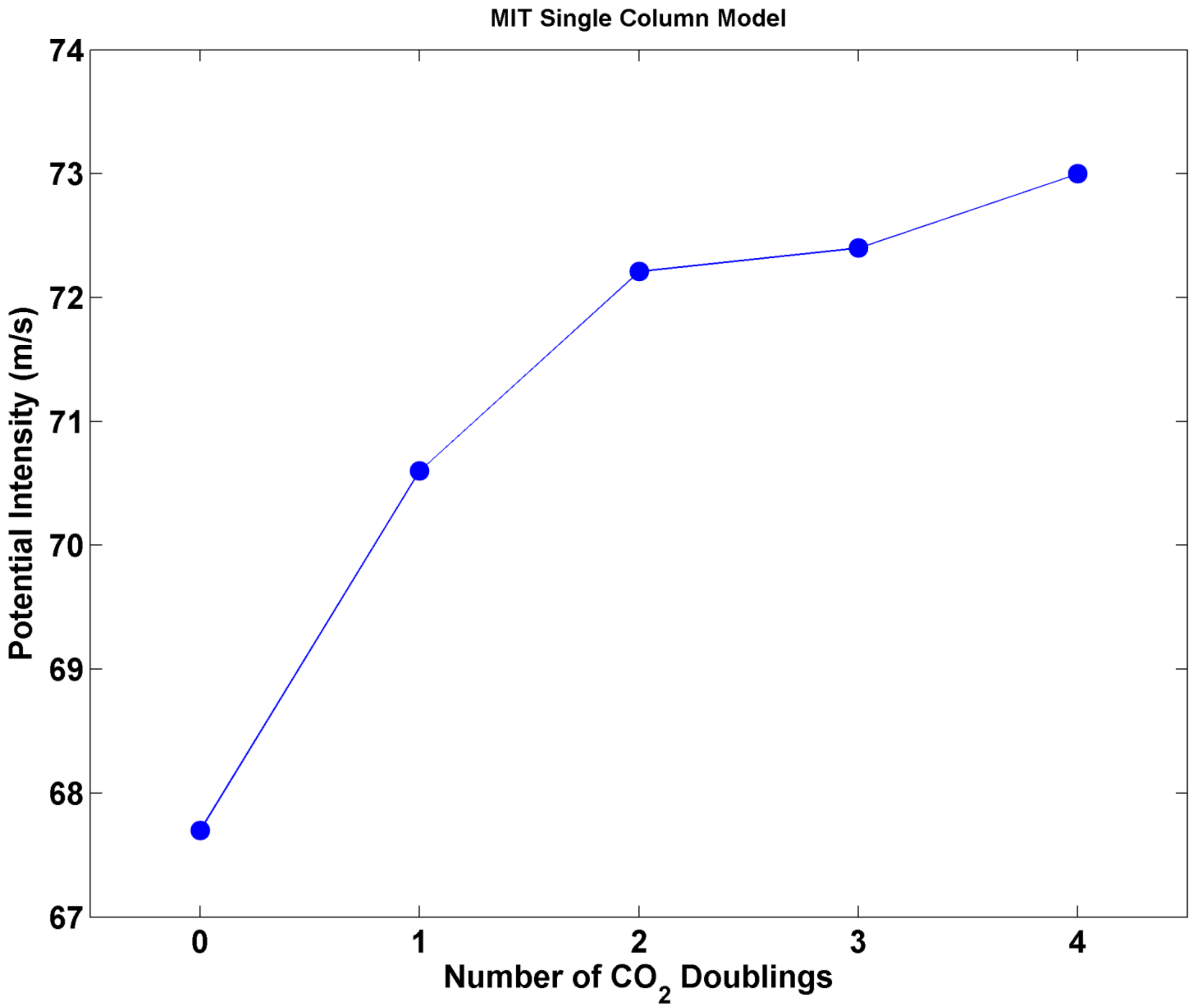
Woodruff et al., *Quatern. Sci. Rev.*, 2009



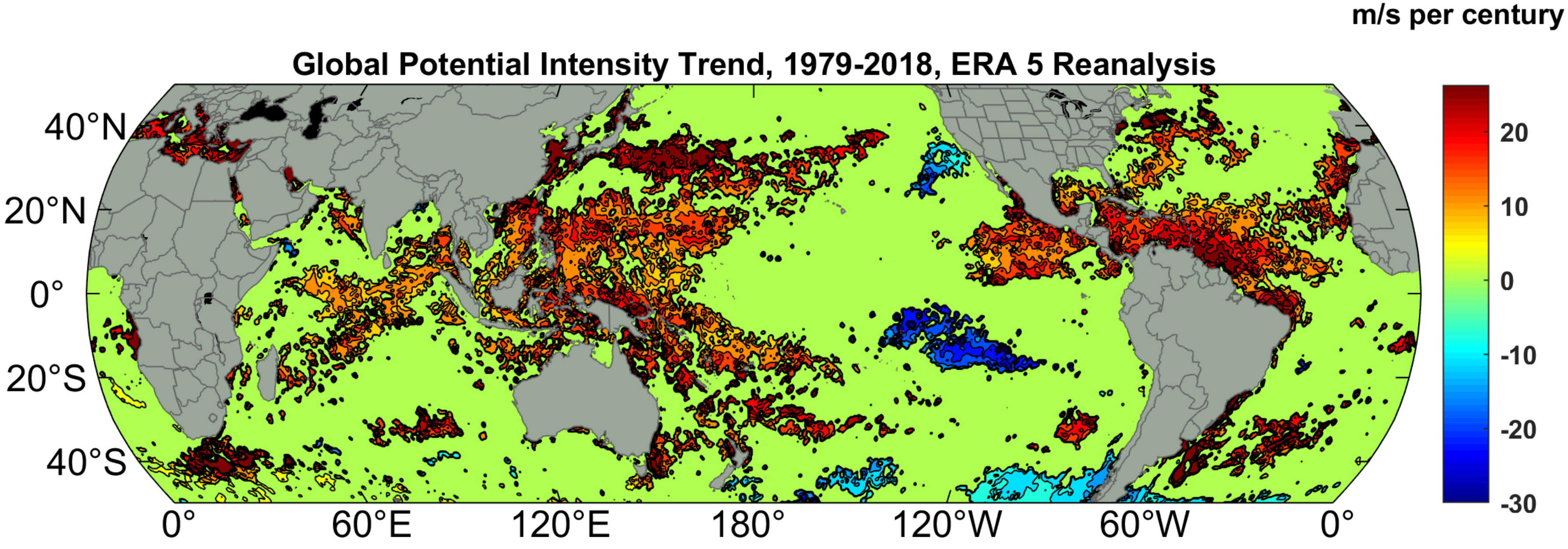
Sr time-series for cores NKI5 (black) and KI2 (gray), compared to b) El Niño reconstructions from Laguna Pallcocha, Ecuador (Moy et al., 2002), and c) proxy records of hurricane-induced sedimentation from Laguna Playa Grande, Vieques, Puerto Rico (Donnelly and Woodruff, 2007).

Woodruff et al., *Quatern. Sci. Rev.*, 2009

Potential Intensity and CO_2

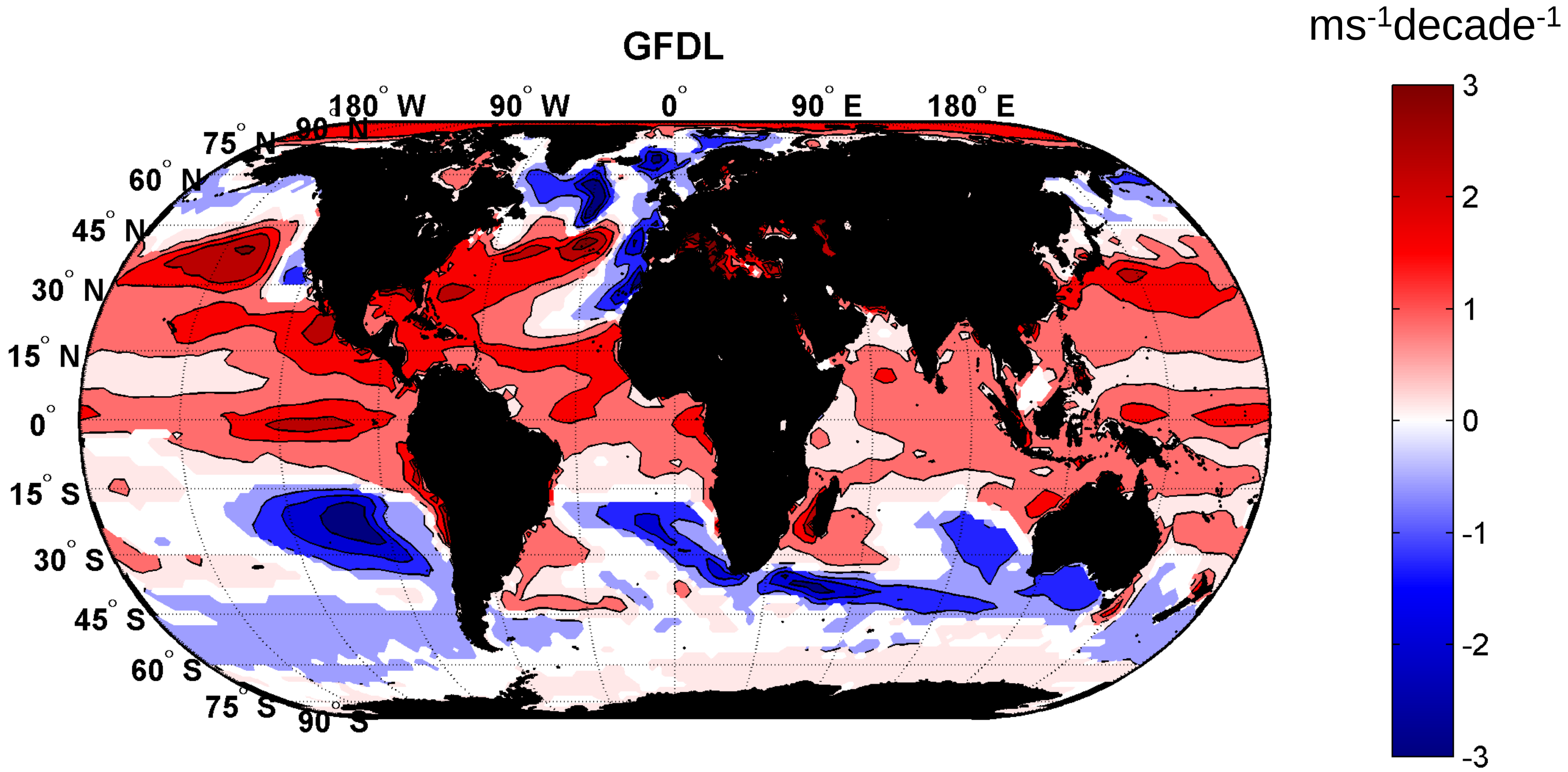


Potential Intensity Trend, 1979-2018, ERA 5 Reanalysis



(Trend shown only where p value < 0.05)

Projected Trend Over 21st Century: GFDL model under RCP 8.5

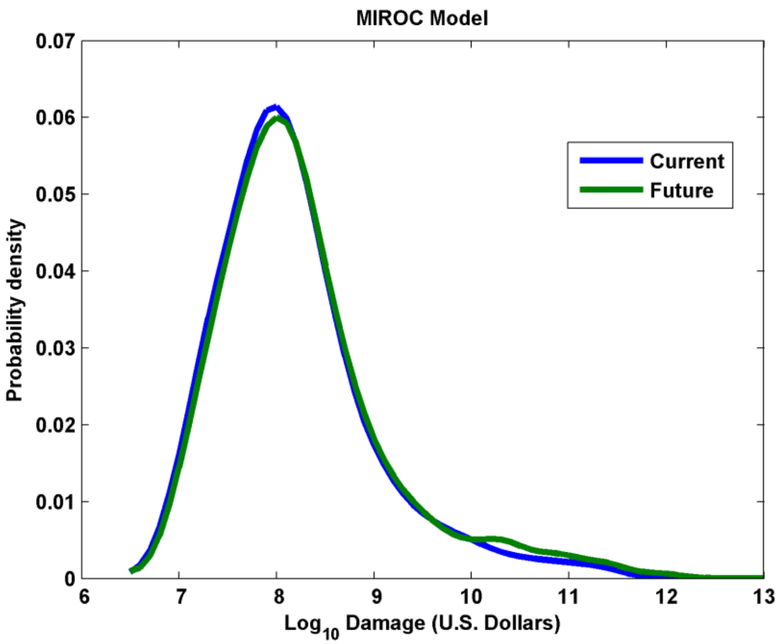


Inferences from Basic Theory:

- Potential intensity increases with global warming
- Incidence of high-intensity hurricanes should increase
- Increases in potential intensity should be faster in sub-tropics
- Hurricanes will produce substantially more rain: Clausius-Clapeyron yields ~7% increase in water vapor per 1^{o}C warming

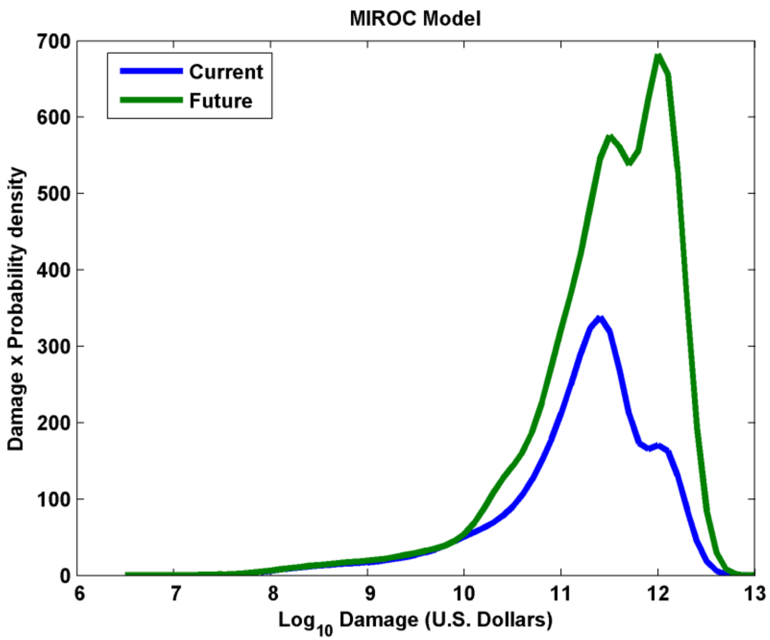
Risk Assessment in a Changing Climate: The Problem

Event Probability



Current and Future Probability Density of U.S. TC Wind Damages

Damage Probability



Current and Future Damage Probability

The Heart of the Problem:

- Societies are usually well adapted to frequent events (> 1/100 yr)
- Societies are often poorly adapted to rare events (< 1/100 yr)
- Robust estimates of the character of ~100 yr events require ~1,000 years of data
- We do not have ~1,000 years of meteorological observations

How We Deal with This:

- For local events, accumulate statistics over locations far enough apart to sample different individual events, but close enough to sample the same overall climatology.
  - Example: 500 mm of TC rain in metro Houston may be a 100-year event, but a 20-year event over coastal Texas
- Extrapolate well-sampled events to rare events using extreme value theory. Dicey!

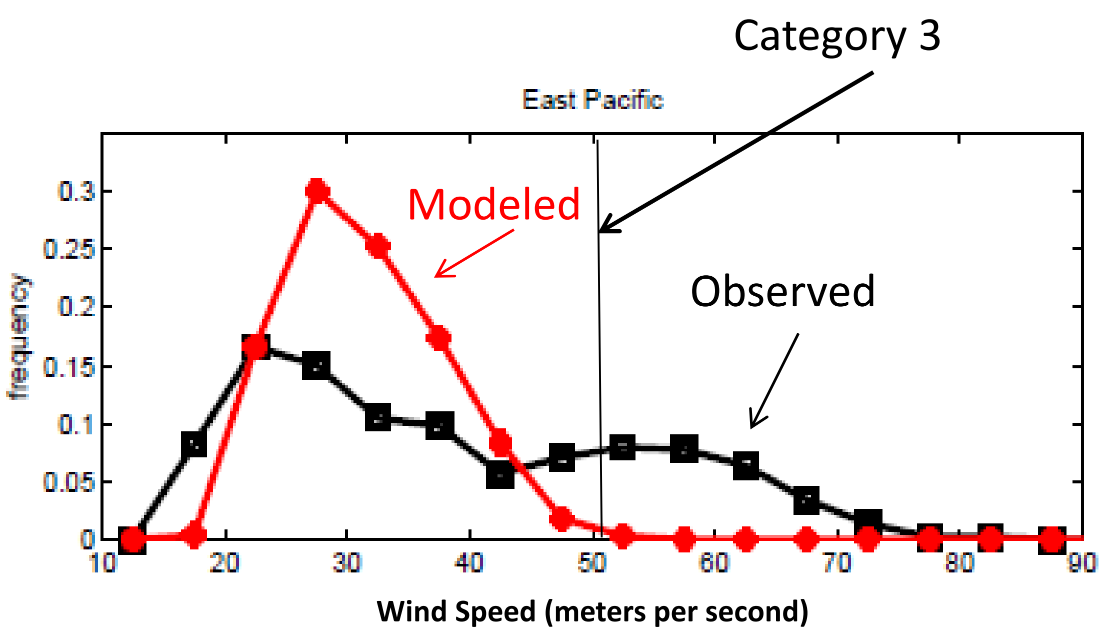
How We COULD Deal with This:

- Bring physics to bear on natural hazard risk assessment… problem too important to leave to statisticians
- But several impediments:
  - Academic stove-piping: Too applied for scientists; too complicated for risk professionals
  - Brute force modeling probably too expensive to be practical for many applications

Using Physics to Estimate Hurricane Risk

Why Not Use Global Climate Models to Simulate Hurricanes?

Problem: Today's models are far too coarse to simulate destructive hurricanes



Histograms of Tropical Cyclone Intensity as Simulated by a Global Model with 30 mile grid point spacing. (Courtesy Isaac Held, GFDL)

Global models do not simulate the storms that cause destruction

How to deal with this?

- **Embed high-resolution, fast coupled ocean-atmosphere hurricane model in global climate model or climate reanalysis data**
- **Coupled Hurricane Intensity prediction Model (CHIPS) has been used for 18 years to forecast real hurricanes in near-real time**

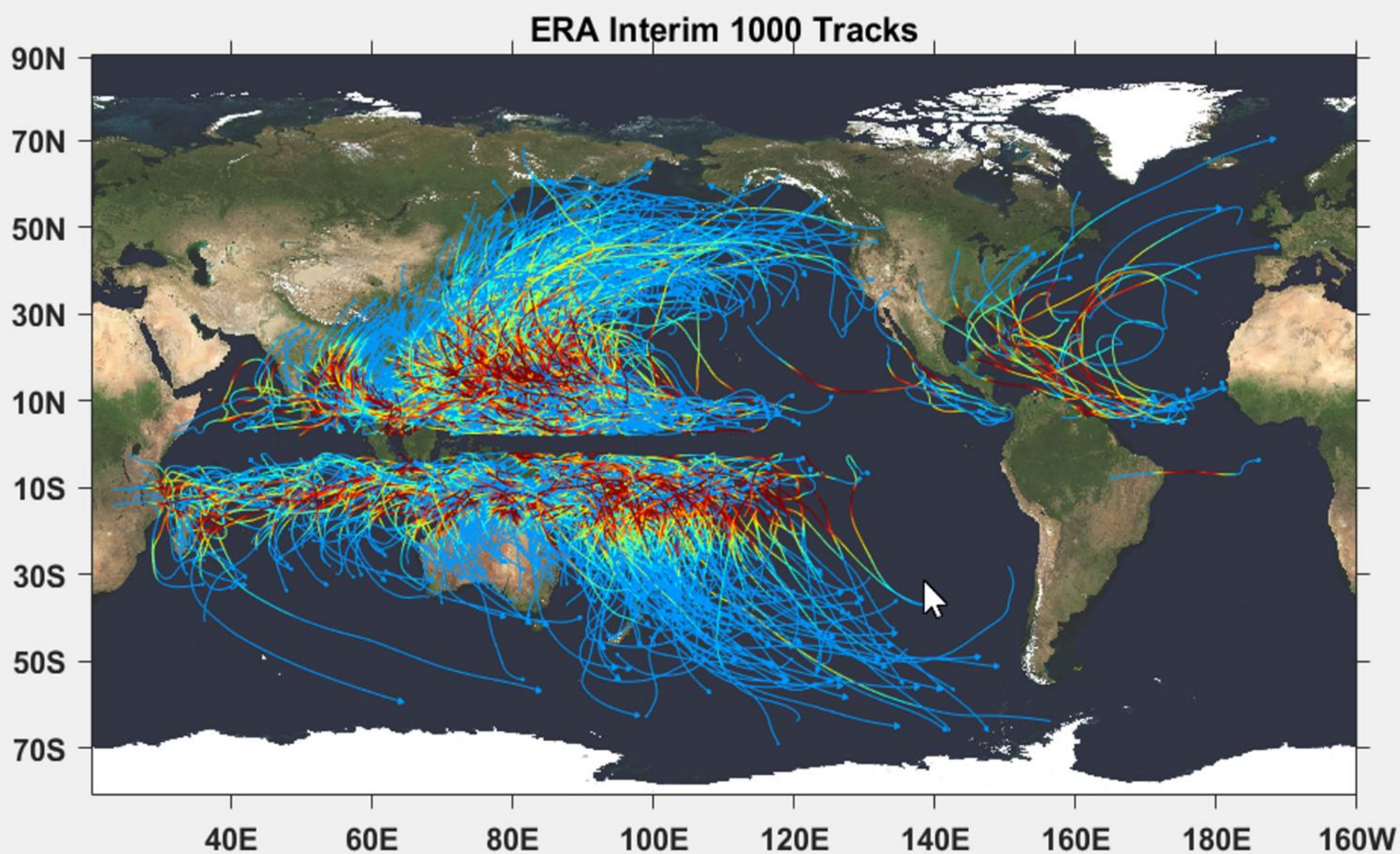
Risk Assessment Approach:

- **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 the earth's rotation and sphericity
- **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. Can easily generate 100,000 events

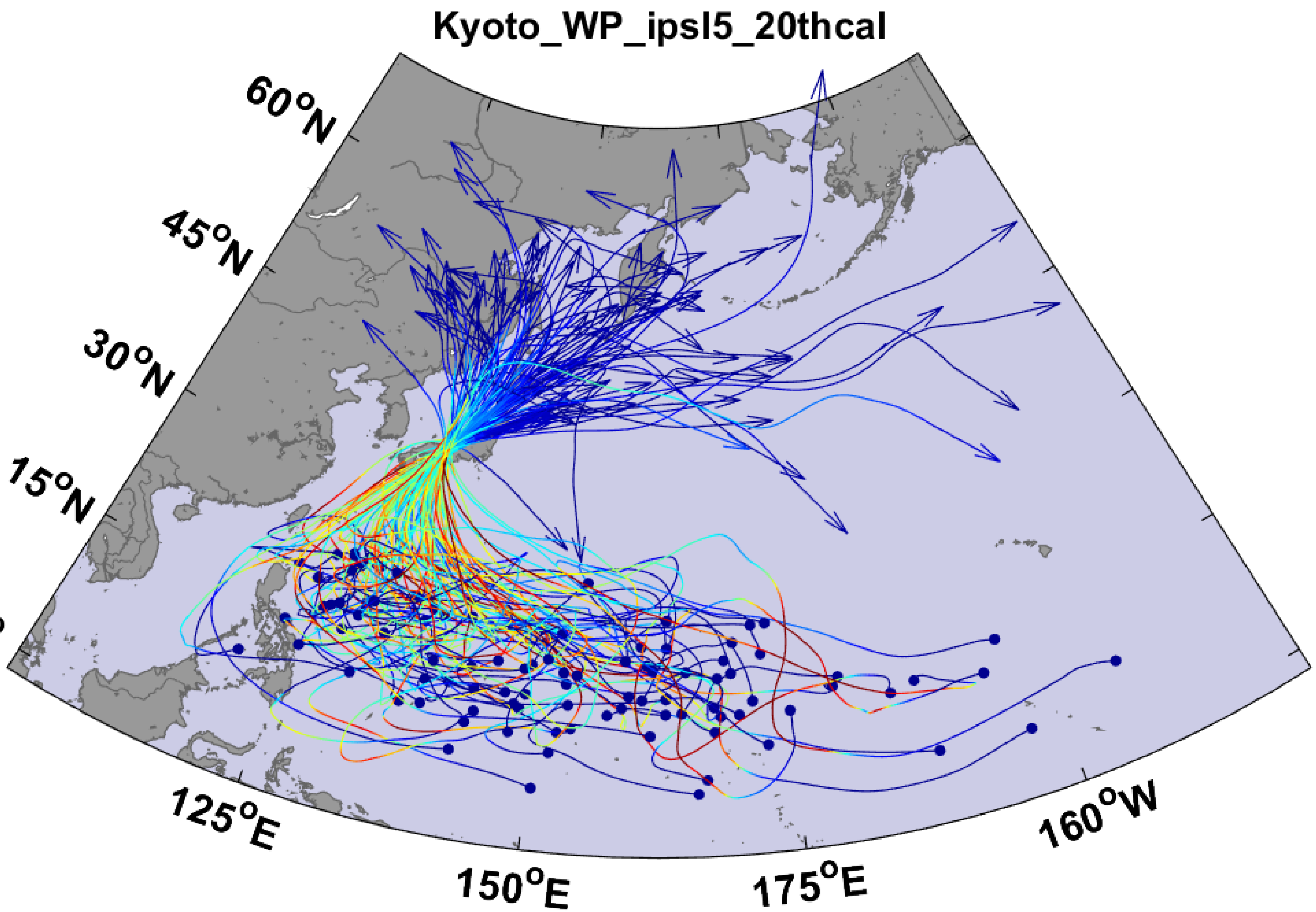
Details: Emanuel et al., *Bull. Amer. Meteor. Soc*, 2008

Calibration

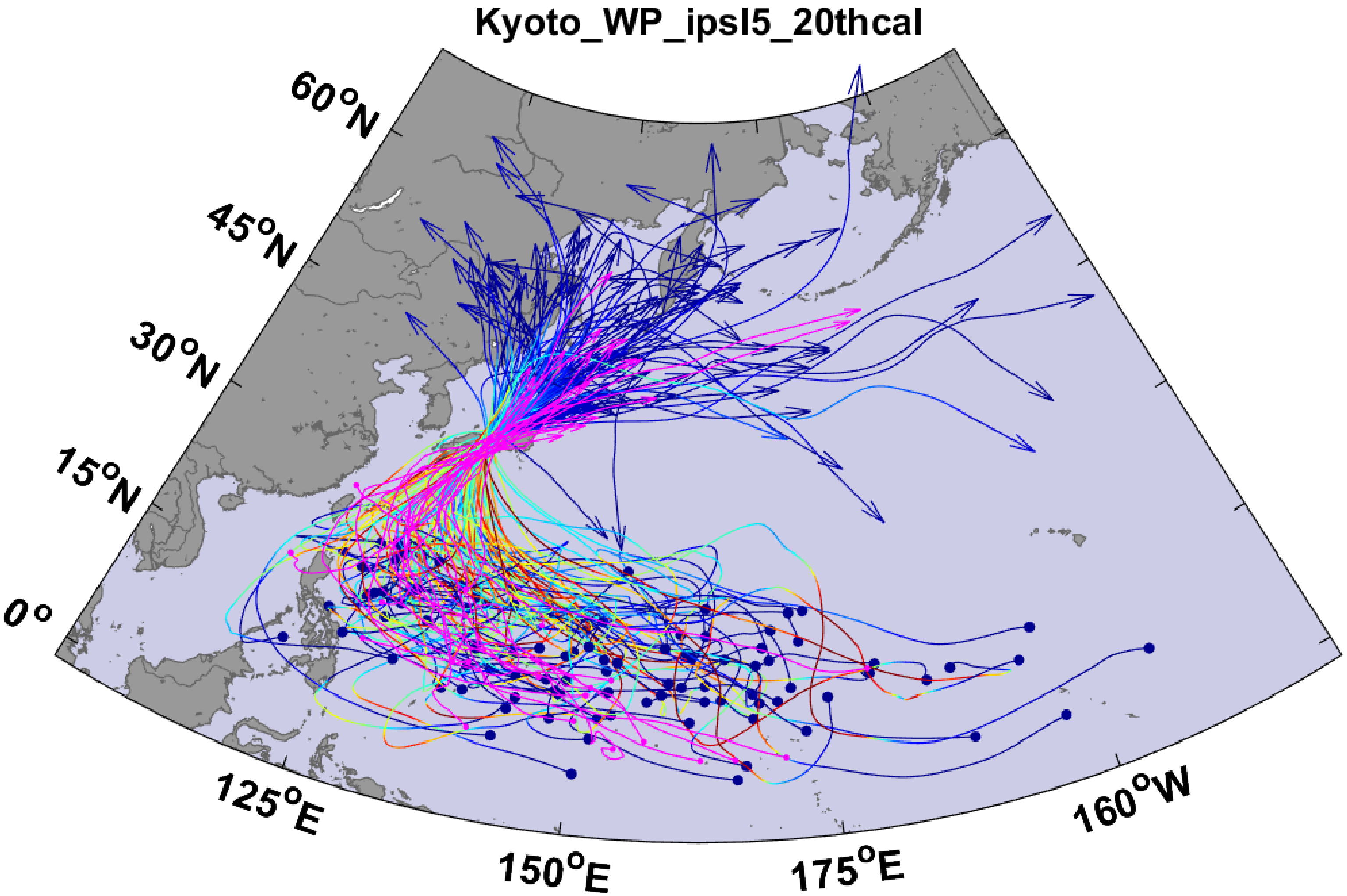
- **Absolute genesis frequency calibrated to globe during the period 1980-2005**


ERA Interim 1000 Tracks
90N
70N
50N
30N
10N
10S
30S
50S
70S
40E
60E
80E
100E
120E
140E
160E
180E
160W

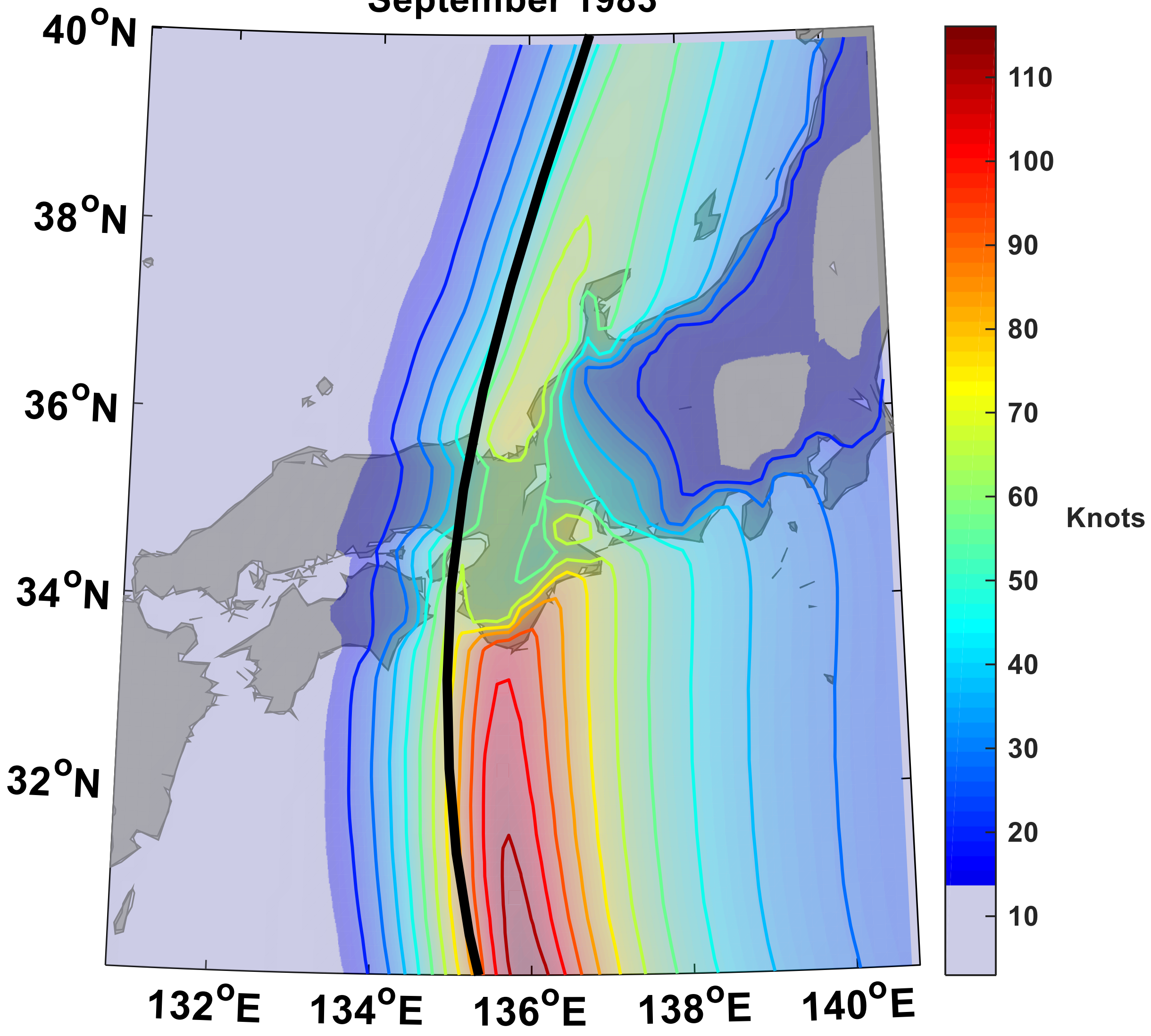
Top 100 out of 2000 TCs Affecting Kyoto, 1981-2000



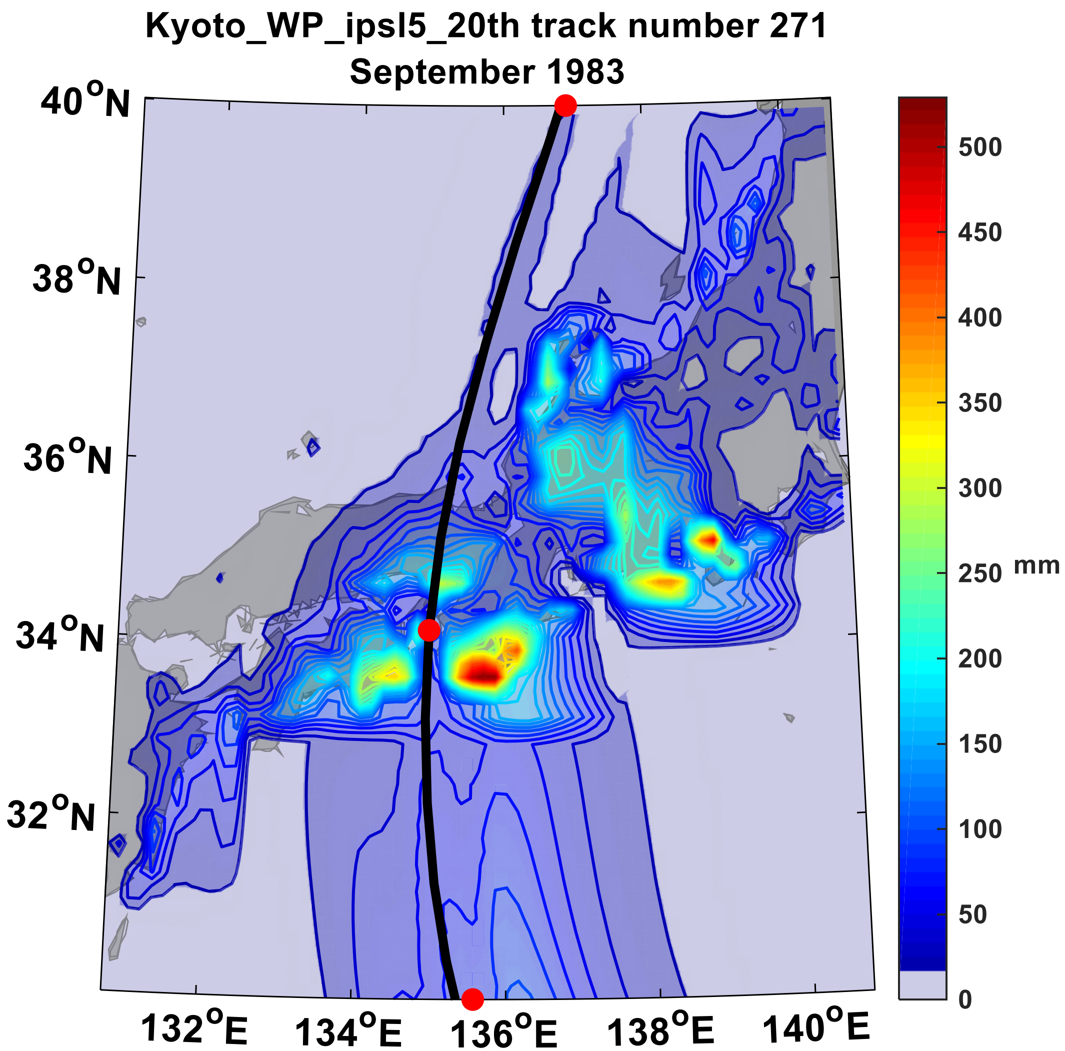
Same, but with top 20 historical tracks



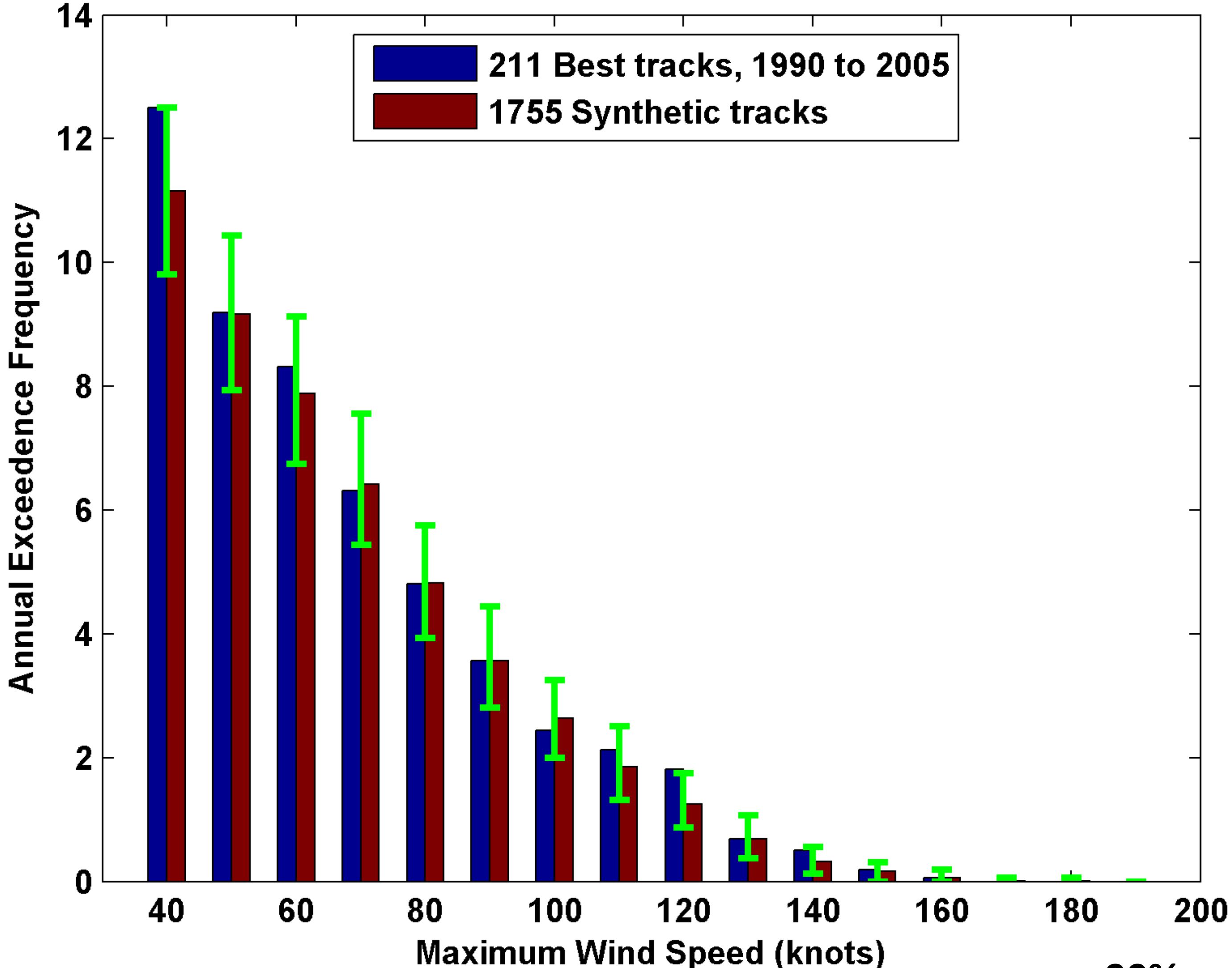
Kyoto_WP_ipsl5_20th track number 271
September 1983



Storm total rainfall

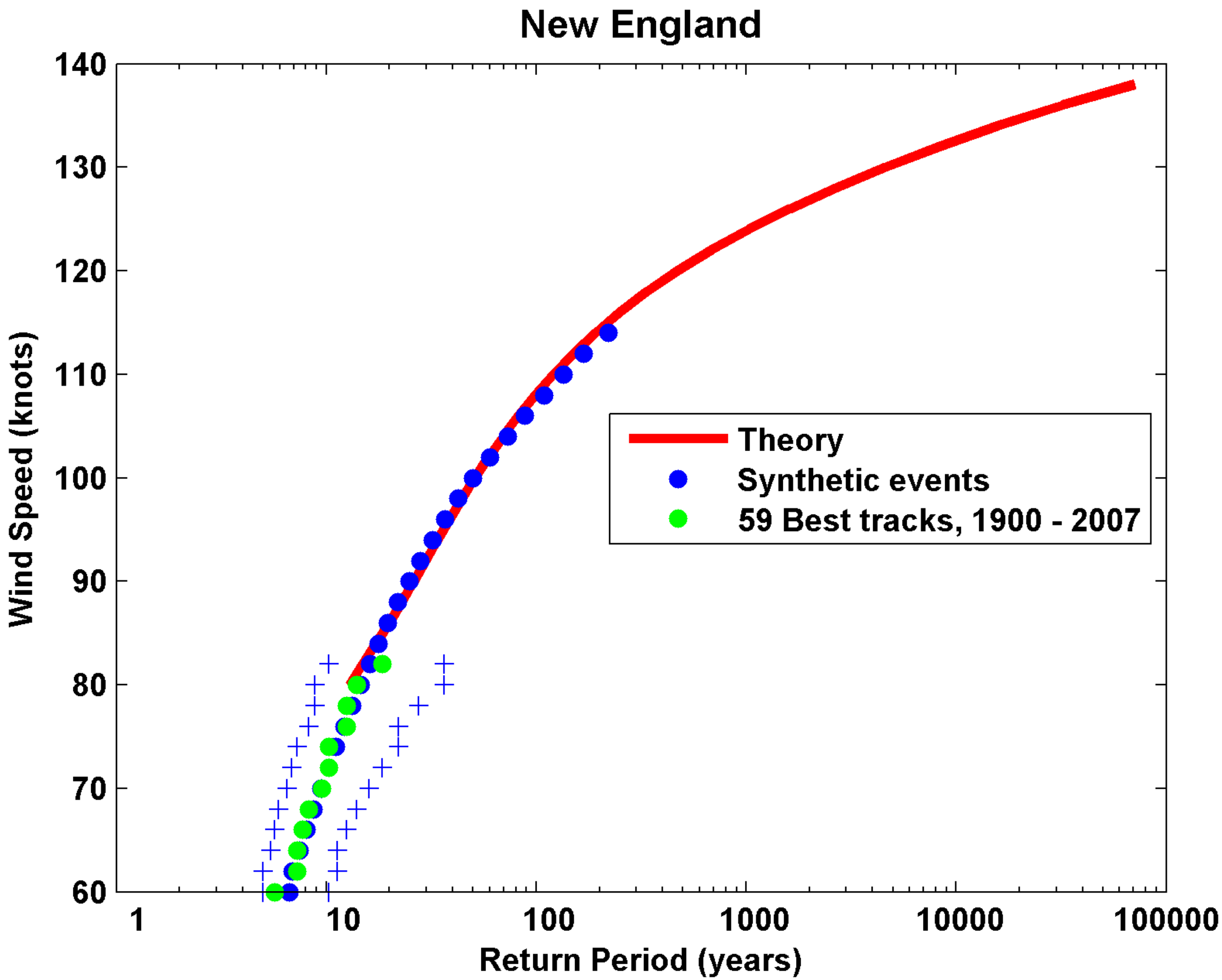


Cumulative Distribution of Storm Lifetime Peak Wind Speed, with Sample of 1755 Synthetic Tracks

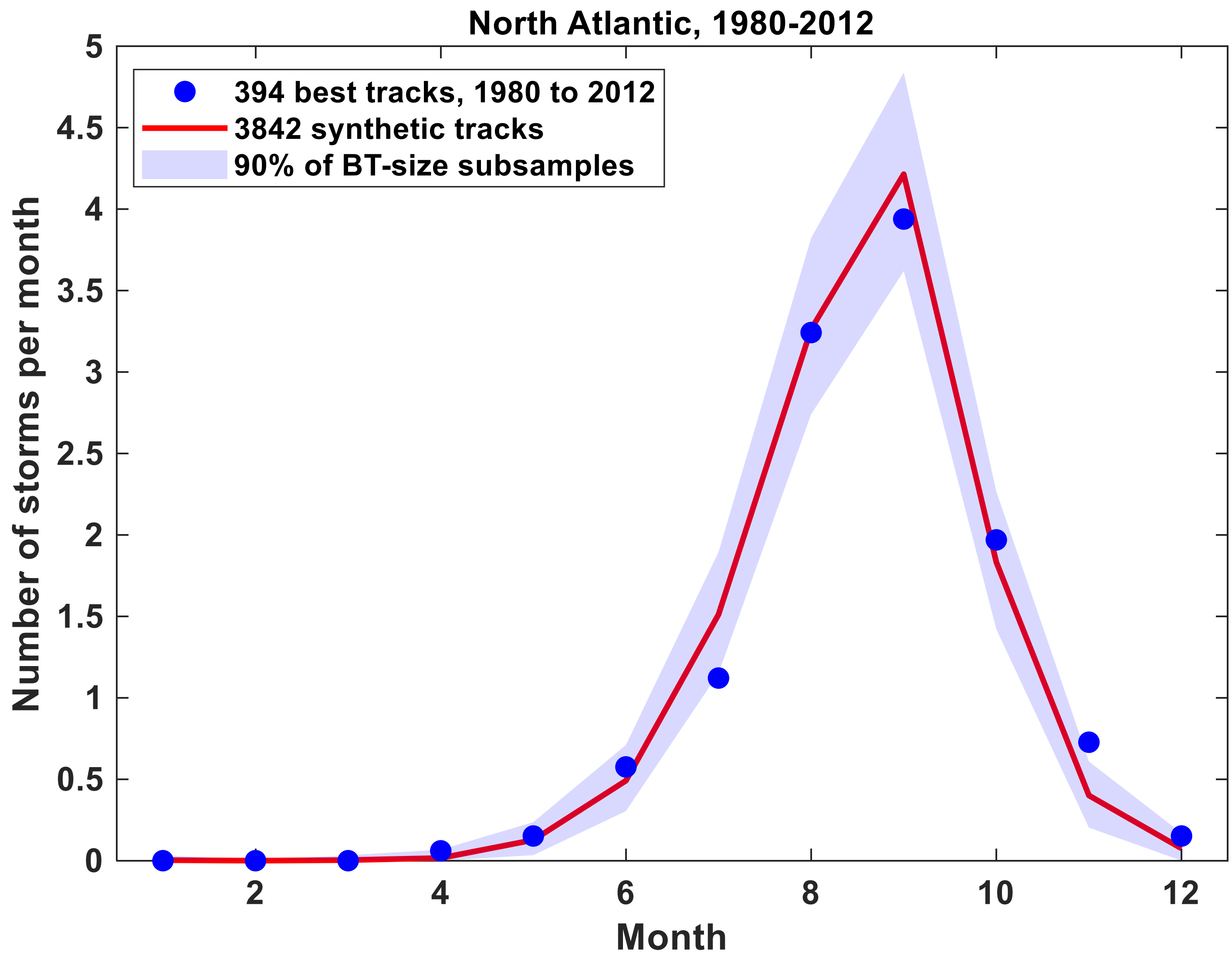


90% confidence bounds

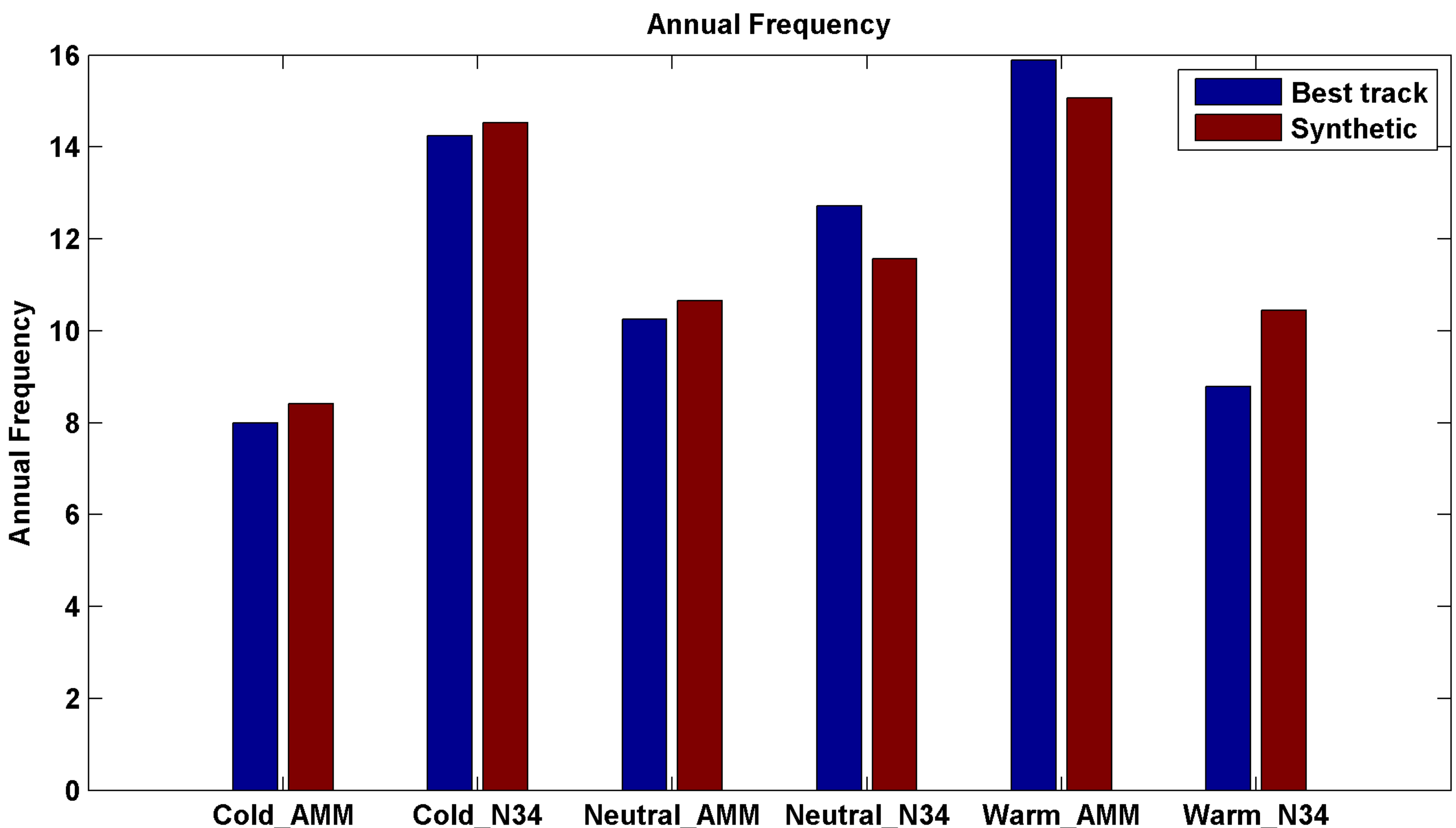
Return Periods



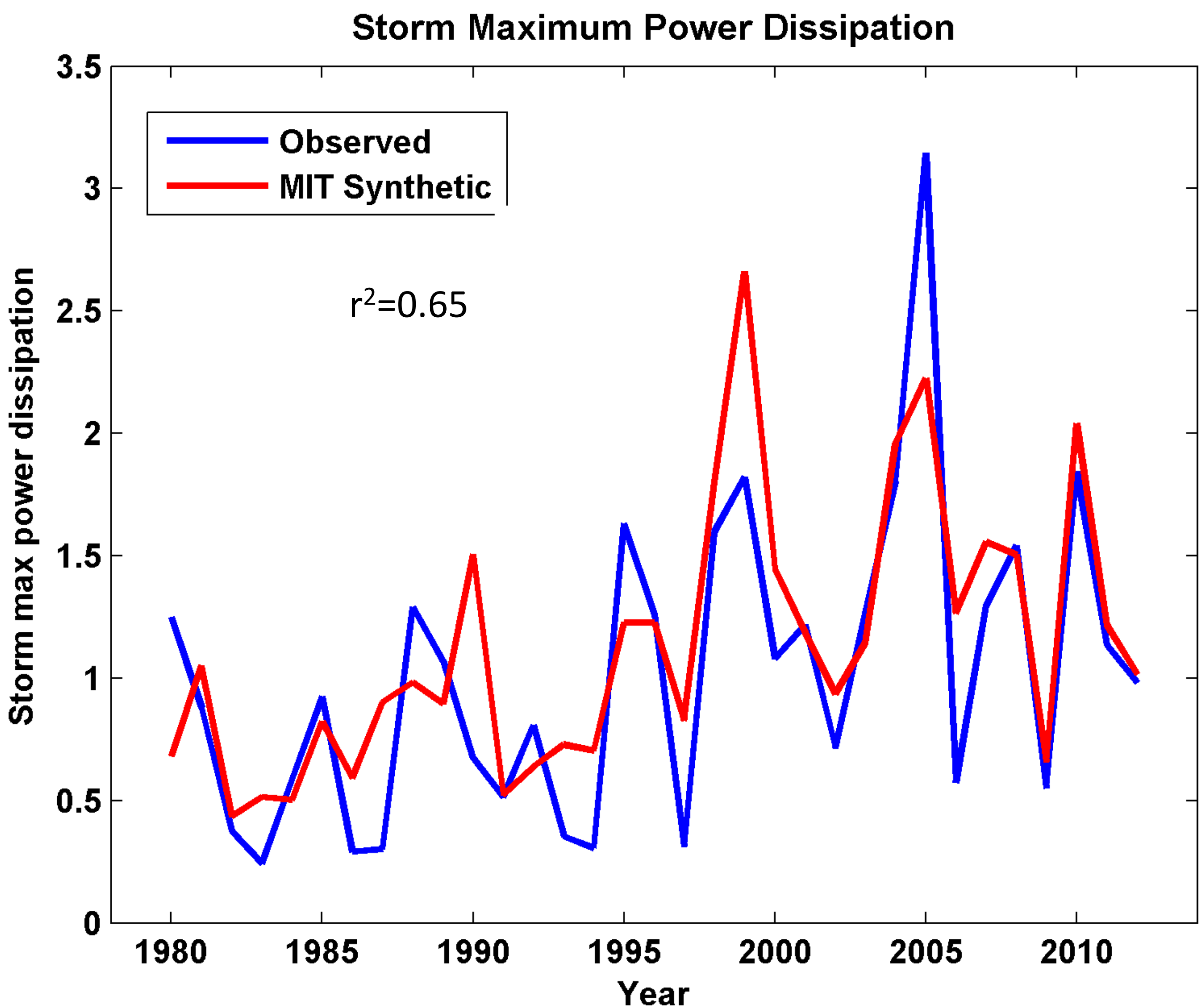
Atlantic Annual Cycle



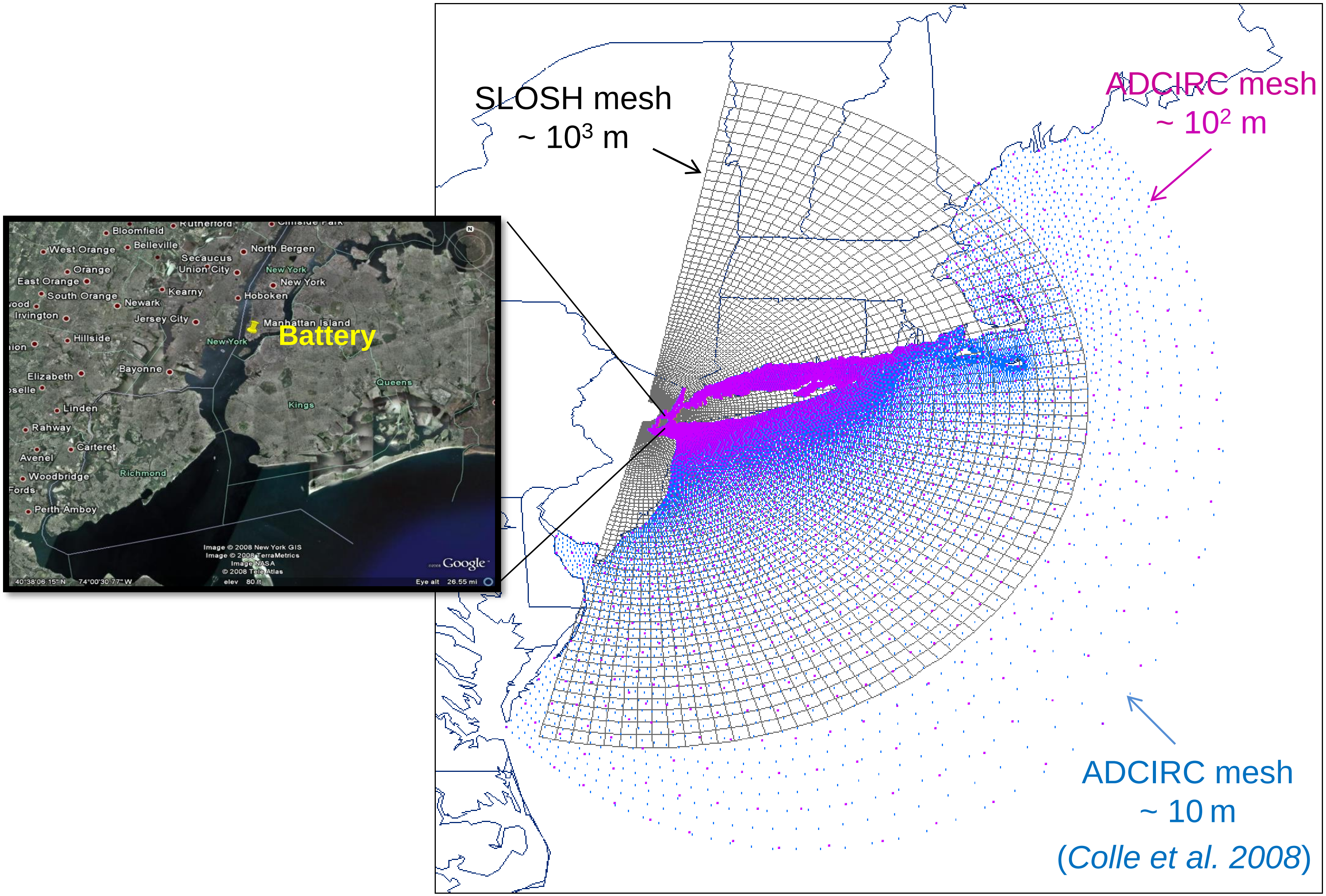
Captures effects of regional climate phenomena (e.g. ENSO, AMM)

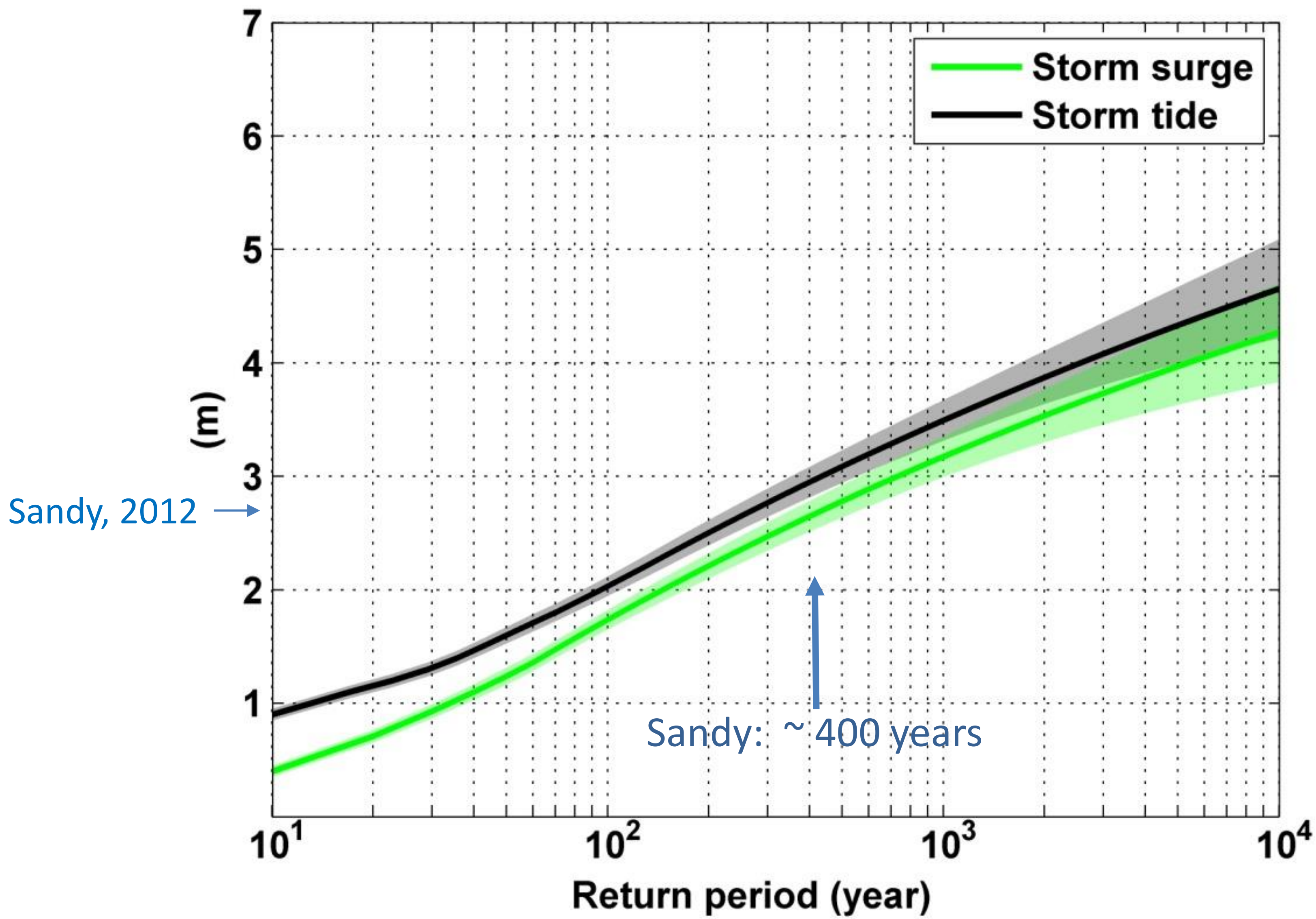


Captures Much of the Observed North Atlantic Interannual Variability



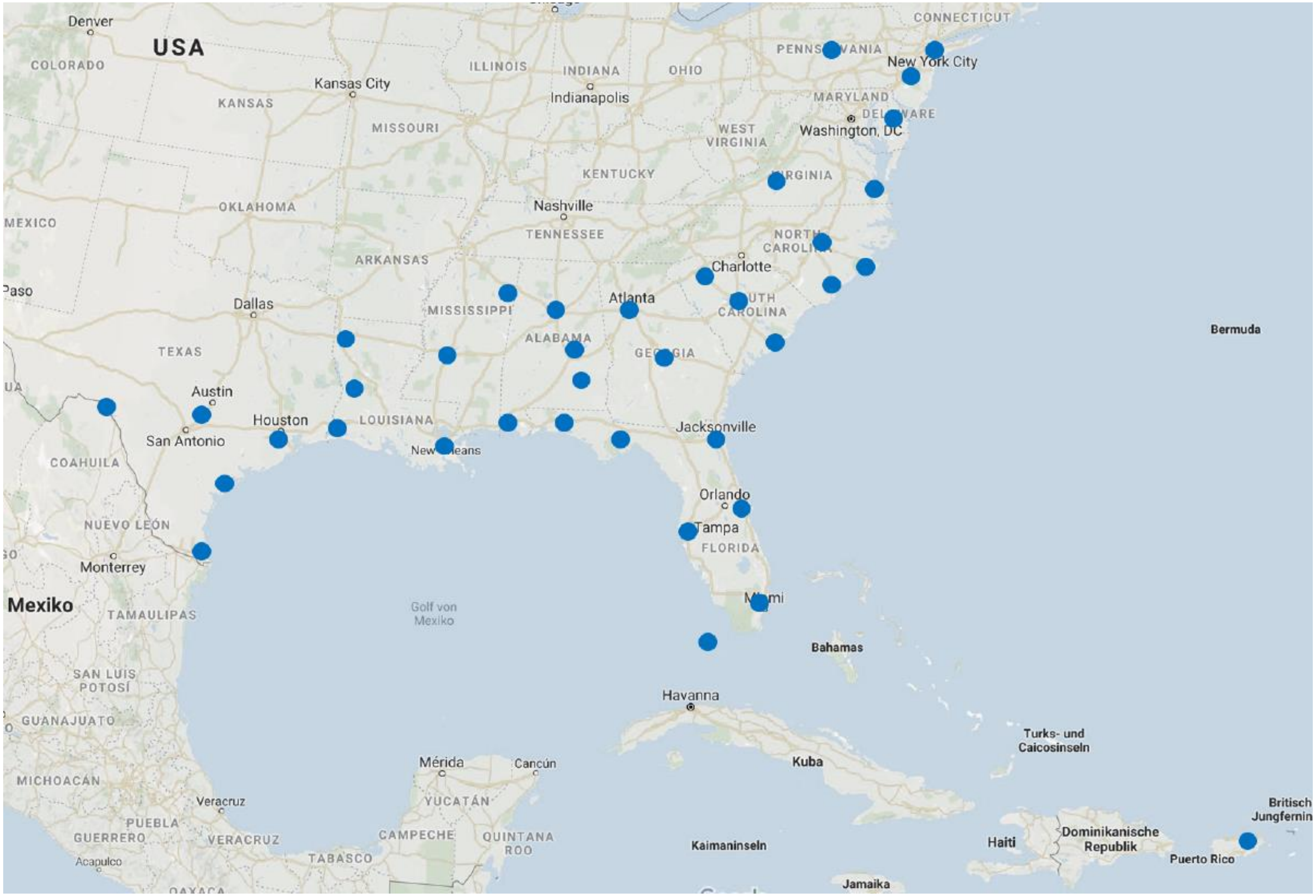
Storm Surge Simulation (Ning Lin)



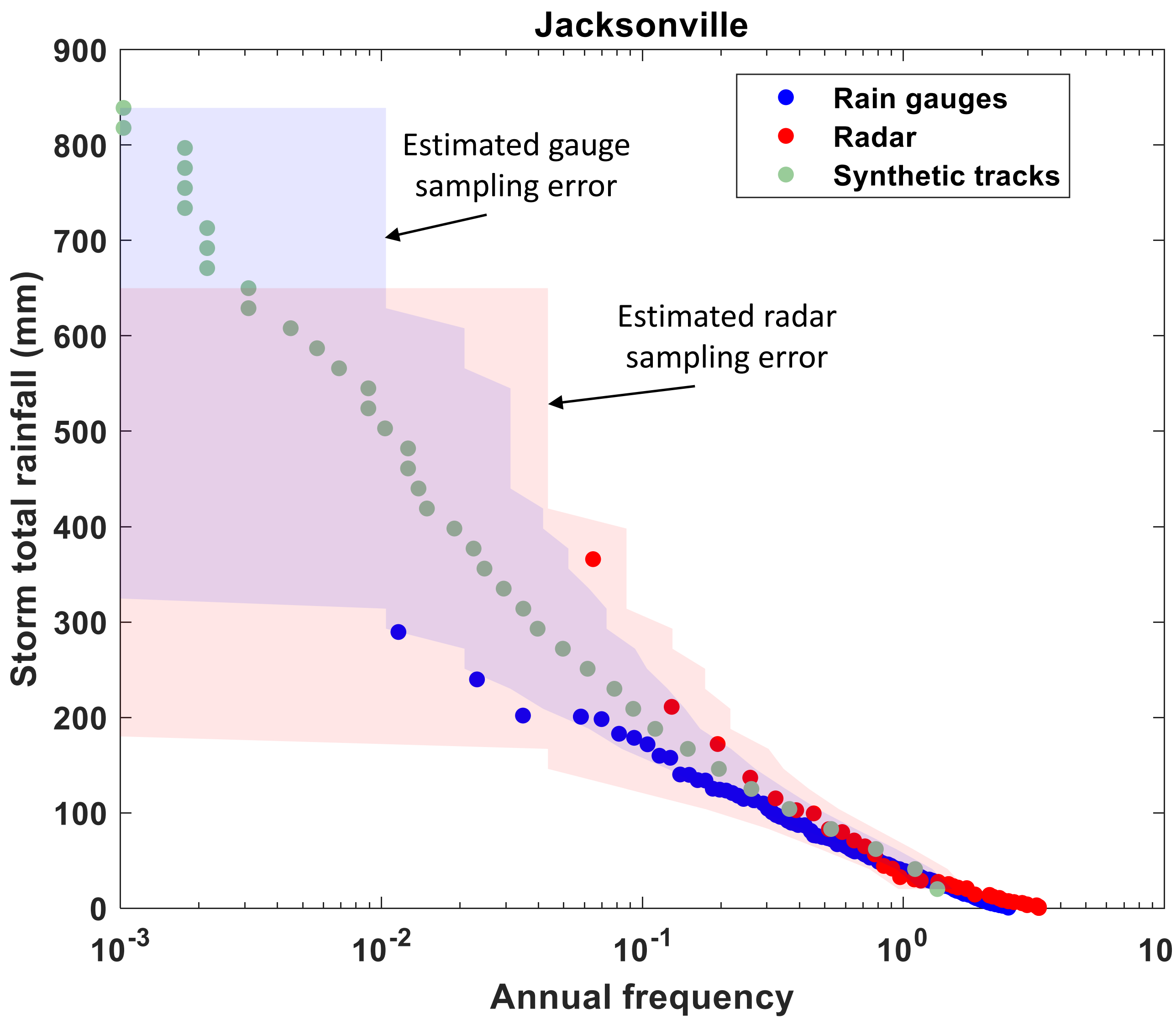


Lin, N., K. A. Emanuel, J. A. Smith, and E. Vanmarcke, 2010: Risk assessment of hurricane storm surge for New York City. *J. Geophys. Res.*, **115**, D18121, doi:10.1029/2009JD013630

NEXRAD Sites



An Example:



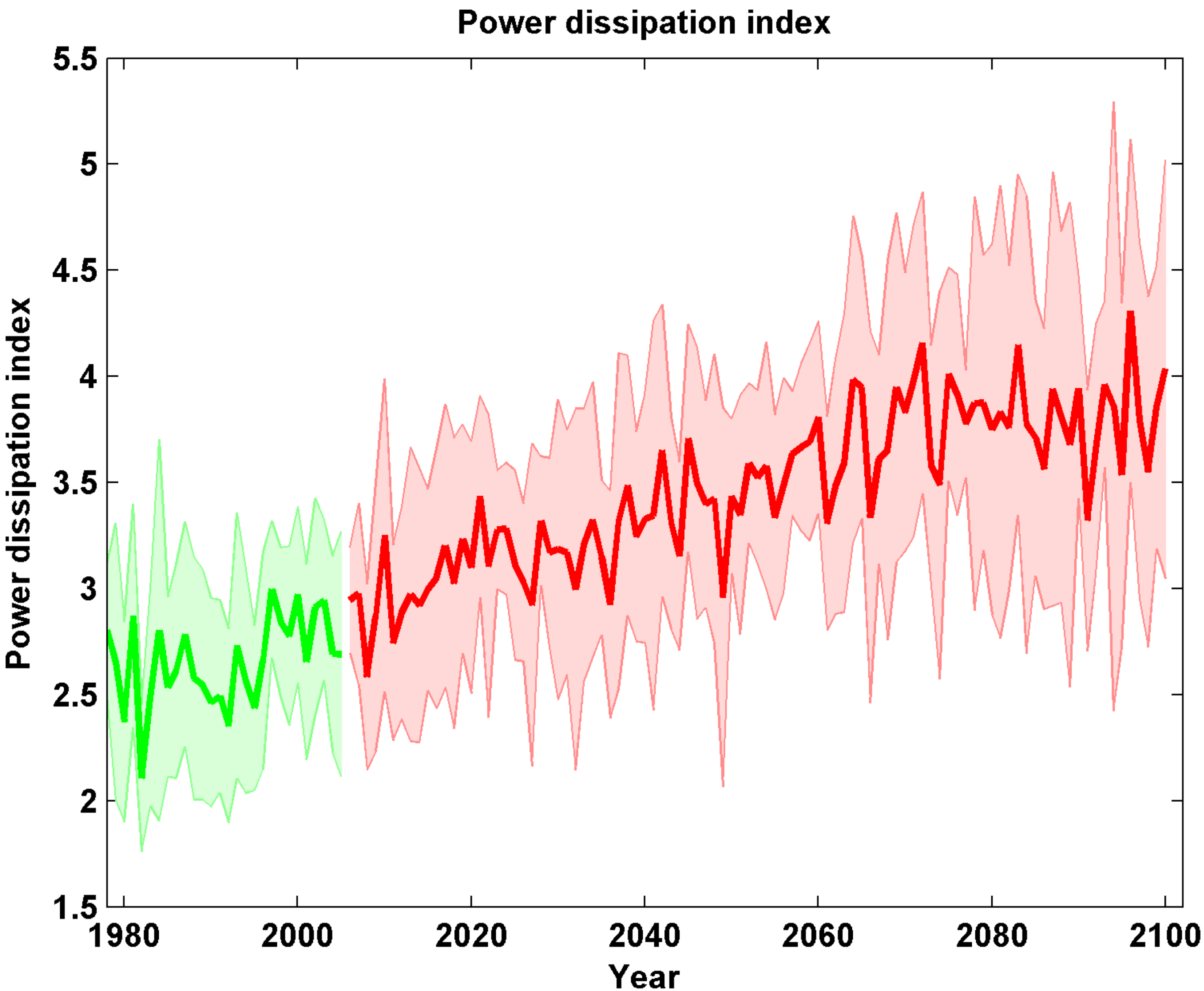
Jacksonville
Rain gauges
Radar
Synthetic tracks
Estimated gauge sampling error
Estimated radar sampling error
Storm total rainfall (mm)
Annual frequency
900
800
700
600
500
400
300
200
100
0
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}

Effects of Climate Change

- More moisture in boundary layer
- Stronger storms but more compact inner regions
- Possibly larger storm diameters
- Storms may be moving faster or slower

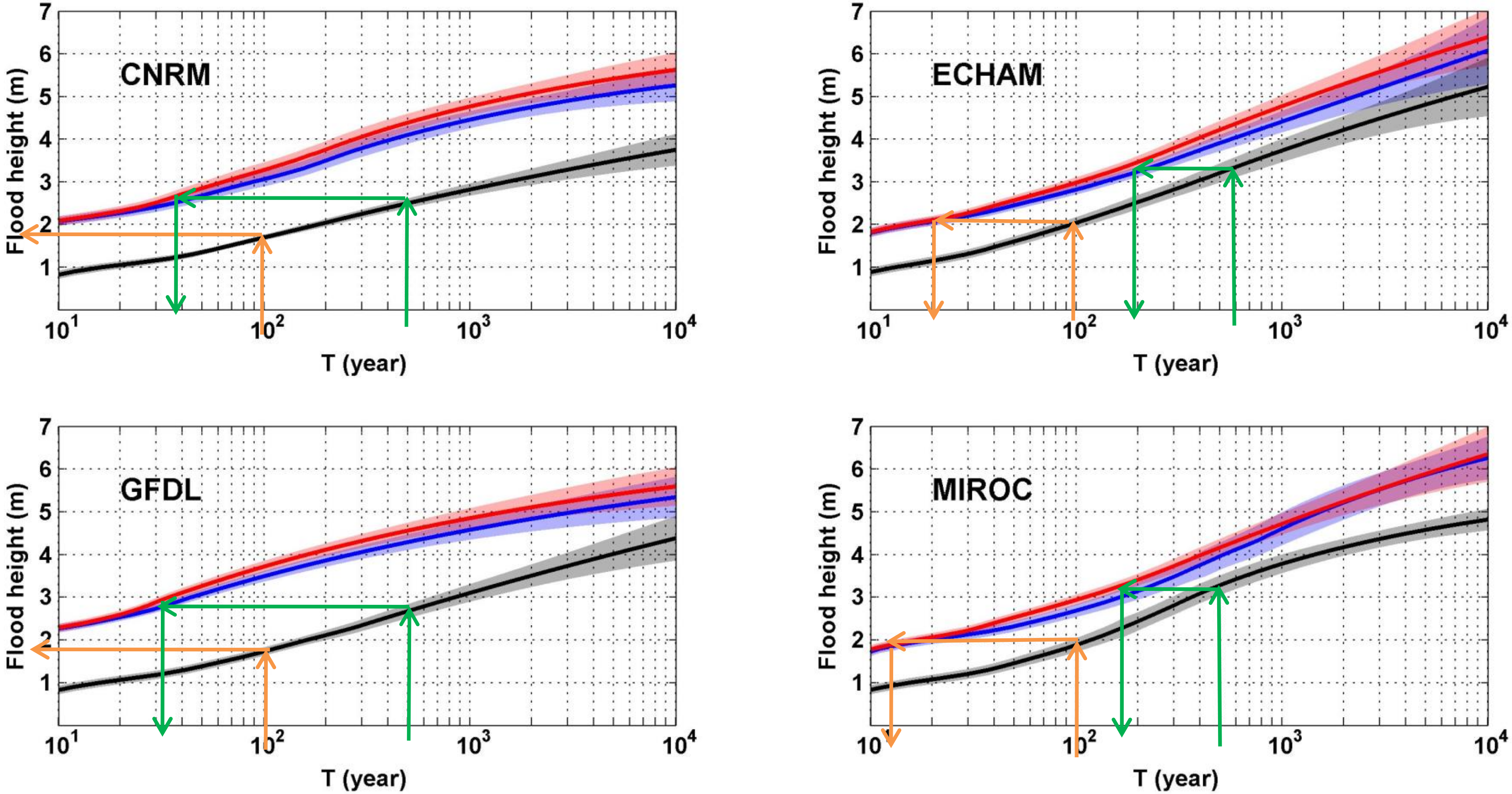
Taking Climate Change Into Account

Global Hurricane Power under RCP 8.5
Six CMIP5 Models



GCM flood height return level, Battery, Manhattan

(assuming SLR of 1 m for the future climate)

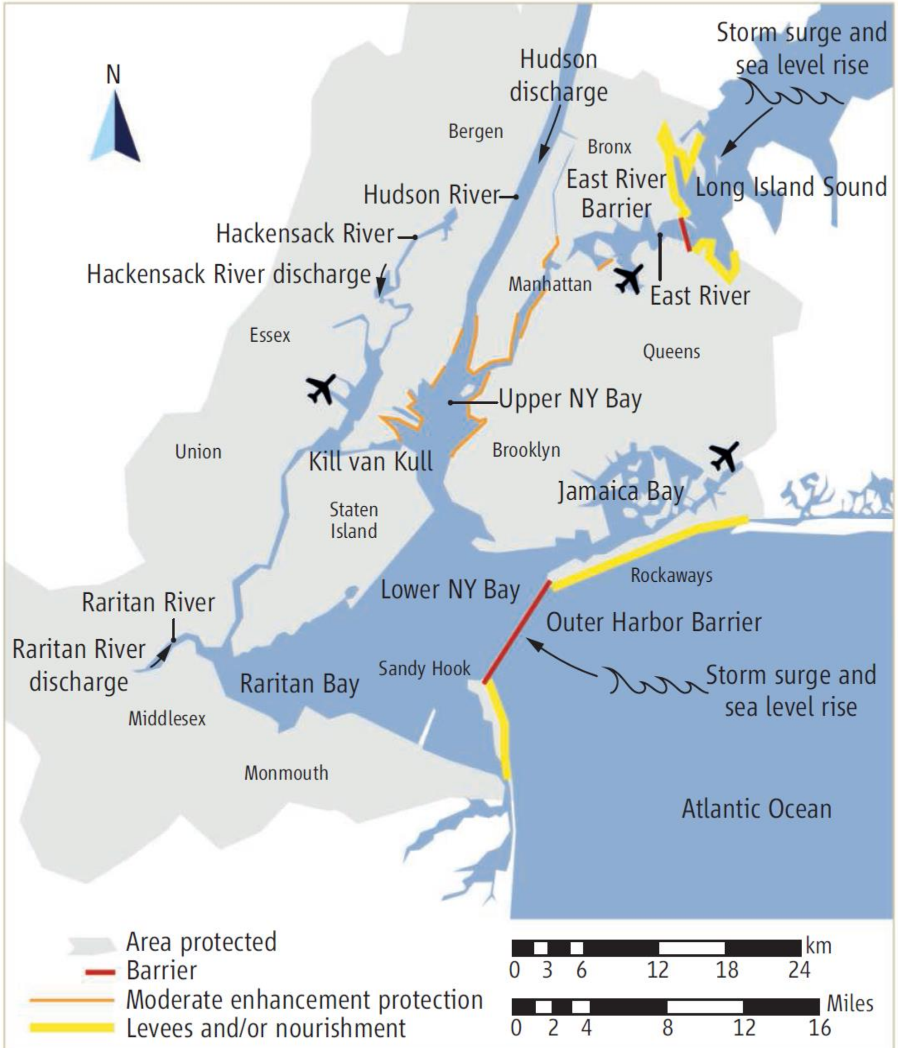


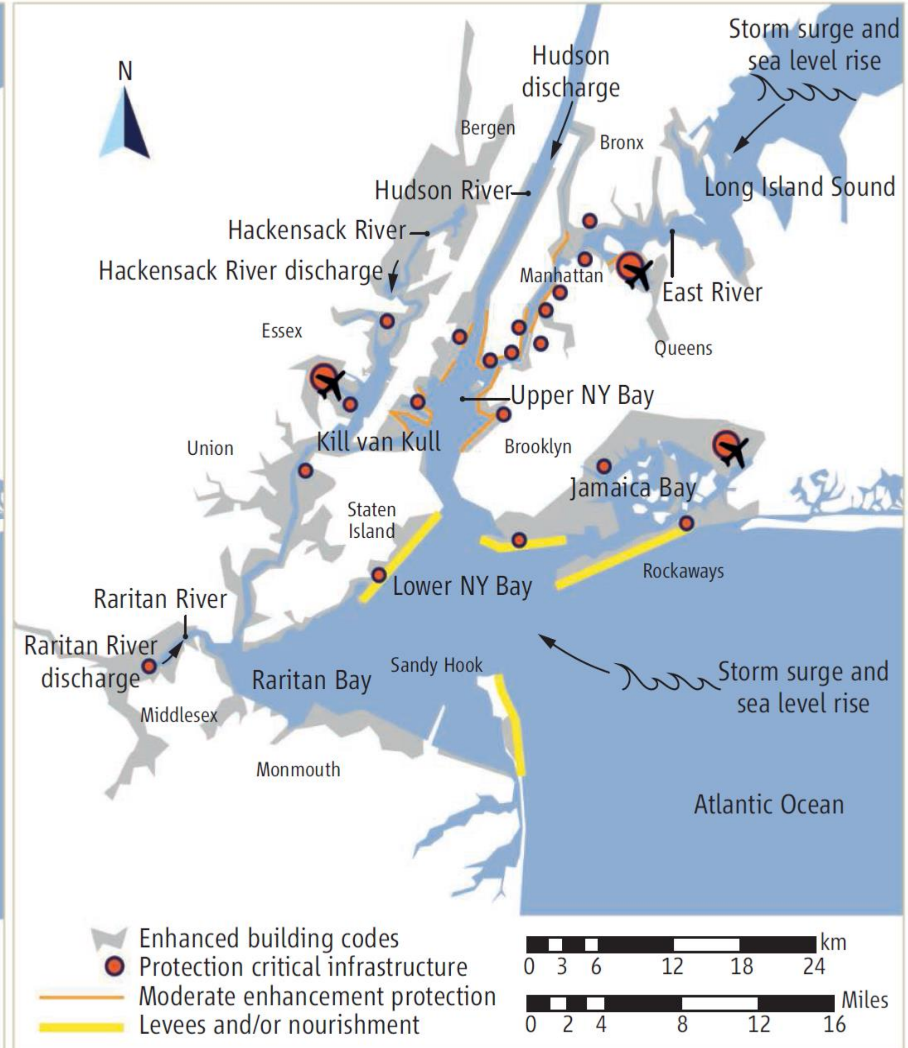
Black: Current climate (1981-2000)

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)





Strategies for protection vs. reducing vulnerability. (**Left**) Strategy S2c reduces the length of the coastline of the NYC-NJ area as much as possible, to minimize flood protection costs. Two storm-surge barriers are developed: one large barrier that connects Sandy Hook in NJ and the tip of the Rockaways in Queens, NY, and a barrier in the East River. Some lower spots (bulkheads, levees, or landfill) on the inside of the protection system will be elevated to accommodate rising water levels caused by Hudson River peak discharges during a storm event. (**Right**) Strategy S3 combines cost-effective flood-proofing measures with local protection measures of critical infrastructure. Such a "hybrid solution" aims at keeping options open: either (a) building codes can be enhanced in the future with additional local protection measures or (b) storm-surge barriers can be developed. See SM for details.

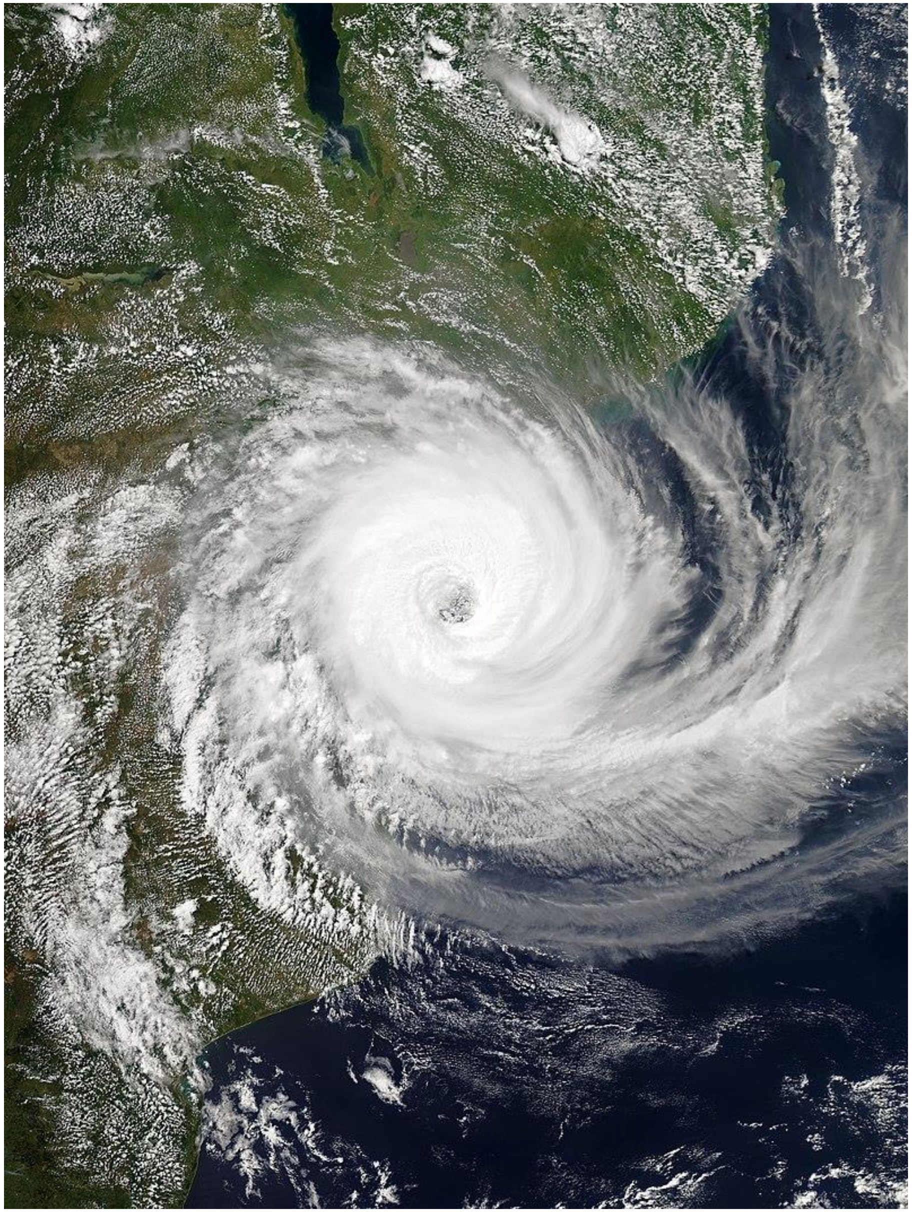
Aerts, C. J. H. J., W. J. W. Botzen, K. Emanuel, N. Lin, H. de Moel, and E. O. Michel-Kerjan, 2014: Evaluating flood resilience strategies for coastal megacities. *Science*, **344**, 473-475.

Benefit-Cost Ratios

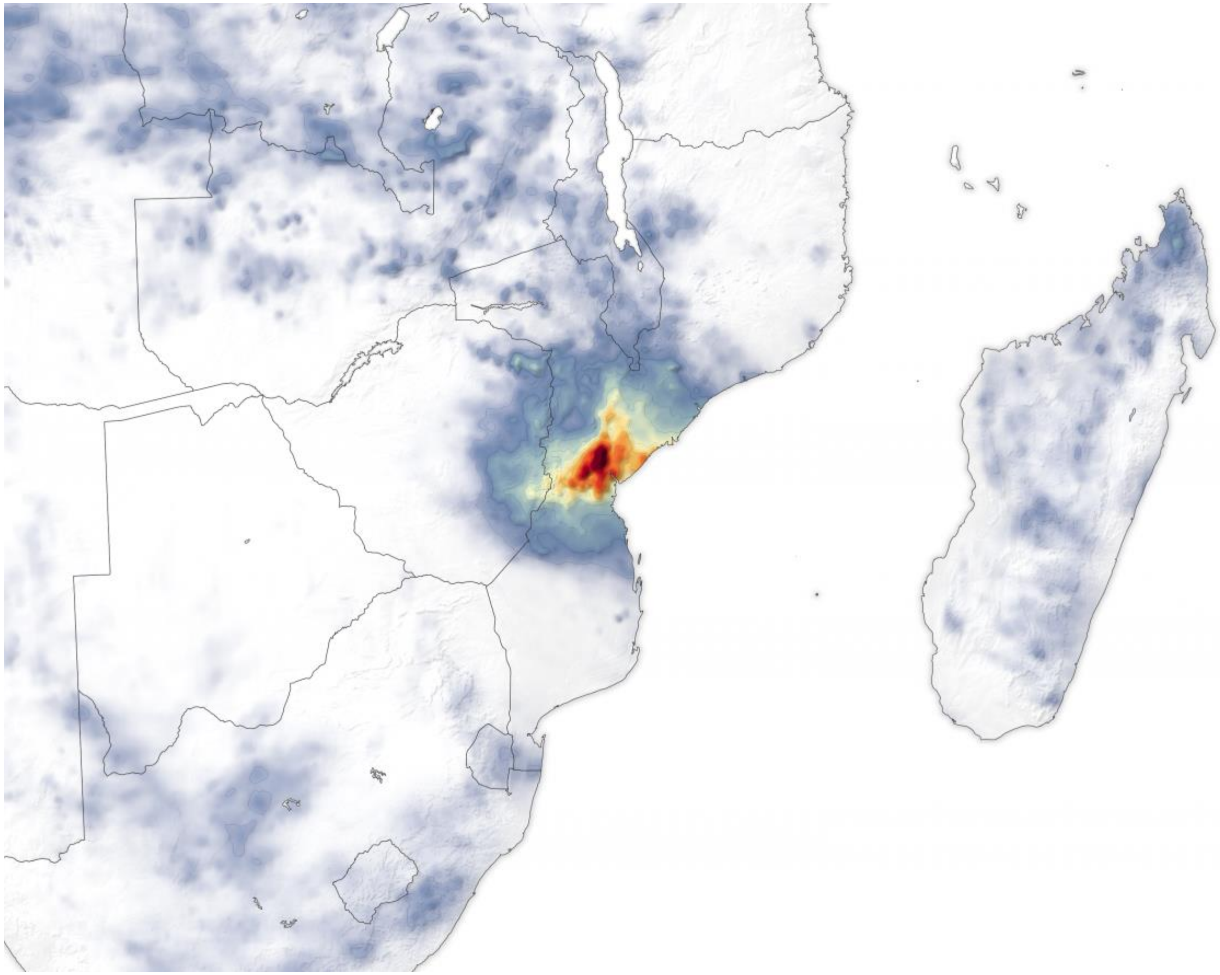
	Where/ how much	Environ.dyn. S2a	Bay closed S2b	NJ-JY connect S2c	Hybrid solution S3
Costs					
Total investment	NYC	\$16.9–21.1 billion	\$15.9–21.8 billion	\$11.0–14.7 billion	\$6.4–7.6 billion
Total investment	NJ	\$2 billion	\$2 billion	n/a	\$4 billion
Total investment	NYC+NJ	\$18.9–23.1 billion	\$17.9–23.8 billion	\$11.0–14.7 billion	\$10.4–11.6 billion
Maintenance	NYC+NJ	\$98.5 million	\$126 million	\$117.5 million	\$13.5 million
BCR for current climate					
BCR	4% discount	0.21 (0.11; 0.35)	0.21 (0.11; 0.34)	0.36 (0.18; 0.59)	0.45 (0.23; 0.73)
	7% discount	0.13 (0.07; 0.21)	0.12 (0.07; 0.20)	0.23 (0.12; 0.37)	0.26 (0.13; 0.43)
BCR for middle climate change scenario					
BCR	4% discount	1.32 (0.67; 2.16)	1.29 (0.65; 2.11)	2.24 (1.14; 3.67)	2.45 (1.24; 4.00)
	7% discount	0.60 (0.30; 0.98)	0.60 (0.30; 0.97)	1.06 (0.54; 1.74)	1.09 (0.55; 1.78)

Costs and main BCA results of flood management strategies.(Top) Total costs. Environ. dyn., environmental dynamics; inv., total investment as billions of U.S. dollars; maintenance, maintenance costs as millions of U.S. dollars per year; n.a., not applicable. (**Bottom**) BCA results with modeling uncertainty as 95% confidence intervals (in parentheses). If BCR > 1, then the measure is cost effective. For S3, BCA results are shown for the scenario of high effectiveness of wet flood-proofing. See SM for details.

Tropical Cyclone Idai, 2019

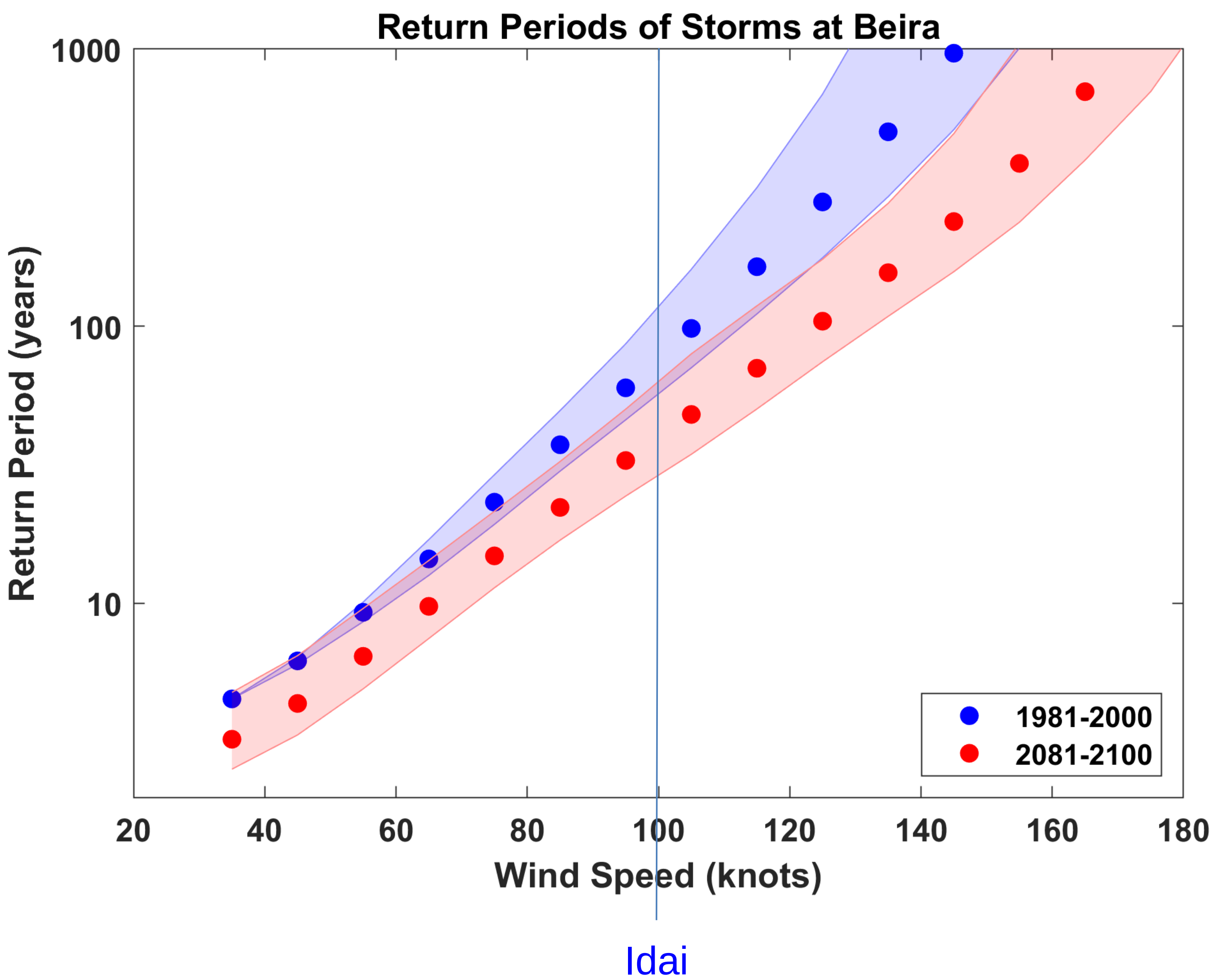


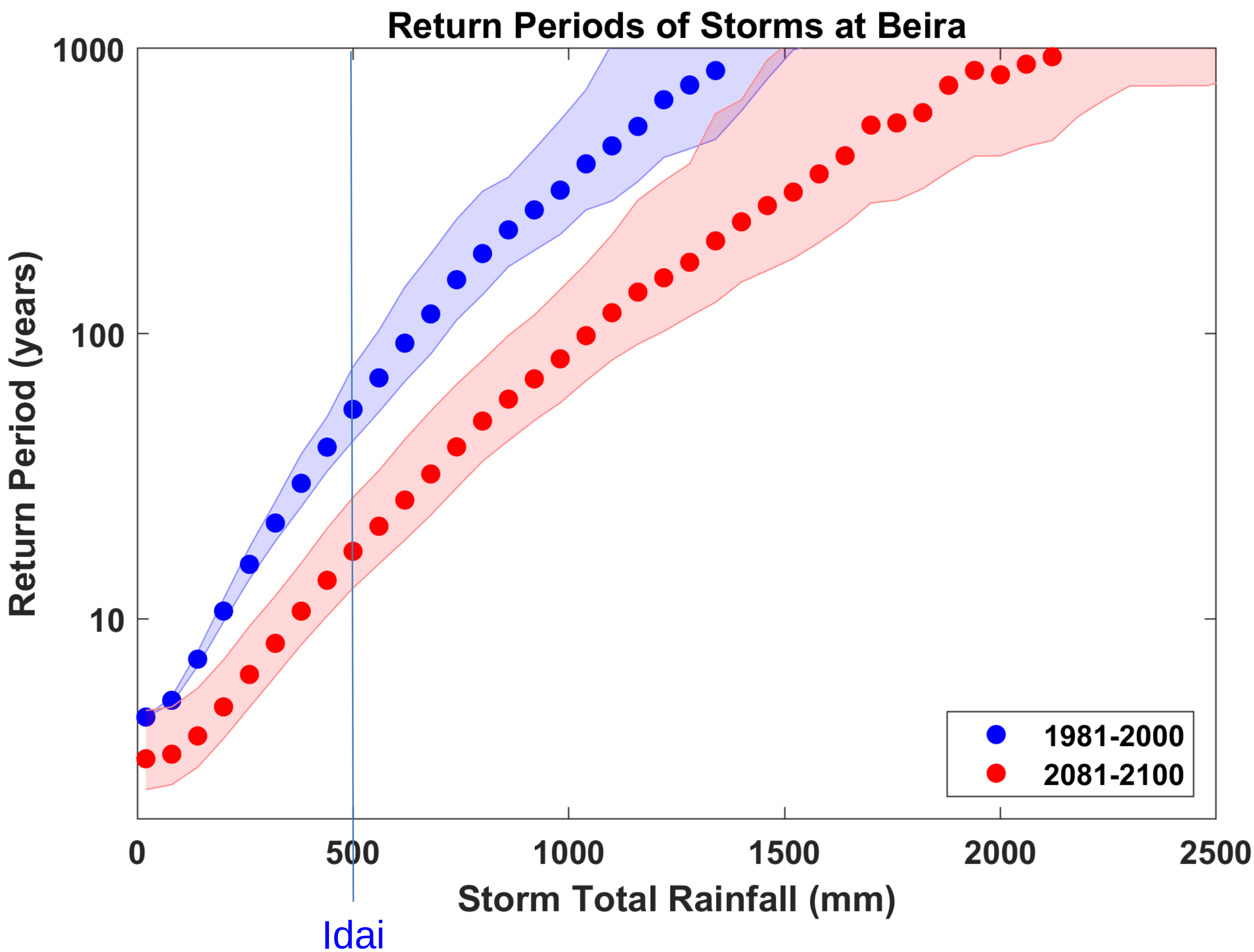
- Second-deadliest tropical cyclone recorded in the South-West Indian Ocean basin
- Third-deadliest tropical cyclone on record in the southern hemisphere
- Peak winds of 100 knots
- > 500 mm rainfall in some locations
- Storm surge of 4.4 m at Beira
- ~90% of Beira destroyed
- > 1,000 lives lost



Rainfall accumulation from March 13 to March 20, 2019. Many areas received as much as 50 centimeters (20 inches) of rain. These data are remotely-sensed estimates that come from the Integrated Multi-Satellite Retrievals (IMERG), a product of the Global Precipitation Measurement (GPM) mission. Local rainfall amounts can be significantly higher when measured from the ground. Credit: NASA

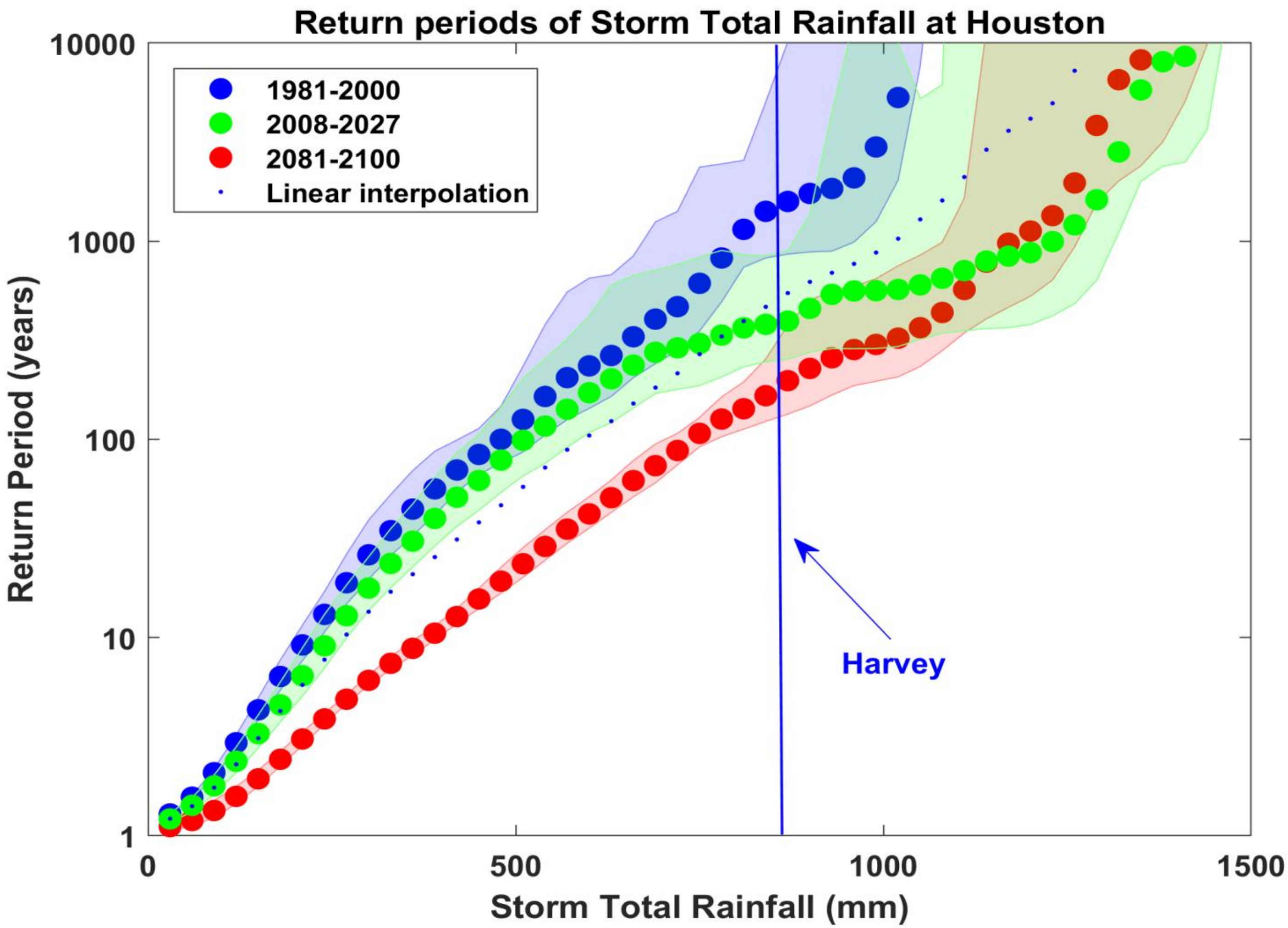
Based on 7 CMIP5 models



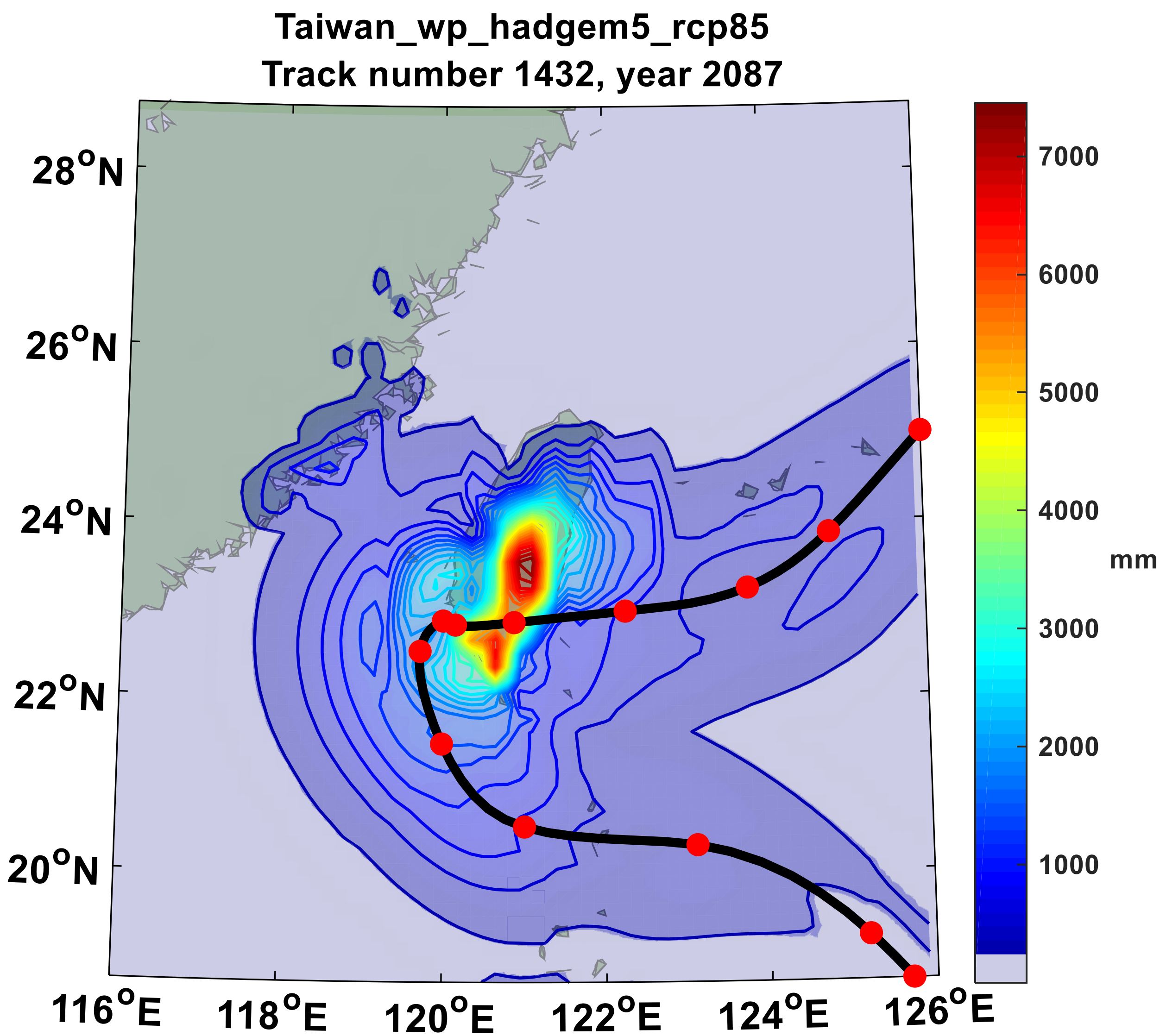


Return Periods of Storms at Beira
Return Period (years)
1000
100
10
0
500
1000
1500
2000
2500
Storm Total Rainfall (mm)
Idai
1981-2000
2081-2100

Probability of Storm Accumulated Rainfall in Harris County, from 6 Climate models, 1981-2000, 2008-2027, and 2081-2100, Based on 2000 Events Each, and Using RCP 8.5. Shading Shows Spread Among the Models.



A Black Swan Event



Summary

- The observational record of hurricanes is too short and noisy, and of a quality too low to make robust inferences of climate signals
- Satellite data do show a migration of peak intensity toward higher latitudes and some indication of a greater fraction of intense storms
- Recovery of hurricane proxies from the geological record is beginning to show some climate signals

Summary (continued)

- Potential intensity theory demonstrates that the thermodynamic limit on hurricane intensity rises with temperature
- Observations show that this limit is indeed increasing
- Physics can be used to model hurricane risk in current and future climates
- Global warming is not merely a problem for the future; current risk estimates are *already* out of date

Spare Slides

Calculating vertical motion in middle troposphere from time-dependent azimuthal gradient wind. Four components:

- Vertical motion at the top of the boundary layer owing to frictional effects within the boundary layer. This is estimated using a slab boundary layer model forced by the model gradient wind as well as the low-level environmental wind used as an input to the storm synthesizer. Use spatially varying drag coefficient.
- Vertical motion at the top of the boundary layer forced by topography interacting with the combination of storm and environmental flow.

- Vertical stretching between the top of the boundary layer and the middle troposphere associated with changes in the vorticity of the (axisymmetric) gradient wind.
- Add mid-tropospheric vertical motion caused by the dynamical interaction of the axisymmetric vortical flow and the background shear/horizontal temperature gradient. Classical quasi-balance reasoning!

Given mid-tropospheric vertical motion, rainfall is calculated by assuming ascent along a moist adiabat, calculated using the environmental 600 hPa temperature plus a correction for the storm’s warm core