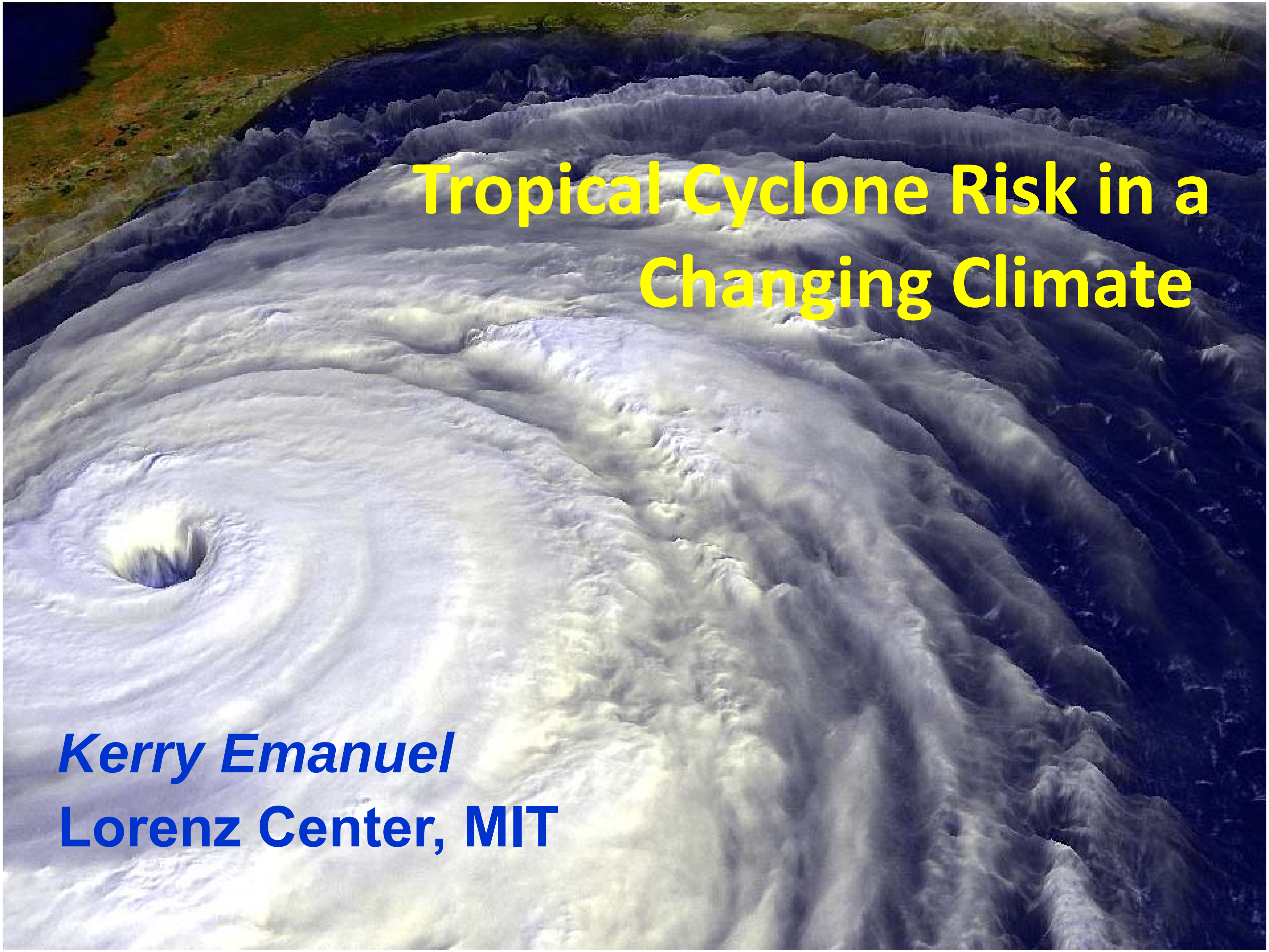


Tropical Cyclone Risk in a Changing Climate

Kerry Emanuel

Lorenz Center, MIT

Hurricane Risks:

- Wind

- Rain

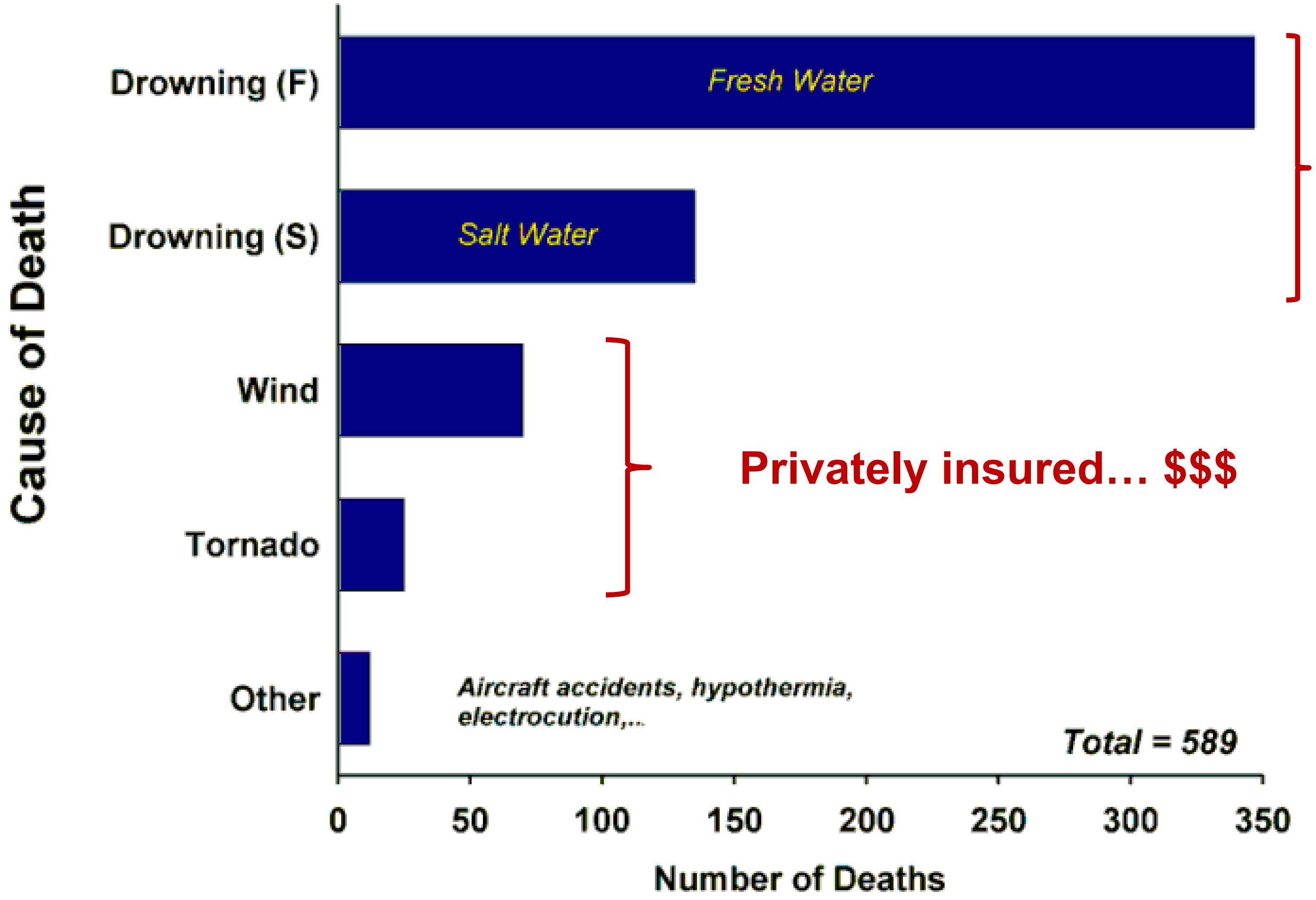
- Storm Surge

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)

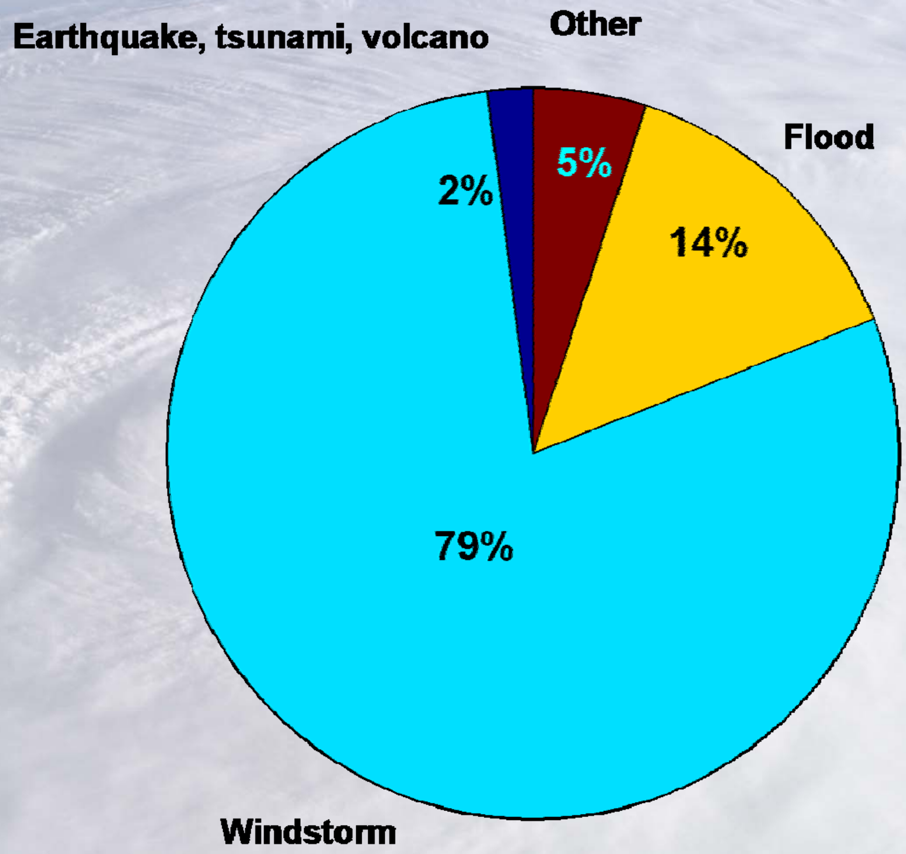


Publicly insured… No $$$

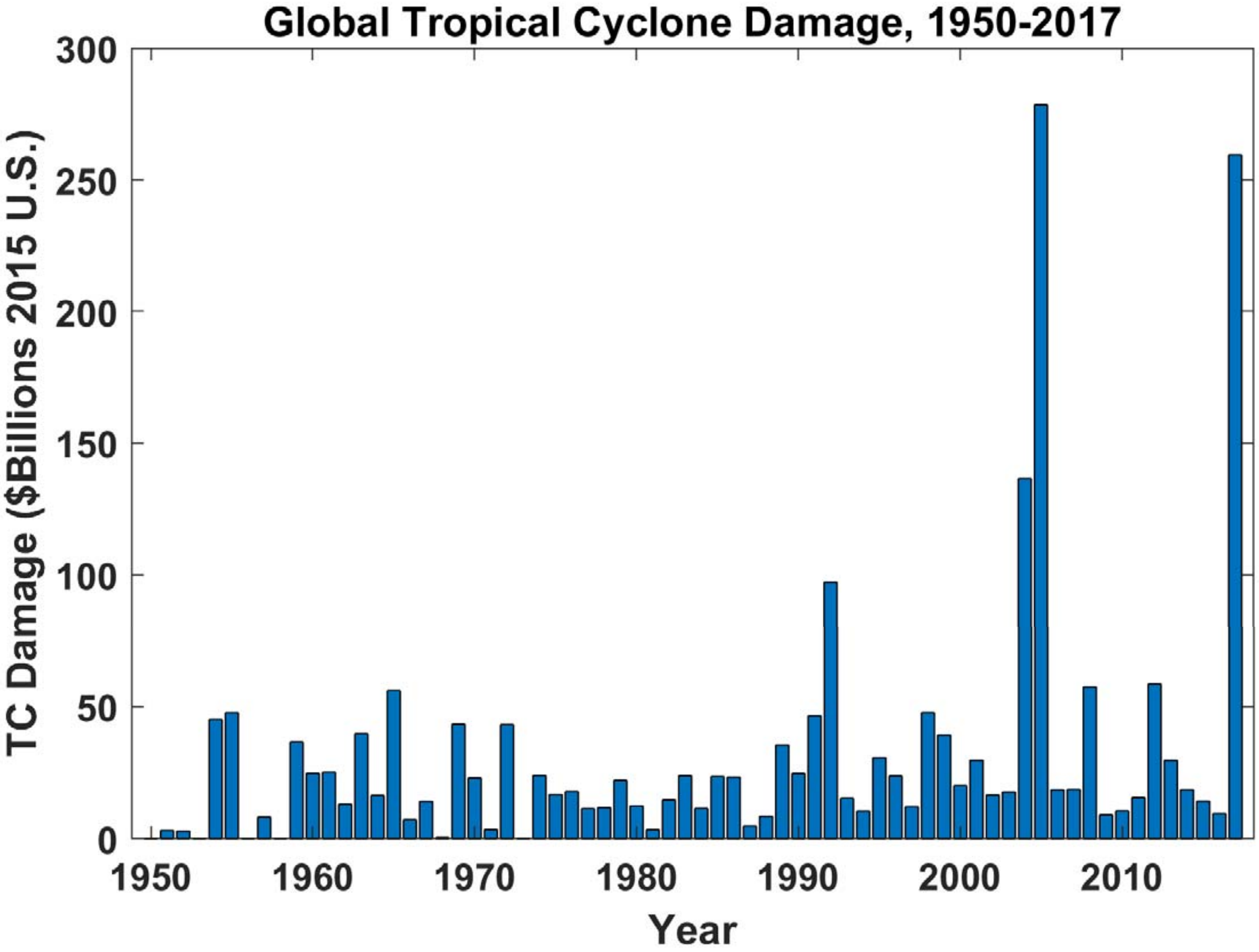
Privately insured… $$$

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)



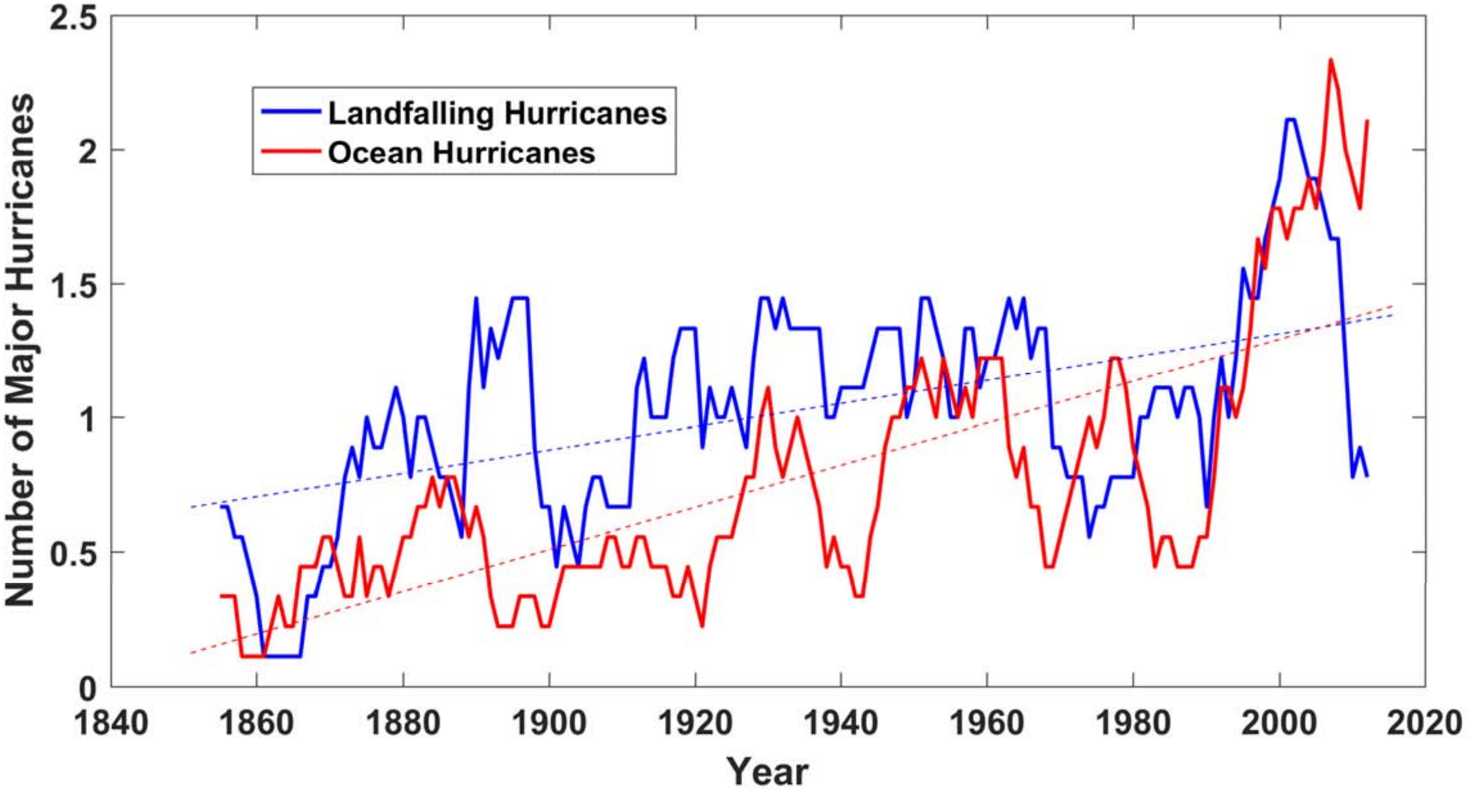
EM-DAT, 2018: The OFDA/CRED International Disaster Database
http://www.emdat.be/. GDP correction from Federal Reserve Bank

Is Hurricane Risk Changing?

Historical Records

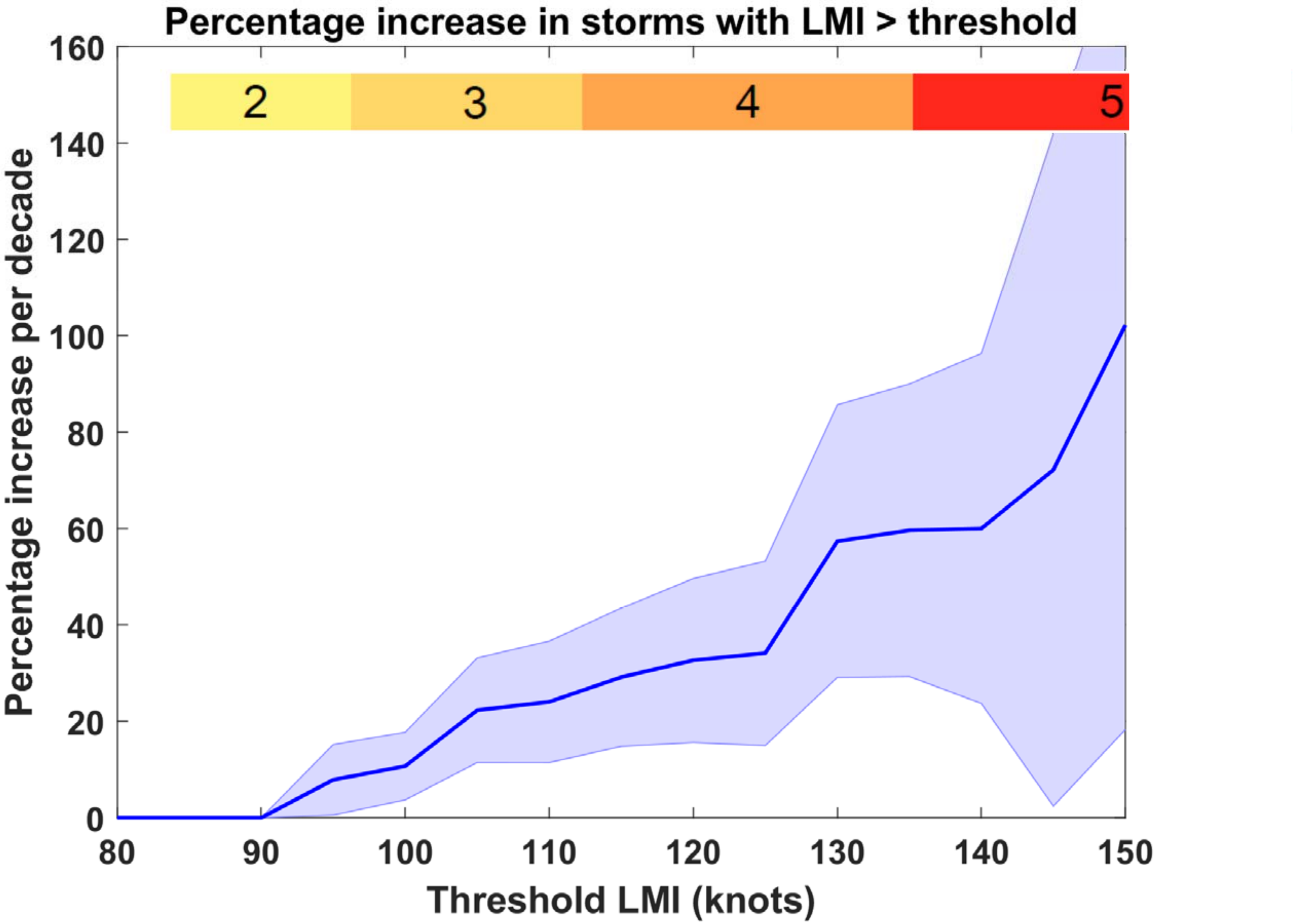
- Pre-1943: Anecdotal accounts from coastal cities and ships
- 1943: Introduction of routine aircraft reconnaissance in Atlantic, western North Pacific
- 1958: Inertial navigation permits direct measurement of wind speed at flight level
- 1970: Complete global detection by satellites
- 1978: Introduction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

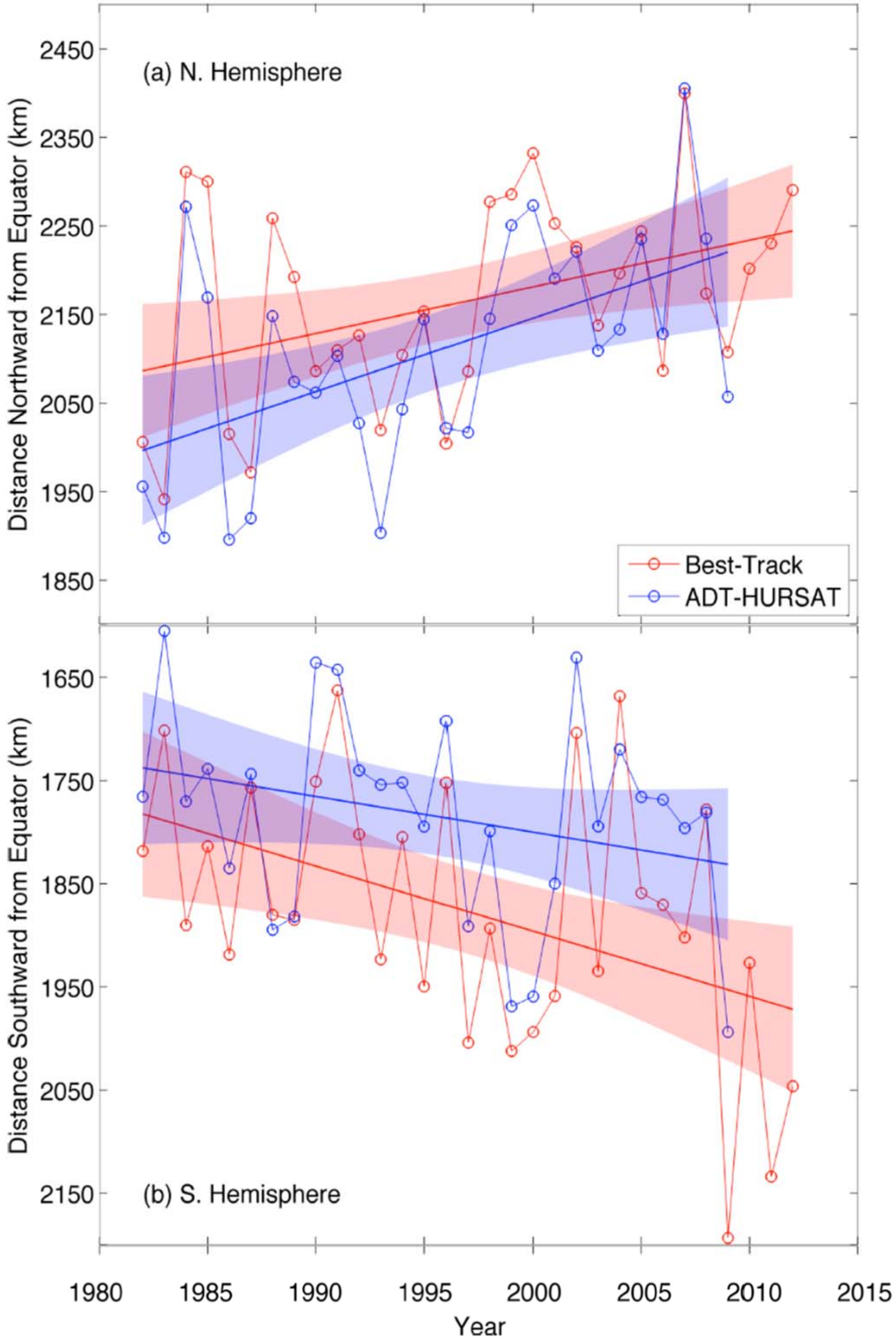
Historical Records:
Prior to 1970, Many Storms Were Missed



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 $p < 0.05$.



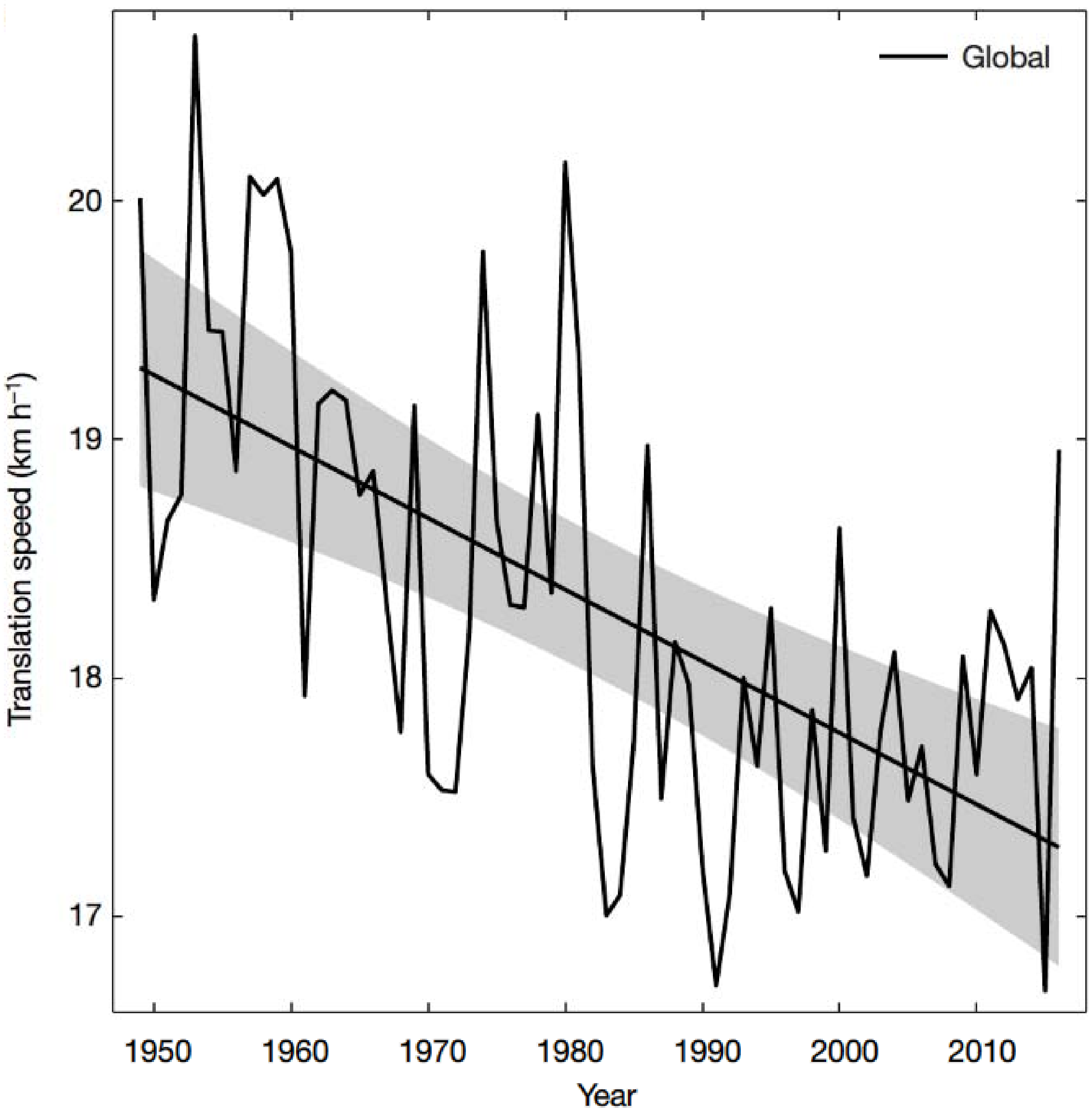


Hurricanes are reaching peak intensity at higher latitudes

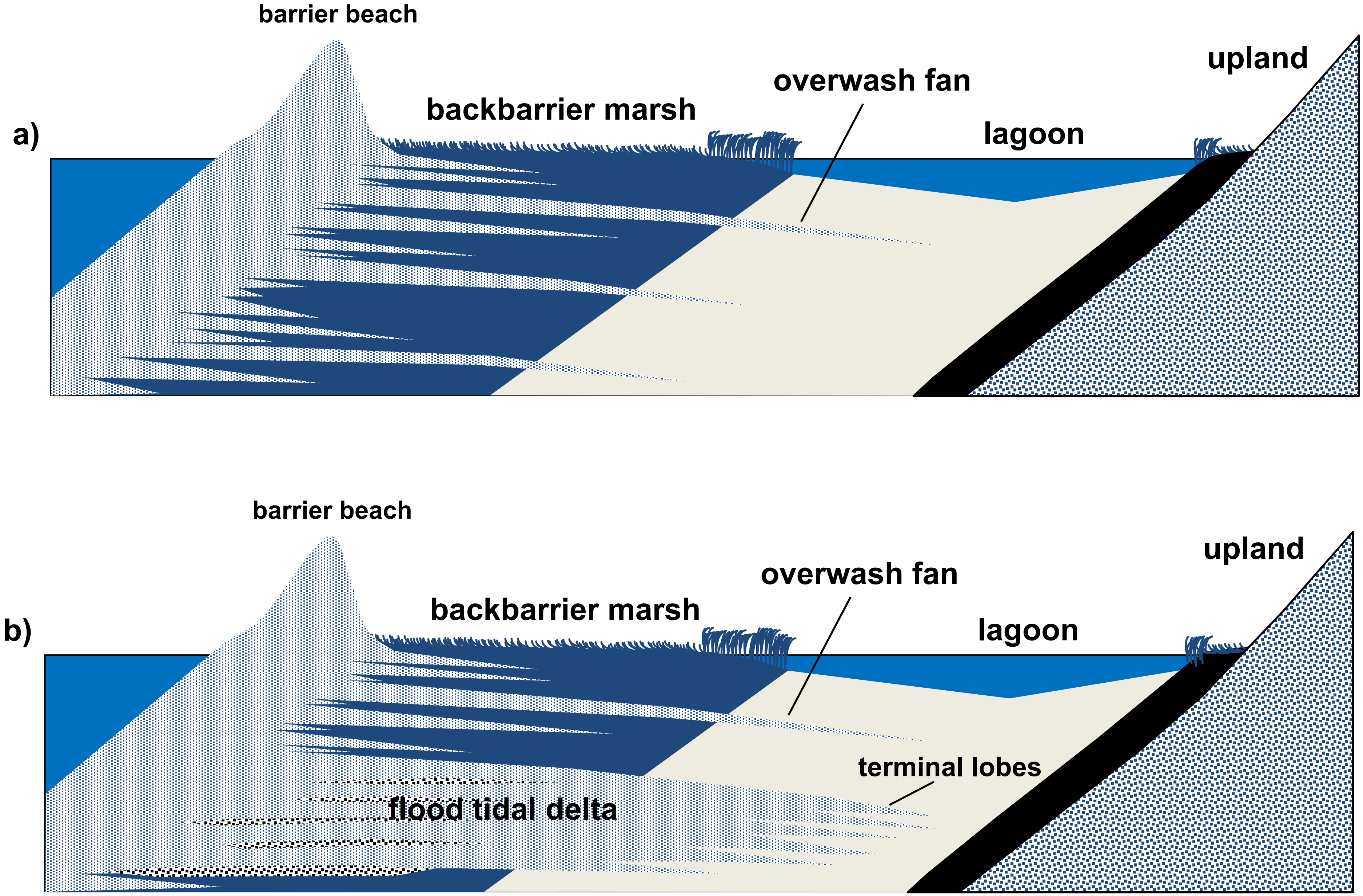
Time series of the latitudes at which tropical cyclones reach maximum intensity.

From *Kossin et al. (2014)*

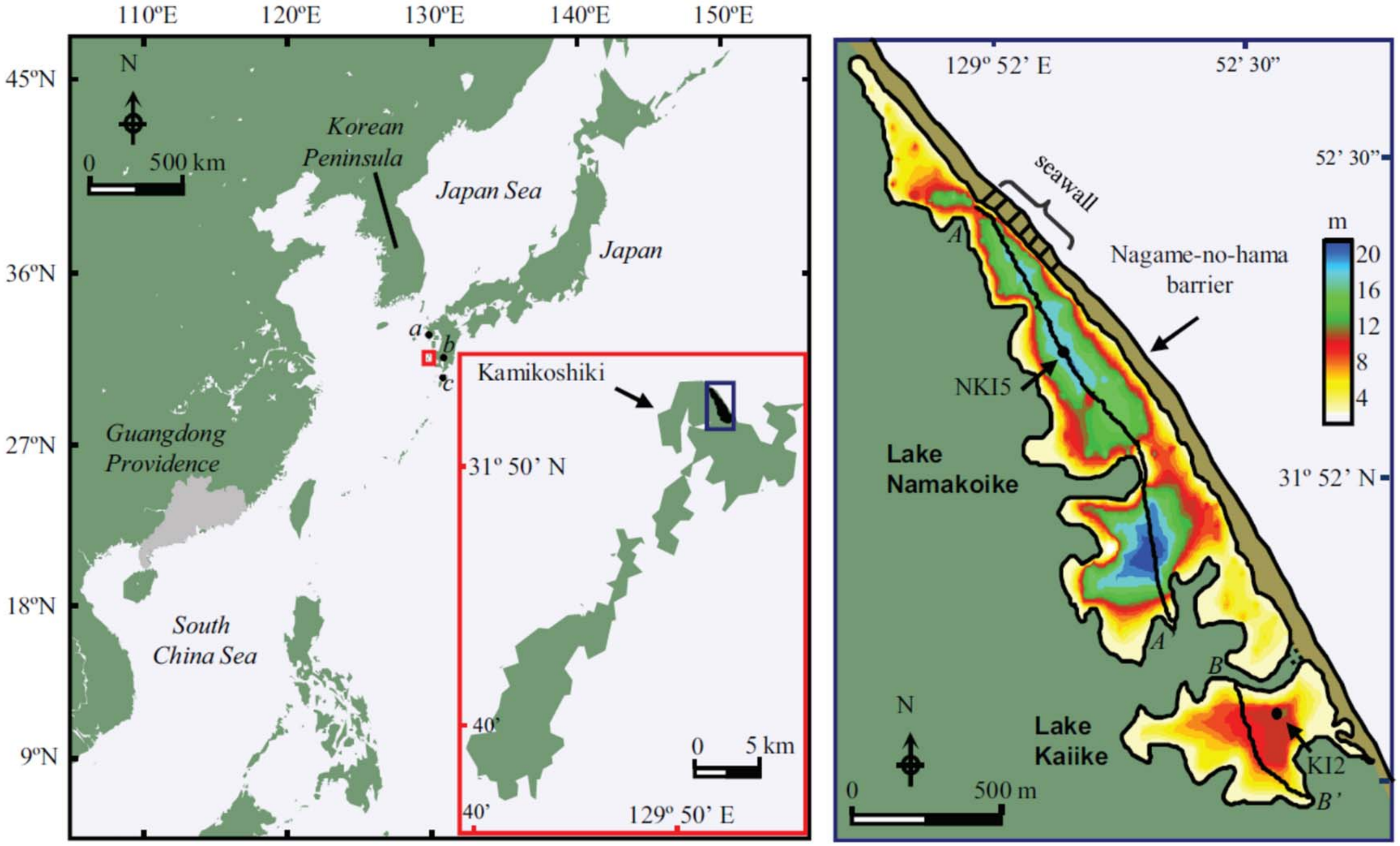
Tropical Cyclones are Slowing Down (Kossin, Nature, 2018)



Paleotempestology

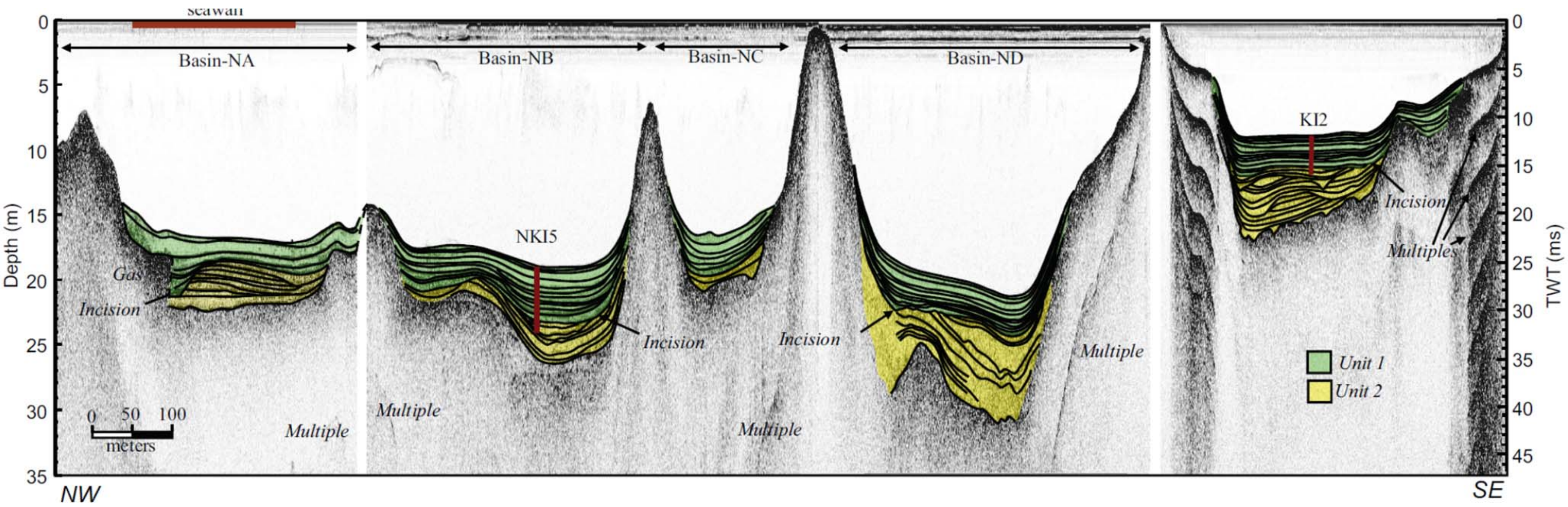


Source: Jeff Donnelly, WHOI



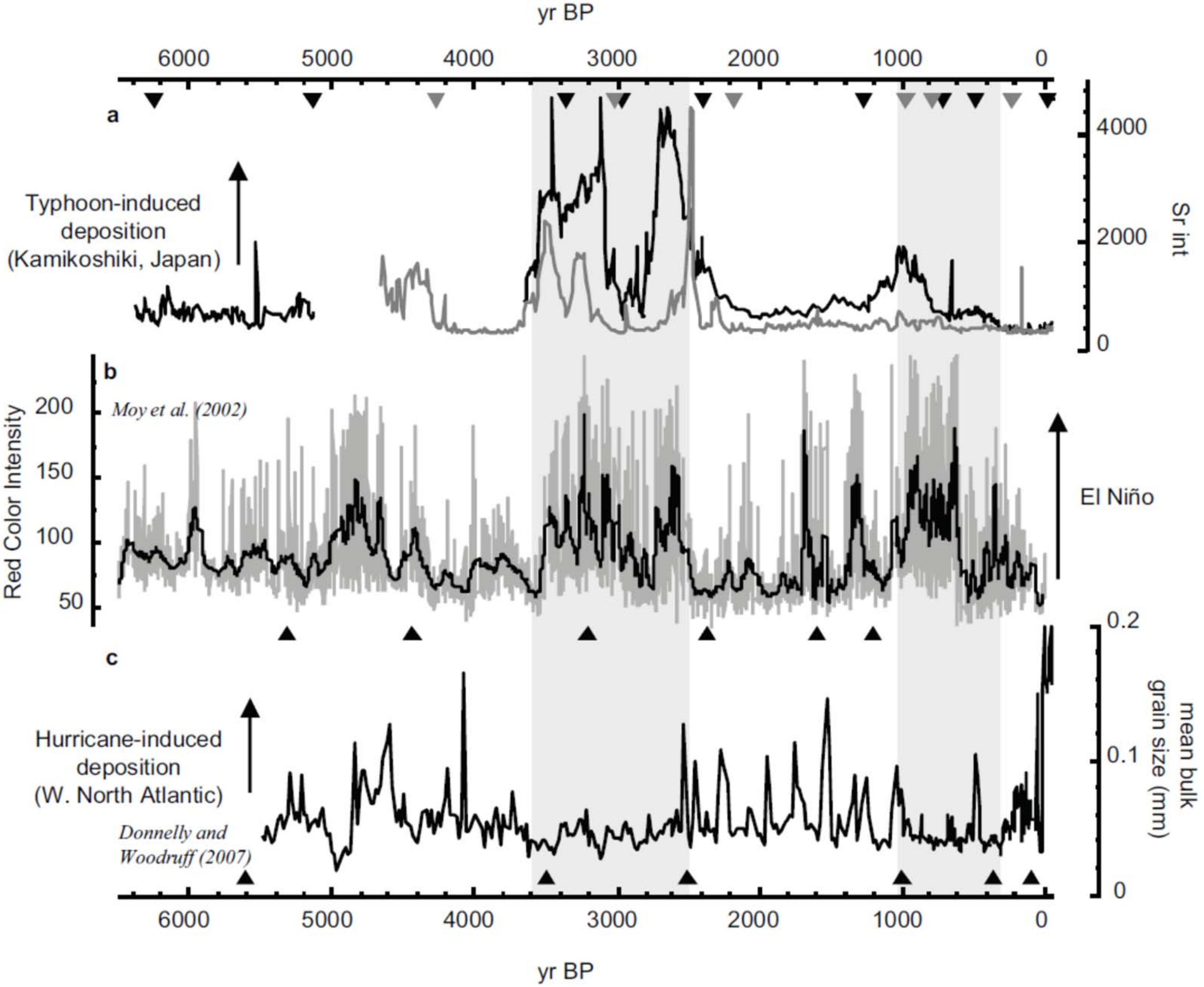
Map of the western North Pacific showing study area (open red square). The locations of Nagasaki, Kagoshima Bay, and Tanegashima are identified by a, b, and c, respectively.

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



Seismic surveys for Lake Namakoike and Lake Kaiike .
Tracklines are shown in Figure 1. Green shading identifies top sedimentary unit described in text (Unit 1), and yellow shading identifies lower unit (Unit 2). Truncated stratigraphy and cut/fill features at the contact between the two units are suggestive of an erosional incision. Vertical lines indicate locations and approximate depths for cores NKI5 and KI2.

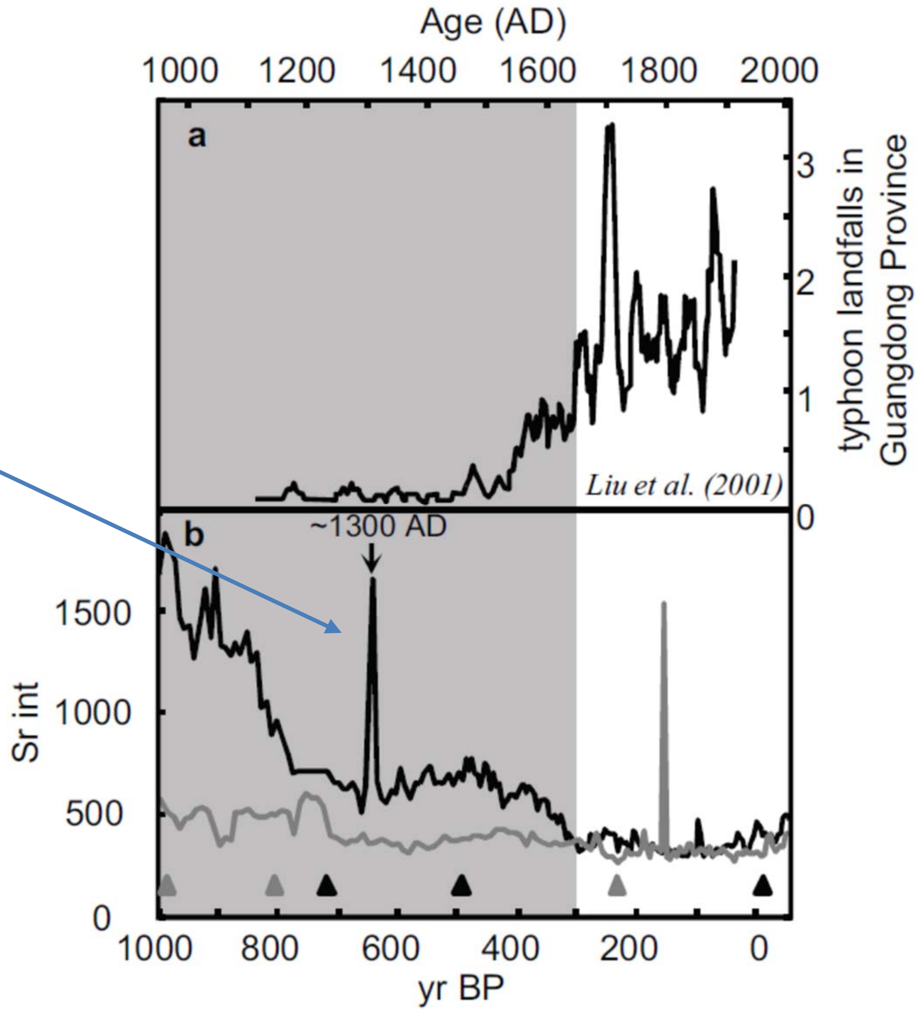
Woodruff et al., *Quatern. Sci. Rev.*, 2009



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).

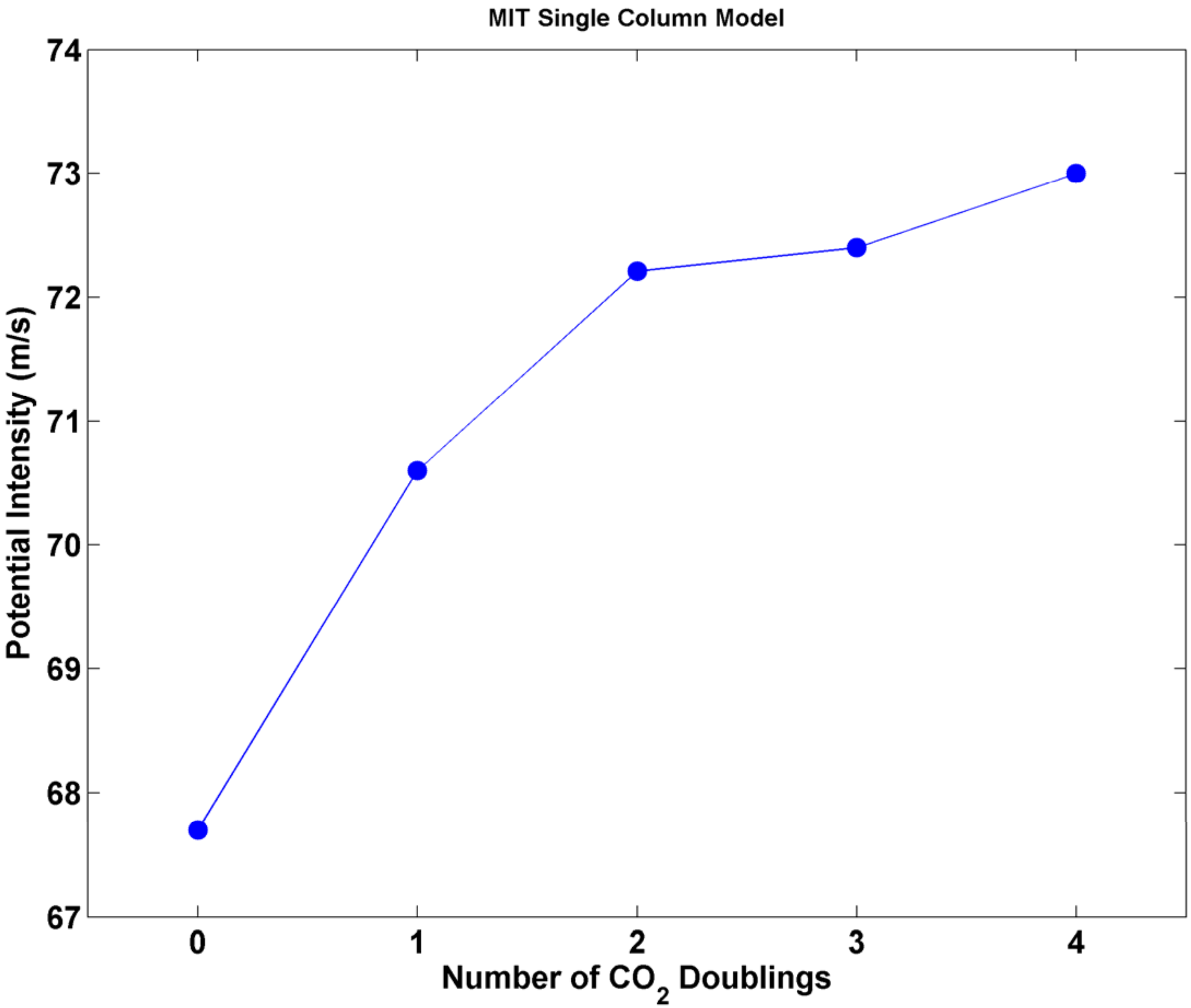
Woodruff et al., *Quatern. Sci. Rev.*, 2009

Possible Mongol invasion typhoon

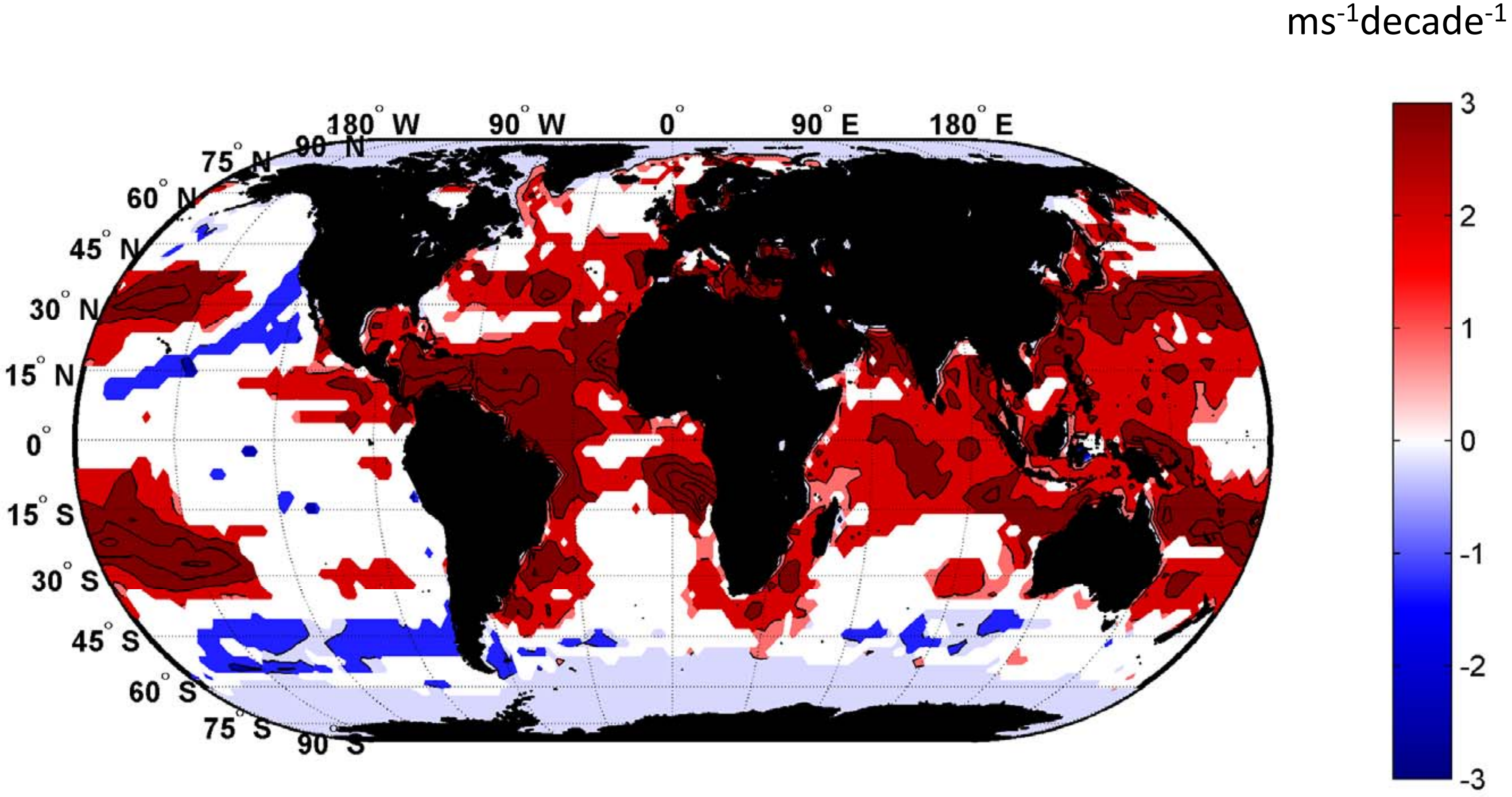


Woodruff et al., *Quatern. Sci. Rev.*, 2009

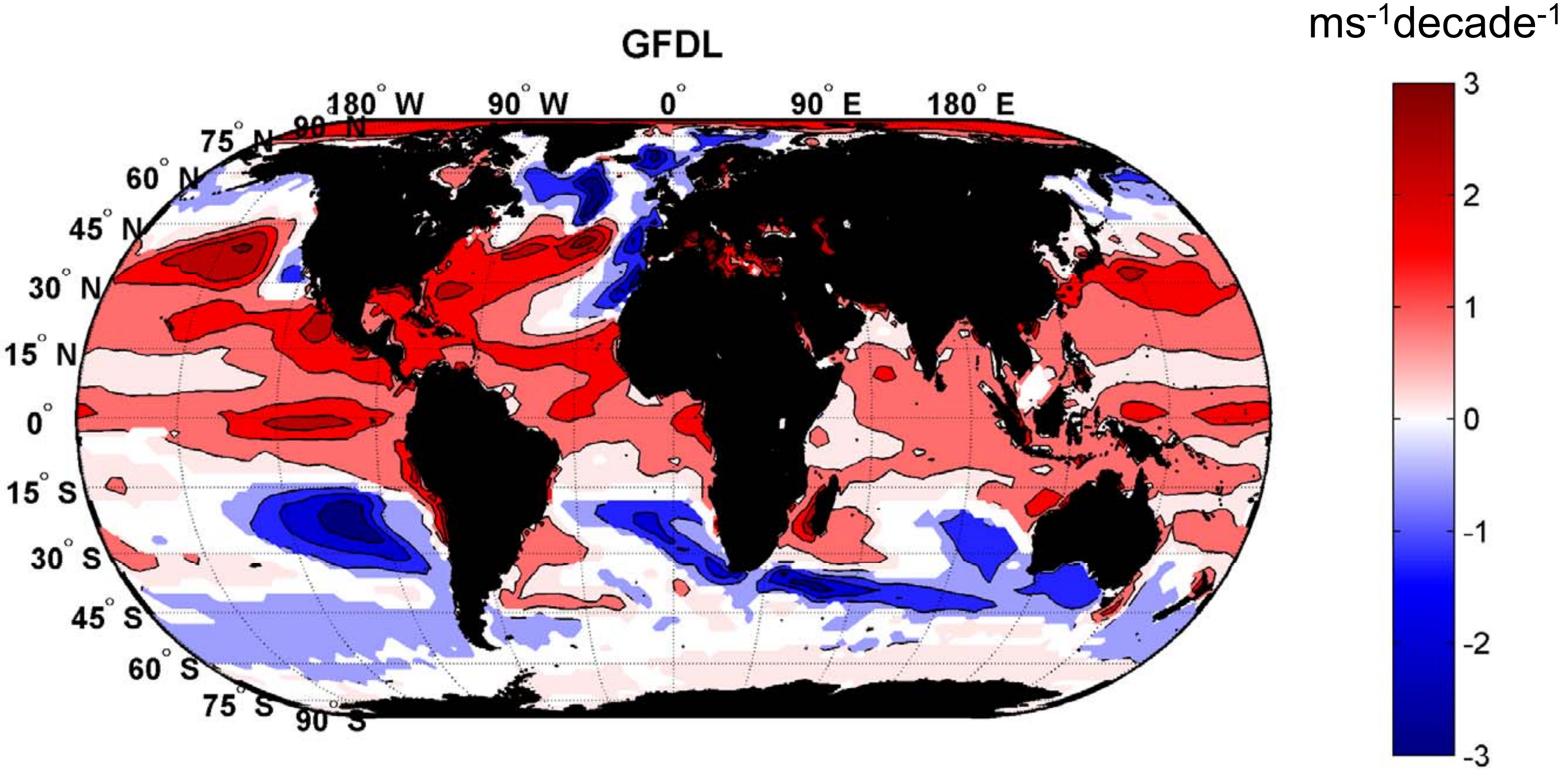
Potential Intensity and CO_2



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



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

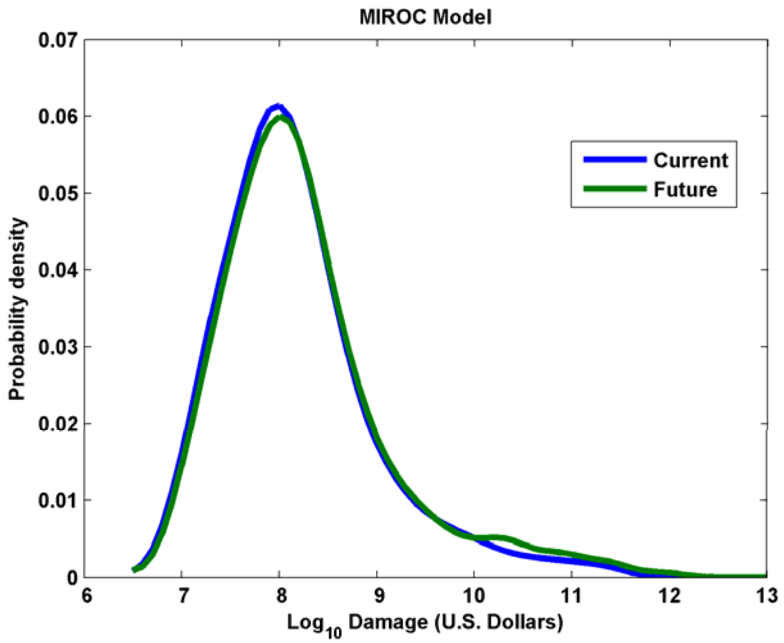


Inferences from Basic Theory:

- 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

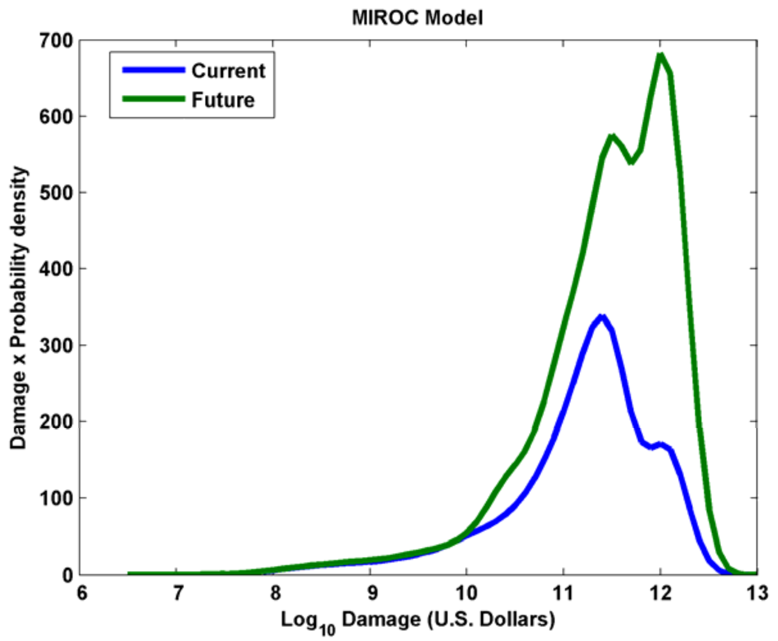
Risk Assessment in a Changing Climate: The Problem

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!

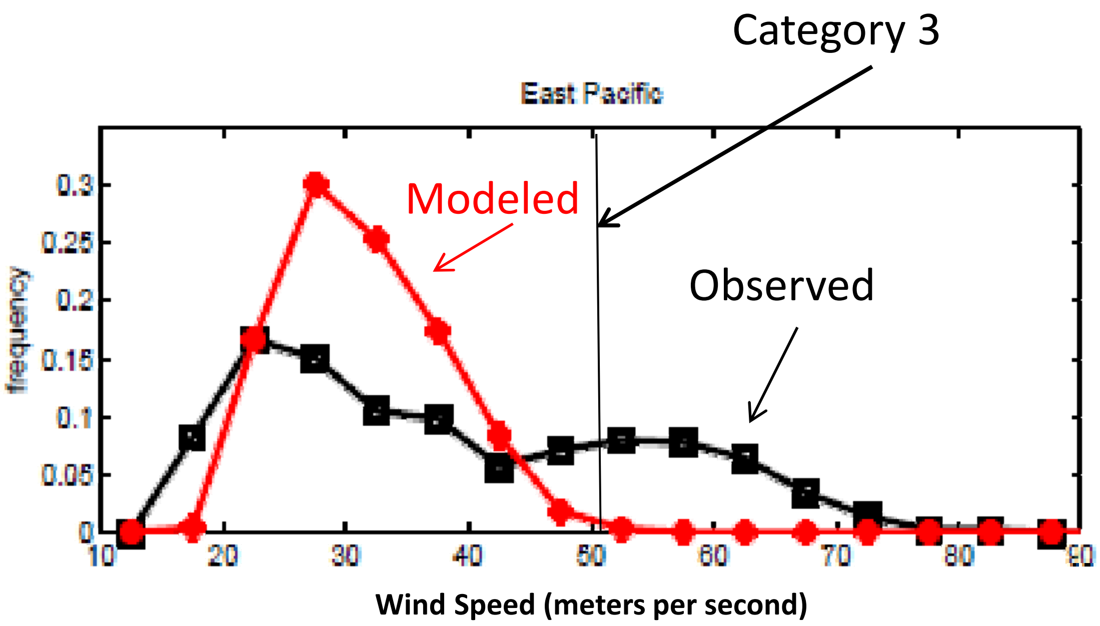
How We COULD Deal with This:

- 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
    - May now be impractical to run WRF for ~1,000 years, driven by GCMs, but that day is coming

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**

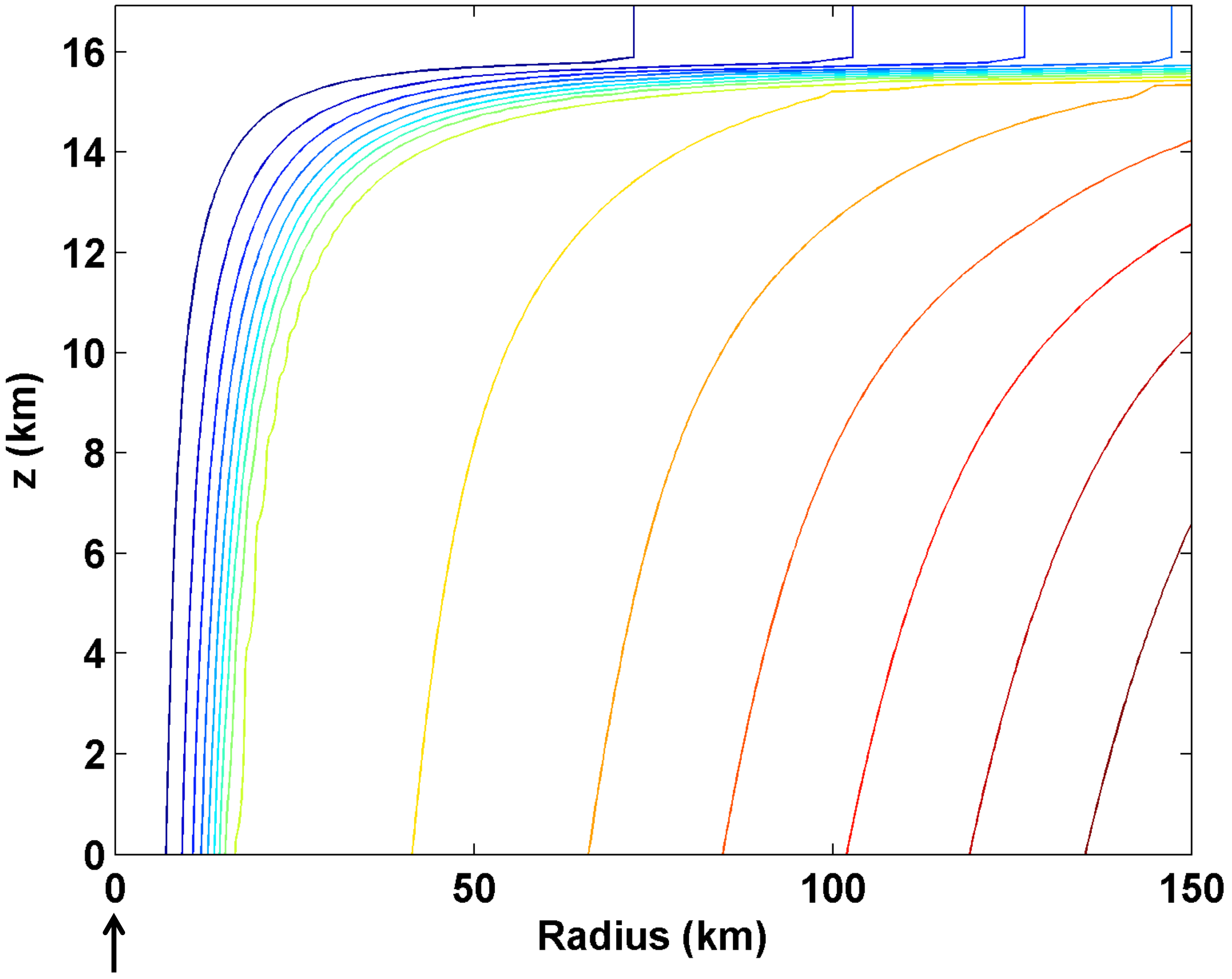
Time-dependent, axisymmetric model phrased in R space (CHIPS)

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

- **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***

Angular Momentum Distribution

Altitude
(km)

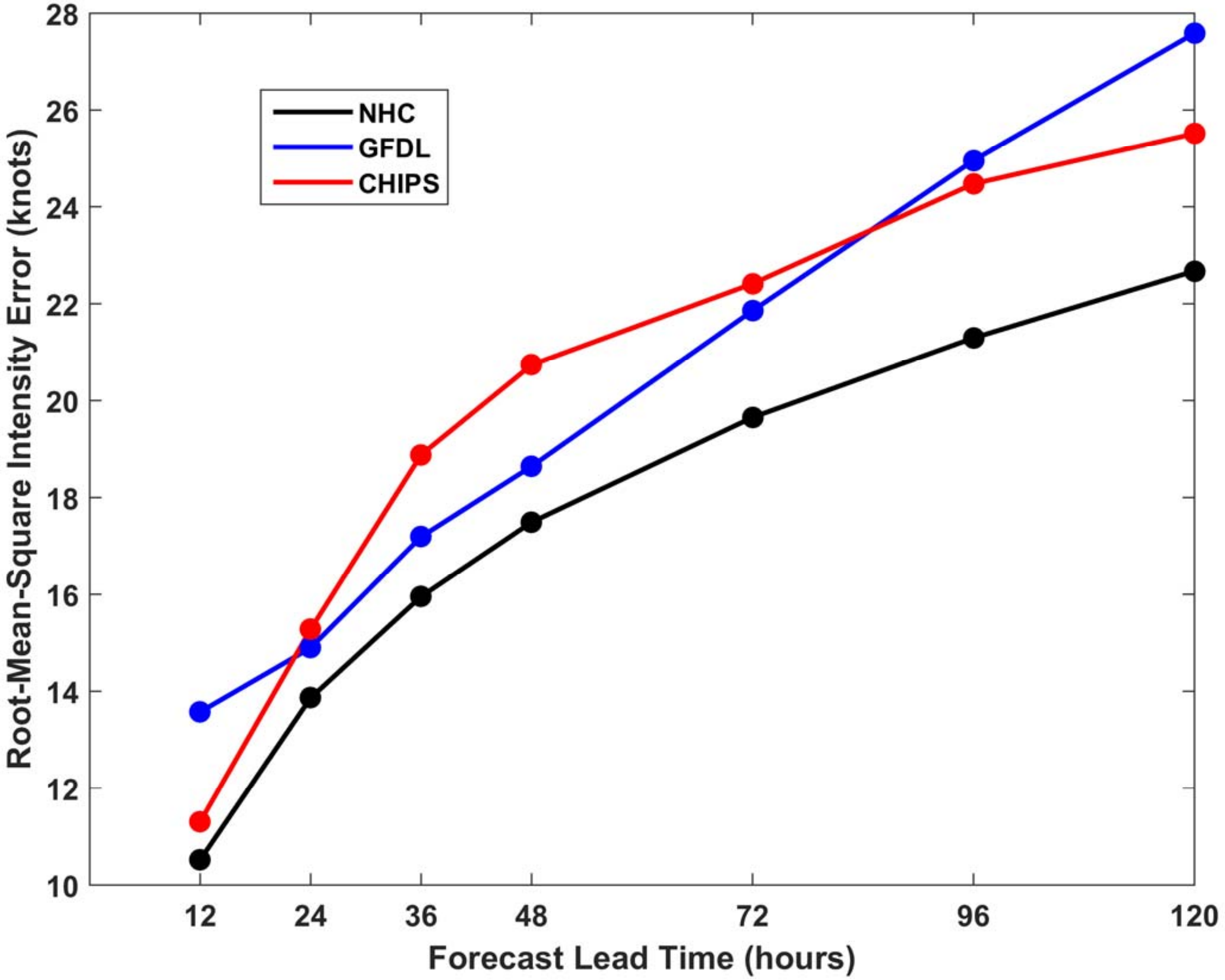


↑

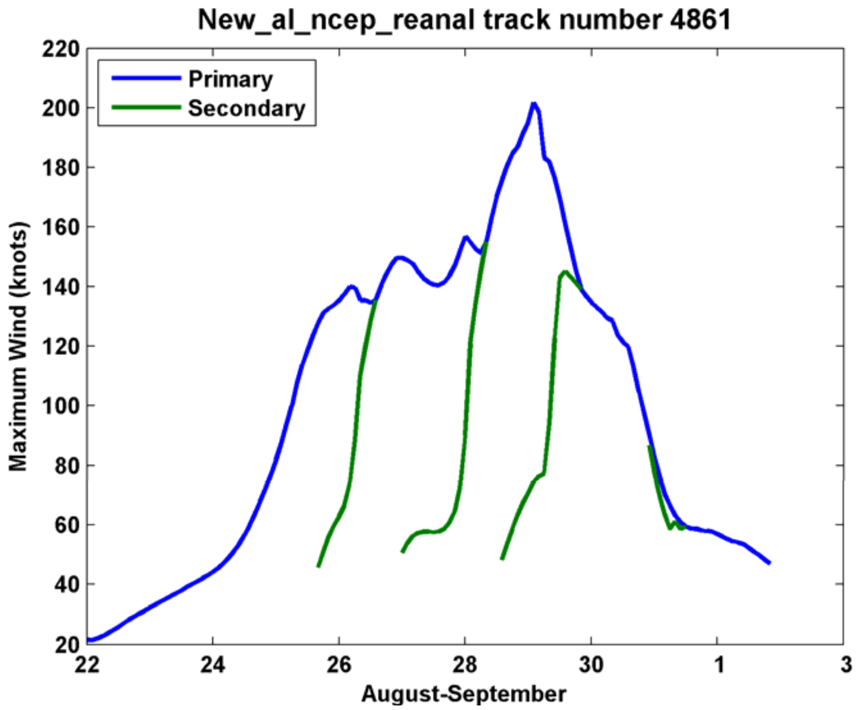
Storm Center

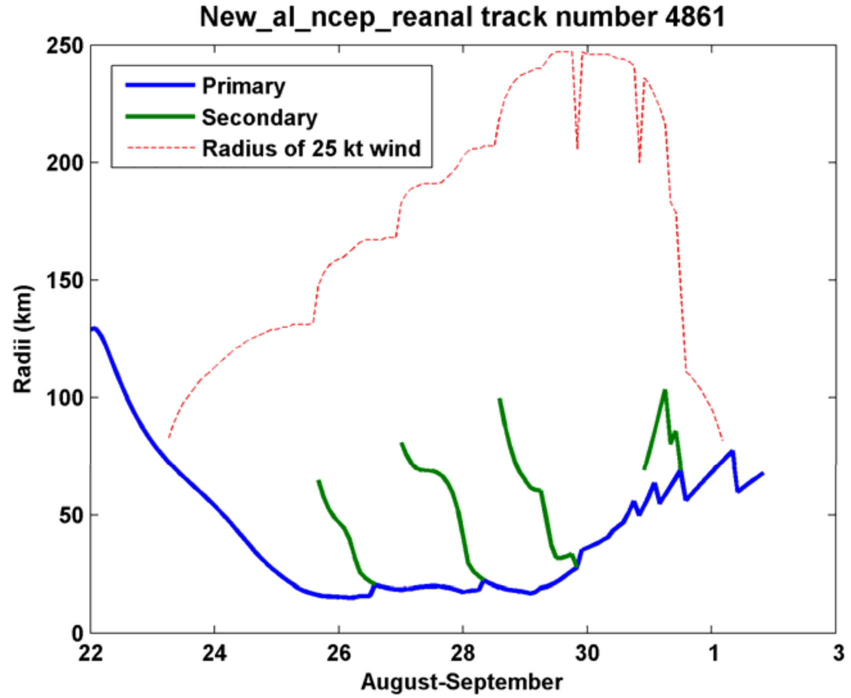
RMS Intensity Error, 2009-2015

North Atlantic

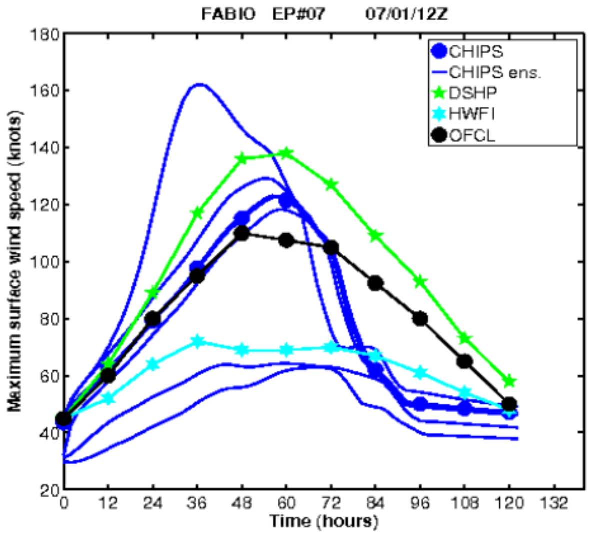


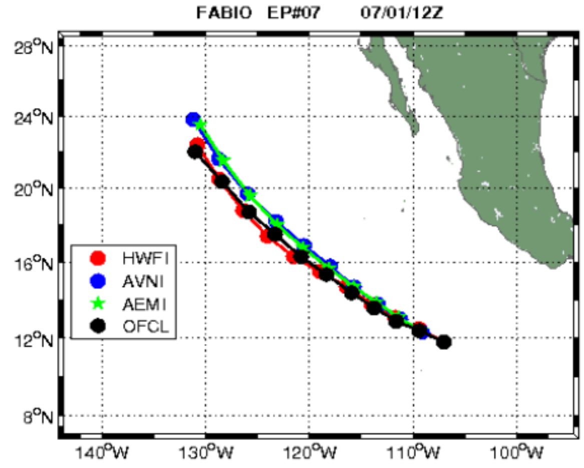
Secondary eyewalls

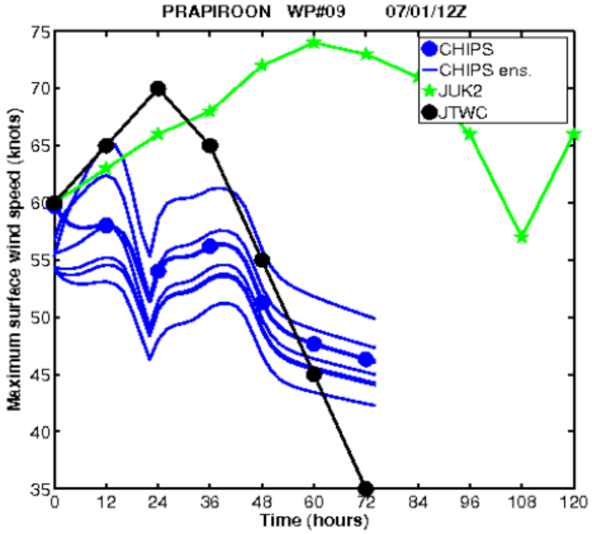

New_al_ncep_reanal track number 4861

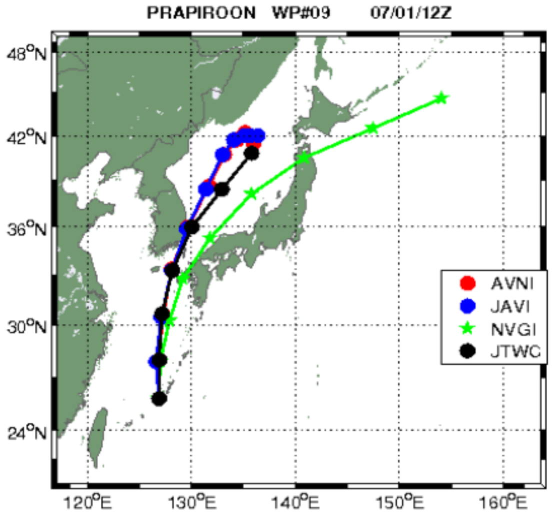

New_al_ncep_reanal track number 4861

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

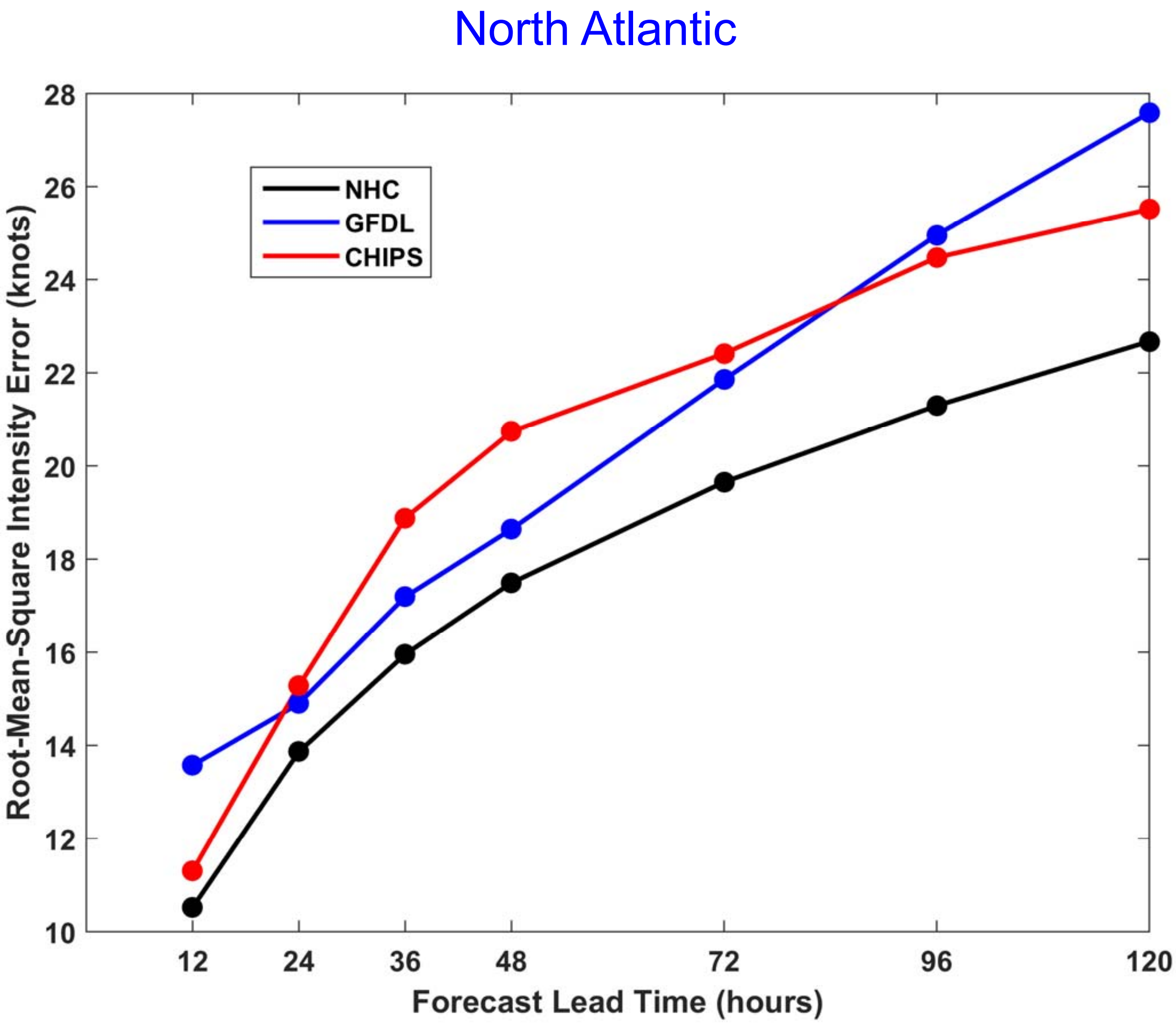








RMS Intensity Error, 2009-2015



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

Synthetic Track Generation:
Generation of Synthetic Wind Time Series

- **Postulate that TCs move with vertically averaged environmental flow plus a “beta drift” correction**

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

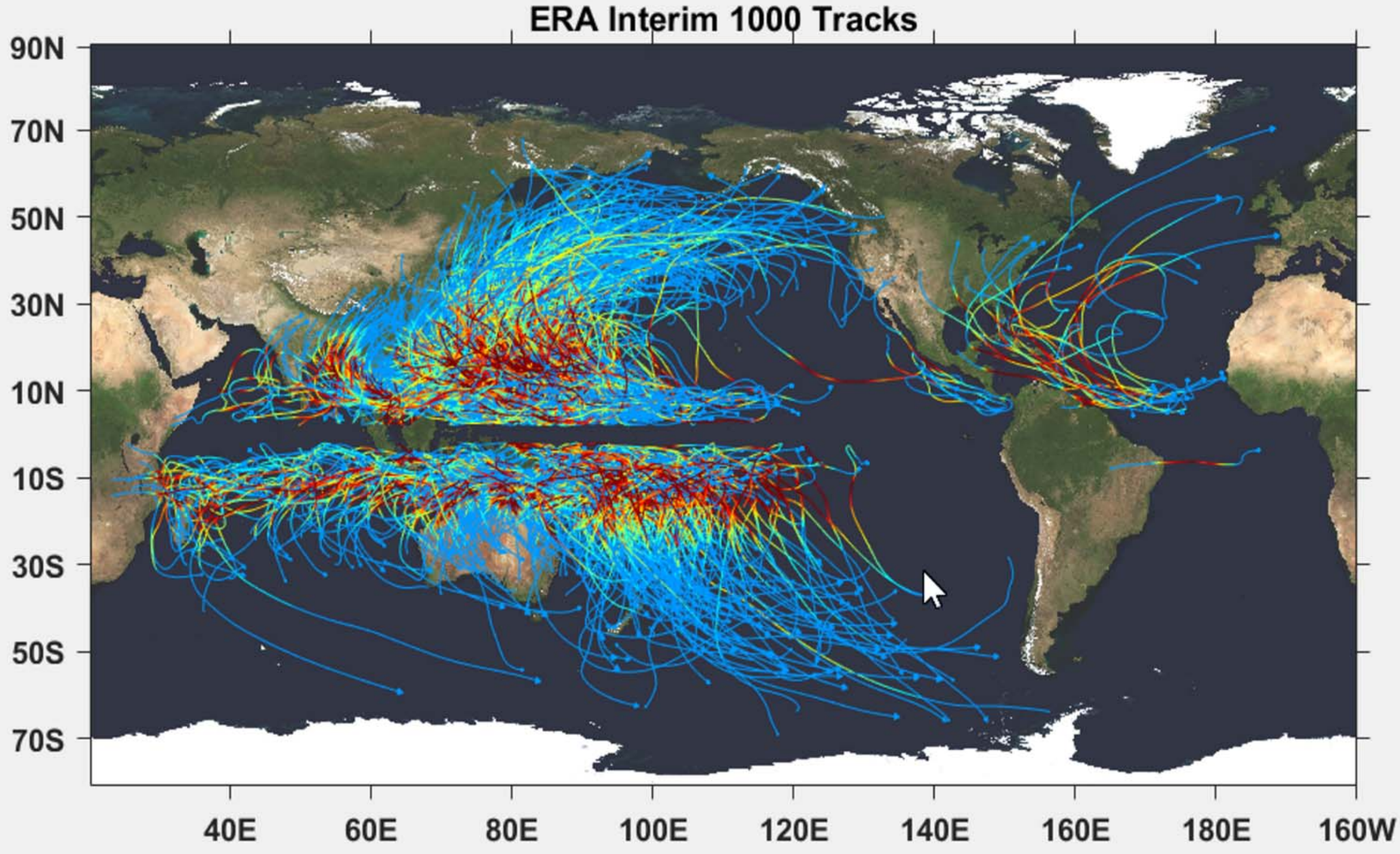
Synthetic wind time series

- **Monthly mean, variances and co-variances from re-analysis or global climate model data**

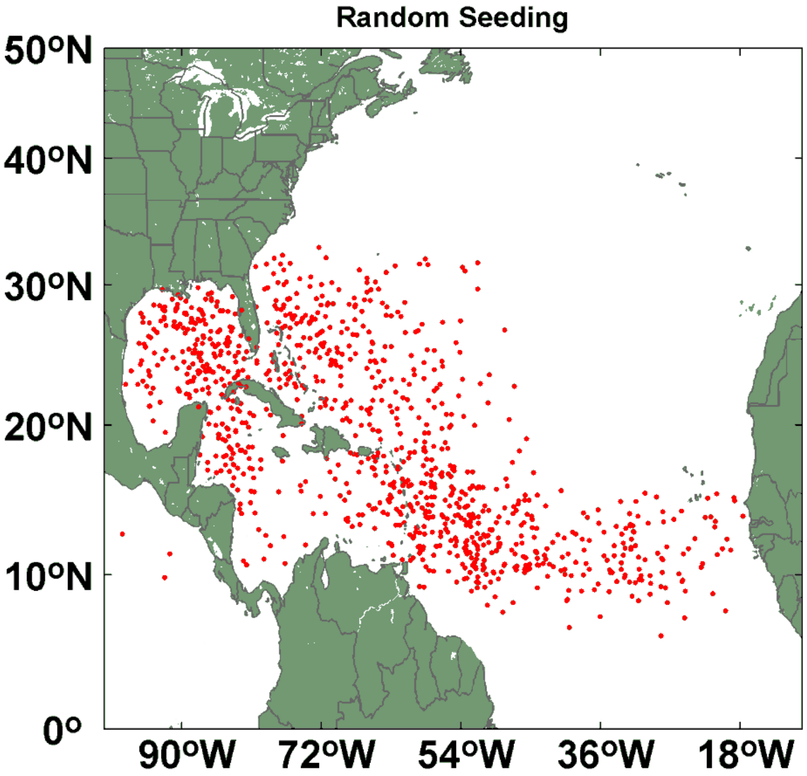
- **Synthetic time series constrained to have the correct monthly mean, variance, co-variances and an ω^{-3} power series**

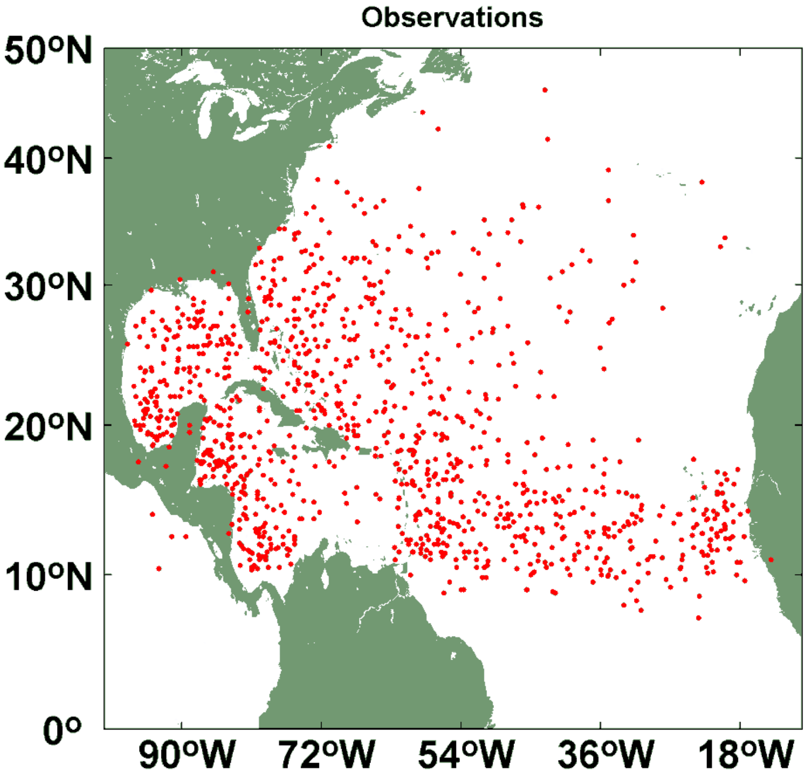
Calibration

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

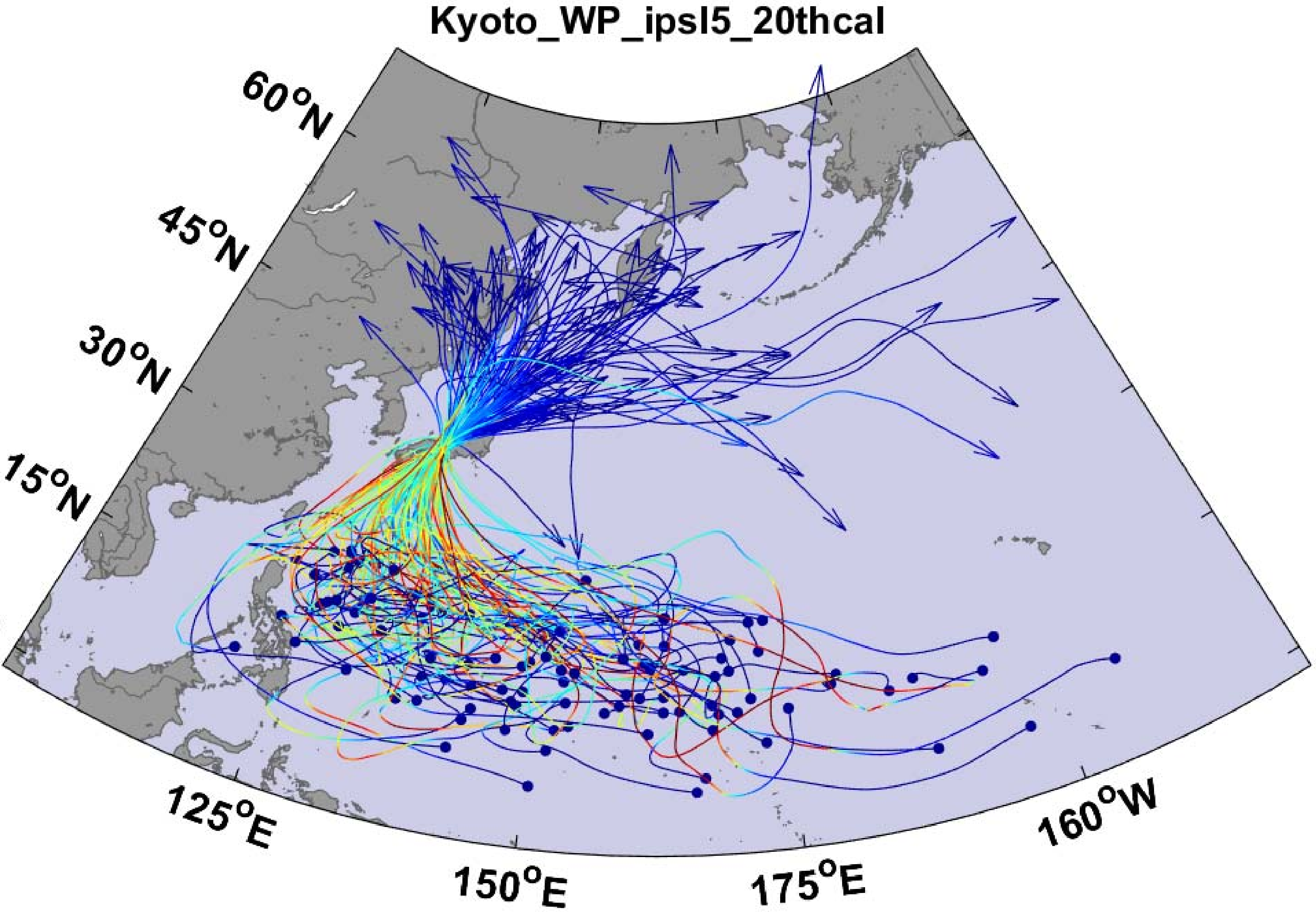

ERA Interim 1000 Tracks
90N
70N
50N
30N
10N
10S
30S
50S
70S
40E
60E
80E
100E
120E
140E
160E
180E
160W

Comparison of Random Seeding Genesis Locations with Observations

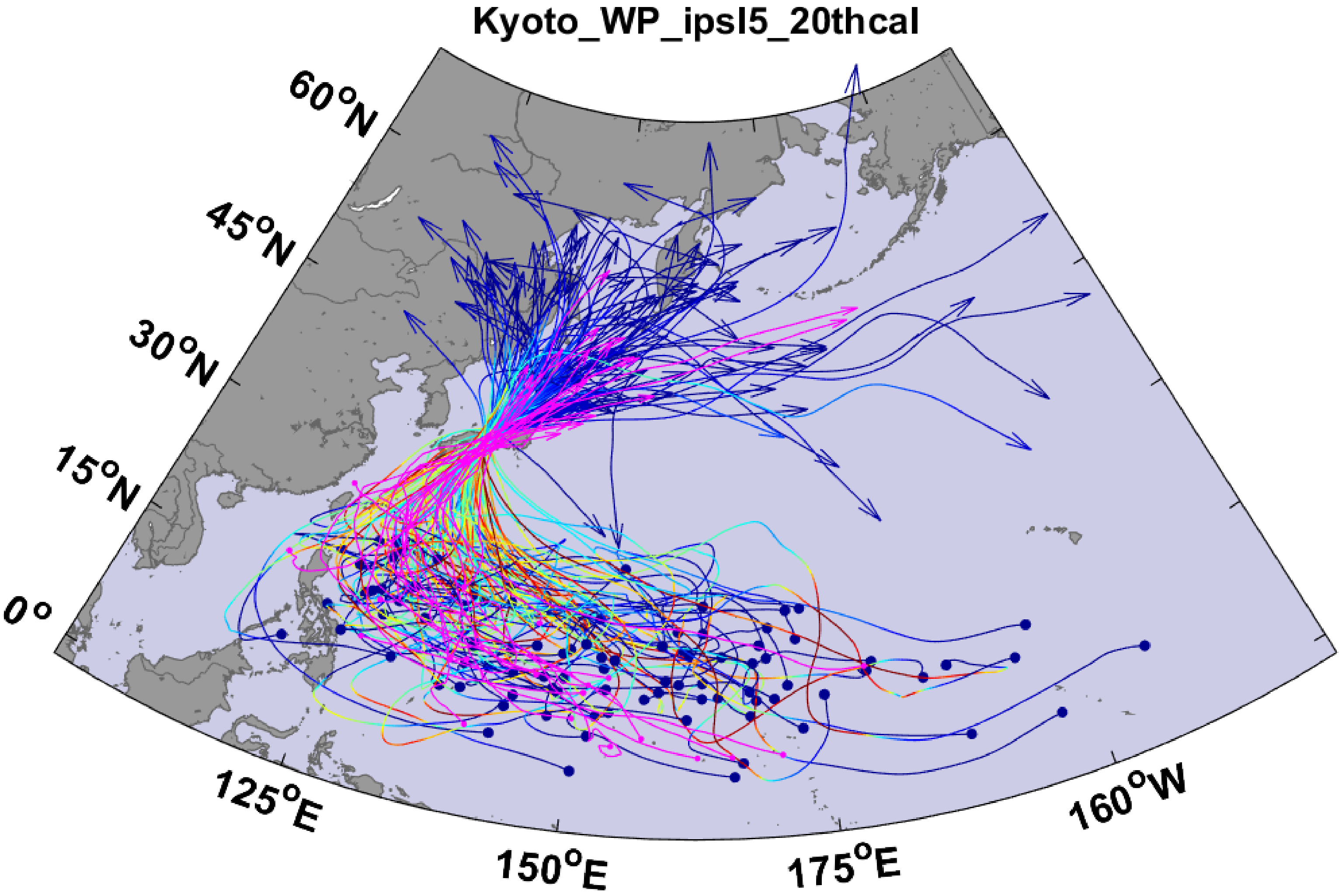




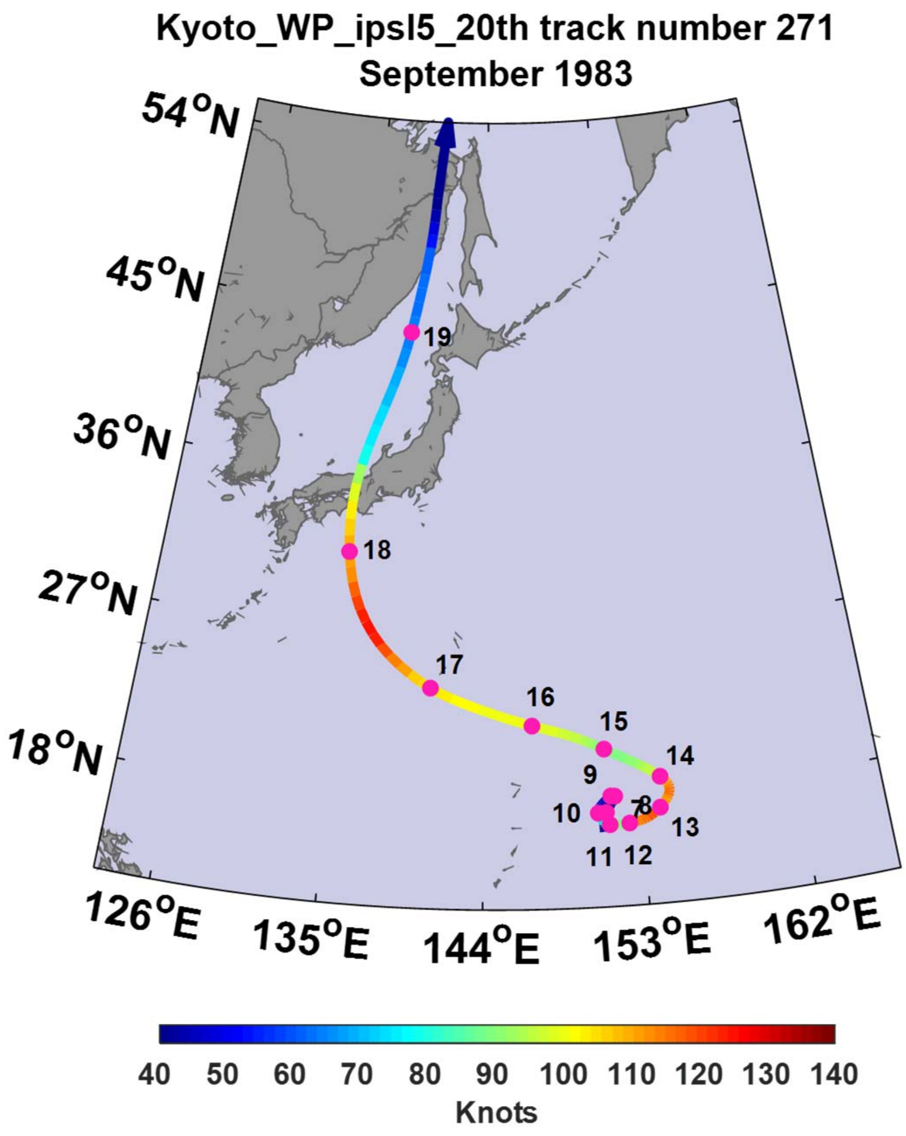
Top 100 out of 2000 TCs Affecting Kyoto, 1981-2000



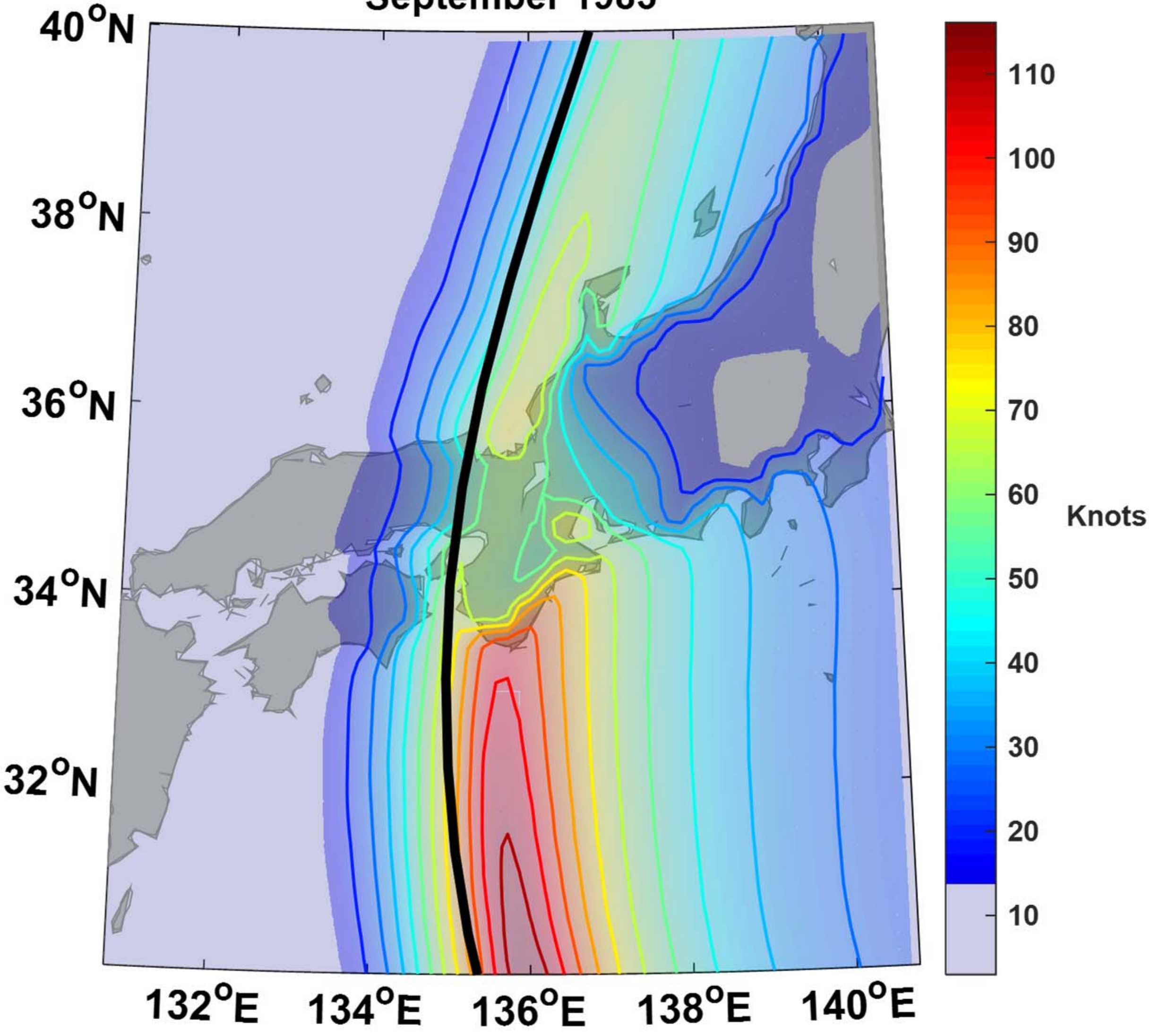
Same, but with top 20 historical tracks

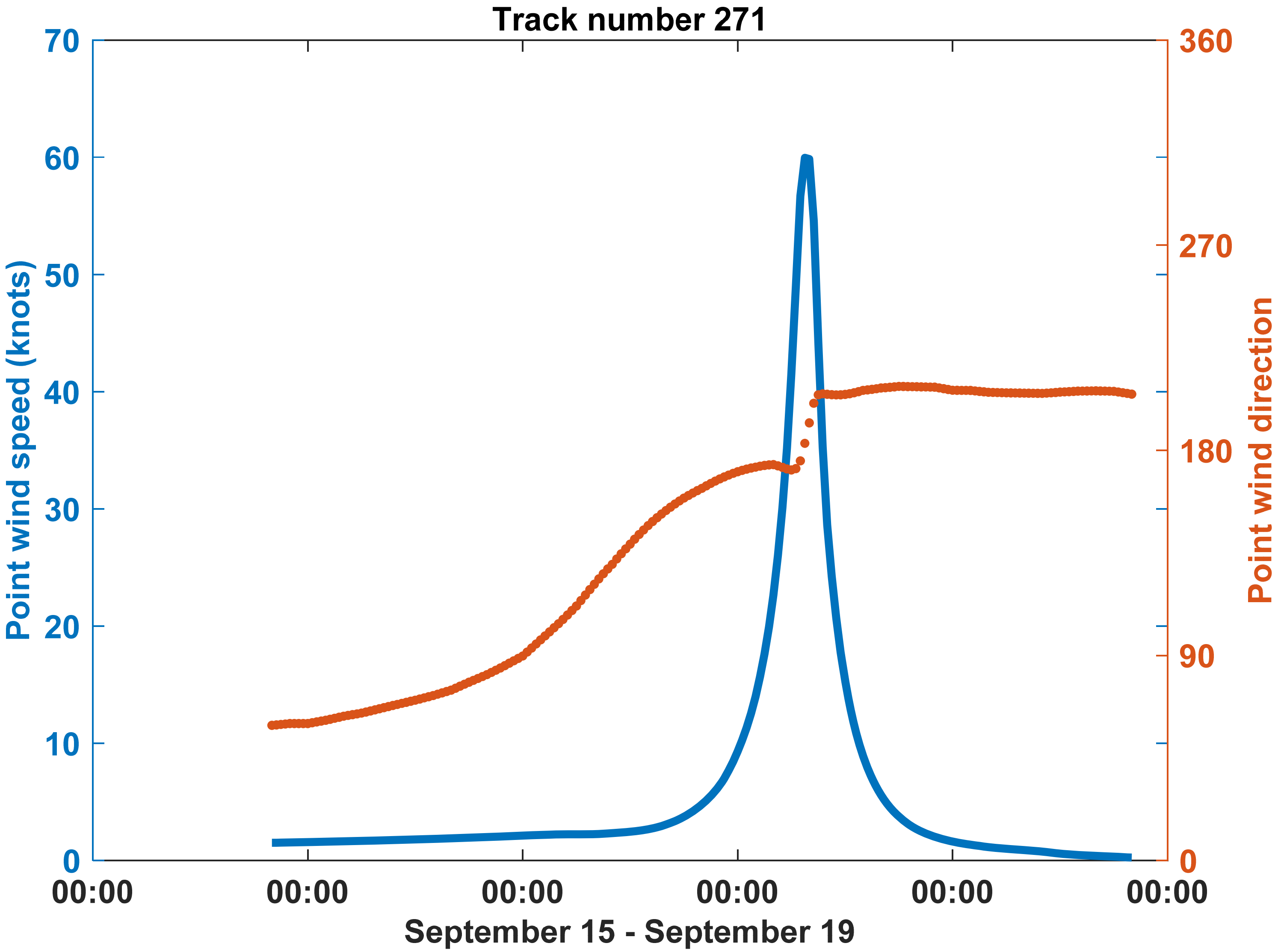


Sample Kyoto track

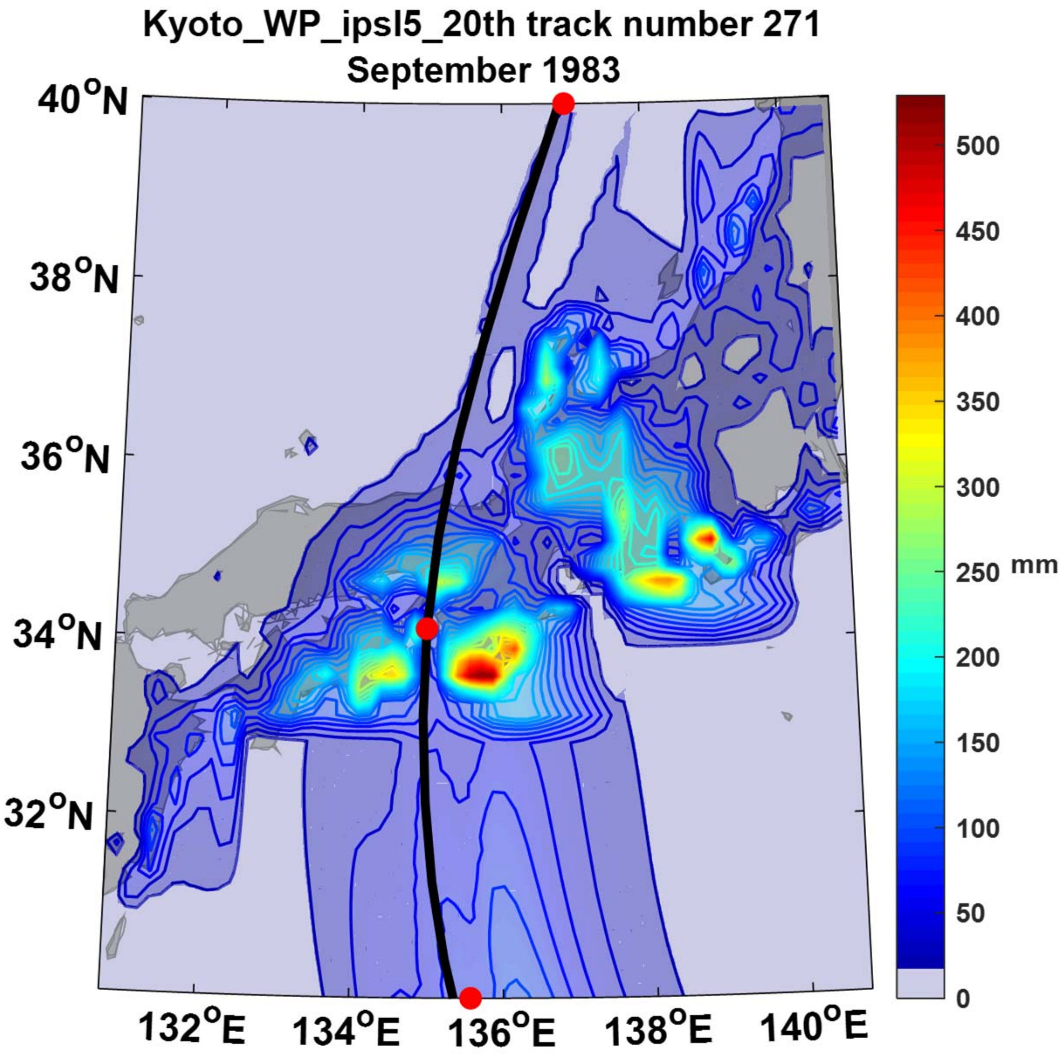


Kyoto_WP_ipsl5_20th track number 271
September 1983

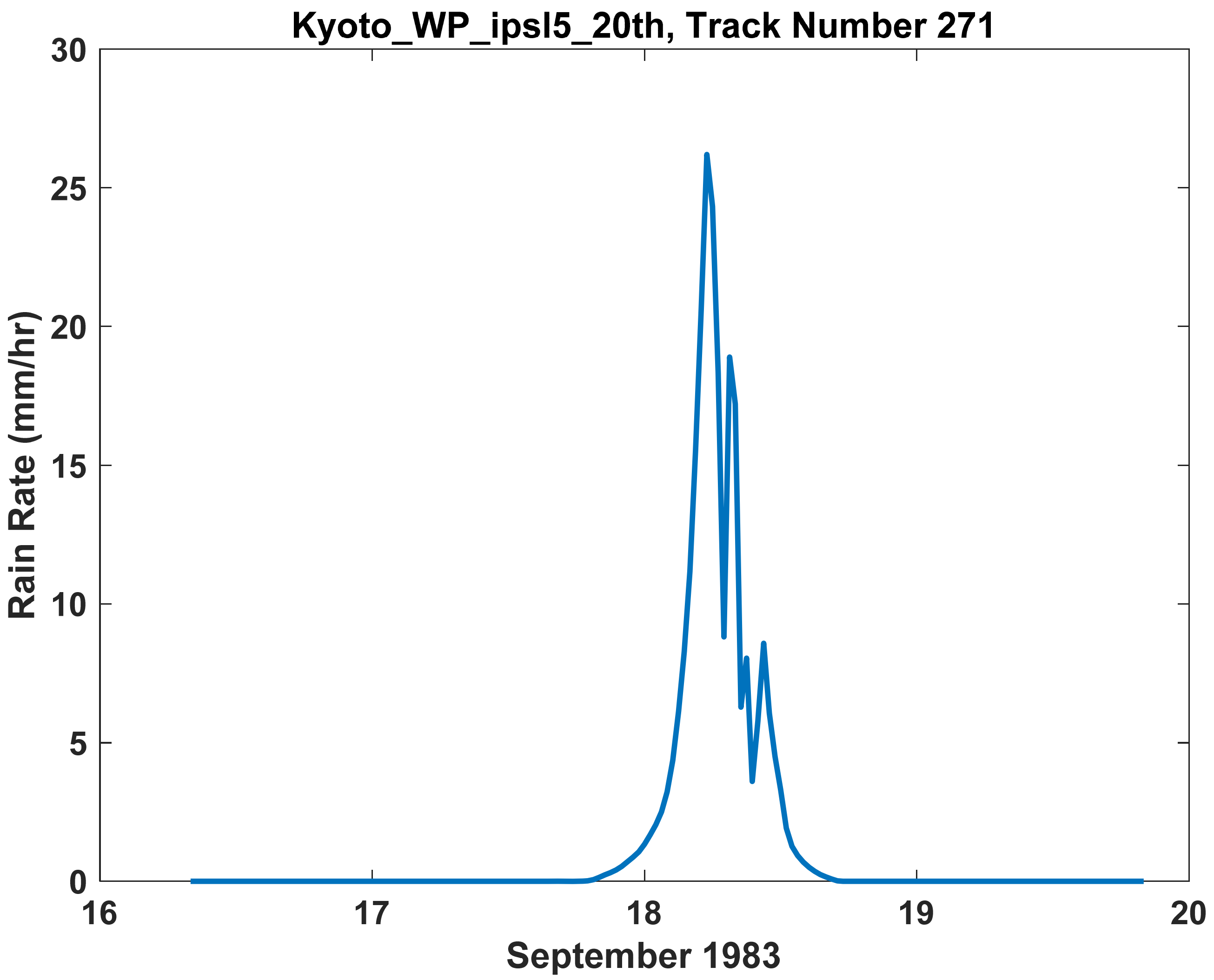


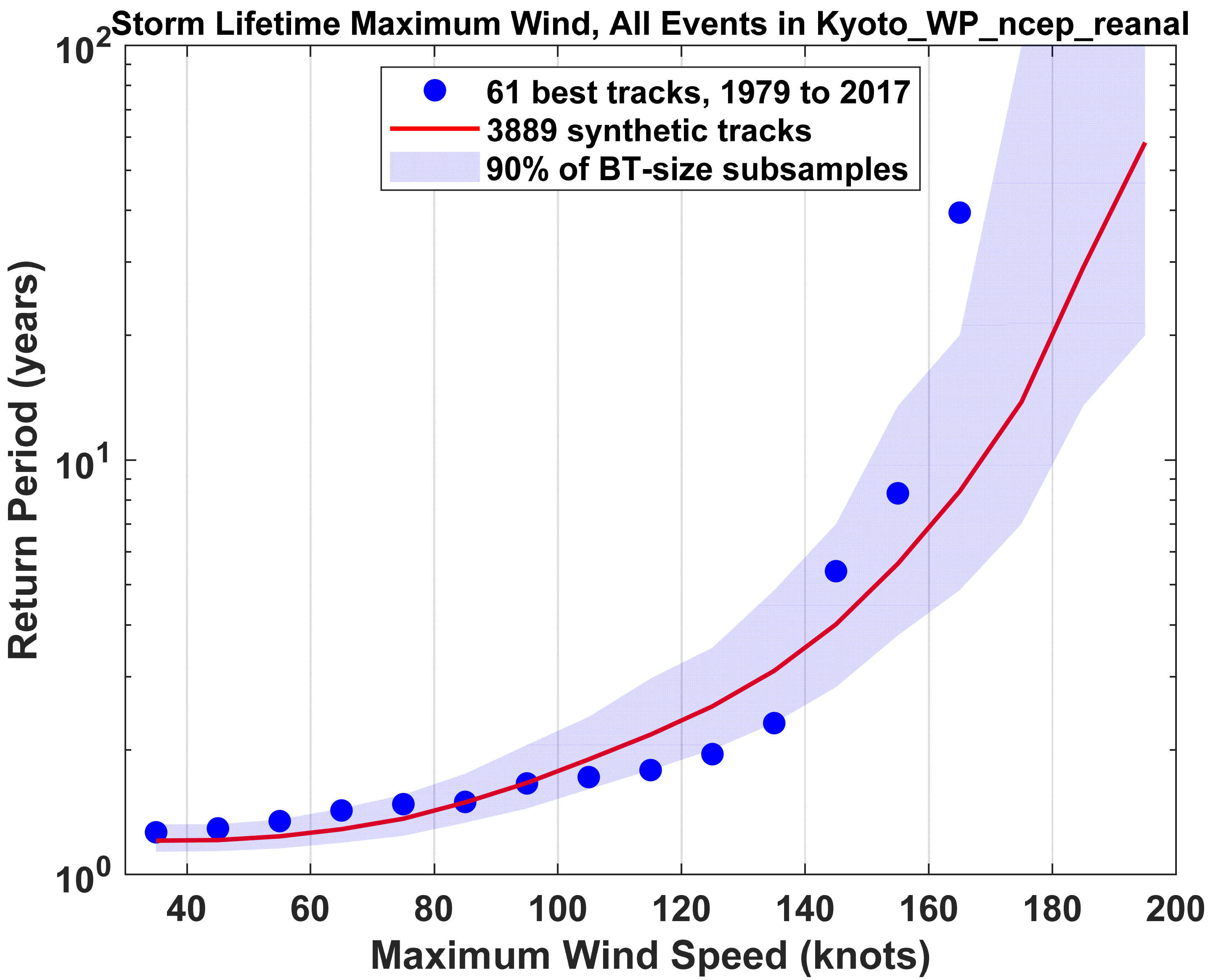

Track number 271
Point wind speed (knots)
0
10
20
30
40
50
60
70
Point wind direction
0
90
180
270
360
00:00
00:00
00:00
00:00
00:00
00:00
September 15 - September 19

Storm total rainfall

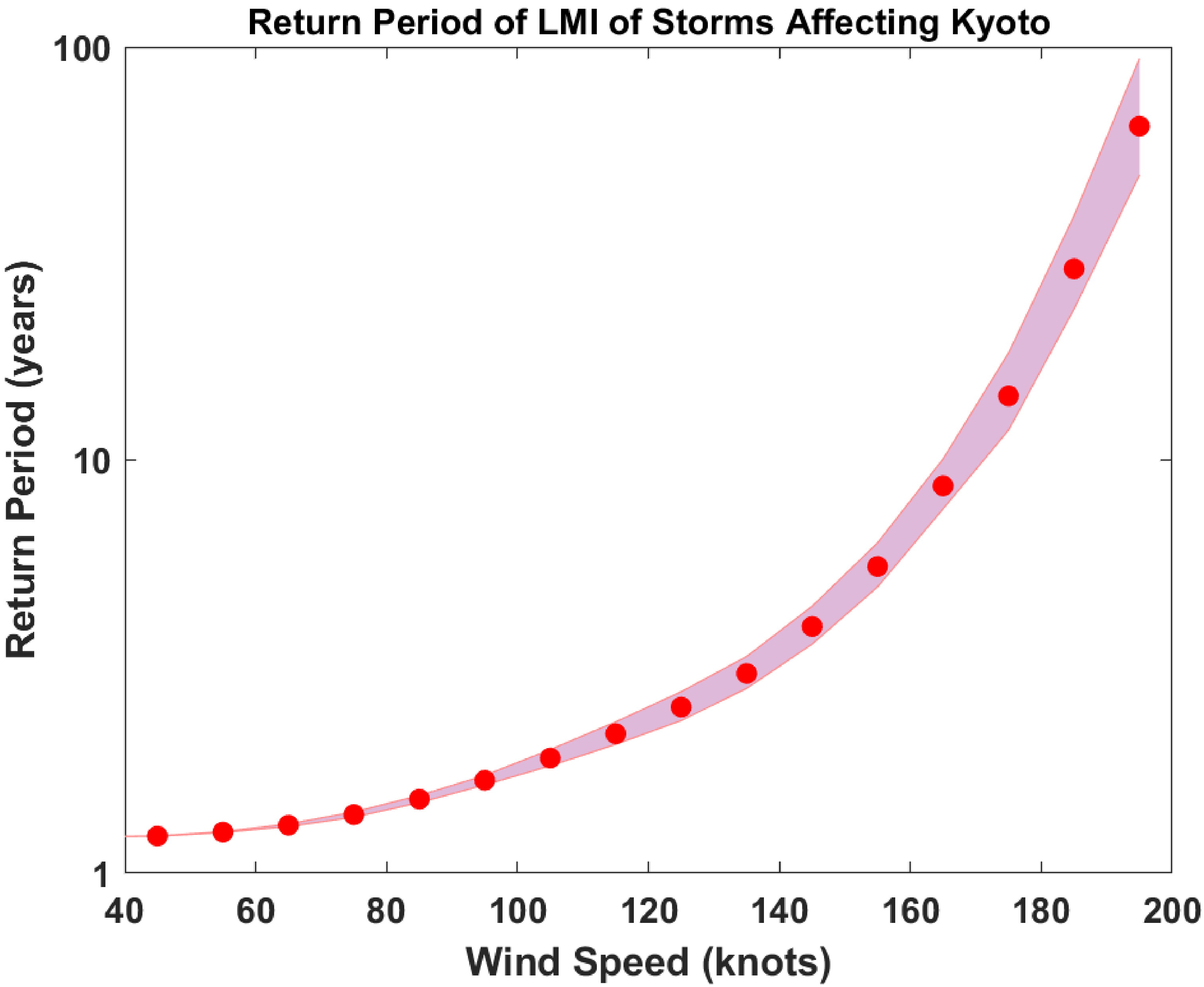


Rain rate at Kyoto

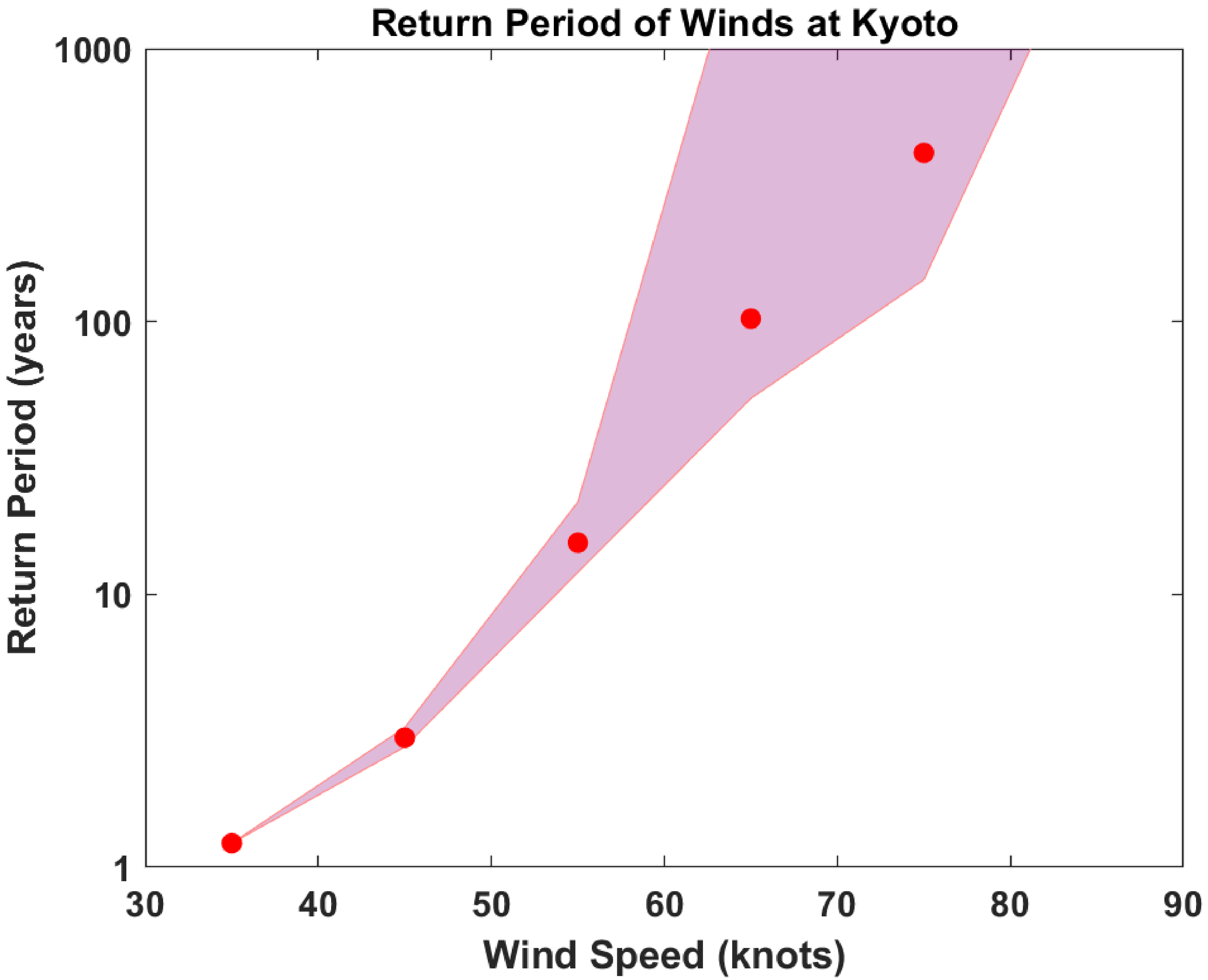



Storm Lifetime Maximum Wind, All Events in Kyoto_WP_ncep_reanal
61 best tracks, 1979 to 2017
3889 synthetic tracks
90% of BT-size subsamples
Return Period (years)
10^2
10^1
10^0
40
60
80
100
120
140
160
180
200
Maximum Wind Speed (knots)

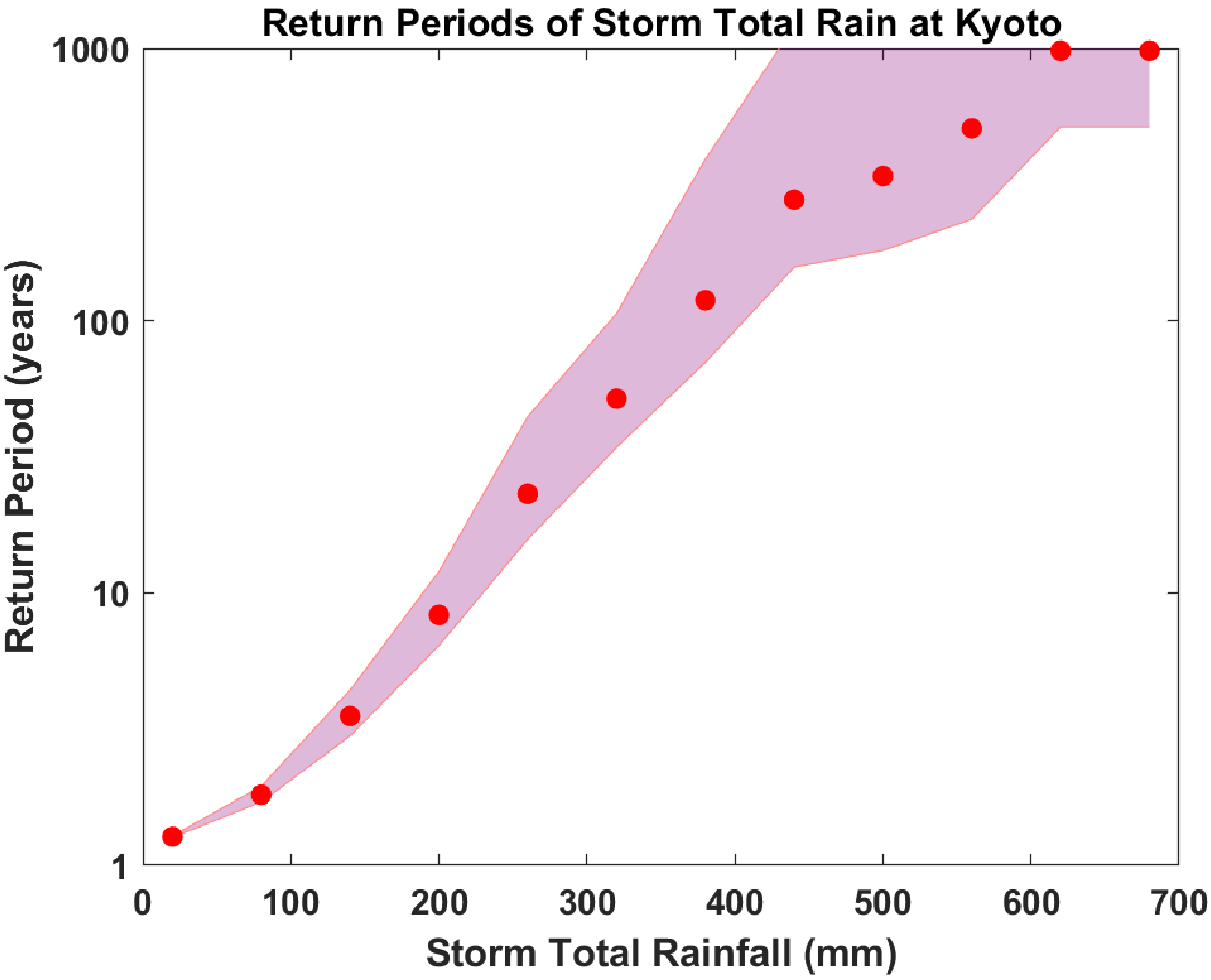
(Showing scatter among 4 reanalysis products)



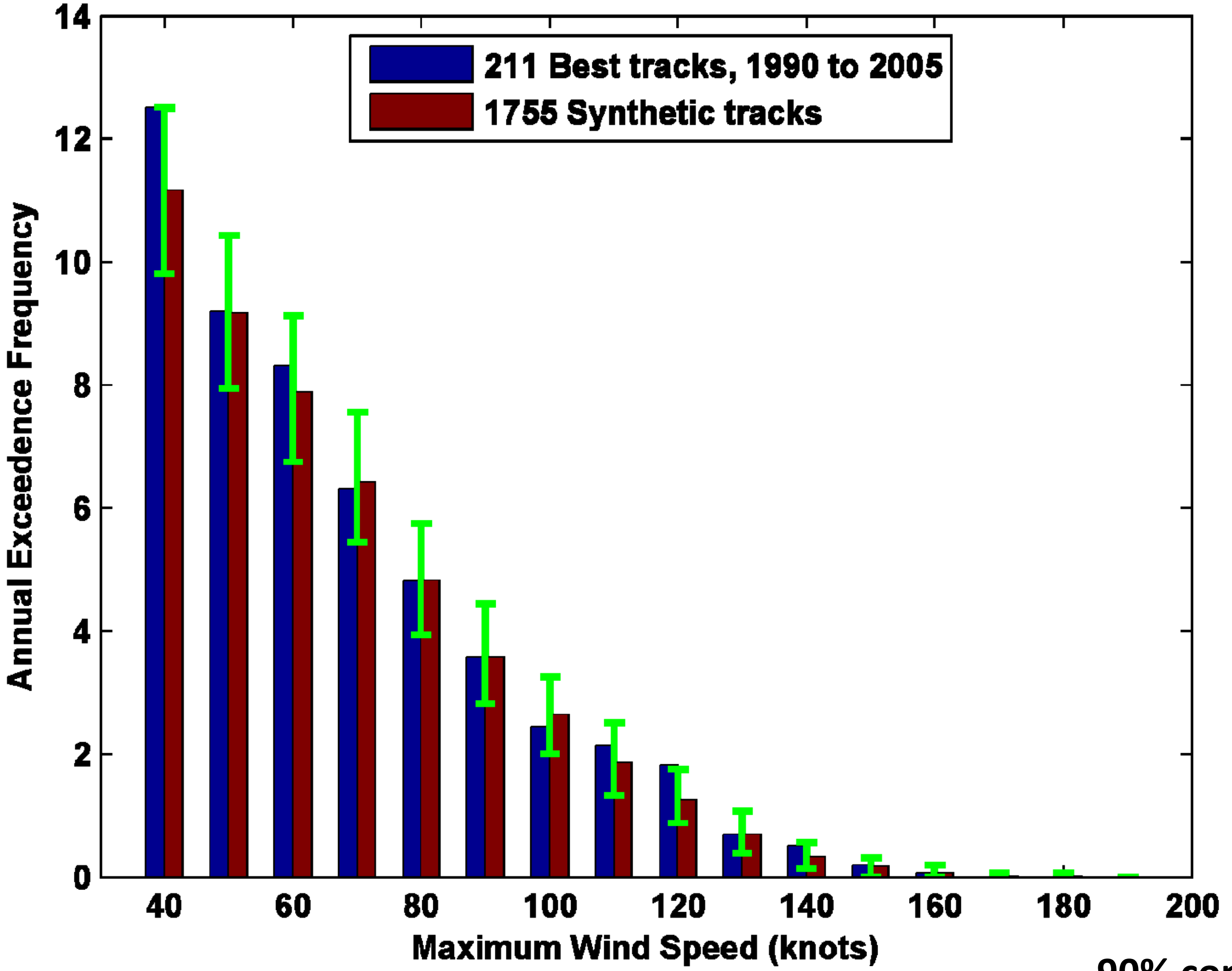
(Showing scatter among 4 reanalysis products)



(Showing scatter among 4 reanalysis products)

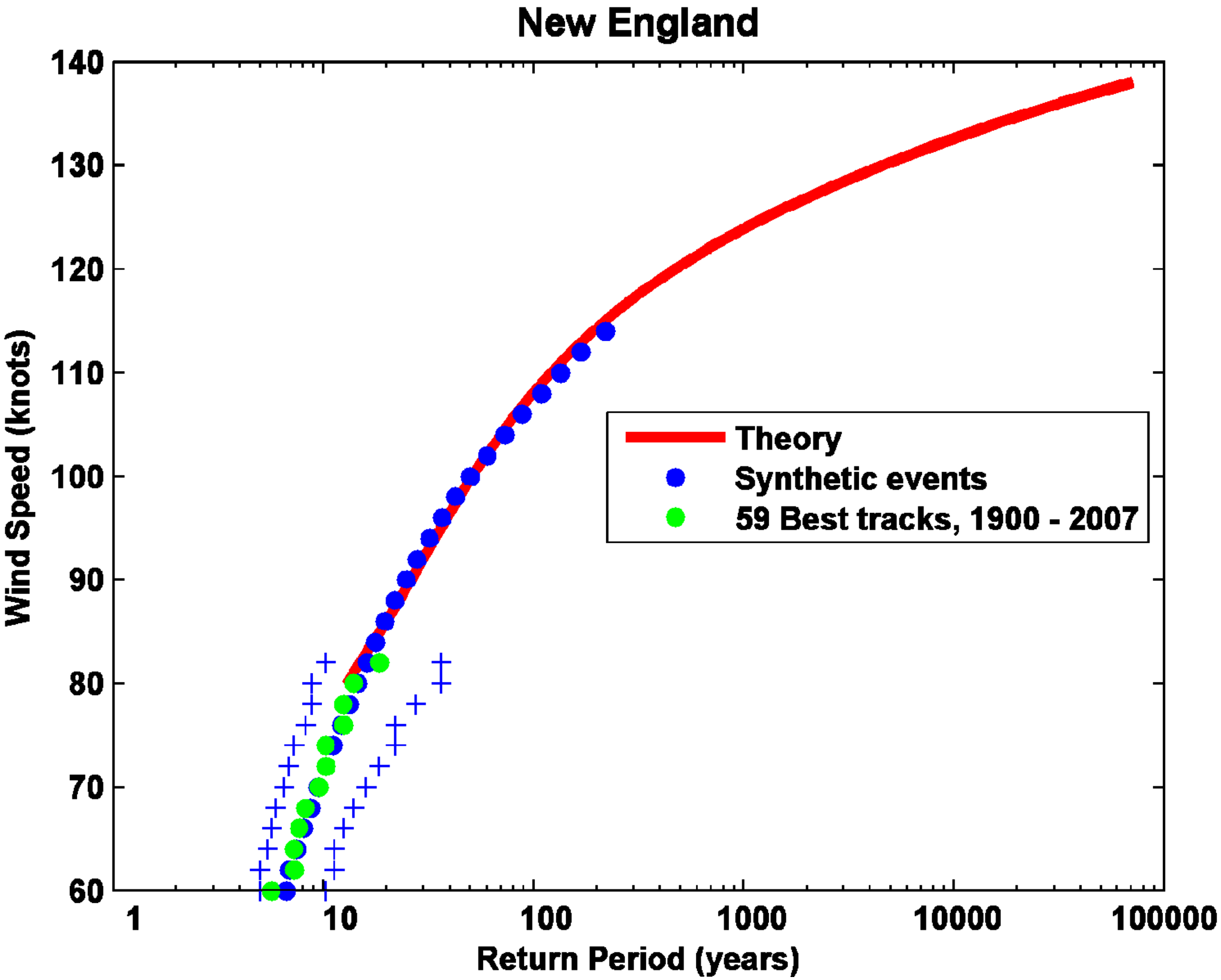


Cumulative Distribution of Storm Lifetime Peak Wind Speed, with Sample of 1755 Synthetic Tracks

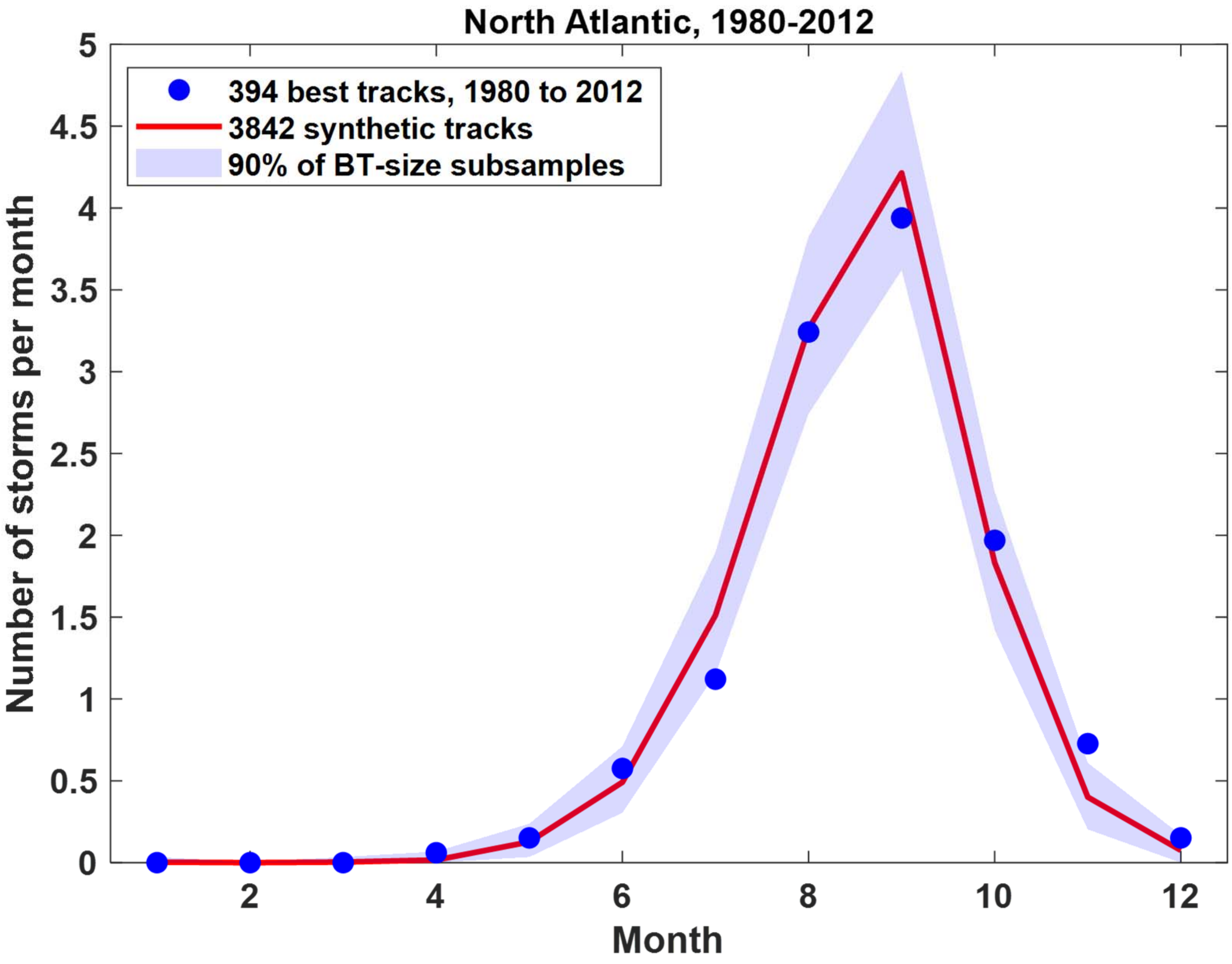


90% confidence bounds

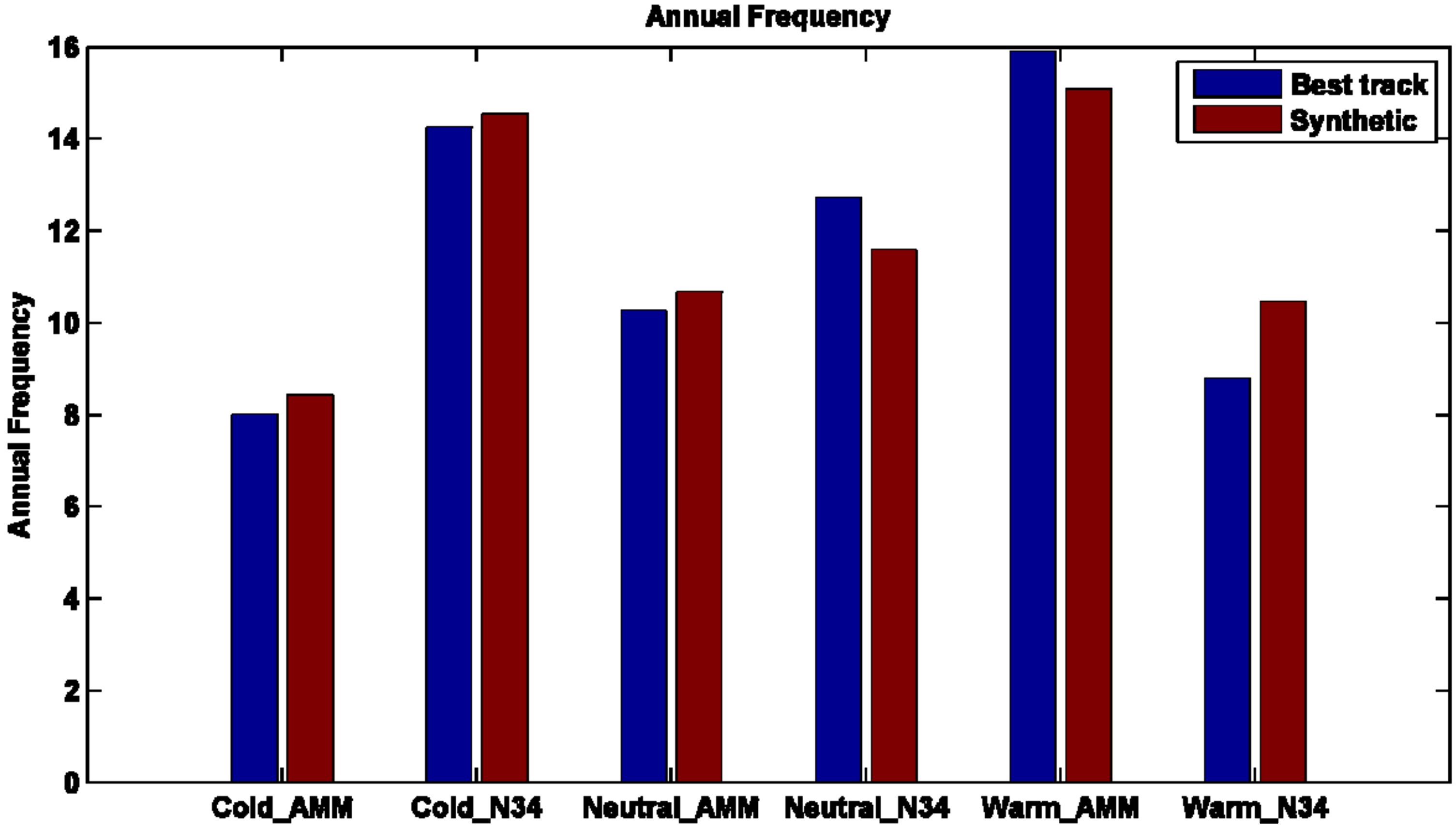
Return Periods



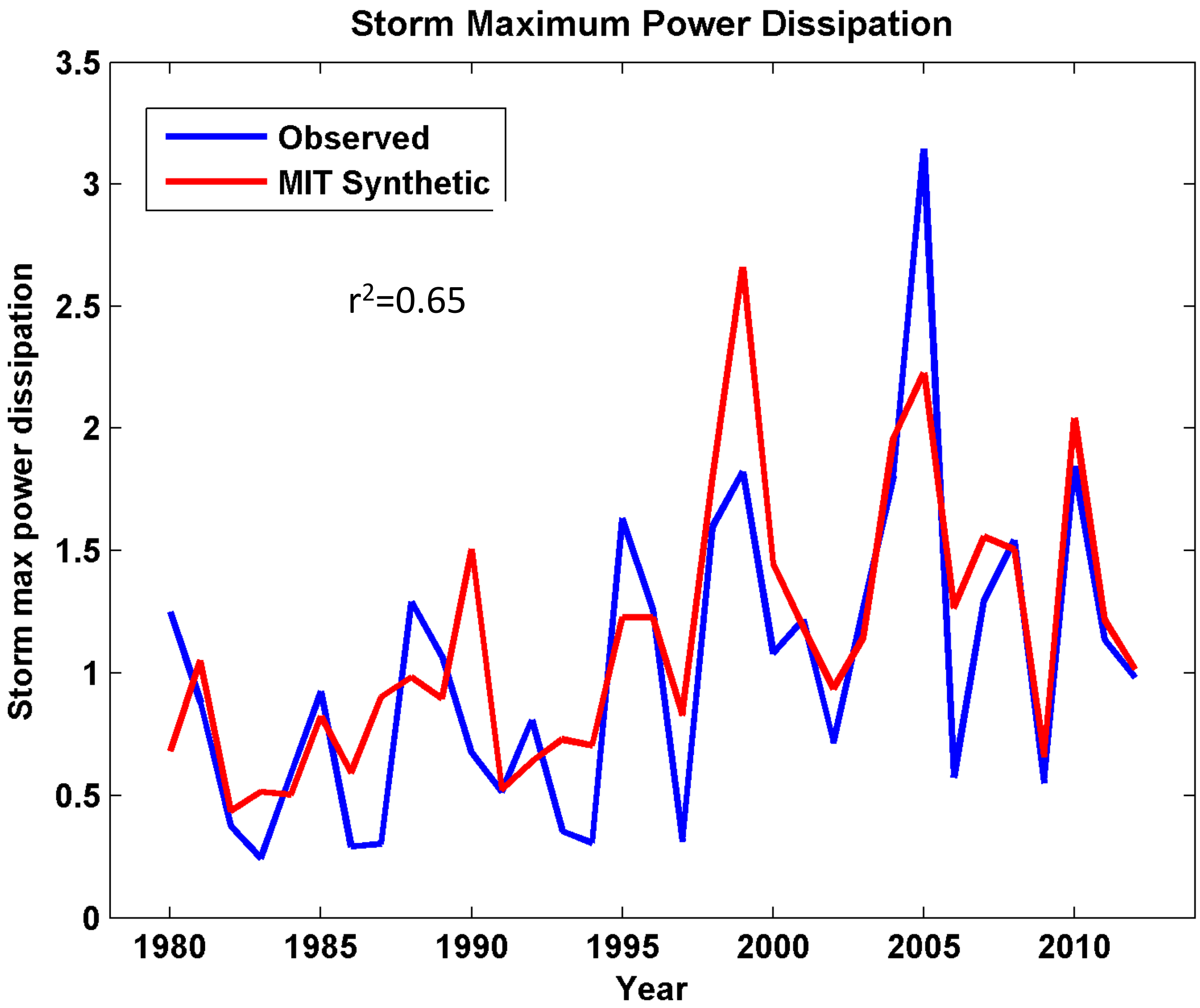
Atlantic Annual Cycle



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

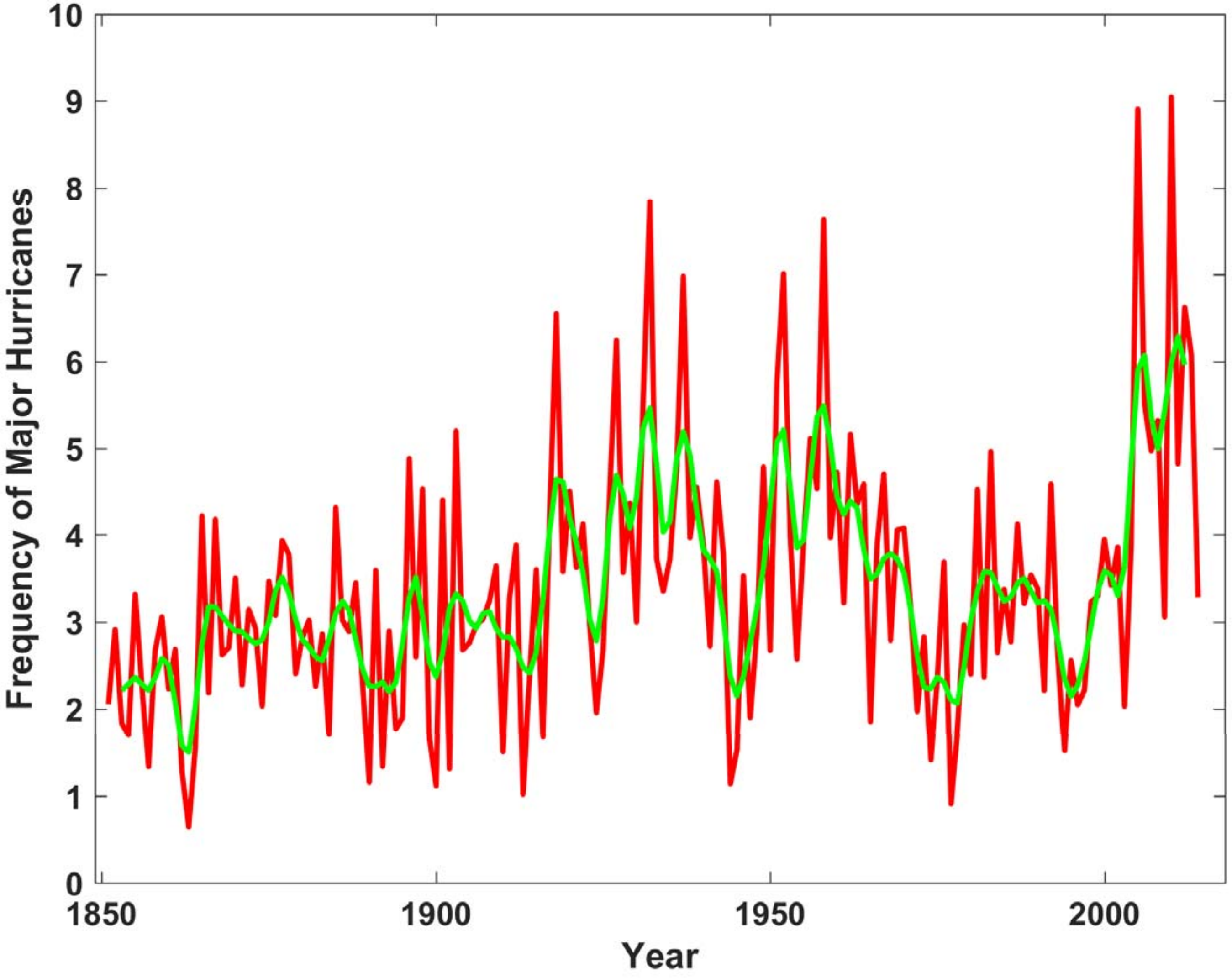


Captures Much of the Observed North Atlantic Interannual Variability



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

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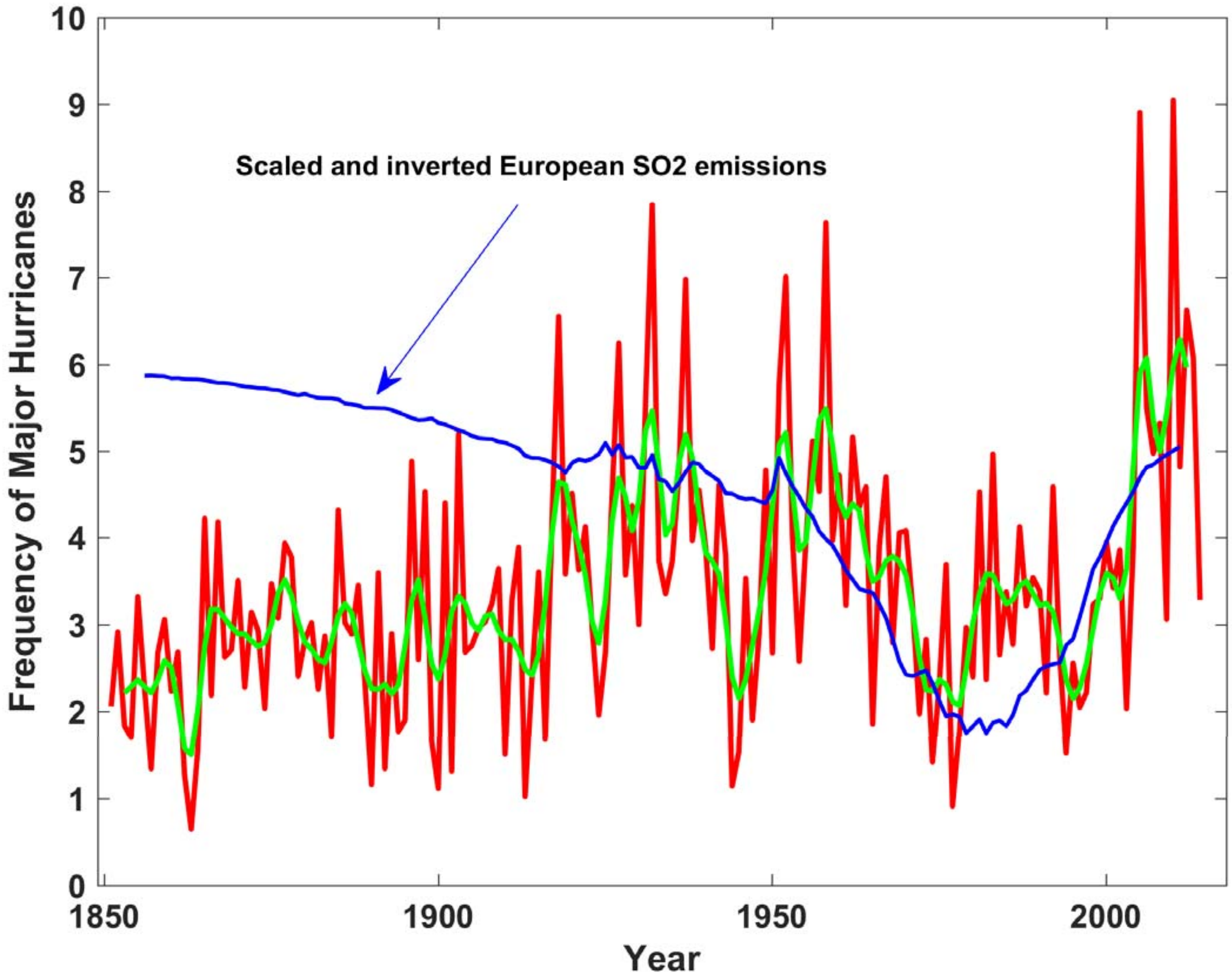
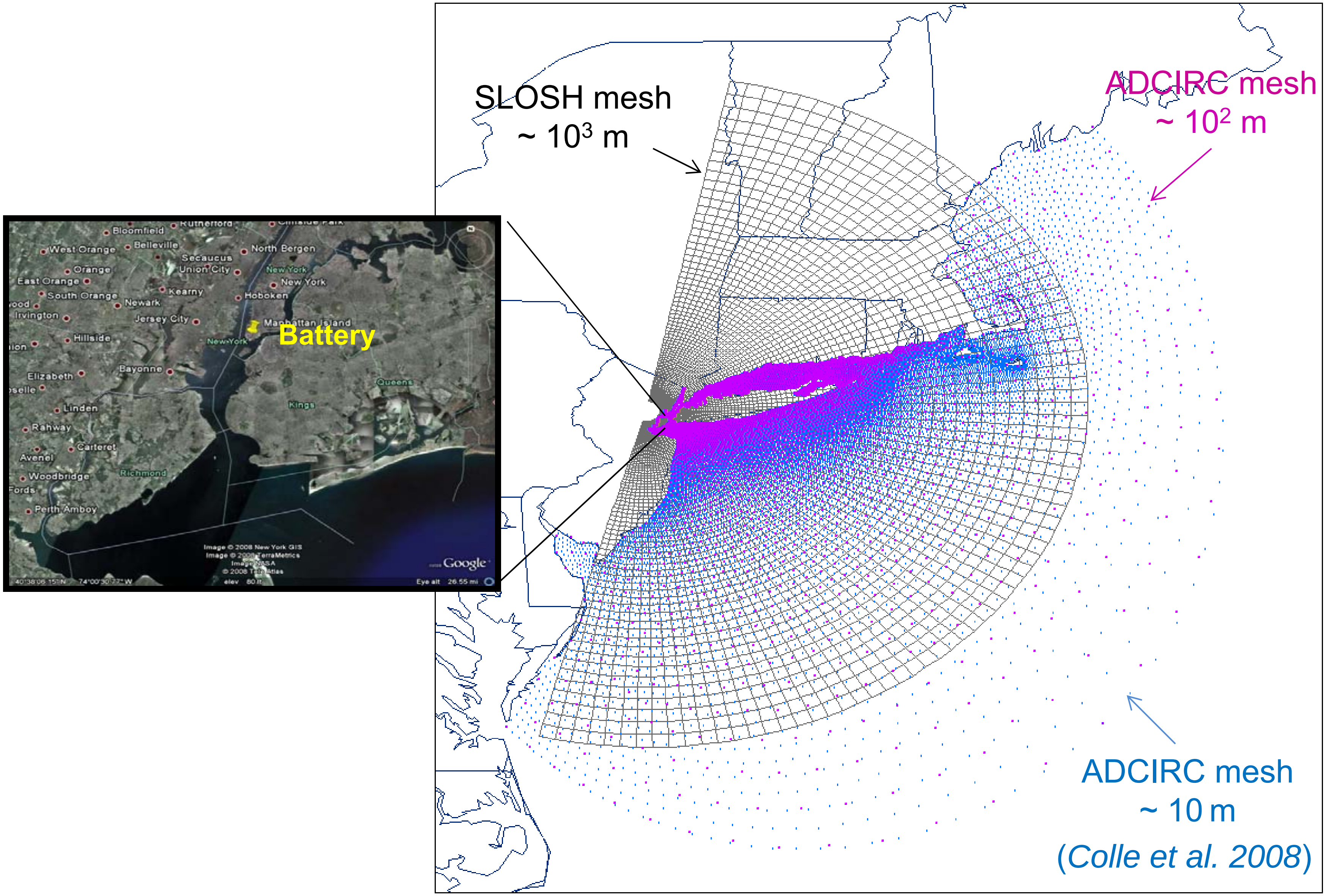


Storm Surge Simulation (Ning Lin)

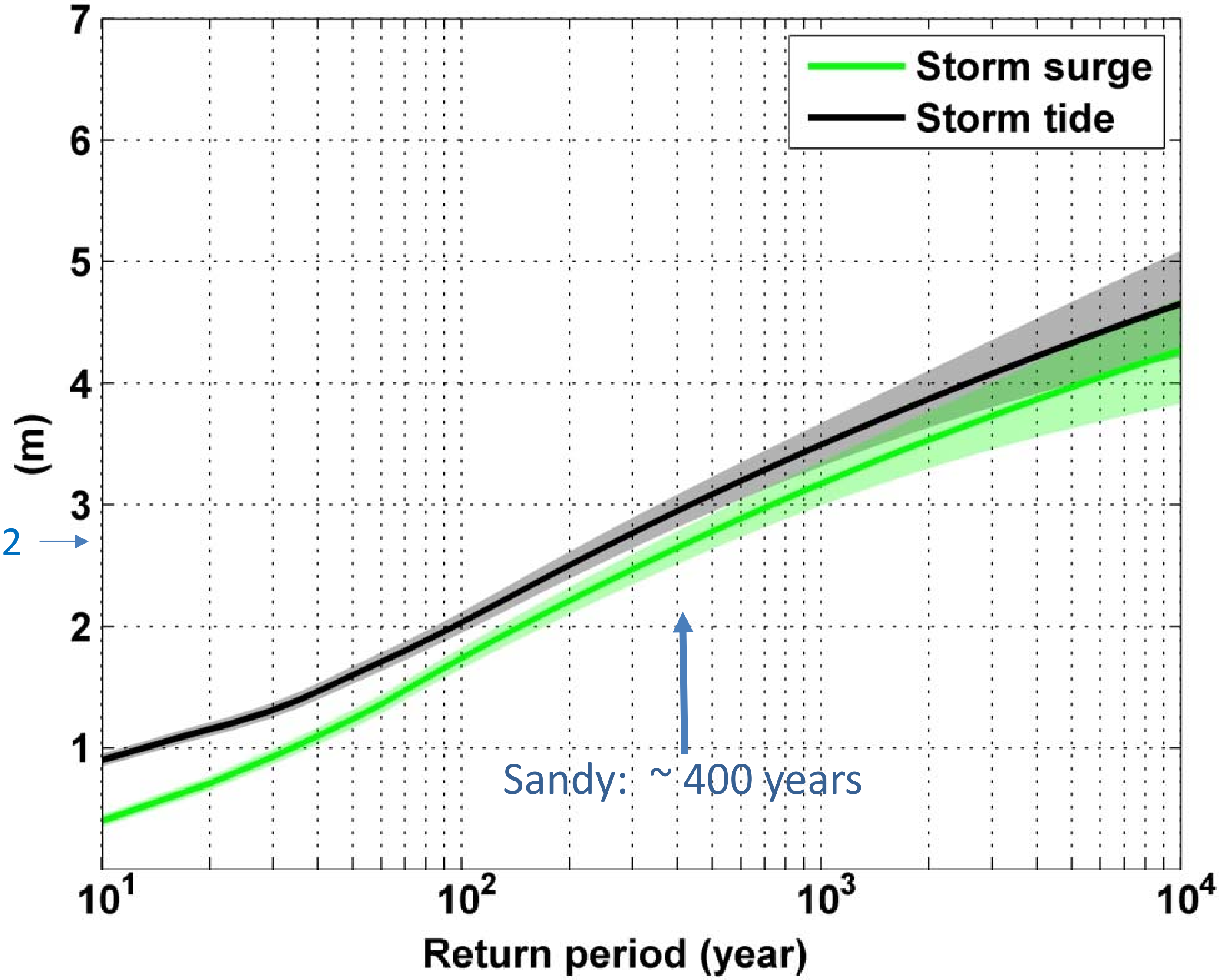


SLOSH mesh
~ 10^3 m

ADCIRC mesh
~ 10^2 m

ADCIRC mesh
~ 10 m

(*Colle et al. 2008*)



Sandy, 2012 →

Sandy: ~ 400 years

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

Predicting Rainfall

The CHIPS models predicts updraft and downdraft convective mass flux as a function of time and potential radius, BUT:

Storing these variables at all radii would increase overall storage requirements by a factor of ~50

(We are dealing with 10,000-100,000 individual events)

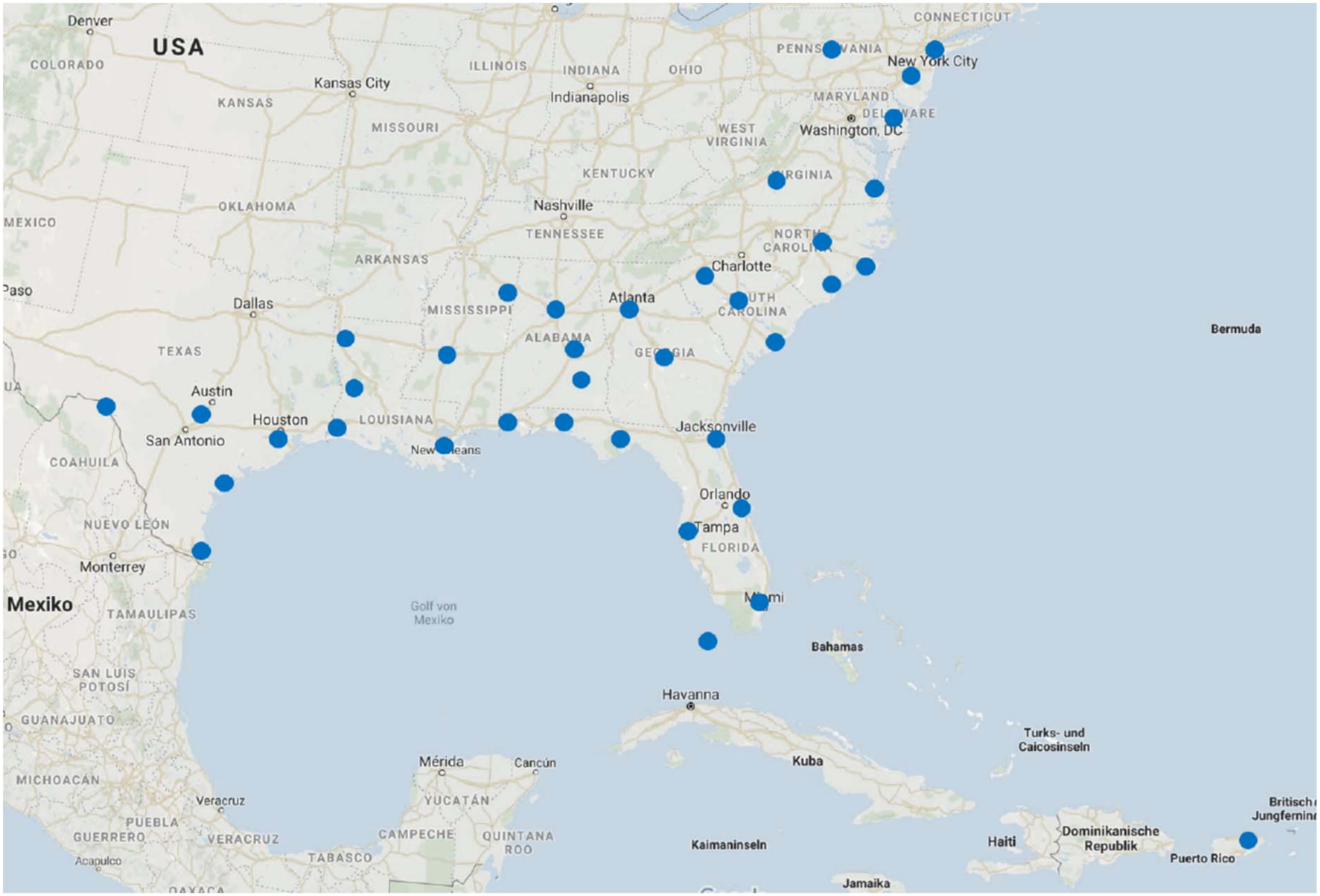
Rainfall calculated using quasi-balanced dynamics

Basic strategy: Reconstruct time-evolving 2-D wind field by fitting a canonical radial wind profile to predicted values of V_{max} and r_{max} and adding a constant background wind. Allow resulting vortex to interact with background wind and thermodynamic fields.

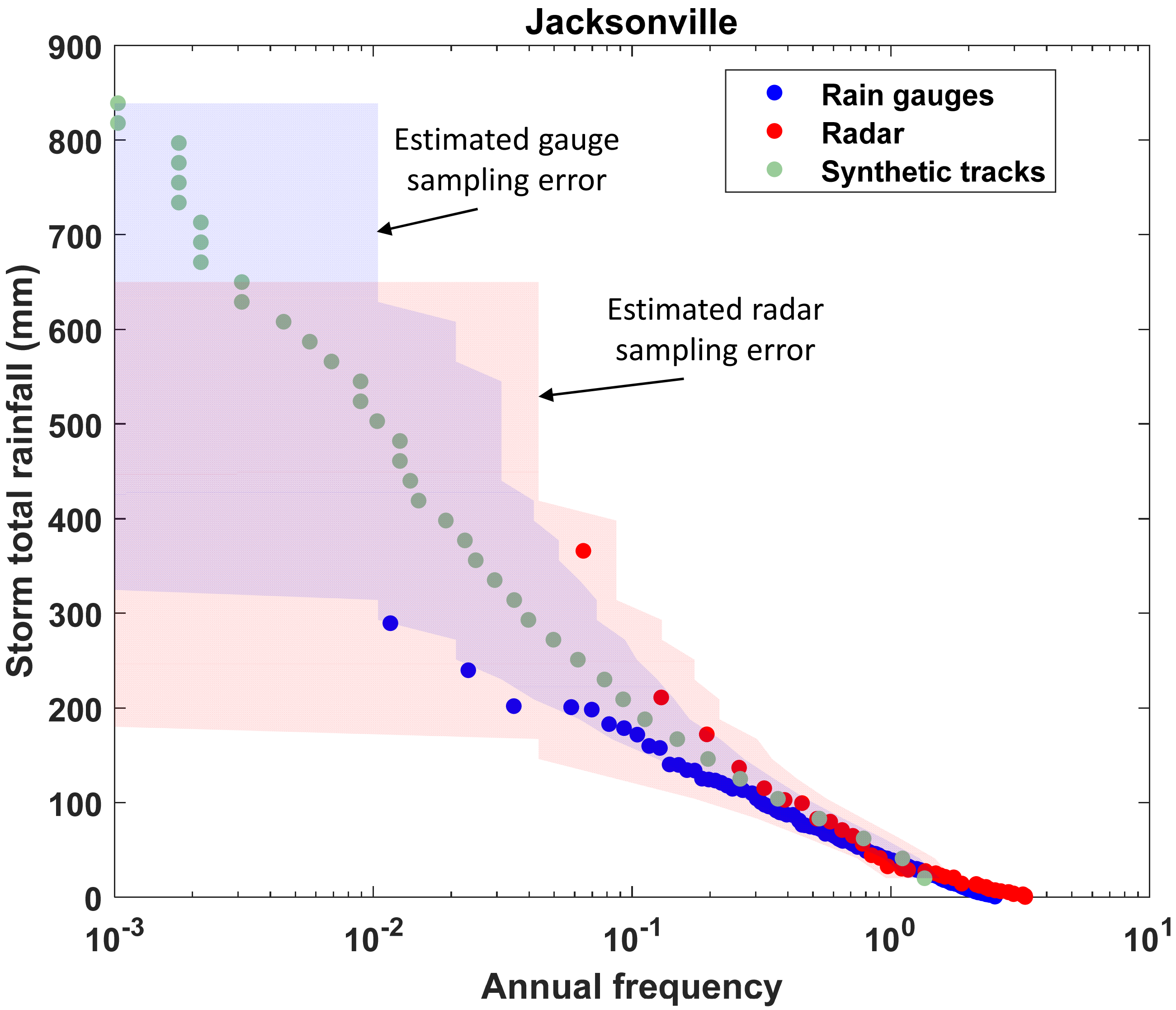
QB is fine, but how do we evaluate how well it works?

- Evaluation of rainfall predictions against observations is tough!
  - Only 32 years of NEXRAD data
  - Rain gauges go back much further in time but can be unreliable in strong winds and are subject to large sampling error
- We used both radar and gauge data and averaged both over circles of 100 km radius of 35 radar sites. (*Feldmann and Emanuel, 2019, in review)*
- Many thanks to Monika Feldmann

NEXRAD Sites

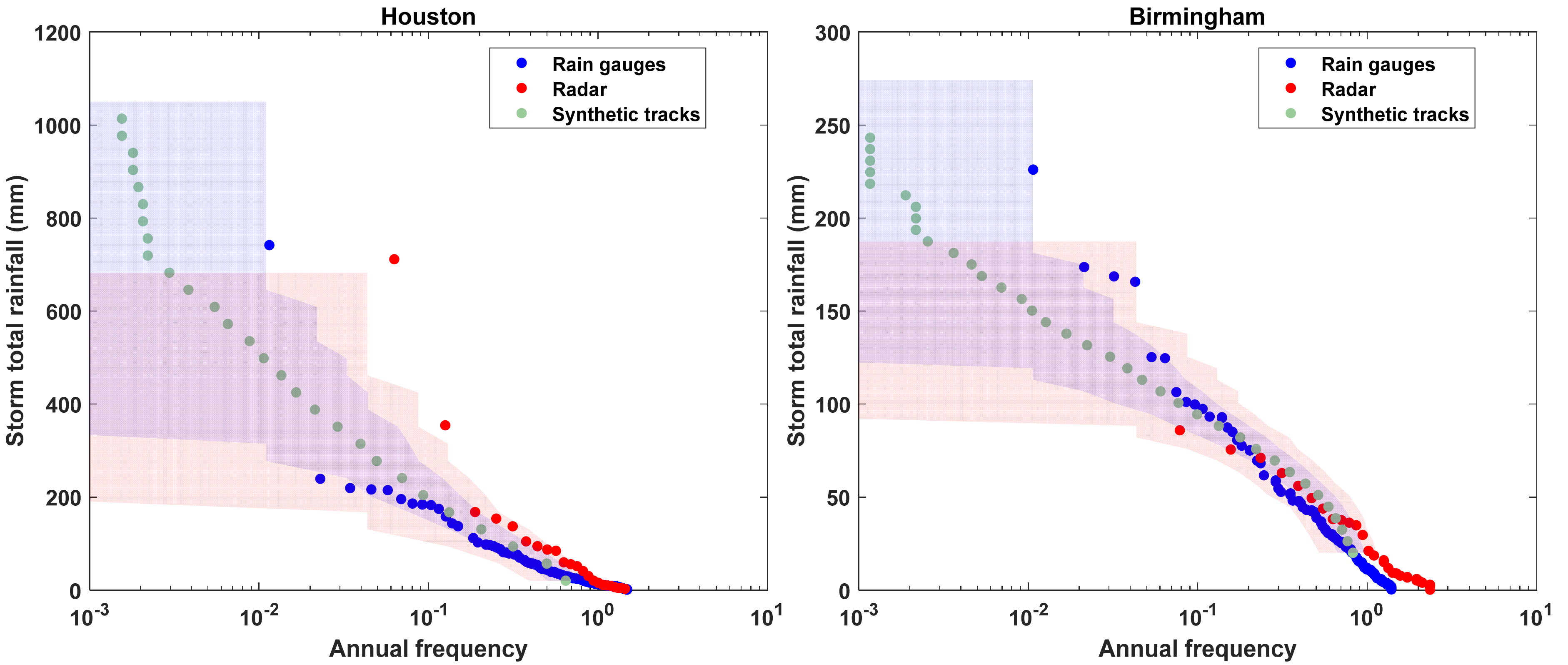


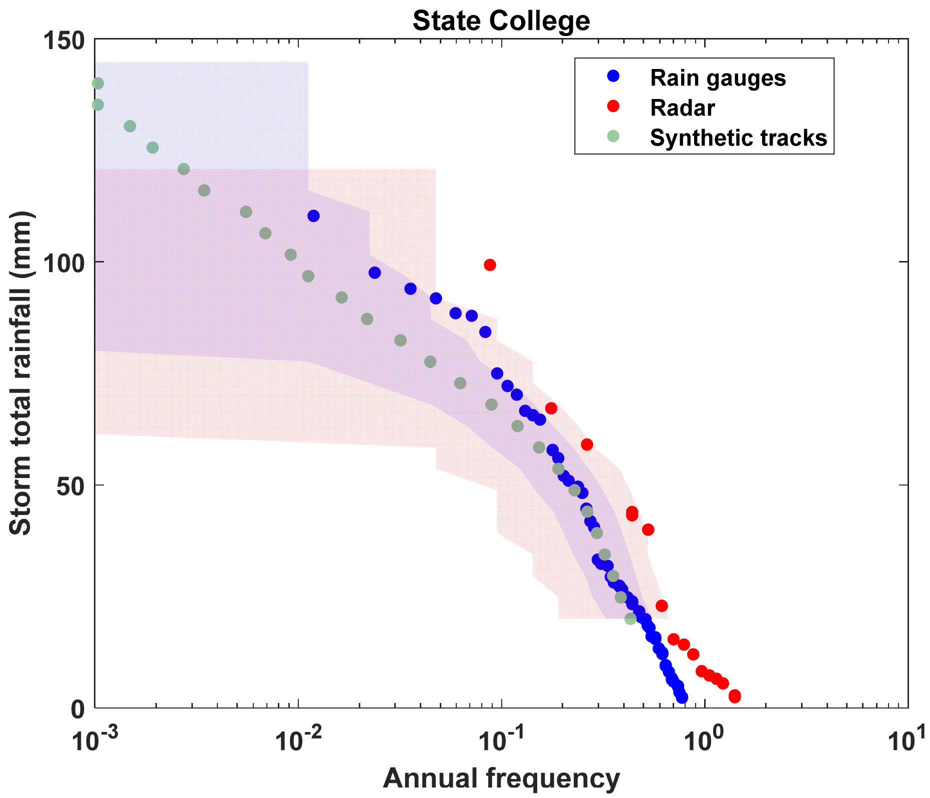
Some Examples

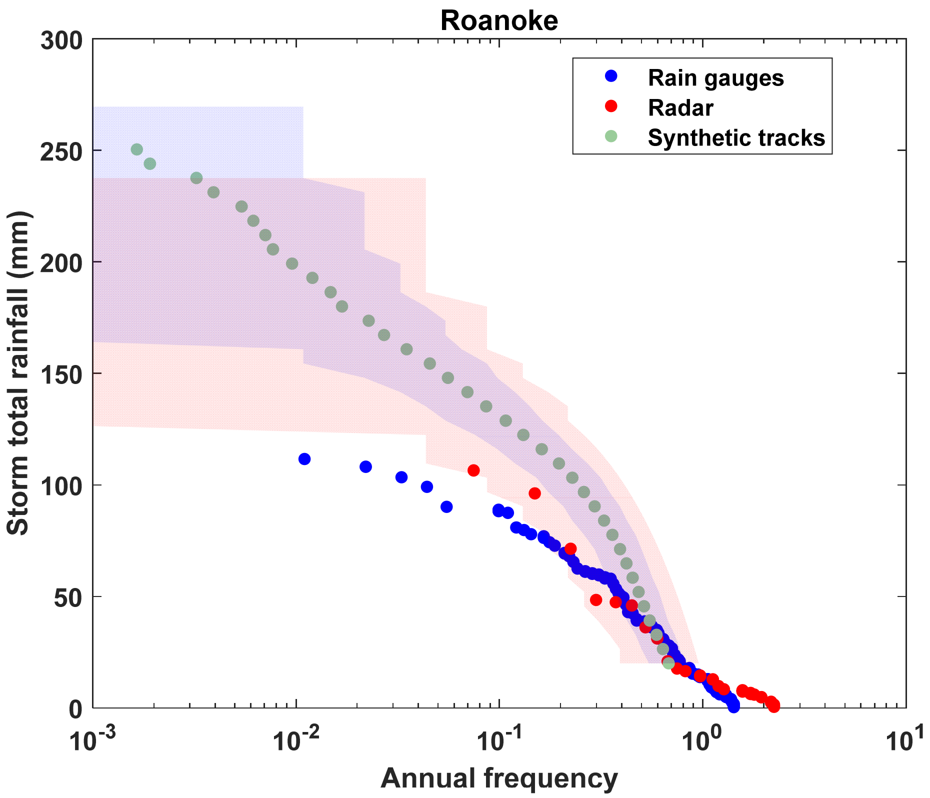


Estimated gauge sampling error

Estimated radar sampling error


Houston
Birmingham
Rain gauges
Radar
Synthetic tracks
Storm total rainfall (mm)
Annual frequency
0
200
400
600
800
1000
1200
50
100
150
250
300
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}


State College
Rain gauges
Radar
Synthetic tracks
Storm total rainfall (mm)
150
100
50
0
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
Annual frequency

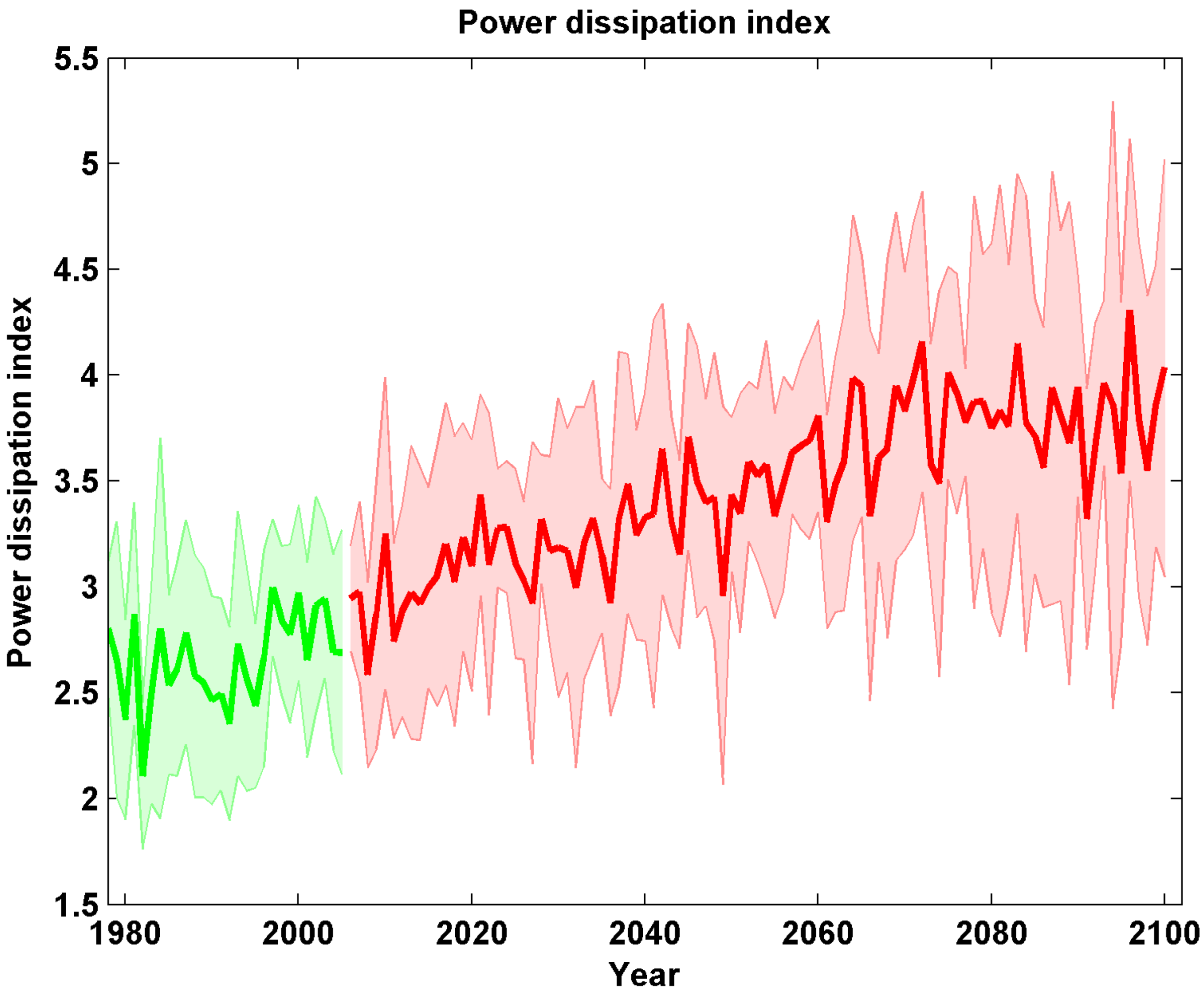

Roanoke
Rain gauges
Radar
Synthetic tracks
Storm total rainfall (mm)
300
250
200
150
100
50
0
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
Annual frequency

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

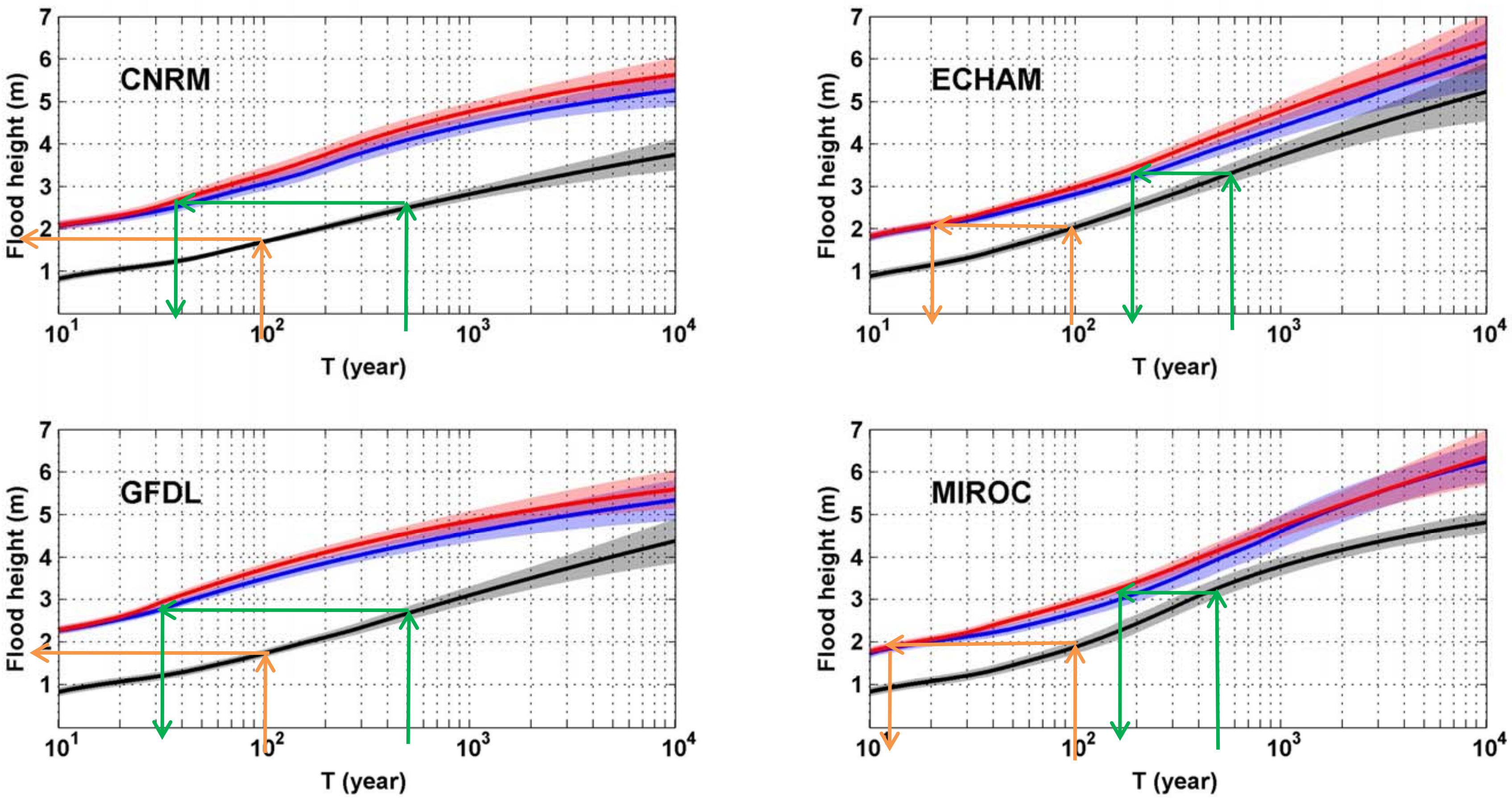
Taking Climate Change Into Account

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)

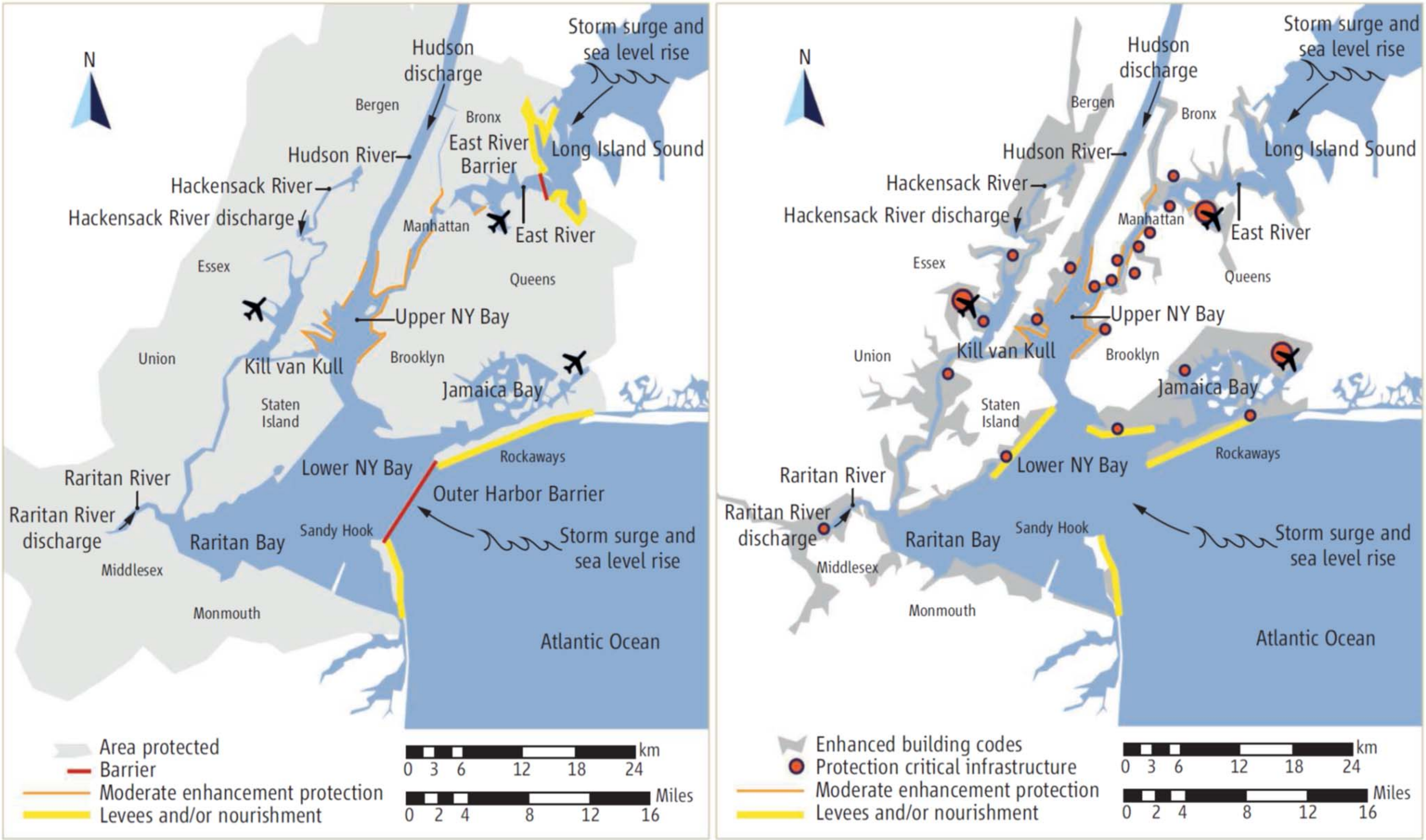


Black: Current climate (1981-2000)

Blue: A1B future climate (2081-2100)

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

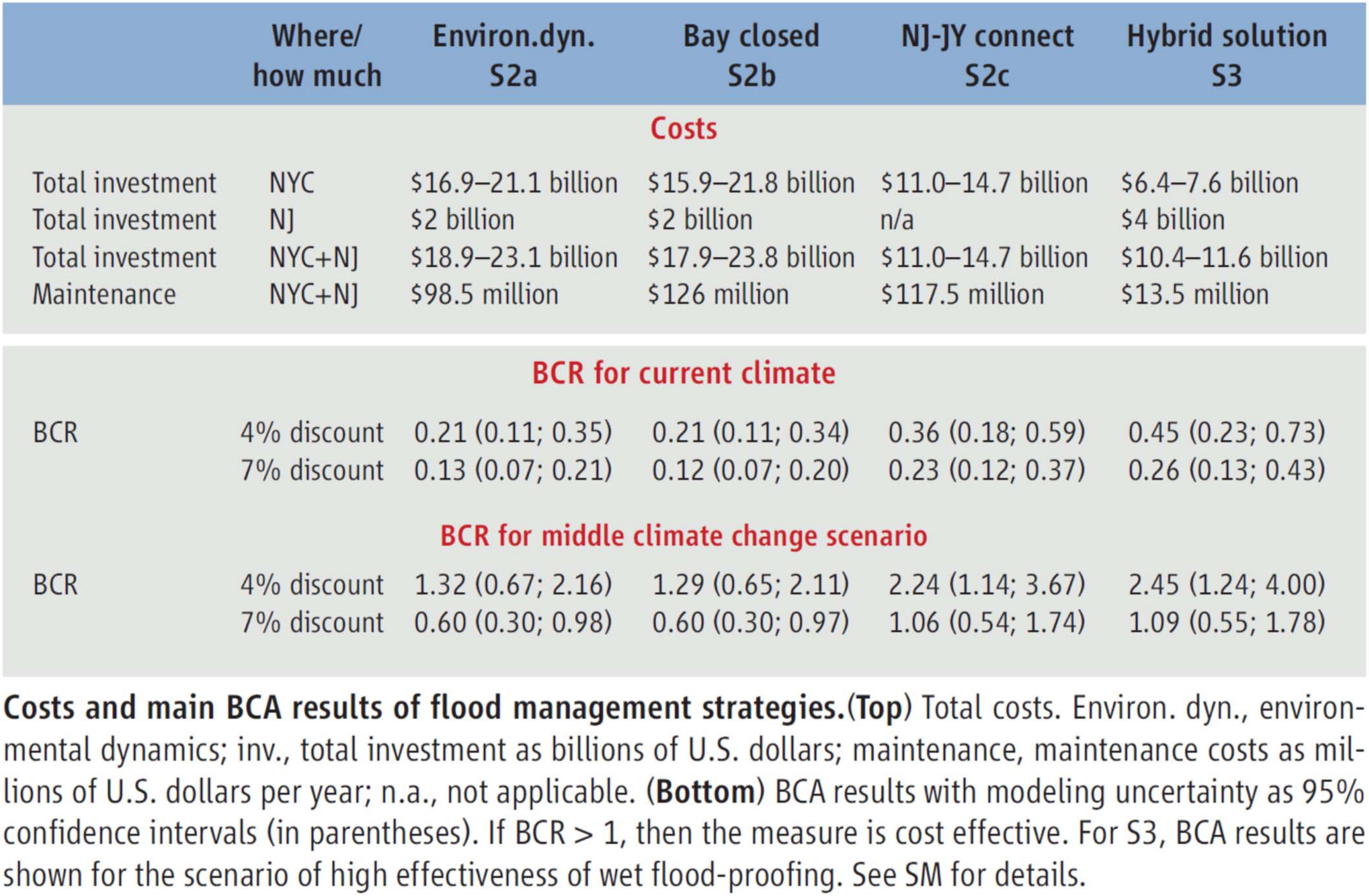
Lin et al. (2012)



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.

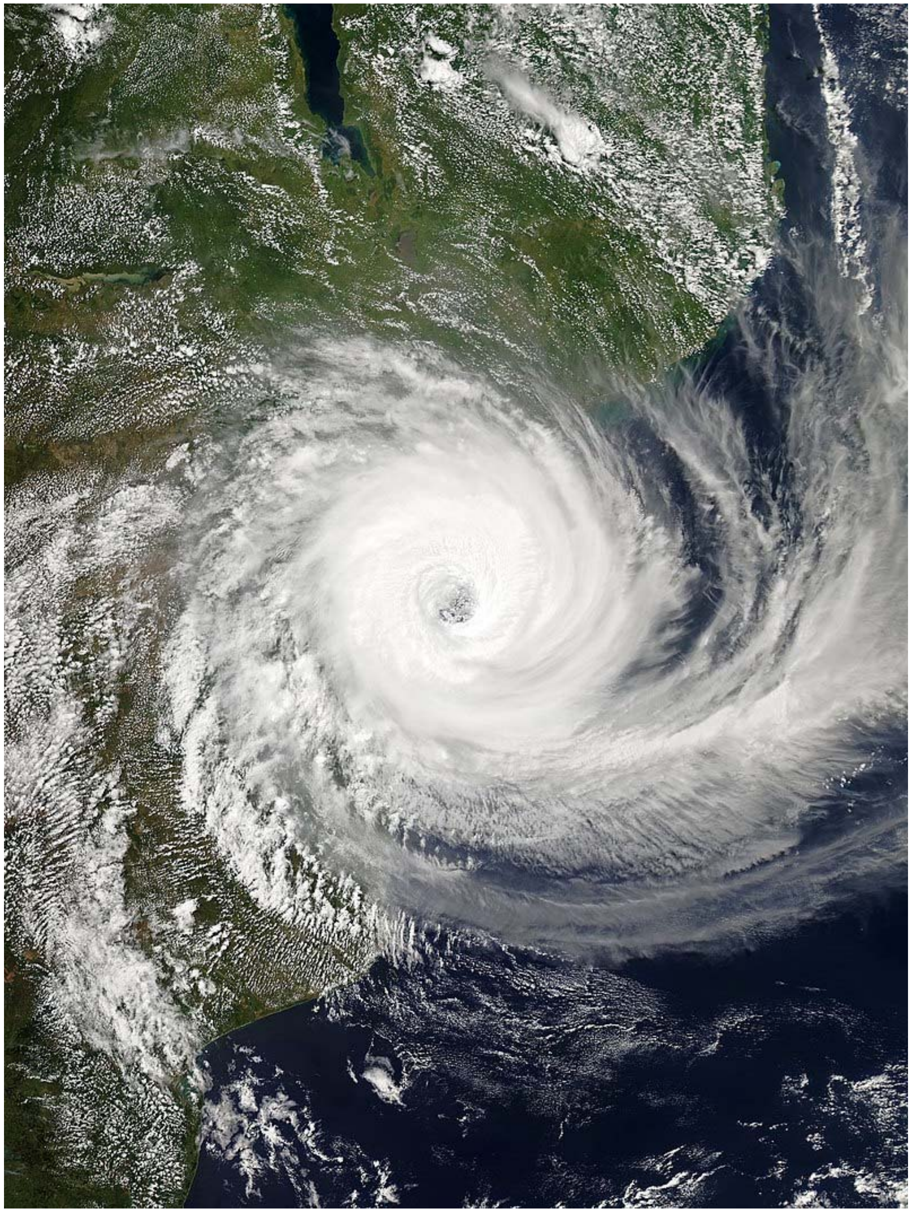
Benefit-Cost Ratios



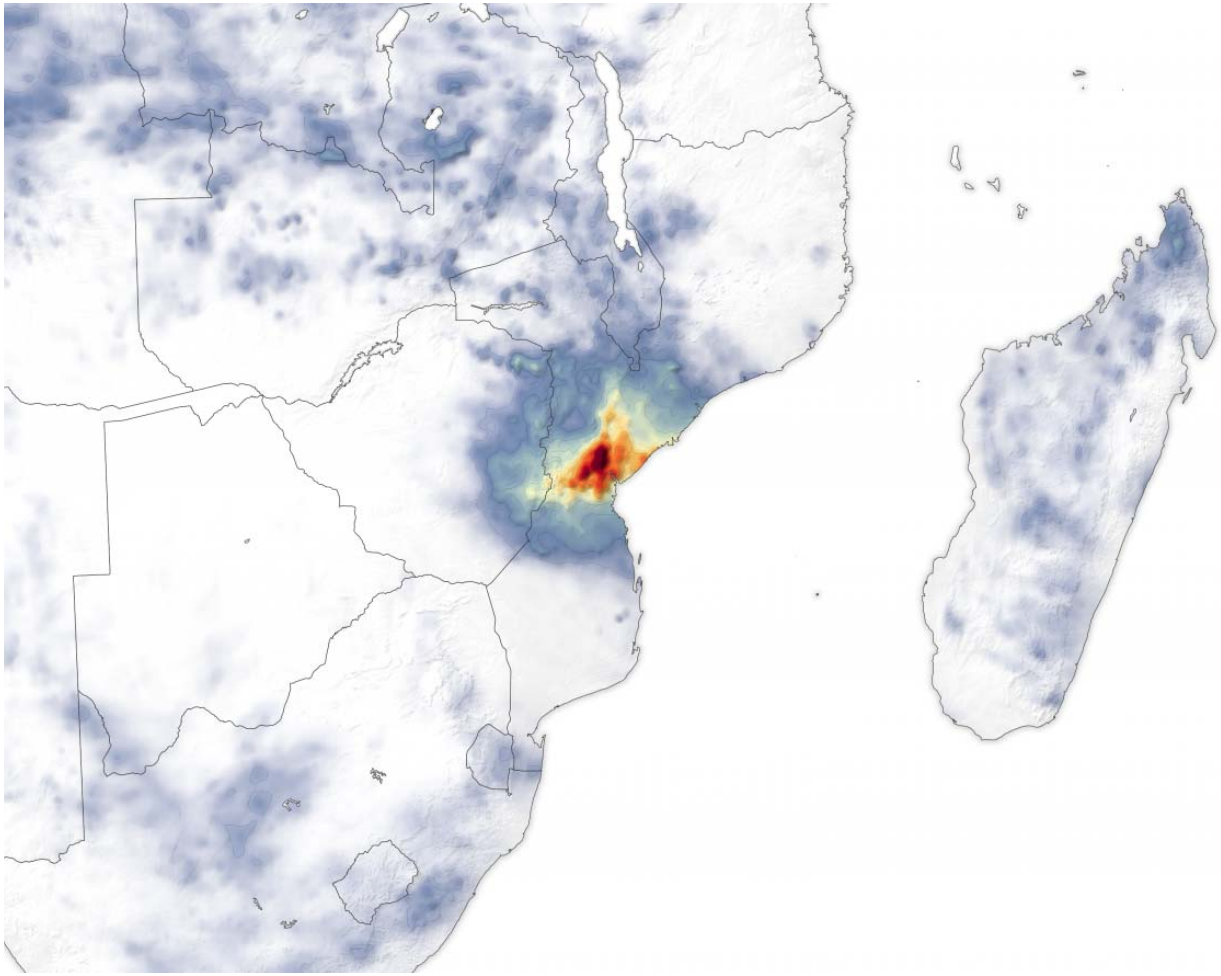
	Where/ how much	Environ.dyn. S2a	Bay closed S2b	NJ-JY connect S2c	Hybrid solution S3
Costs					
Total investment	NYC	\$16.9–21.1 billion	\$15.9–21.8 billion	\$11.0–14.7 billion	\$6.4–7.6 billion
Total investment	NJ	\$2 billion	\$2 billion	n/a	\$4 billion
Total investment	NYC+NJ	\$18.9–23.1 billion	\$17.9–23.8 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

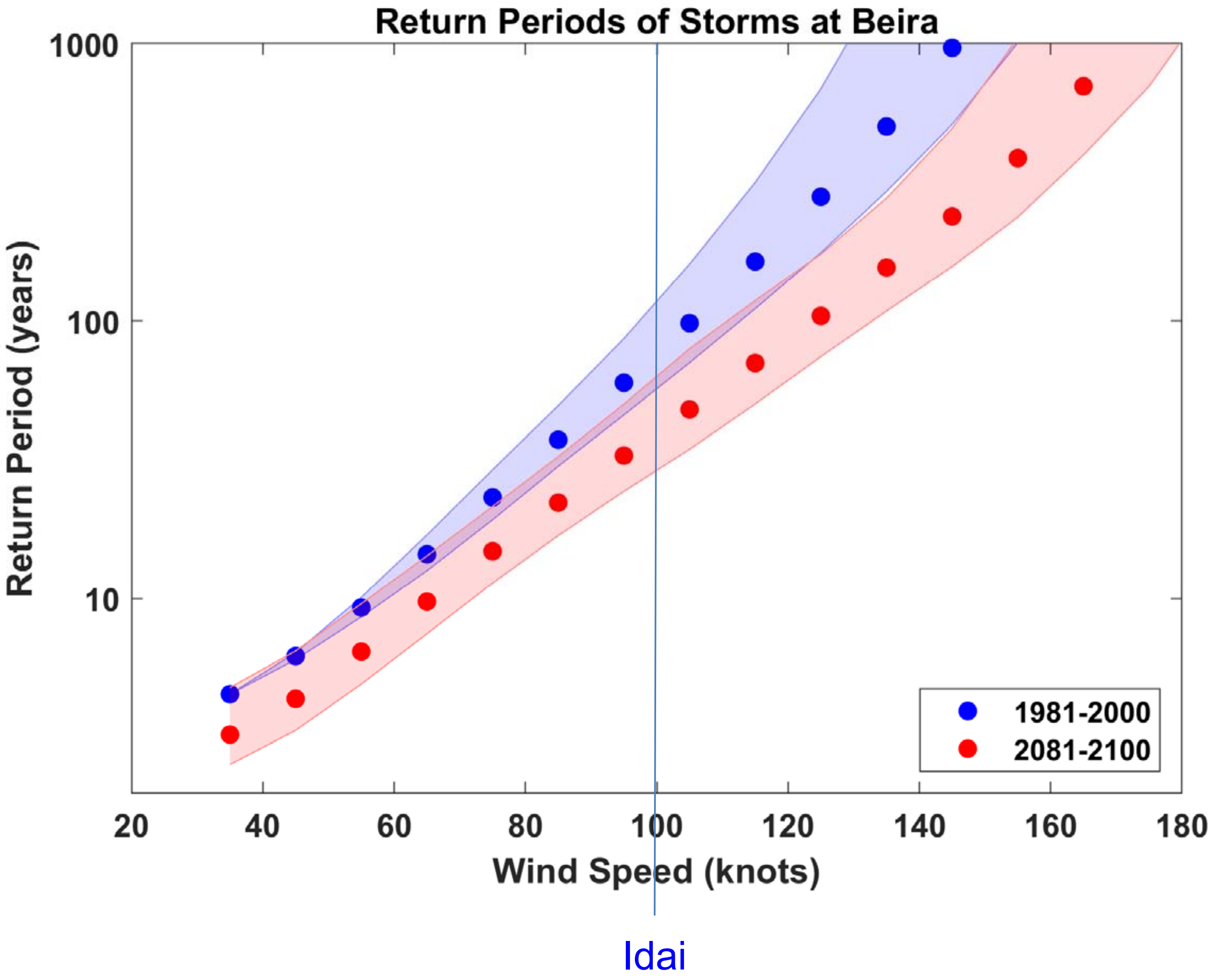


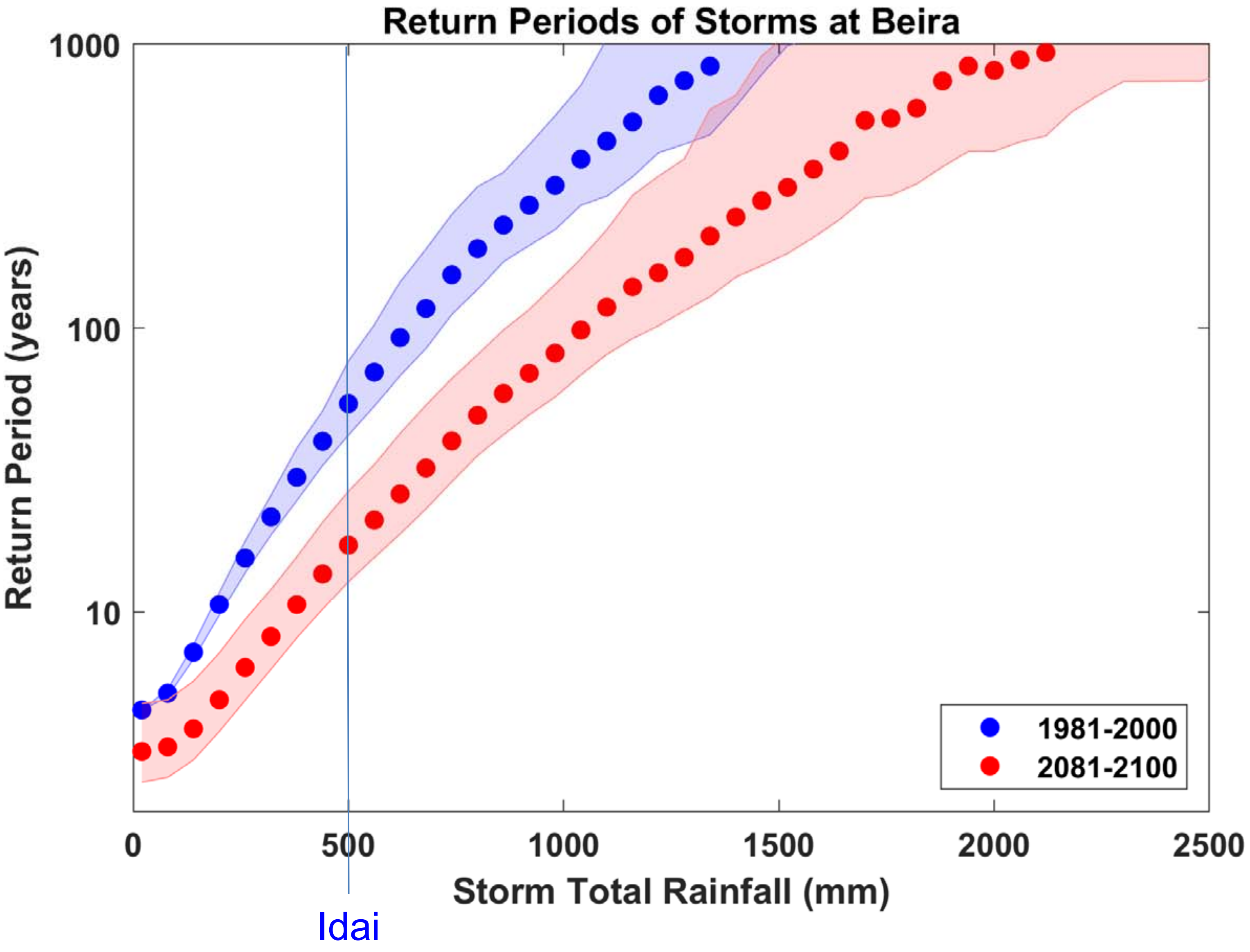
- Second-deadliest tropical cyclone recorded in the South-West Indian Ocean basin
- Third-deadliest tropical cyclone on record in the southern hemisphere
- Peak winds of 100 knots
- > 500 mm rainfall in some locations
- Storm surge of 4.4 m at Beira
- ~90% of Beira destroyed
- > 1,000 lives lost



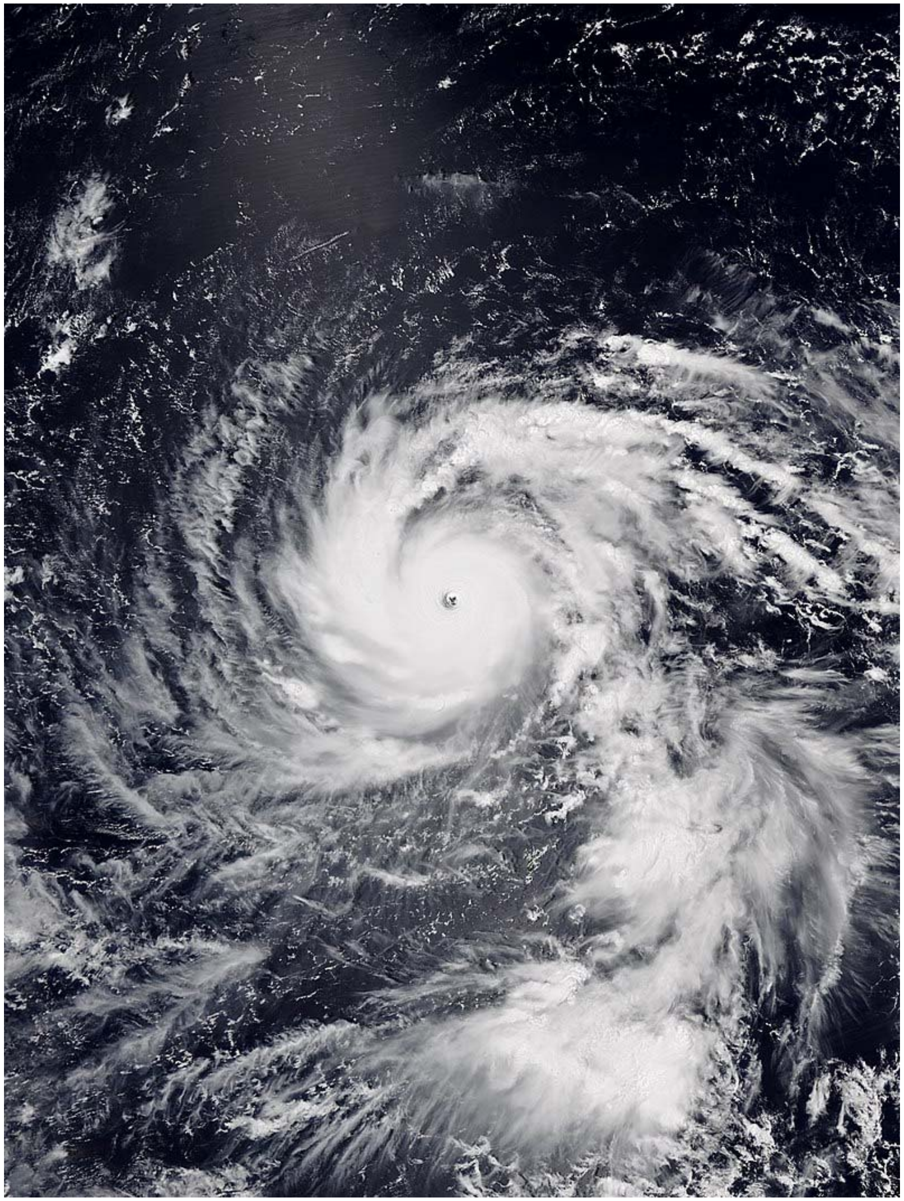
Rainfall accumulation from March 13 to March 20, 2019. Many areas received as much as 50 centimeters (20 inches) of rain. These data are remotely-sensed estimates that come from the Integrated Multi-Satellite Retrievals (IMERG), a product of the Global Precipitation Measurement (GPM) mission. Local rainfall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

Based on 7 CMIP5 models



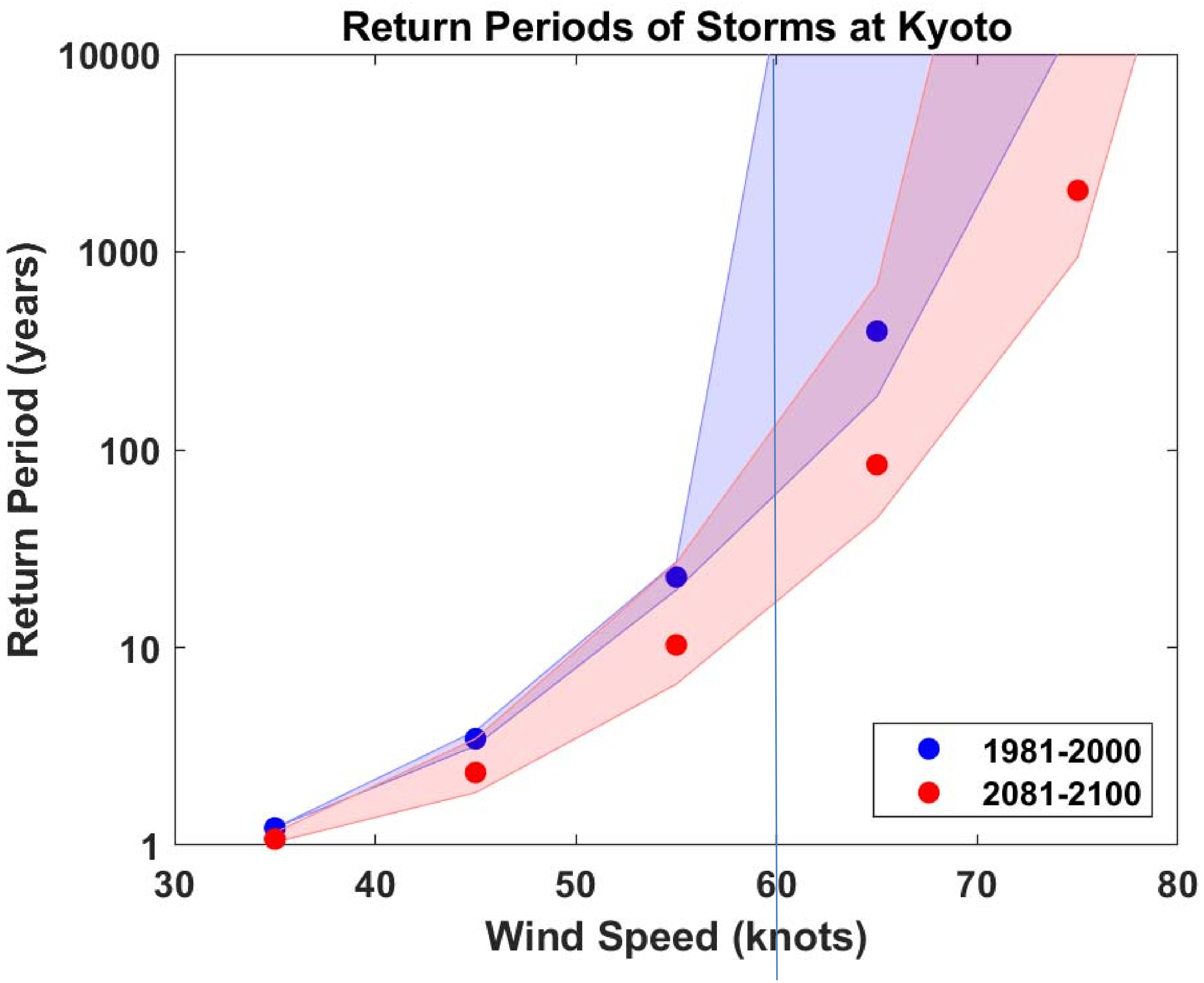

Return Periods of Storms at Beira
Return Period (years)
1000
100
10
0
500
1000
1500
2000
2500
Storm Total Rainfall (mm)
● 1981-2000
● 2081-2100
Idai

Typhoon Jebi, 2018

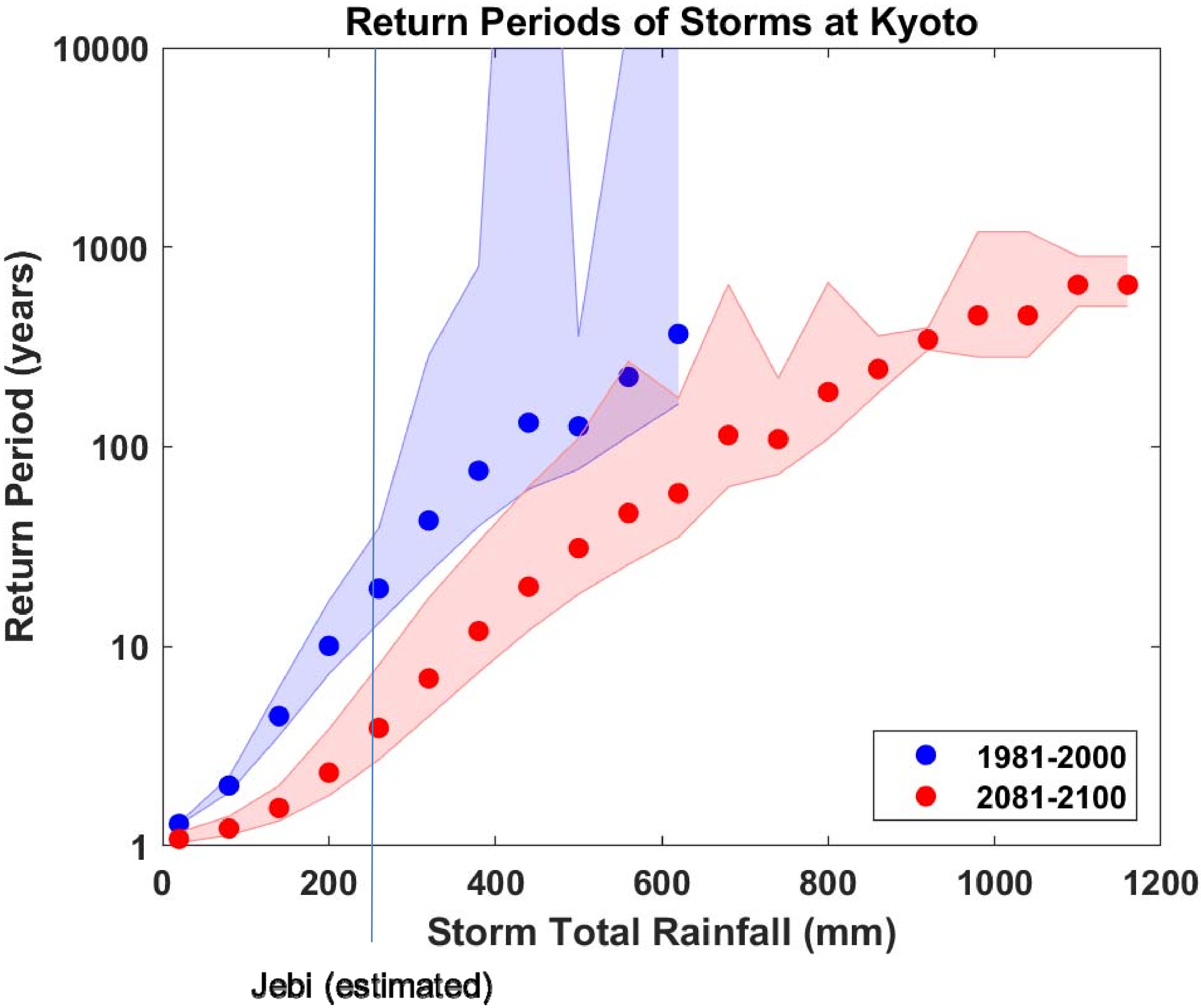


- Strongest typhoon to strike Japan since Typhoon Yancy in 1993
- 90 kts sustained wind at landfall
- Broke the historical records of sustained winds at 53 weather stations and maximum gust at 100 weather stations in Japan
- Storm surge of 3.3 m at Osaka
- 11 deaths, >600 injured

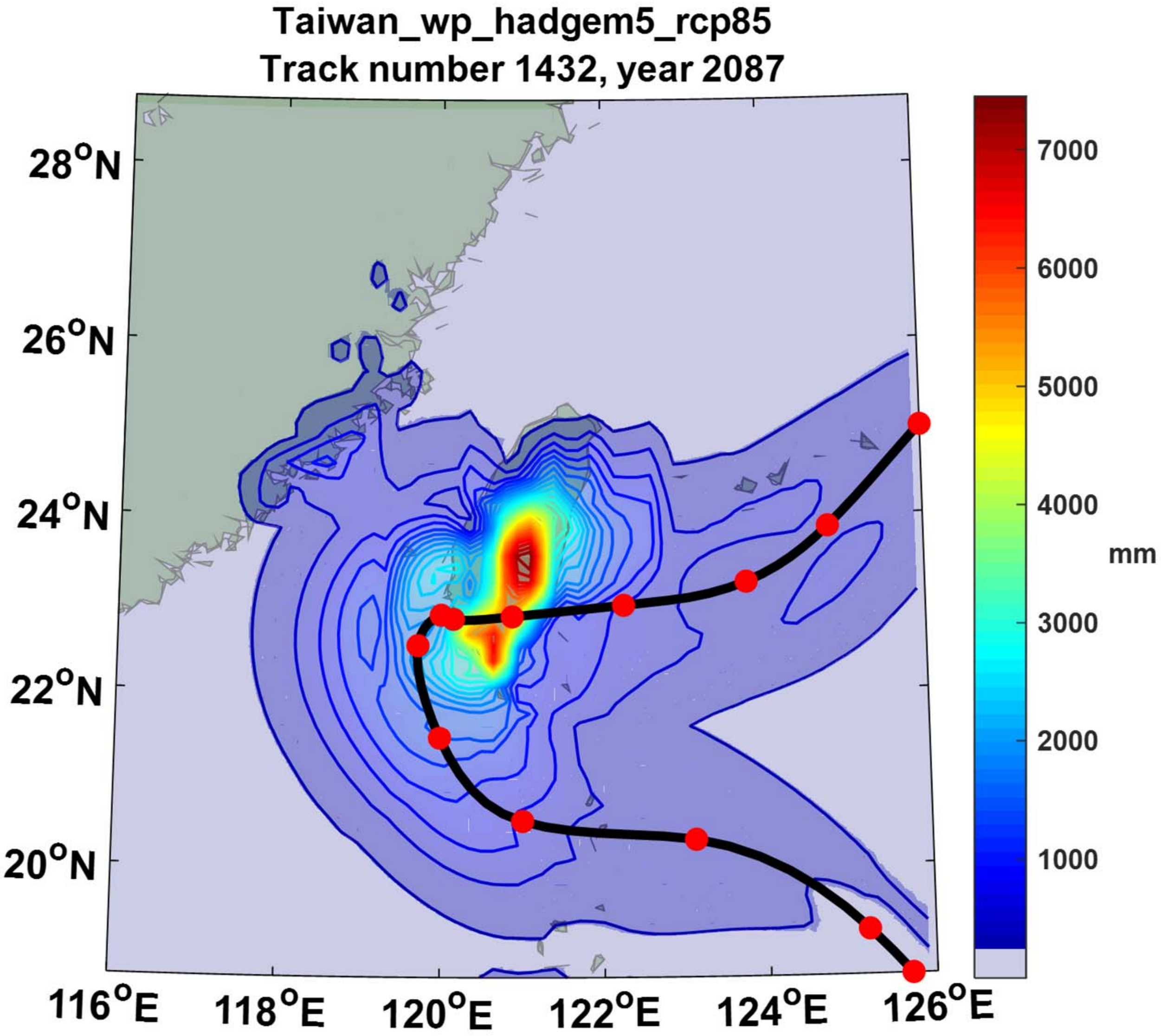
Based on 5 CMIP5 models



Jebi (estimated)


Return Periods of Storms at Kyoto
Return Period (years)
10000
1000
100
10
1
0
200
400
600
800
1000
1200
Storm Total Rainfall (mm)
● 1981-2000
● 2081-2100
Jebi (estimated)

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