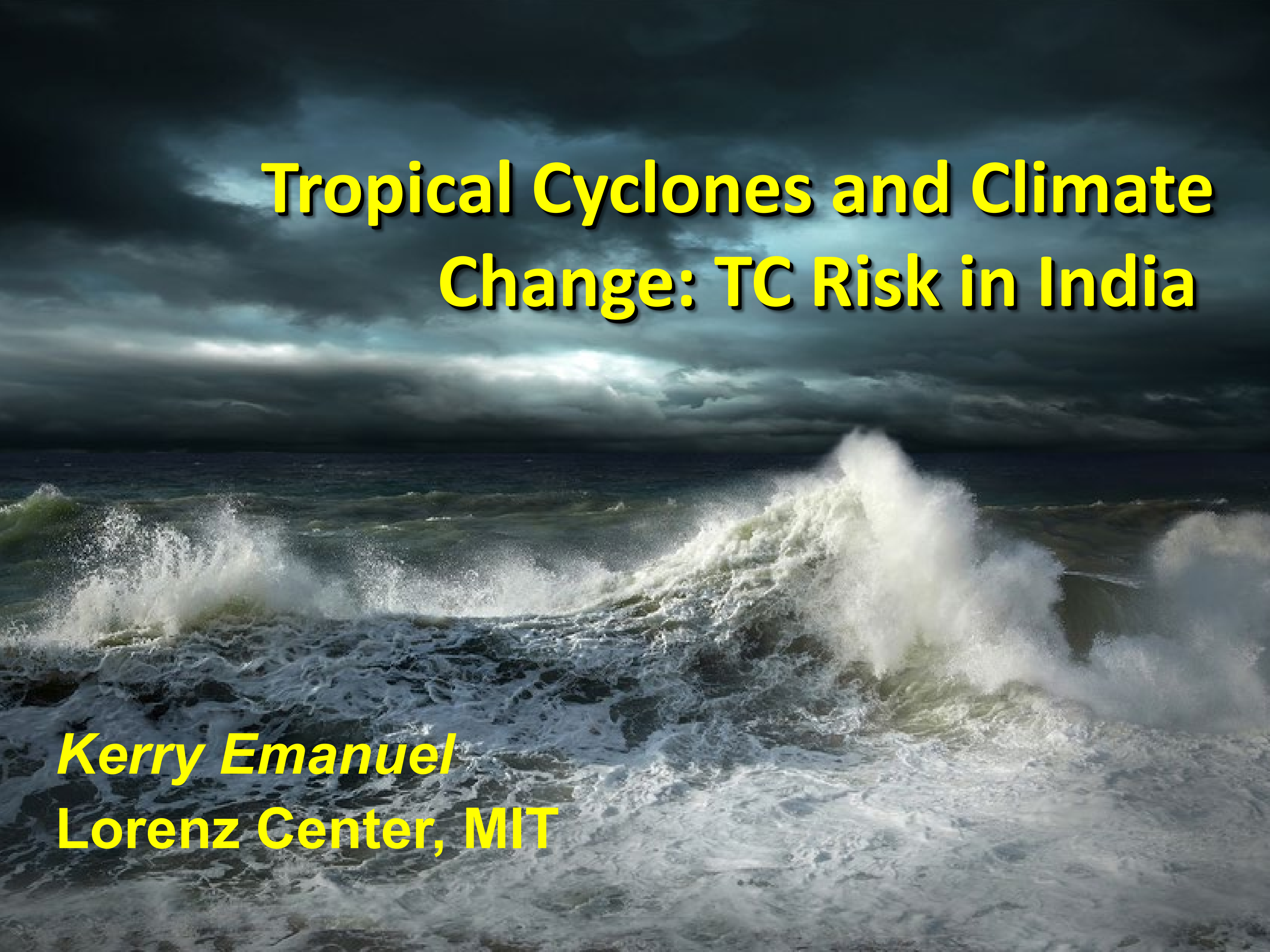


Tropical Cyclones and Climate Change: TC Risk in India

Kerry Emanuel
Lorenz Center, MIT

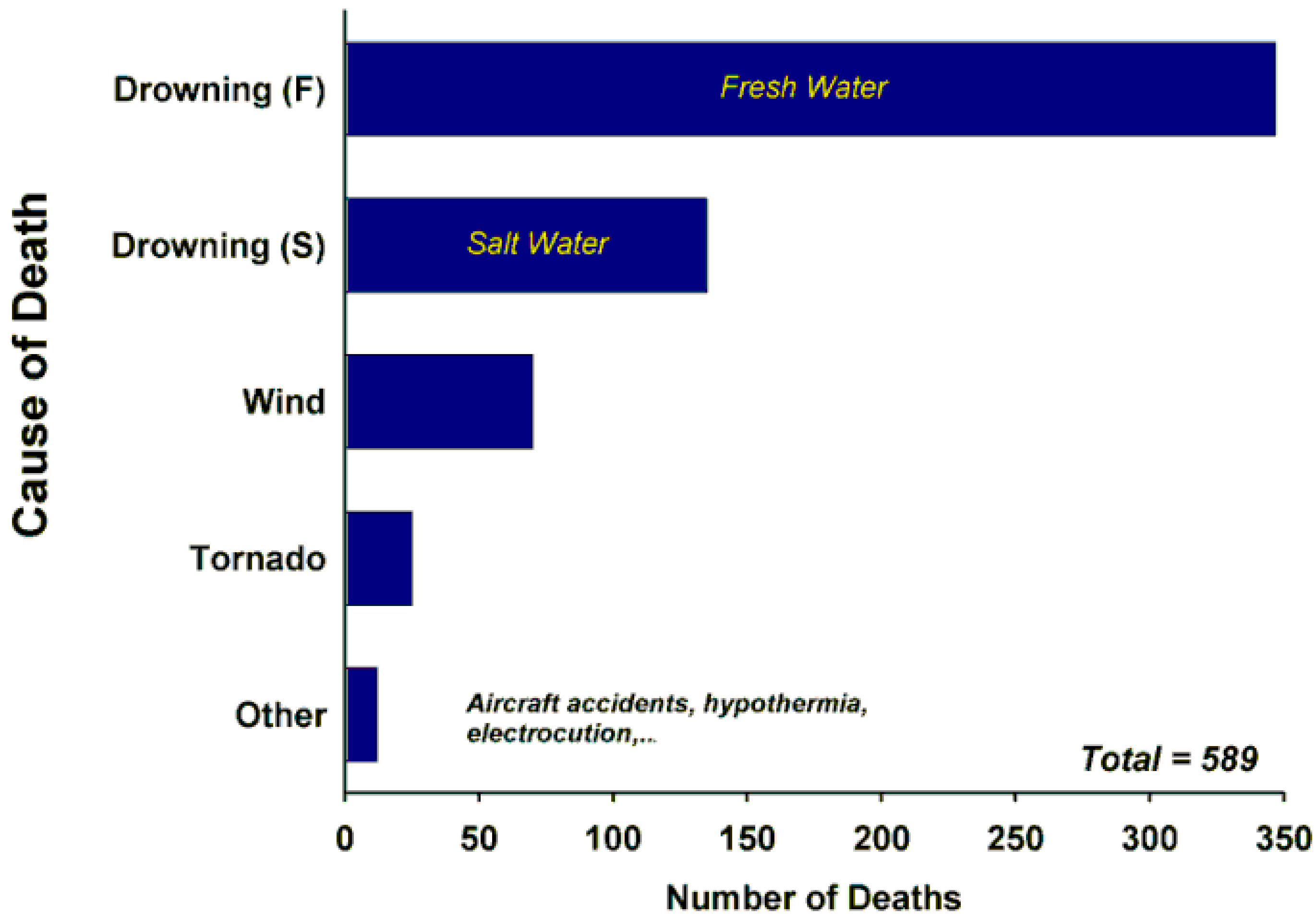
Hurricane Risks:

- Wind

- Rain

- Storm Surge

U. S. Hurricane Mortality (1970-1999)



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.

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

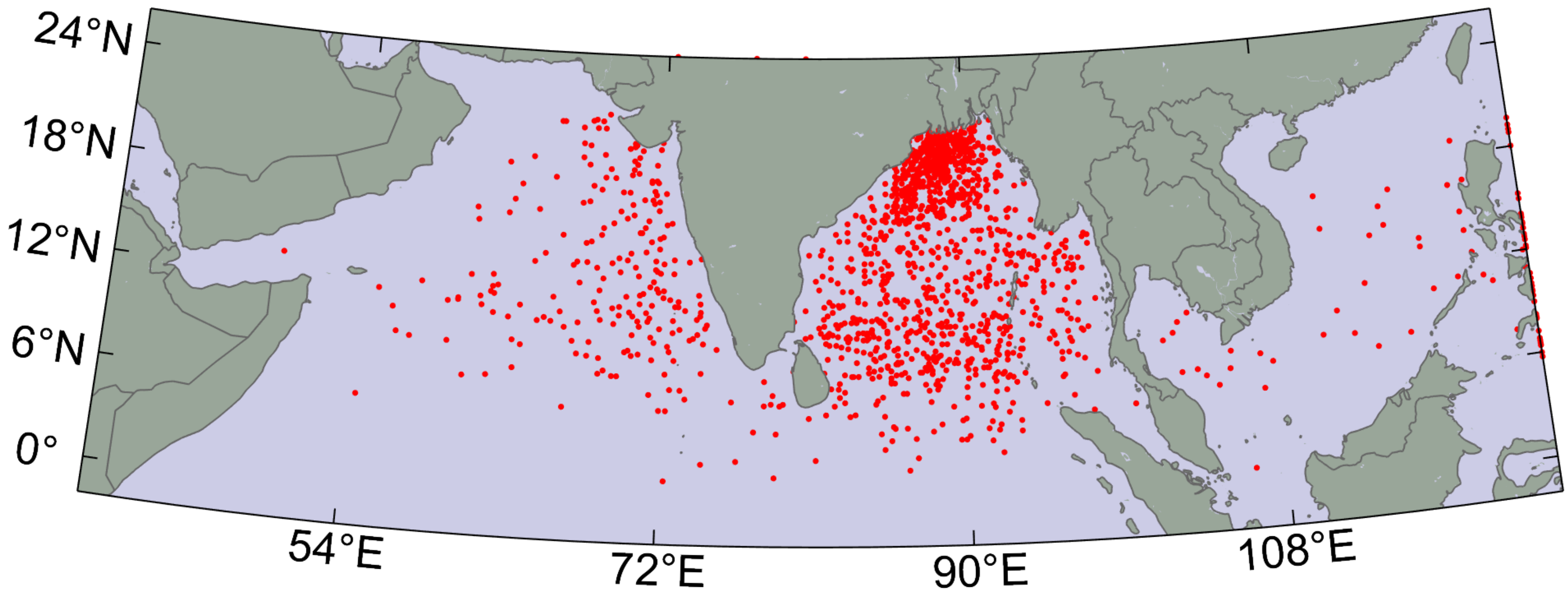
EM-DAT, 2016: The OFDA/CRED International Disaster Database http://www.emdat.be/.

Tropical Cyclones in India

- About 160,000 deaths since 1916 (~1500/yr)
- $200 million 2015 U.S. dollars in damages annually since 1916
- 370 million people are exposed to tropical cyclones in India

EM-DAT, 2016: The OFDA/CRED International Disaster Database
http://www.emdat.be/ and Government of India
https://ncrmp.gov.in/cyclones-their-impact-in-india/

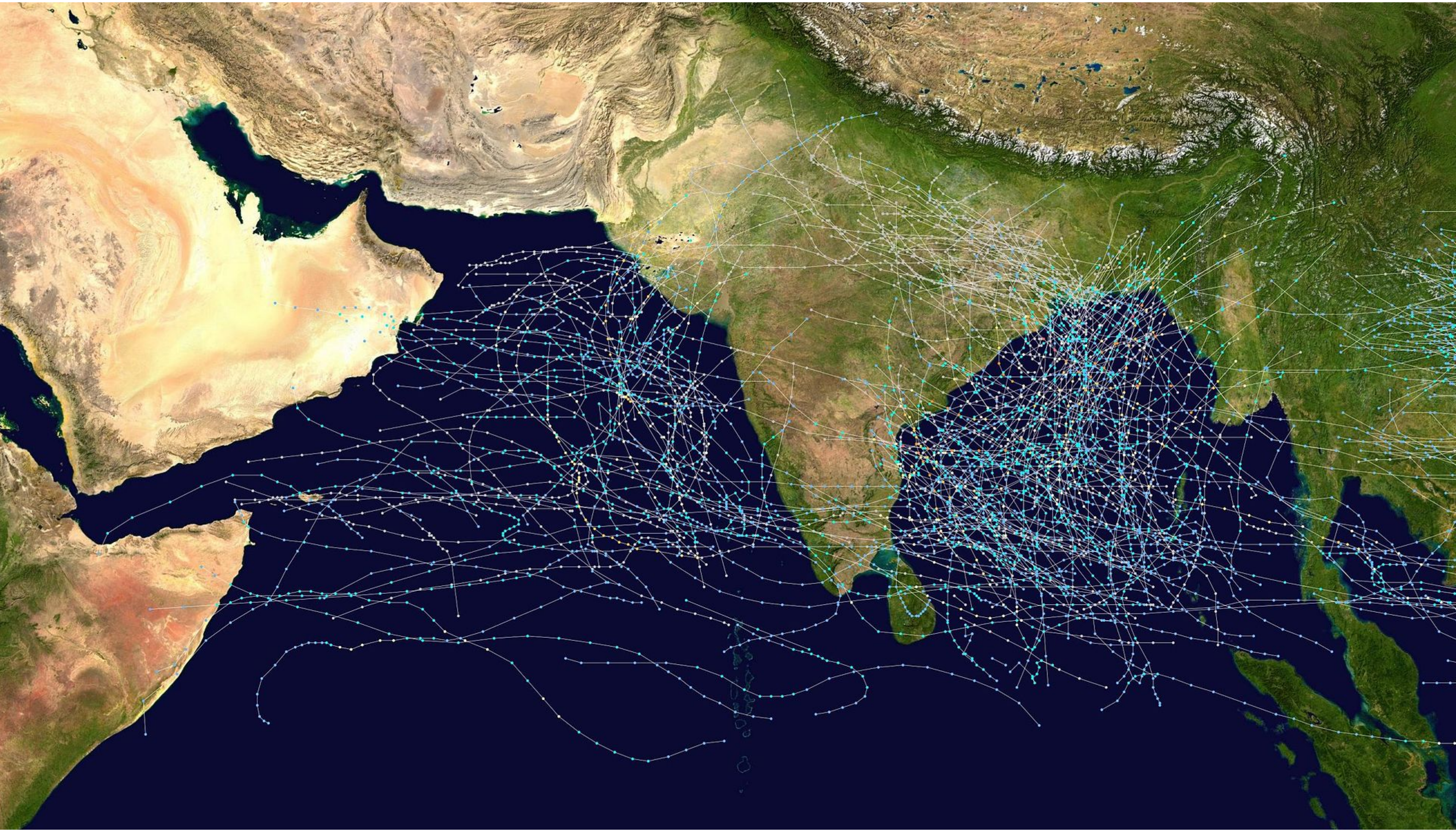
All Over-Ocean Genesis Points in IBTrACS Data



1686 Indian Ocean events in IBTrACS

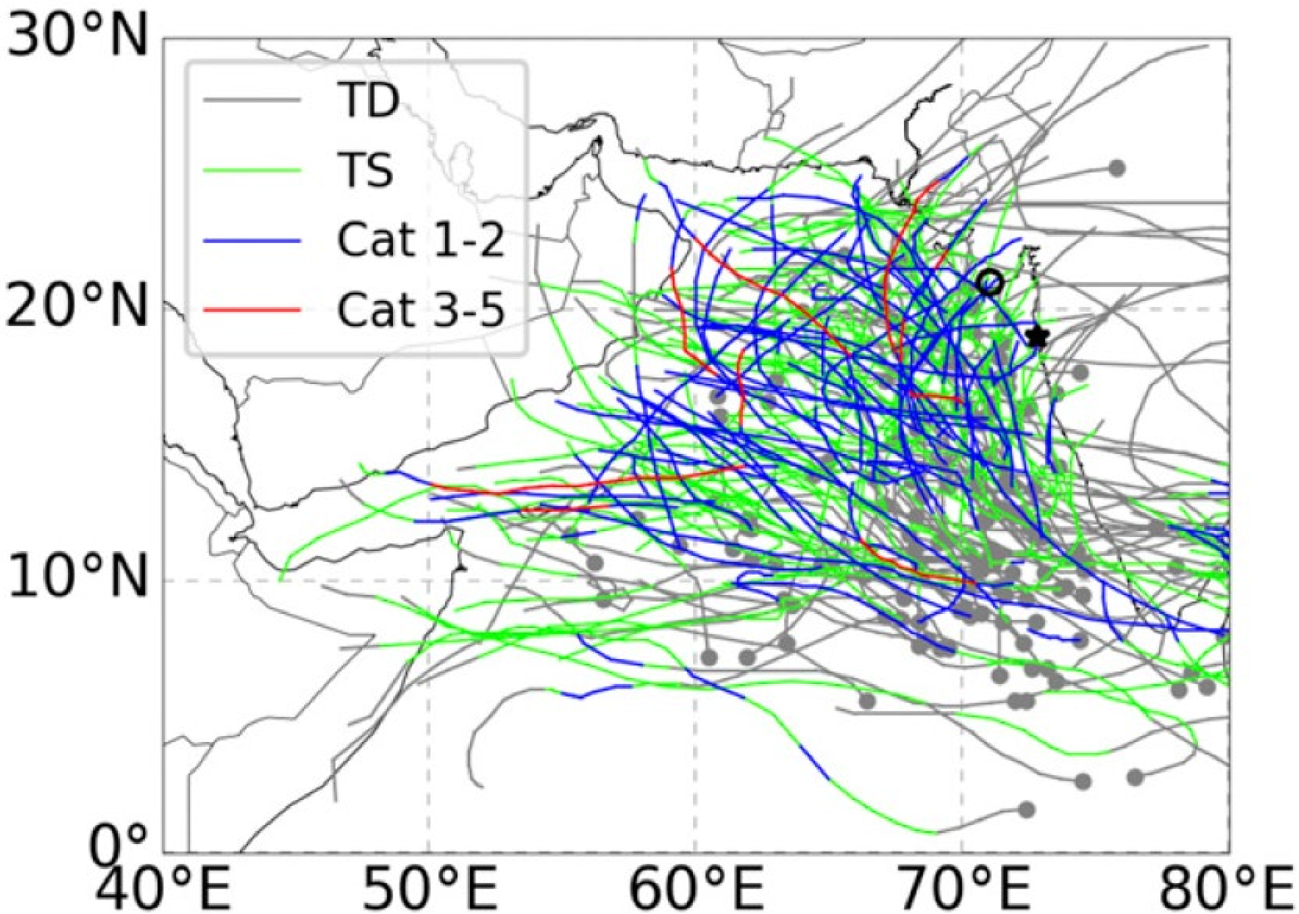
(points on eastern boundary originated east of boundary)

Tropical Cyclone Tracks, India, 1970-2005



Source: Wikipedia https://en.wikipedia.org/wiki/North_Indian_Ocean_tropical_cyclone

Arabian Sea Tropical Cyclones, 1879-2016



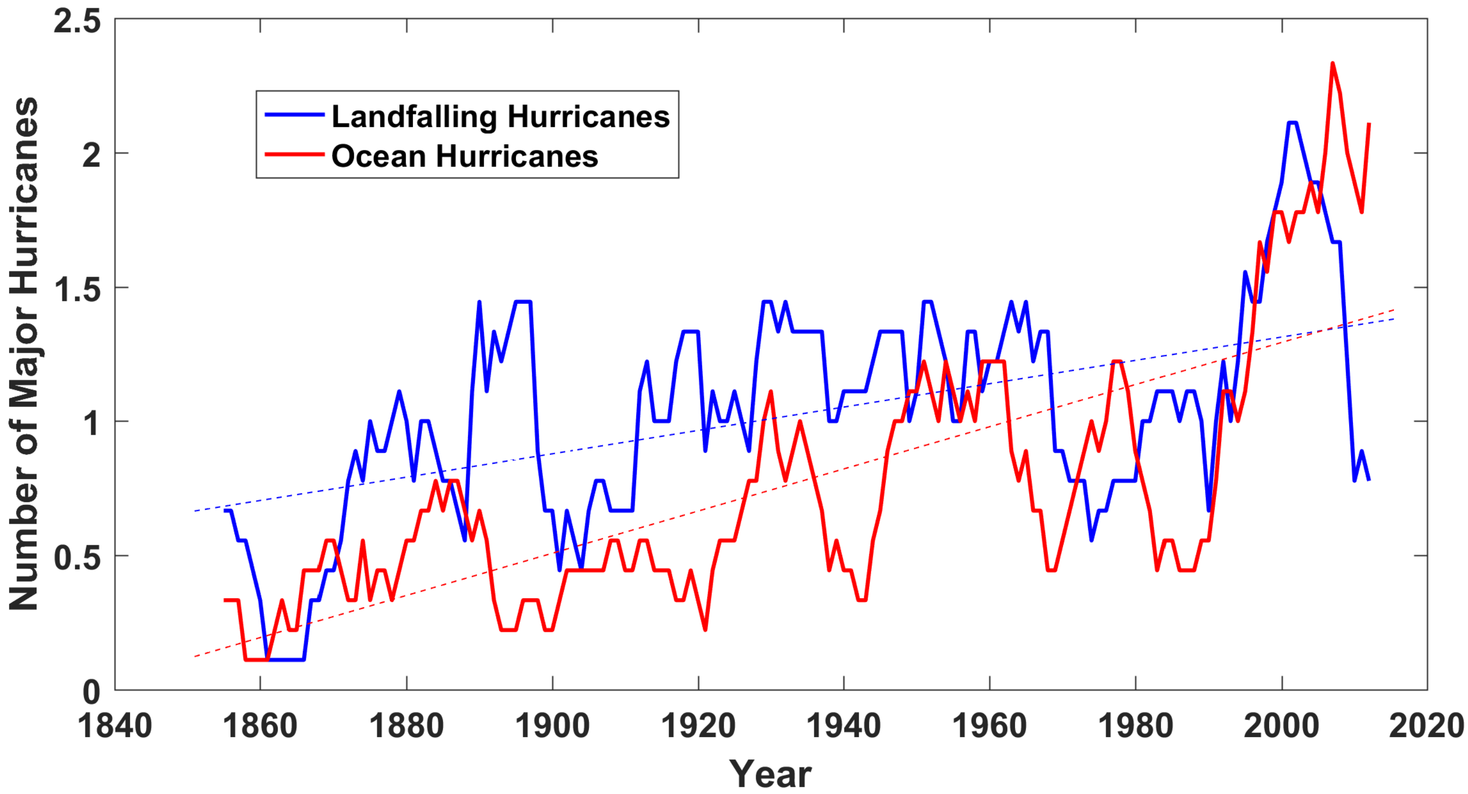
Tropical cyclone tracks from the India Meteorological Department's extended dataset, 1879–2016, color coded by intensity using the U.S. Saffir–Simpson hurricane wind scale. **Sobel et al. *Mon. Wea. Rev.*, 2019**

Is Hurricane Risk Changing?

Historical Records

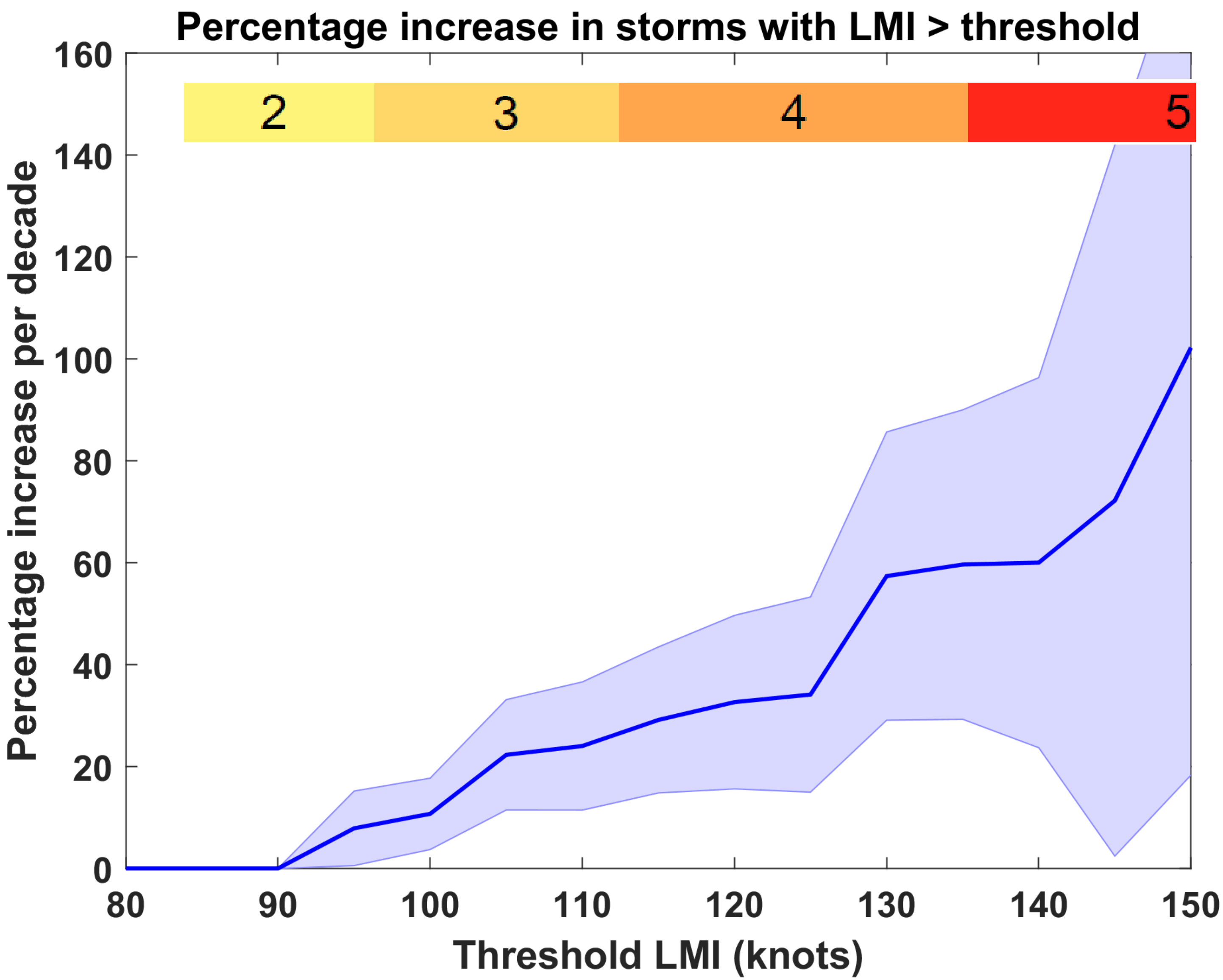
- Pre-1943: Anecdotal accounts from coastal cities and ships
- 1943: Introduction of routine aircraft reconnaissance in Atlantic, western North Pacific
- 1958: Inertial navigation permits direct measurement of wind speed at flight level
- 1970: Complete global detection by satellites
- 1978: Introduction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

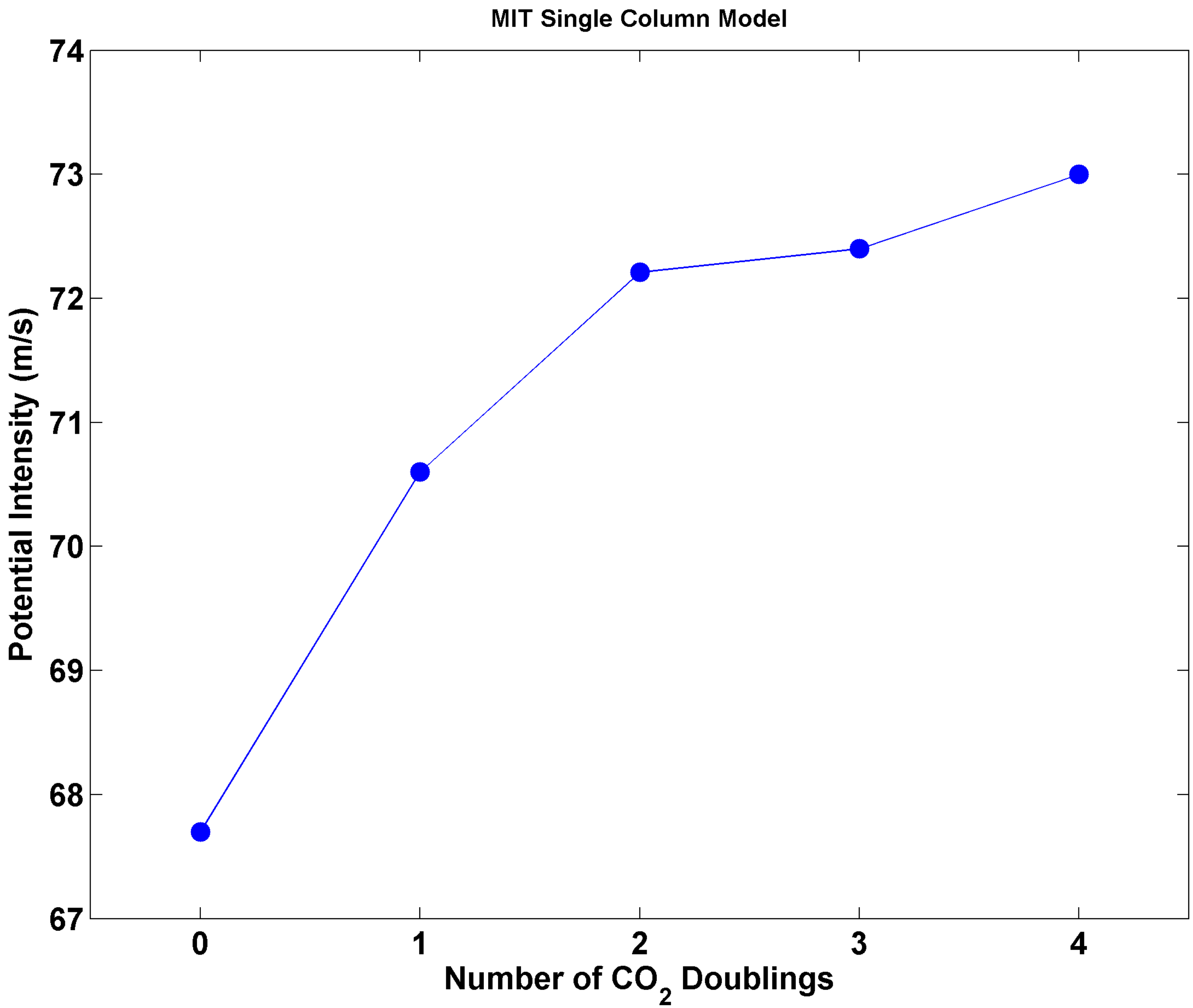
Trends in Global TC Frequency Over Threshold Intensities, from Historical TC Data, 1980-2016. Trends Shown Only When $p < 0.05$.



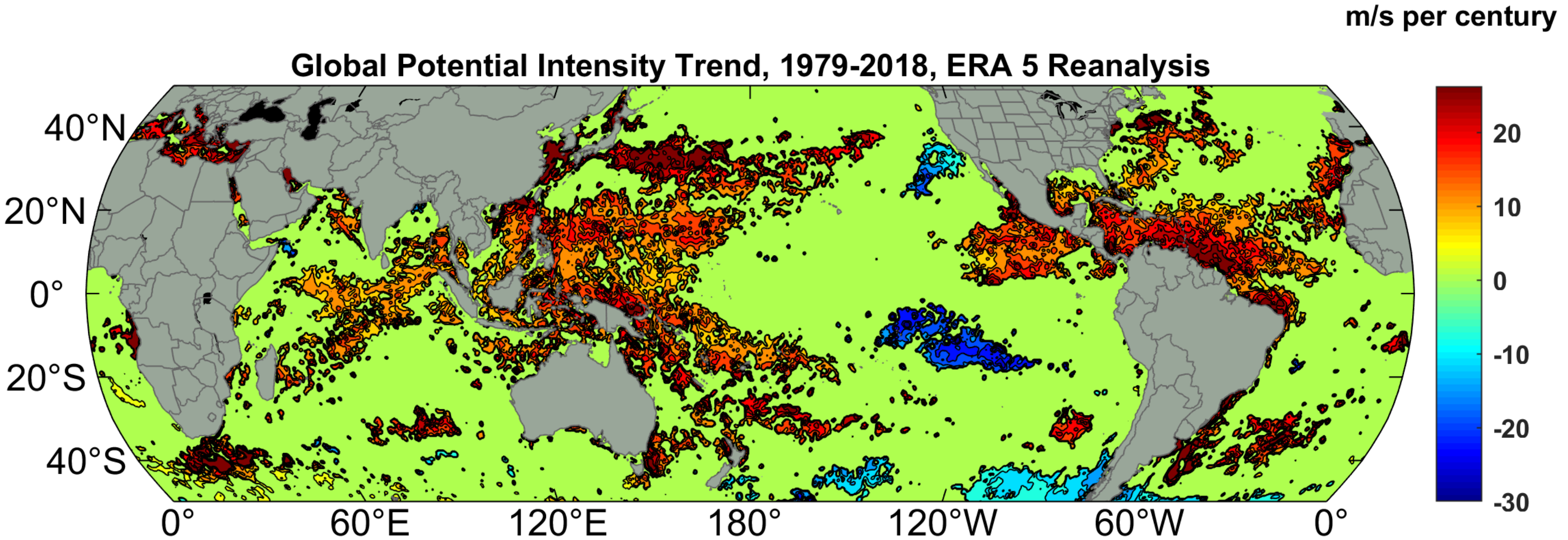
Potential Intensity

- The highest azimuthally averaged surface wind speed achievable in a given thermodynamic environment, derived from treating the cyclone as a Carnot engine

Potential Intensity and CO_2

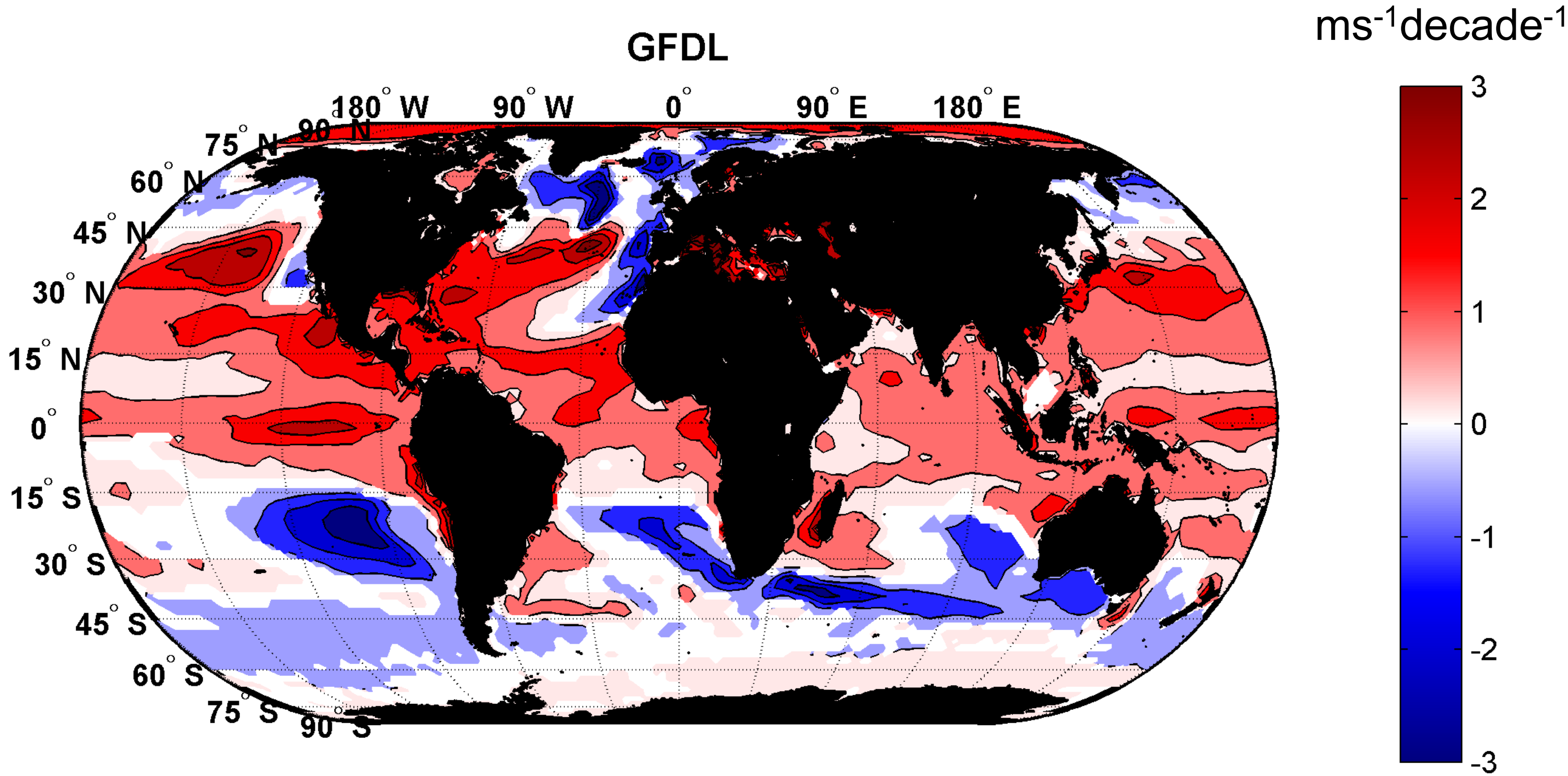


Potential Intensity Trend, 1979-2018, ERA 5 Reanalysis



(Trend shown only where p value < 0.05)

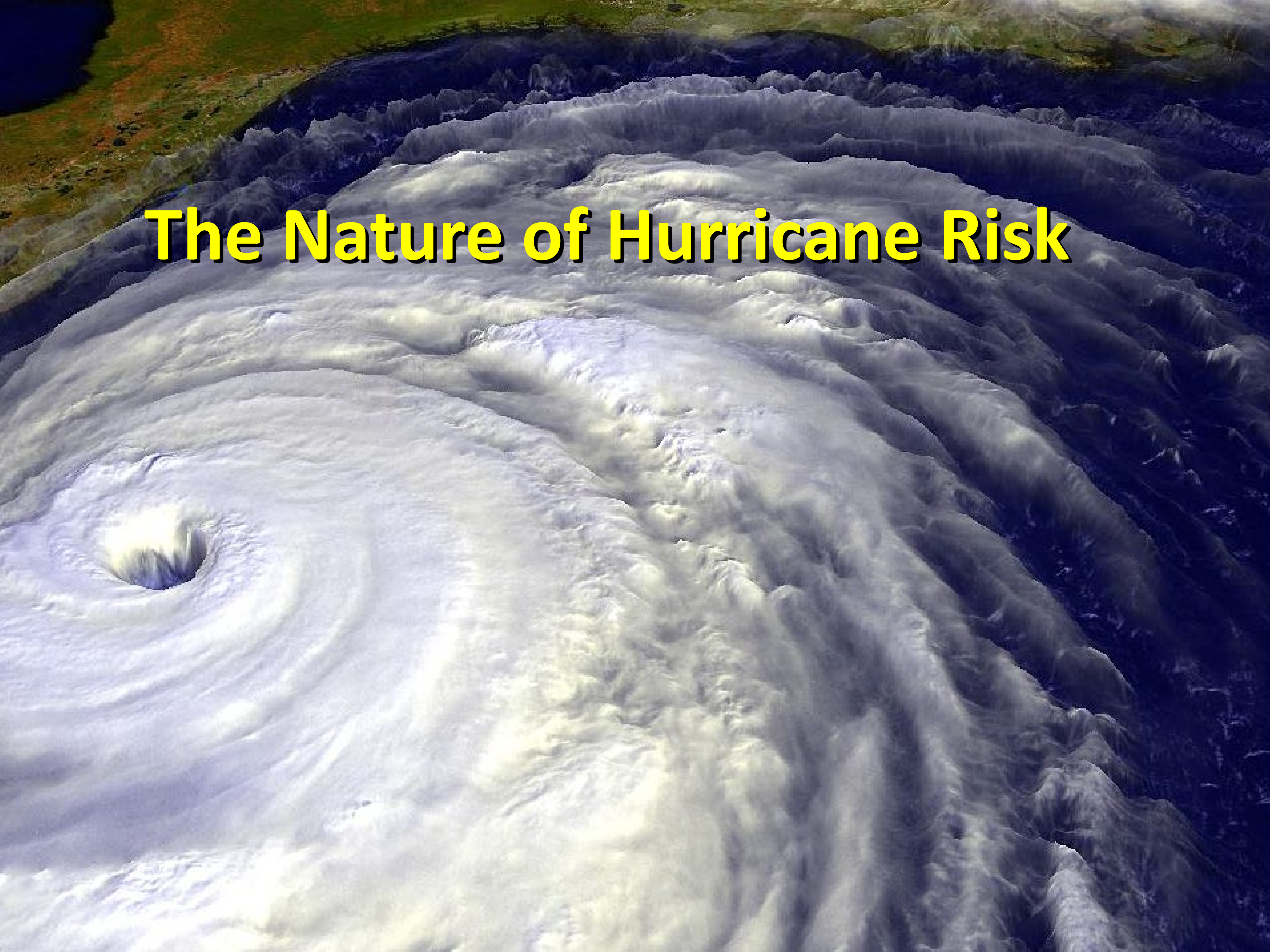
Projected Trend Over 21st Century: GFDL model under RCP 8.5



Inferences from Basic Theory:

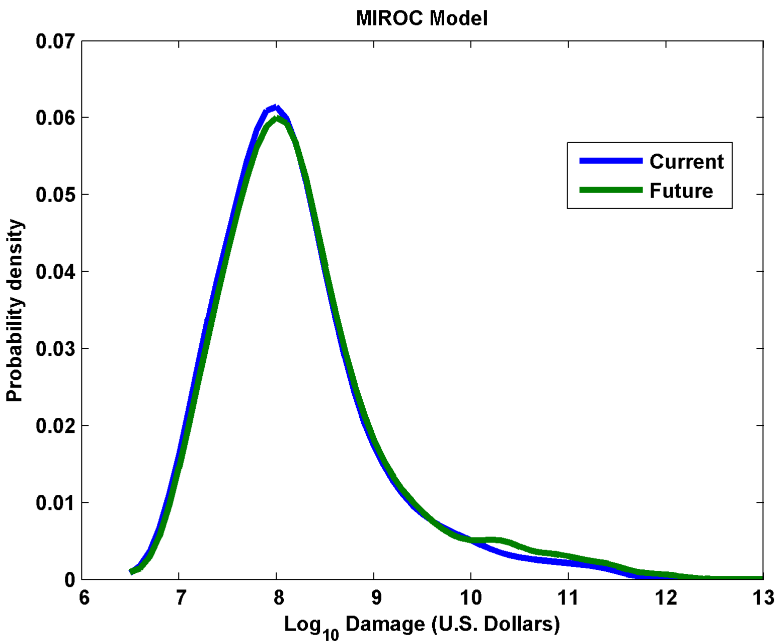
- Potential intensity increases with global warming
- Incidence of high-intensity hurricanes should increase
- Increases in potential intensity should be faster in sub-tropics
- Hurricanes will produce substantially more rain: Clausius-Clapeyron yields ~7% increase in water vapor per 1^{o}C warming

The Nature of Hurricane Risk



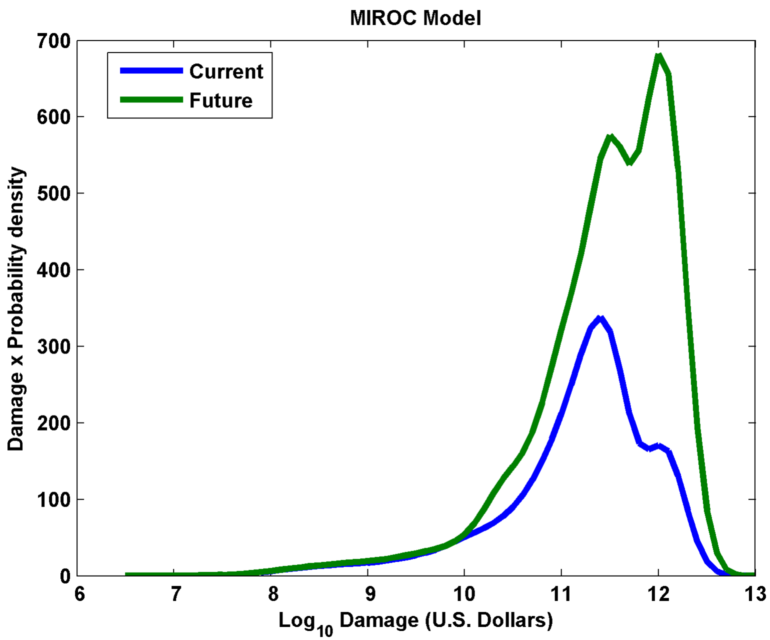
Risk Assessment in a Changing Climate: The Problem

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!

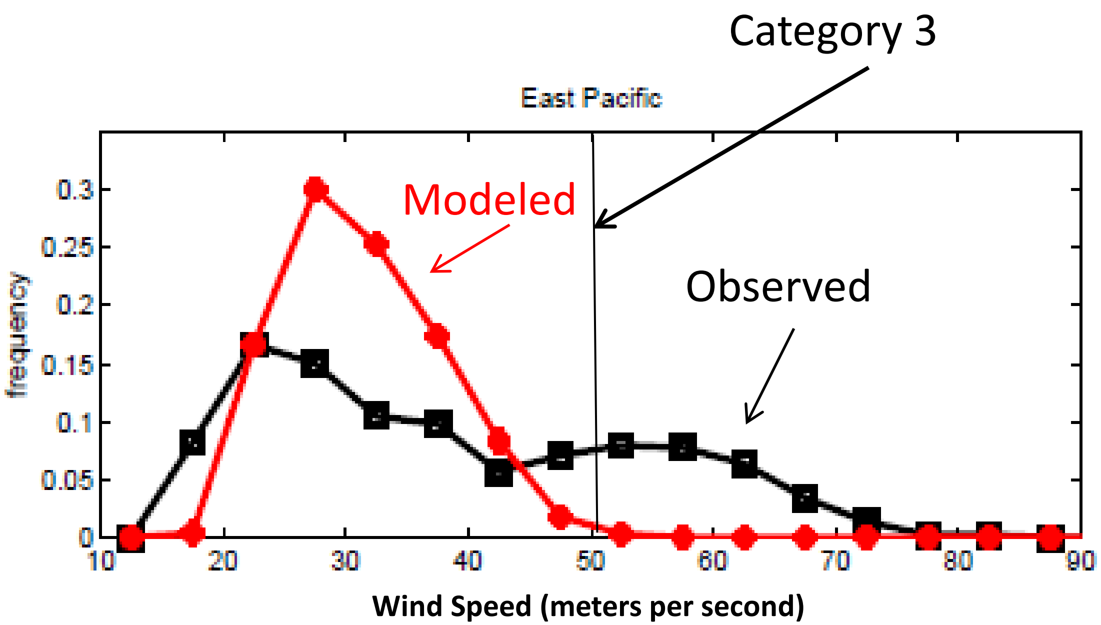
How We COULD Deal with This:

- 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

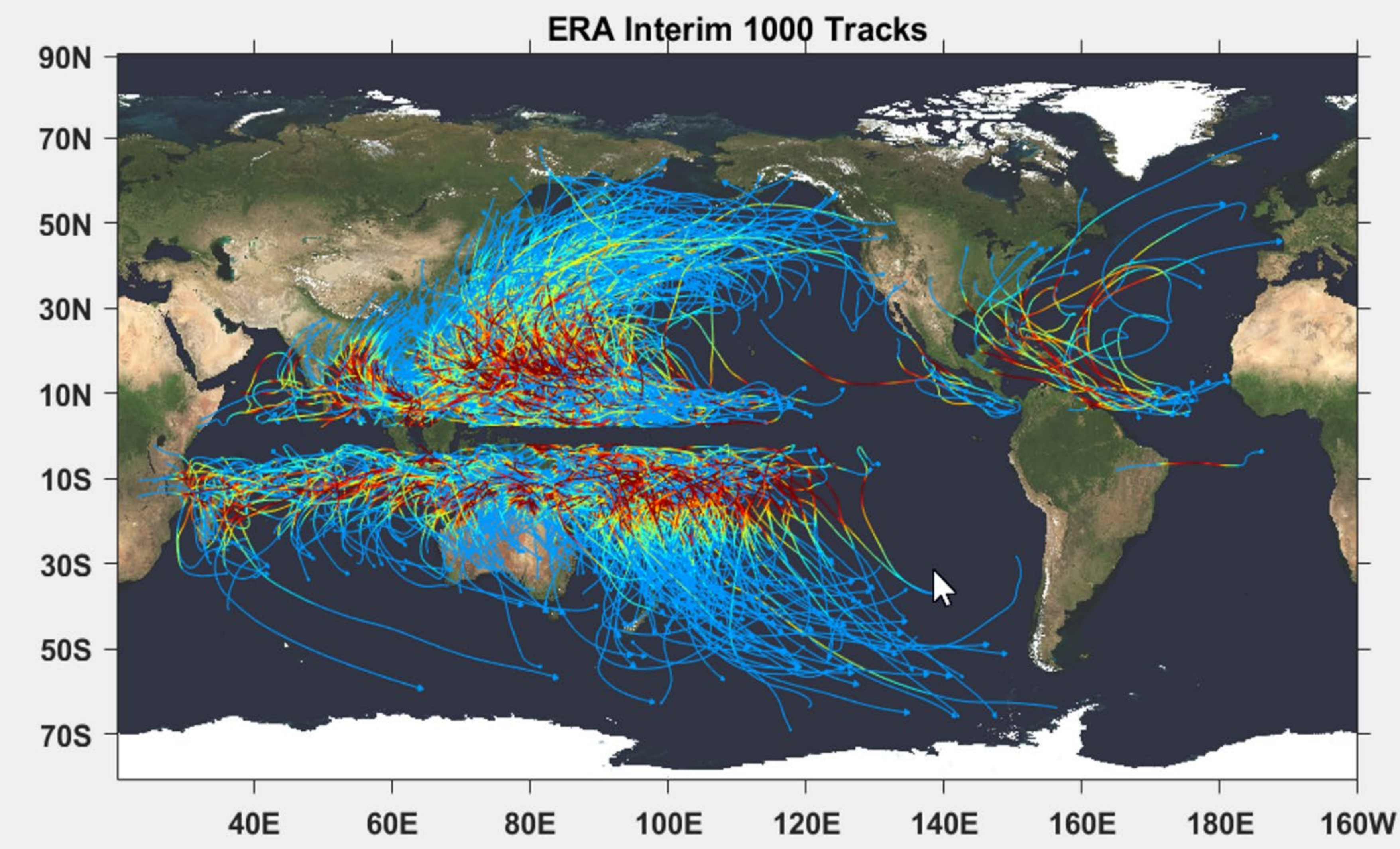
How to deal with this?

- **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**
- **Can easily generate > 100,000 storms**

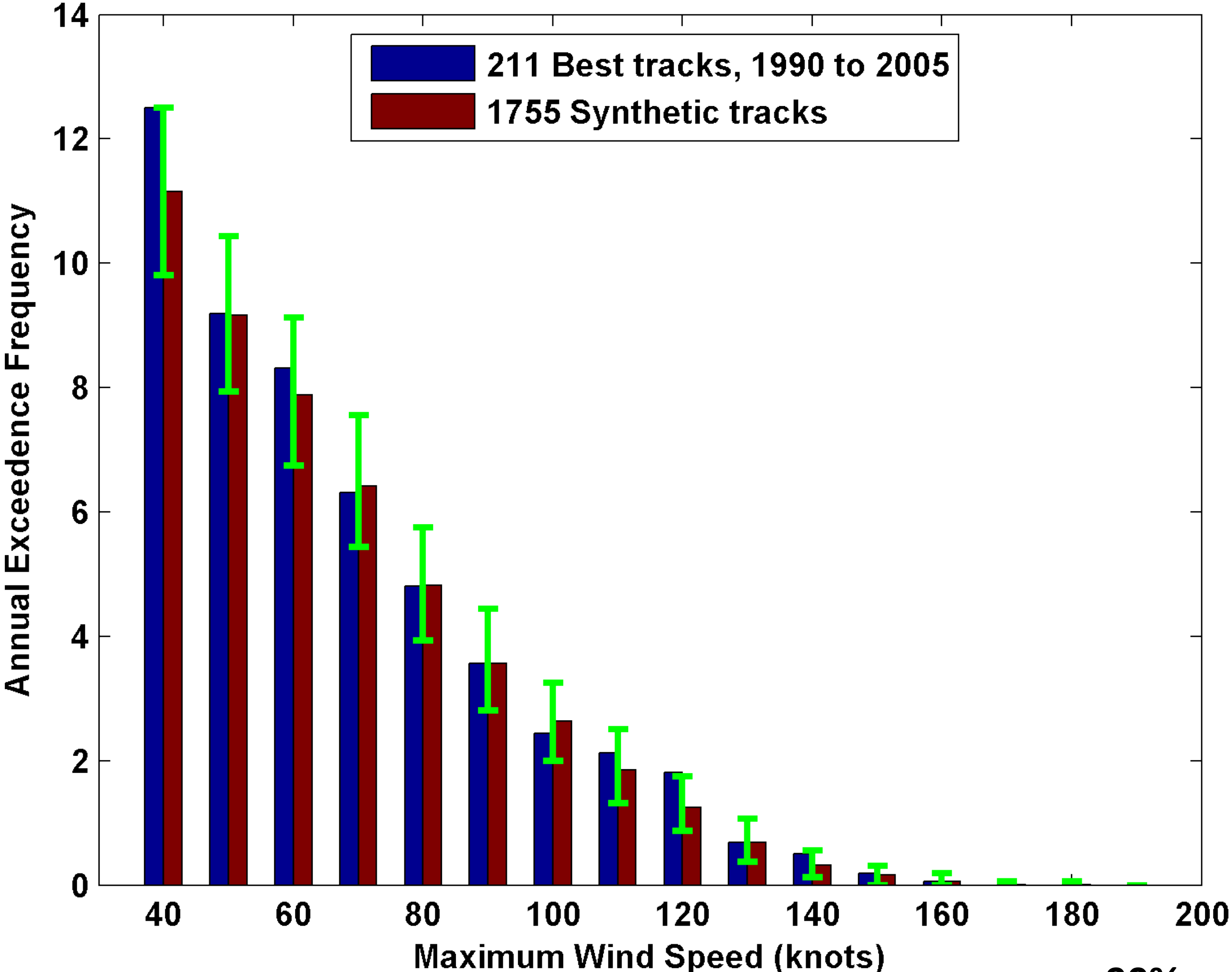
Risk Assessment Approach:

- **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

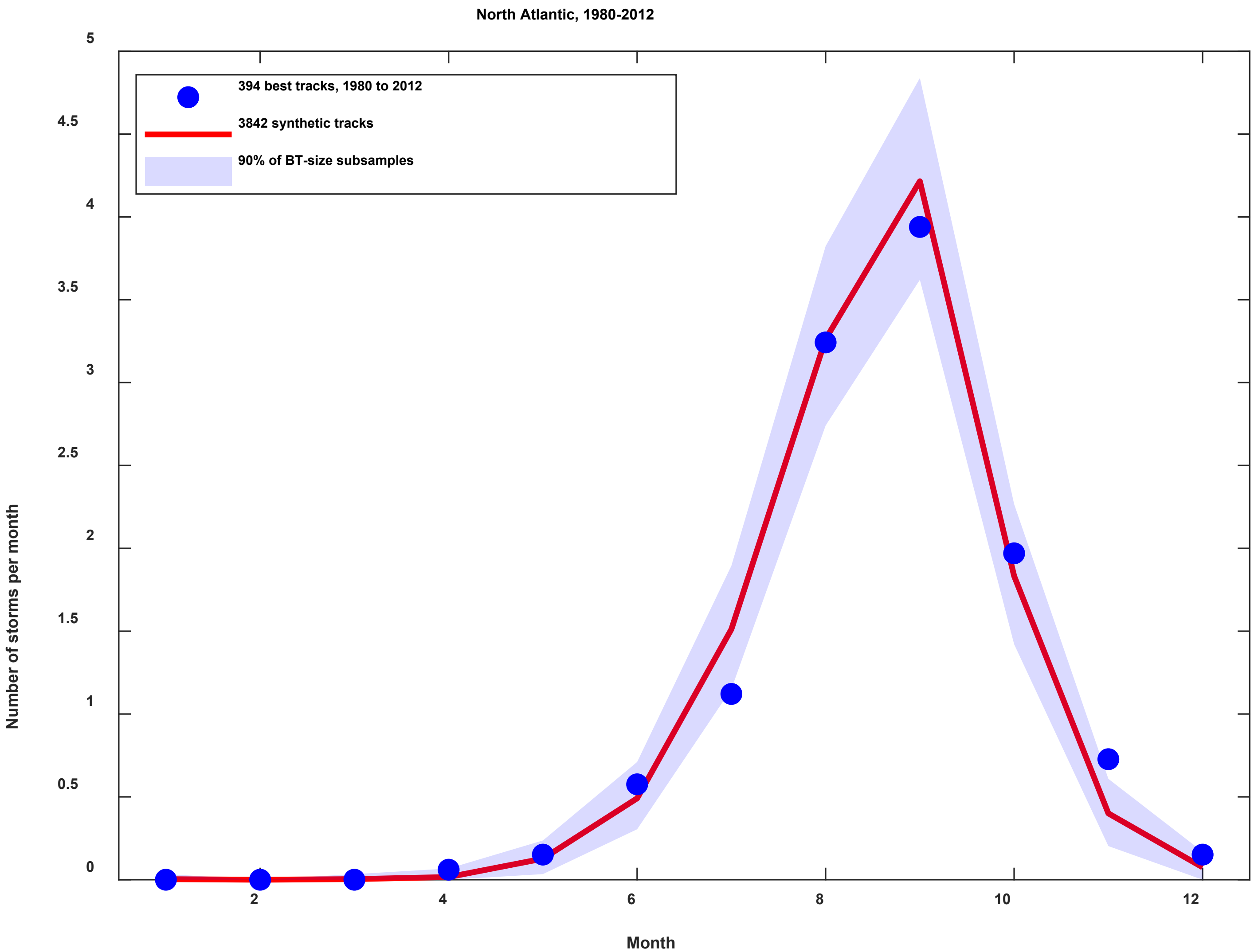

ERA Interim 1000 Tracks
90N
70N
50N
30N
10N
10S
30S
50S
70S
40E
60E
80E
100E
120E
140E
160E
180E
160W

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

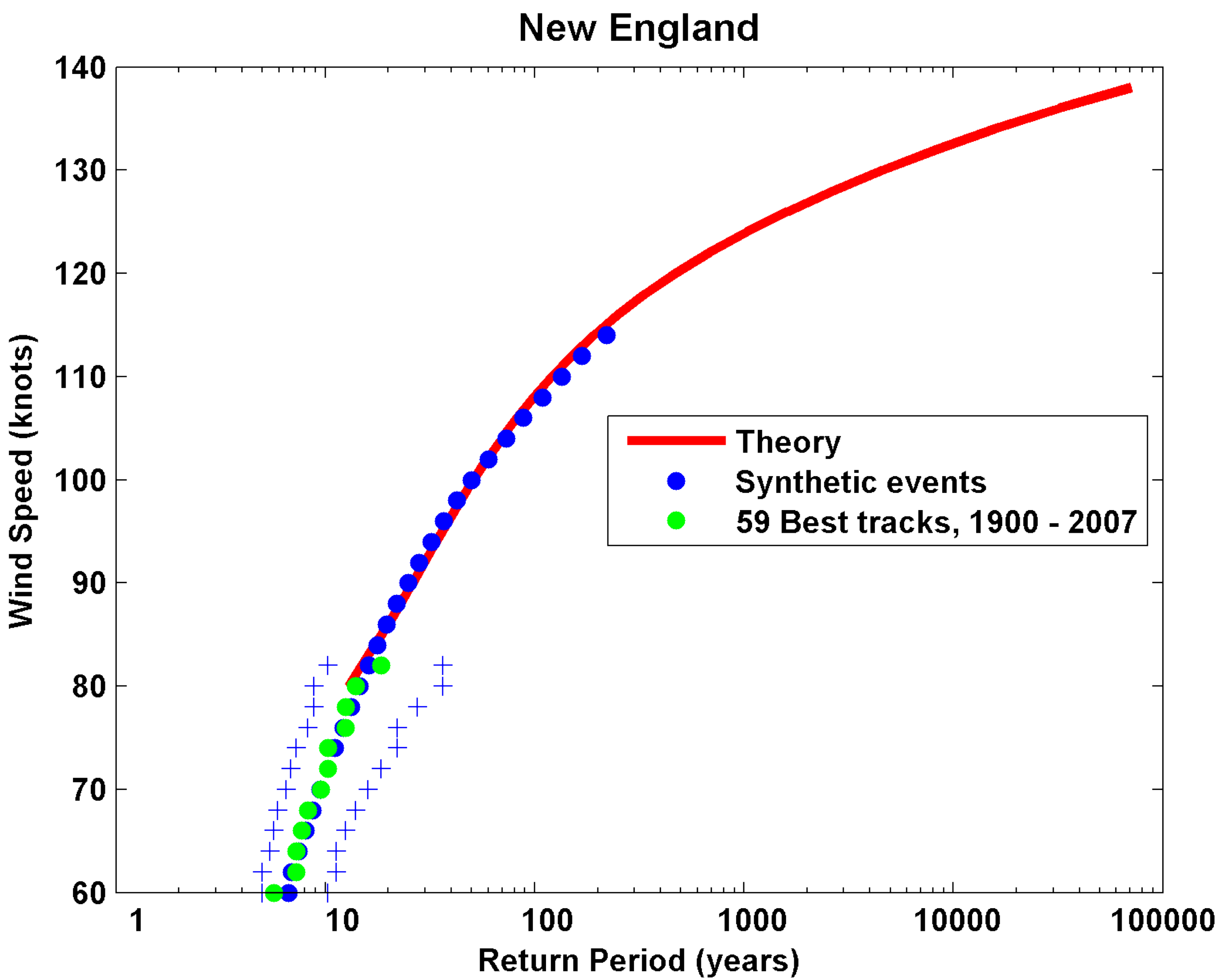


90% confidence bounds

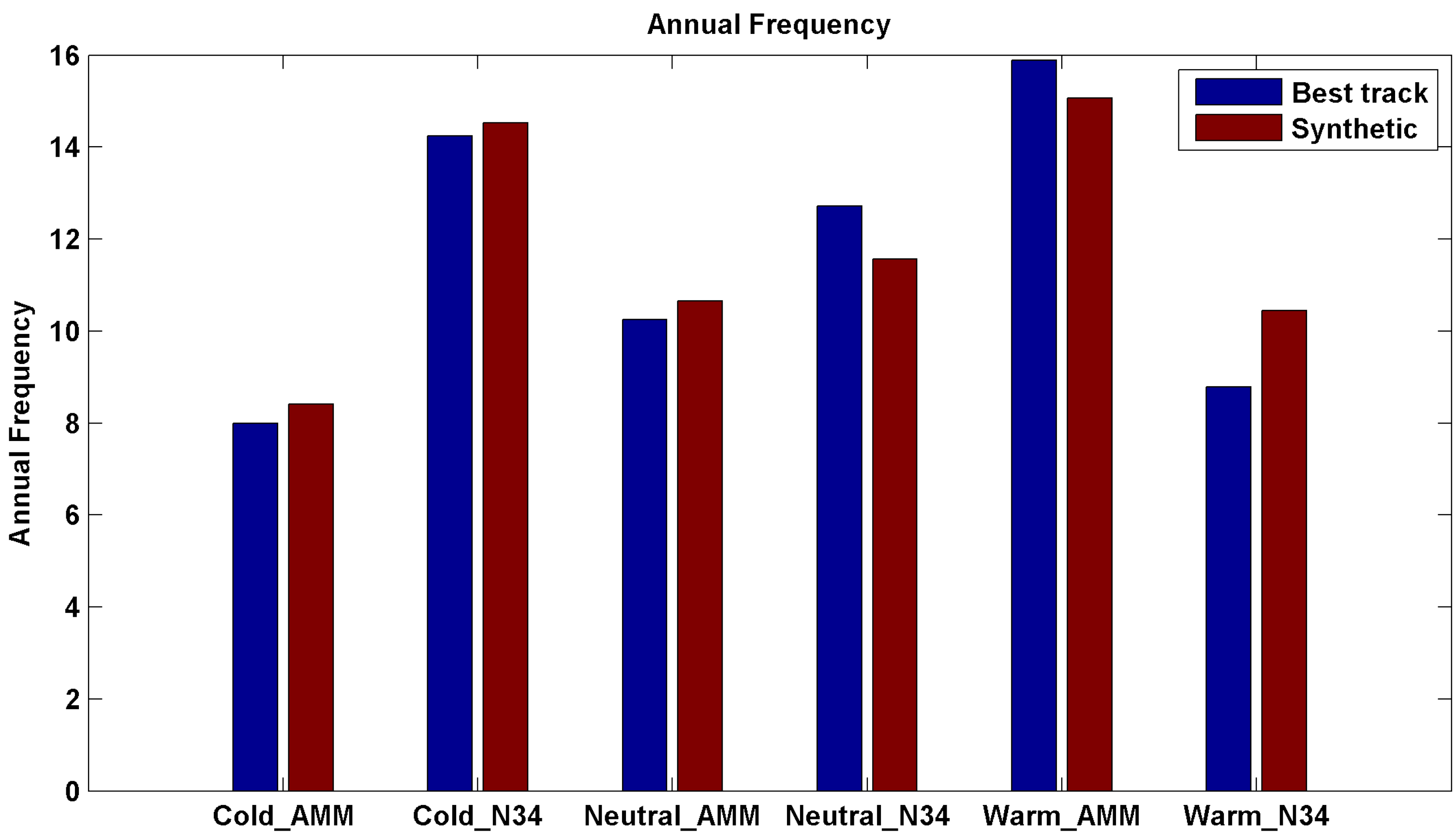
Atlantic Annual Cycle



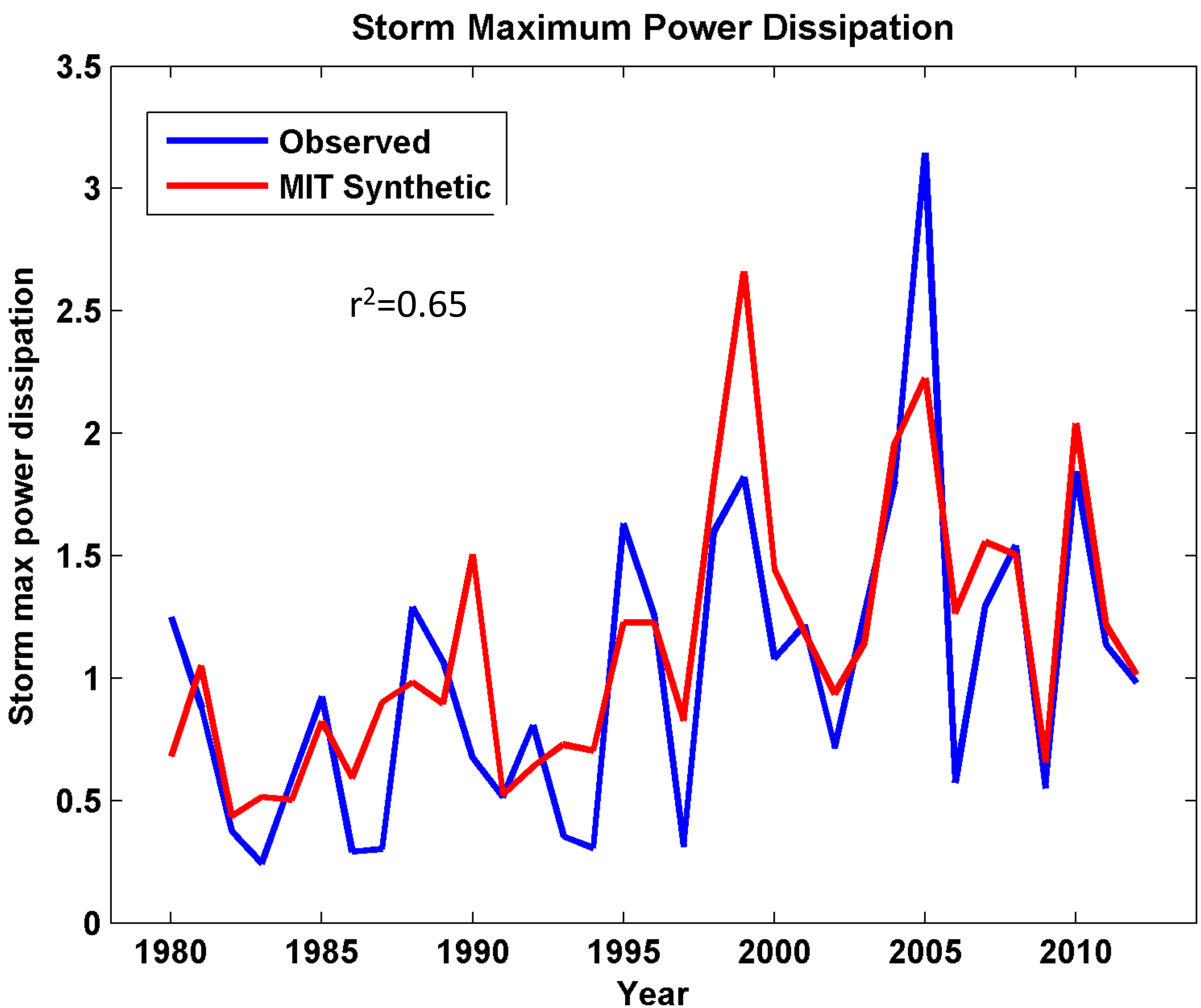
Return Periods



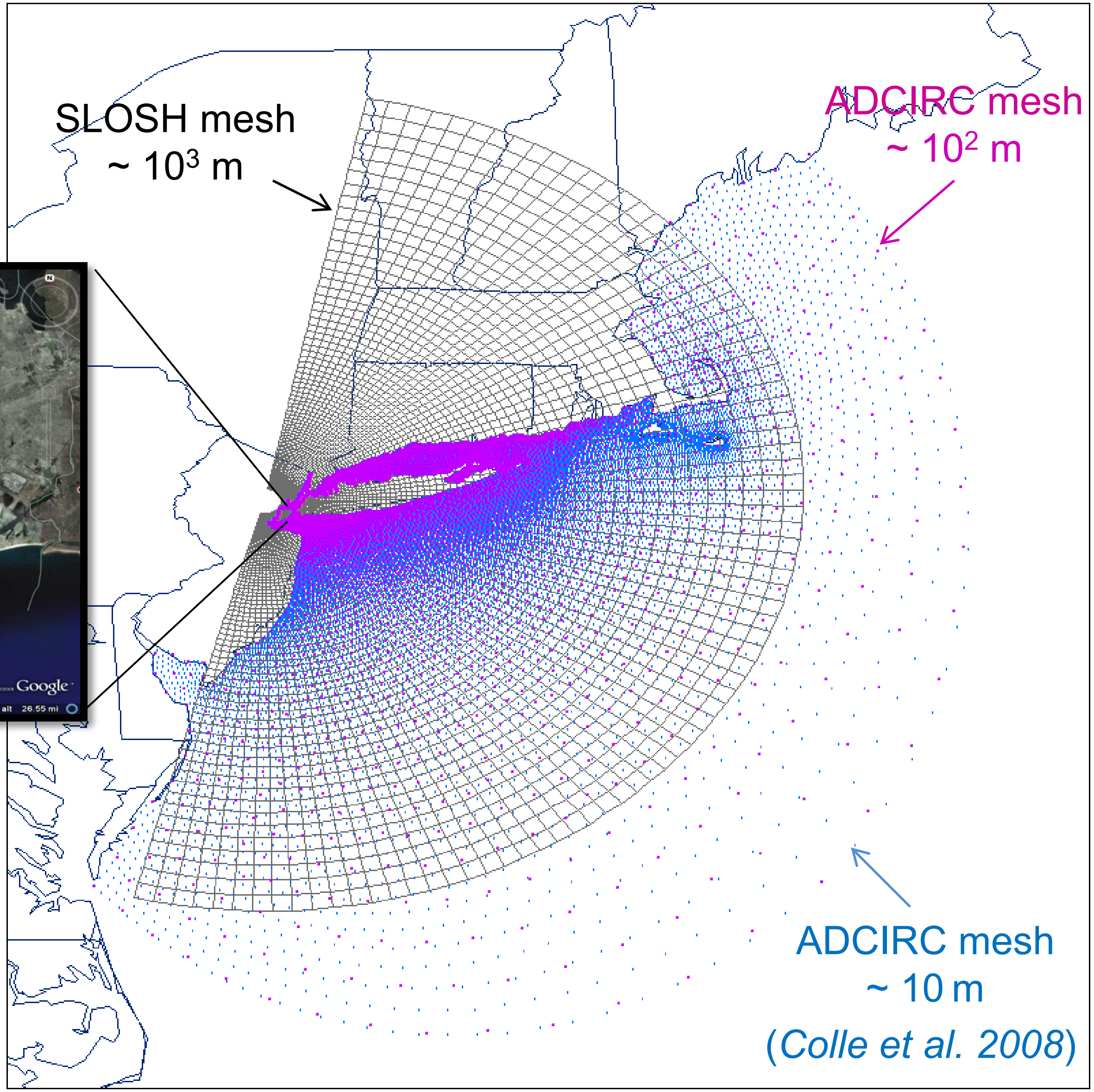
Captures effects of regional climate phenomena (e.g. ENSO, AMM)

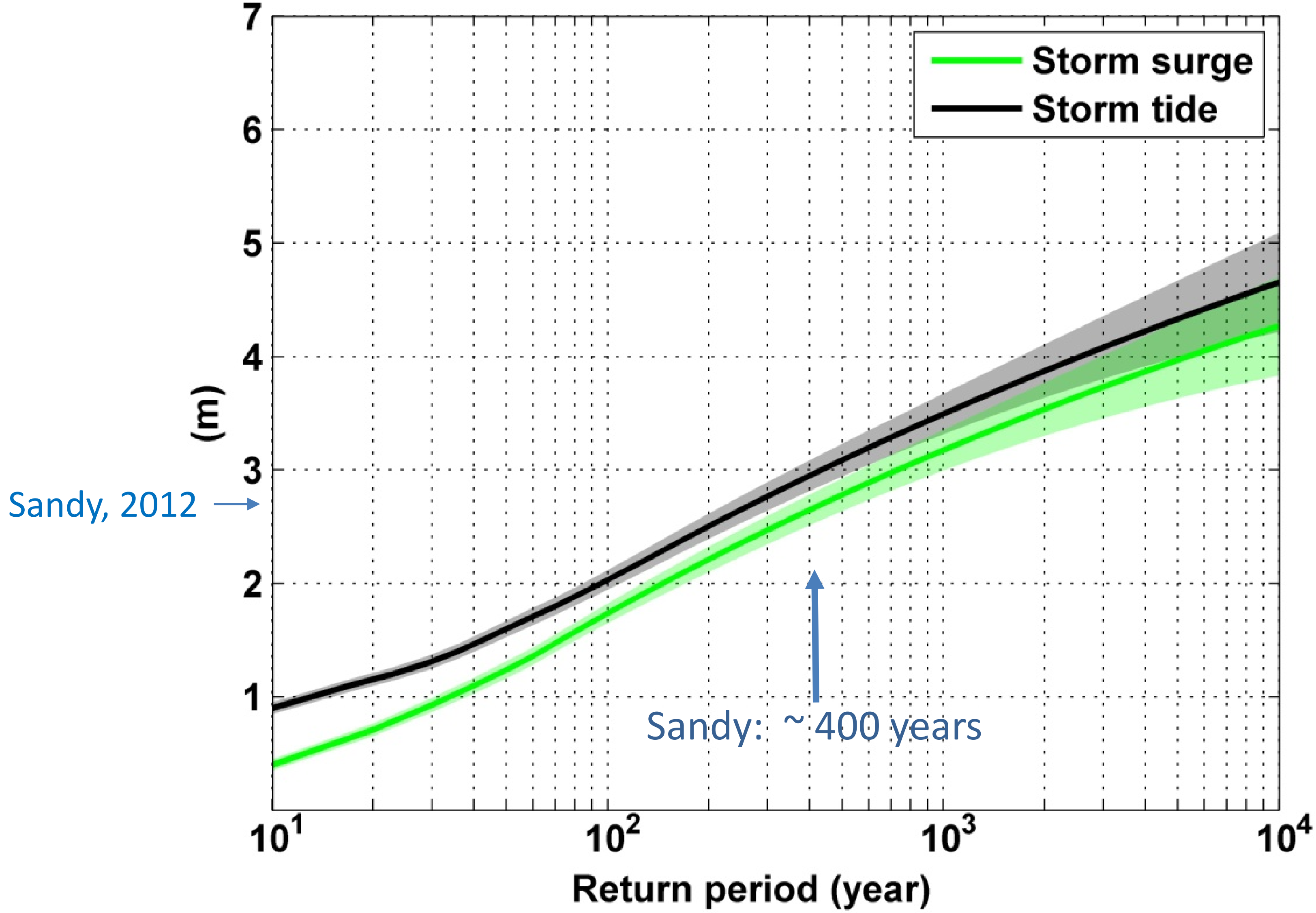


Captures Much of the Observed North Atlantic Interannual Variability



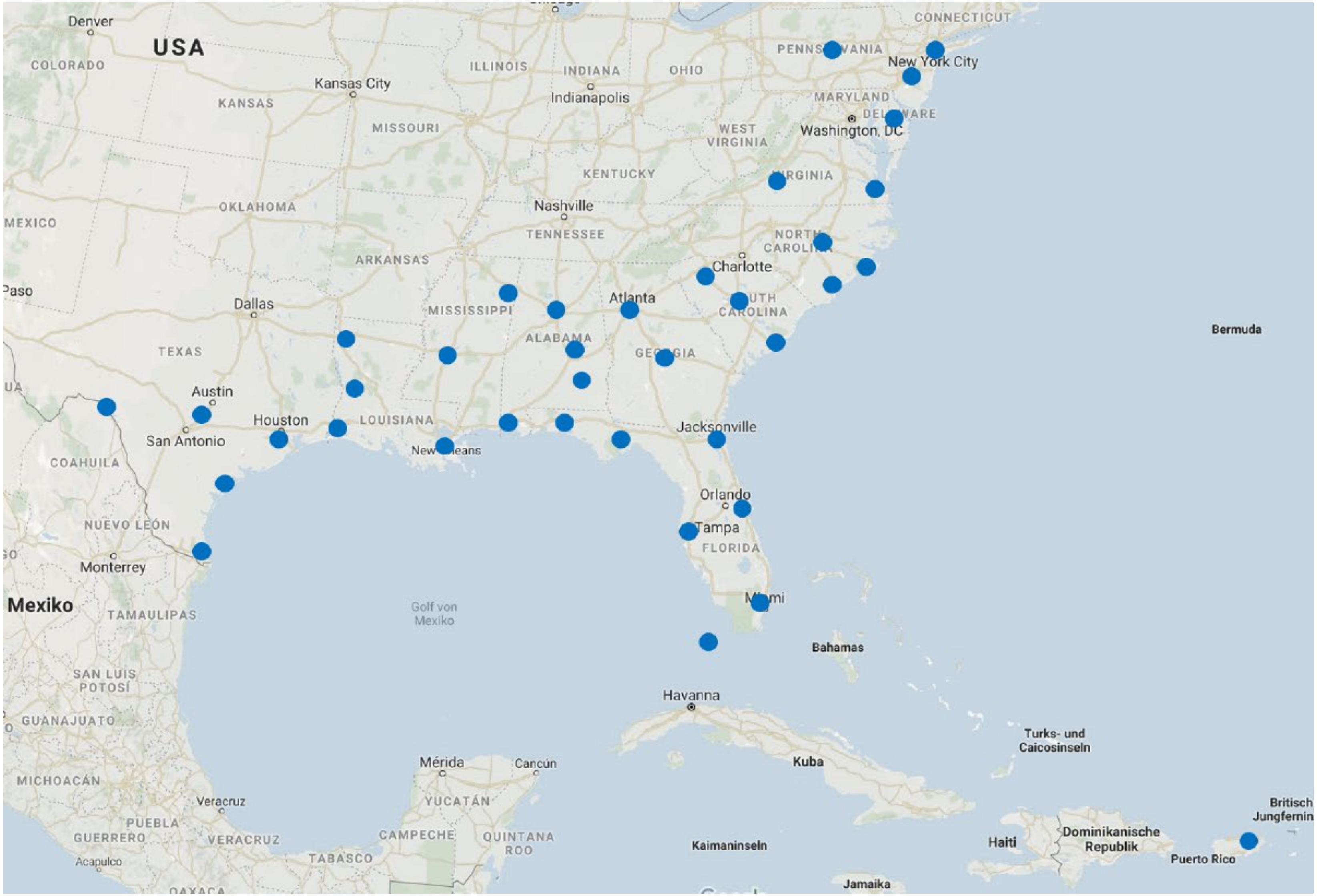
Storm Surge Simulation (Ning Lin)



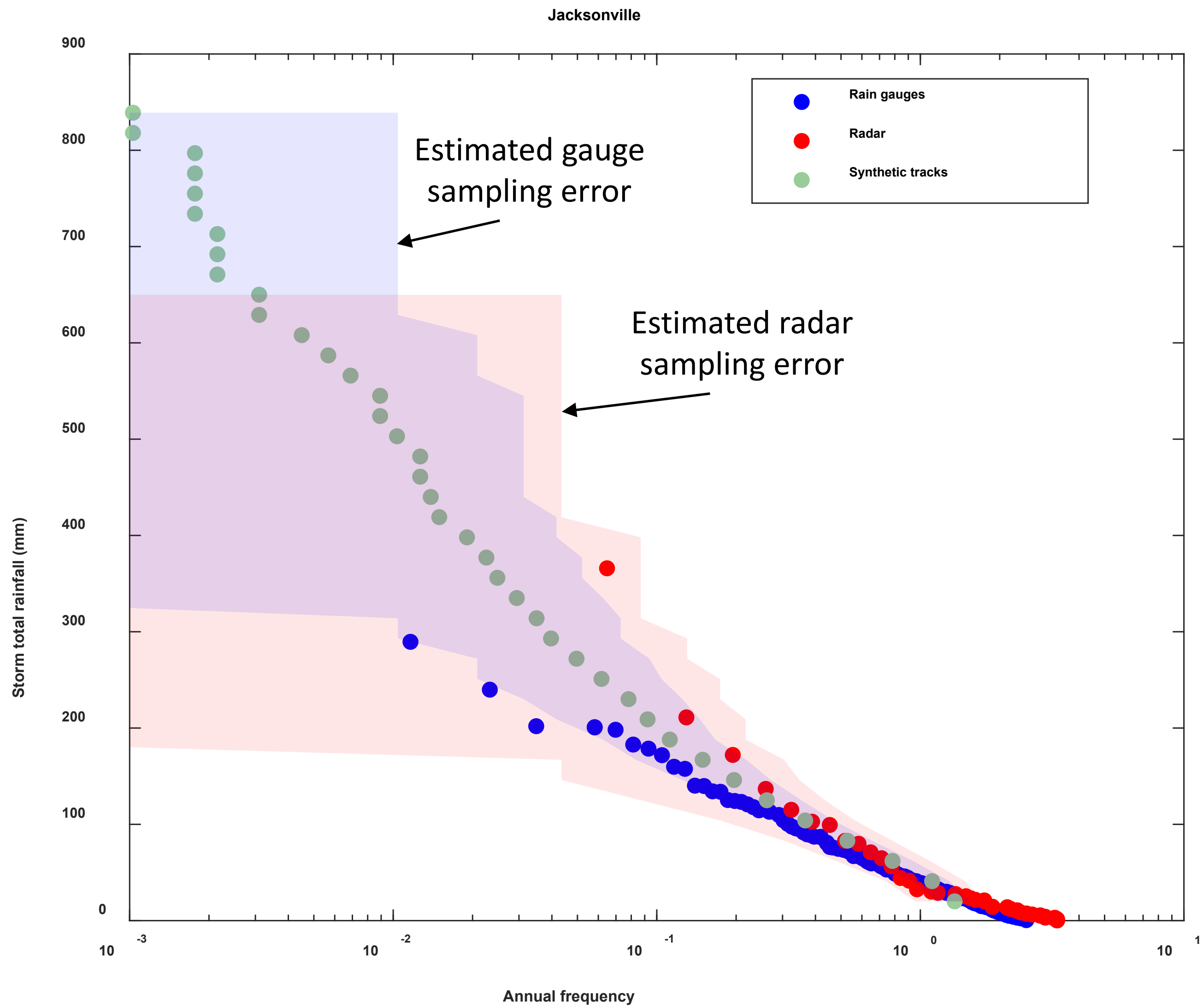


Lin, N., K. A. Emanuel, J. A. Smith, and E. Vanmarcke, 2010: Risk assessment of hurricane storm surge for New York City. *J. Geophys. Res.*, **115**, D18121, doi:10.1029/2009JD013630

NEXRAD Sites



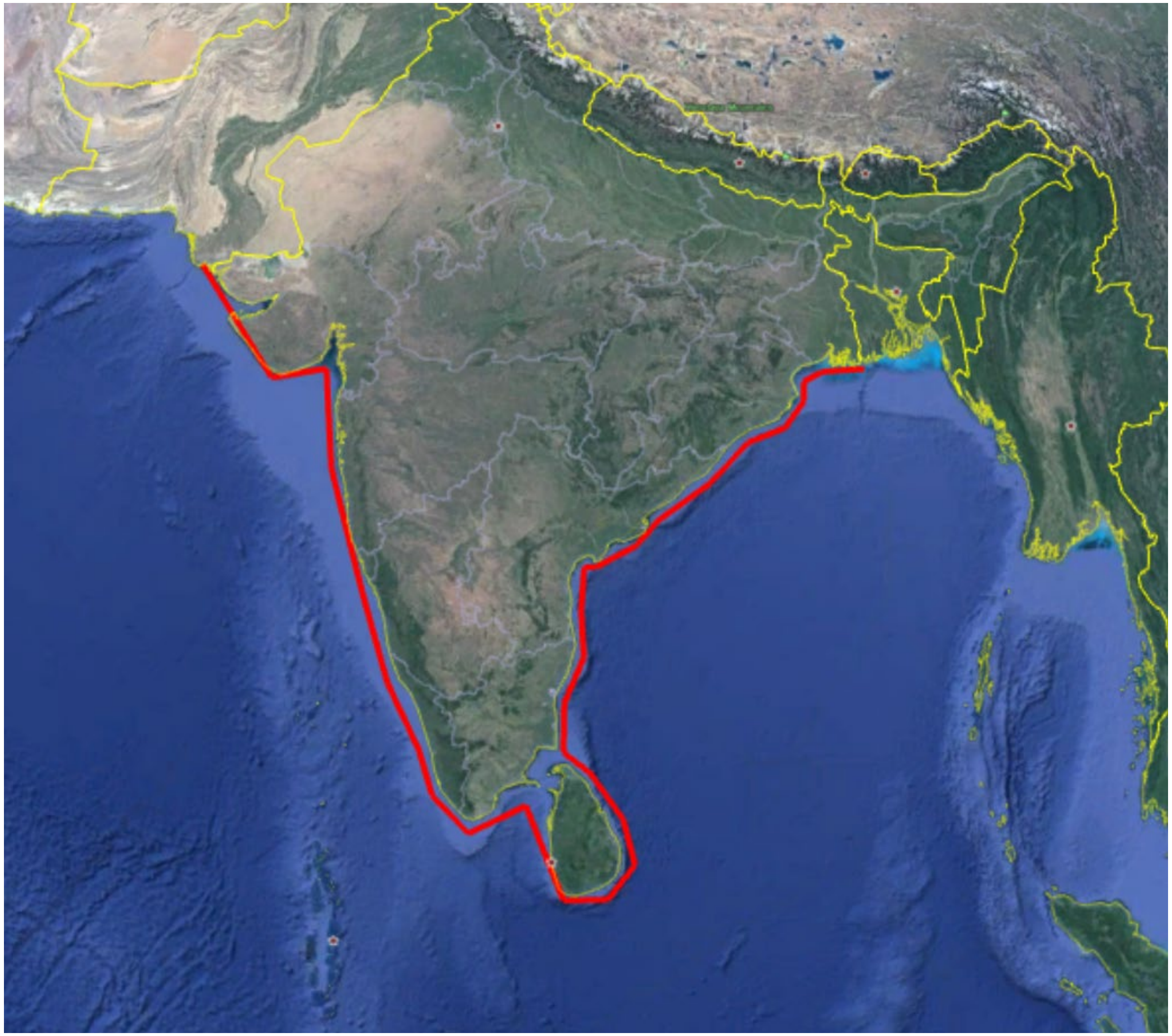
An Example:



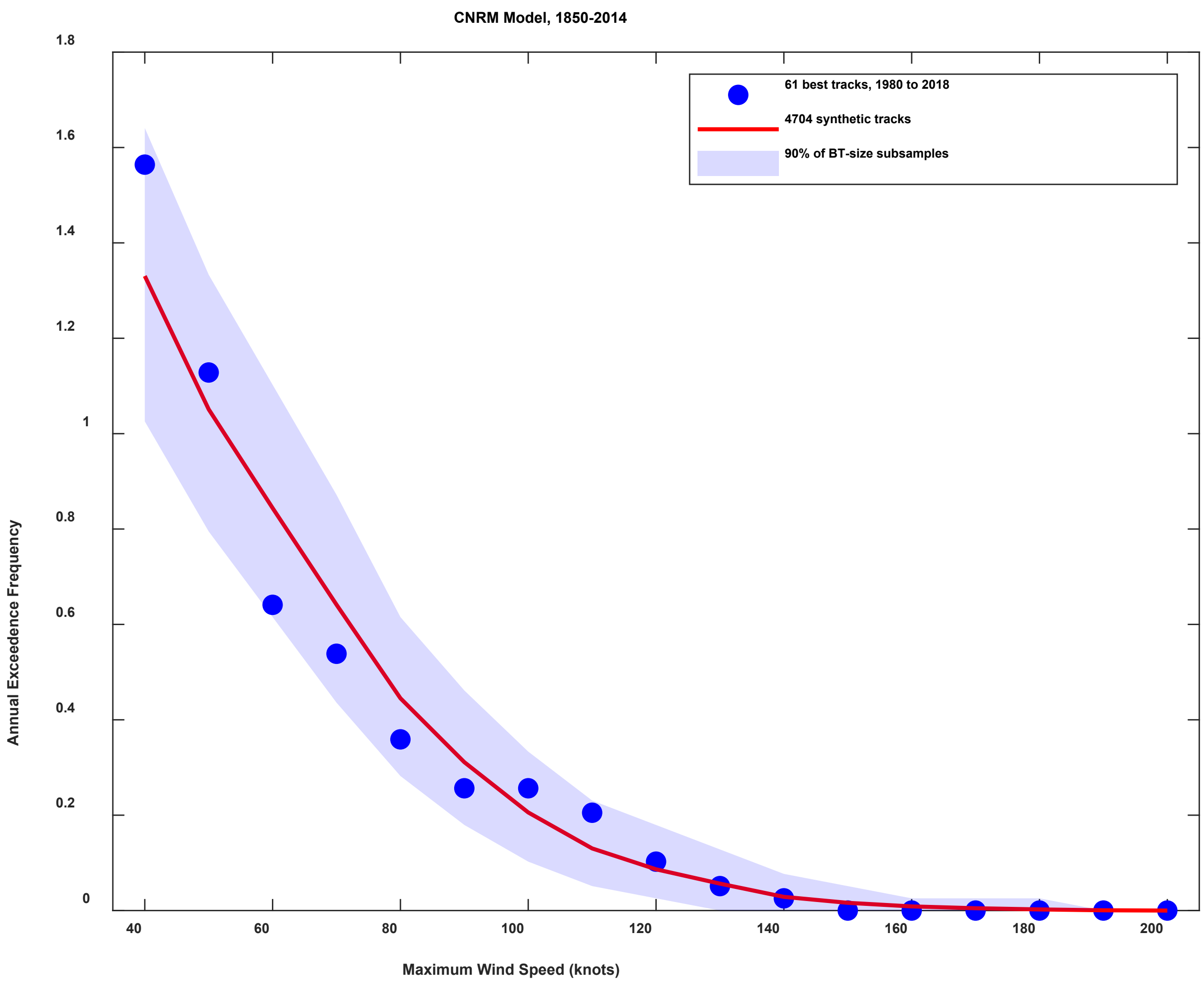
Jacksonville
Estimated gauge sampling error
Estimated radar sampling error
Rain gauges
Radar
Synthetic tracks
900
800
700
600
500
400
300
200
100
0
Storm total rainfall (mm)
10^-3
10^-2
10^-1
10^0
10^1
Annual frequency

TC Risk in India

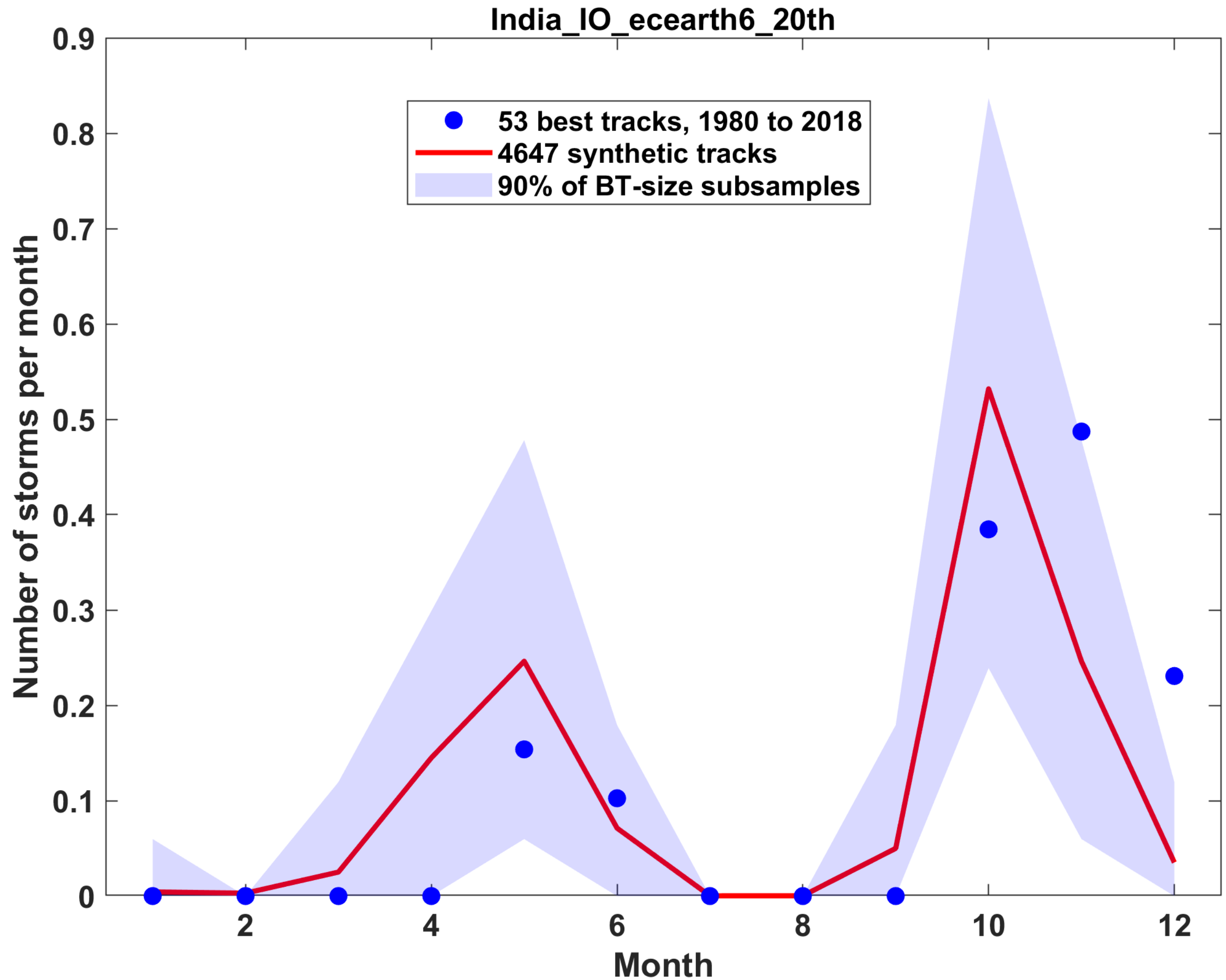
India Filter



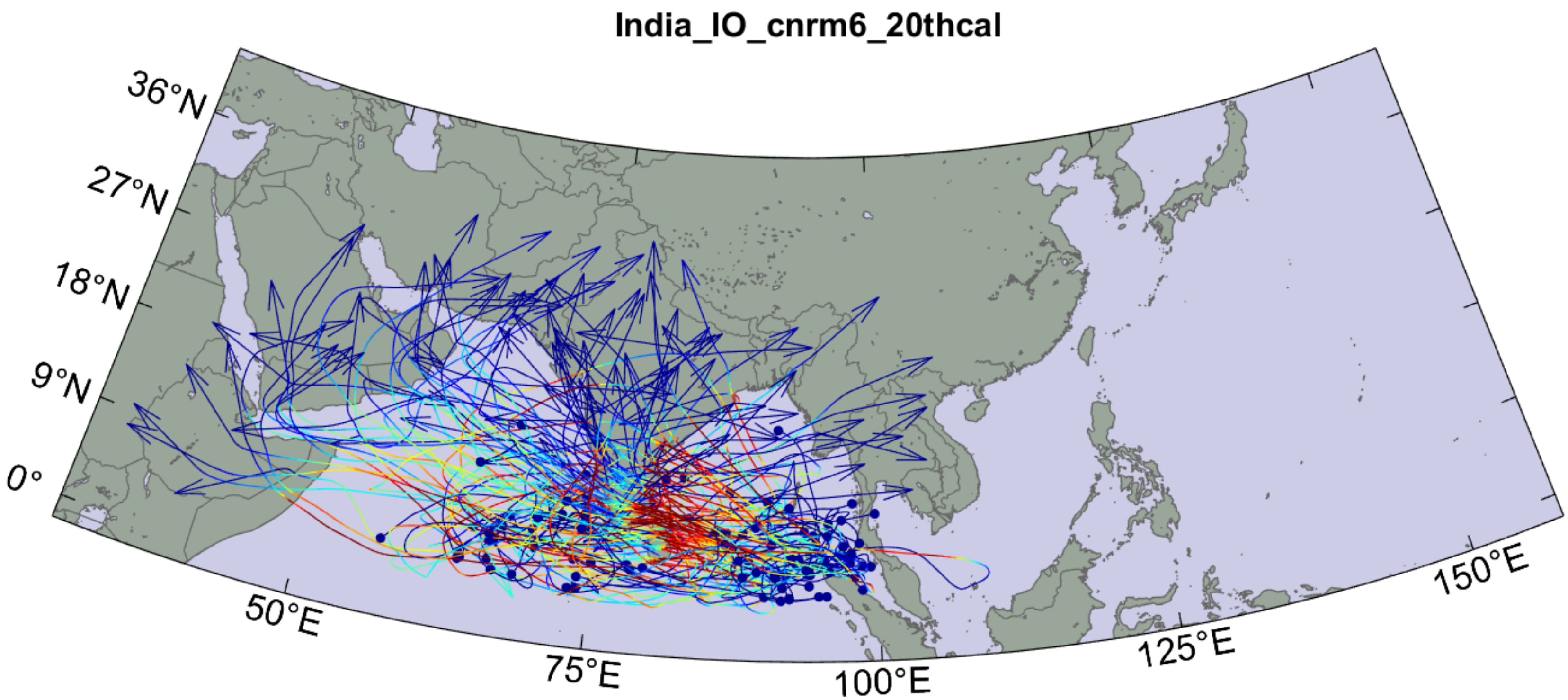
Annual Frequency



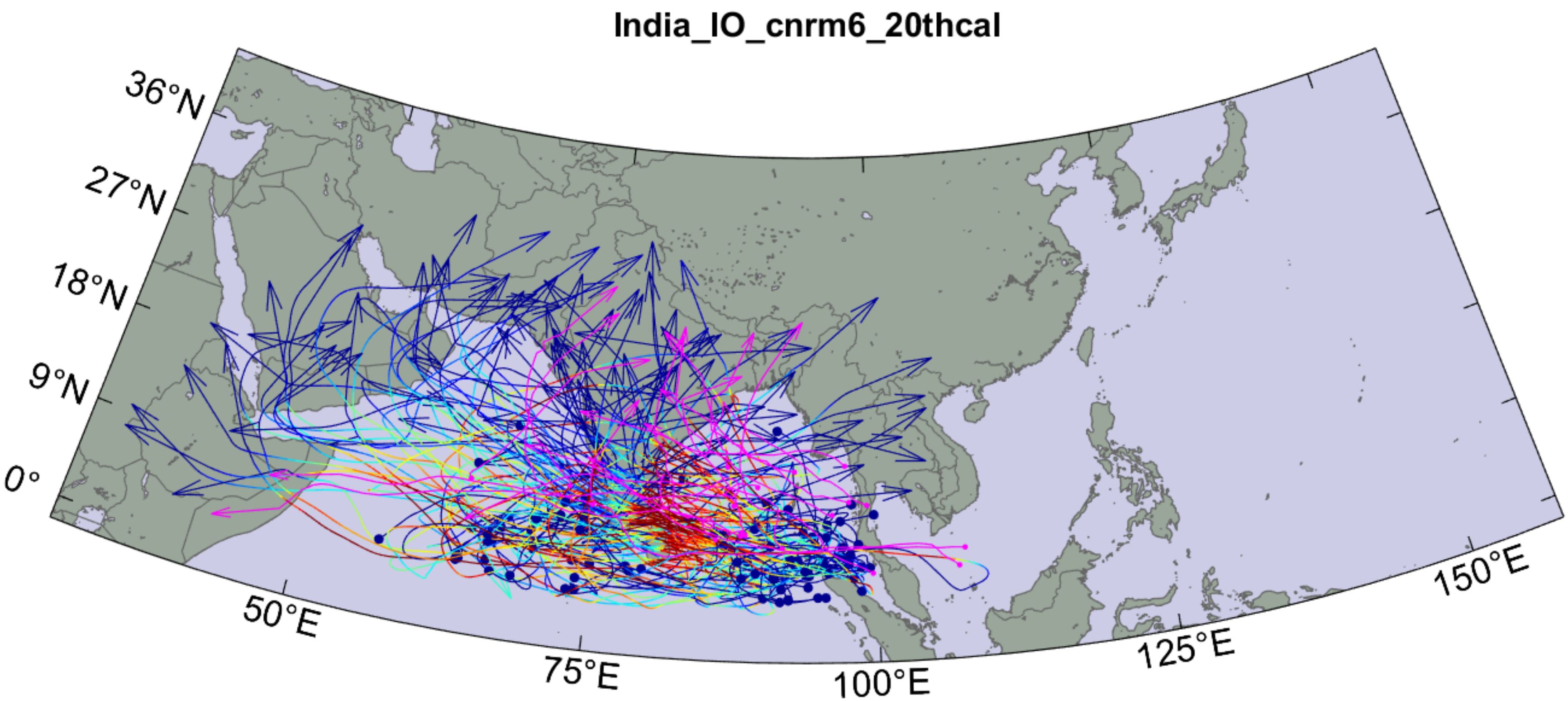
Annual Cycle



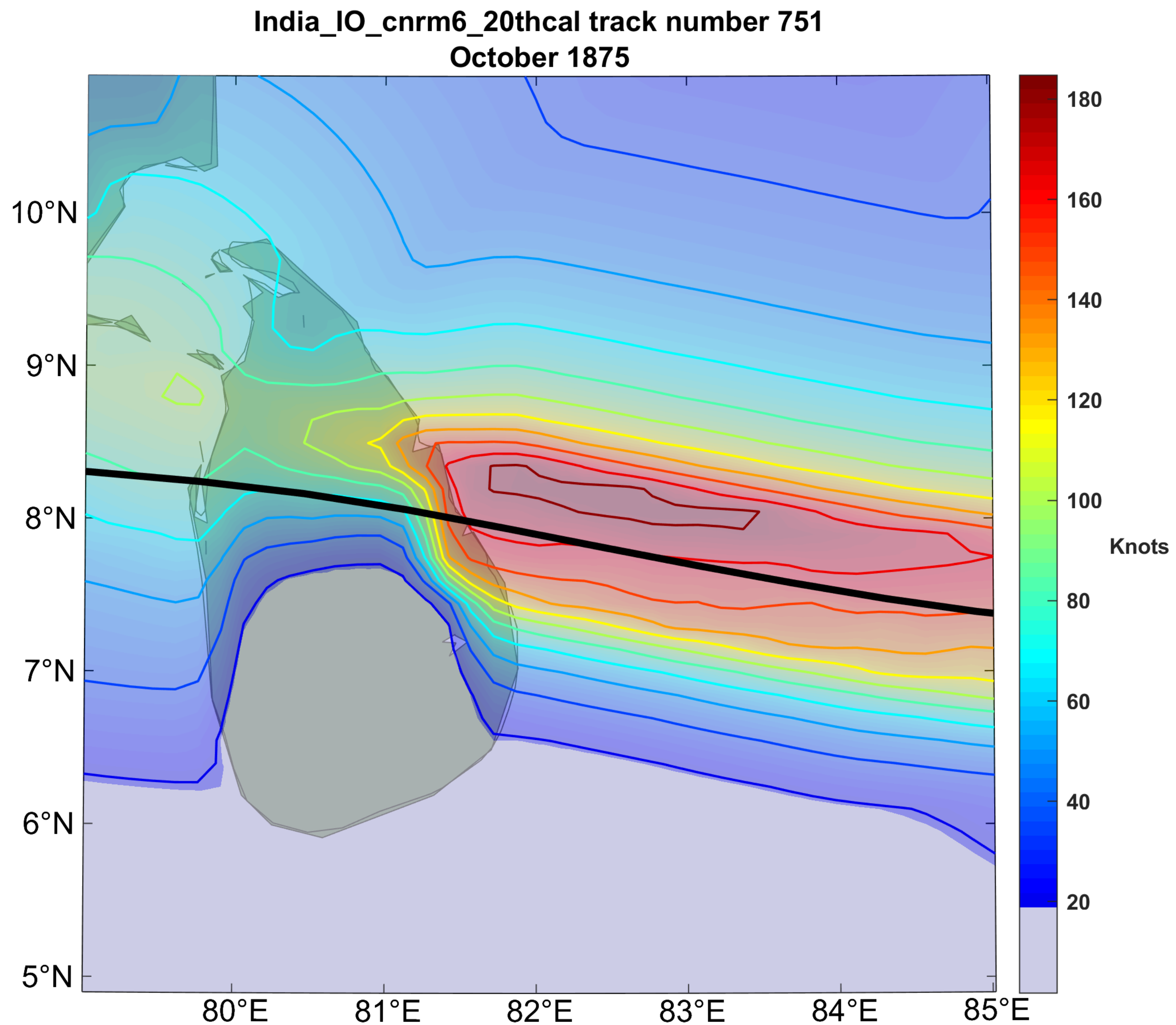
Top 100 out of 5000 TCs Affecting India, 1850-2014



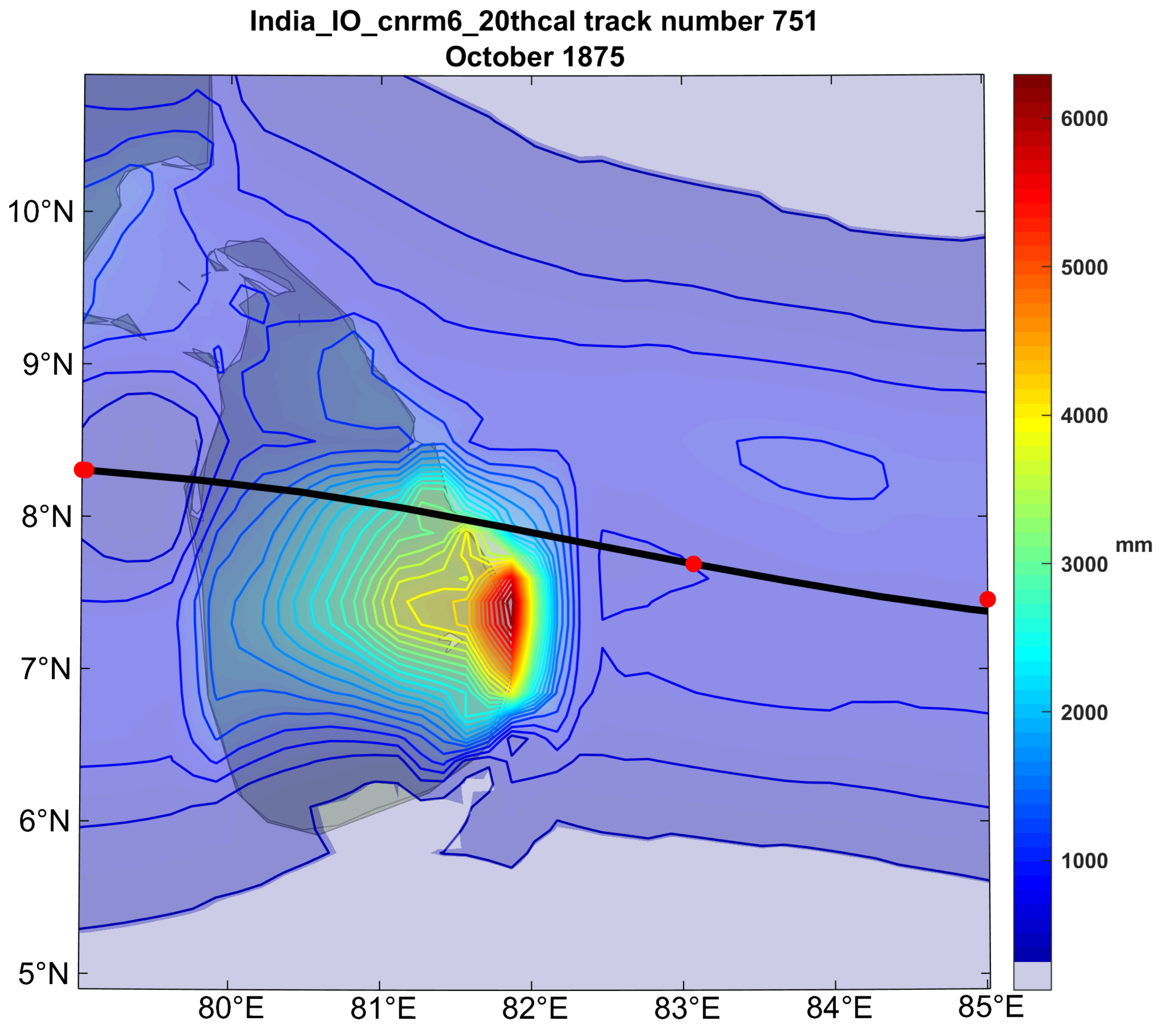
Same, but with top 20 historical tracks



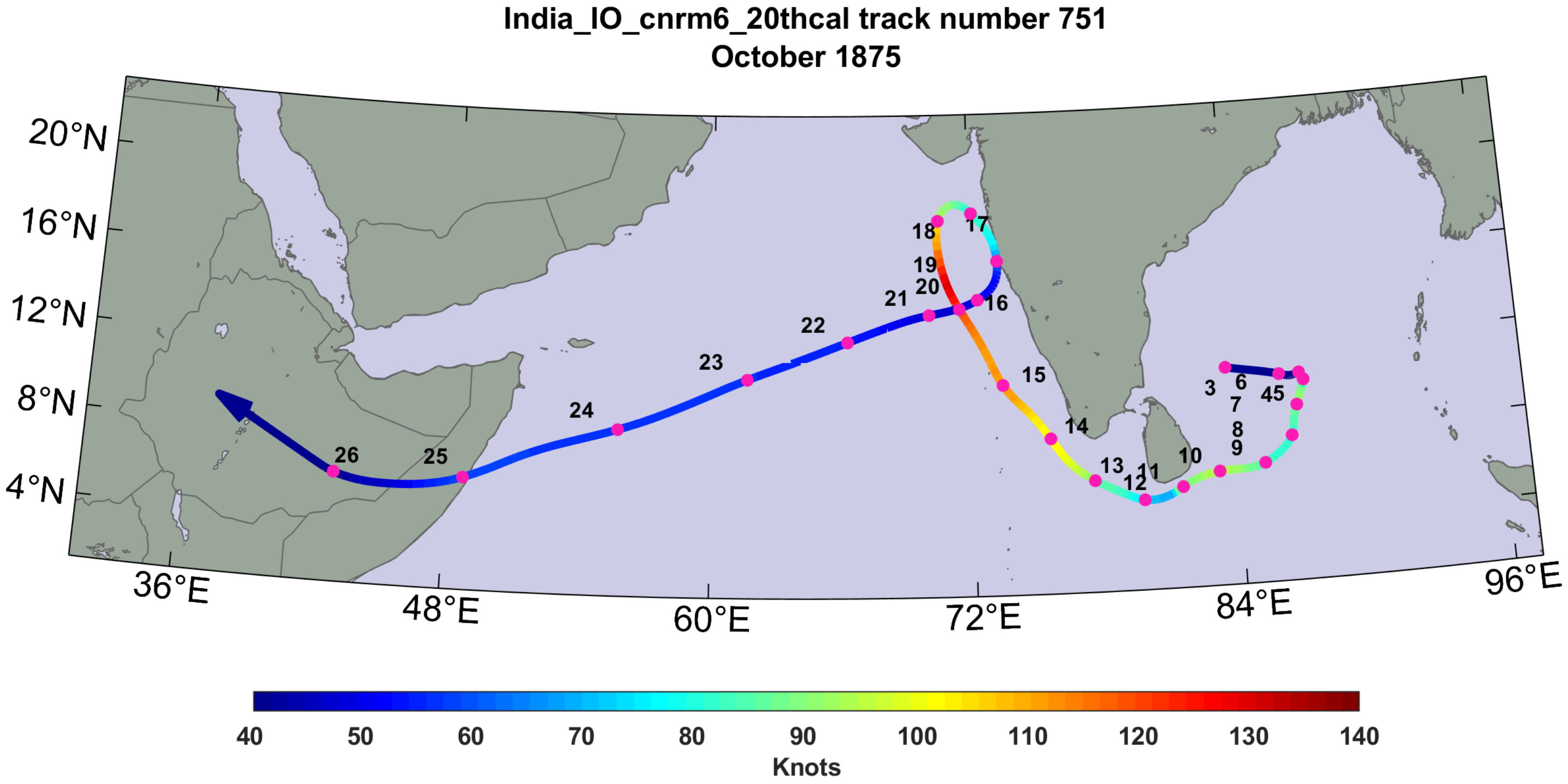
Top Landfall Wind

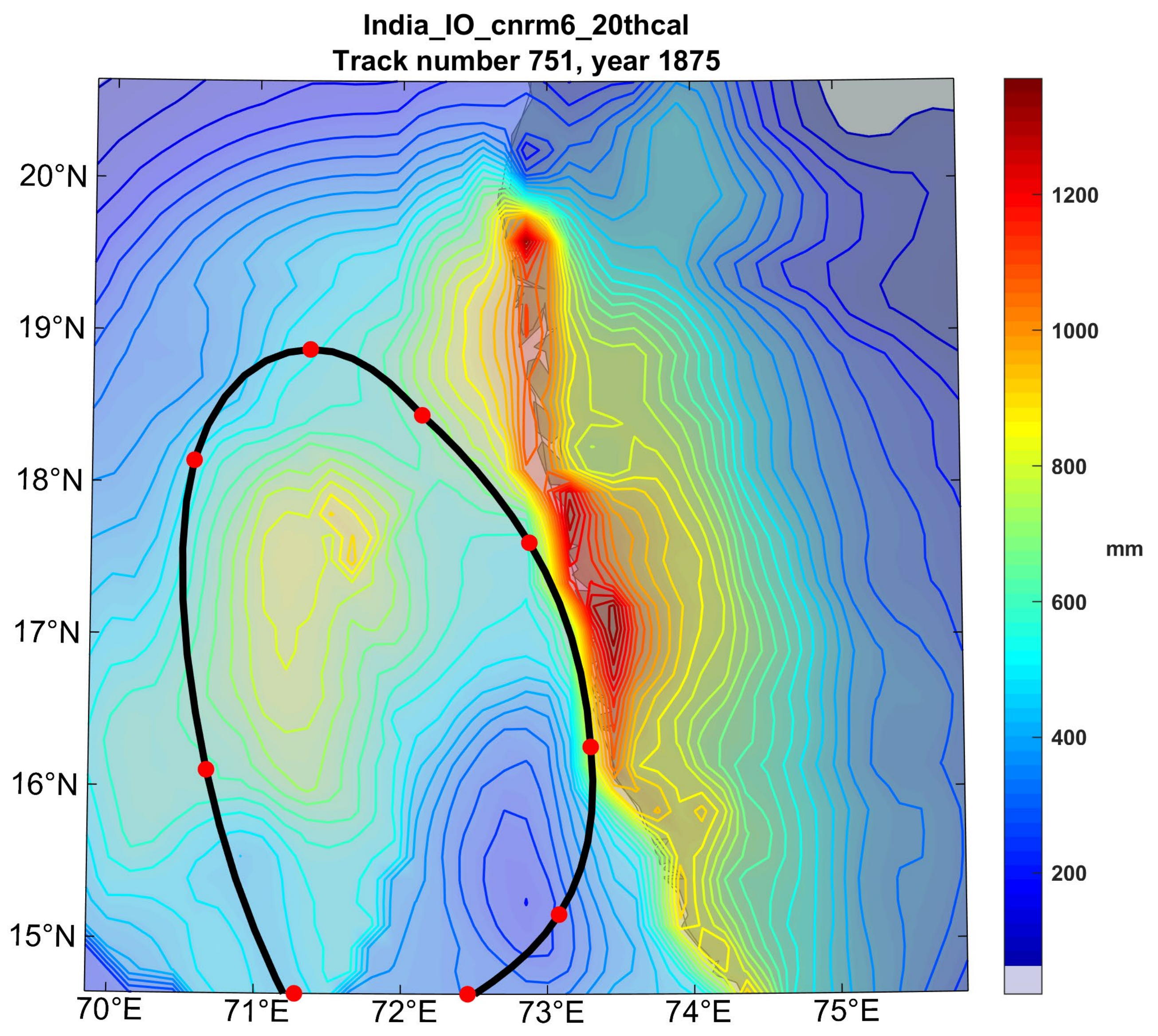


Storm total rainfall for top wind event



A Heavy Rainfall TC Event near the West Coast

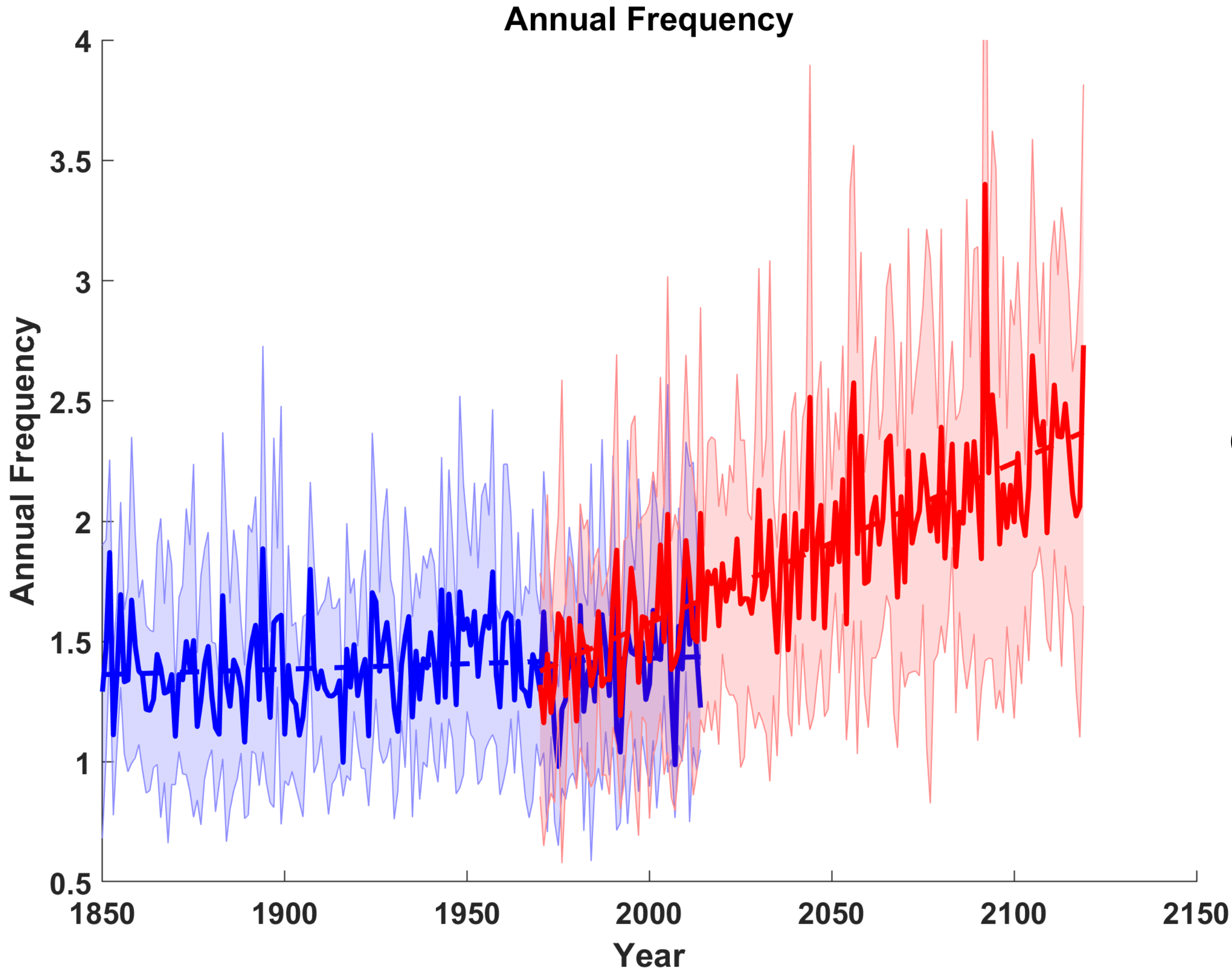



India_IO_cnrm6_20thcal
Track number 751, year 1875
20°N
19°N
18°N
17°N
16°N
15°N
70°E
71°E
72°E
73°E
74°E
75°E
1200
1000
800
600
400
200
mm

Effects of Climate Change

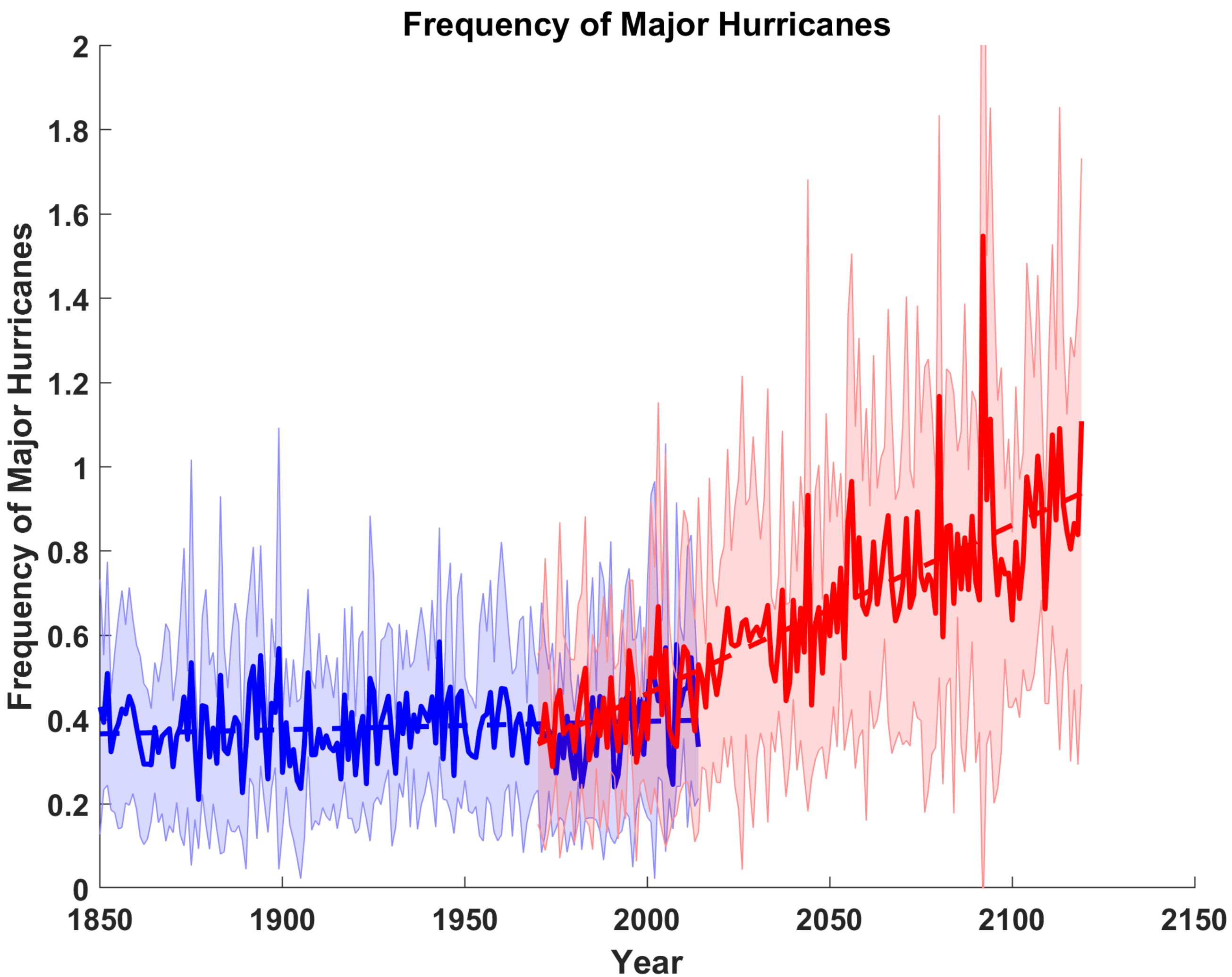
- More moisture in boundary layer
- Stronger storms but more compact inner regions
- Possibly larger storm diameters
- Storms may be moving faster or slower

Response of Annual Frequency of India Storms to 1%yr^{-1} Increase in CO_2 beginning in 1970

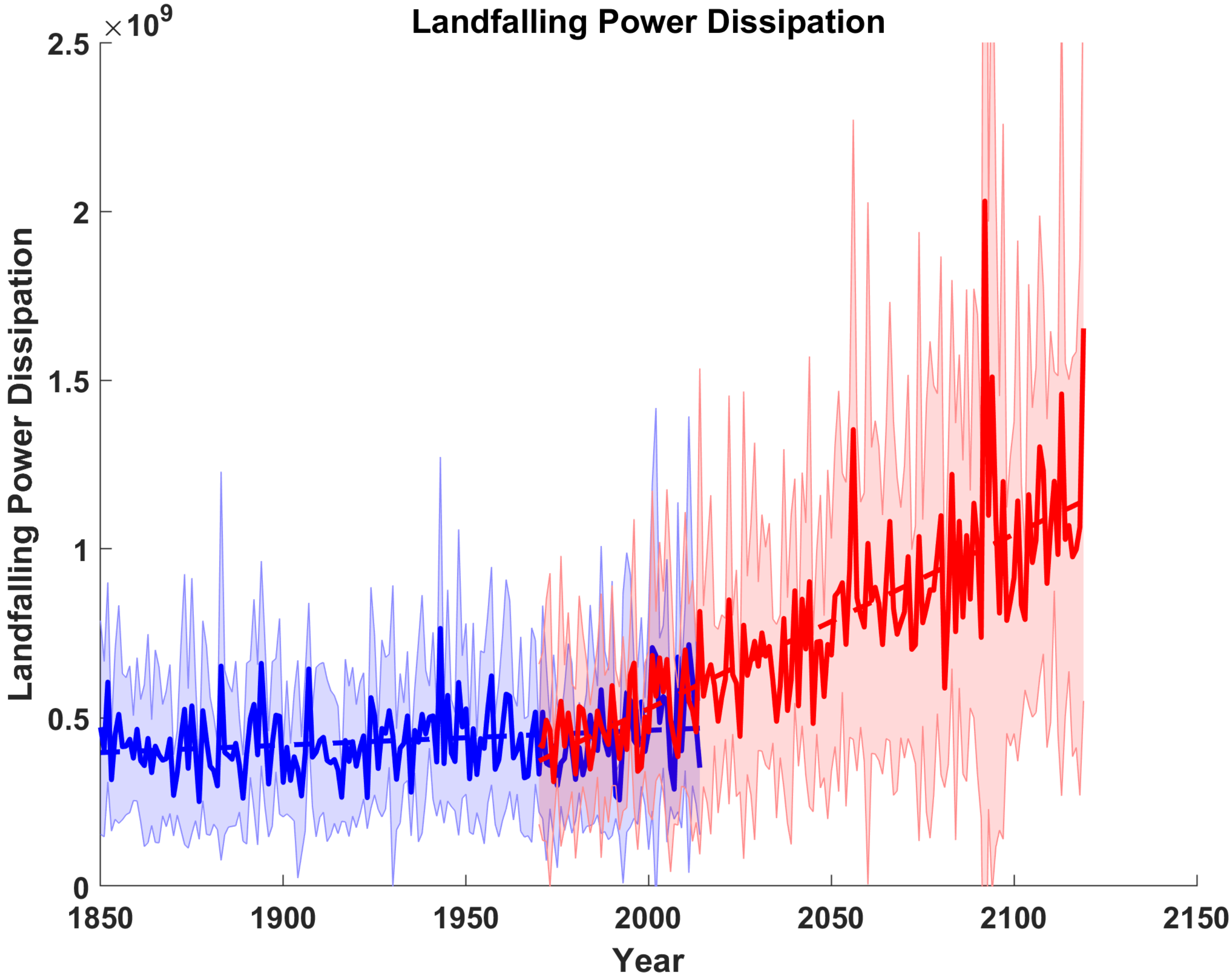


Results from downscaling 8 CMIP6 models

Major Hurricanes

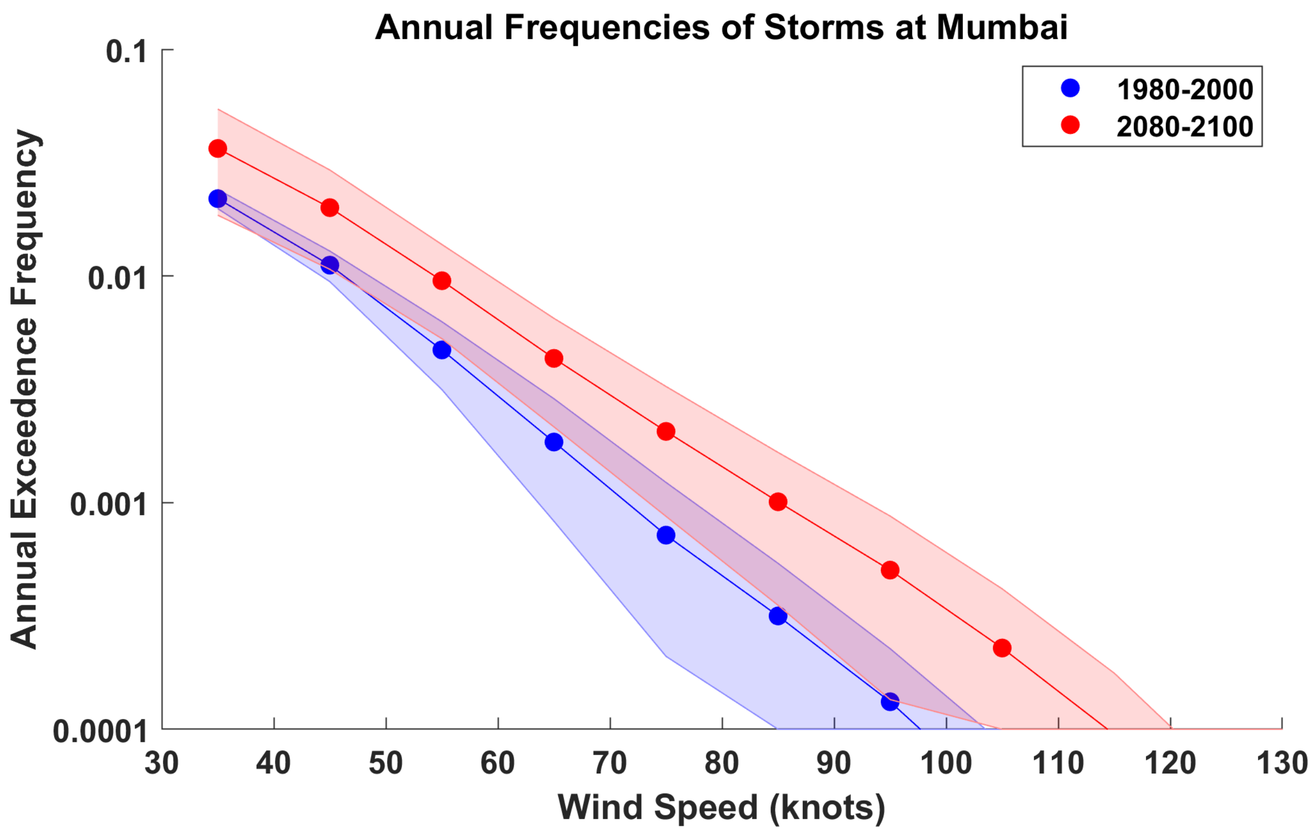


Landfalling Power Dissipation

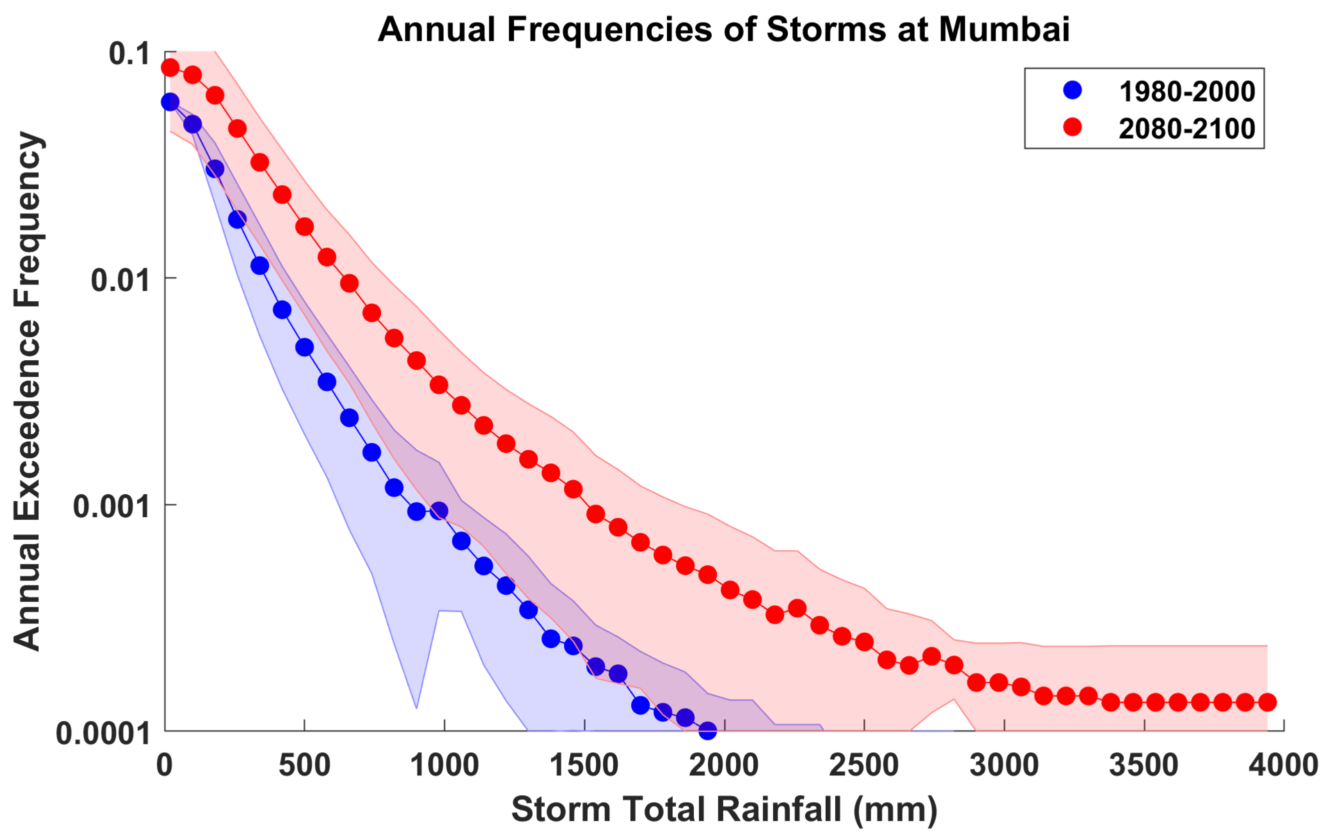


Estimates of Current and Future TC Risk at Mumbai, Based on 7 CMIP5 Models RCP 8.5 Used for Future Climate

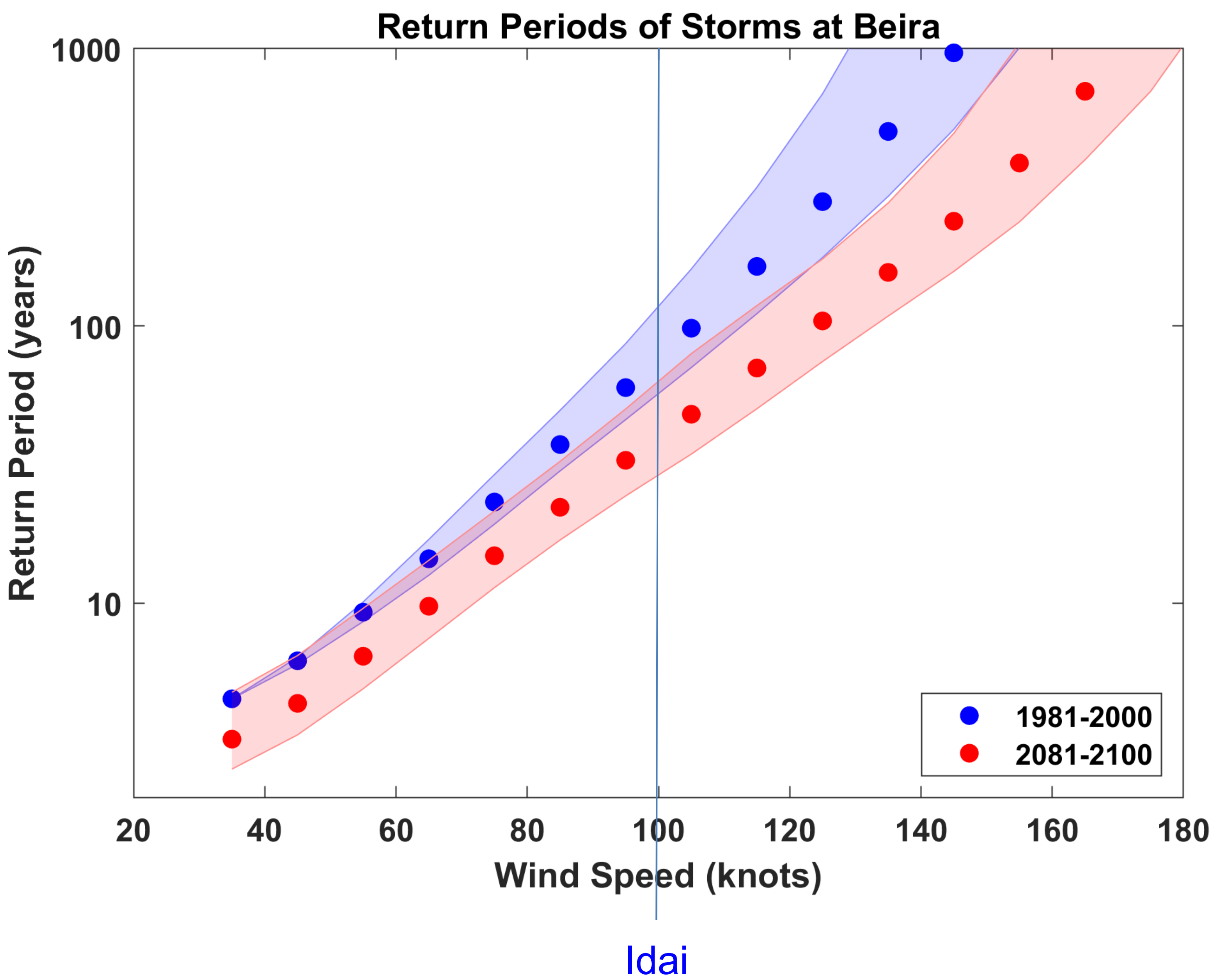
Wind

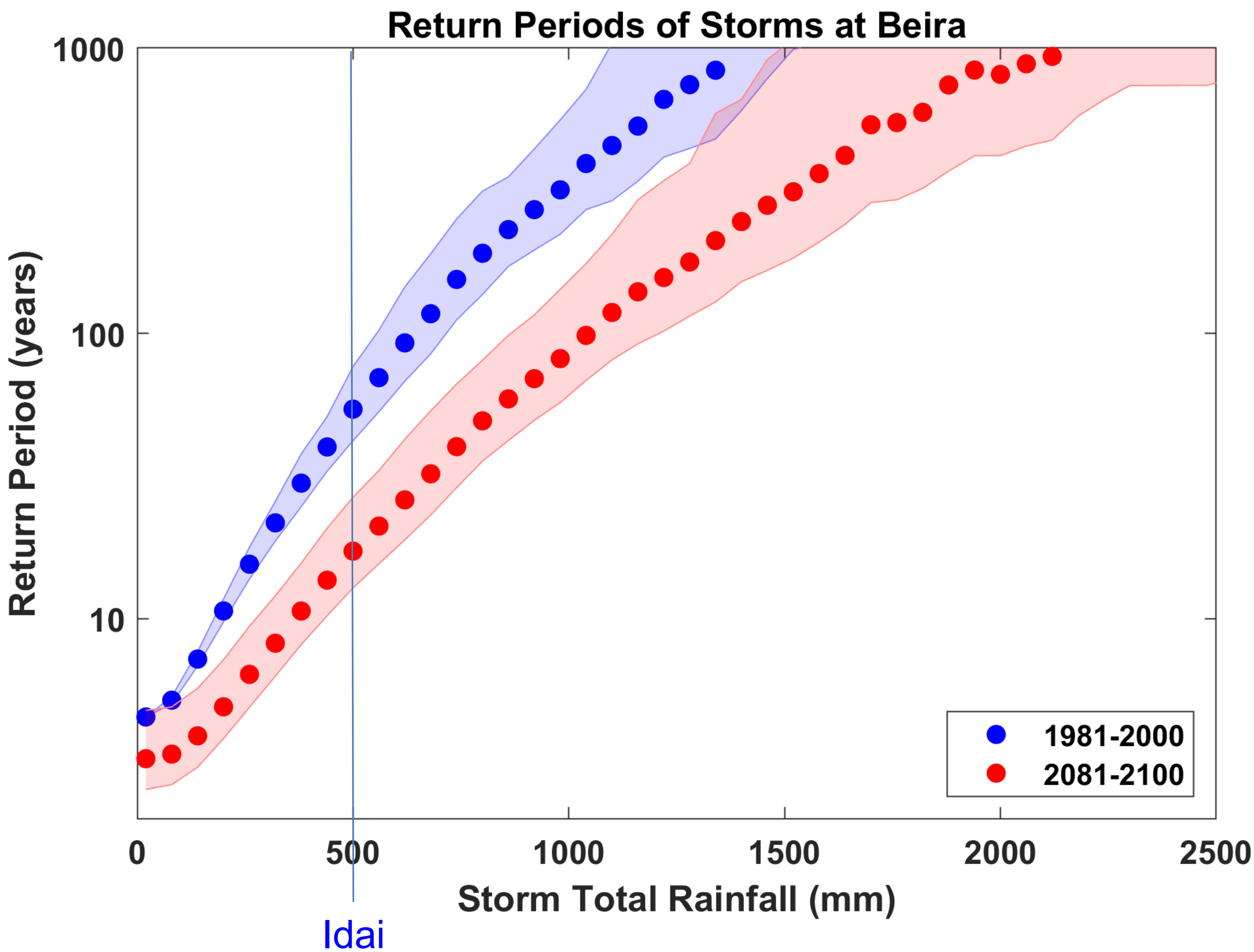


Rain


Annual Frequencies of Storms at Mumbai
1980-2000
2080-2100
Annual Exceedence Frequency
0.1
0.01
0.001
0.0001
0
500
1000
1500
2000
2500
3000
3500
4000
Storm Total Rainfall (mm)

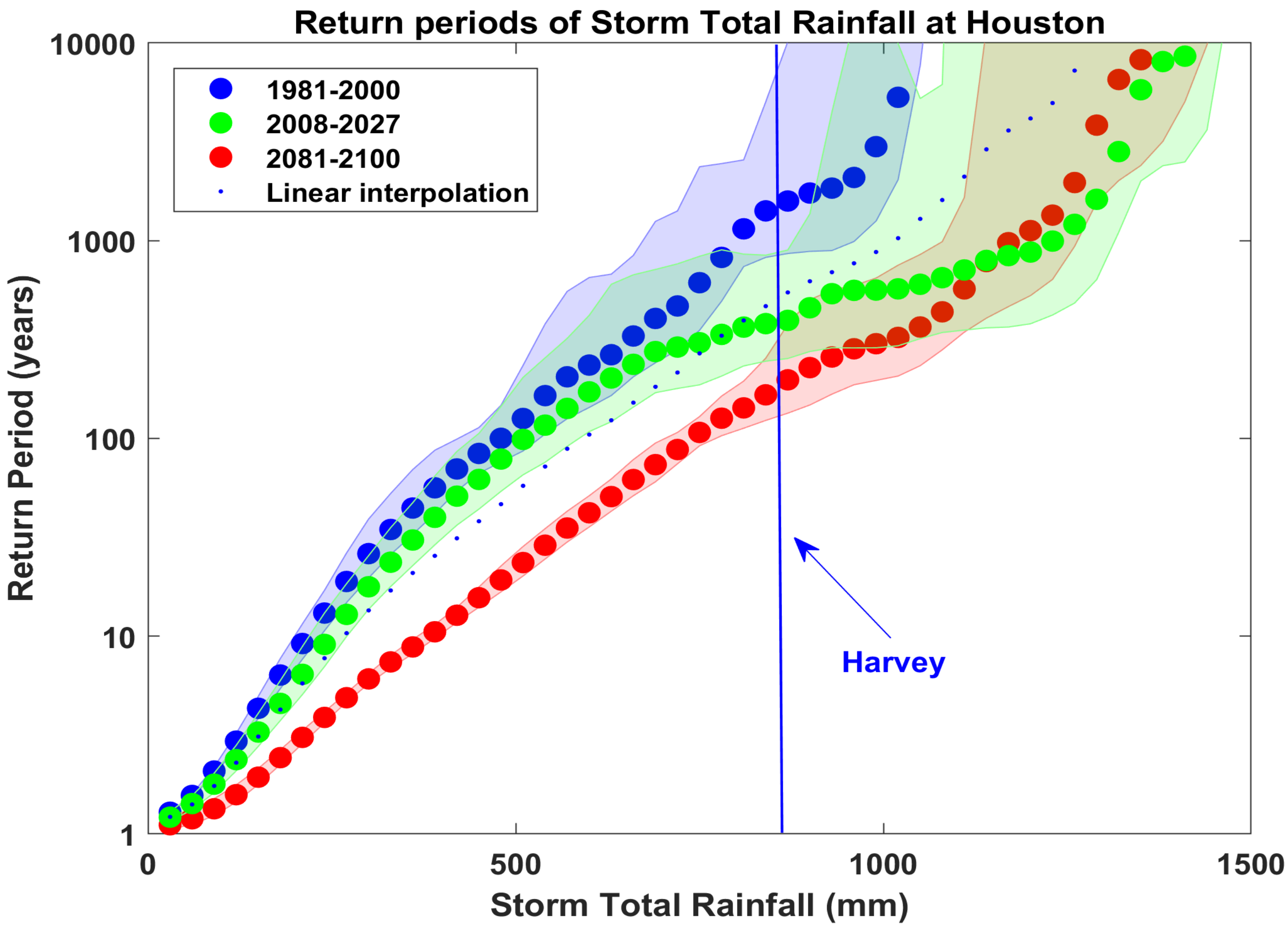
Based on 7 CMIP5 models





Return Periods of Storms at Beira
1000
100
10
Return Period (years)
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.



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

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

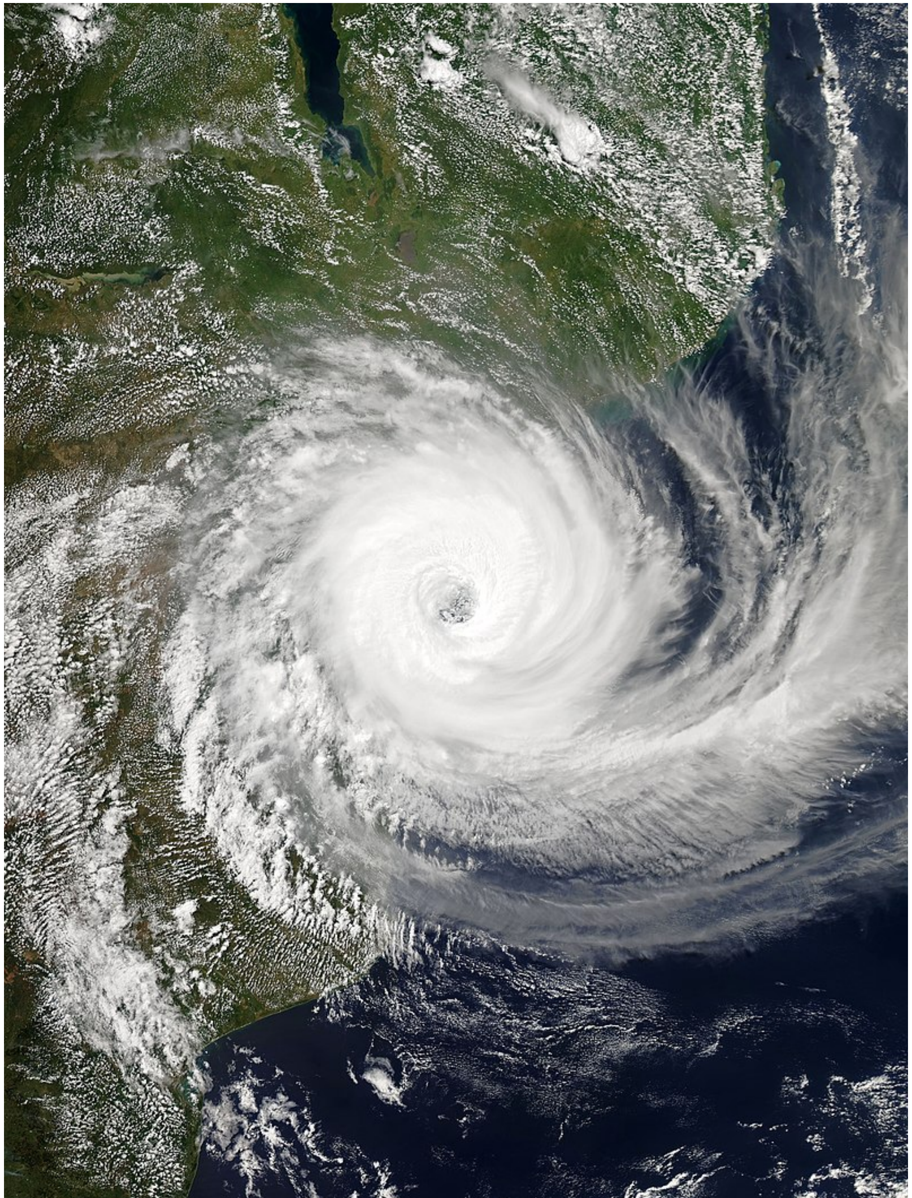
Calculating vertical motion in middle troposphere from time-dependent azimuthal gradient wind. Four components:

- 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.

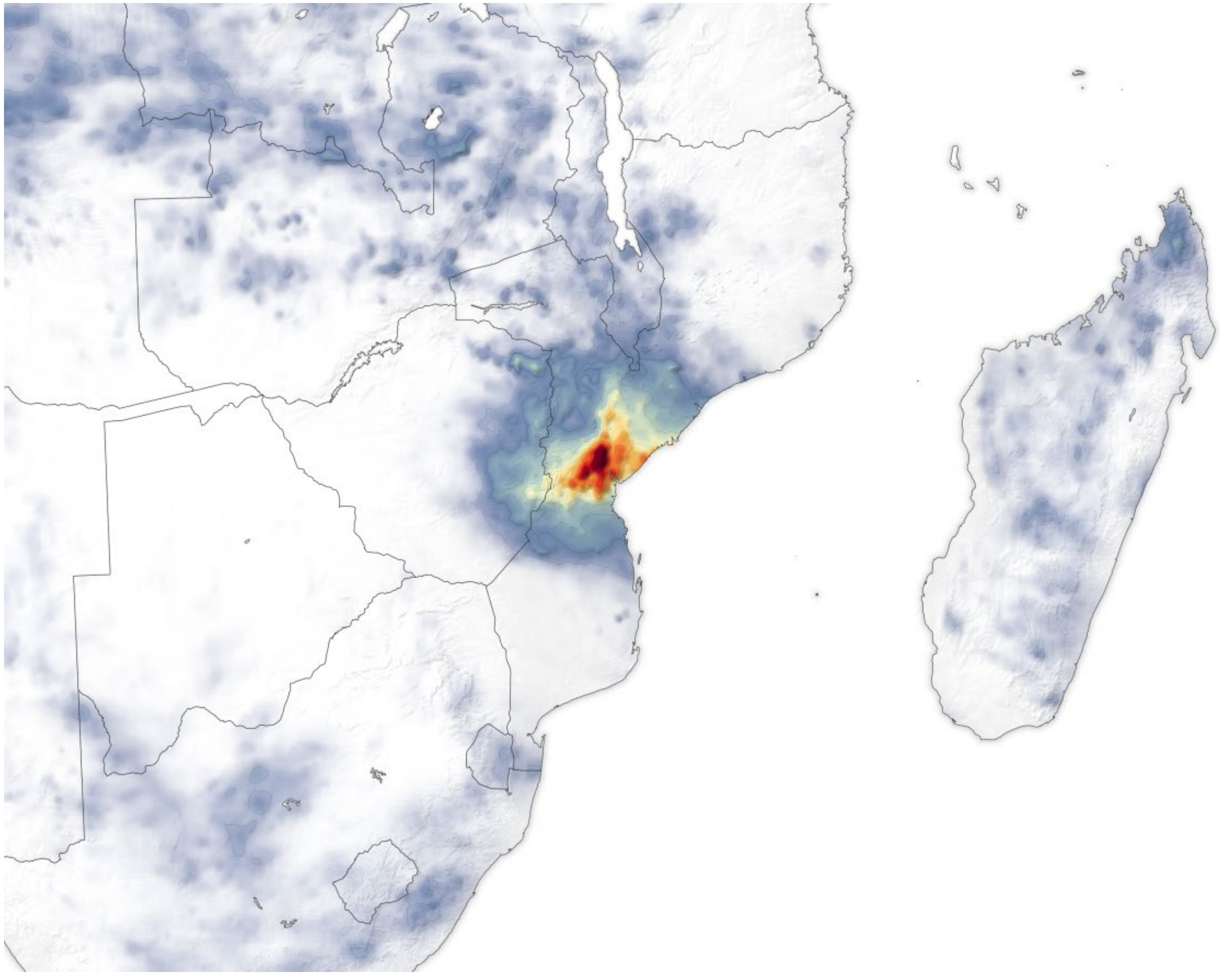
- Vertical stretching between the top of the boundary layer and the middle troposphere associated with changes in the vorticity of the (axisymmetric) gradient wind.
- Add mid-tropospheric vertical motion caused by the dynamical interaction of the axisymmetric vortical flow and the background shear/horizontal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

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