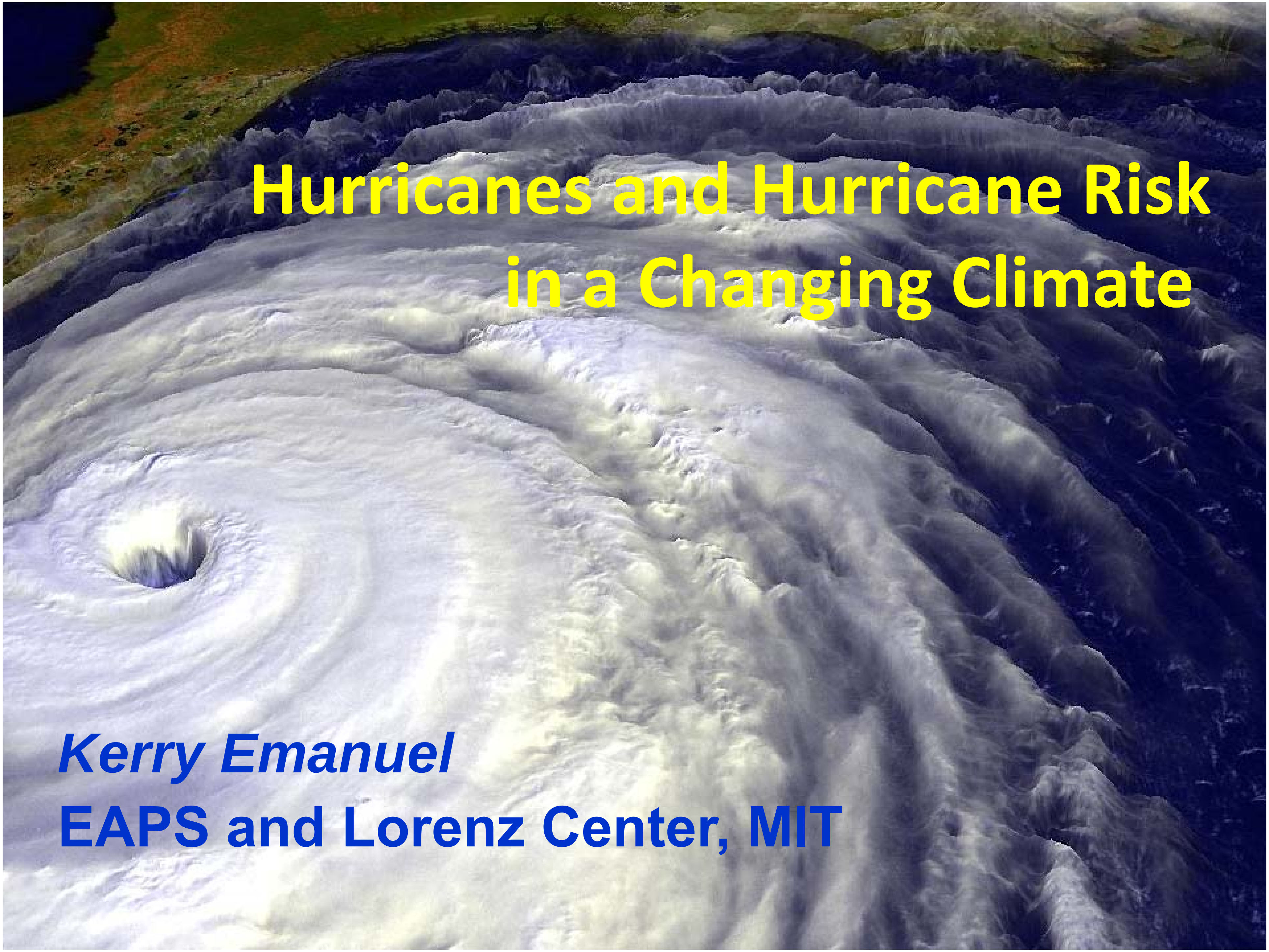


# Hurricanes and Hurricane Risk in a Changing Climate

*Kerry Emanuel*

**EAPS and Lorenz Center, MIT**

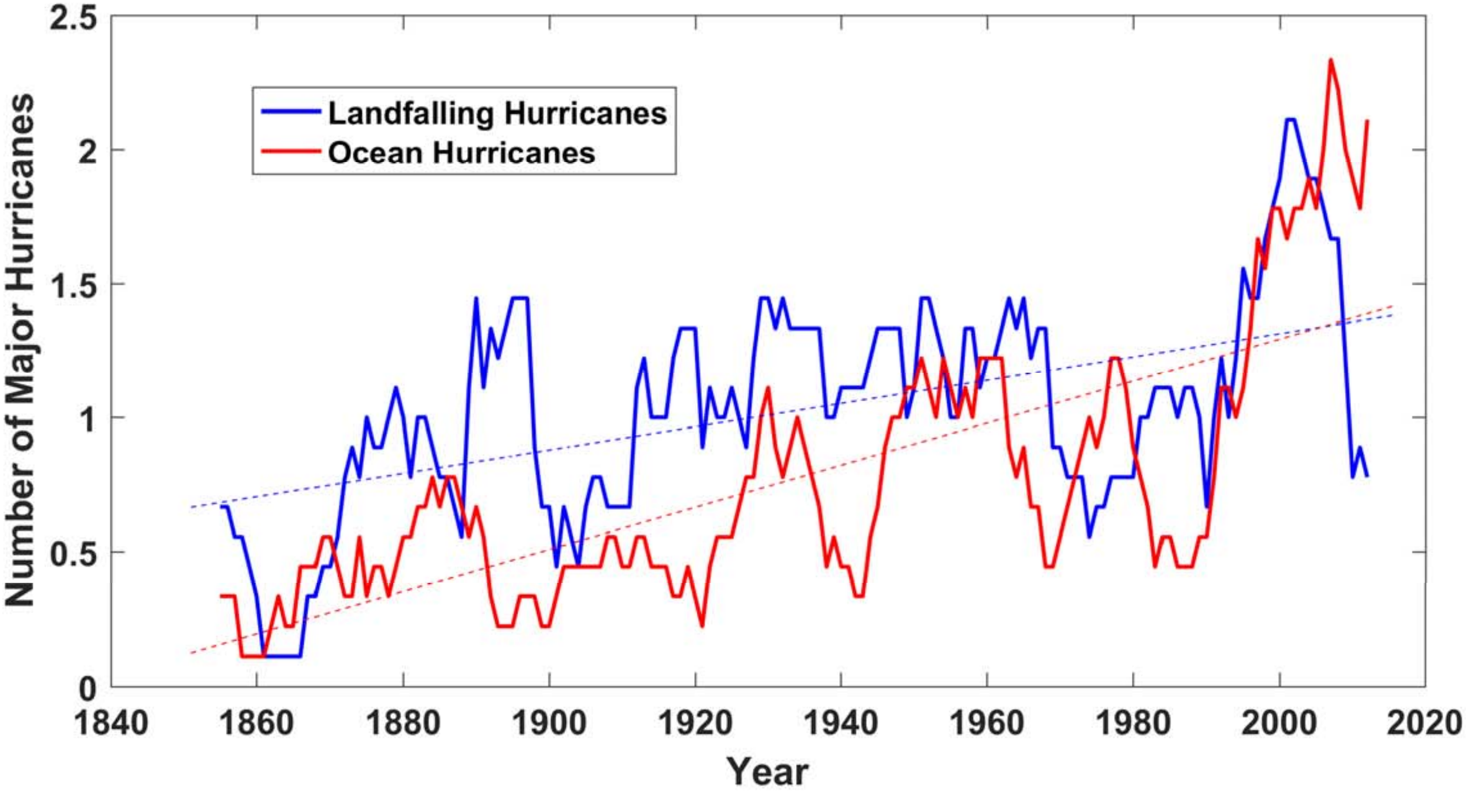
# Program

- Inferences from historical and geological records
- Inferences from basic physics
- Using physics to estimate risk
- Examples of changing risk

# Historical Records

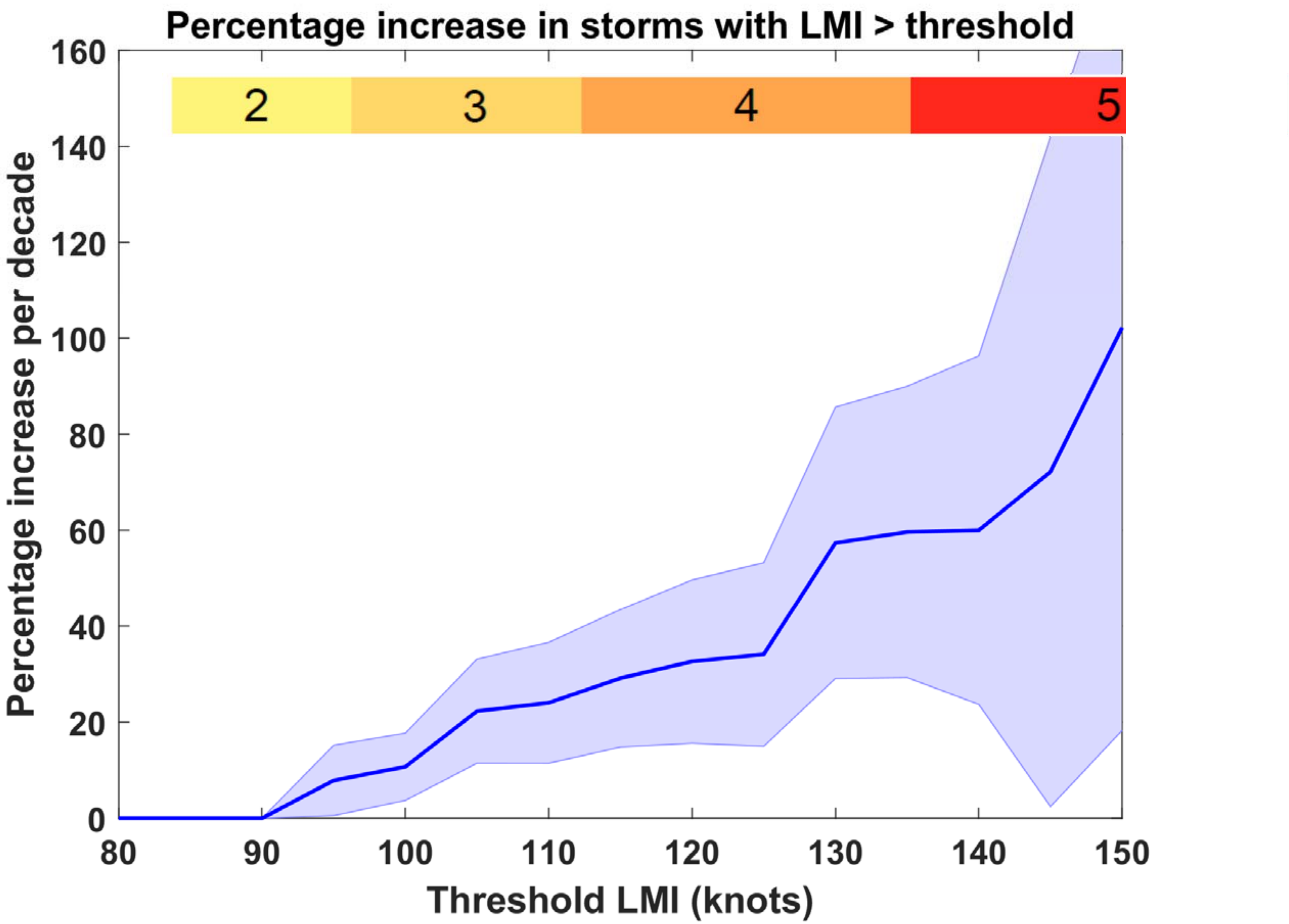
- Pre-1943: Anecdotal accounts from coastal cities and ships
- 1943: Introduction of routine aircraft reconnaissance in Atlantic, western North Pacific
- 1958: Inertial navigation permits direct measurement of wind speed at flight level
- 1970: Complete global detection by satellites
- 1978: Introduction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

# Prior to 1970, Many Storms Were Missed

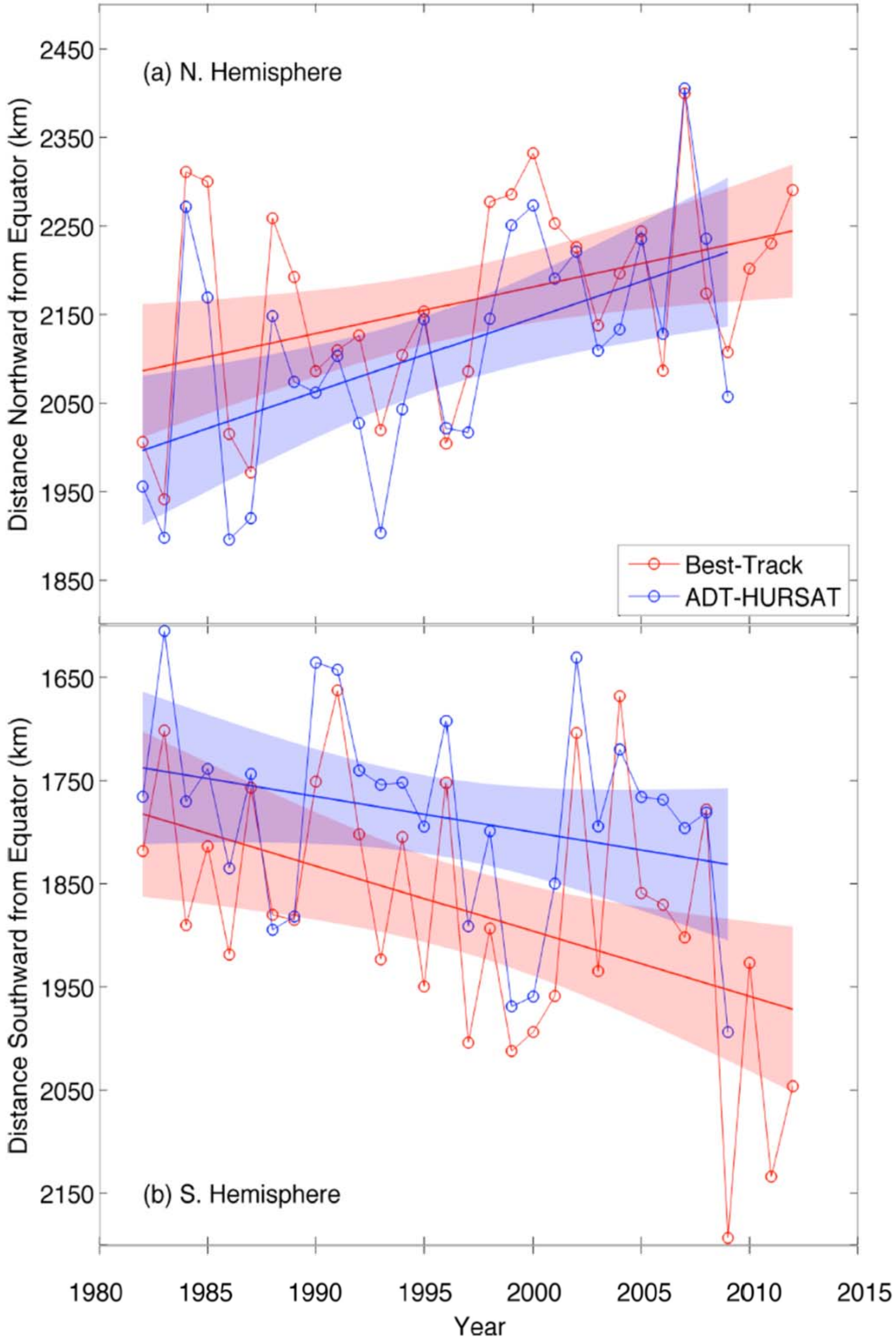


*Major hurricanes in the North Atlantic, 1851-2016, smoothed using a 10-year running average. Shown in blue are storms that either passed through the chain of Lesser Antilles or made landfall in the continental U.S.; all other major hurricanes are shown in red. The dashed lines show the best fit trend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

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



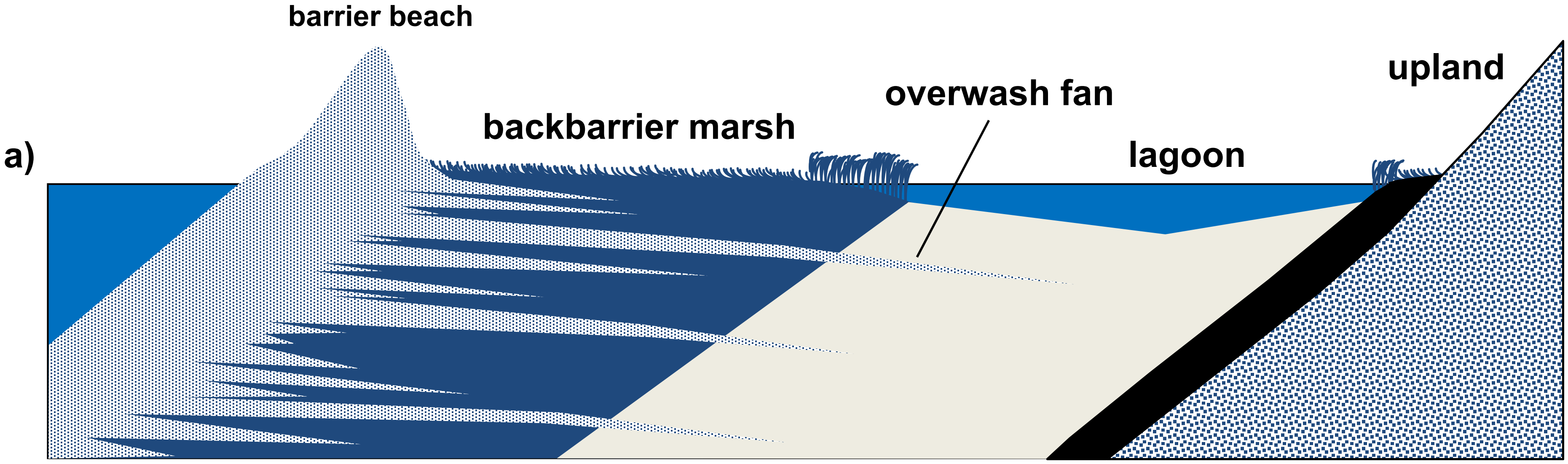
# Hurricanes are reaching peak intensity at higher latitudes

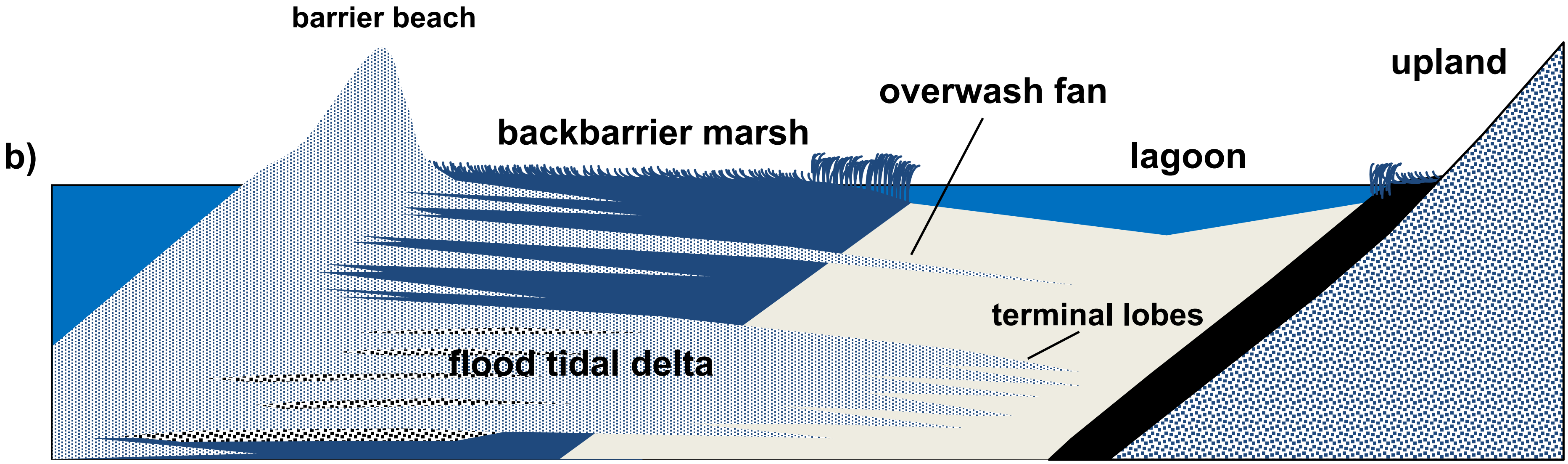


Time series of the latitudes at which tropical cyclones reach maximum intensity.

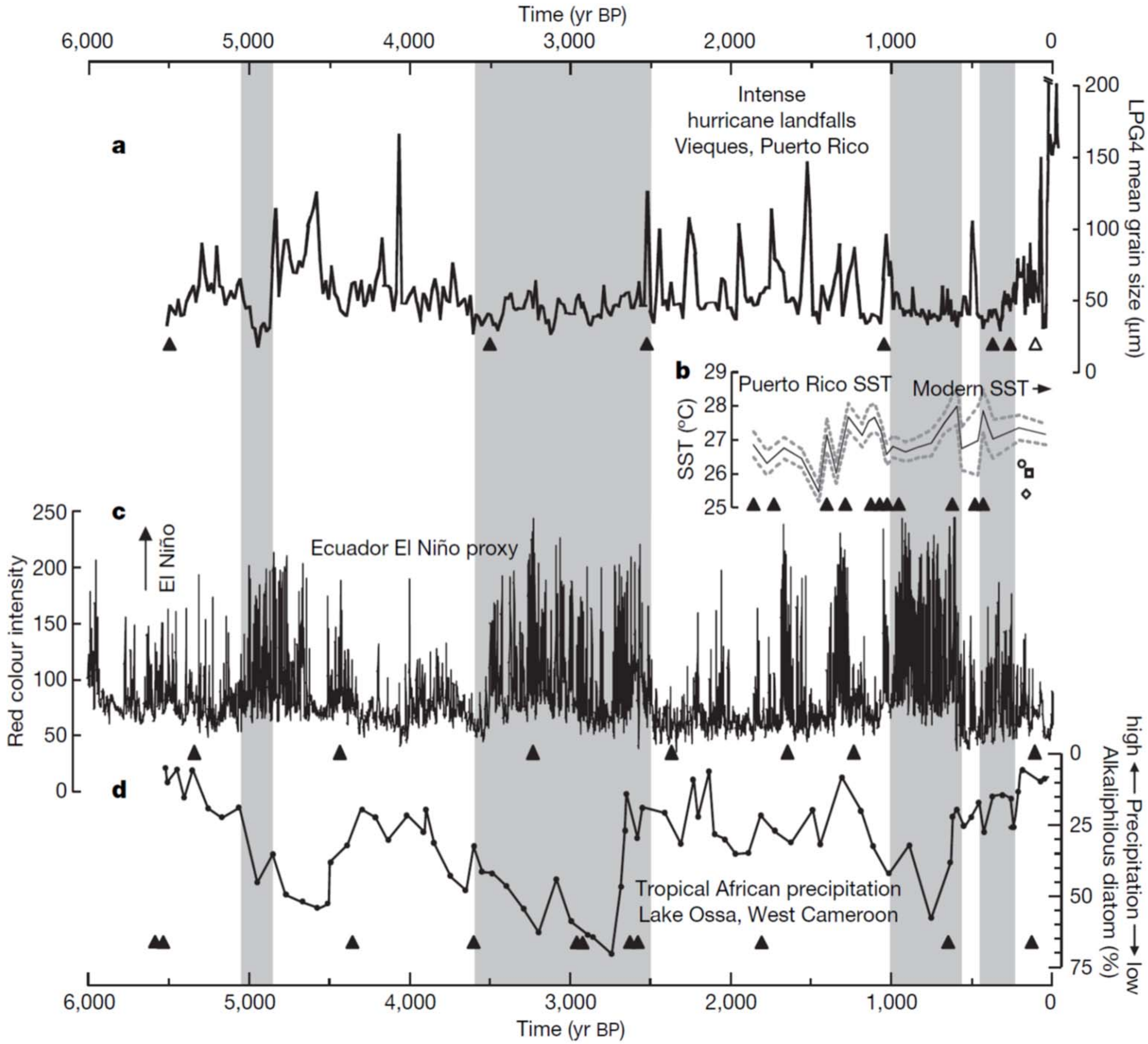
From *Kossin et al. (2014)*

# Paleotempestology



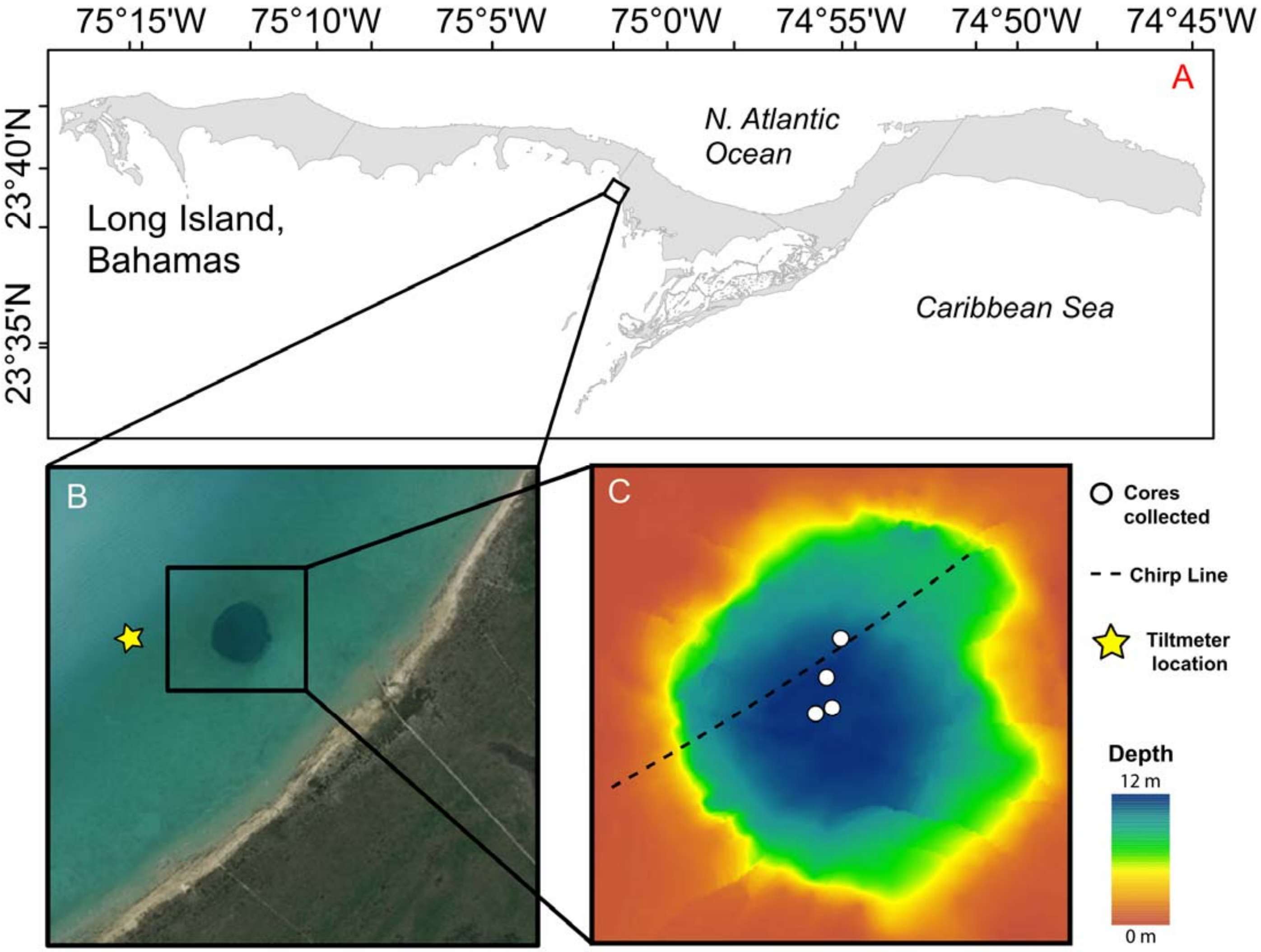


Source: Jeff Donnelly, WHOI

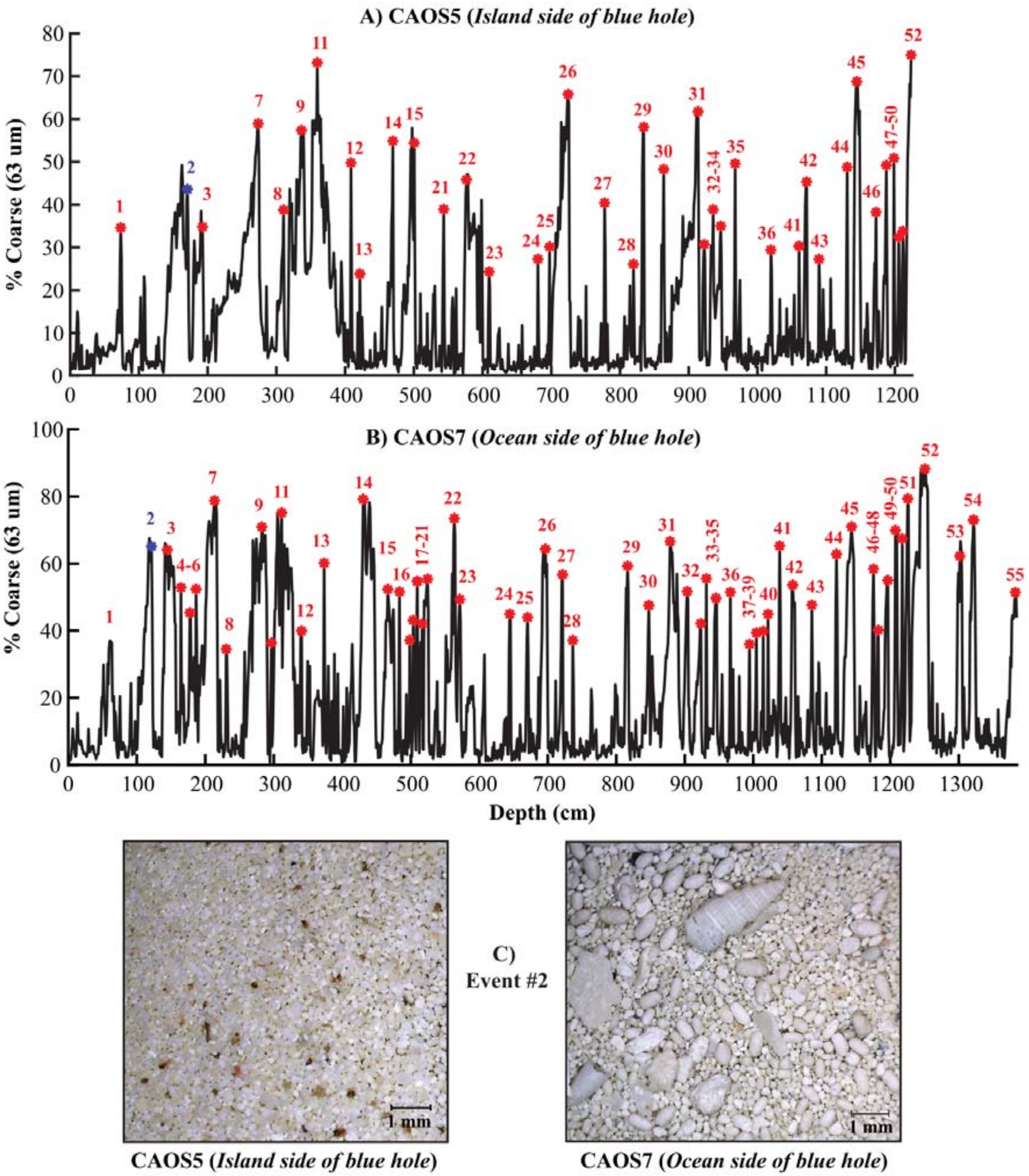


Jeffrey P. Donnelly and Jonathan D. Woodruff, *Nature*, 2007

# Extension to "Blue Holes" (e.g. in the Bahamas)

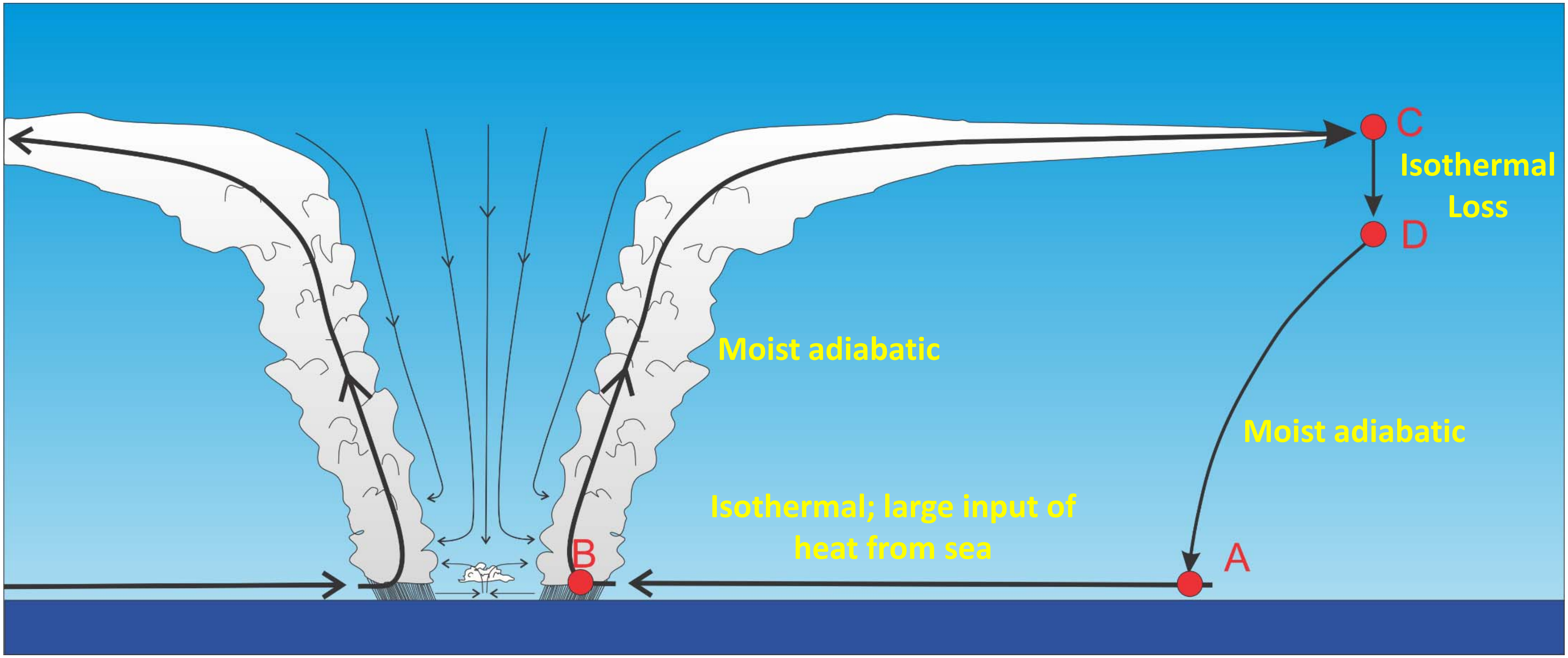


Courtesy Lizzie Wallace, WHOI

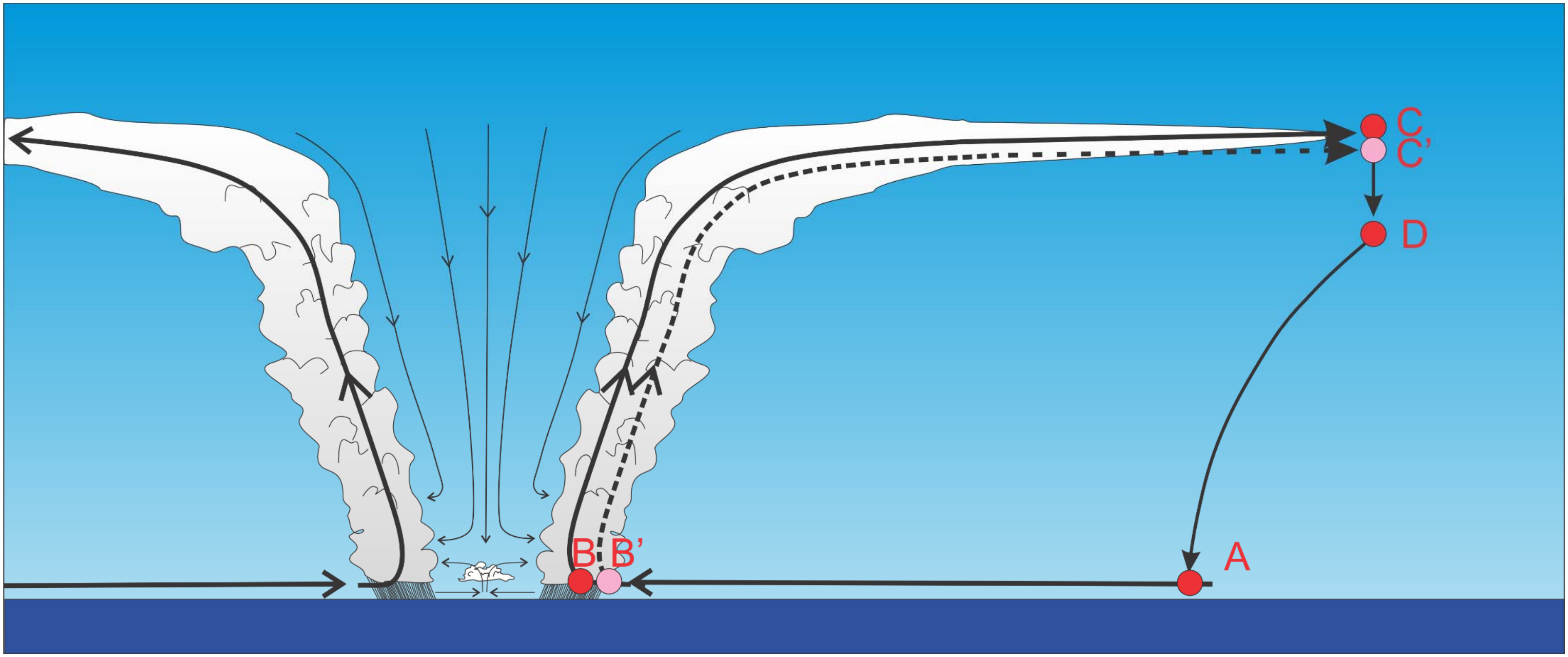


Courtesy Lizzie Wallace, WHOI

# Basic Physics: Energy Production



# Add nearby cycle; take difference between two cycles



# Theoretical Steady-State Maximum Hurricane Wind Speed:

**Surface temperature**

**Saturation static energy of sea surface**

**Saturation static energy of the boundary layer**

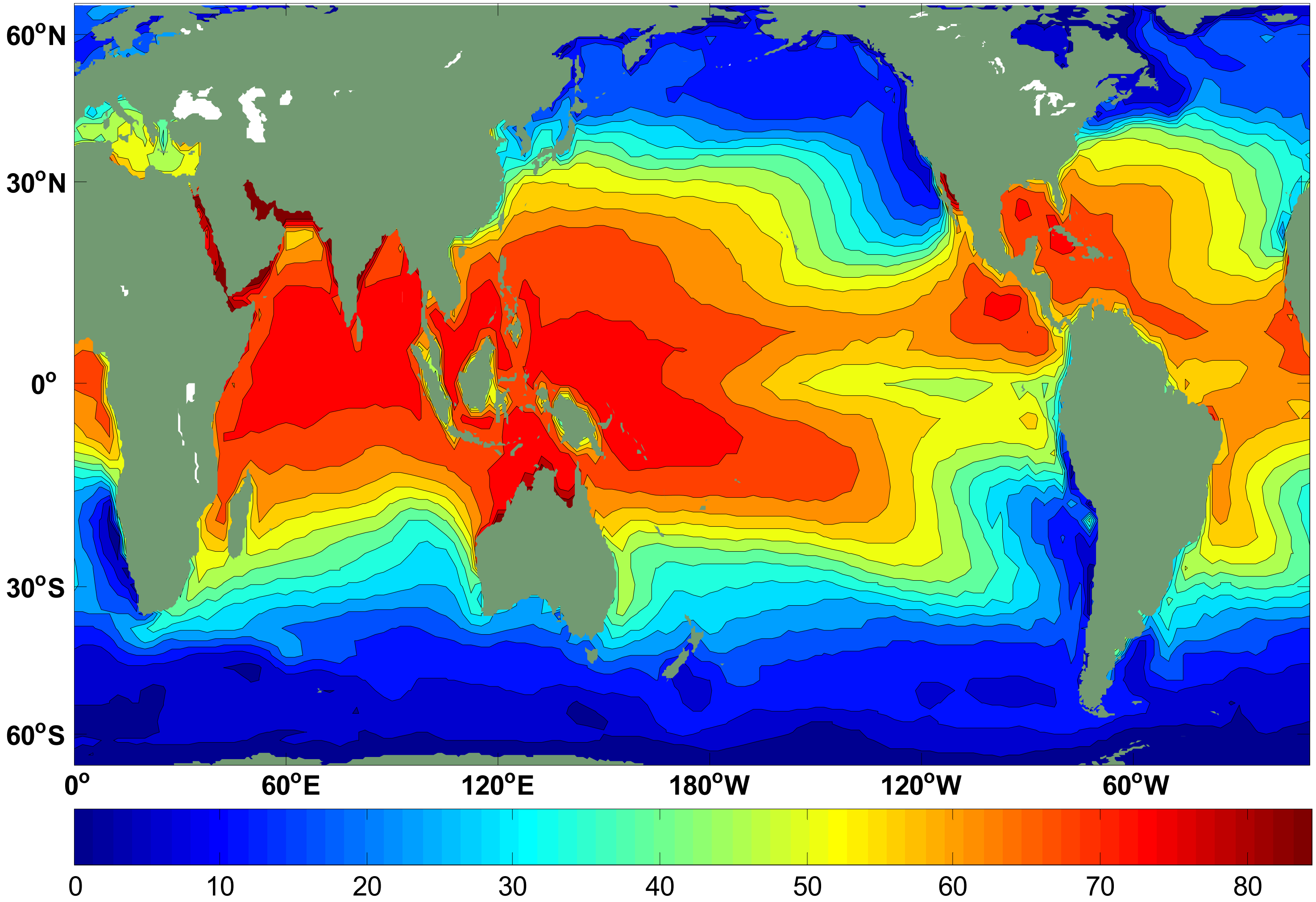
$$V_{10}^2 \equiv V_{pot}^2 = \boxed{\frac{C_k}{C_D}} \frac{T_s - T_o}{T_0} \left( h_0^* - h_b \right)$$

**Ratio of surface exchange coefficients of enthalpy and momentum**

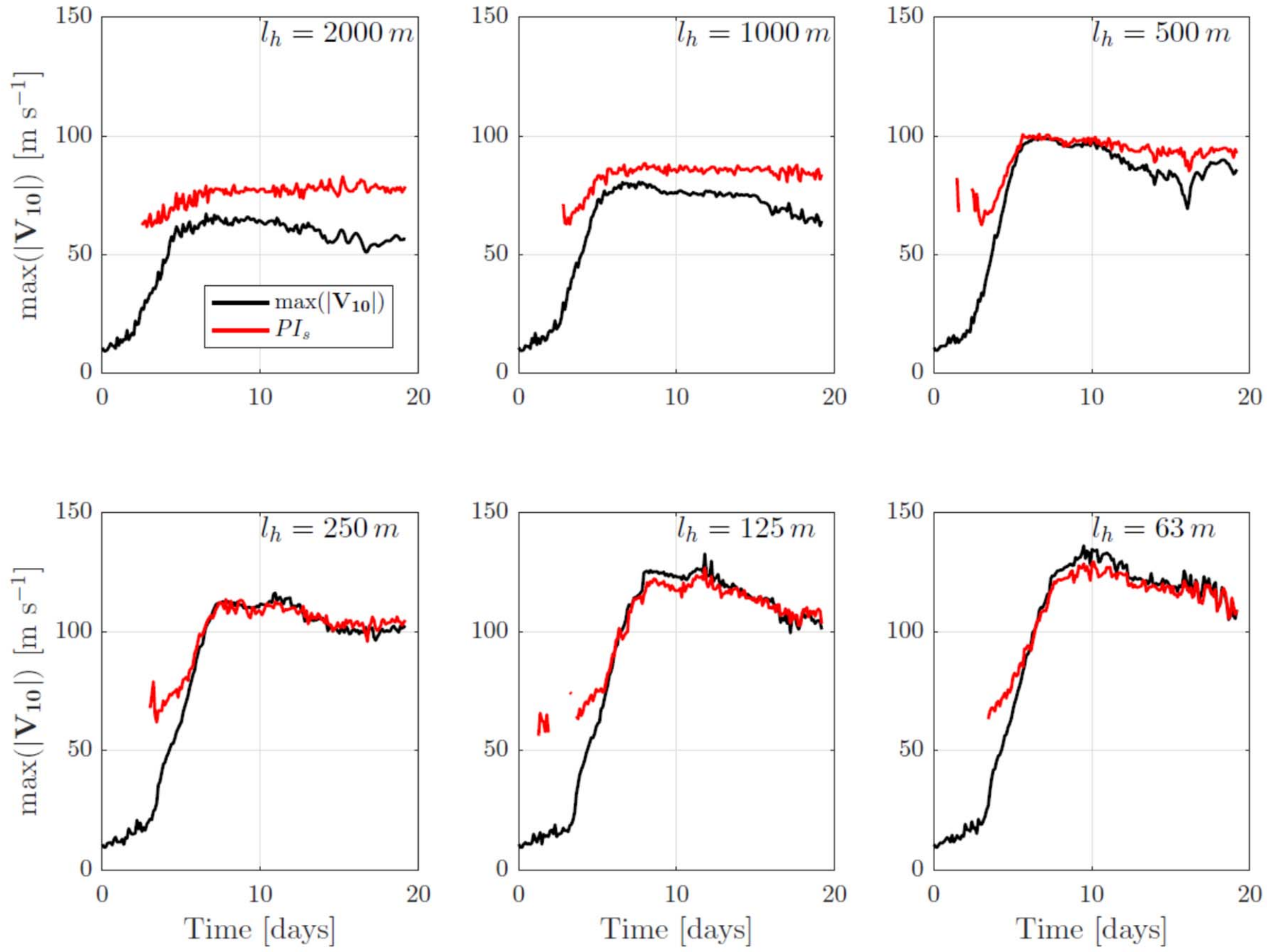
**Outflow temperature**

**Air-sea enthalpy disequilibrium of moist static energy**

# Annual Maximum Potential Intensity (m/s)

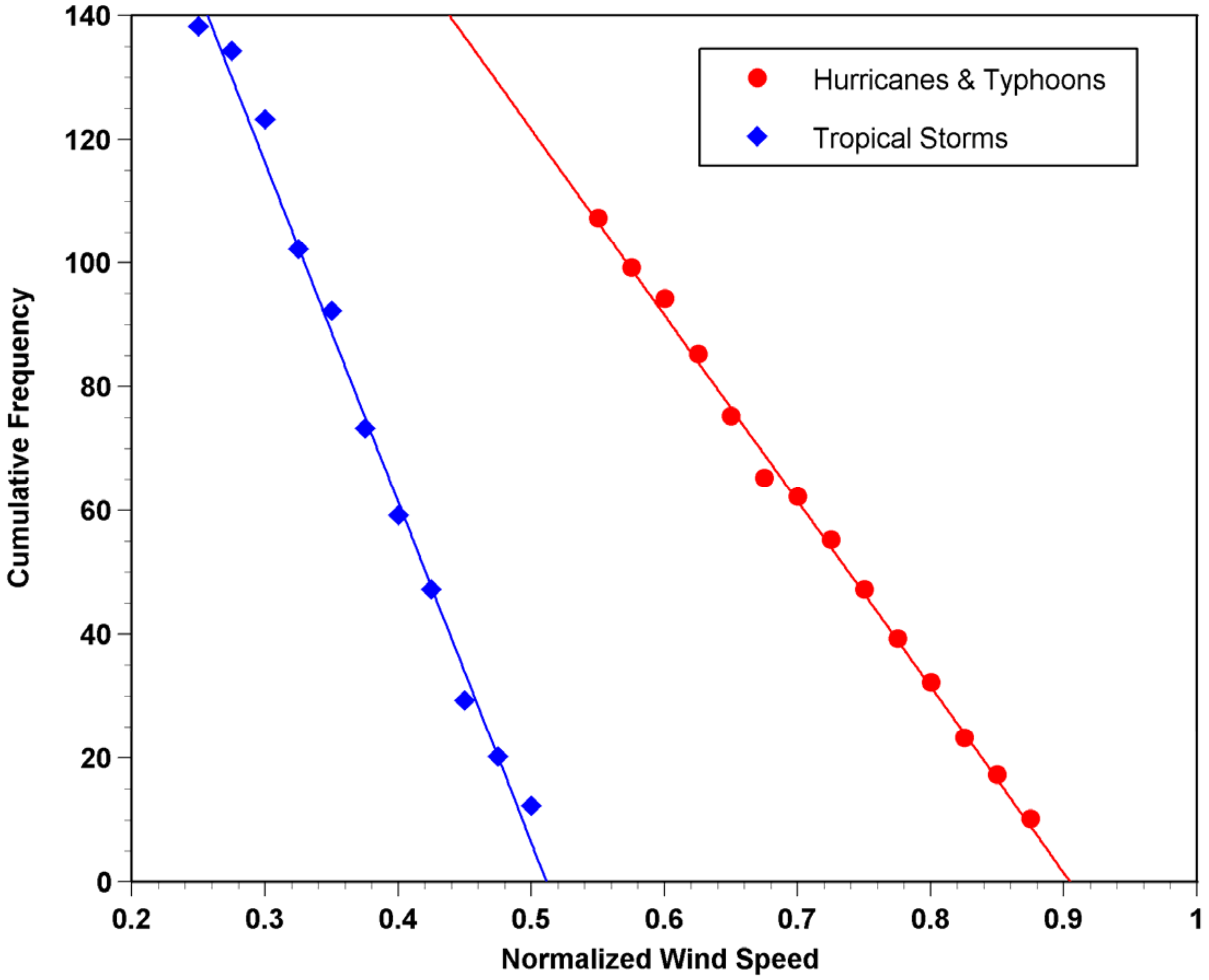


# Comparison of numerically simulated and theoretical intensities

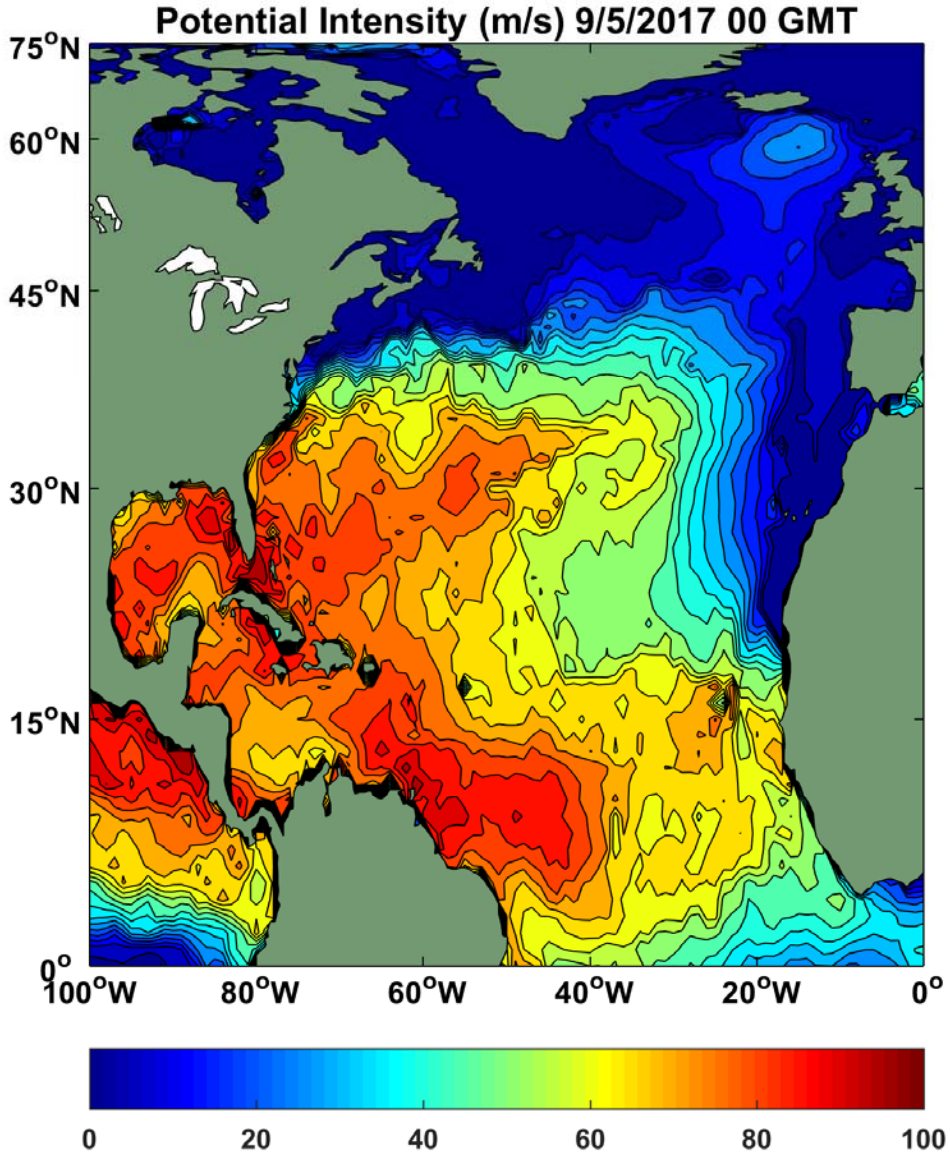


Courtesy Raphael Rousseau-Rizzi

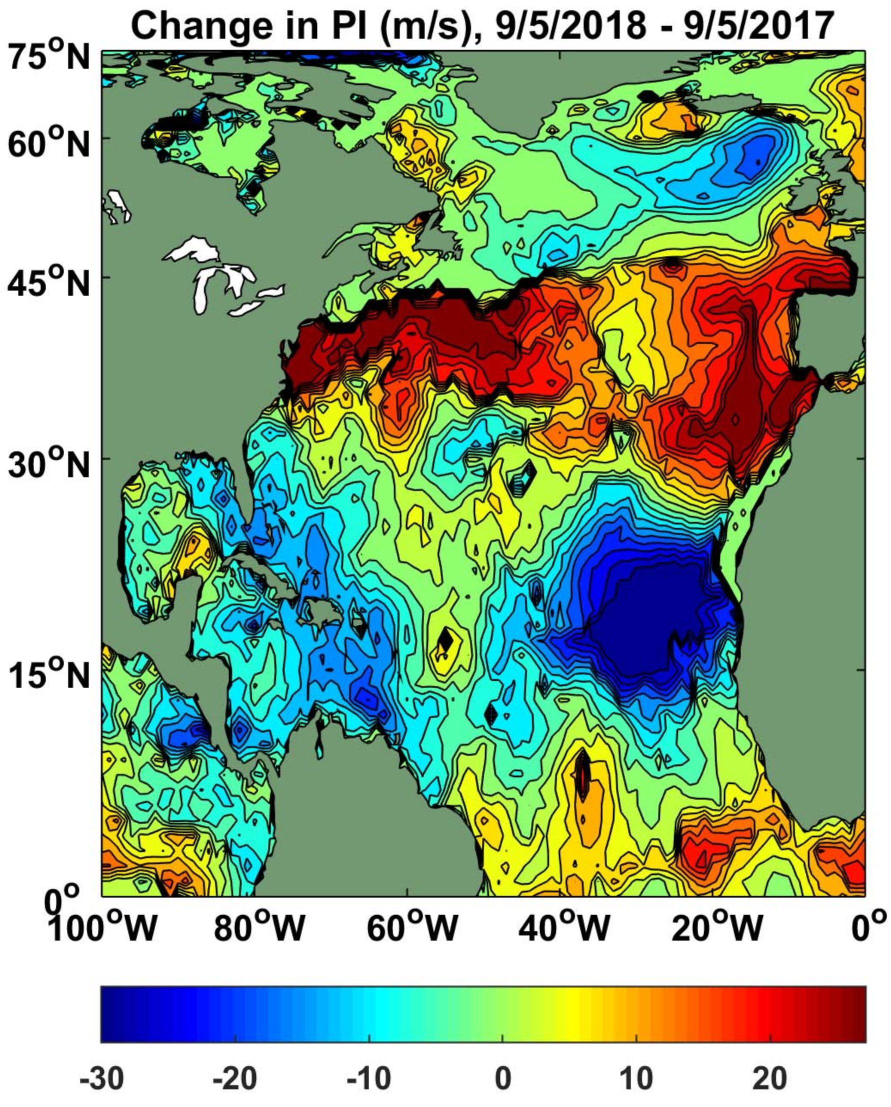
# Cumulative Frequency of Storm Lifetime Maximum Intensity Normalized by Potential Intensity



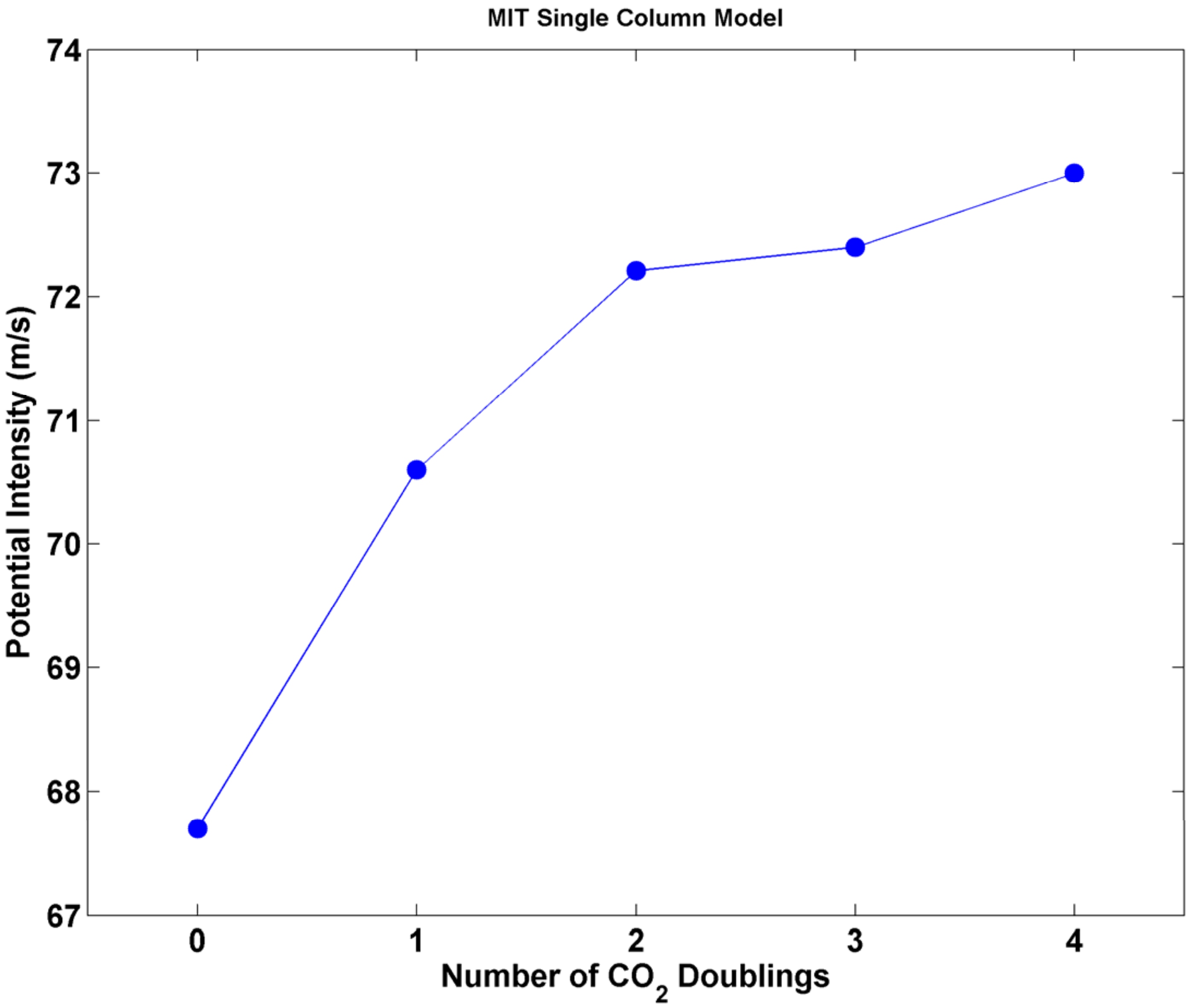
# Potential Intensity at Onset of Hurricane Irma



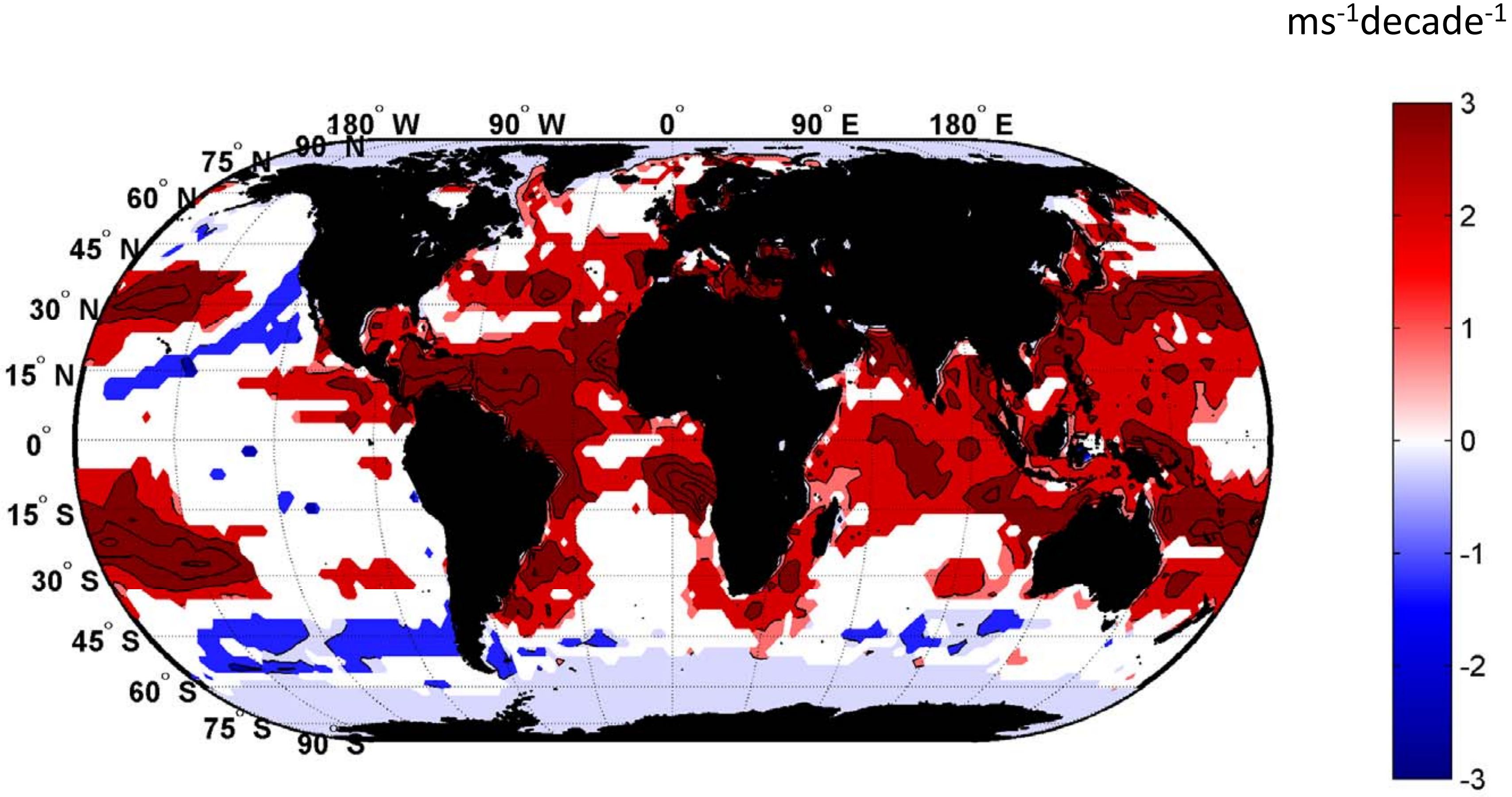
# Change in Potential Intensity After 1 year



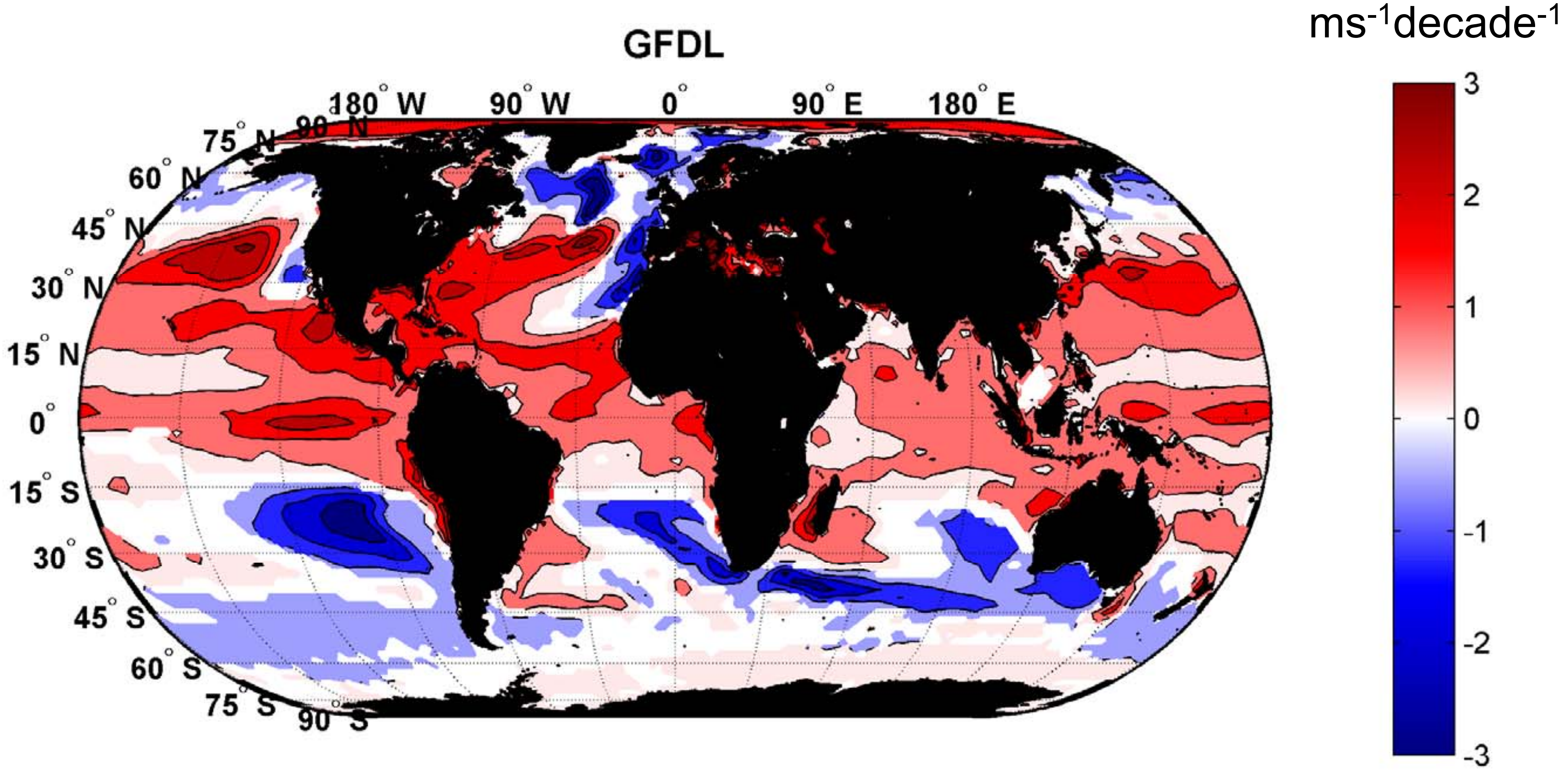
# Potential Intensity and $CO_2$



# Trends in Thermodynamic Potential for Hurricanes, 1980-2010 (NCAR/NCEP Reanalysis)



# Projected Trend Over $21^{st}$ Century: GFDL model under RCP 8.5



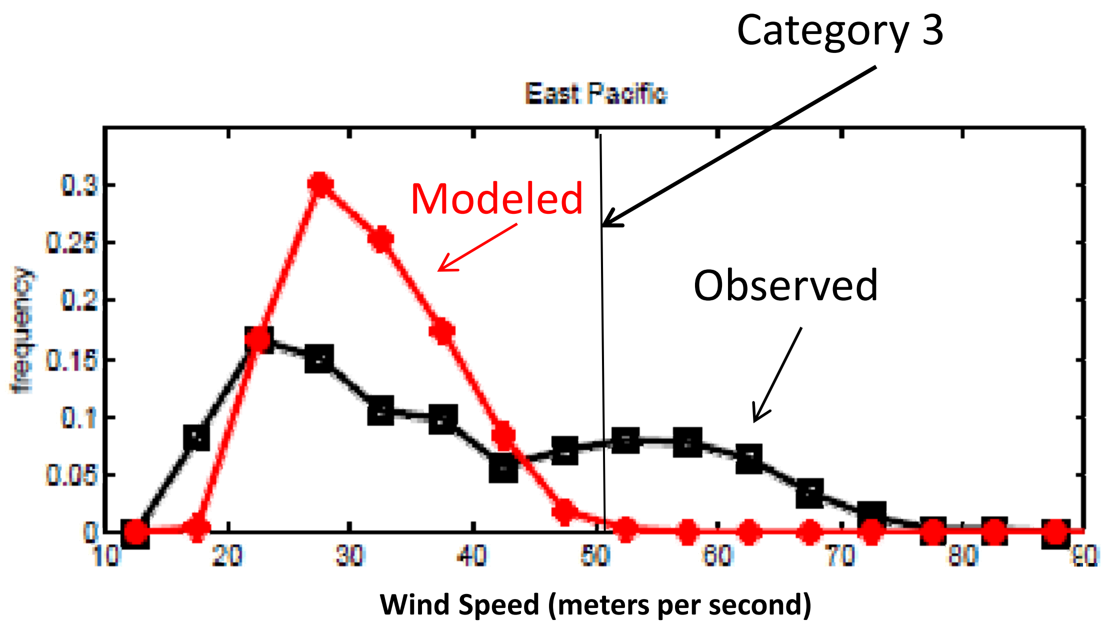
# Inferences from Basic Theory:

- 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

# 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



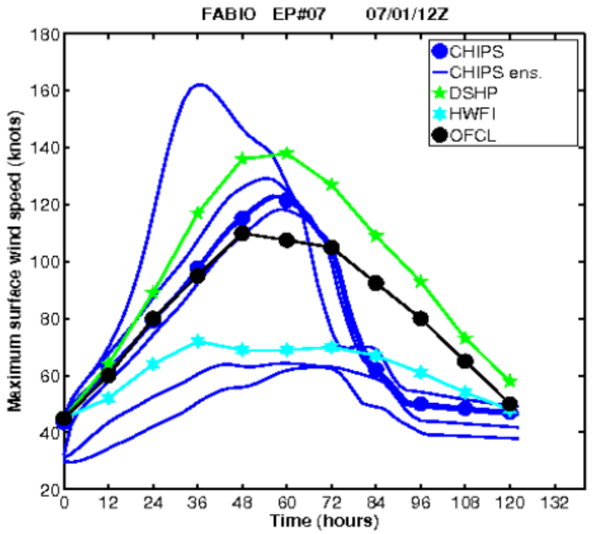
Histograms of Tropical Cyclone Intensity as Simulated by a Global Model with 30 mile grid point spacing. (Courtesy Isaac Held, GFDL)

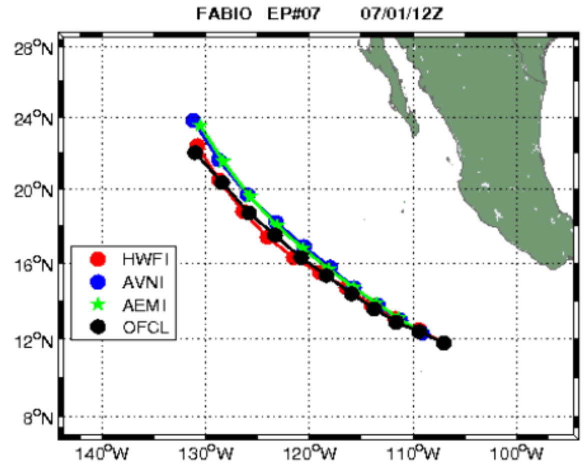
**Global models do not simulate the storms that cause destruction**

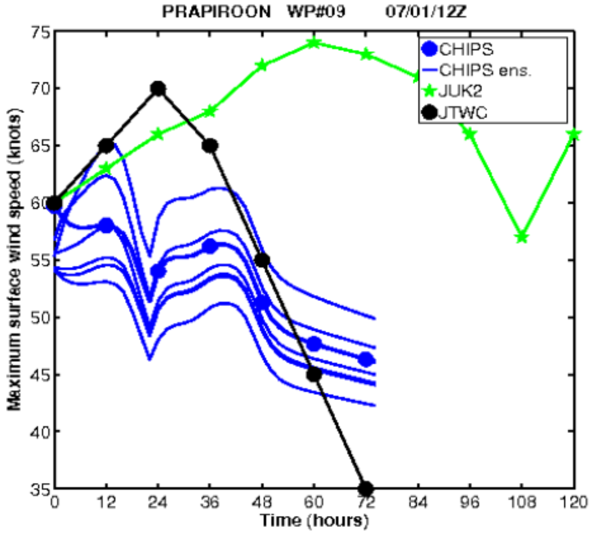
# How to deal with this?

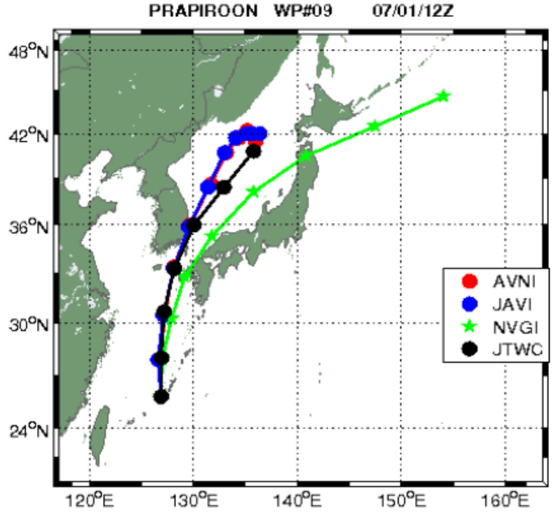
- **Embed high-resolution, fast coupled ocean-atmosphere hurricane model in global climate model or climate reanalysis data**
- **Coupled Hurricane Intensity prediction Model (CHIPS) has been used for 16 years to forecast real hurricanes in near-real time**

Real-time forecasts at http://wind.mit.edu/~emanuel/storm.html

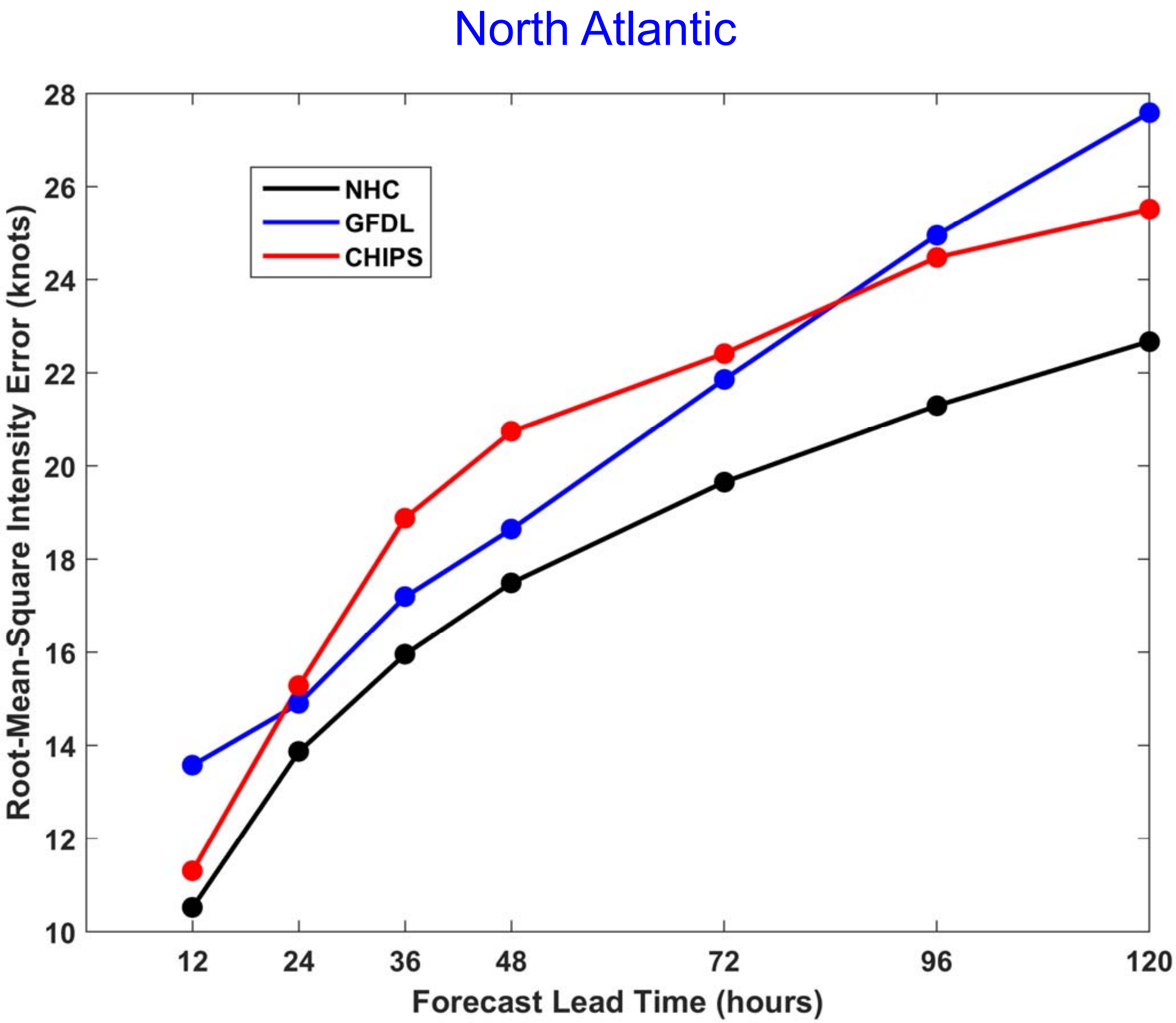








# RMS Intensity Error, 2009-2015



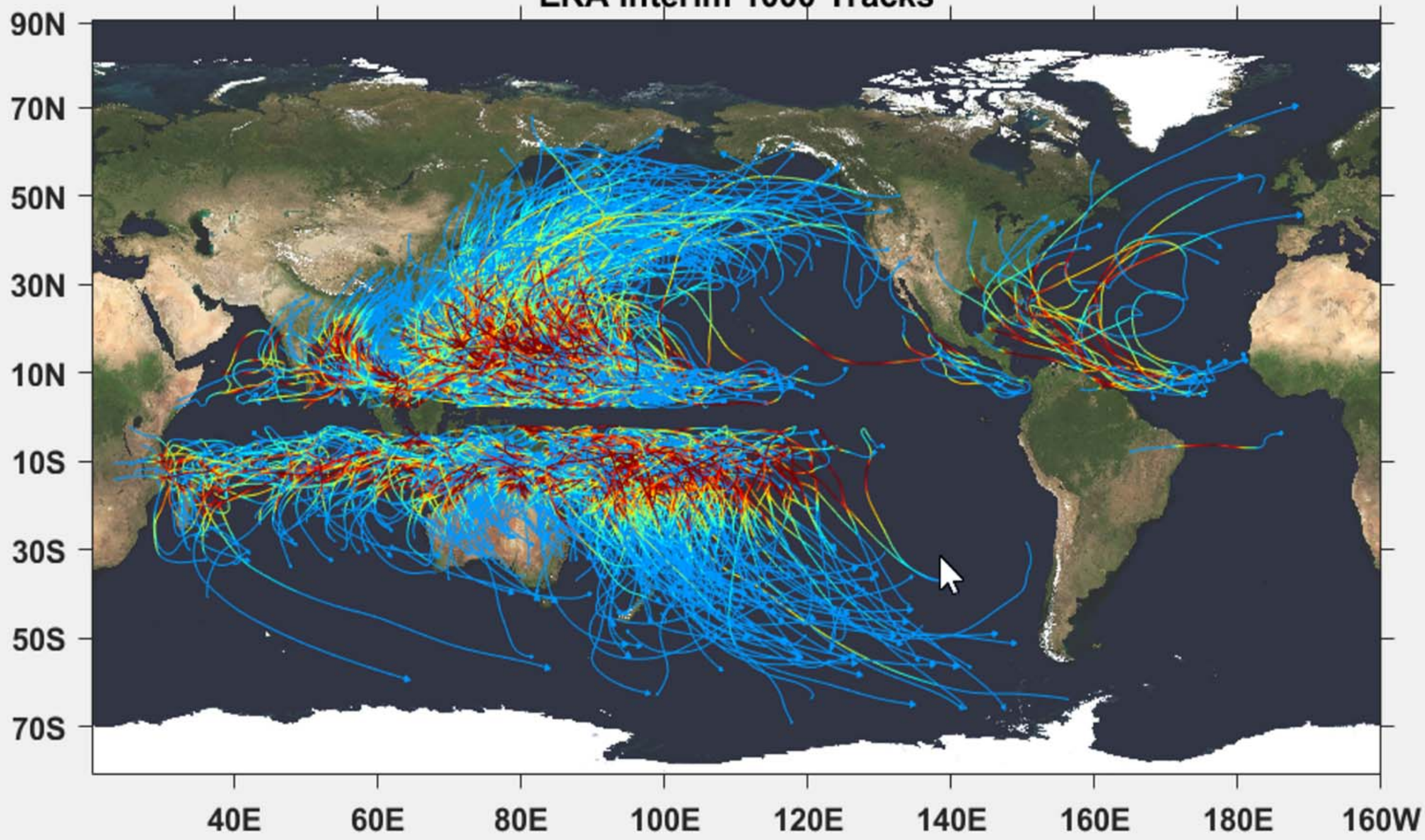
# How Can We Use This Model to Help Assess Hurricane Risk in Current and Future Climates?

# Risk Assessment Approach:

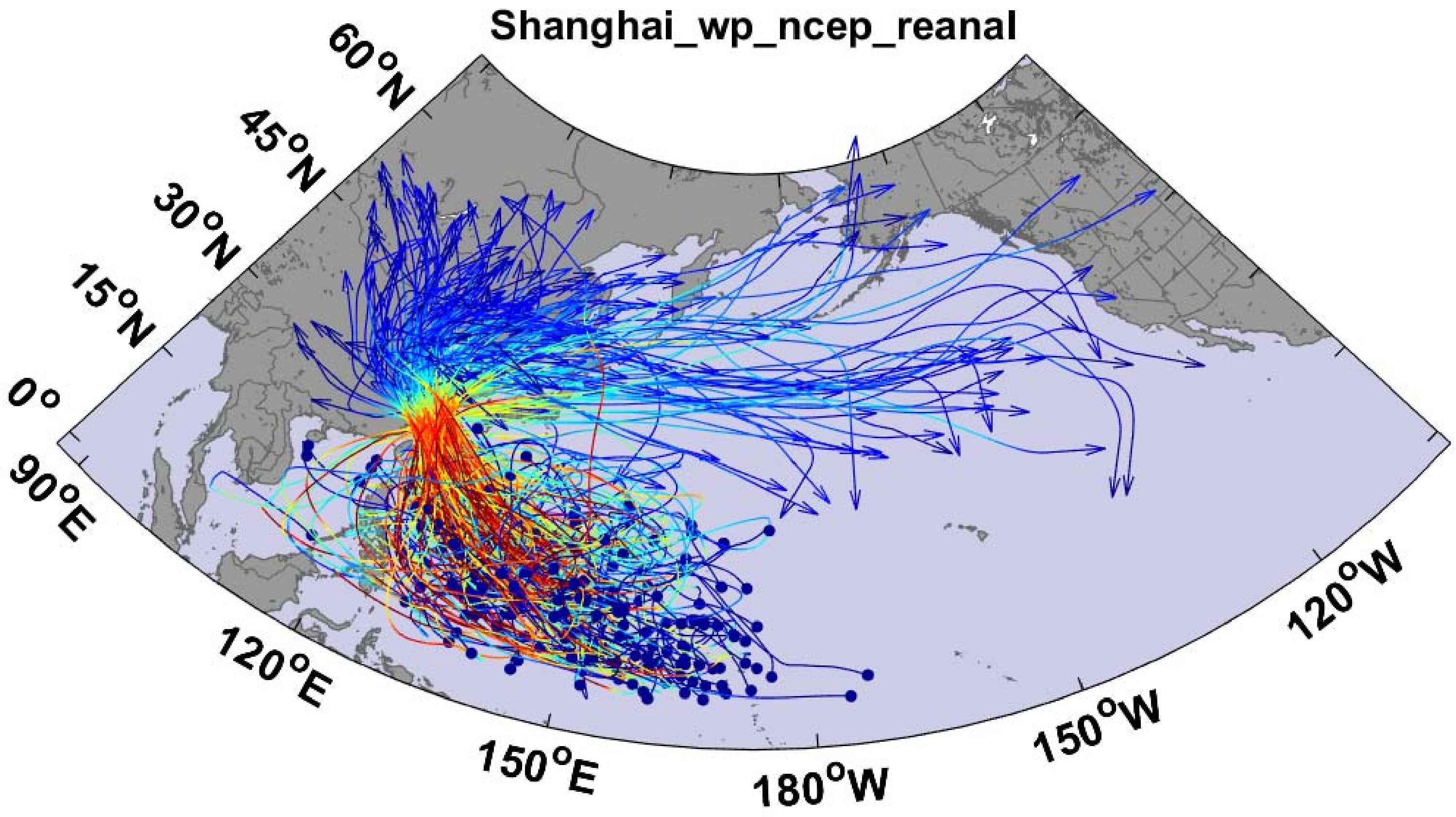
- **Step 1**: Seed each ocean basin with a very large number of weak, randomly located cyclones
- **Step 2**: Cyclones are assumed to move with the large scale atmospheric flow in which they are embedded, plus a correction for the earth's rotation and sphericity
- **Step 3**: Run the CHIPS model for 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

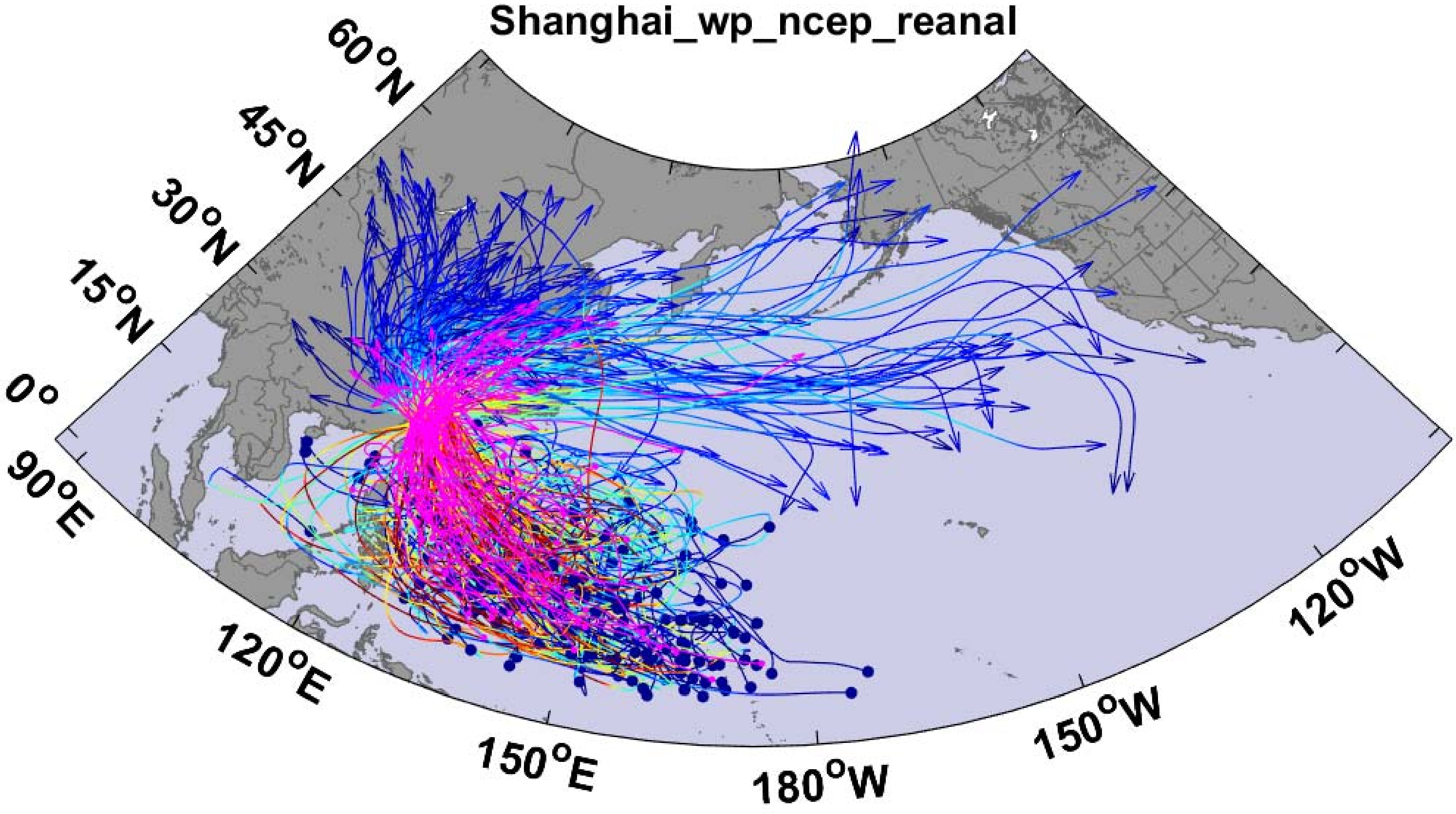
# ERA Interim 1000 Tracks



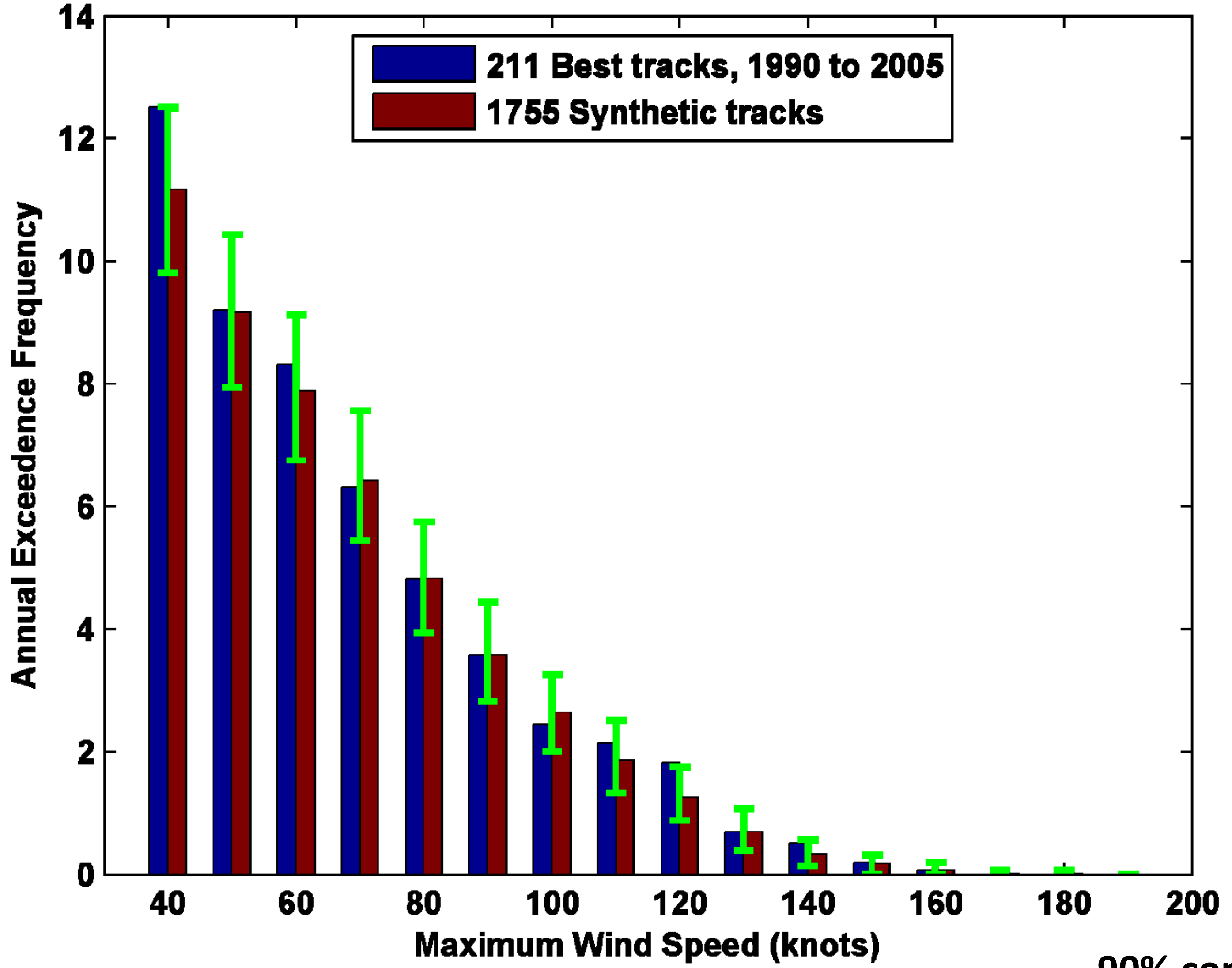
# Top 200 out of 5180 TCs Affecting Shanghai



# Top 200 out of 5180 TCs Affecting Shanghai

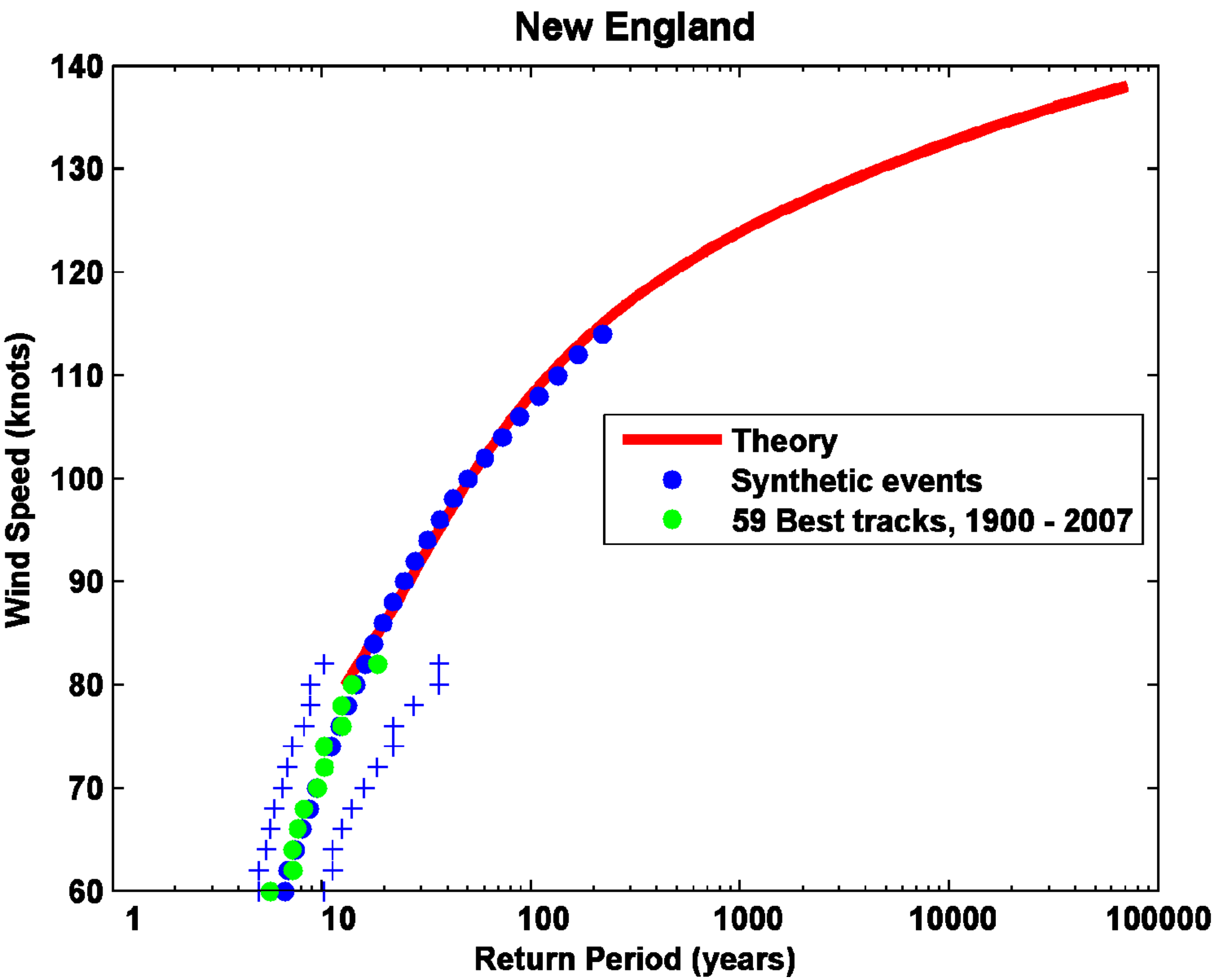


# Cumulative Distribution of Storm Lifetime Peak Wind Speed, with Sample of 1755 Synthetic Tracks

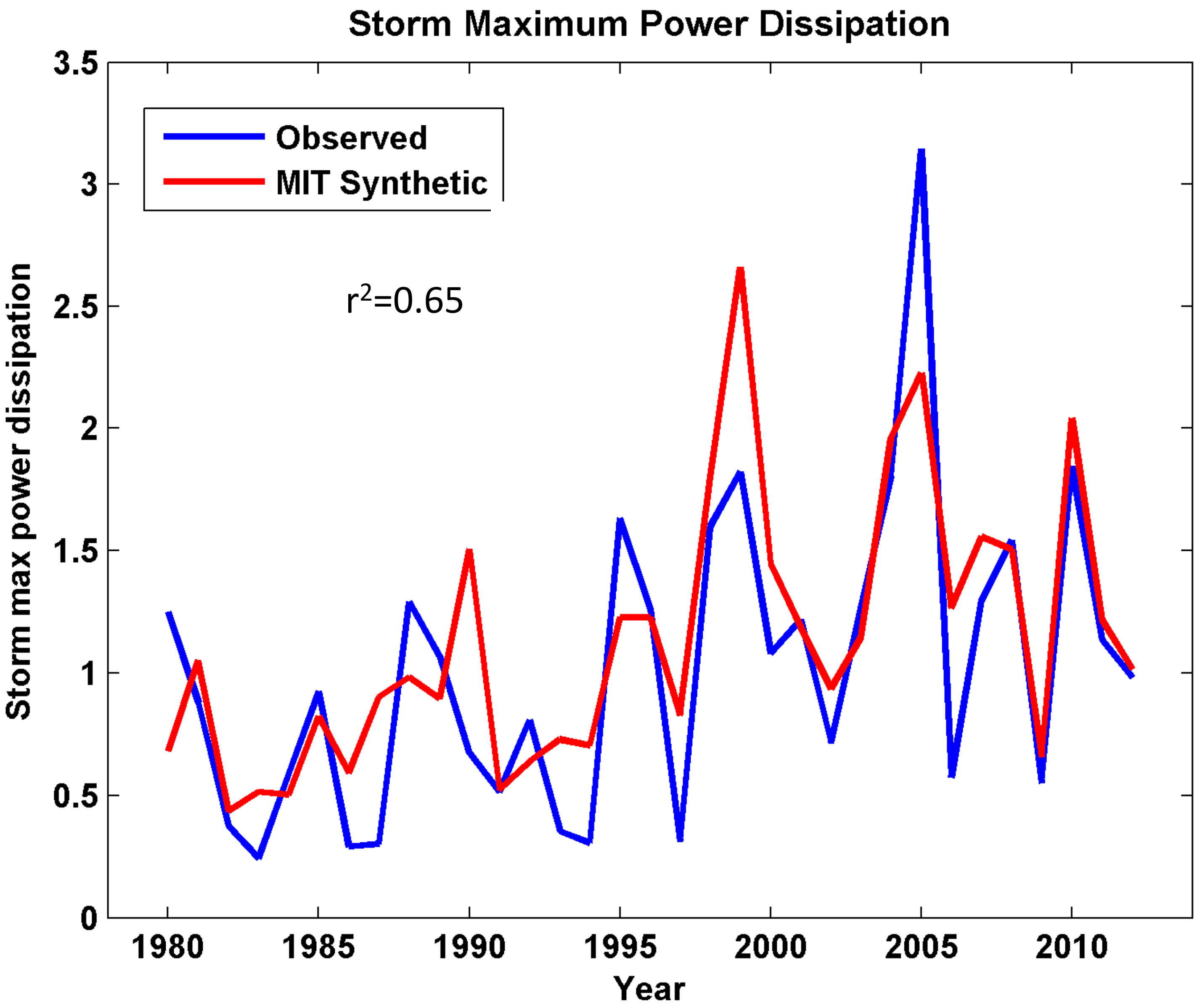


90% confidence bounds

# Return Periods

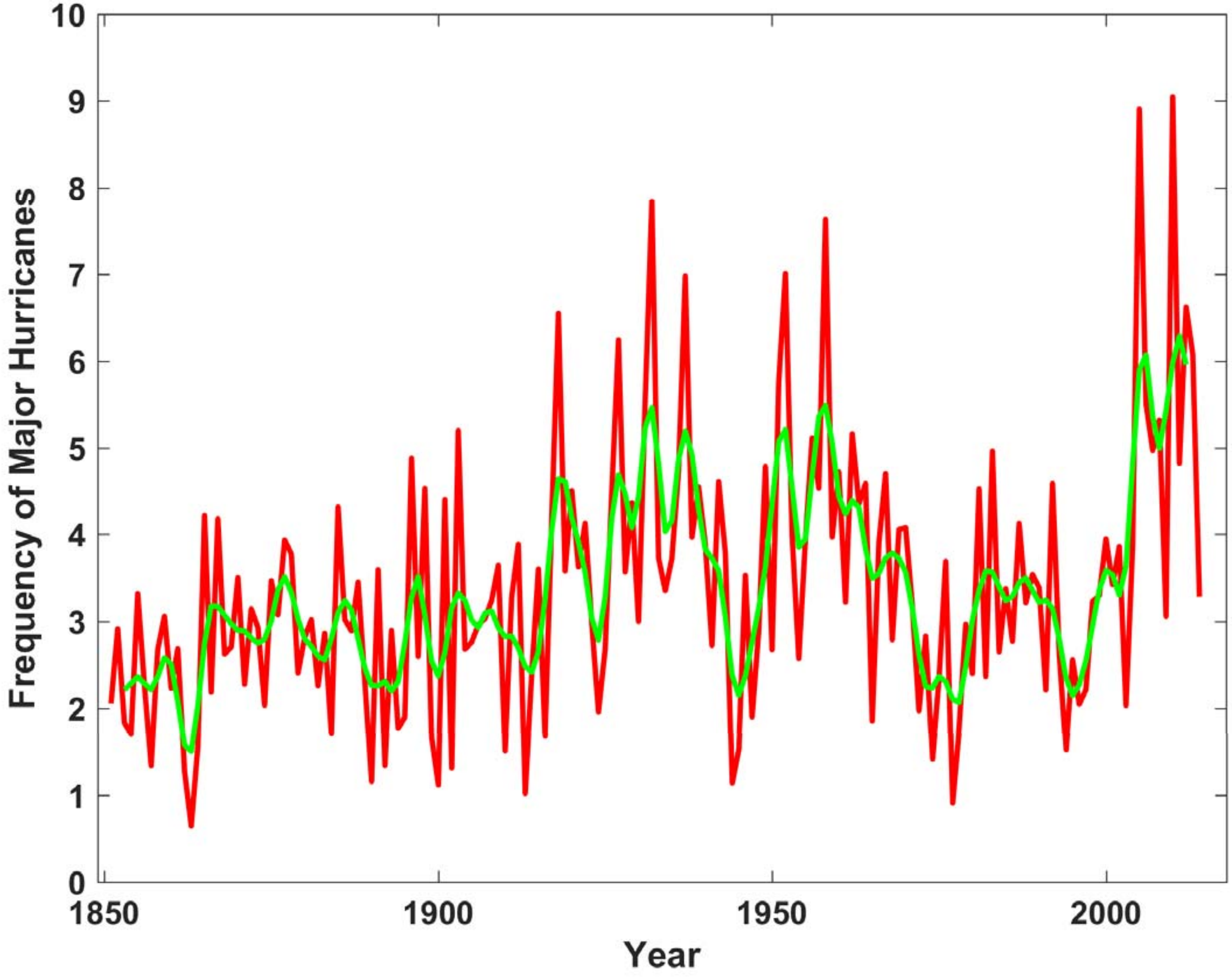


# Captures Much of the Observed North Atlantic Interannual Variability



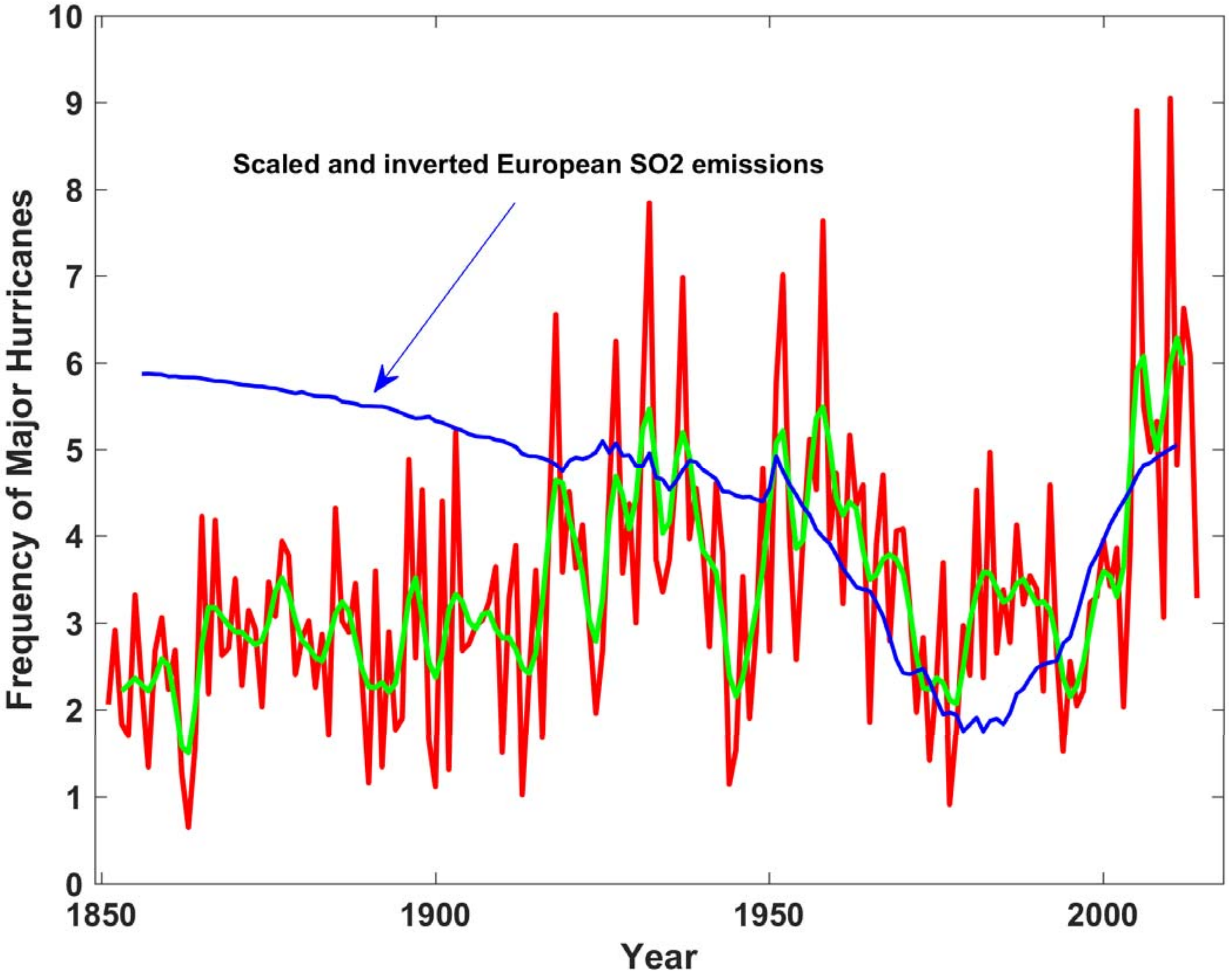
# North Atlantic Major Hurricanes Downscaled from NOAA 20th Century Reanalysis

(Forced by sea surface temperature, surface pressure, and sea ice only)

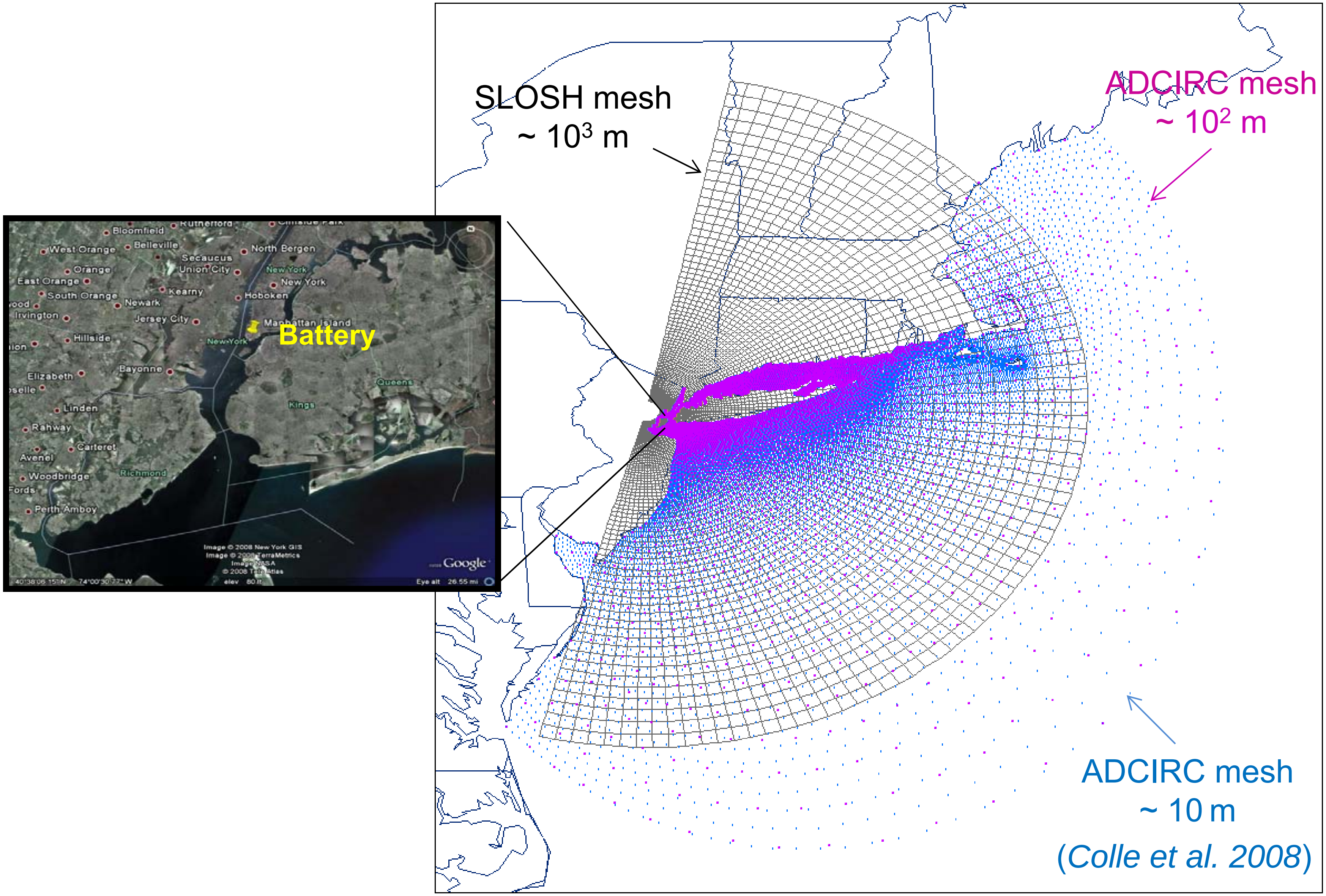


# North Atlantic Major Hurricanes Downscaled from NOAA 20th Century Reanalysis

(Forced by sea surface temperature, surface pressure, and sea ice only)



# Storm Surge Simulation (Ning Lin)



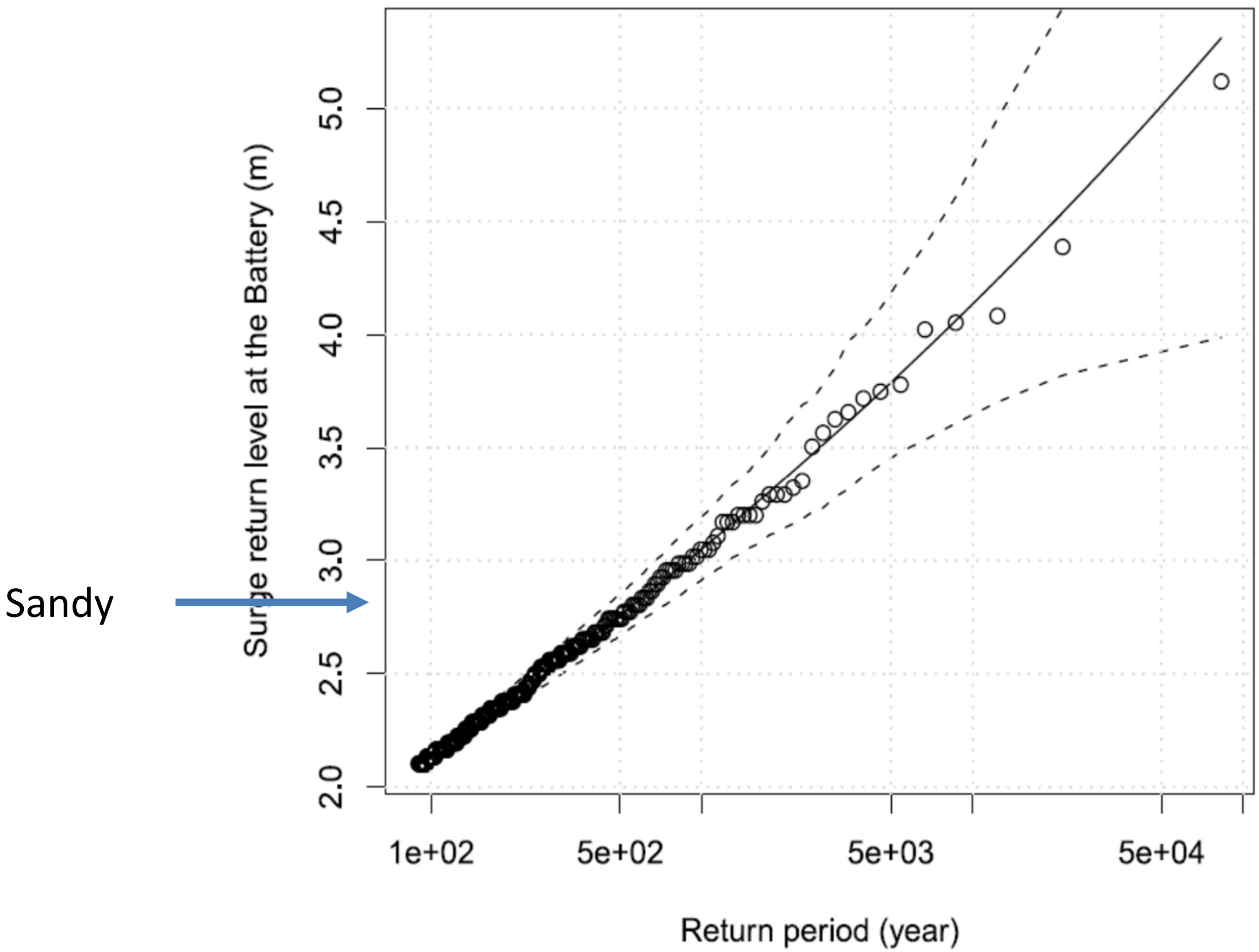
SLOSH mesh
~ $10^3$ m

ADCIRC mesh
~ $10^2$ m

ADCIRC mesh
~ 10 m

(*Colle et al. 2008*)

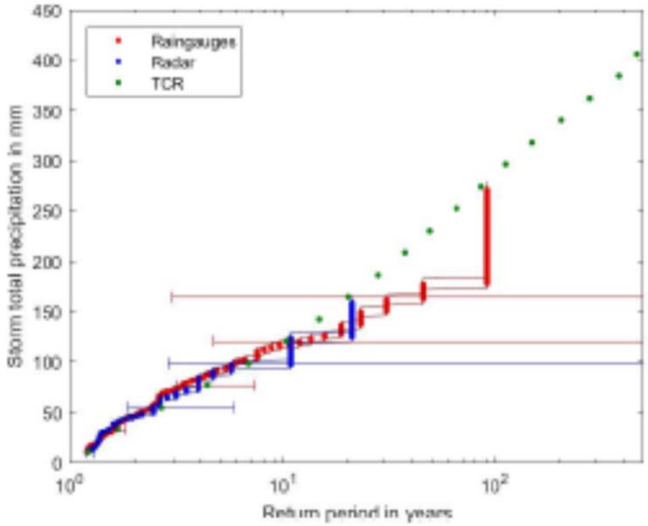
# Surge Return Periods for The Battery, New York



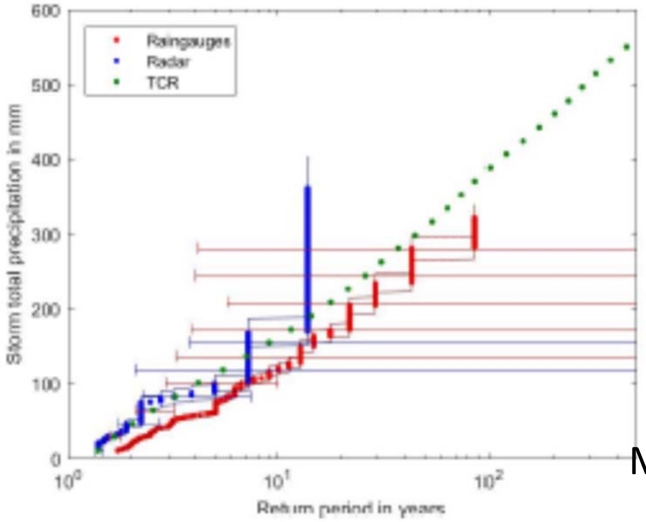
Sandy

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

## Charleston, SC



## Corpus Christi, TX



● Radar

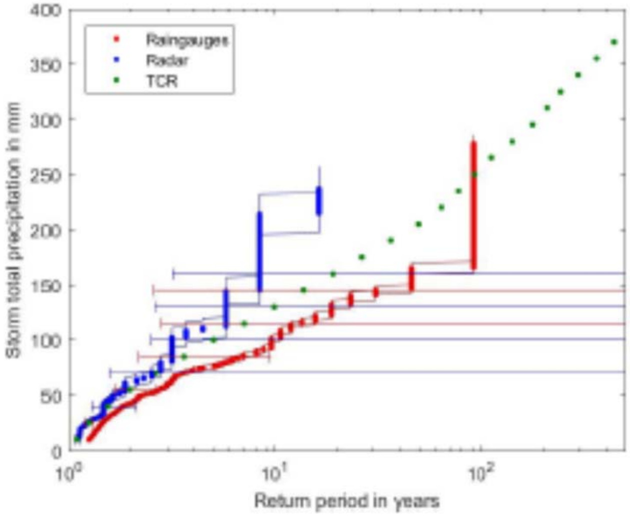
● Rain gauge

● Model

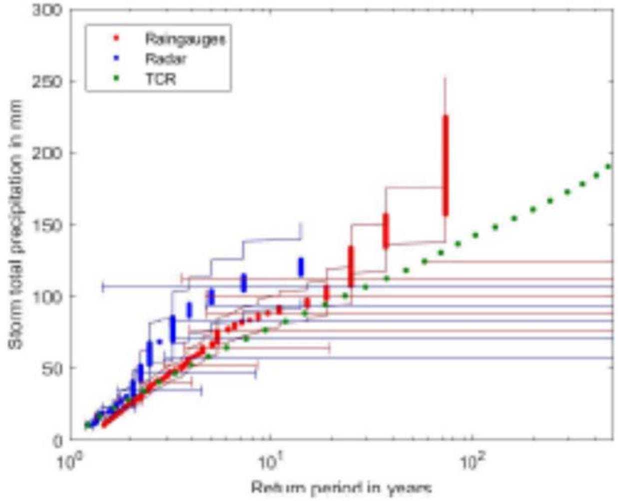
Missing radar data

Sampling uncertainty

## Raleigh, NC



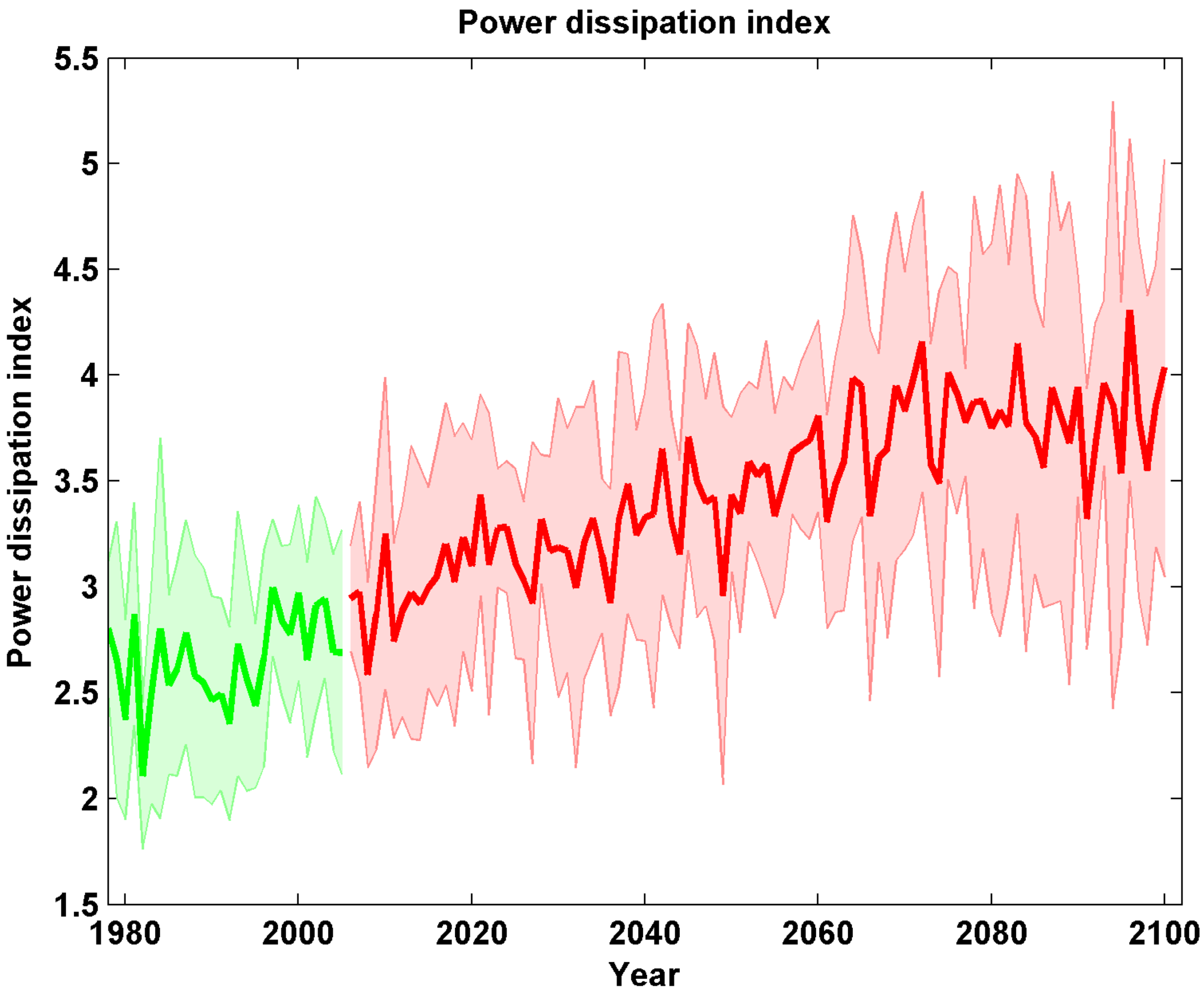
## New York, NY



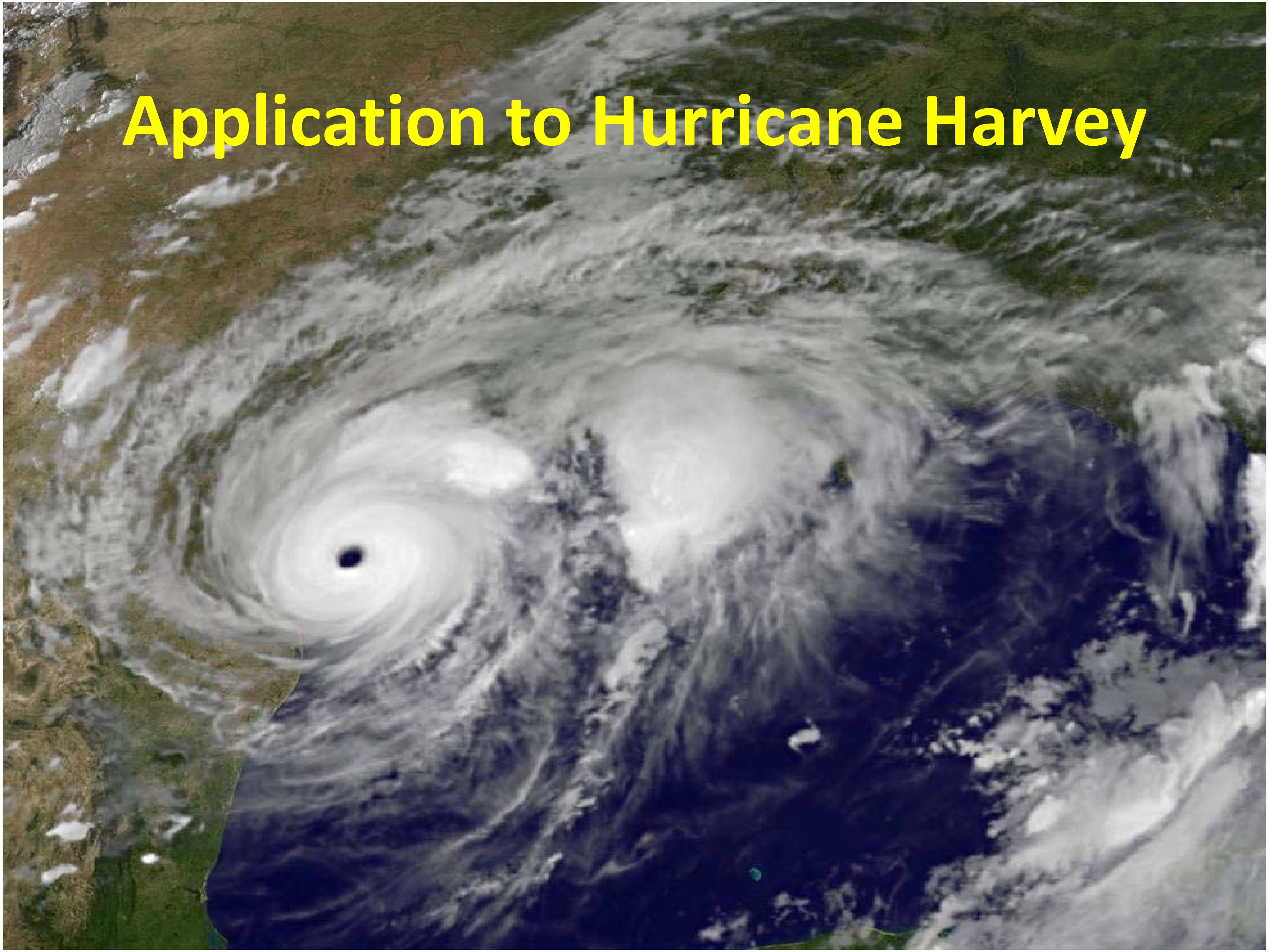
(with Monika Feldmann, ETH)

# Taking Climate Change Into Account

# Global Hurricane Power under RCP 8.5
# Six CMIP5 Models



# Application to Hurricane Harvey



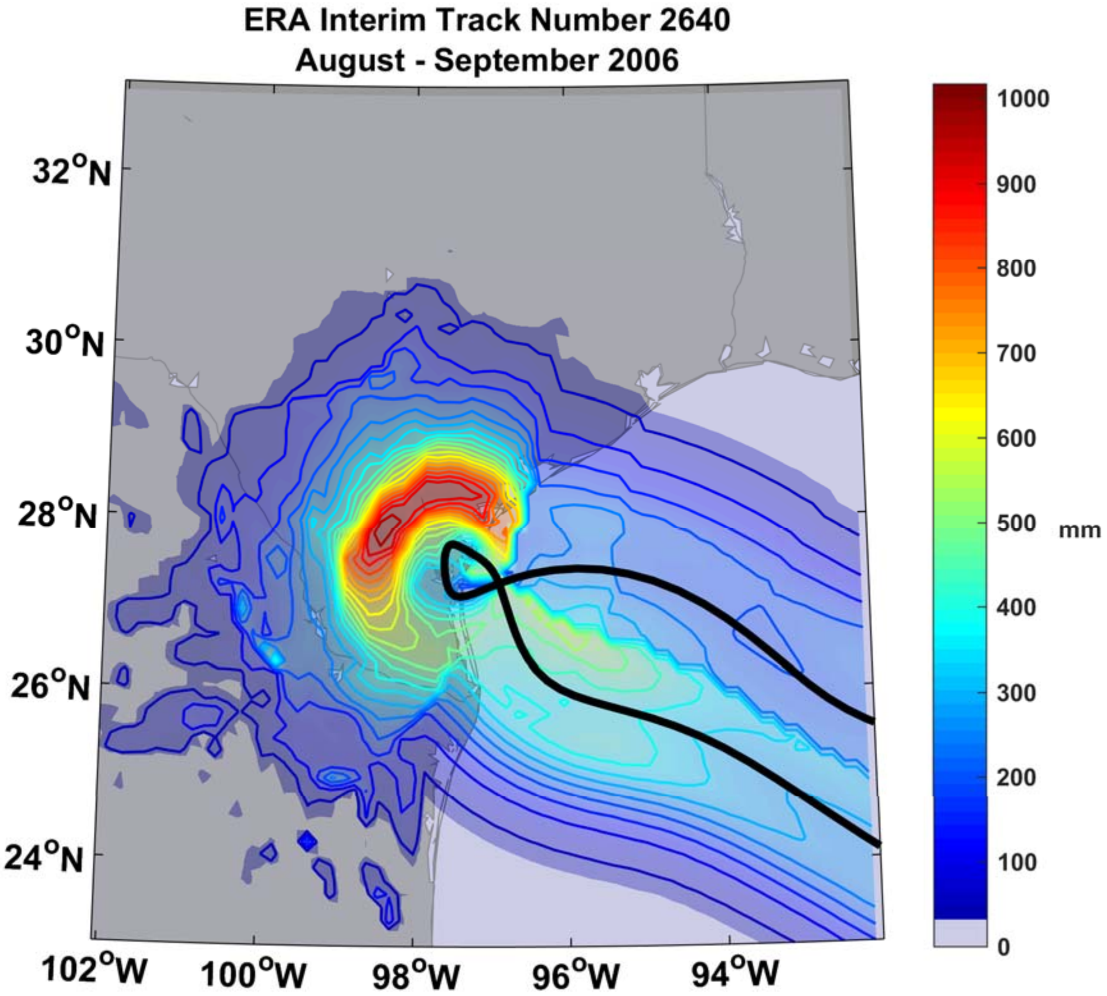
# Risk Assessment for Houston and Texas:

- Run 100 events for each year from 1980 to 2016 (3700 events total) passing within 300 km of Houston, downscaled from three climate reanalyses

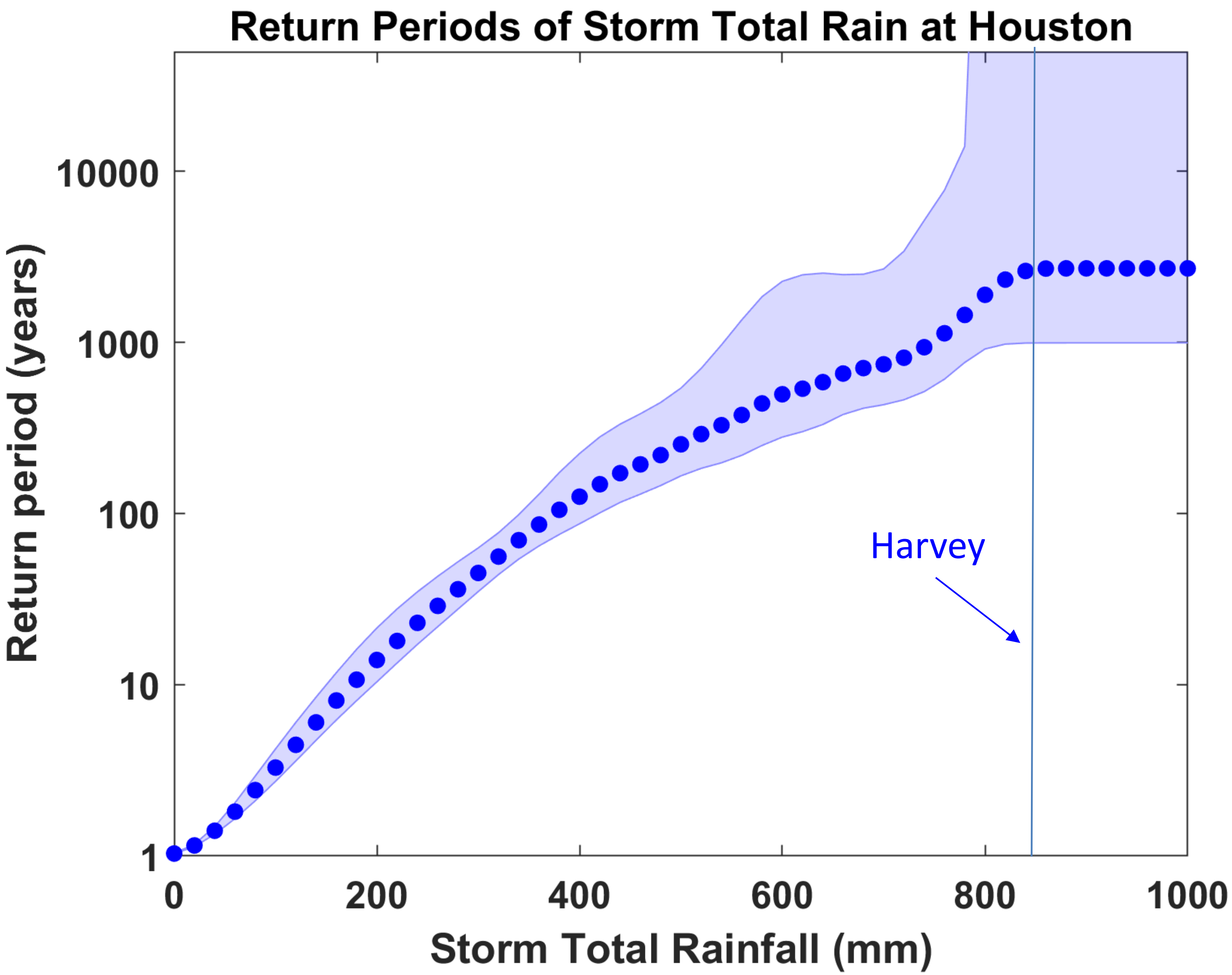
- Run 100 events each year from 1979-2015 passing over the Texas coastline, downscaled from NCAR/NCEP reanalyses. Calculate storm total rainfall for each event at each of 78 points constituting a grid extending from 26° N to 31° N and from 99° W to 94° W, at increments of 0.5°, but excluding points over the Gulf

- Run 100 events each year during two periods: 1981-2000 and 2081-2100, passing within 300 km of Houston, downscaled from six climate models

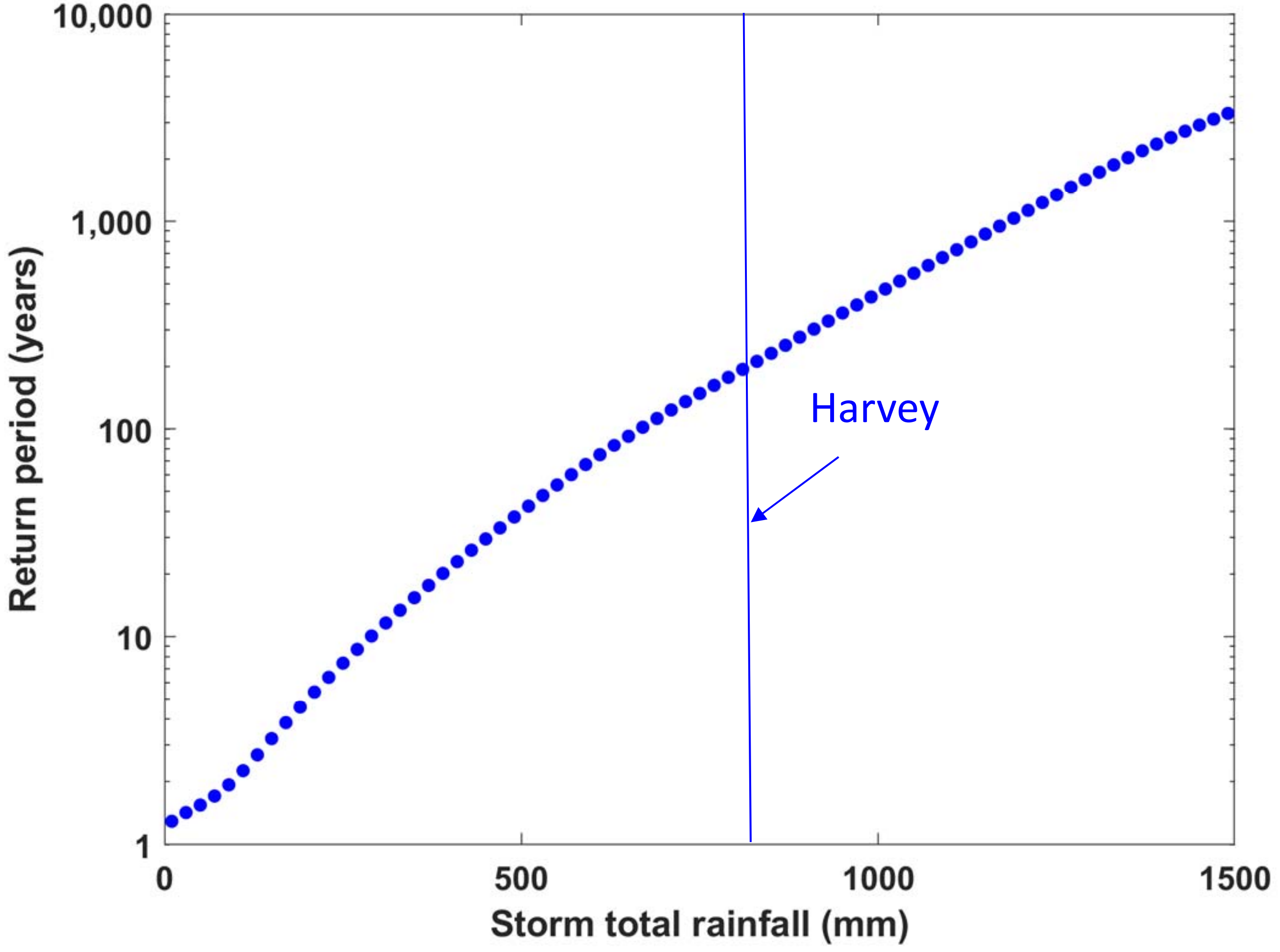
# Example of Accumulated Rainfall from a Harvey-like Event Downscaled from ERA Interim Reanalysis



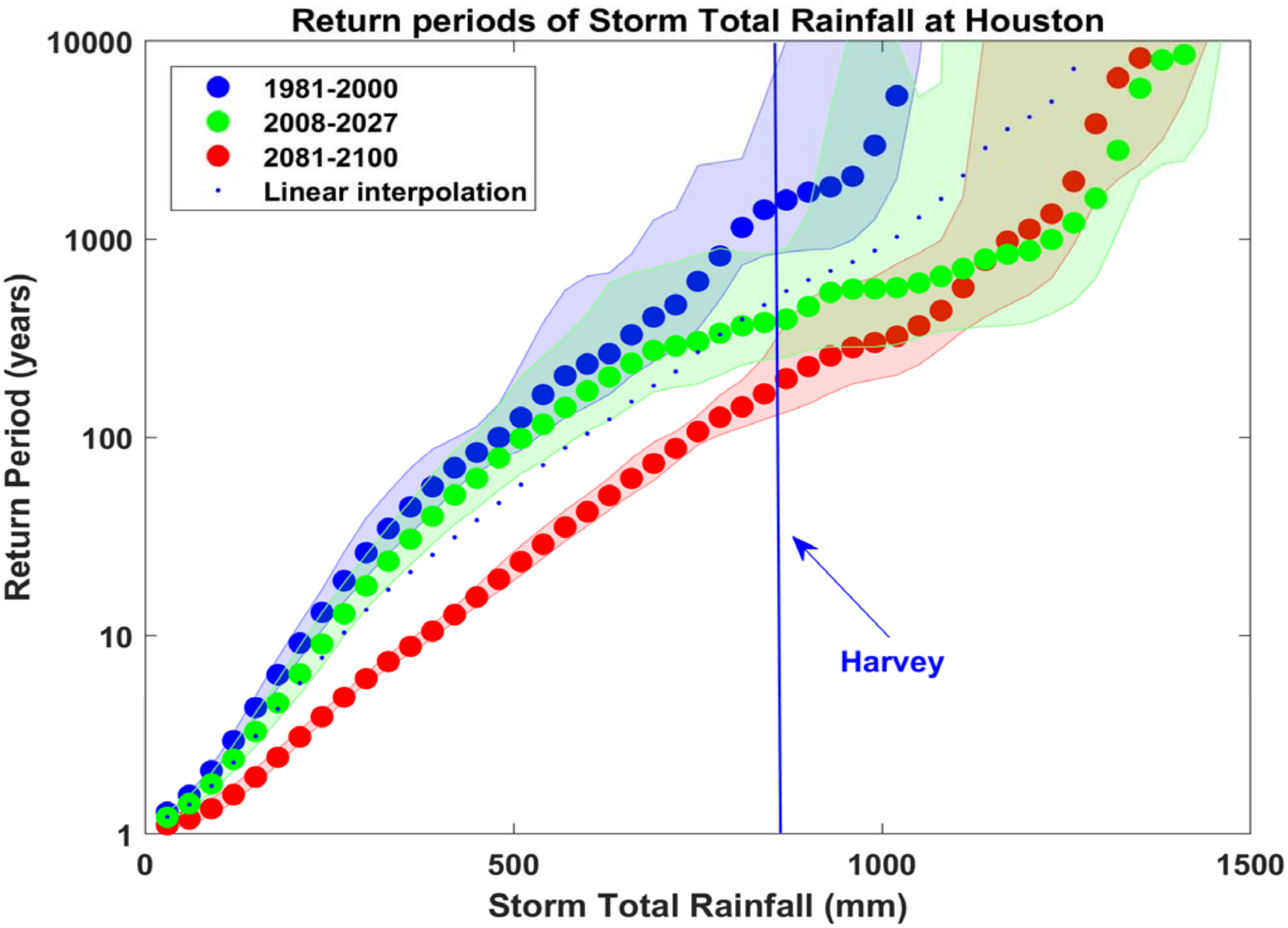
# Probability of Storm Accumulated Rainfall at Houston, from 3 Climate Reanalyses, 1980-2016 Based on 3700 Events Each. Shading shows spread among the reanalyses.



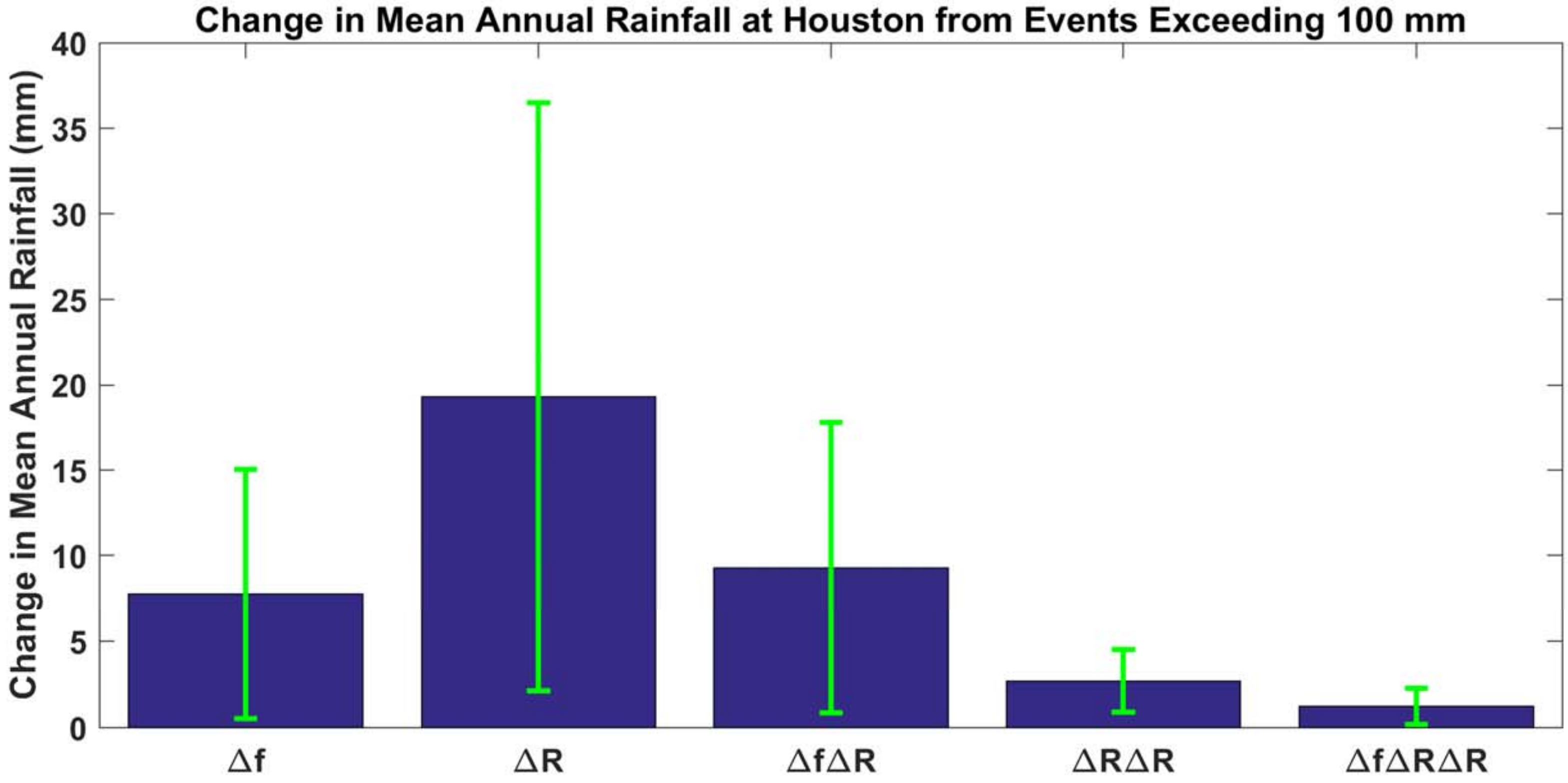
# Probability of a Accumulated Hurricane Rain Anywhere in Texas, based on 3700 Events Downscaled from NCAR/NCEP Reanalysis with Rainfall Analyzed at 78 Points



# 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.

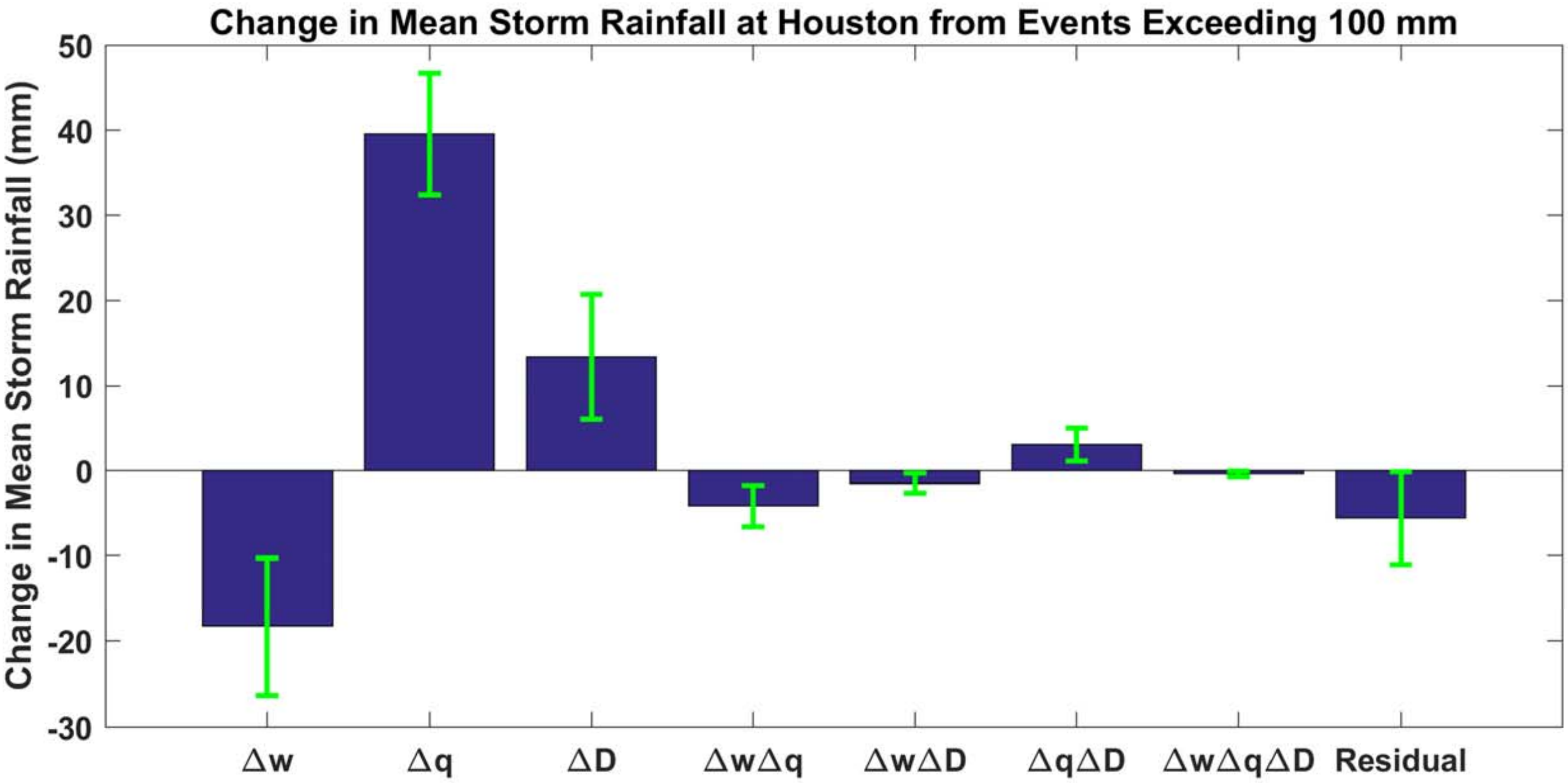


# Contributions to Changes in Annual Mean Hurricane Rainfall at Houston from Changes in Overall Event Frequency and in Average Storm Rainfall



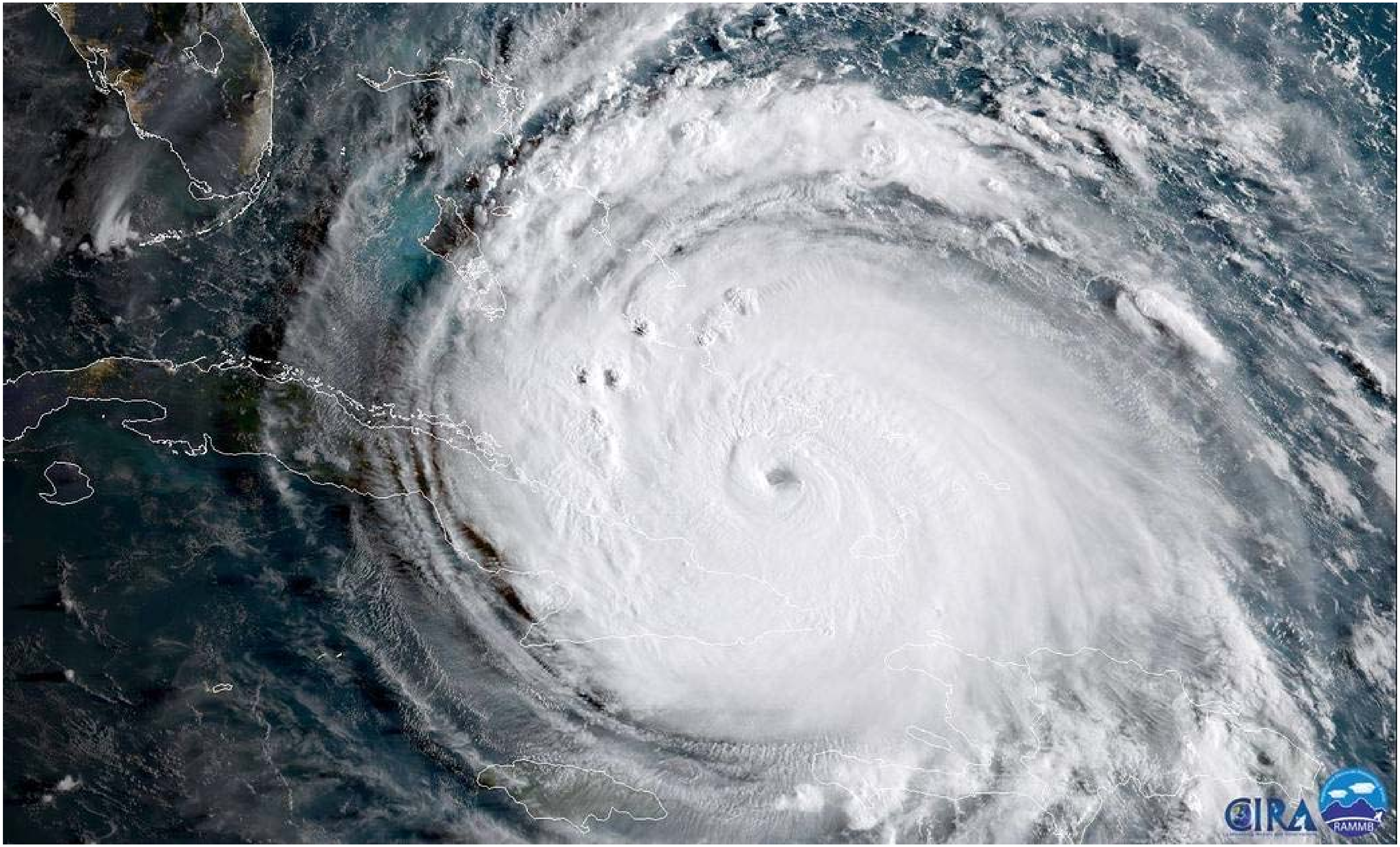
Δf = Change in overall hurricane frequency
ΔR= Change in Rainfall amounts in excess of 100 mm

# Contributions to Changes in Hurricane Rainfall at Houston from Changes in Updraft Speed, Water Vapor Content, and Storm Duration



Δw = Change in updraft speed
Δq =  Change in water vapor concentration
ΔD = Change in storm duration

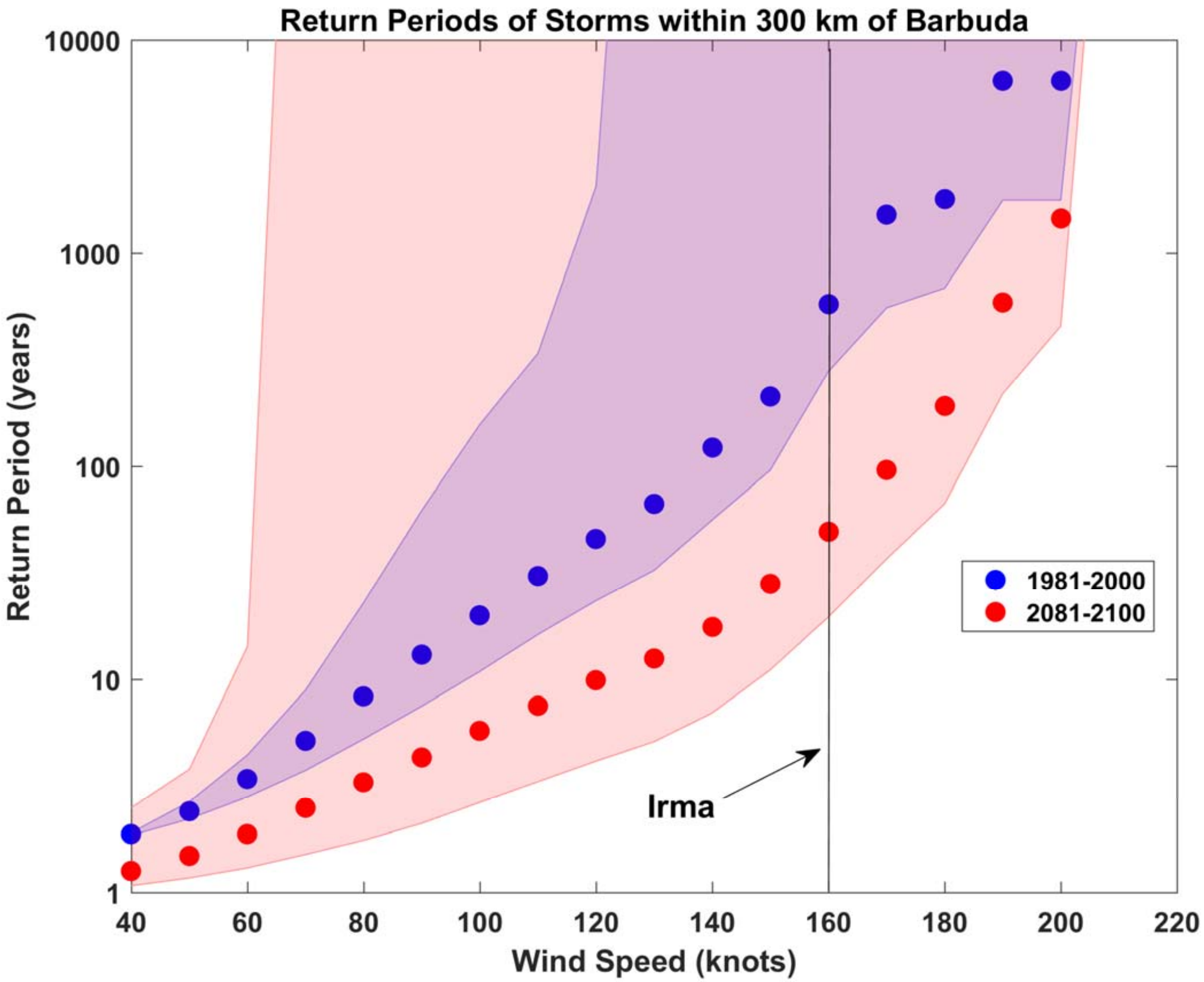
# Hurricane Irma



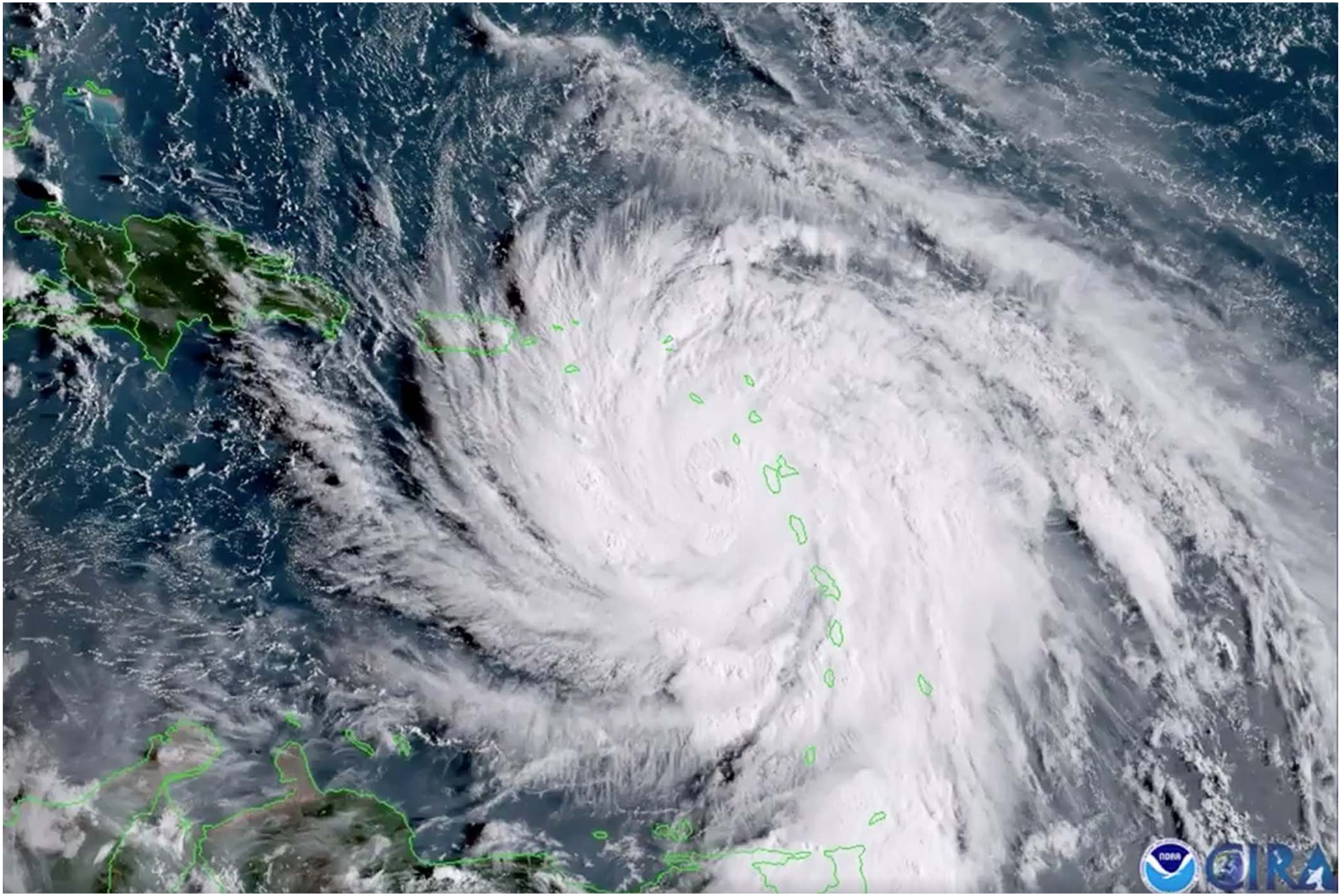
# Irma

- Run 100 events each year during two periods: 1981-2000 and 2081-2100, passing within 300 km of Barbuda, downscaled from six climate models

# Probabilities of Storms of Irma's Intensity within 300 km of Barbuda, from 6 Climate models, 1981-2000 and 2081-2100, Based on 2000 Events Each. Shading shows spread among the models.

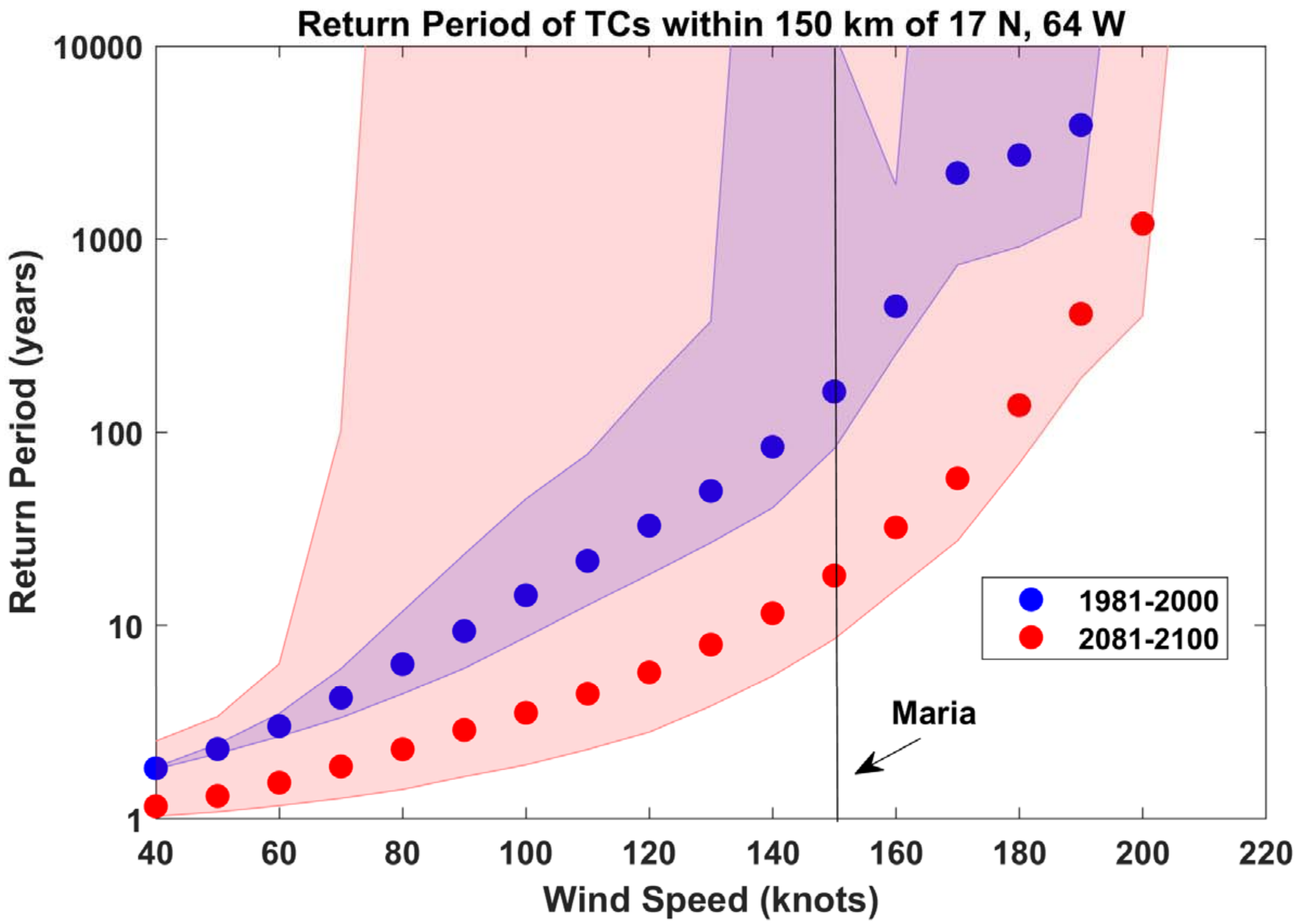


# Hurricane Maria



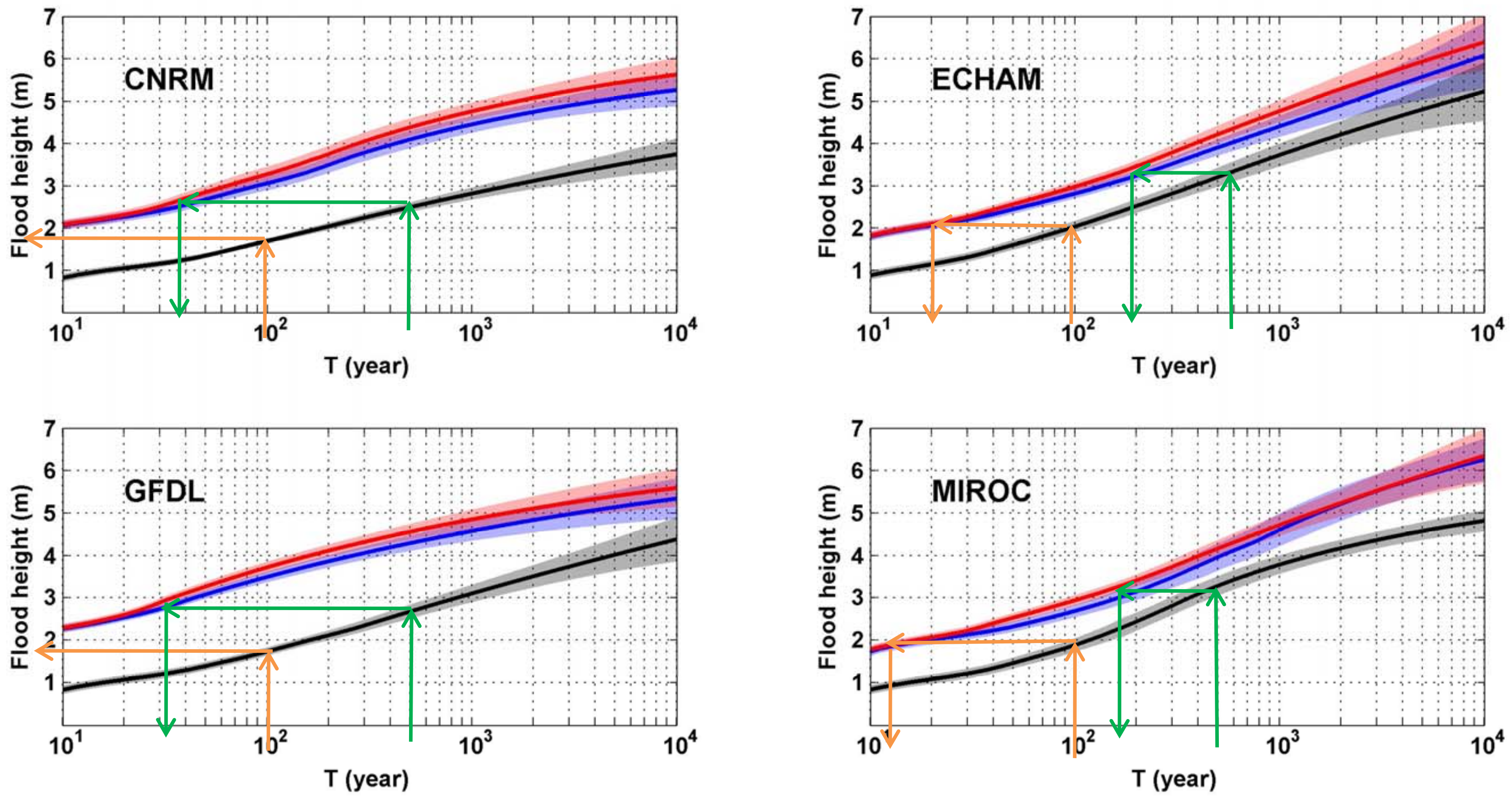
# Maria

- Run 100 events each year during two periods: 1981-2000 and 2081-2100, passing within 150 km of 17$^o$N, 64$^o$W, downscaled from four climate models


Return Period of TCs within 150 km of 17 N, 64 W
Return Period (years)
10000
1000
100
10
1
40
60
80
100
120
140
160
180
200
220
Wind Speed (knots)
● 1981-2000
● 2081-2100
Maria

# GCM flood height return level, Battery, Manhattan

## (assuming SLR of 1 m for the future climate )



**Black: Current climate (1981-2000)**

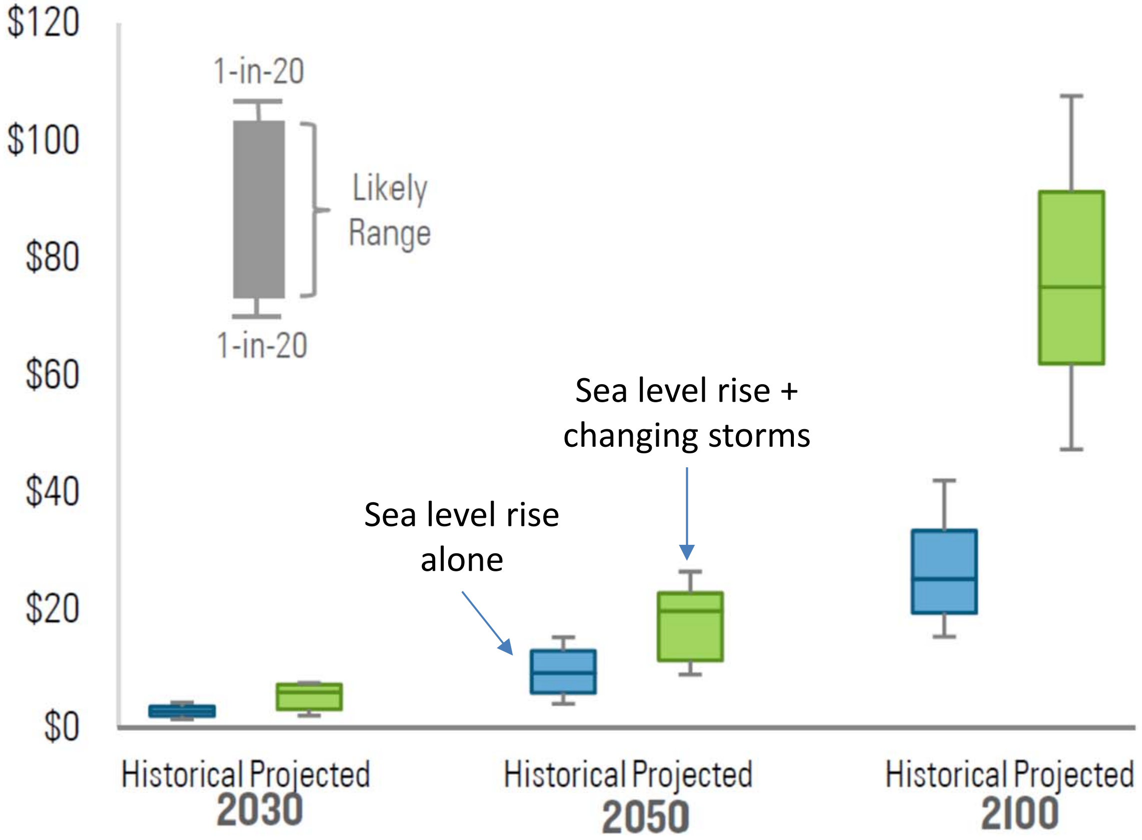
**Blue: A1B future climate (2081-2100)**

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

*Lin et al. (2012)*

**Figure 11.17: Increase in average annual losses with historical and projected hurricane activity**

Billion 2011 USD, RCP 8.5 ensemble tropical cyclone activity projections from Emanuel (2013)



Sea level rise alone

Sea level rise + changing storms

From: *American Climate Prospectus Economic Risks in the United States*

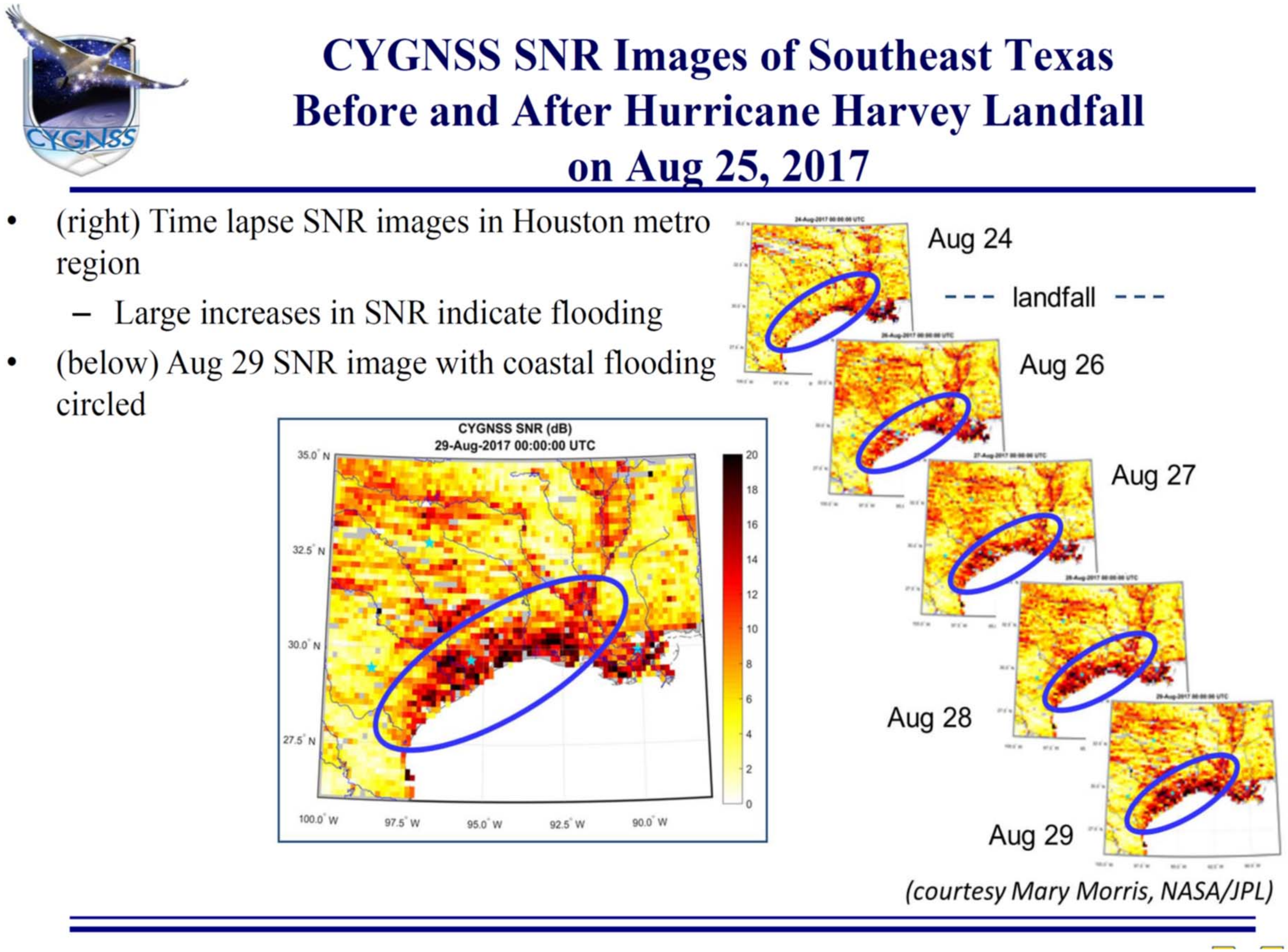
# Summary

- 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

# Spare Slides



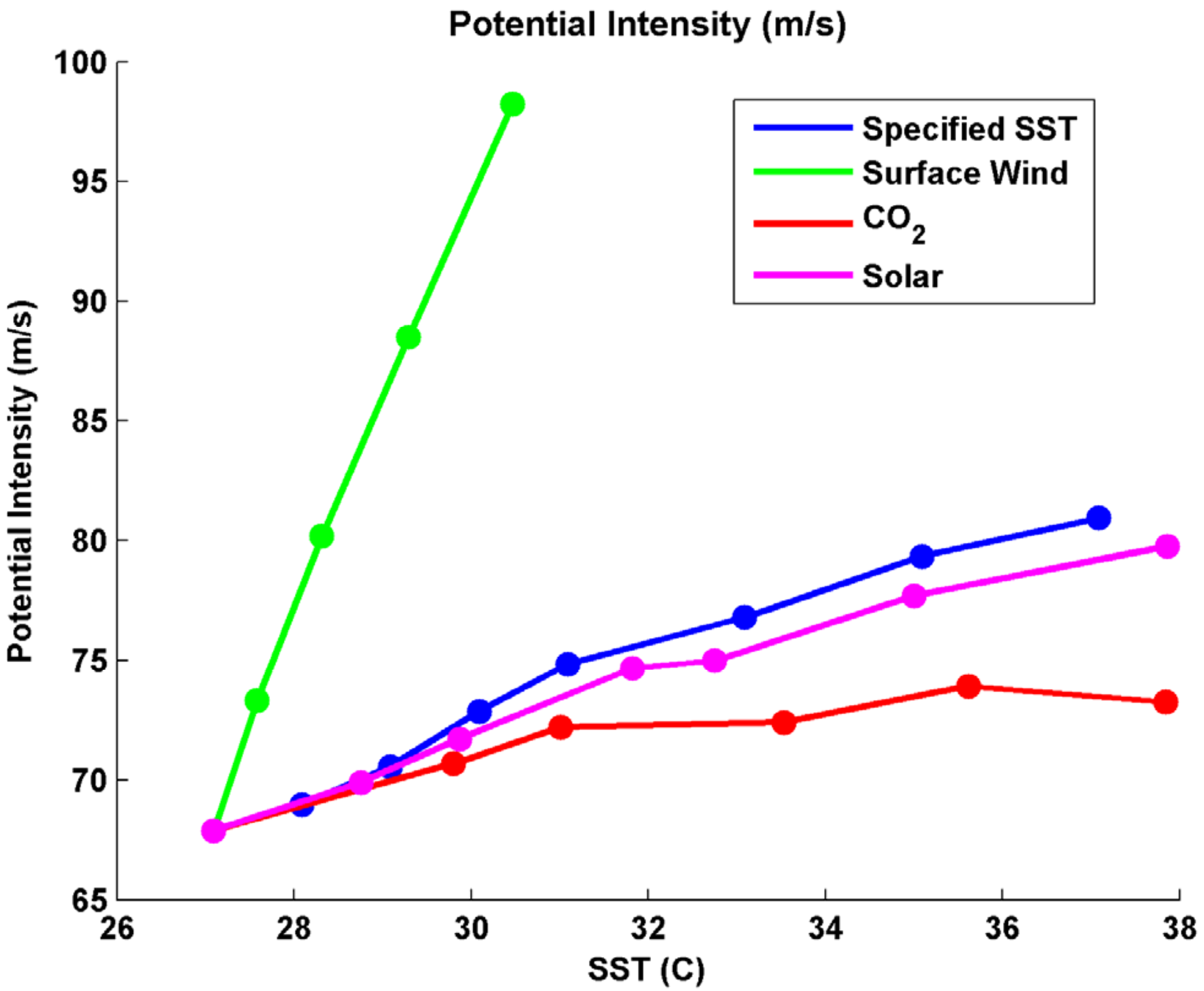
## CYGNSS SNR Images of Southeast Texas Before and After Hurricane Harvey Landfall on Aug 25, 2017

- (right) Time lapse SNR images in Houston metro region
  - Large increases in SNR indicate flooding
- (below) Aug 29 SNR image with coastal flooding circled

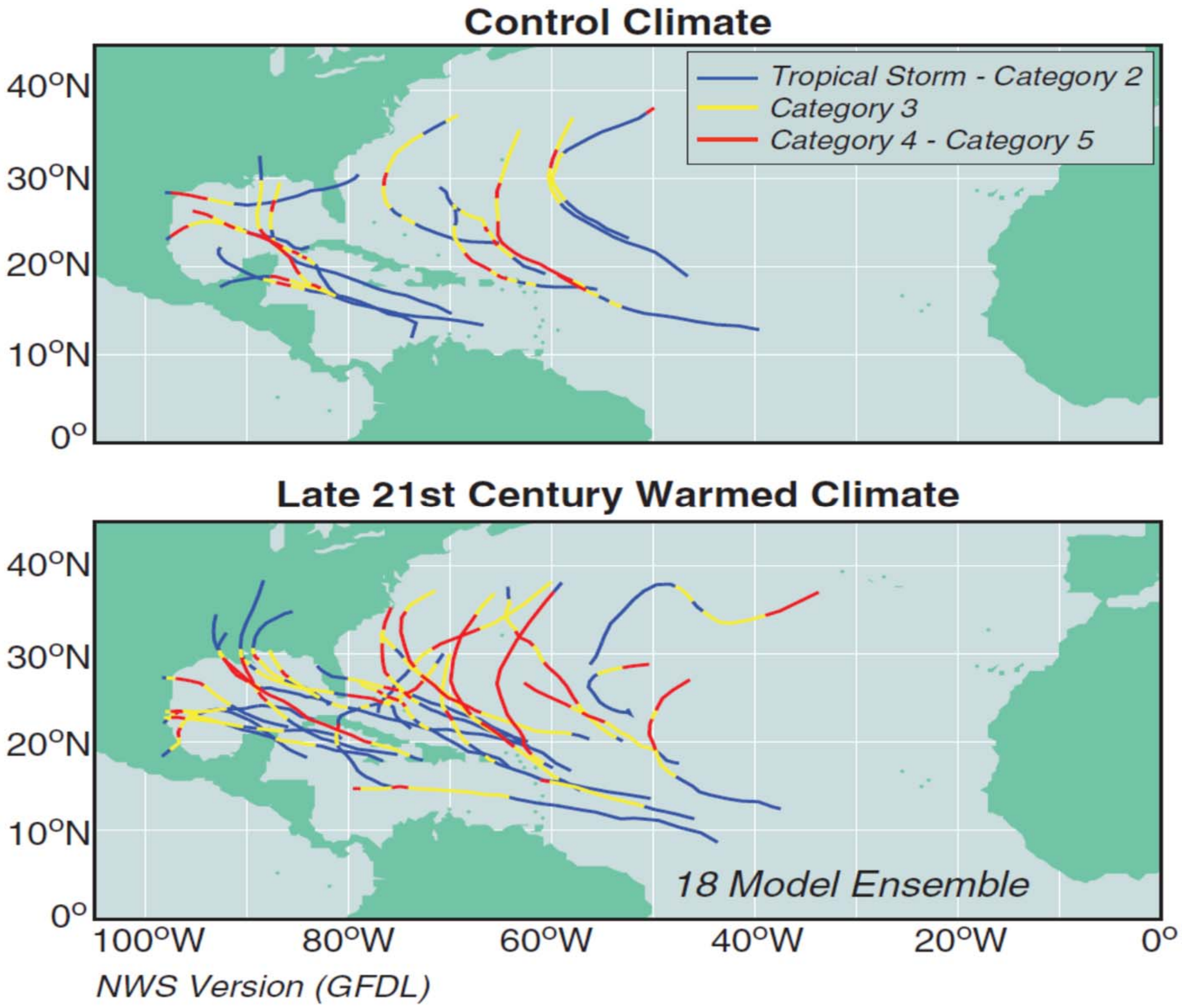
(courtesy Mary Morris, NASA/JPL)

Flood inundation signal. Courtesy Chris Ruf

# Variation of Potential Intensity with Ocean Heat Flux, Surface Wind Speed, $CO_2$, and Solar Forcing



Emanuel, K., and A. Sobel, 2013: Response of tropical sea surface temperature, precipitation, and tropical cyclone-related variables to changes in global and local forcing. *J. Adv. Model. Earth Sys.*, **5**, doi:10.1002/jame.20032

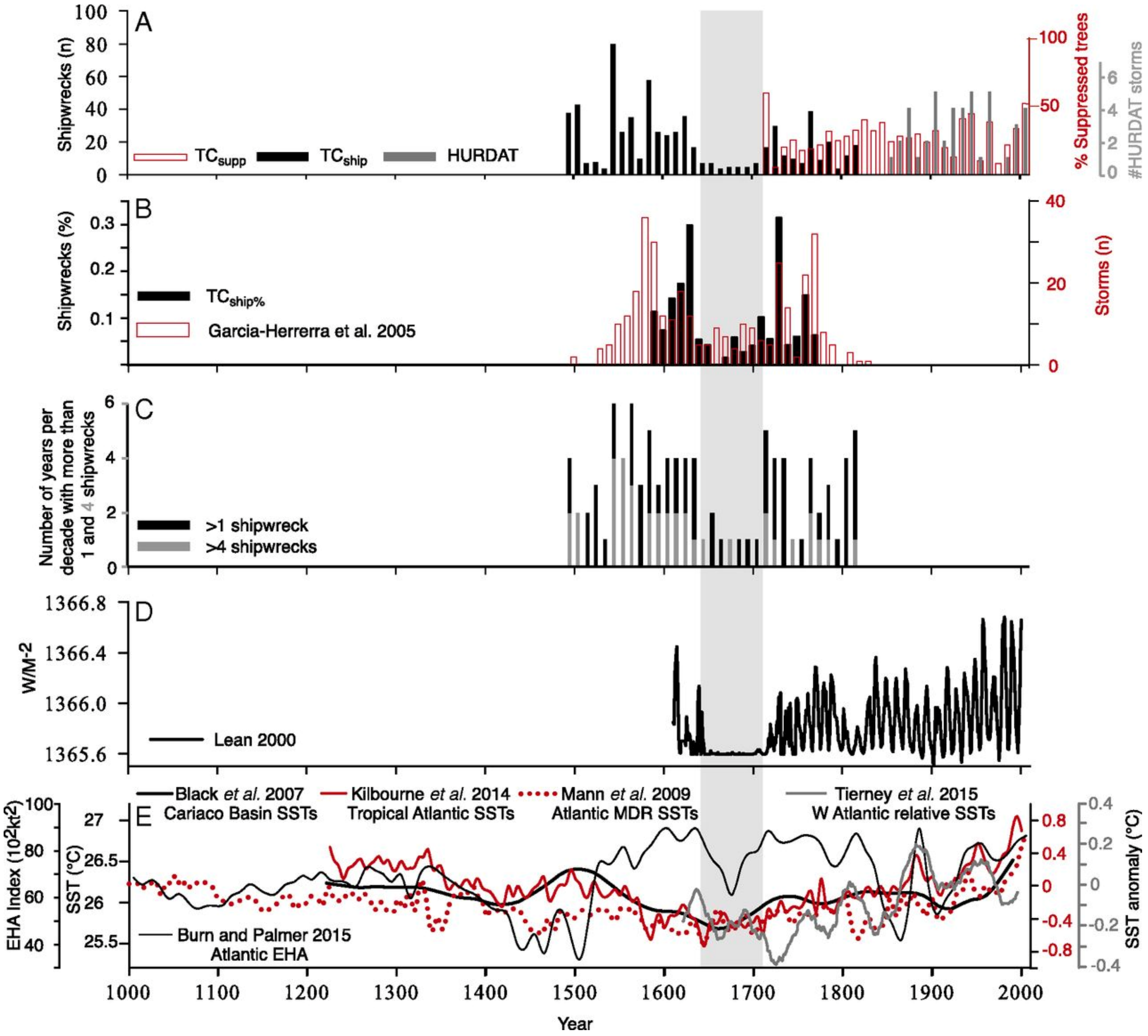

Control Climate

Late 21st Century Warmed Climate

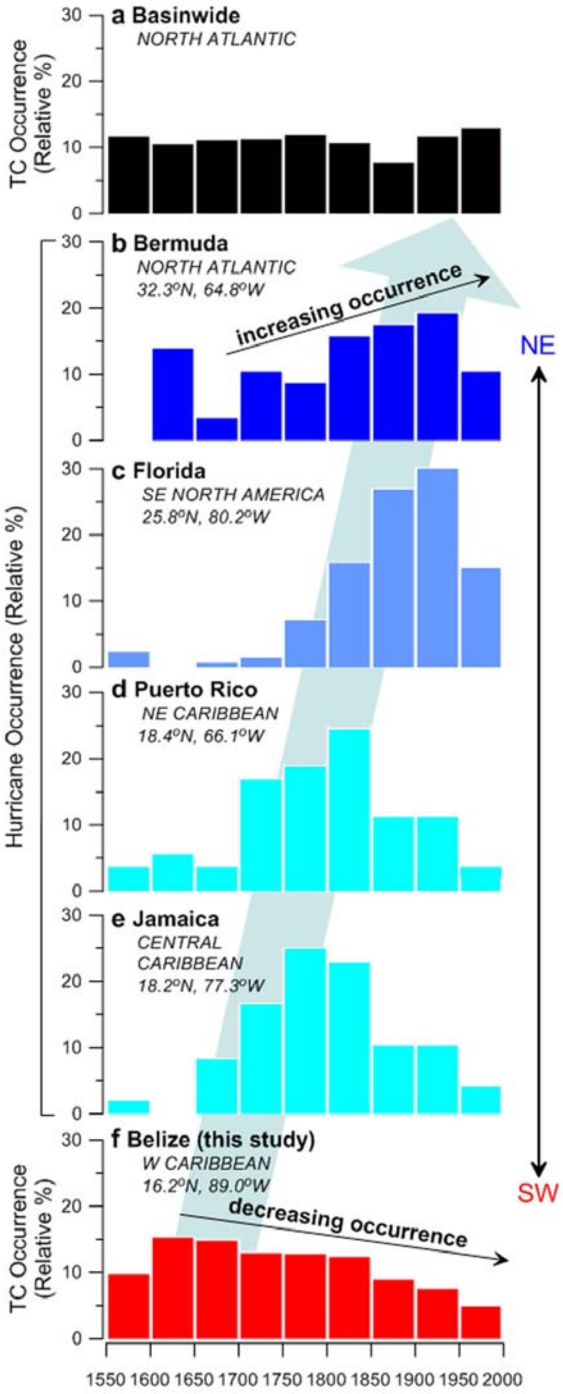
NWS Version (GFDL)

Tracks of North Atlantic hurricanes that reaches at least Category 4 intensity in the climate of the late 20th century (top) and late 21st century (bottom). These storms were simulated by a high resolution regional model driven by the global climate state representing an average of 18 global climate models. The regional model was developed at NOAA's Geophysical Fluid Dynamics Laboratory in Princeton, NJ. From Bender and co-authors, *Science*, 2010.

# Inferences from Spanish Shipwrecks



Trouet at al., PNAS. 2016



**The YOK-GTC reconstruction compared to documentary records of hurricane landfall in the Caribbean and North Atlantic Basins.** Frequency distributions (relative %) of hurricanes affecting (**a**) the entire North Atlantic Basin and locations along the western margin of the North Atlantic (**b**) Bermuda, (**c**) Florida, (**d**) Puerto Rico, and (**e**) Jamaica, calculated from previously published documentary data. From Baldini et al., Nature Scientific Reports, 2016, DOI: 10.1038/srep37522

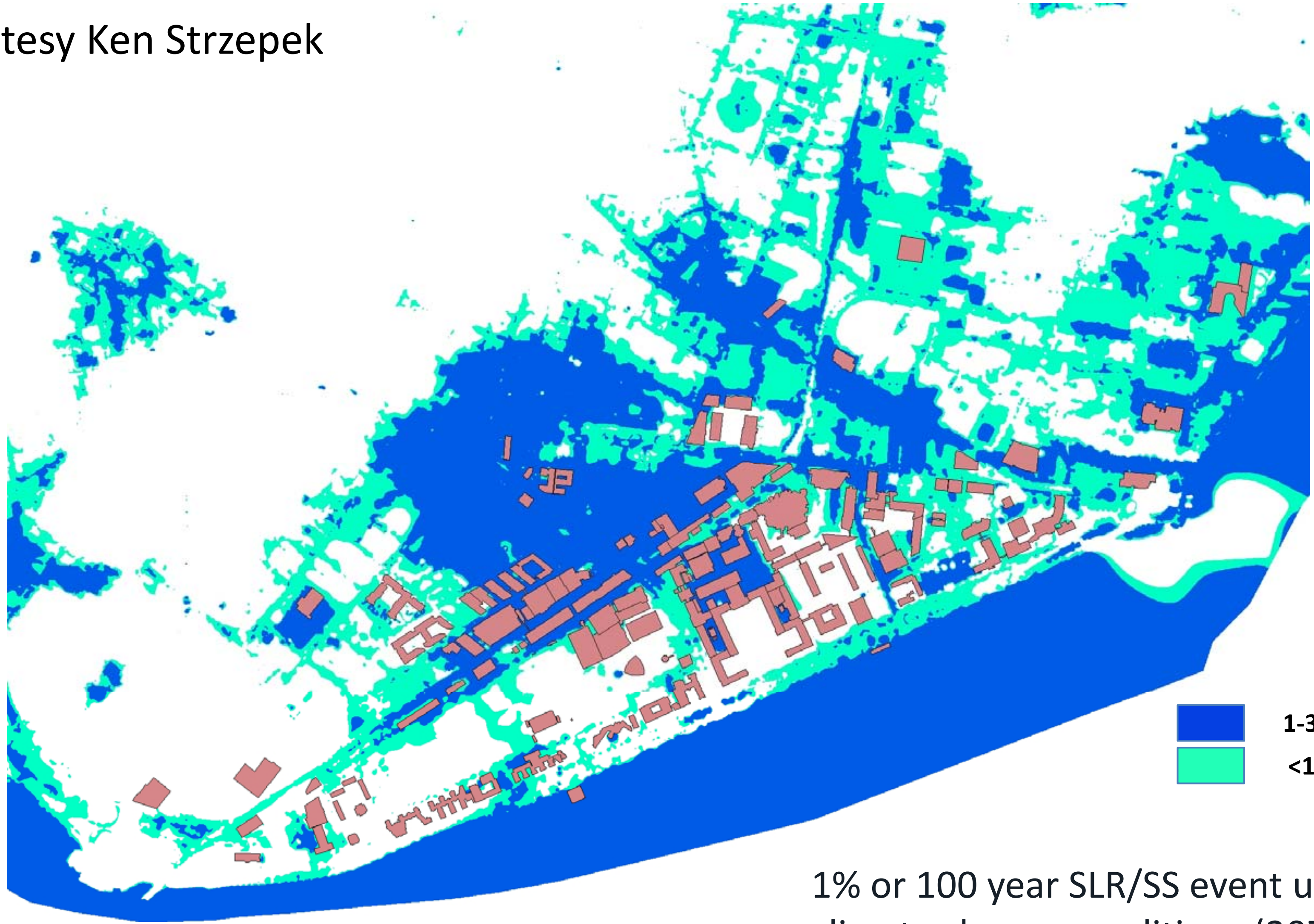
Belize data based on stable isotope analysis of stalagmites at Yoks Balum cave in southern Belize

# MIT's Hurricane Flood Risk

## (with Sai Ravela, Ken Strzepek, and the MIT Resilience Committee)

# Sea Level Rise / Storm Surge Propagation (2070)

Courtesy Ken Strzepek



Note: not for distribution – in-progress MIT Flood Vulnerability Study (Jun 2017); based on MassDOT/Central Artery Flood Modelling assumptions for river levels

1% or 100 year SLR/SS event under climate change conditions (2070) (**precipitation not yet included**)