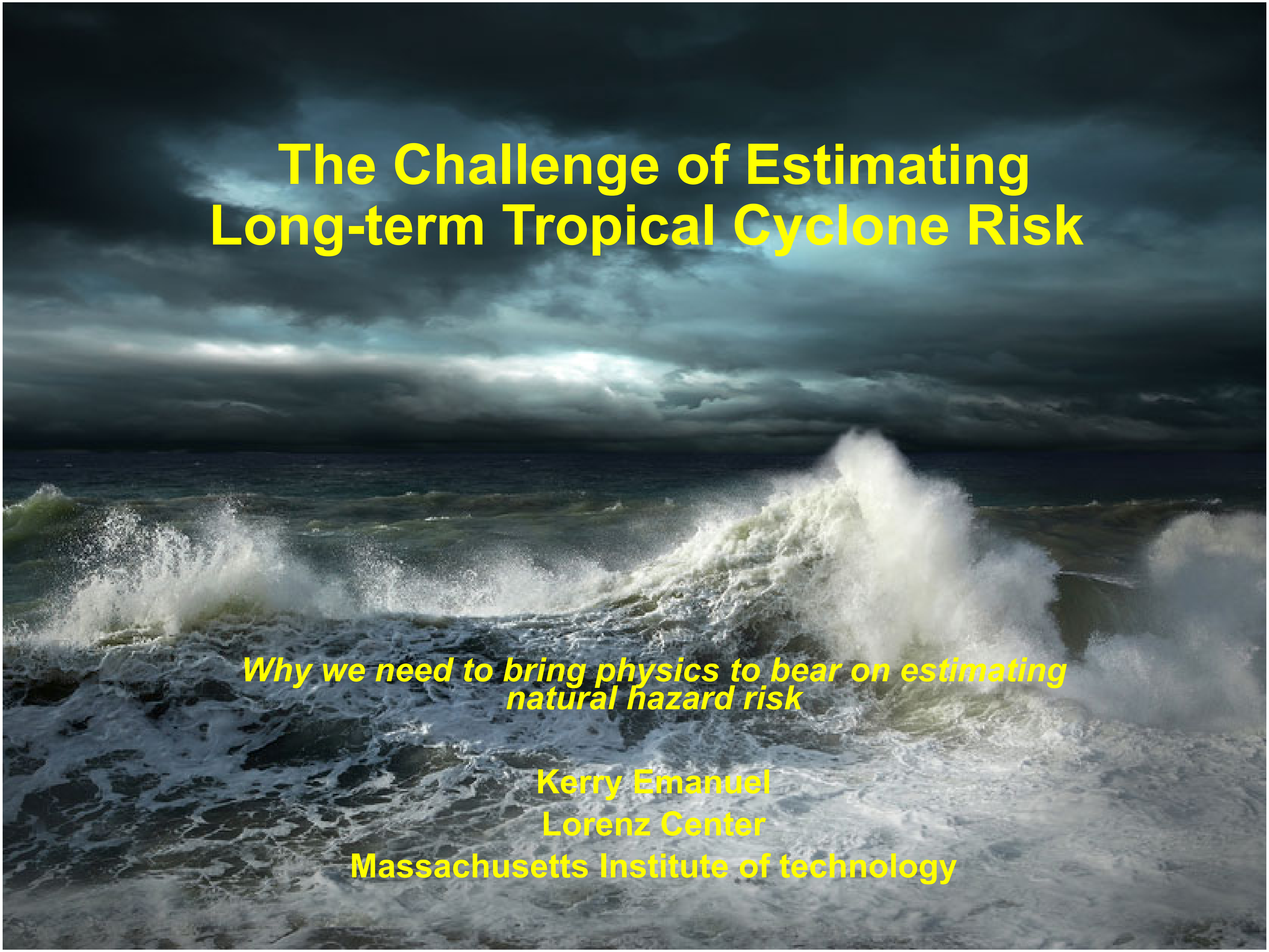


The Challenge of Estimating Long-term Tropical Cyclone Risk

Why we need to bring physics to bear on estimating natural hazard risk

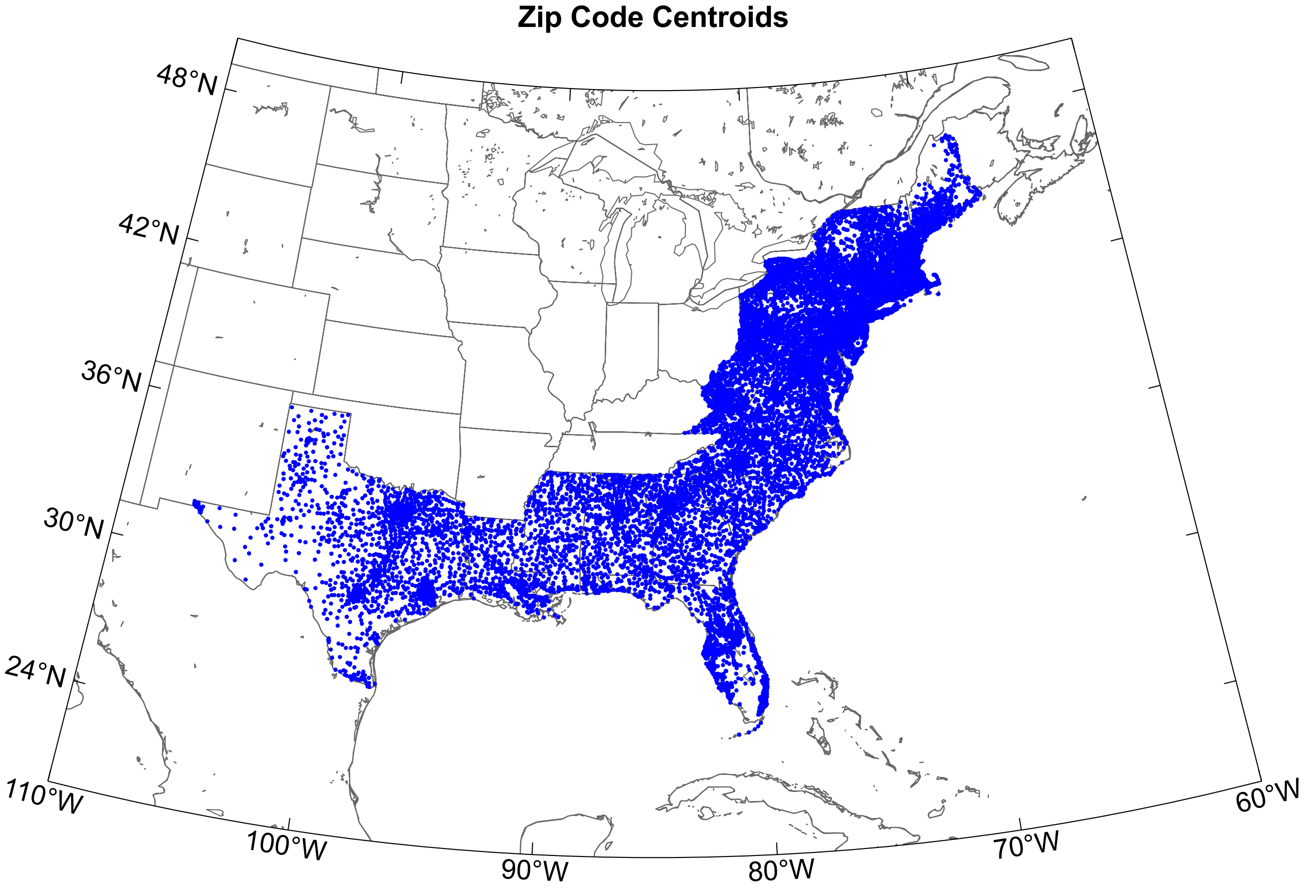
Kerry Emanuel
Lorenz Center
Massachusetts Institute of technology

Flawed Basis of Current Risk Modeling

- Almost all current risk assessments are based on historical statistics
- Historical records are flawed and short
- Moreover, **the past 50-150 years is a poor guide to the present owing to climate change that *has already occurred***
- Risk modelers have been slow to migrate to a physics-based approach
- Risk modeling industry is being challenged by non-profits and start-ups
- Government and the insurance industry should accelerate this transition
- **TC researchers need to get involved in physical modeling of risk**

The Nature of the Beast

Start with total insured values (TIVs) of a particular insurance firm aggregated over zip codes



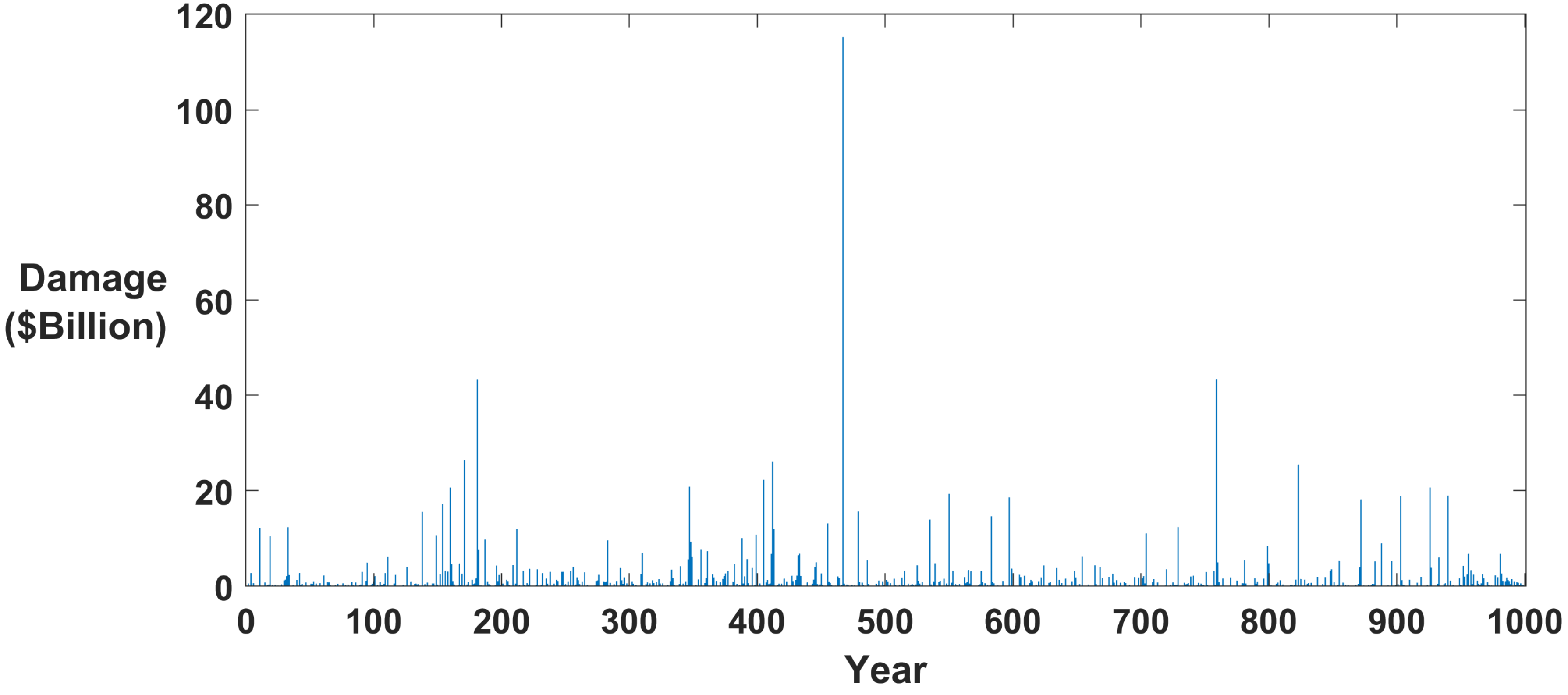
Net TIV: $ 2 trillion

12,968 zip codes

Procedure

- Apply a set of 49,600 tropical cyclones making landfall in the continental U.S.
- These have been generated using a physical model applied to the present climate (technique to be described shortly)
- At each centroid, calculate the peak wind generated and apply a damage function that estimates the fraction of property value destroyed
- Using insured value, calculate loss at each zip code and sum over all zip codes
- From the set of 49,600 storms randomly draw 3 each year and create 1,000-year time series of damage
- This is for stationary climate but the same idea can be applied to evolving climate states

Example:

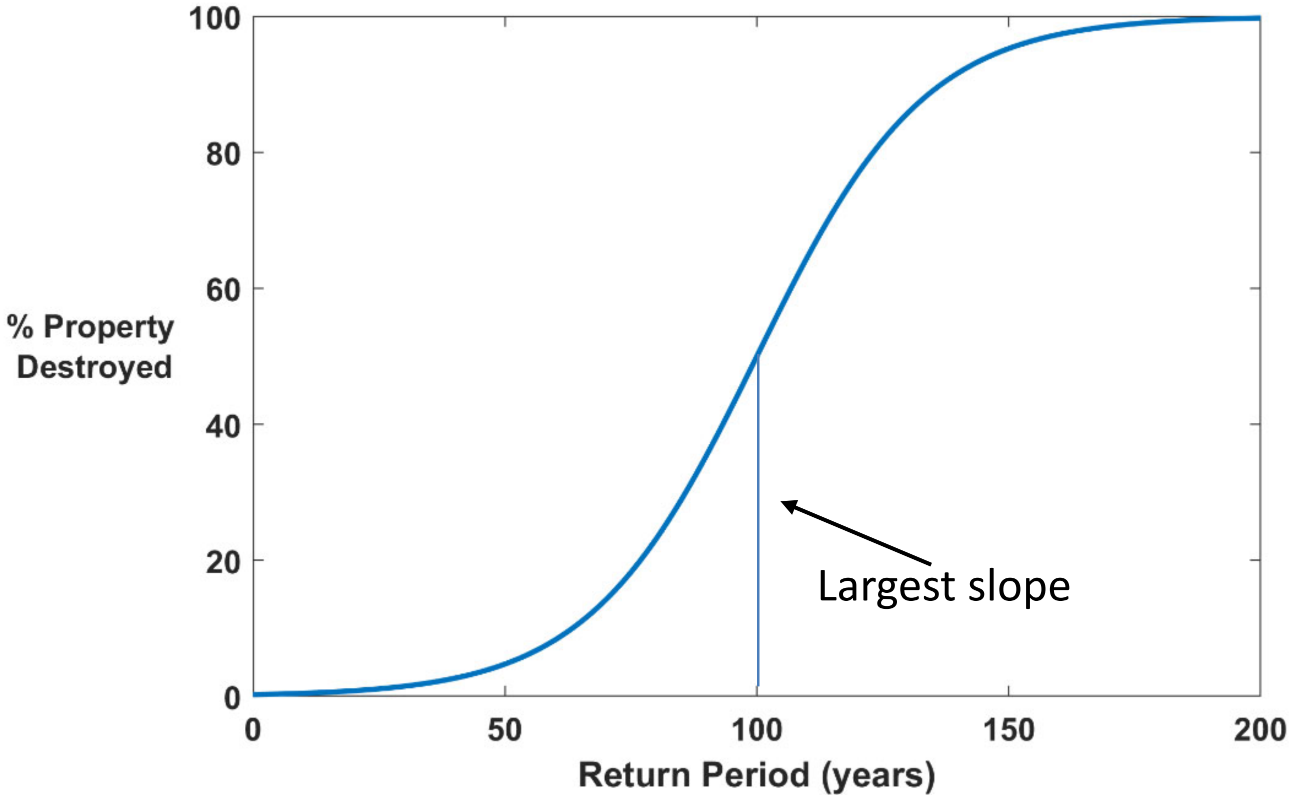


Question: Can we estimate average annual loss (AAL) from 50-100 years of record?

Answer: Good luck with that!

Why Climate Risk is Dominated by Extreme Events:

- Societies are usually well adapted to frequent events (> 1/100 yr)
- Societies are often poorly adapted to rare events (< 1/100 yr)
- Large cost increases result when > 100-yr events become < 100-yr events

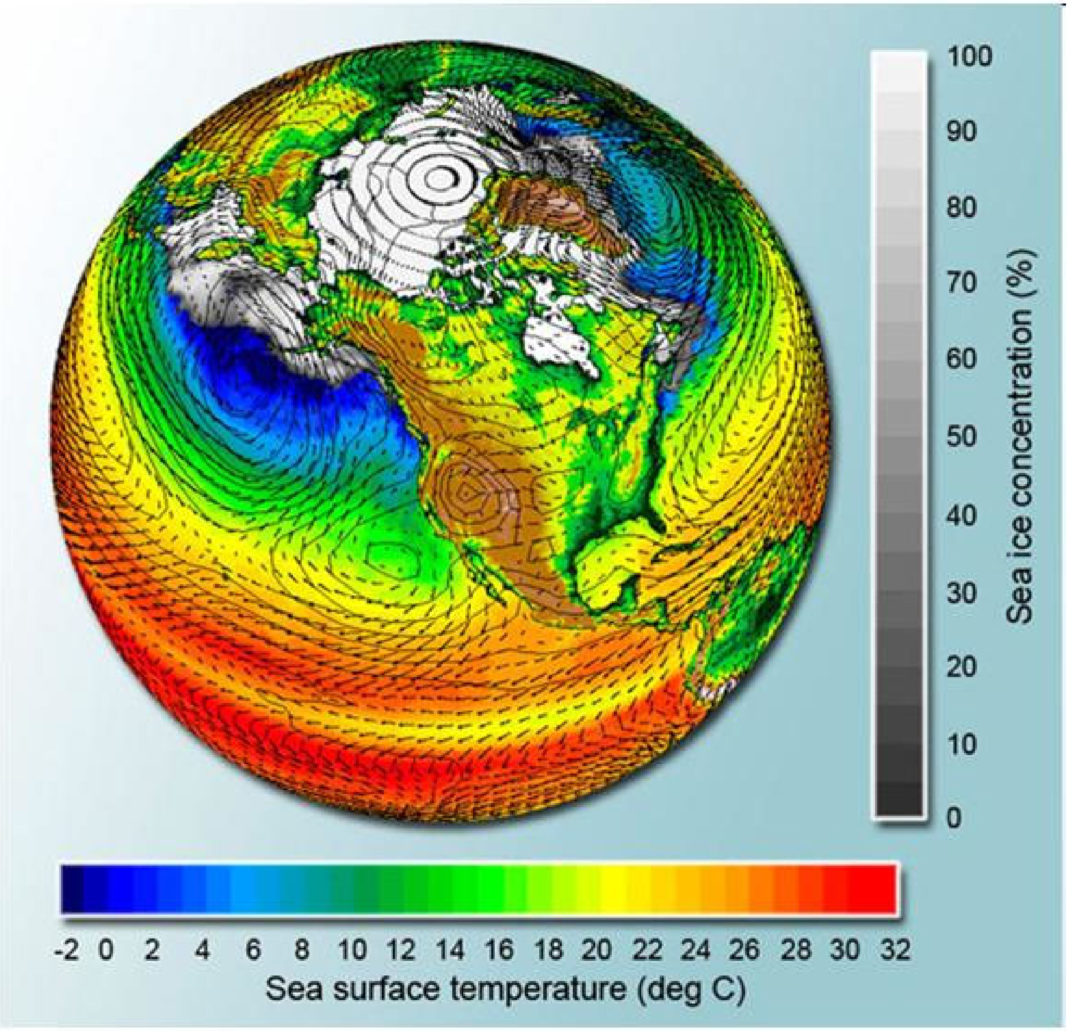


Historical Records

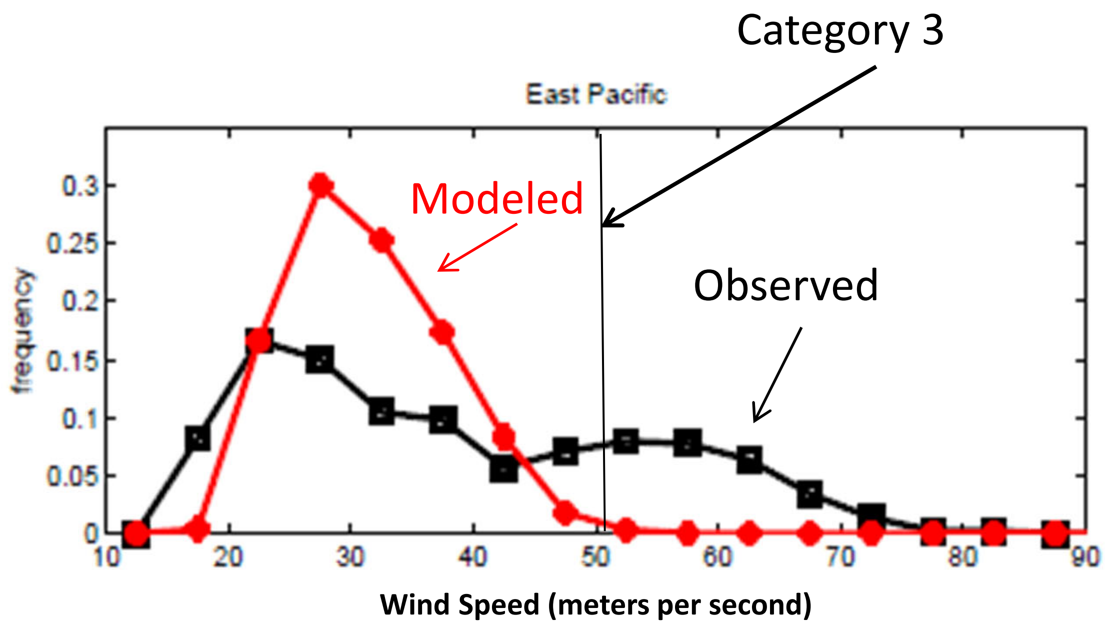
- Tropical cyclones: ~< 100 years of good records (U.S.)
- Even if we had 1000 years of great records, ***the past is no longer a good guide to the present***
- We need to turn to physical models to get better estimates of current (and future) weather risks

How can we bring physical modeling to bear on weather risk assessment?

Global climate models are far too coarse for purpose



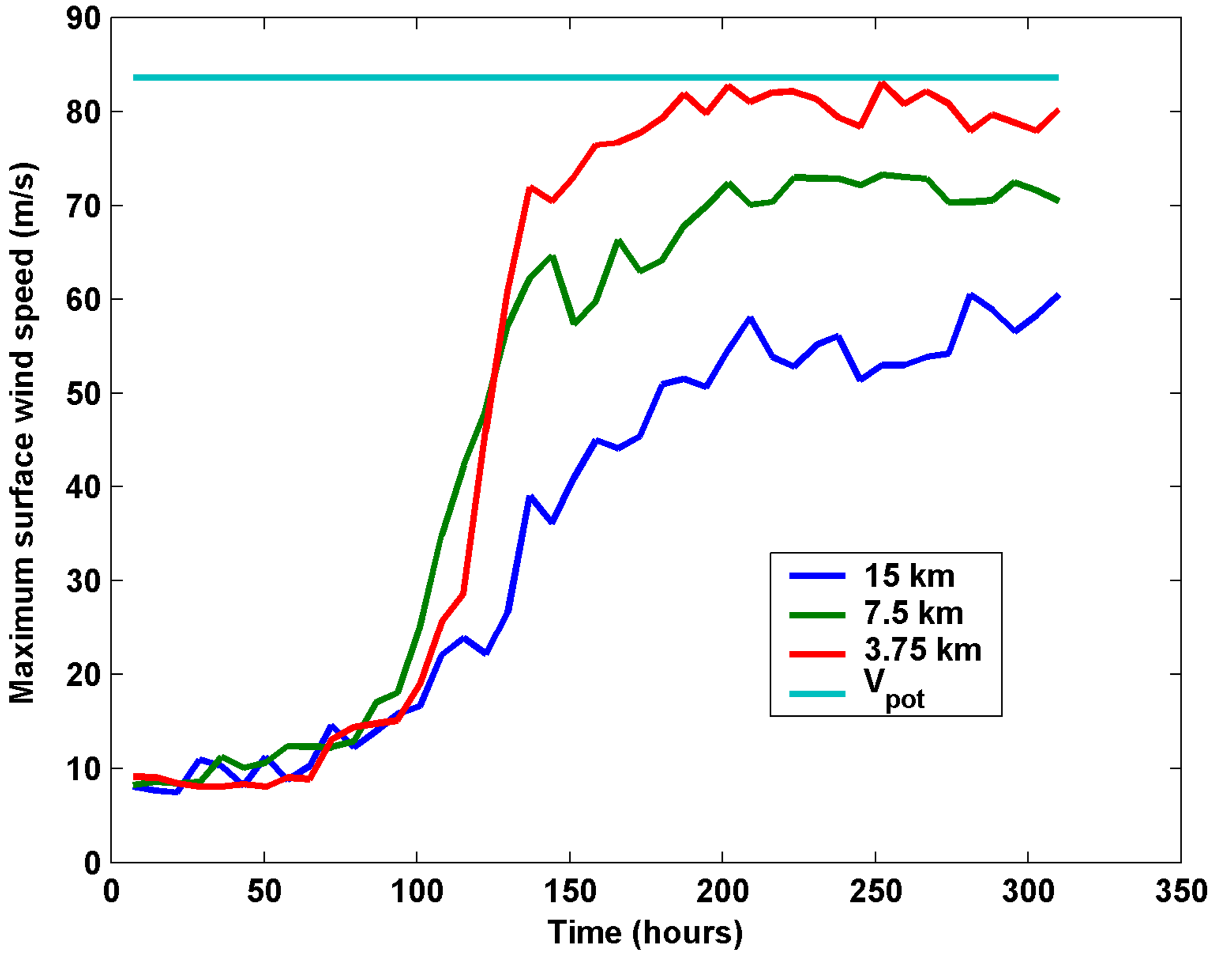
Problem: Today's models are far too coarse to simulate destructive hurricanes



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

Global models do not simulate the storms that cause destruction

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



HighResMip: Grid spacings of 20-200 km (NICAM has short run at 14 km)

We need high resolution AND O(1000 yr) simulations

Using Physics to Assess Hurricane Risk (Downscaling)

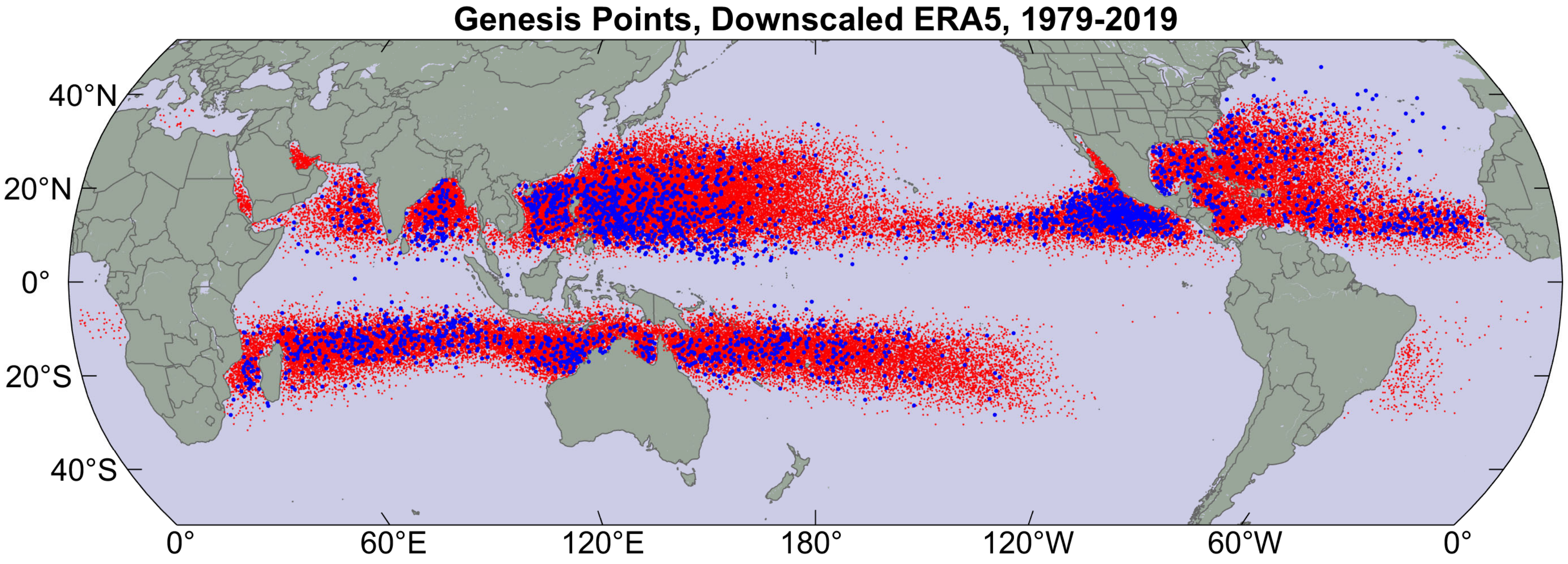
- Reliable, global records of coarse-scale climate are robust and widely available
- Cull from these datasets the key statistics known to control tropical cyclone generation, movement, and intensity evolution
- Bootstrap these key statistic to create unlimited synthetic time series of the hurricane-relevant environmental variables
- Use these to drive specialized, very high resolution *physical hurricane models*
- Extensively evaluate the results against historical hurricane data
- Exact same method can be applied to output of climate models

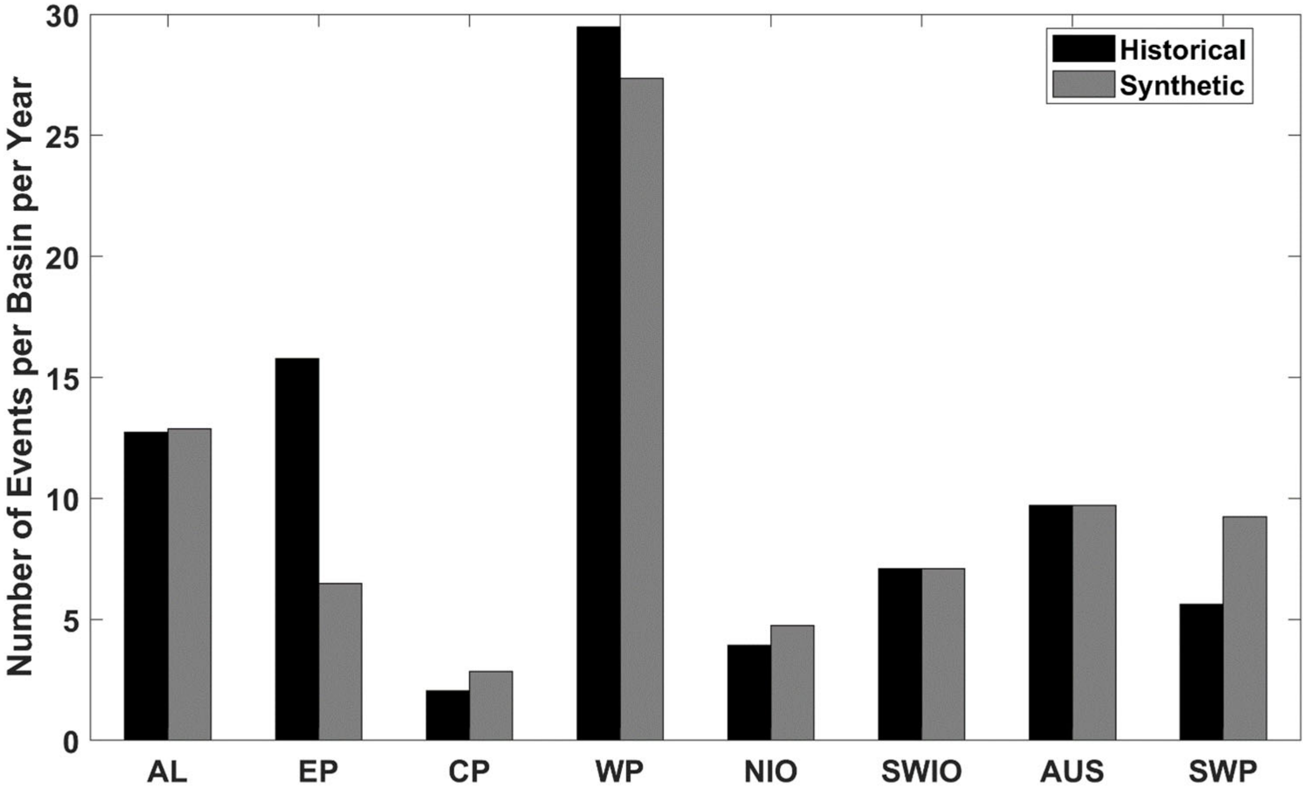
Risk Assessment Approach:

- **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 (beta-drift)
- **Step 3**: Run the CHIPS coupled intensity model for each cyclone, and note how many achieve at least tropical storm strength (**CHIPS is phrased in angular momentum coordinates. Flow-dependent resolution**)
- **Step 4:** Using the small fraction of surviving events, determine storm statistics. Can generate 100,000 events

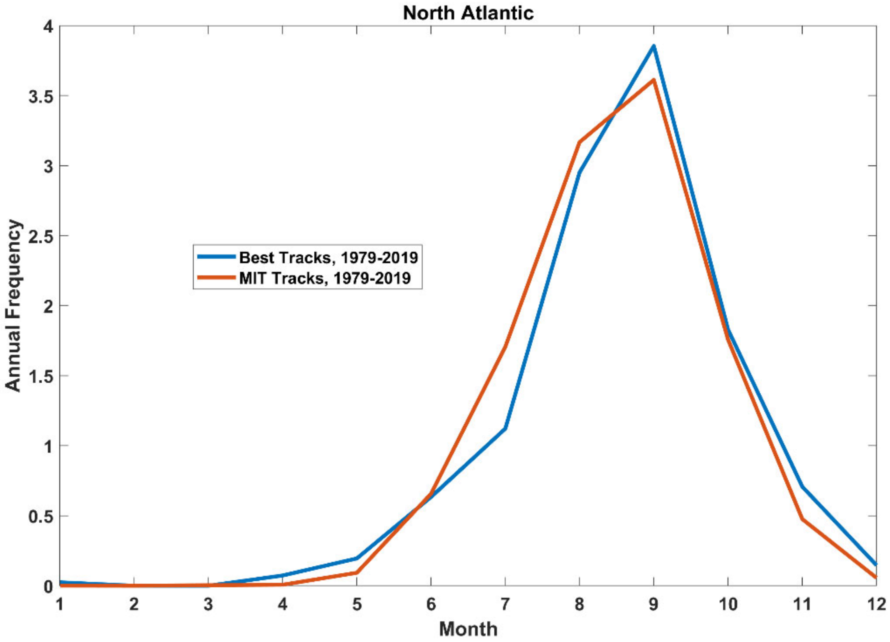
Details: Emanuel et al., *Bull. Amer. Meteor. Soc*, 2008

Origin points of successful seeds (red); observed genesis locations (blue)

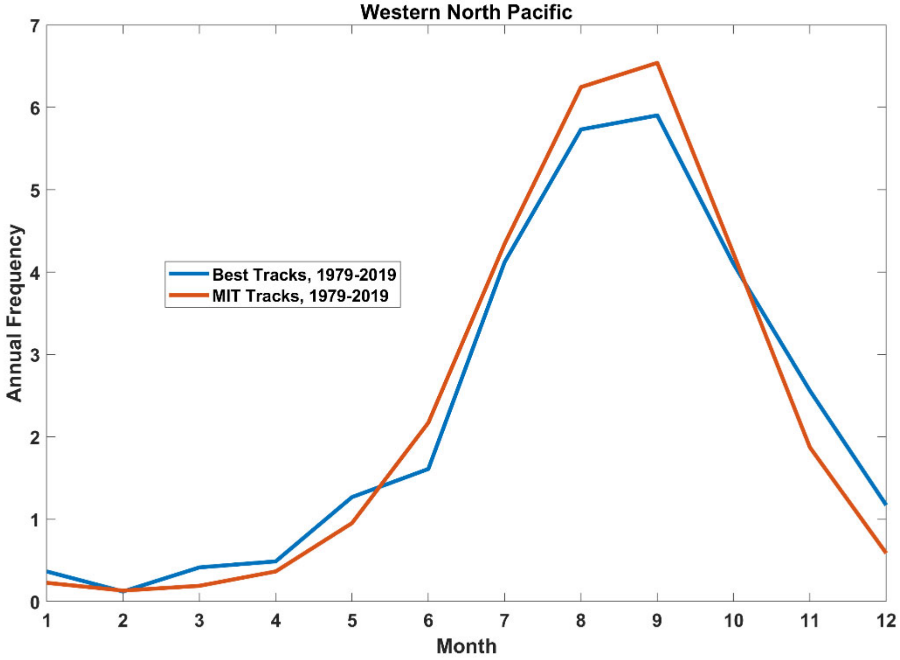




Average annual number of tropical cyclones over the period 1980-2020 in observations (IBTrACS; Knapp et al. 2010; black bars) and from random seeding of ERA-5 (gray bars)

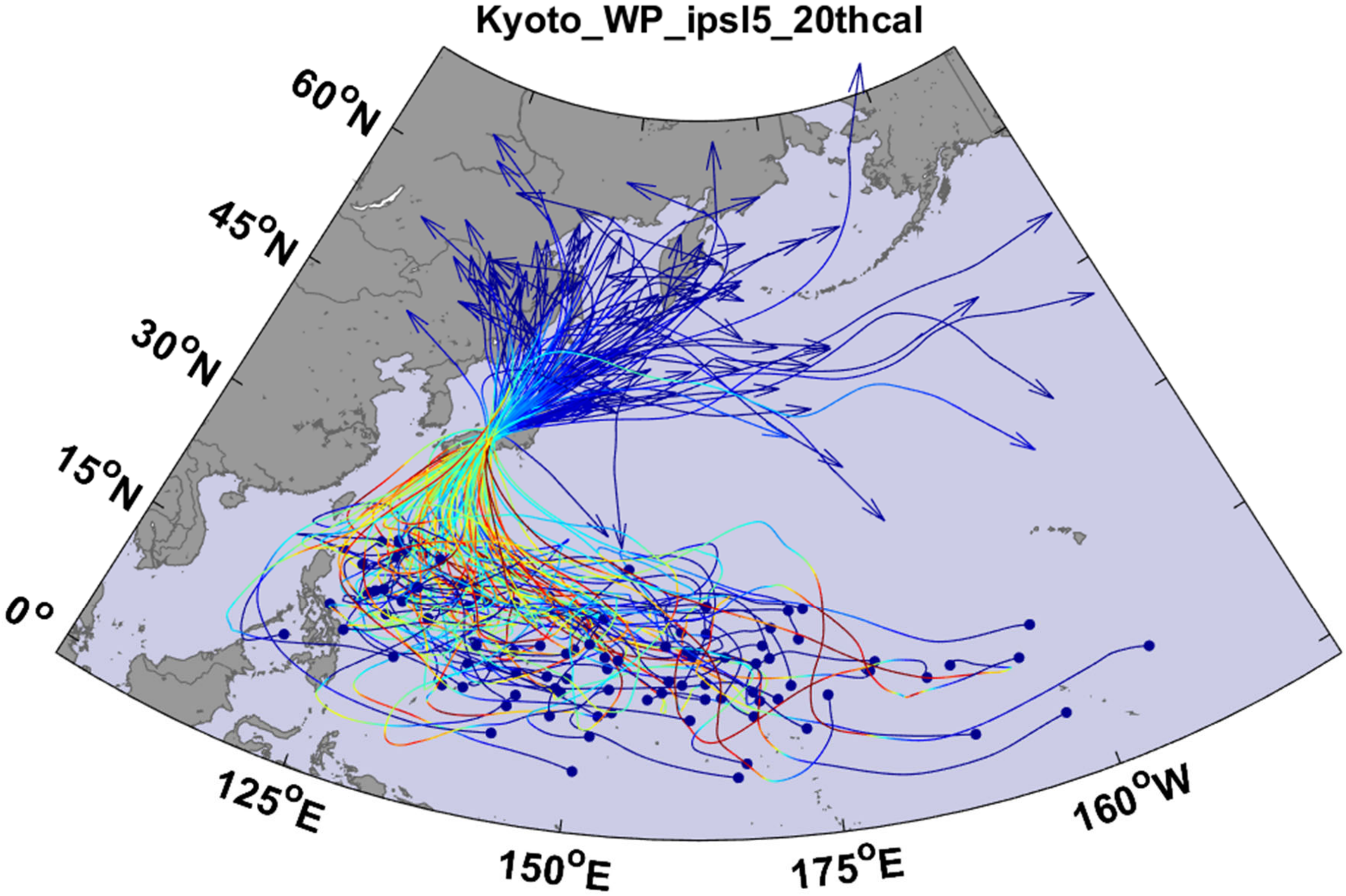


Seasonal Cycle
North Atlantic

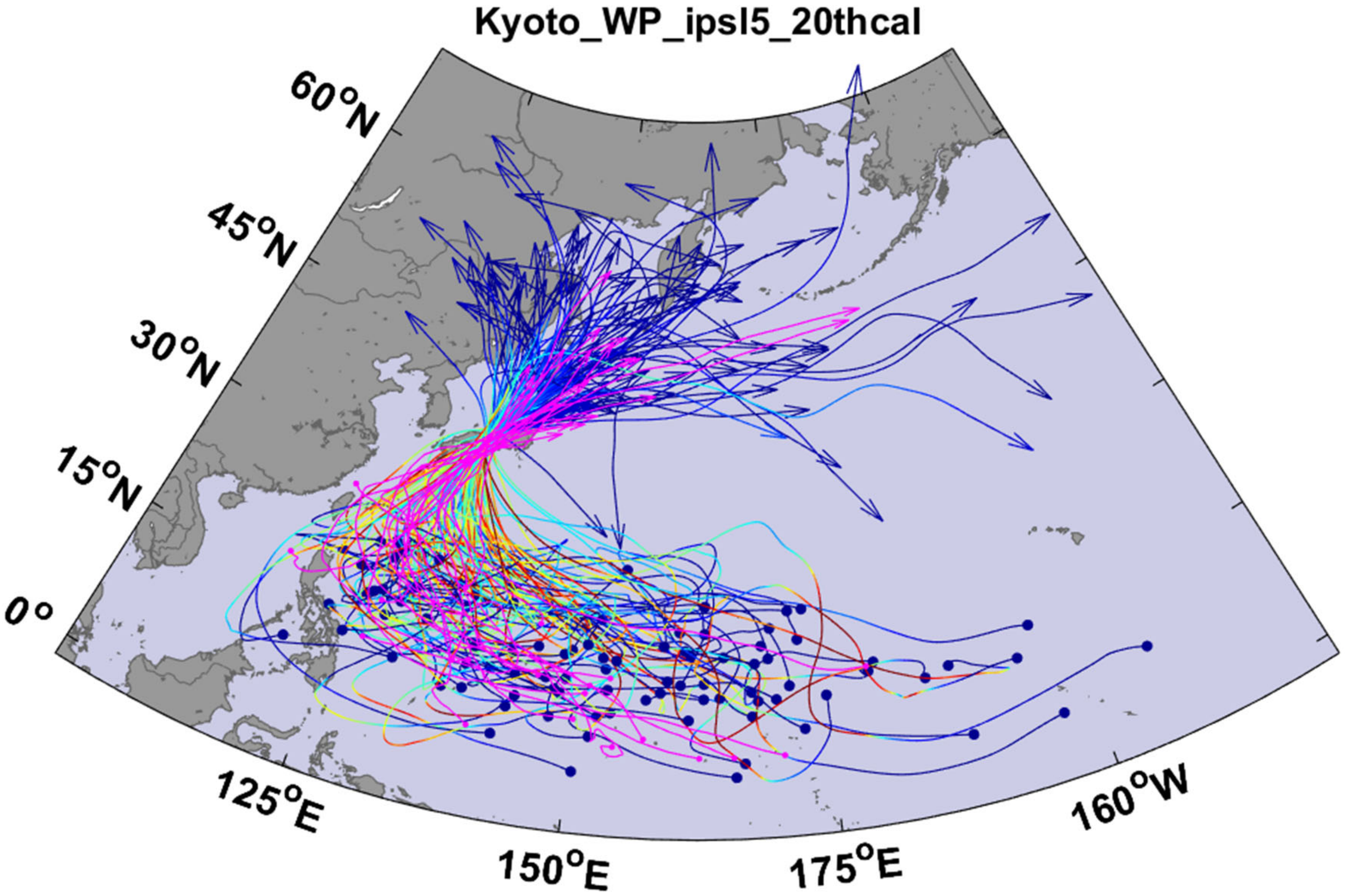


Seasonal Cycle
Northwest Pacific

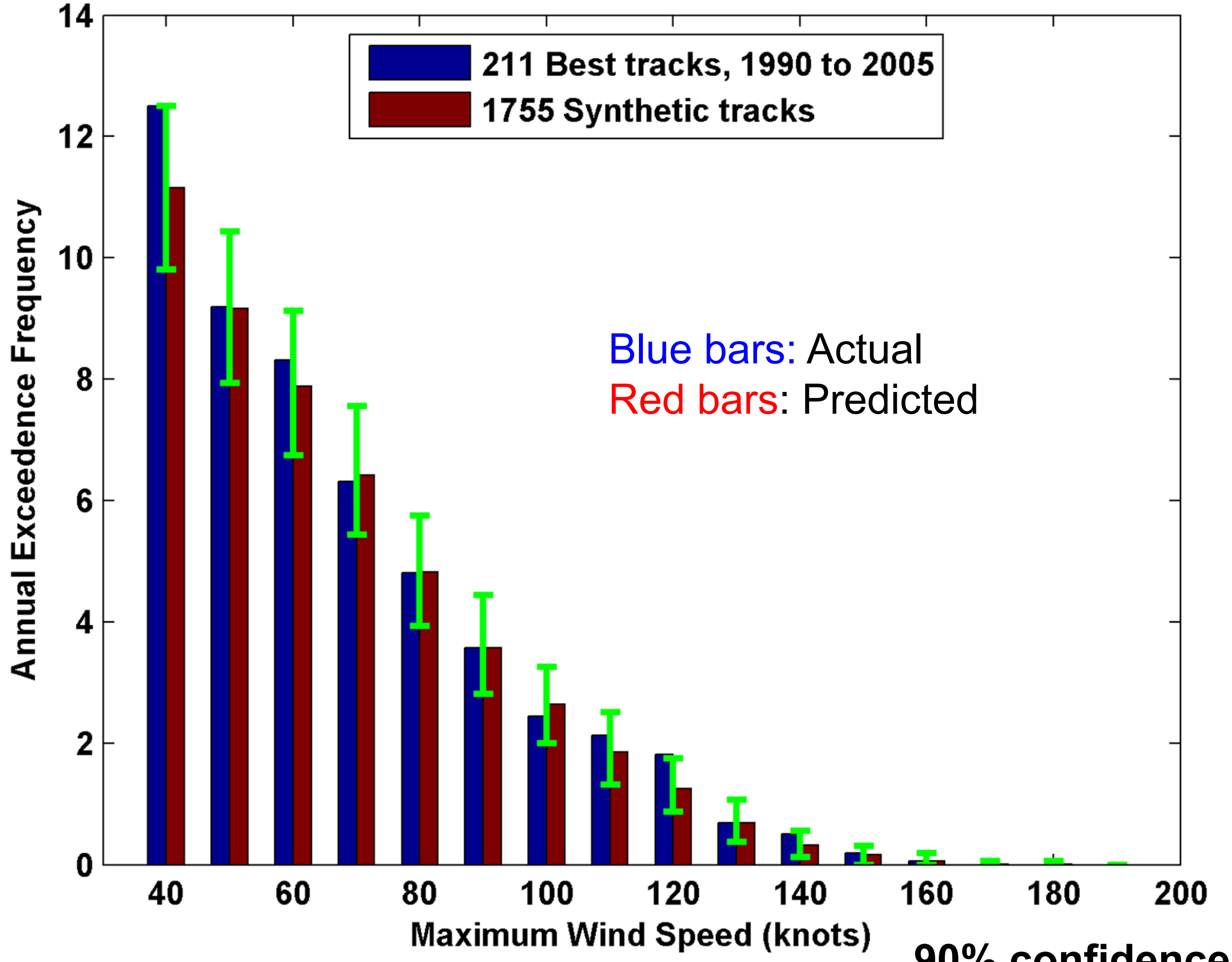
Example:
Top 100 out of 2000 TCs Affecting Kyoto, 1981-2000



Same, but with top 20 historical tracks



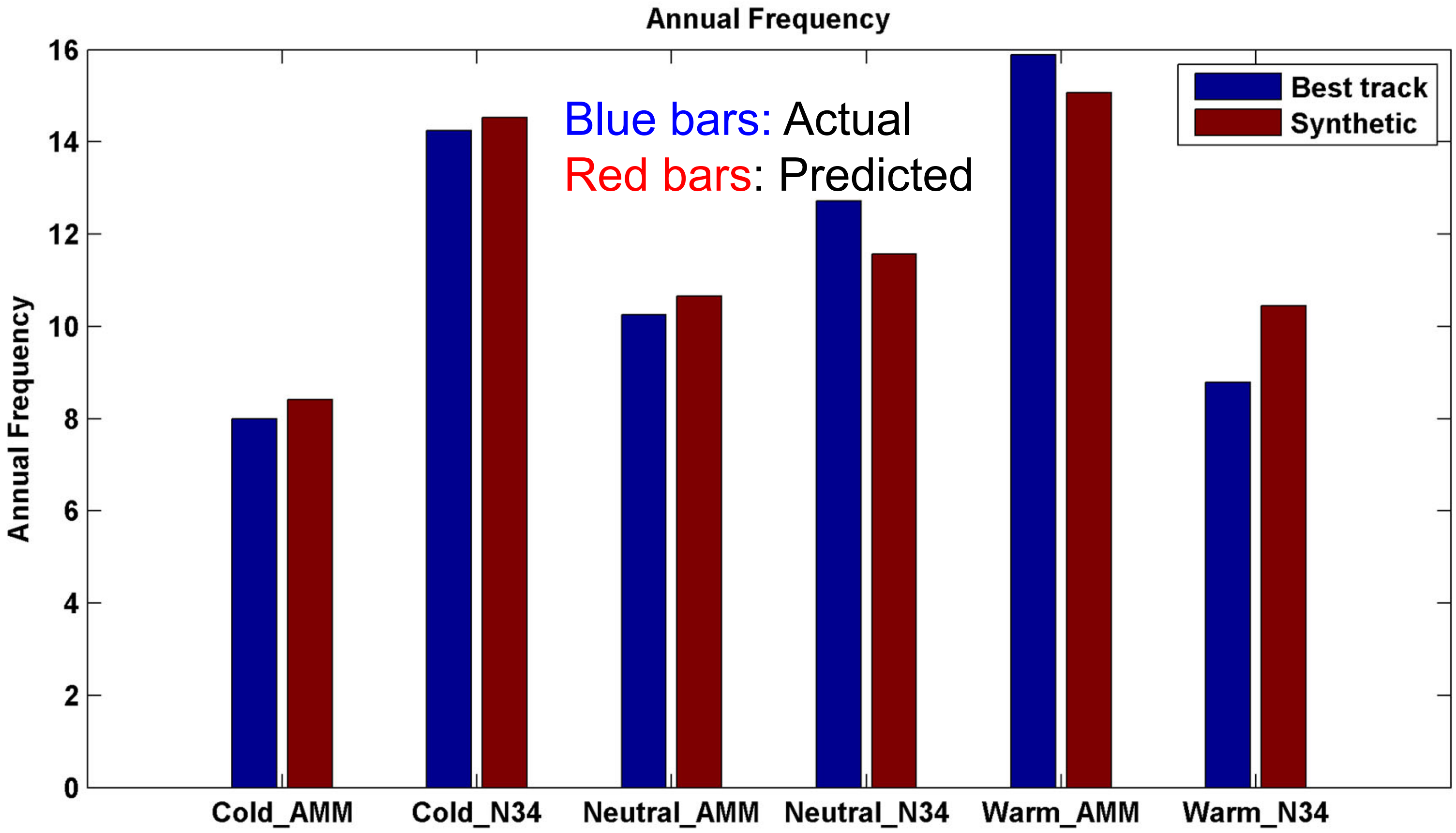
Cumulative Distribution of Storm Lifetime Peak Wind Speed, with Sample of 1755 Synthetic Tracks



Blue bars: Actual
Red bars: Predicted

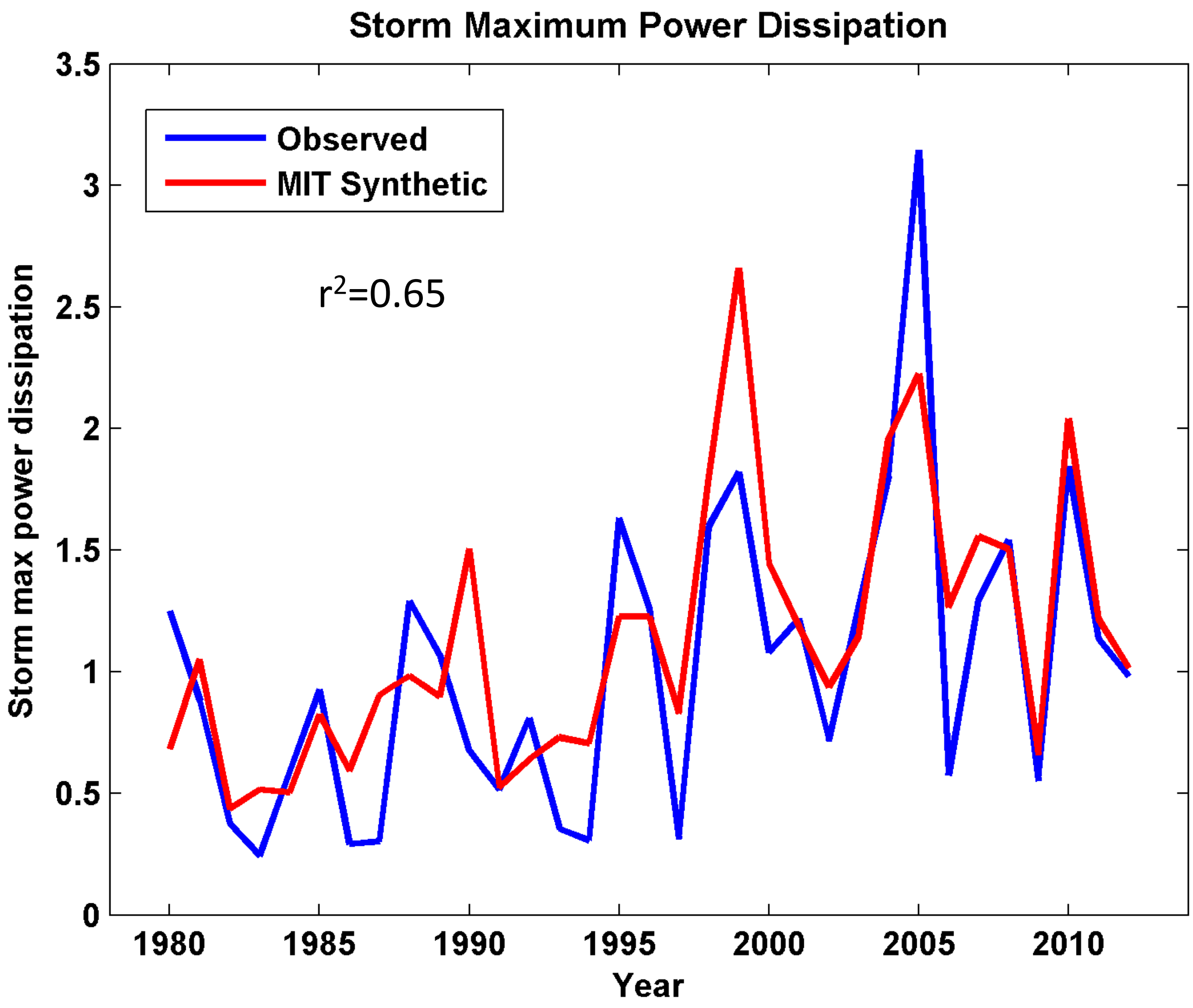
90% confidence bounds

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

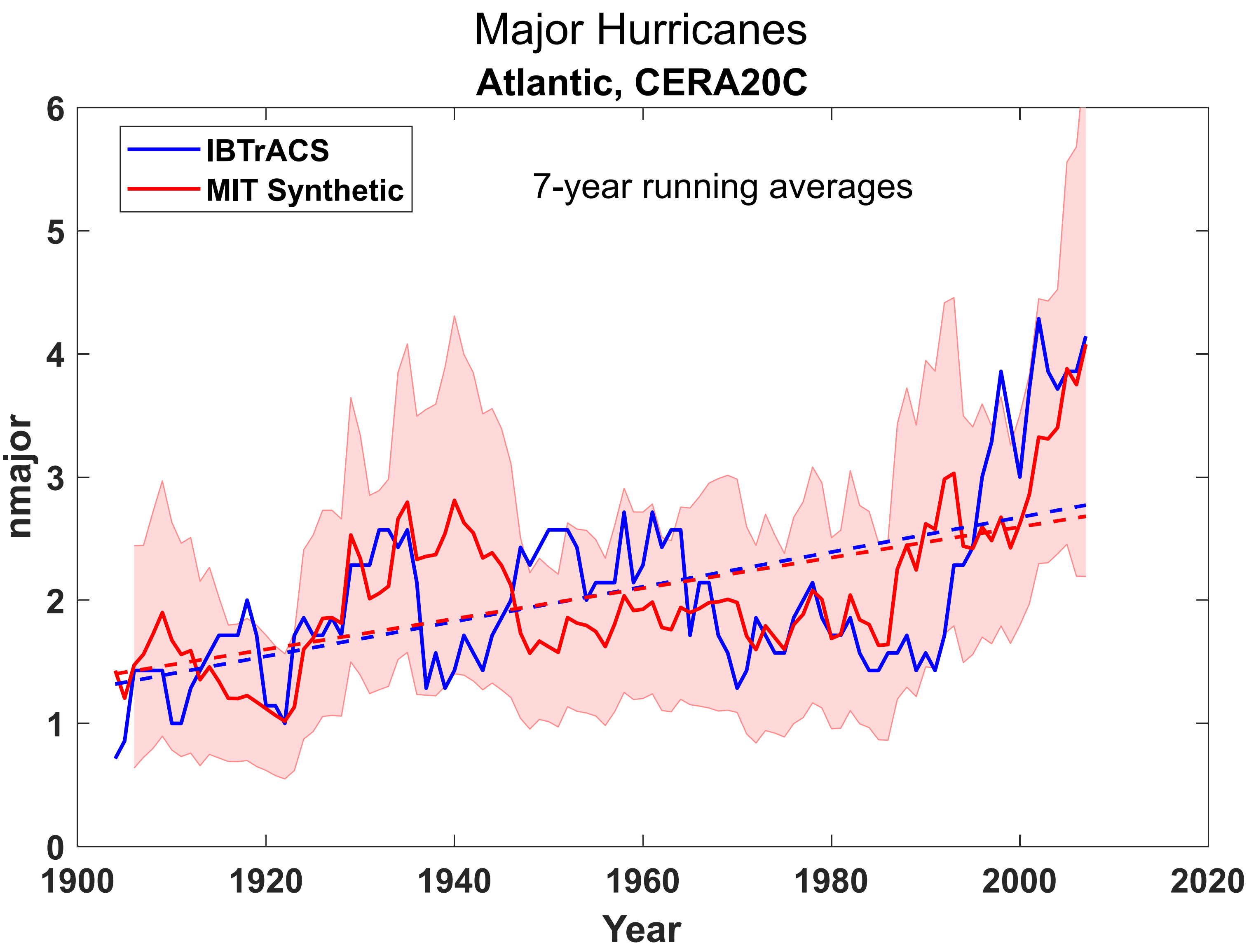


Blue bars: Actual
Red bars: Predicted

Captures Much of the Observed North Atlantic Interannual Variability

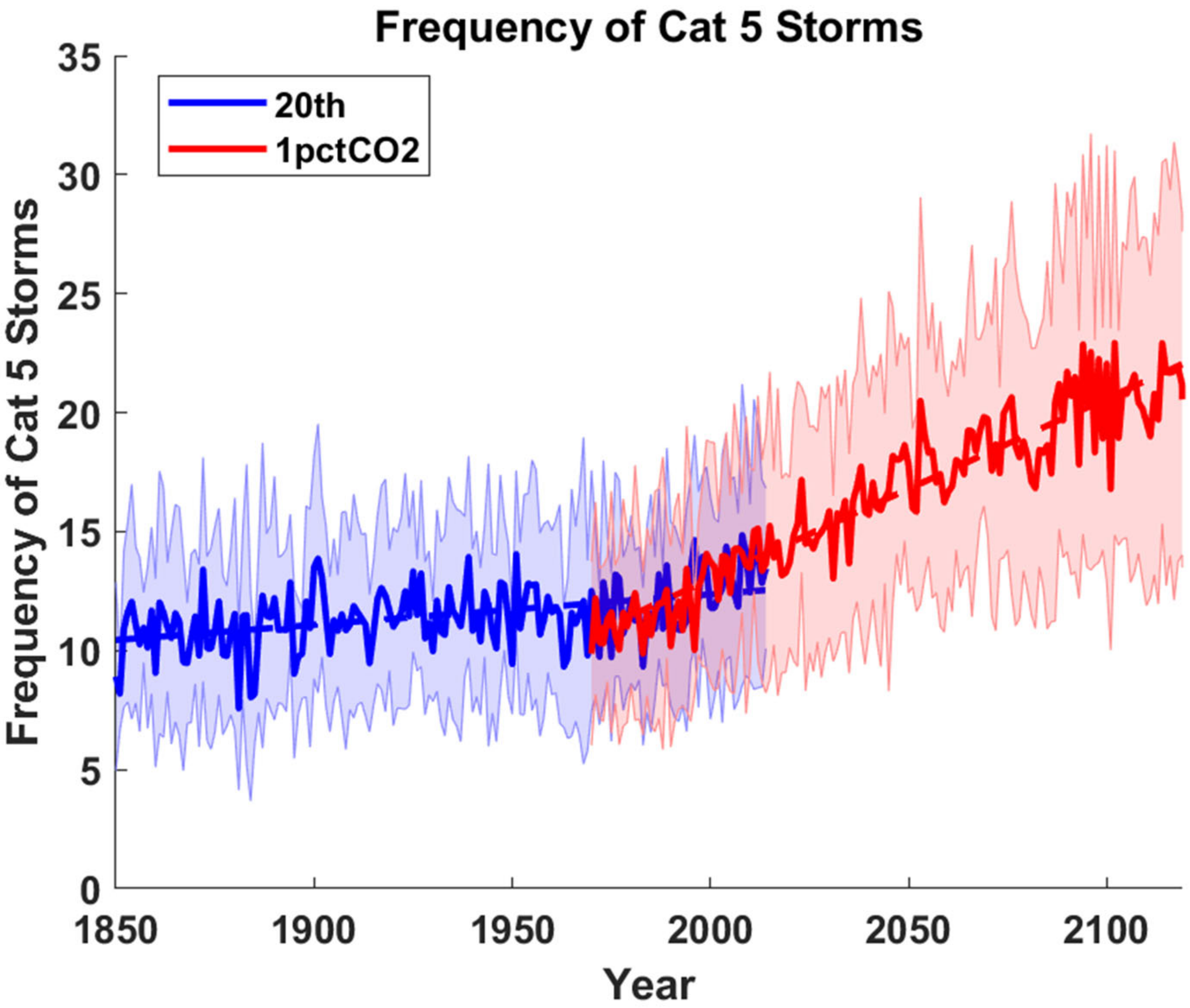


Application to global gridded climate data:

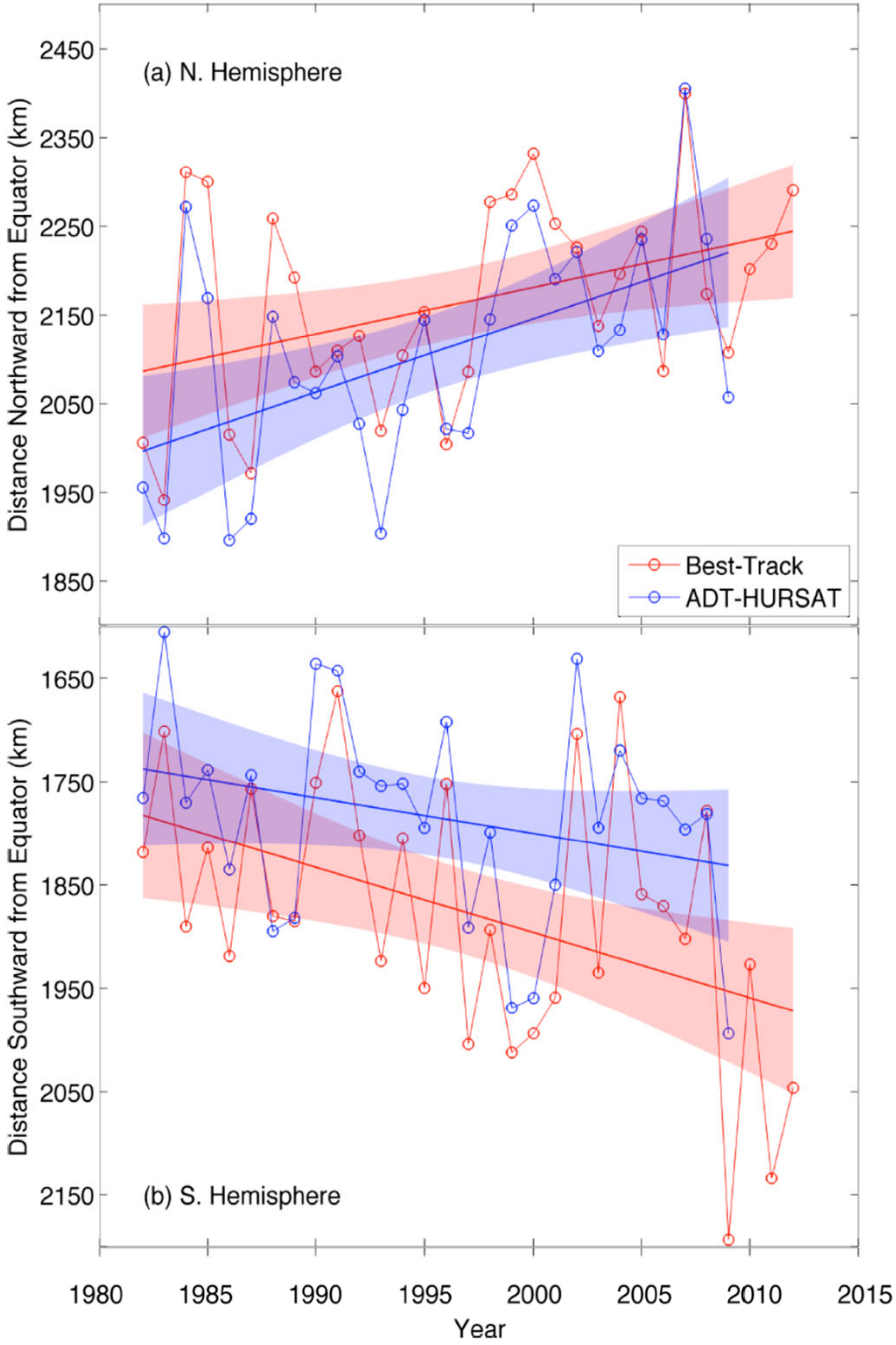


Application to Global Climate Change Simulations:

Global CAT 5 Tropical Cyclone Frequency from 9 Current Generation (CMIP6) Climate Models



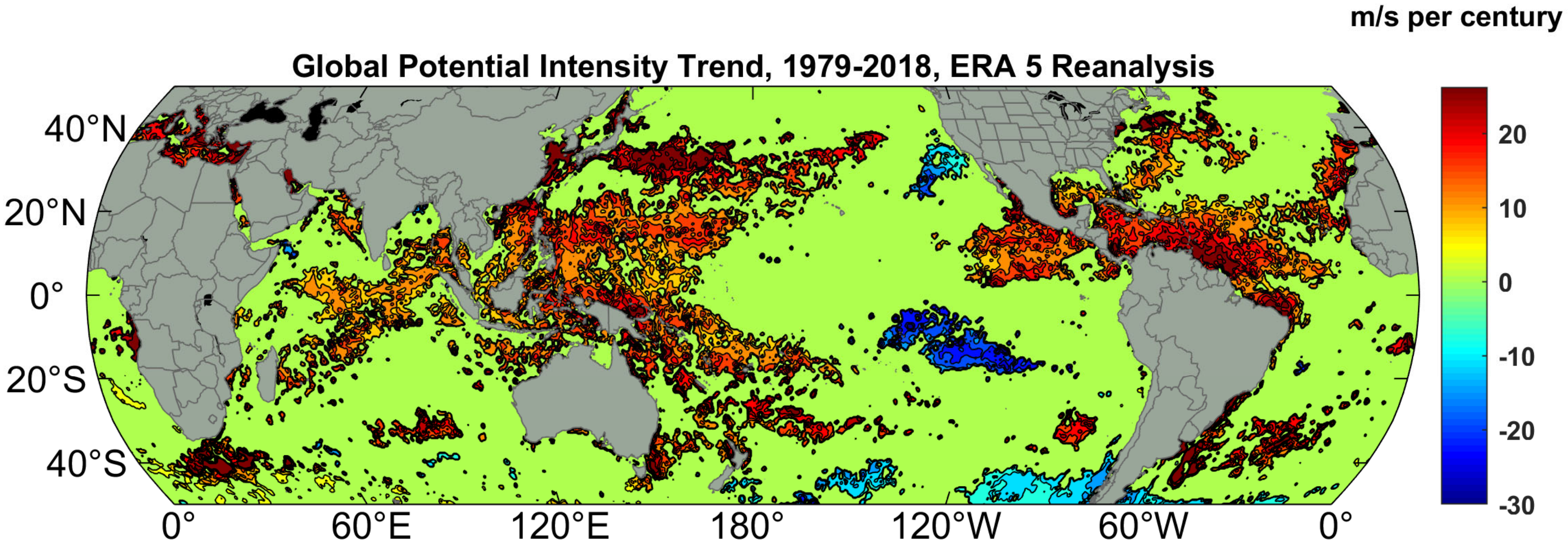
Hurricanes are reaching peak intensity at higher latitudes



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

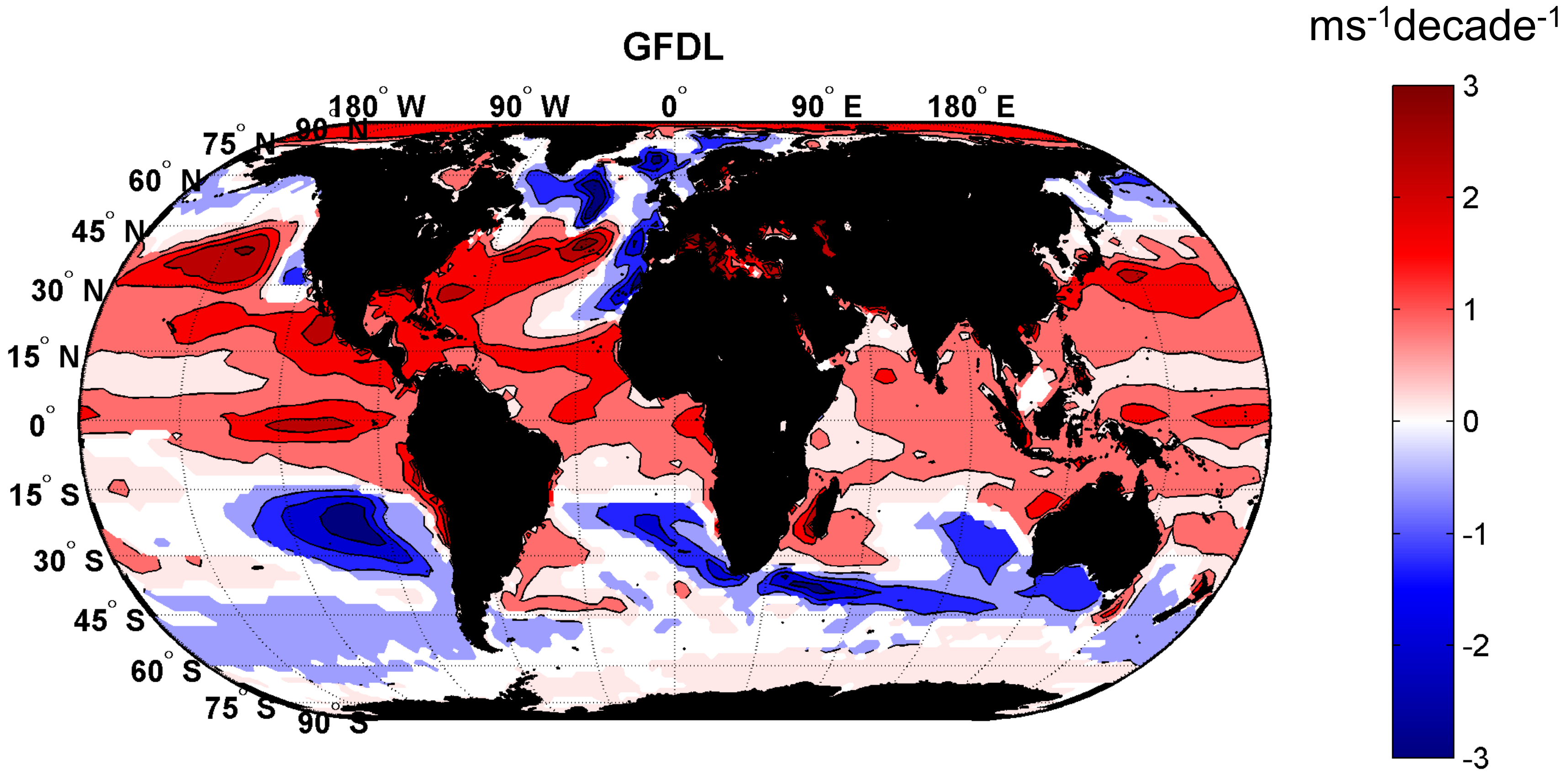
From *Kossin et al. (2014)*

Potential Intensity Trend, 1979-2018, ERA 5 Reanalysis

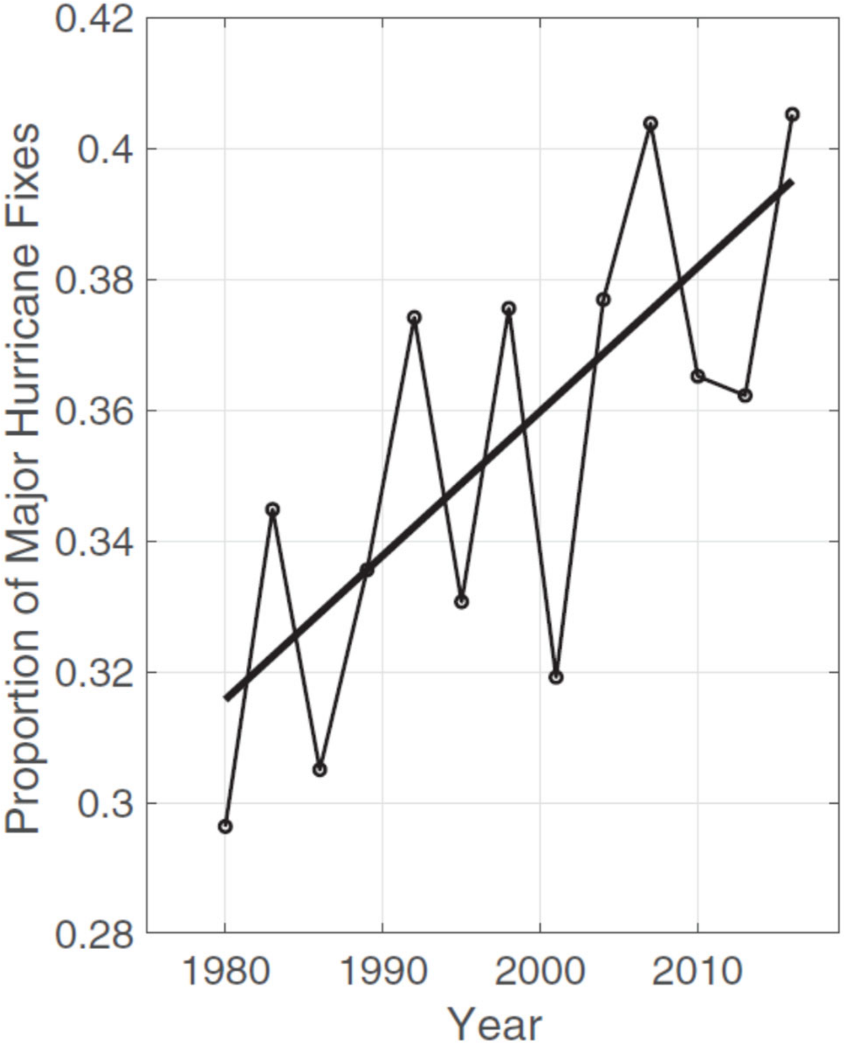


(Trend shown only where p value < 0.05)

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



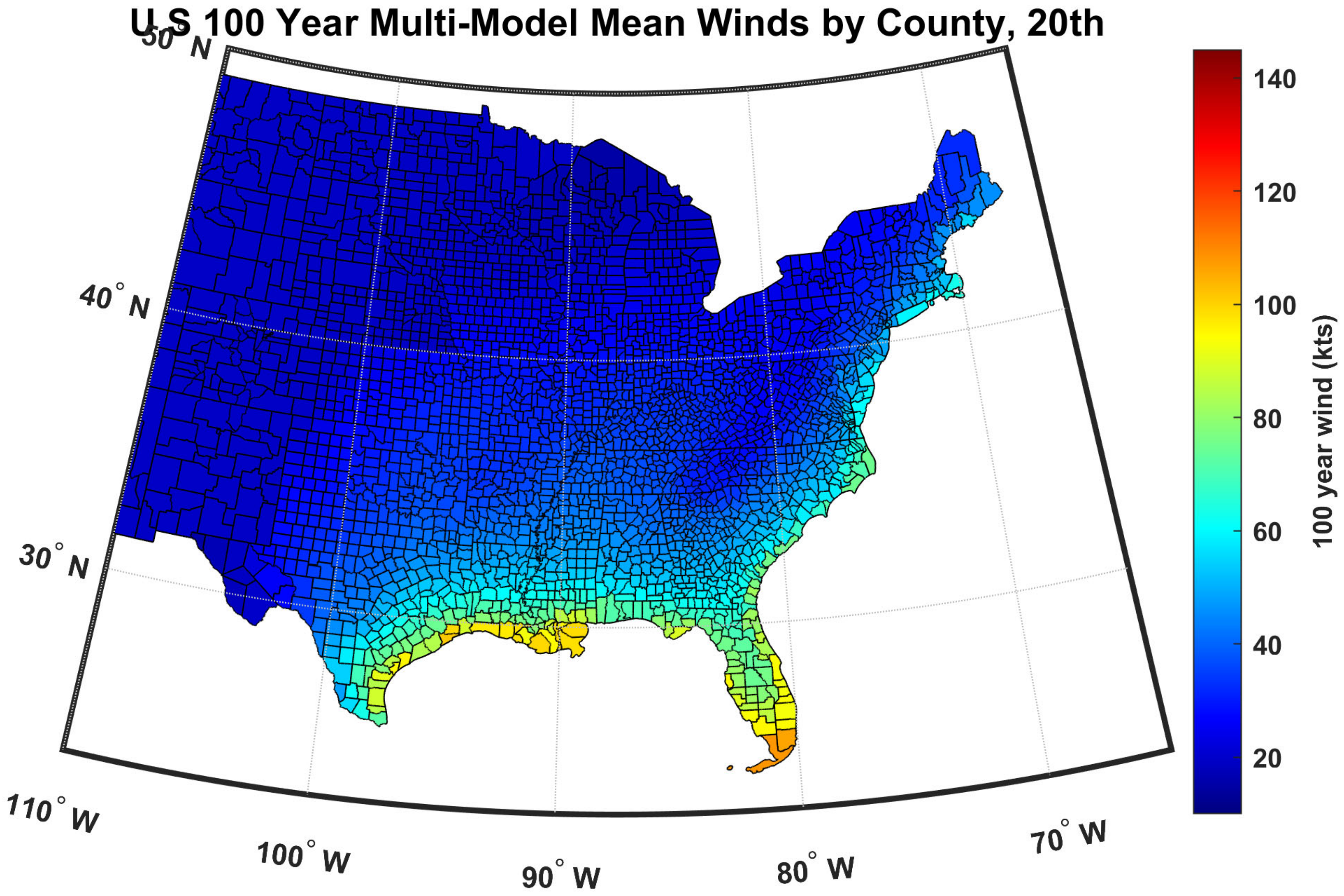
Satellite-derived proportion of major hurricane fixes



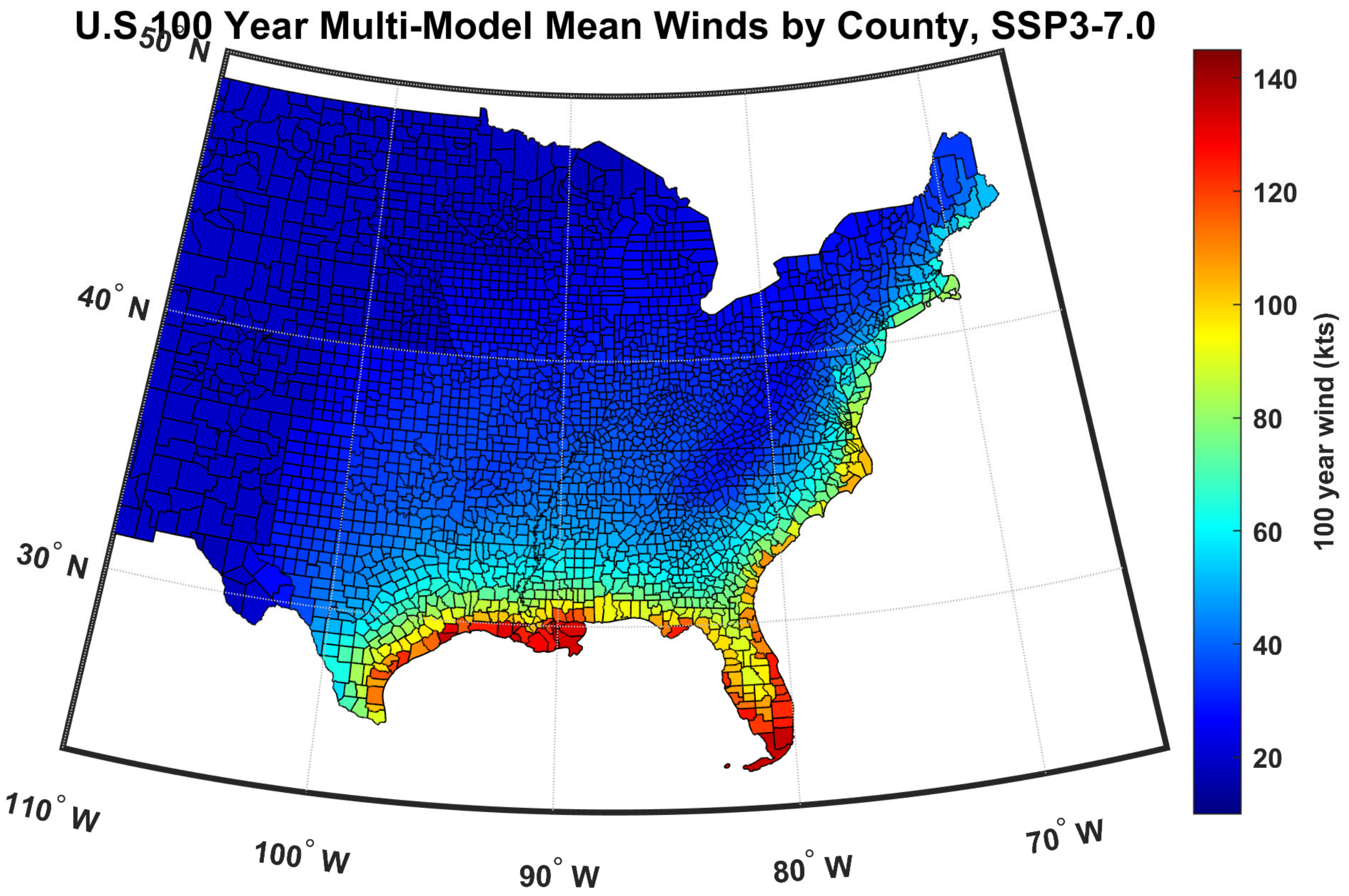
Time series of fractional proportion of global major hurricane estimates to all hurricane estimates for the period 1979–2017. Each point, except the earliest, represents the data in a sequence of 3-y periods. The first data point is based on only 2 y (1979 and 1981) to avoid the years with no eastern hemisphere coverage. The linear Theil−Sen trend (black line) is significant at the 98% confidence level (Mann−Kendall P value = 0.02). The proportion increases by 25% in the 39-y period (about 6% per decade).

Kossin et al., *PNAS*, 2020

100-year hurricane peak wind based on downscaling 8 CMIP6 climate models, 1984-2014

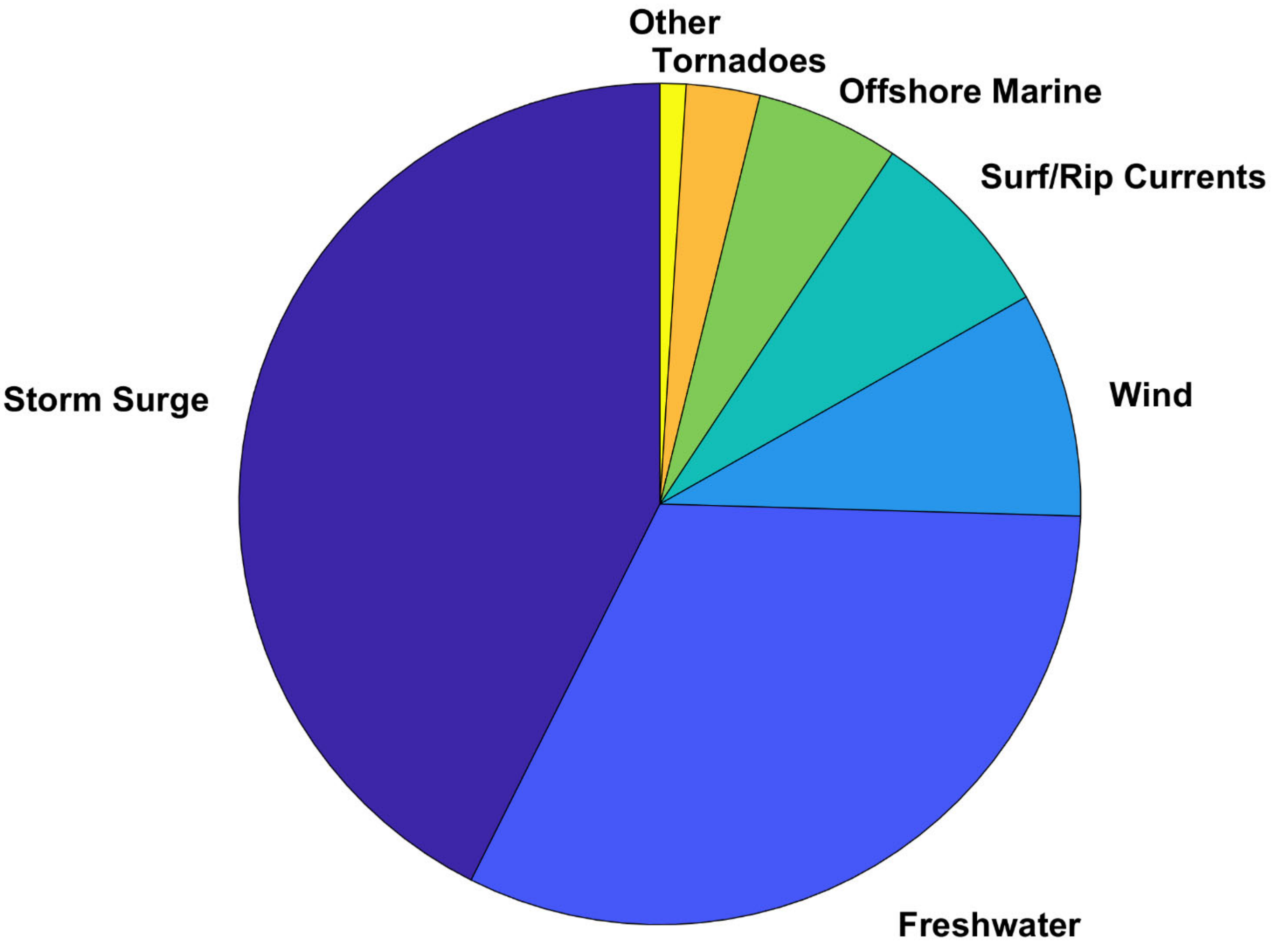


100-year hurricane peak wind based on downscaling 8 CMIP6 climate models, 2070-2100



Hurricane Rain

U.S. Hurricane Fatalities, 1963-2022



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)

Apply Quasi-Balanced Dynamics to Stored TC and Environmental Fields

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 shear and thermodynamic fields.

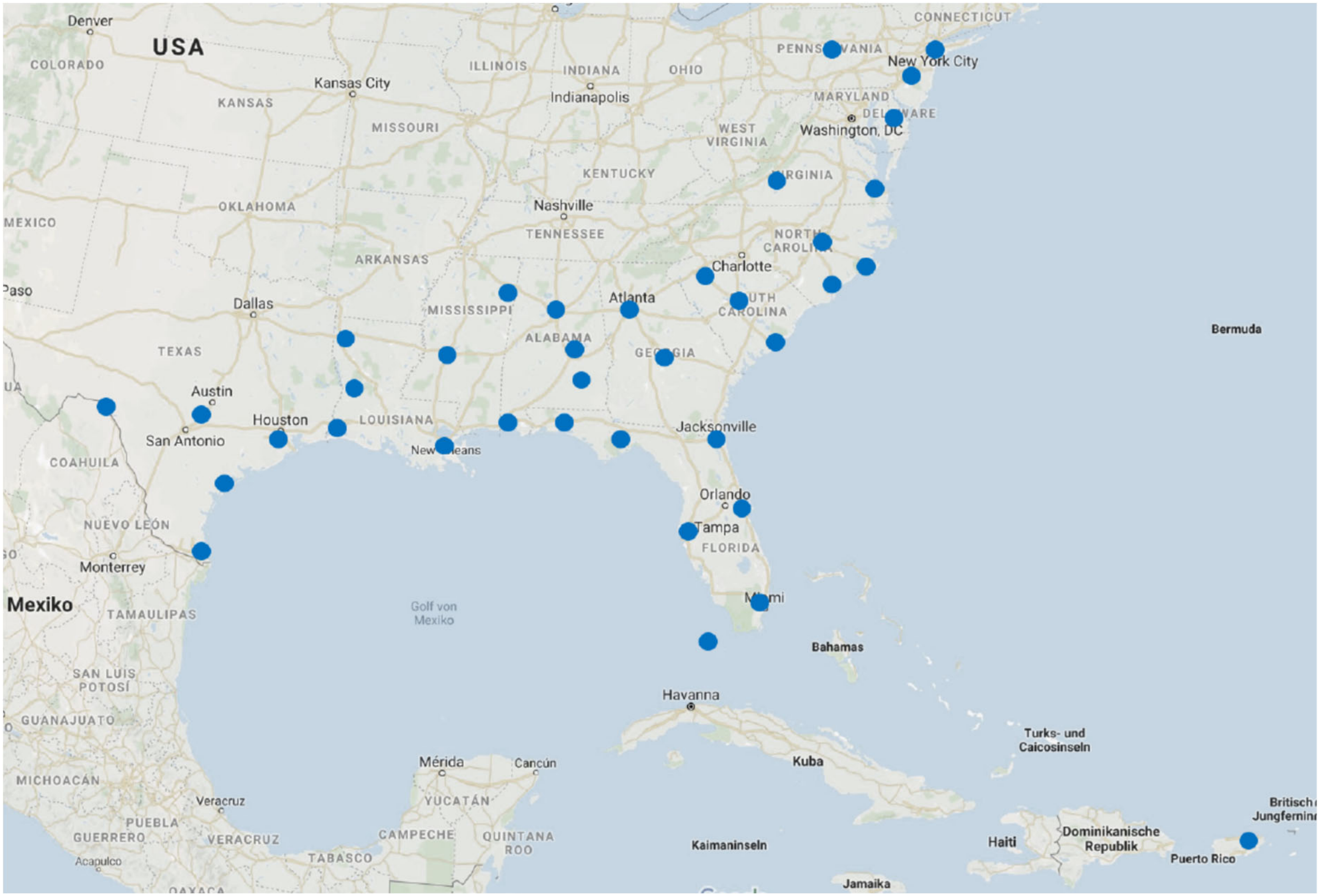
Details: Feldmann et al, *J. App. Meteor. Clim.*, 2019

Testing the Algorithm

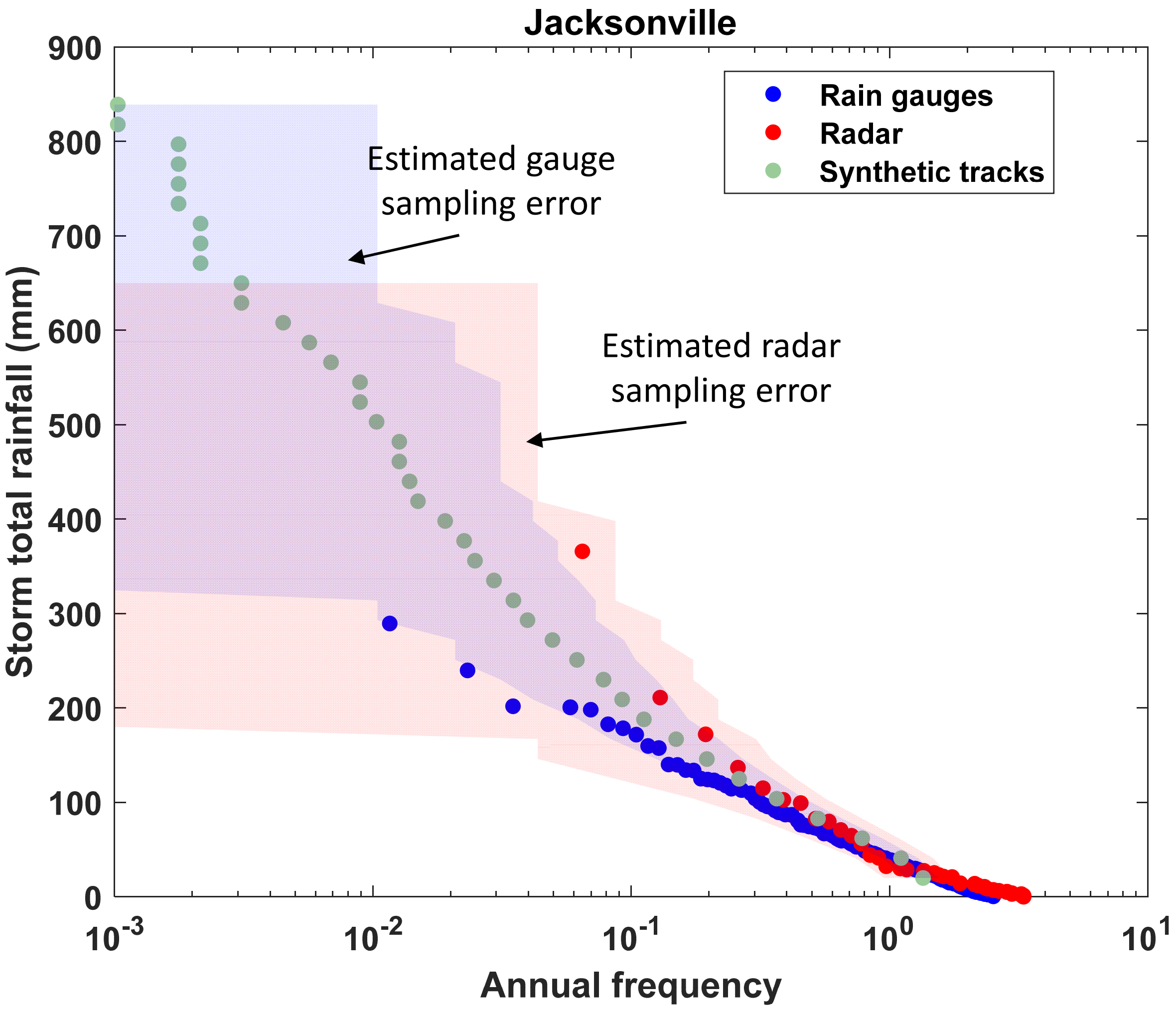
- Identify TC rainfall affecting NEXRAD sites
- Choose local Daily Global Historical Climatology Network (GHCN-D) rain gauges located near NEXRAD sites
- Compare statistical distributions of storm total rainfall from synthetic TCs with NEXRAD-derived rain and rain at nearby gauges

Details: Feldmann et al, *J. App. Meteor. Clim.*, 2019

NEXRAD Sites



An Example:

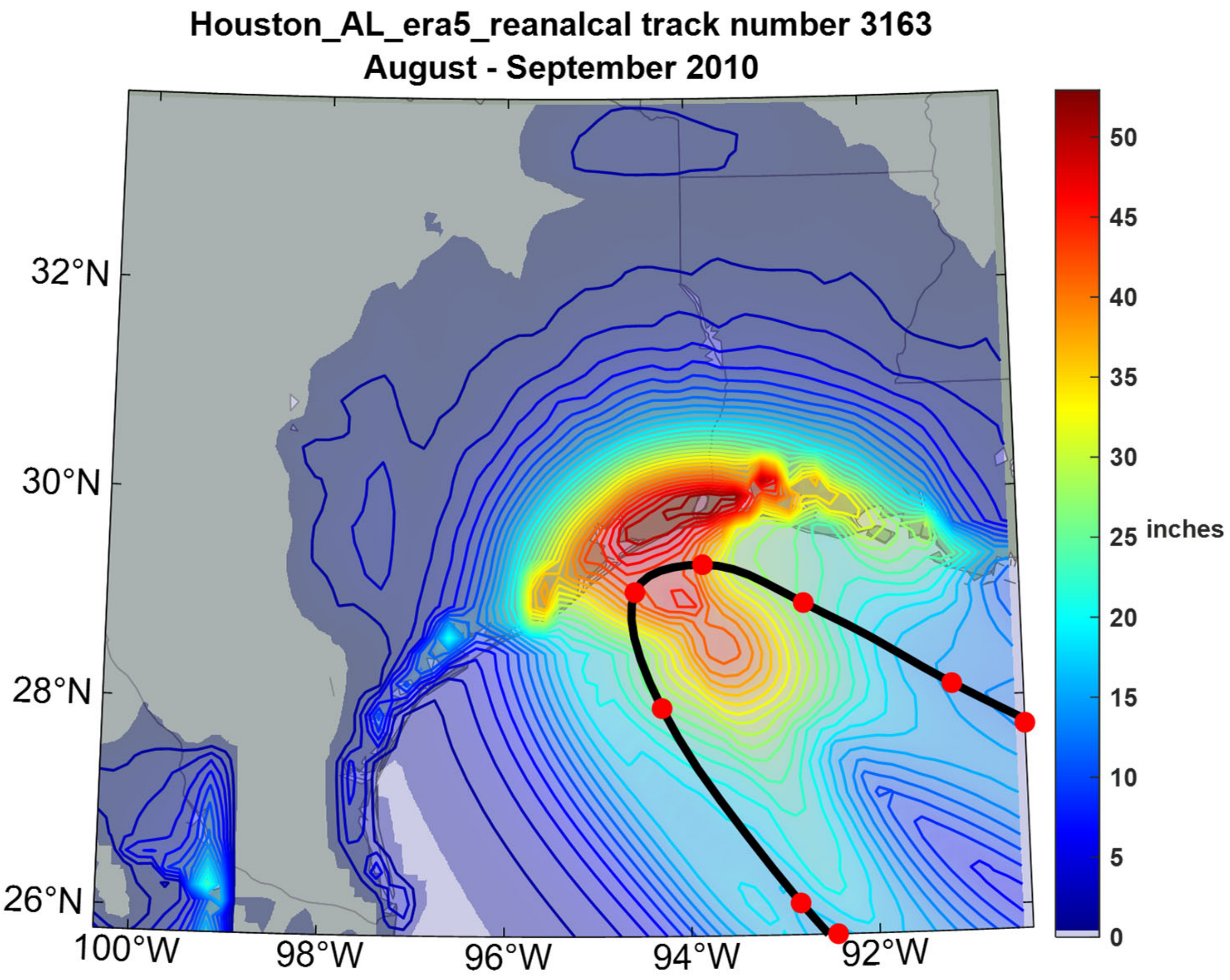


Estimated gauge sampling error

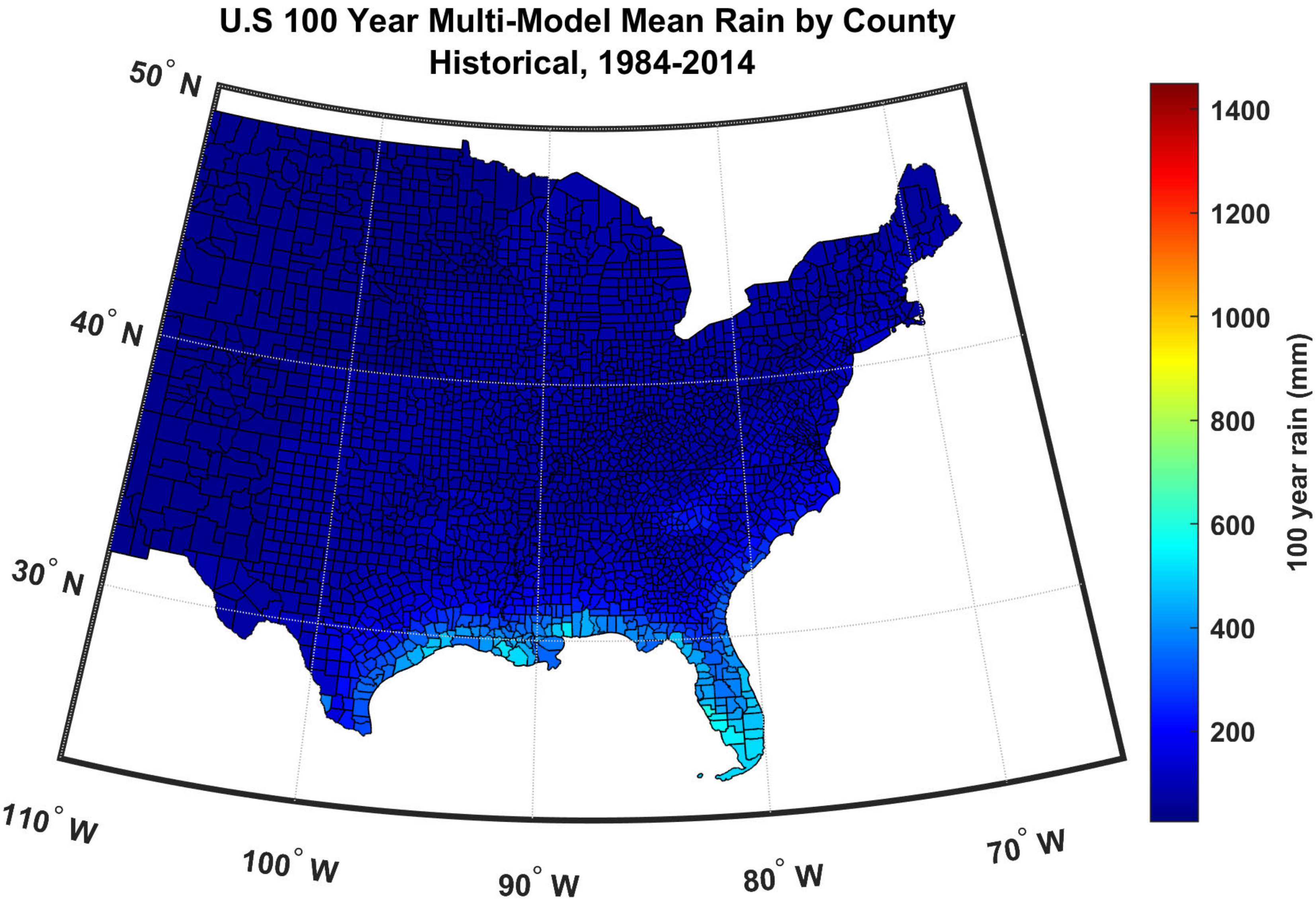
Estimated radar sampling error

Feldmann et al, *J. App. Meteor. Clim.*, 2019

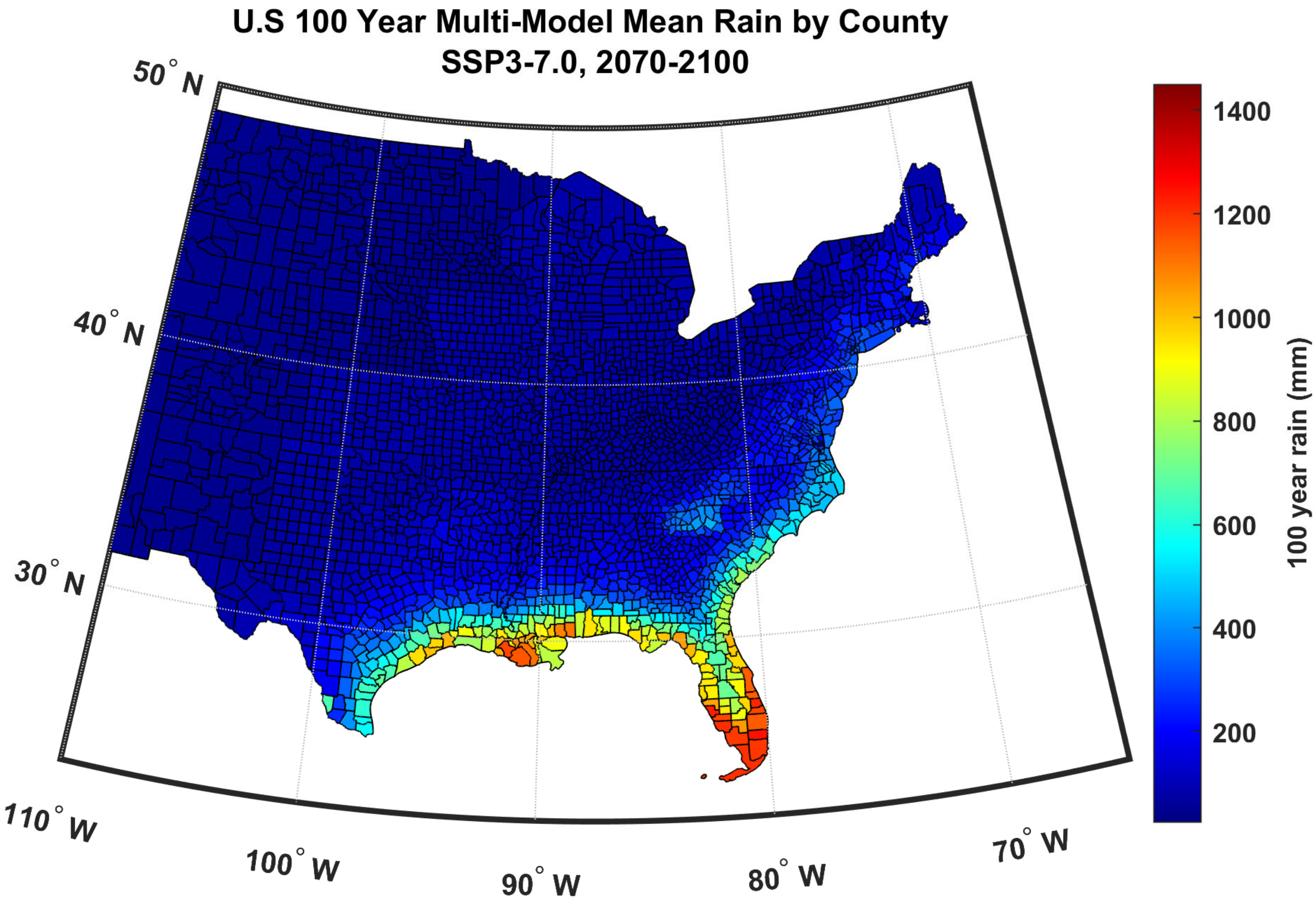
2,000 year rain event for Houston



100-year hurricane storm total rain based on downscaling 8 climate models, 1984-2014



100-year hurricane storm total rain based on downscaling 8 climate models, 2070-2100



A version of this risk model based on the FAST intensity emulator (in place of CHIPS) is freely available at

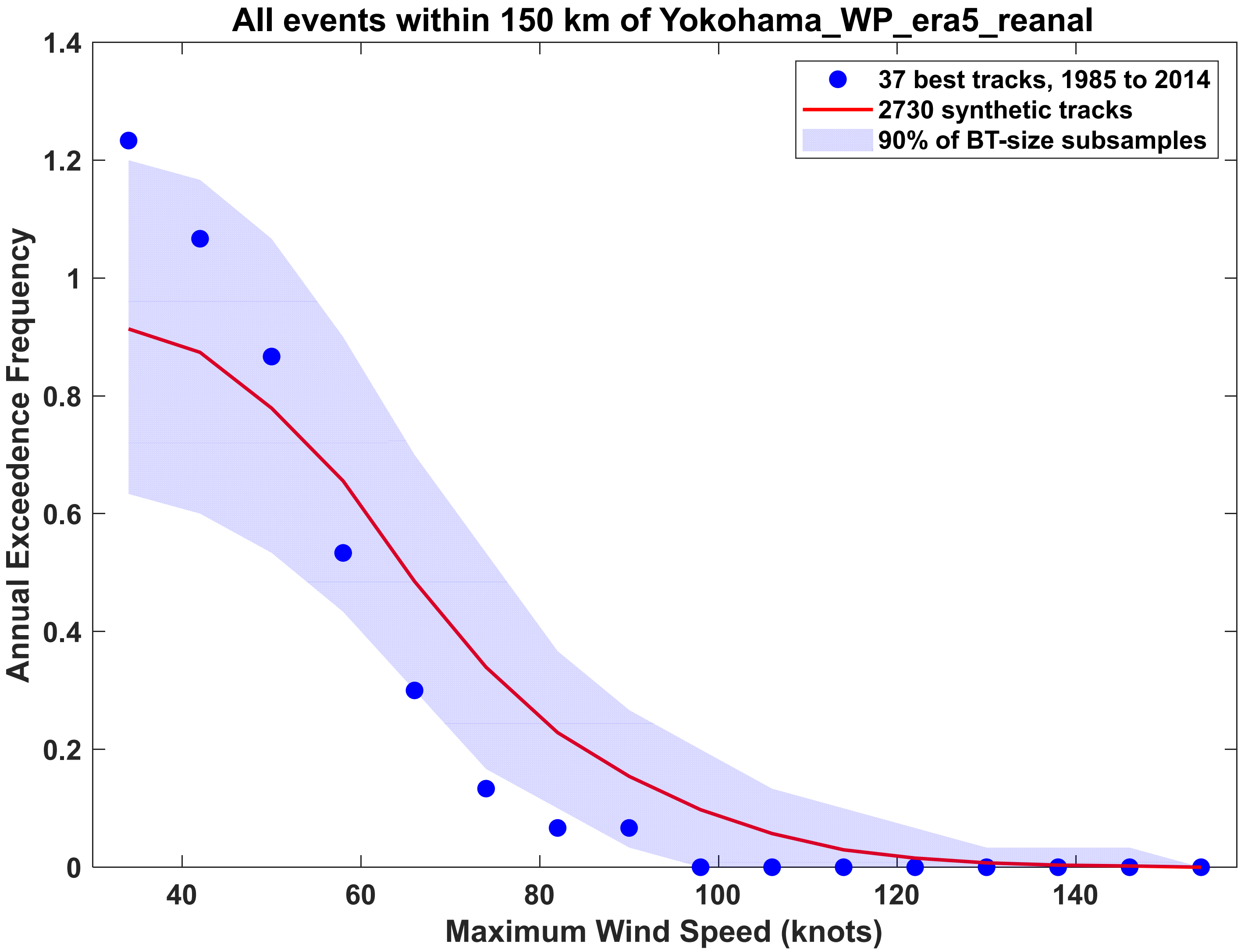
https://github.com/linjonathan/tropical_cyclone_risk

Typhoon Risk in Yokohama

Yokohama

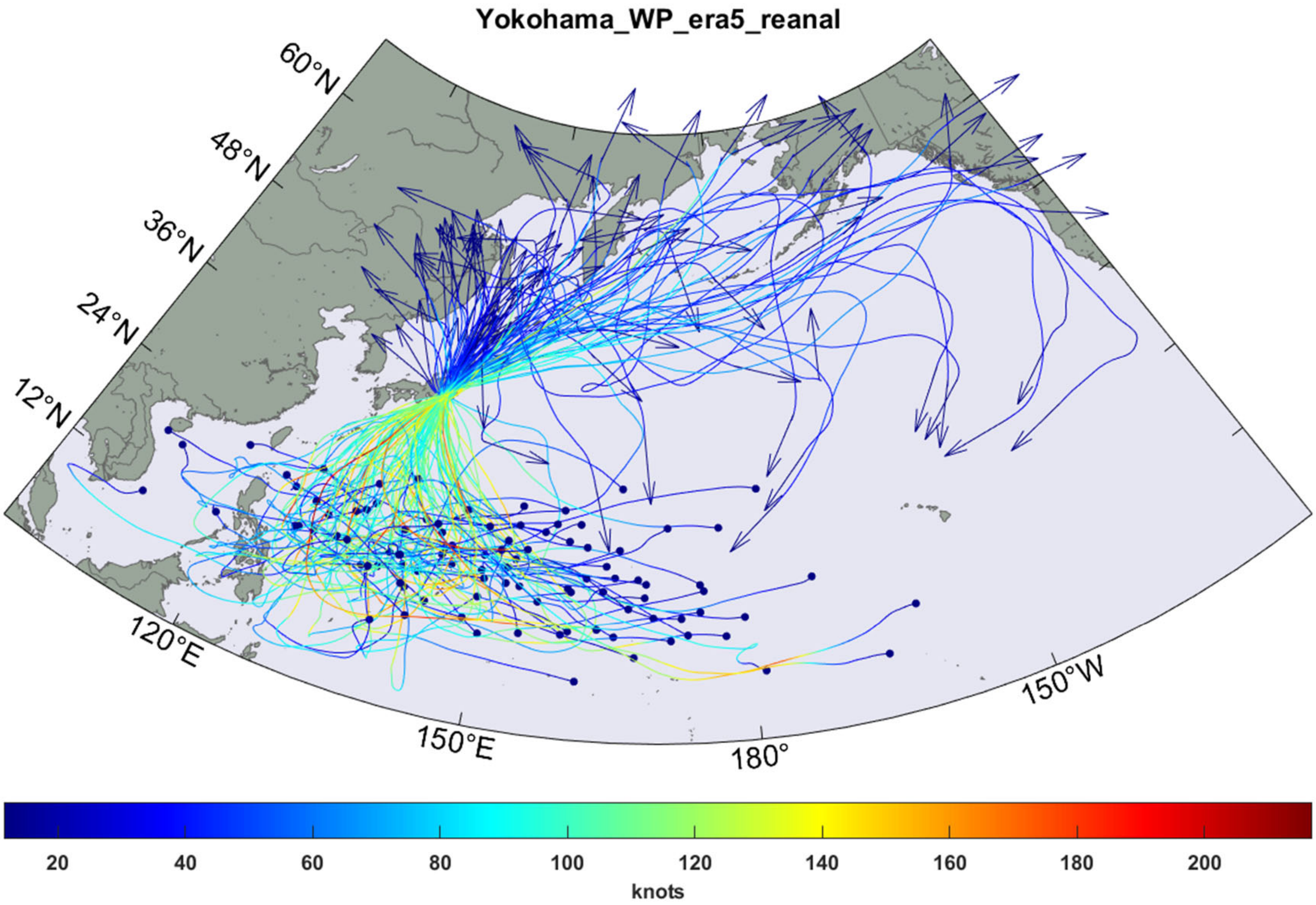
- Downscale 3000 events from ERA-5 reanalyses, 1985-2014, passing within 150 km of Yokohama
- Downscale 3000 events from historical simulations of 8 CMIP6-generation climate models, 1985-2014
- Downscale 3000 events from SSP3-7.0 simulations of 8 CMIP6-generation climate models, 2071-2100

If you would like to use these tropical cyclone sets for research purposes, please write me (emanuel@mit.edu)

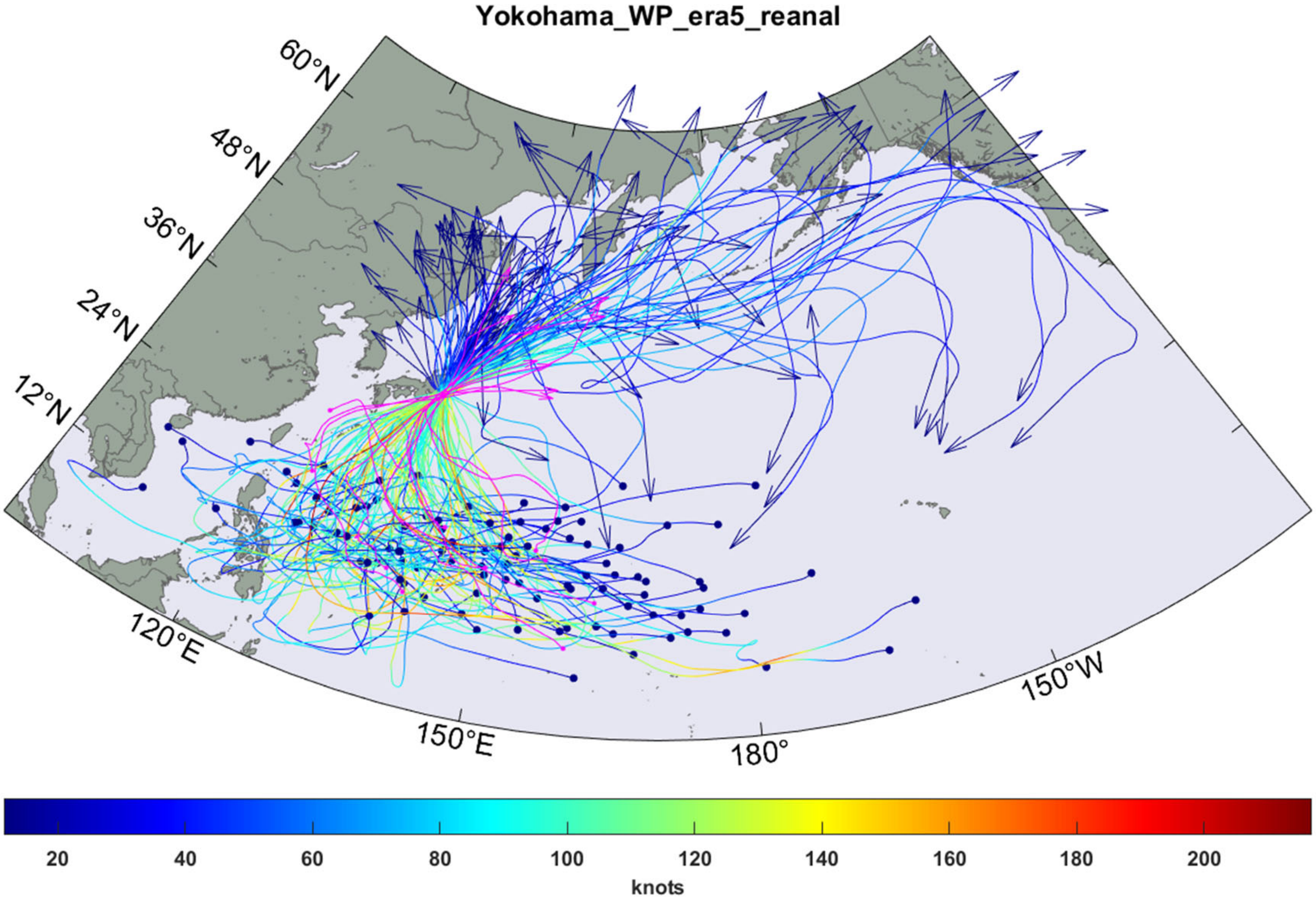


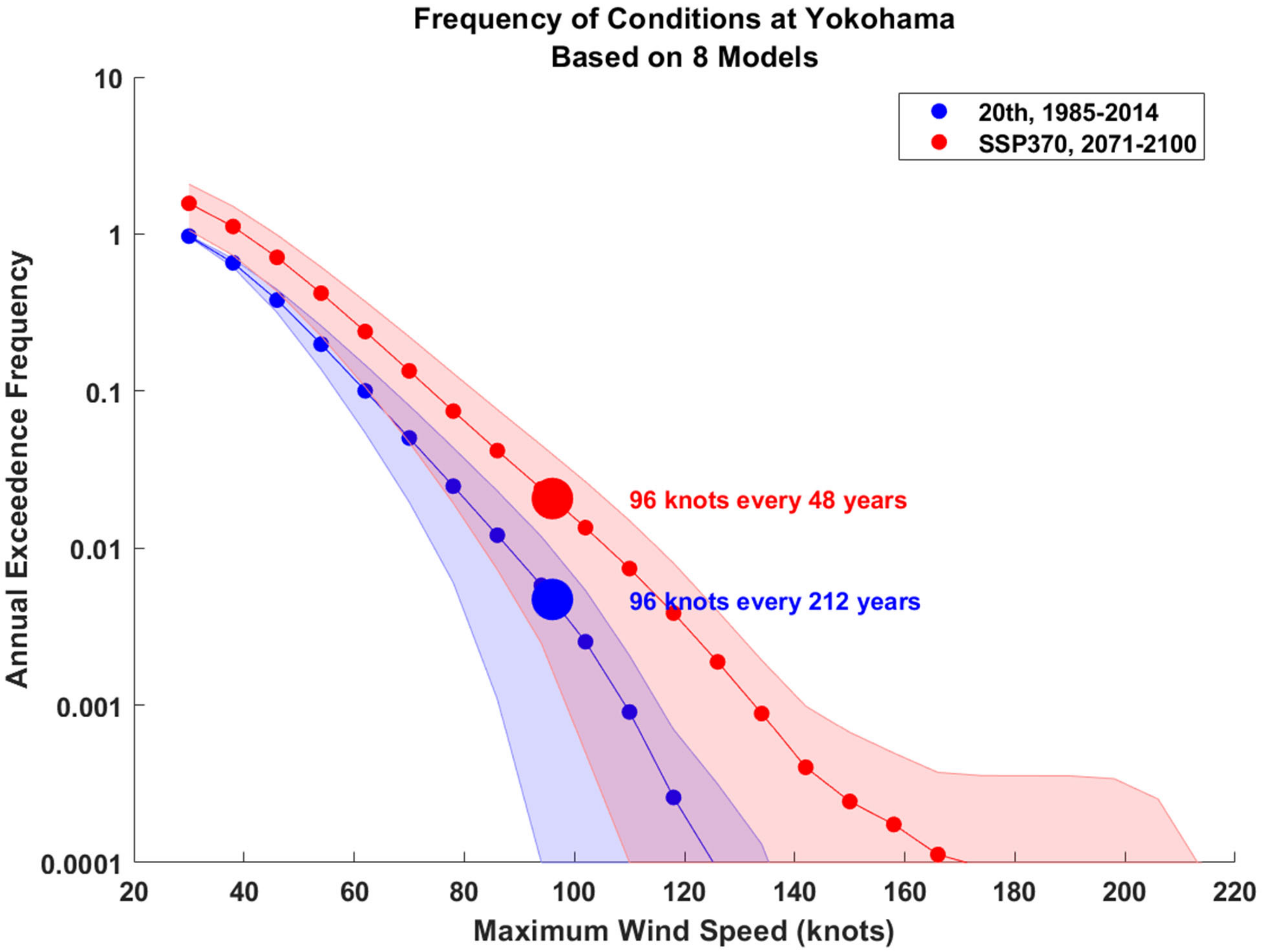
All events within 150 km of Yokohama_WP_era5_reanal
Annual Exceedence Frequency
Maximum Wind Speed (knots)
37 best tracks, 1985 to 2014
2730 synthetic tracks
90% of BT-size subsamples
0
0.2
0.4
0.6
0.8
1
1.2
1.4
40
60
80
100
120
140

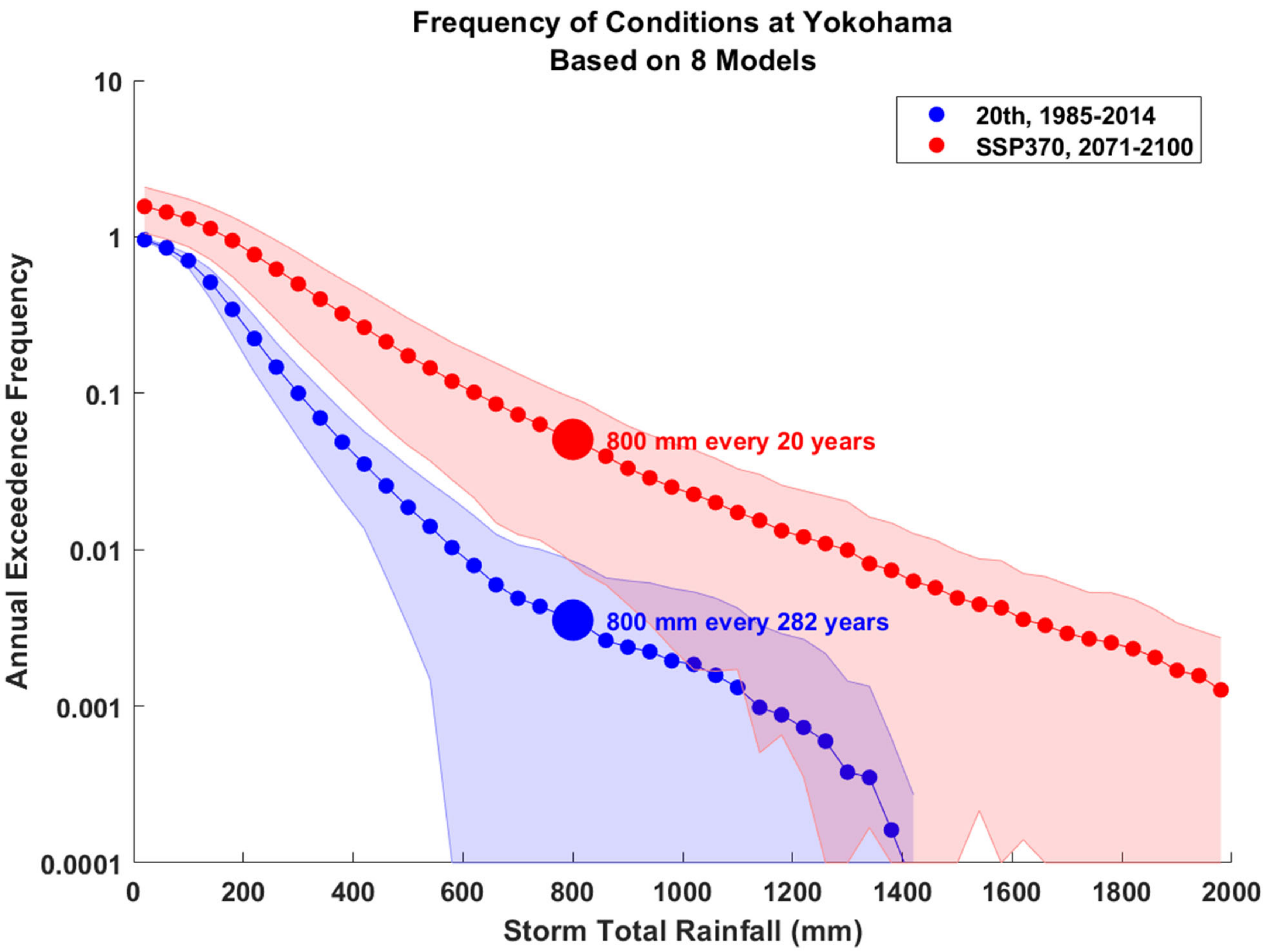
Top 100 out of 3,000 TCs passing within 150 km of Yokohama, downscaled from ERA-5 reanalyses



Same but with top 10 typhoons passing within 150 km of Yokohama, 1985-2014 superimposed (magenta curves)



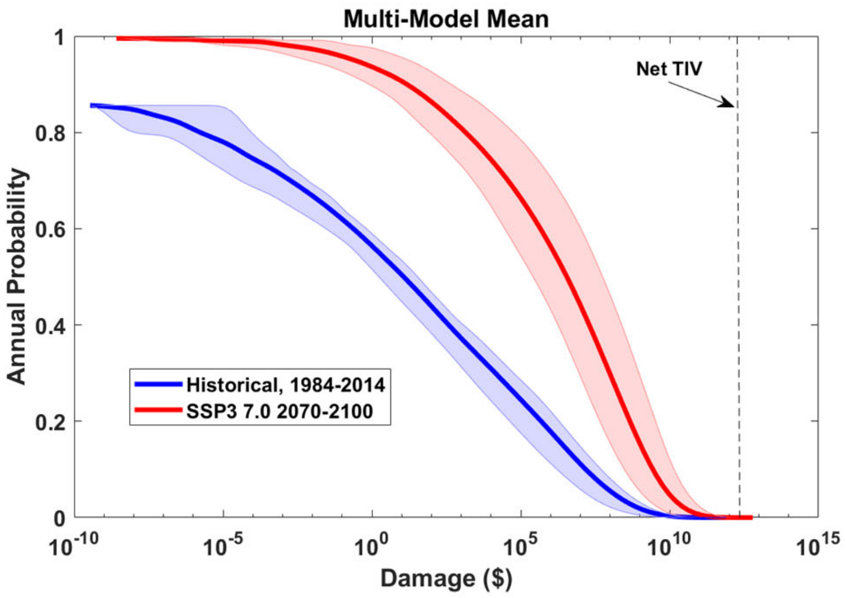

Frequency of Conditions at Yokohama
Based on 8 Models
● 20th, 1985-2014
● SSP370, 2071-2100
96 knots every 48 years
96 knots every 212 years
Annual Exceedence Frequency
10
1
0.1
0.01
0.001
0.0001
20
40
60
80
100
120
140
160
180
200
220
Maximum Wind Speed (knots)

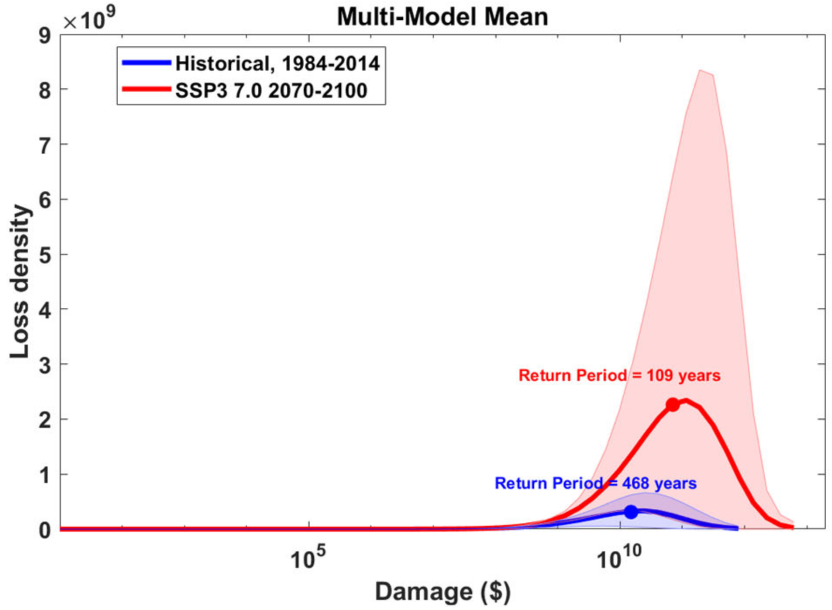

Frequency of Conditions at Yokohama
Based on 8 Models
Annual Exceedence Frequency
10
1
0.1
0.01
0.001
0.0001
Storm Total Rainfall (mm)
0
200
400
600
800
1000
1200
1400
1600
1800
2000
● 20th, 1985-2014
● SSP370, 2071-2100
800 mm every 20 years
800 mm every 282 years

Use synthetic tracks to estimate current and future TC economic risk

Procedure:

- Generate 6,200 synthetic hurricane events affecting eastern U.S. from each of 8 global climate models for two period of time: 1985 – 2014 and 2071 – 2100 (SSP3 7.0)
- Calculate peak wind speed at each zip code centroid for each hurricane event
- Use damage function to convert peak with to percentage of insured value destroyed
- Apply to TIV at each of the 12,968 zip codes and sum over them to estimate total loss to insurance form





Median annual loss (2-year return period)

1984 – 2014: **$ 12** ($2 – $34)

2070 – 2100: **$ 3.5 million** ($260 k – $56 million)

Average annual loss:

1984 – 2014: **$ 536 million** ($108 million – $1.25 billion)

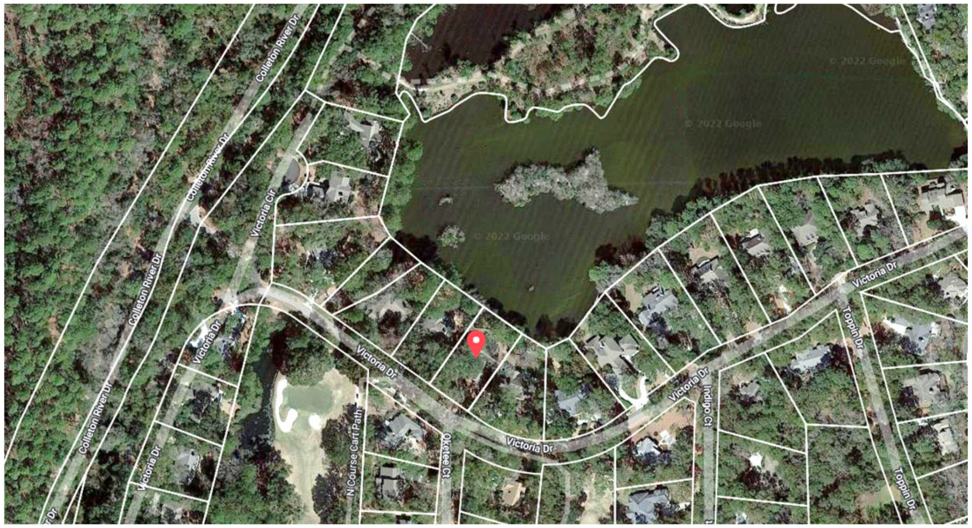
2070 – 2100: **$ 4.1 billion** ($590 million – $13.7 billion)

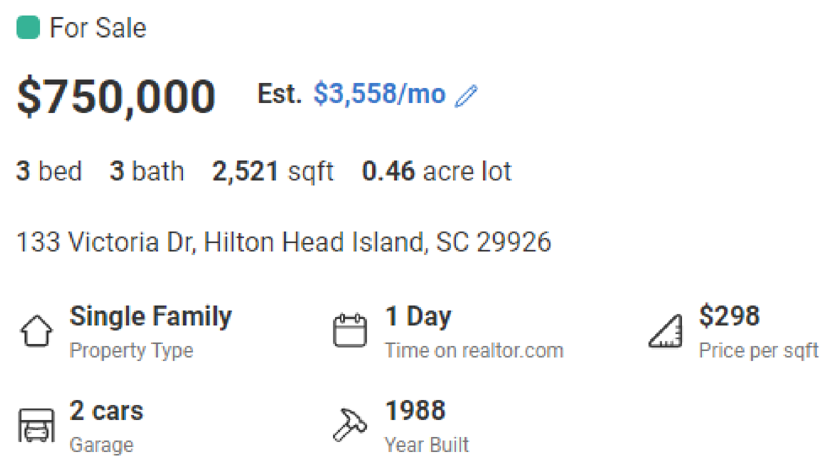
Annual average loss strongly dominated by VERY rare events!
These will not be evident in historical records

Making Risk Personal:

All Climate Change is Local!

Property currently for sale in Hilton Head, SC
Realtor.com




🟩 For Sale

$750,000 Est. $3,558/mo

3 bed **3** bath **2,521** sqft **0.46** acre lot

133 Victoria Dr, Hilton Head Island, SC 29926

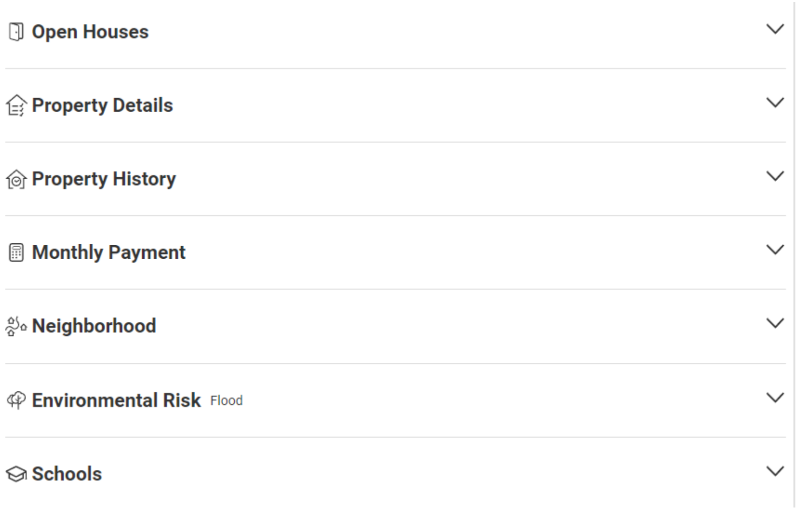
Single Family Property Type

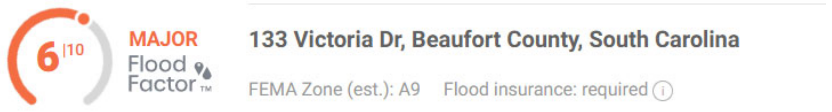
1 Day Time on realtor.com

$298 Price per sqft

2 cars Garage

1988 Year Built

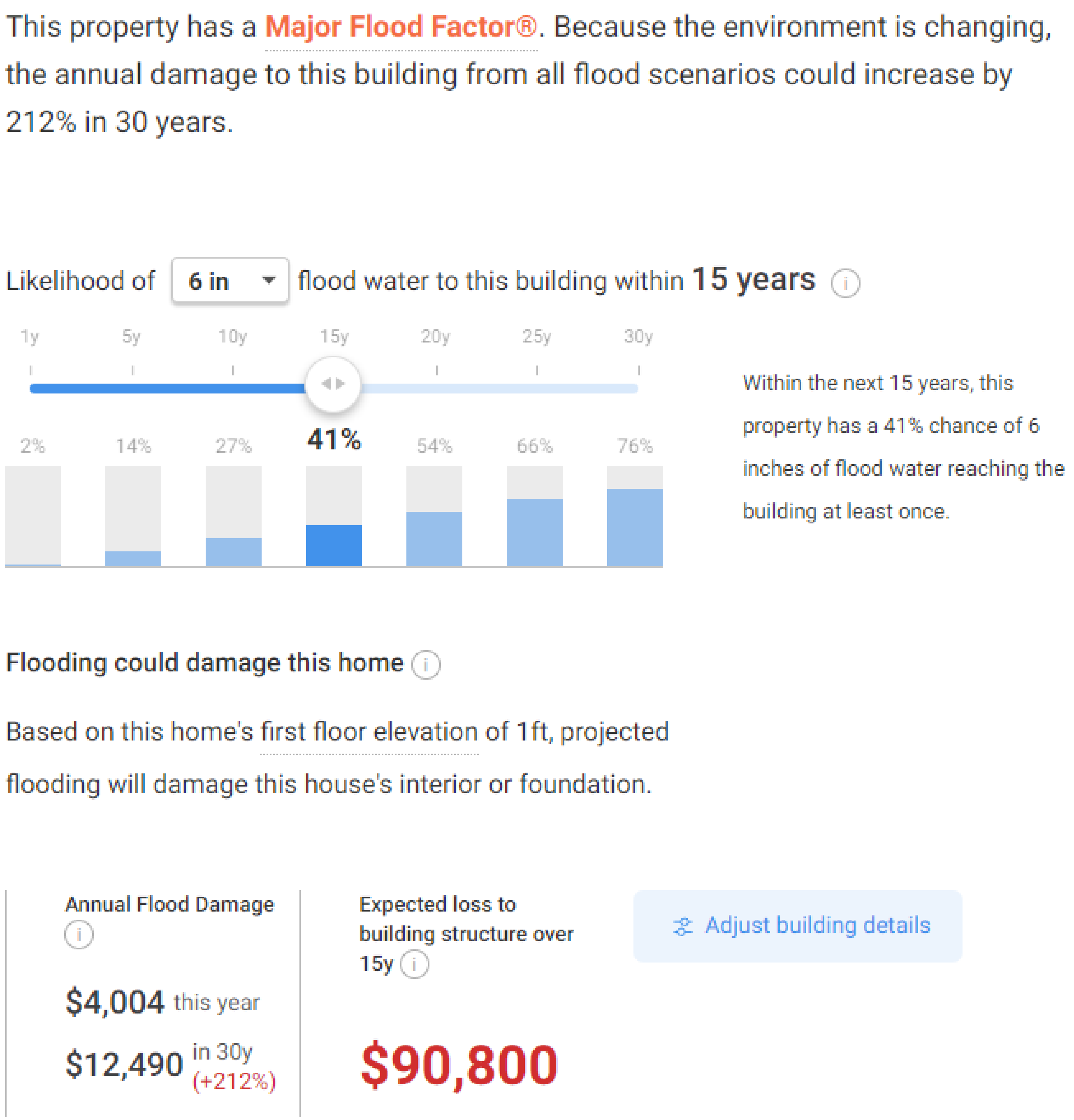




133 Victoria Dr, Beaufort County, South Carolina

FEMA Zone (est.): A9 Flood insurance: required

Work of First Street Foundation



This property has a **Major Flood Factor®**. Because the environment is changing, the annual damage to this building from all flood scenarios could increase by 212% in 30 years.

Likelihood of 6 in ▾ flood water to this building within **15 years** ⓘ

Within the next 15 years, this property has a 41% chance of 6 inches of flood water reaching the building at least once.

Flooding could damage this home ⓘ

Based on this home's first floor elevation of 1ft, projected flooding will damage this house's interior or foundation.

Annual Flood Damage ⓘ

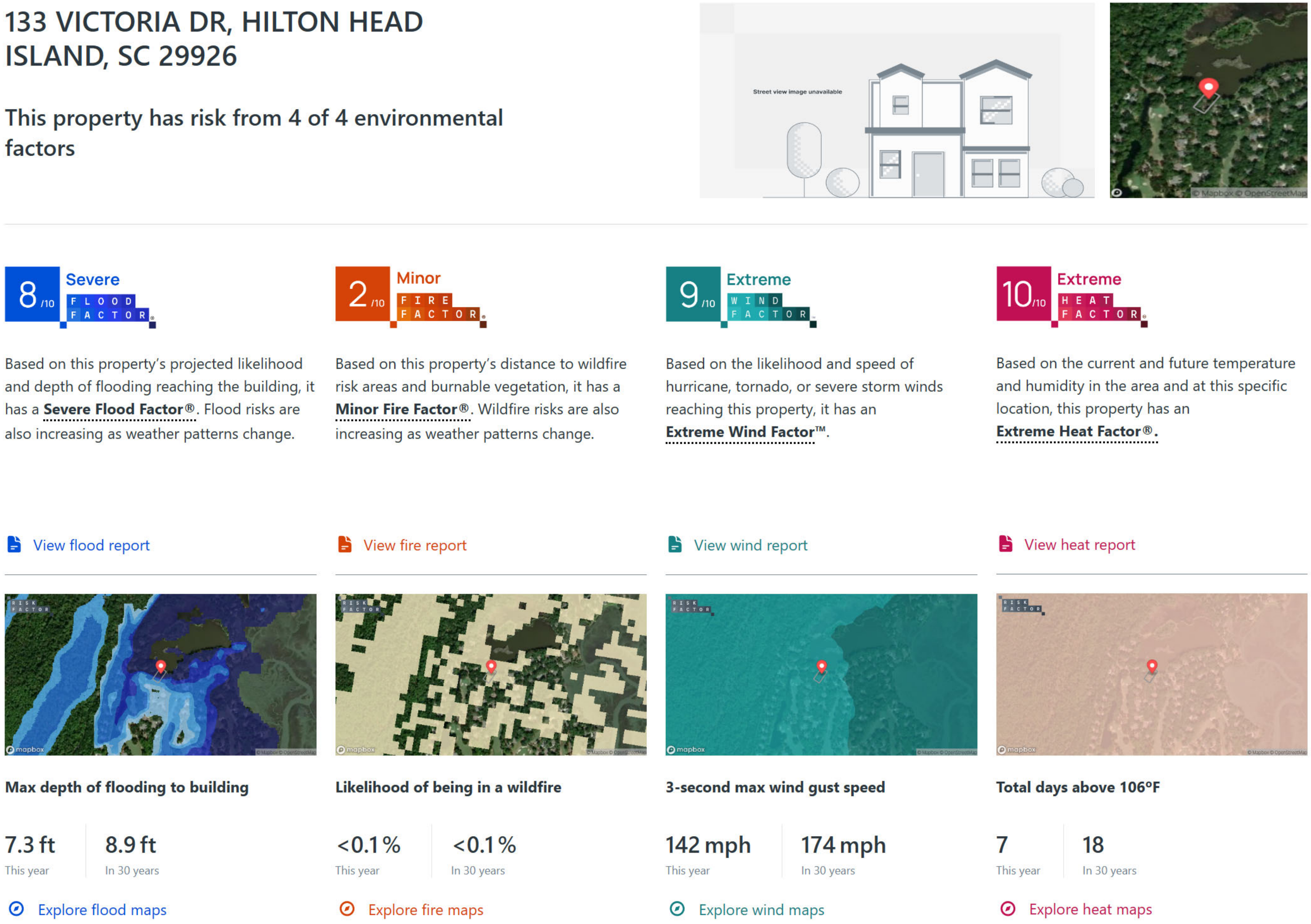
$4,004 this year

$12,490 in 30y (+212%)

Expected loss to building structure over 15y ⓘ

$90,800

Type address into RiskFactor (https://riskfactor.com)



133 VICTORIA DR, HILTON HEAD ISLAND, SC 29926

This property has risk from 4 of 4 environmental factors

8 /10 **Severe** FLOOD FACTOR

Based on this property's projected likelihood and depth of flooding reaching the building, it has a **Severe Flood Factor®**. Flood risks are also increasing as weather patterns change.

View flood report

Max depth of flooding to building

7.3 ft This year | 8.9 ft In 30 years

Explore flood maps

2 /10 **Minor** FIRE FACTOR

Based on this property's distance to wildfire risk areas and burnable vegetation, it has a **Minor Fire Factor®**. Wildfire risks are also increasing as weather patterns change.

View fire report

Likelihood of being in a wildfire

<0.1% This year | <0.1% In 30 years

Explore fire maps

9 /10 **Extreme** WIND FACTOR

Based on the likelihood and speed of hurricane, tornado, or severe storm winds reaching this property, it has an **Extreme Wind Factor™**.

View wind report

3-second max wind gust speed

142 mph This year | 174 mph In 30 years

Explore wind maps

10 /10 **Extreme** HEAT FACTOR

Based on the current and future temperature and humidity in the area and at this specific location, this property has an **Extreme Heat Factor®**.

View heat report

Total days above 106°F

7 This year | 18 In 30 years

Explore heat maps

Take-Away Points

- We need to move away from sole dependence on flawed historical data in assessing climate- and weather-related natural hazard risks and embrace advanced physical modeling techniques
- Government, the insurance industry, research laboratories, and institutions of higher education are crucial to this effort
- We can no longer regard climate change as a problem for the future; it has already tangibly affected important risks, e.g. Hurricane Harvey's rainfall was ~3 times more likely in 2017 than in 1970
- There is a large gap between current practice and what is possible and desirable. Let's fill it.