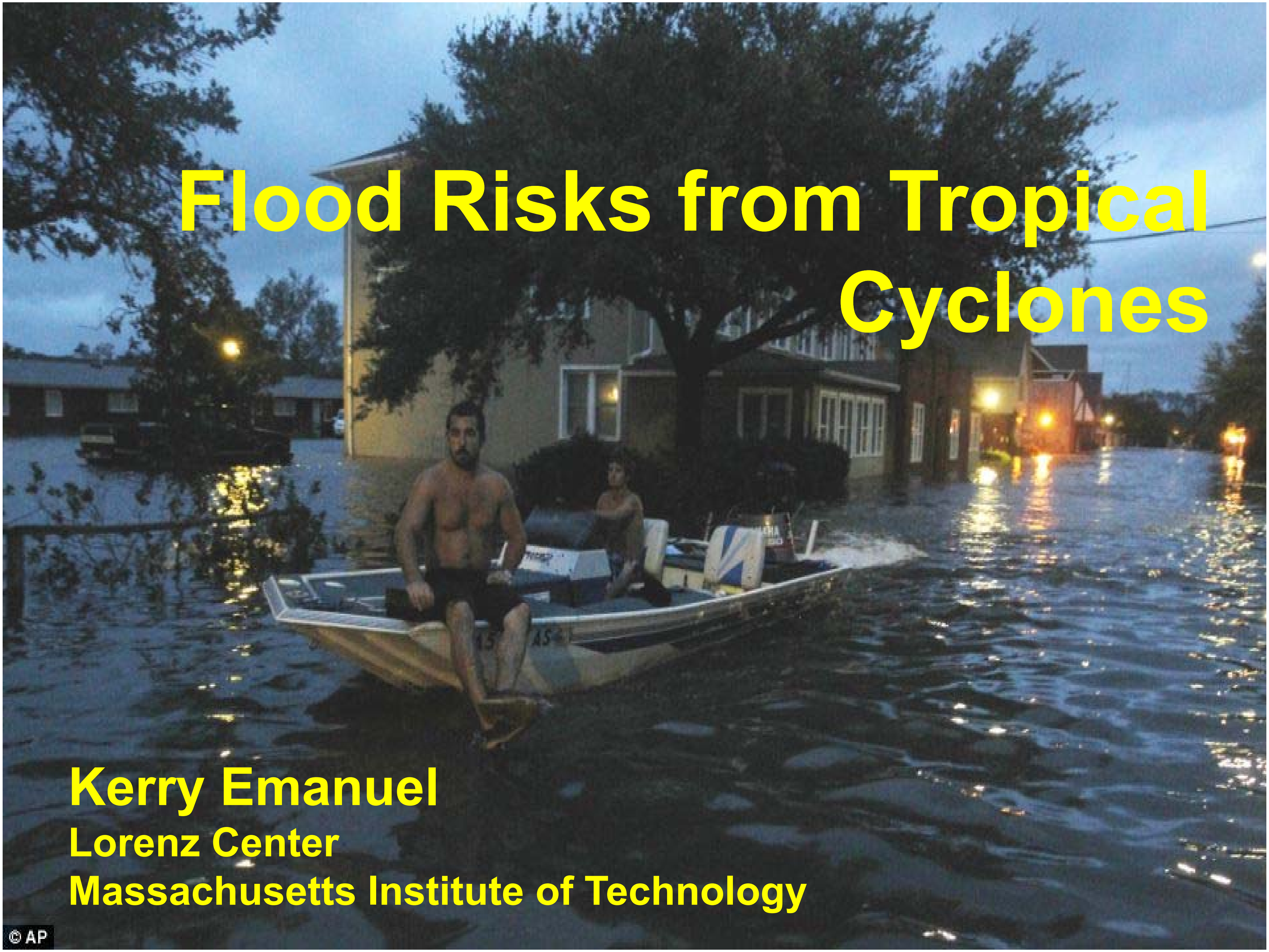
# Flood Risks from Tropical Cyclones



**Kerry Emanuel**
**Lorenz Center**
**Massachusetts Institute of Technology**

# Program

- **Brief Overview of Tropical Cyclone Flooding**
- **Assessment of Tropical Cyclone Flood Risk**
- **How will Global Warming Affect Tropical Cyclone Flood Risk?**

# The Global Hurricane Hazard

- About 10,000 deaths per year
- $700 Billion 2015 U.S. Dollars in Damages Annually

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

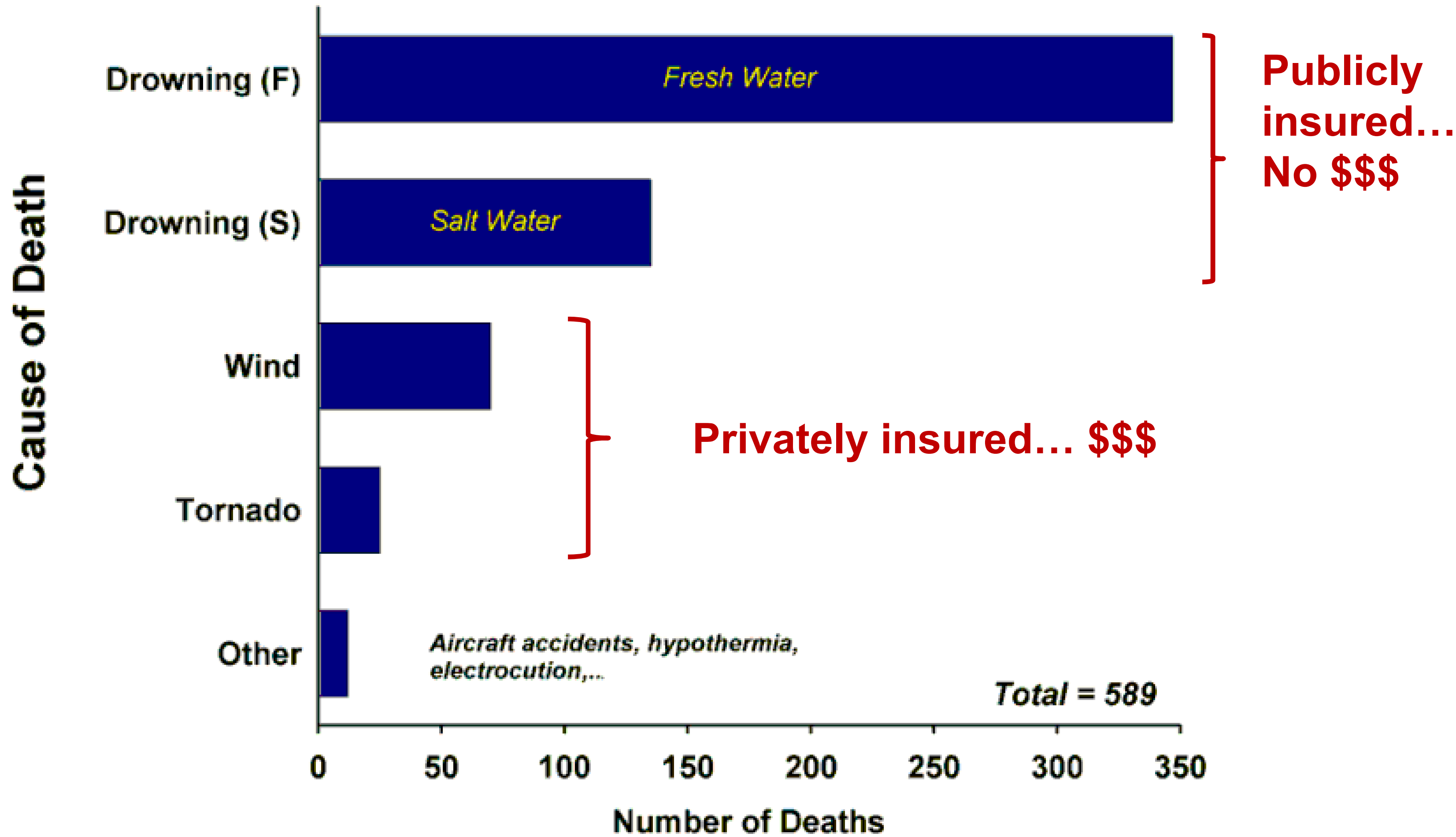
# Hurricane Risks:

- 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.

# Rainfall from Tropical Cyclones

Between 1970 and 1999, nearly 60% of the deaths due to floods associated with U.S. tropical cyclones occurred inland from the storm's landfall.

Over three-fourths (78%) of children killed by tropical cyclones drowned in freshwater floods.

-- NOAA

# Two Particularly Deadly Tropical Cyclone Flooding Events

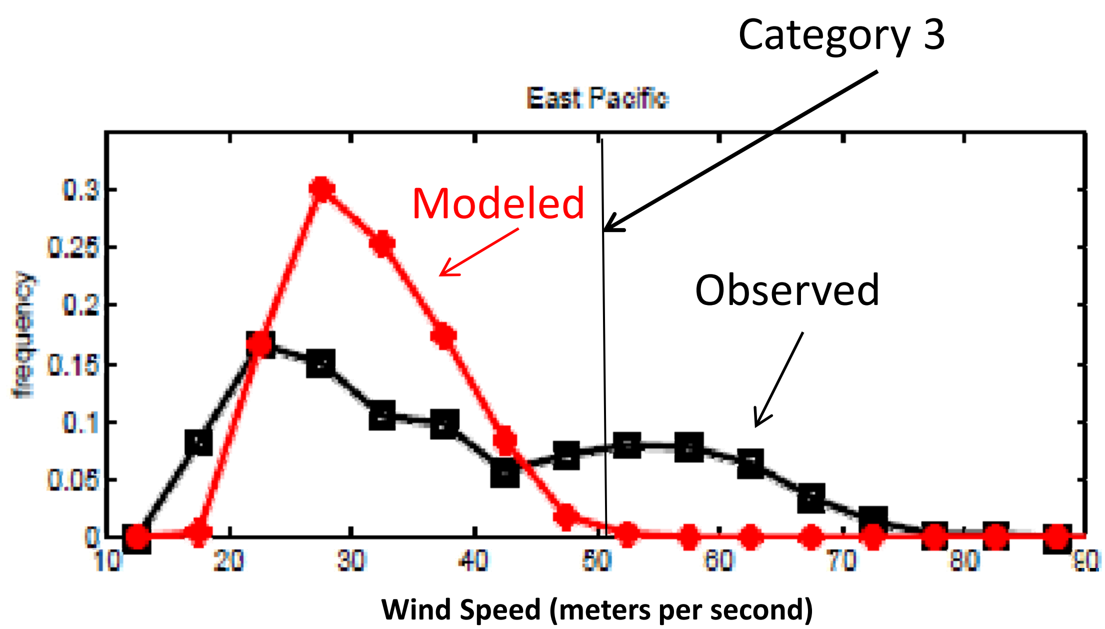
- Bhola Cyclone of 1970, East Pakistan (now Bangladesh): **~500,000 deaths** mostly from **storm surge**. Deadliest tropical cyclone on record
- Hurricane Mitch, Central America, 1998: **19,000 fatalities**, almost entirely from freshwater flooding. Second deadliest hurricane in the western hemisphere (after Great Hurricane of 1780)

# Limitations of a strictly statistical approach to hurricane risk assessment

- >50% of all normalized U.S. hurricane damage caused by **top 8 events**, all category 3, 4 and 5
- >90% of all damage caused by storms of category 3 and greater
- Category 3,4 and 5 events are only 13% of total landfalling events; only 30 since 1870
- ∴ ***Landfalling storm statistics are inadequate for assessing hurricane risk***

# Why Not Use Global Climate Models to Simulate Hurricanes?

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



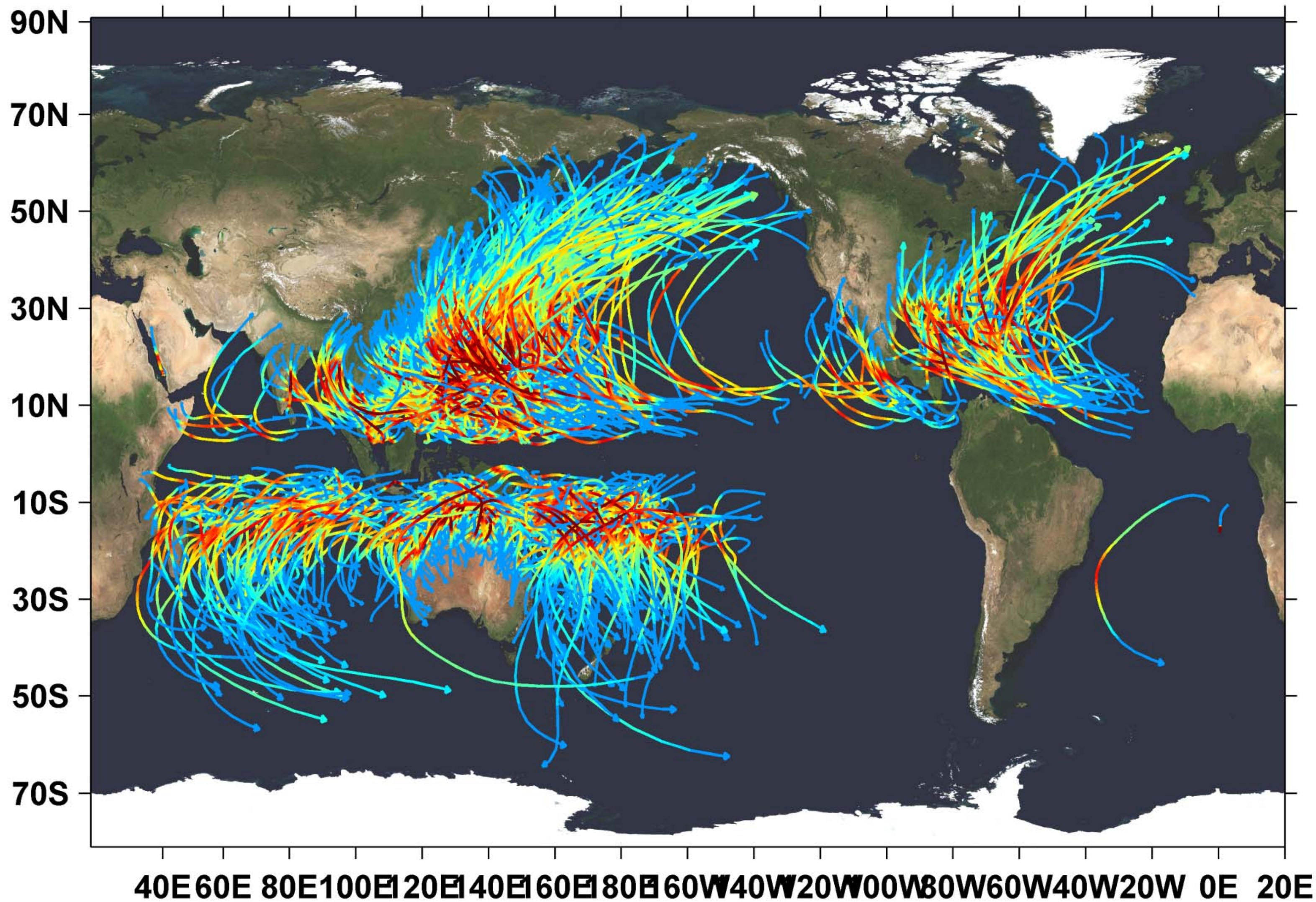

Histograms of Tropical Cyclone Intensity as Simulated by a Global Model with 30 mile grid point spacing. (Courtesy Isaac Held, GFDL)

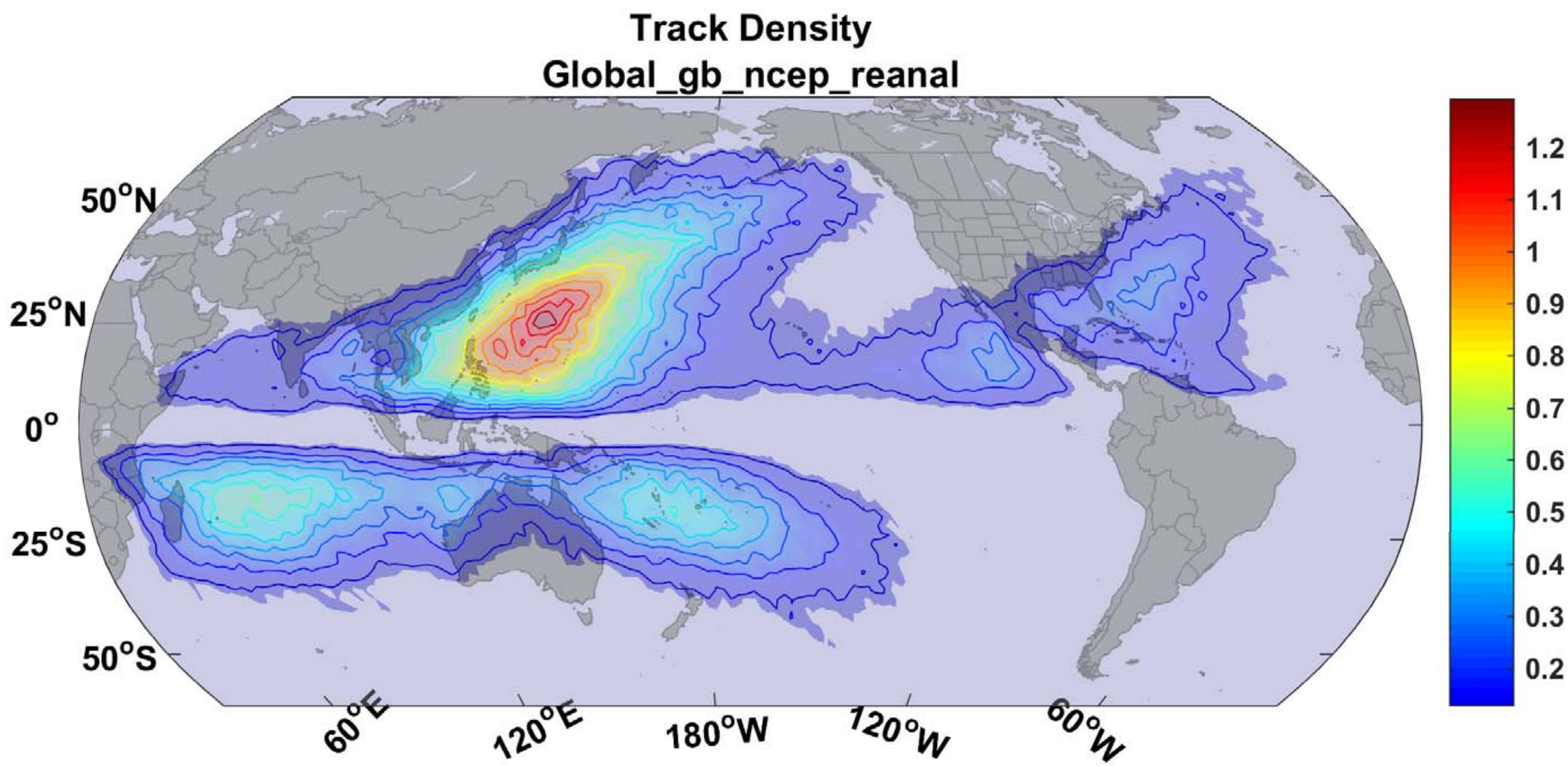
**Global models do not simulate the storms that cause destruction**

Approach:

Embed highly detailed computational hurricane models in large-scale conditions produced by climate analyses or climate models. Generate 1000-100,000 events

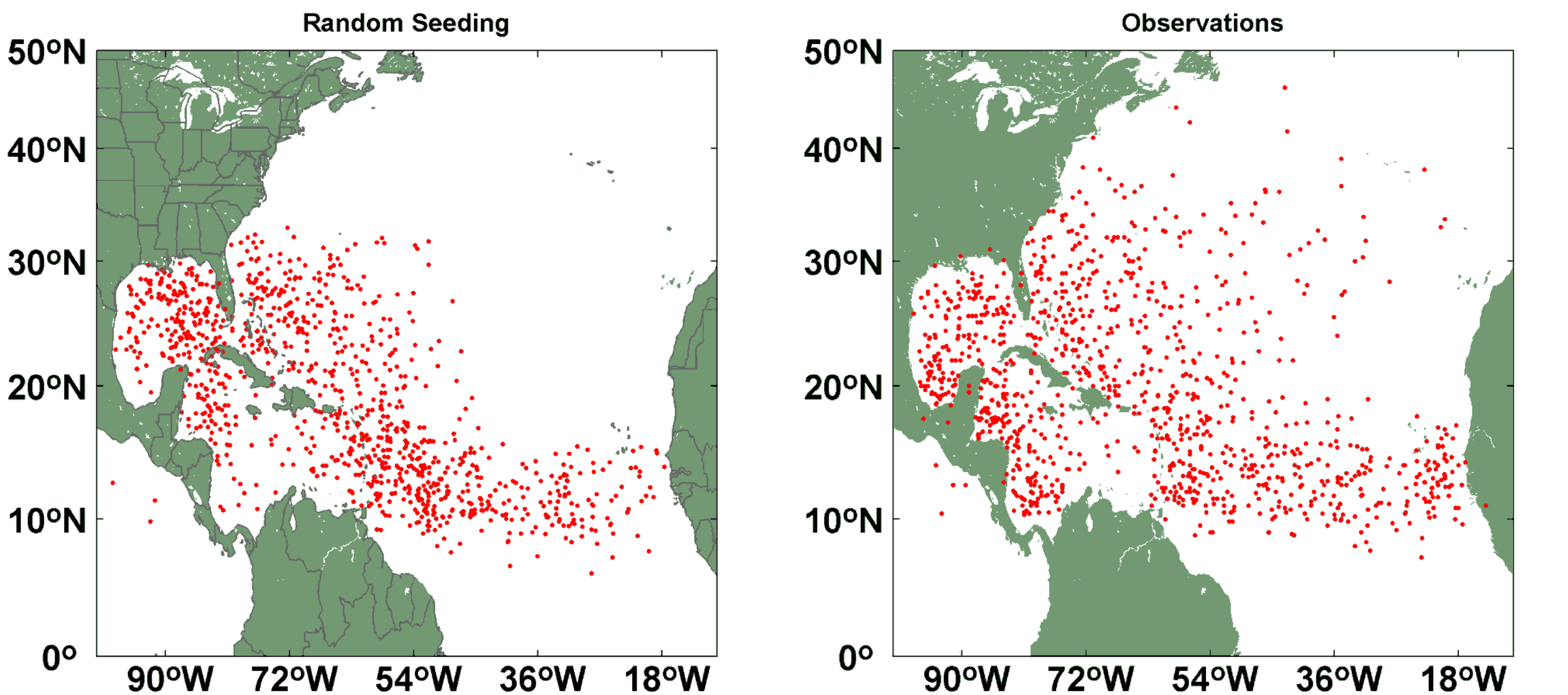
ERA40, 1000 Tracks

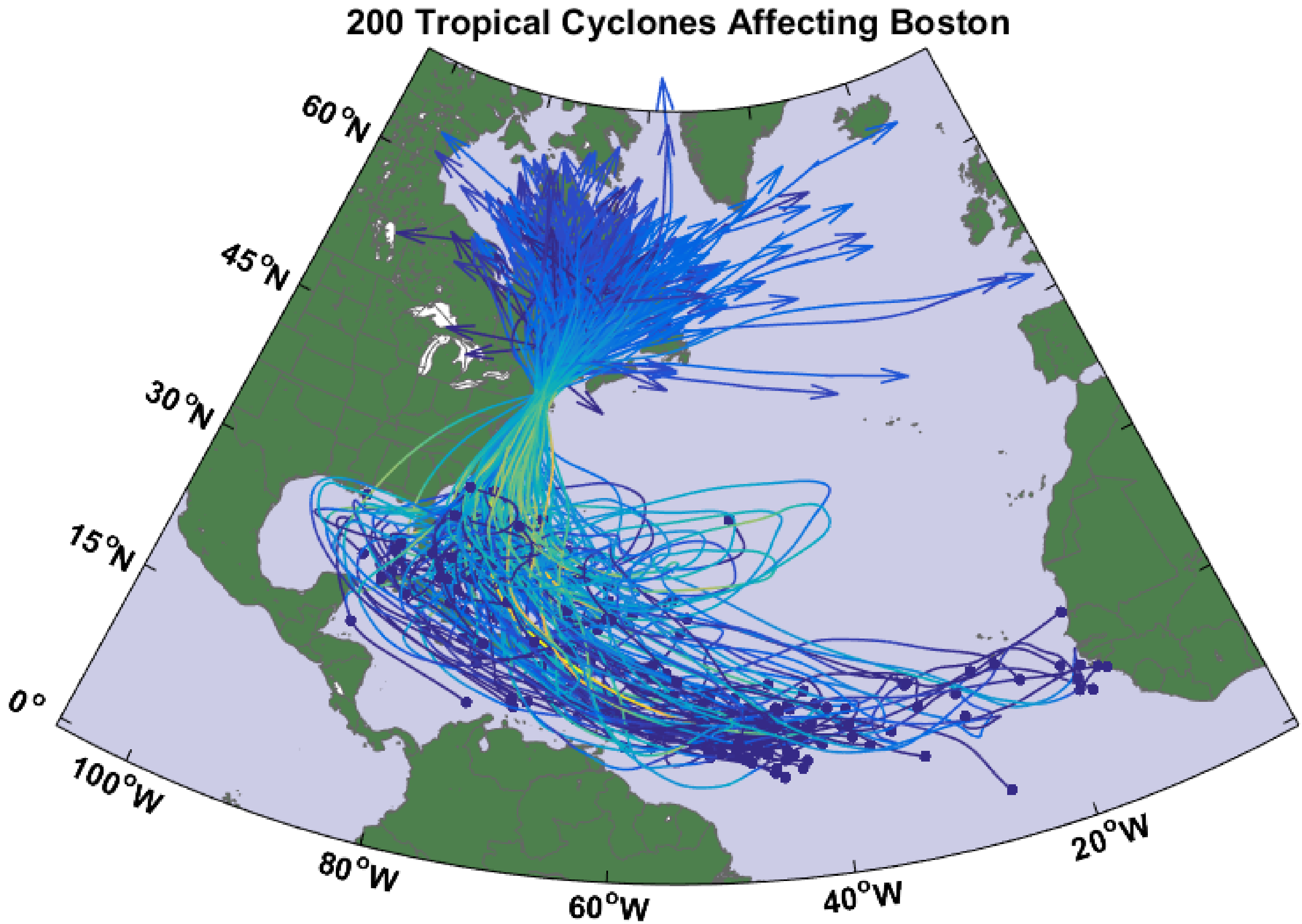


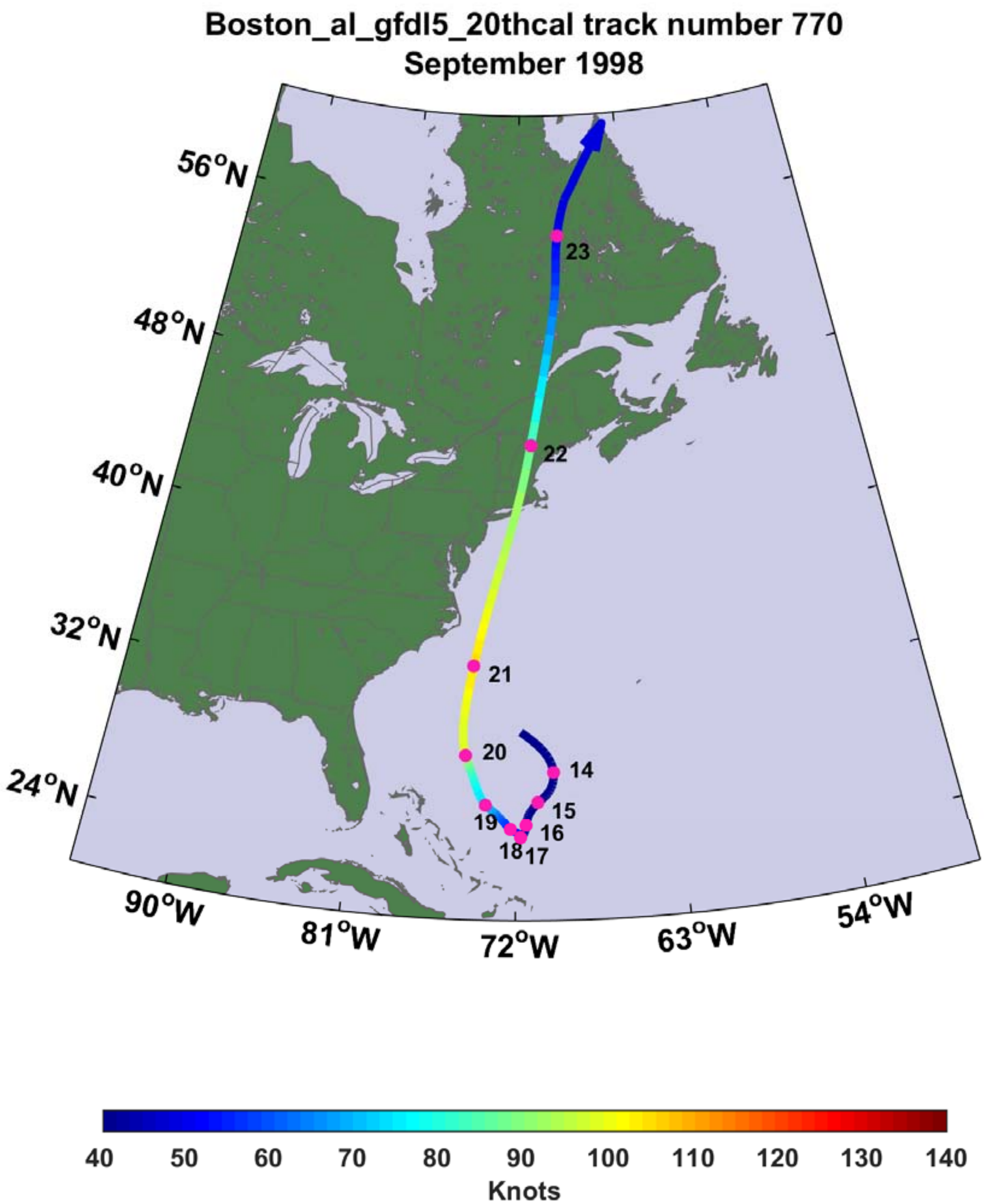


Track Density
Global_gb_ncep_reanal
50°N
25°N
0°
25°S
50°S
60°E
120°E
180°W
120°W
60°W
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2

# Comparison of Genesis Locations with Observations

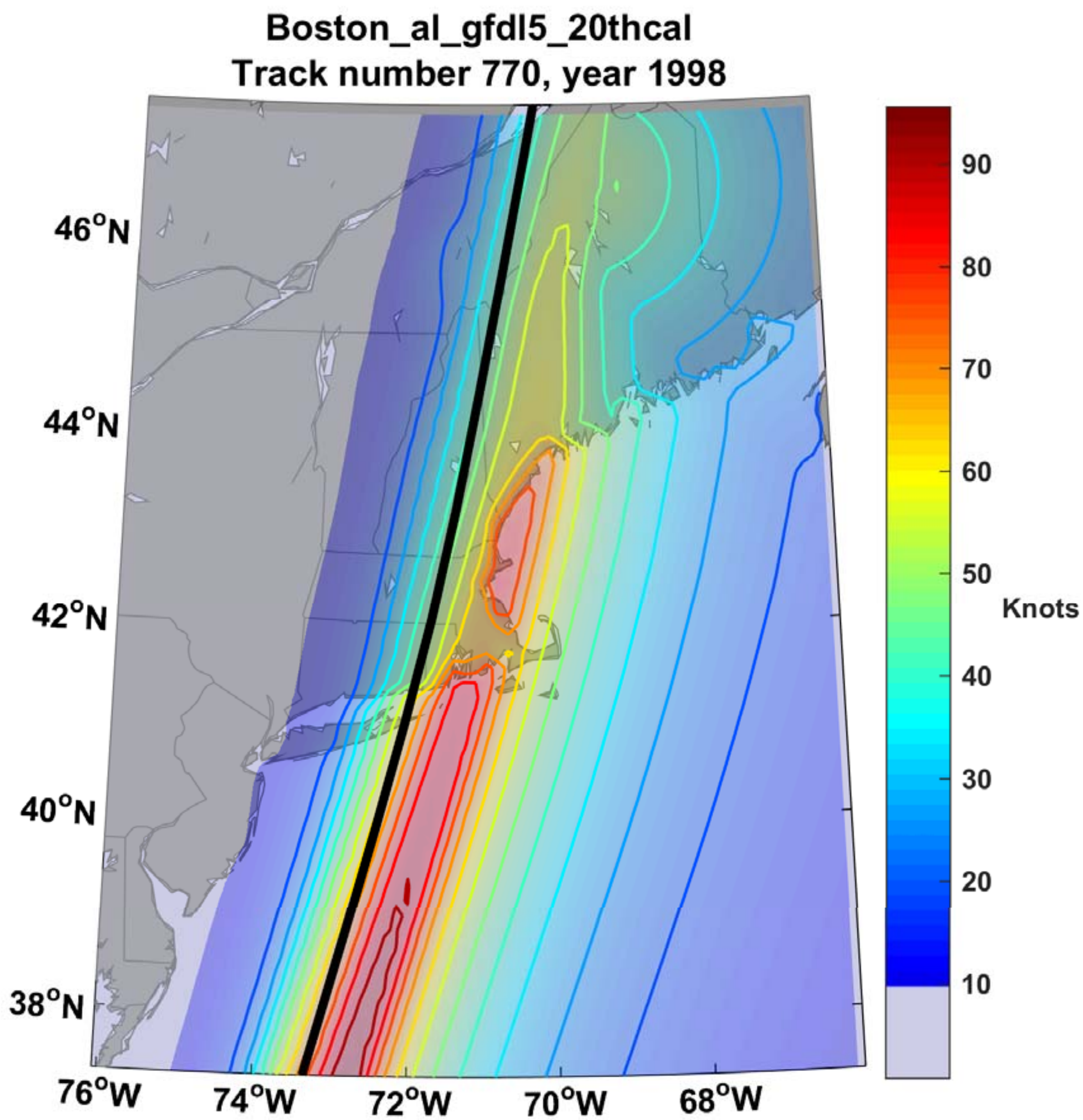



200 Tropical Cyclones Affecting Boston
60°N
45°N
30°N
15°N
0°
100°W
80°W
60°W
40°W
20°W

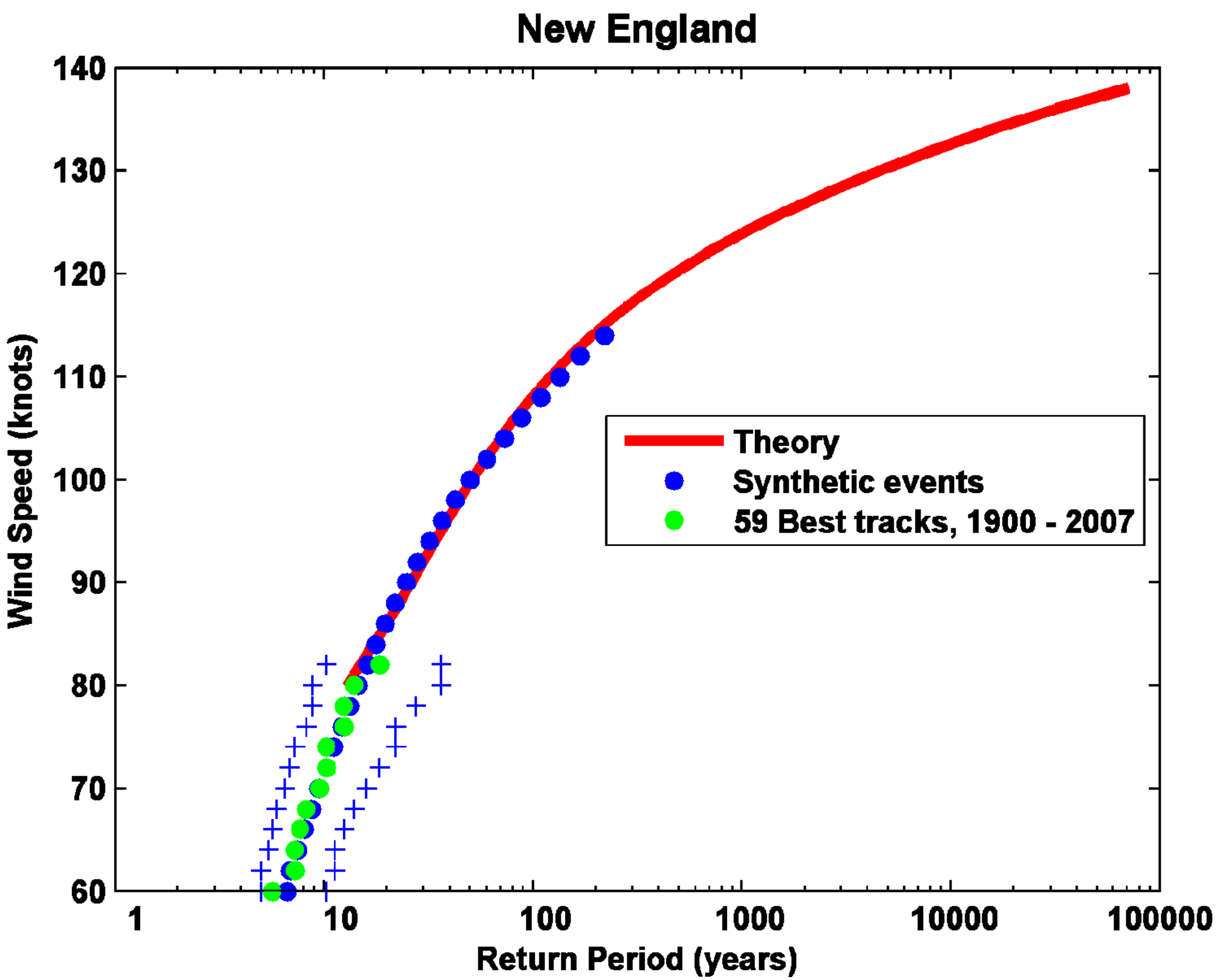



Example of strong hurricane affecting Boston

# Wind Swath

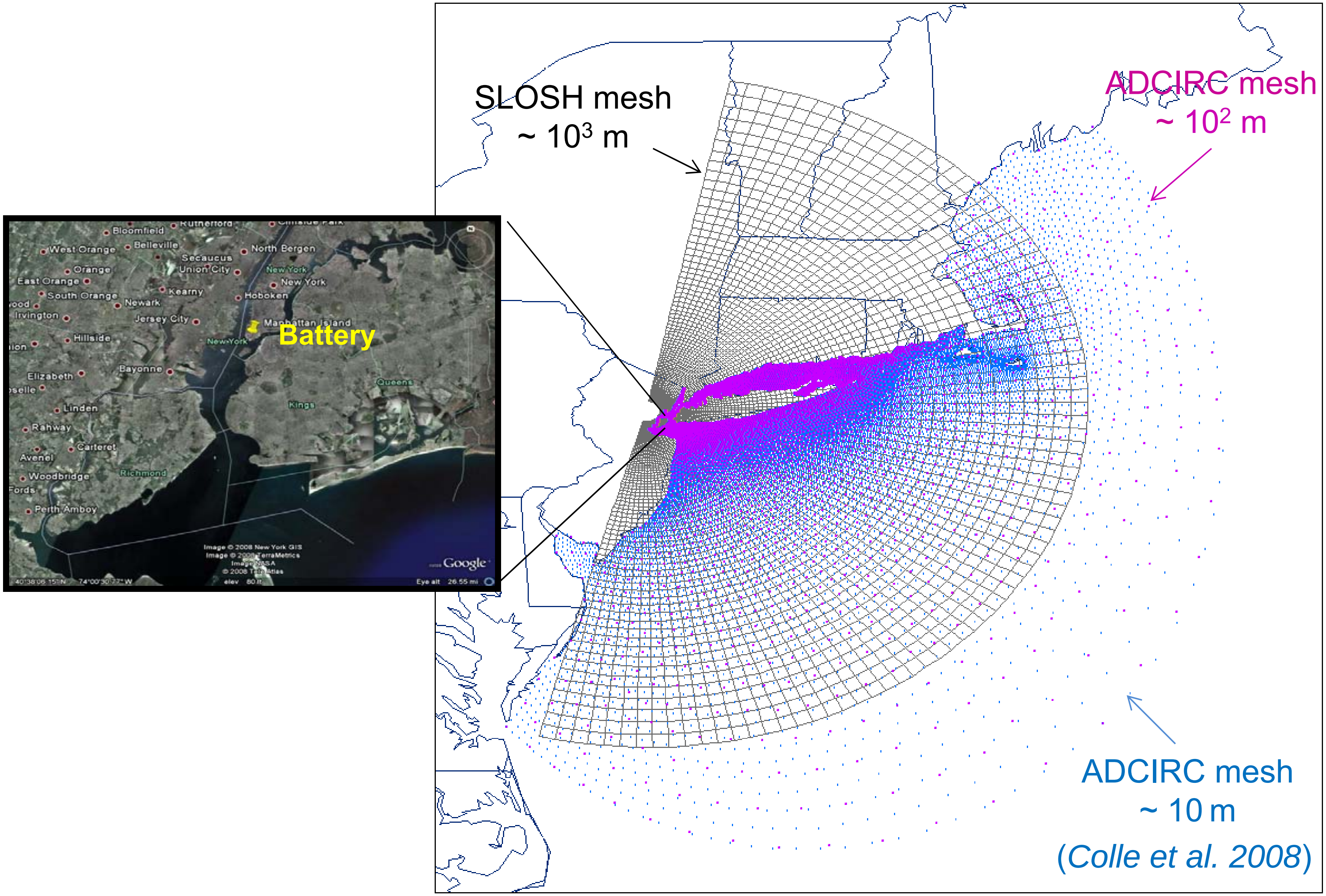

Boston_al_gfdl5_20thcal
Track number 770, year 1998
46°N
44°N
42°N
40°N
38°N
76°W
74°W
72°W
70°W
68°W
90
80
70
60
50
40
30
20
10
Knots

# Return Periods

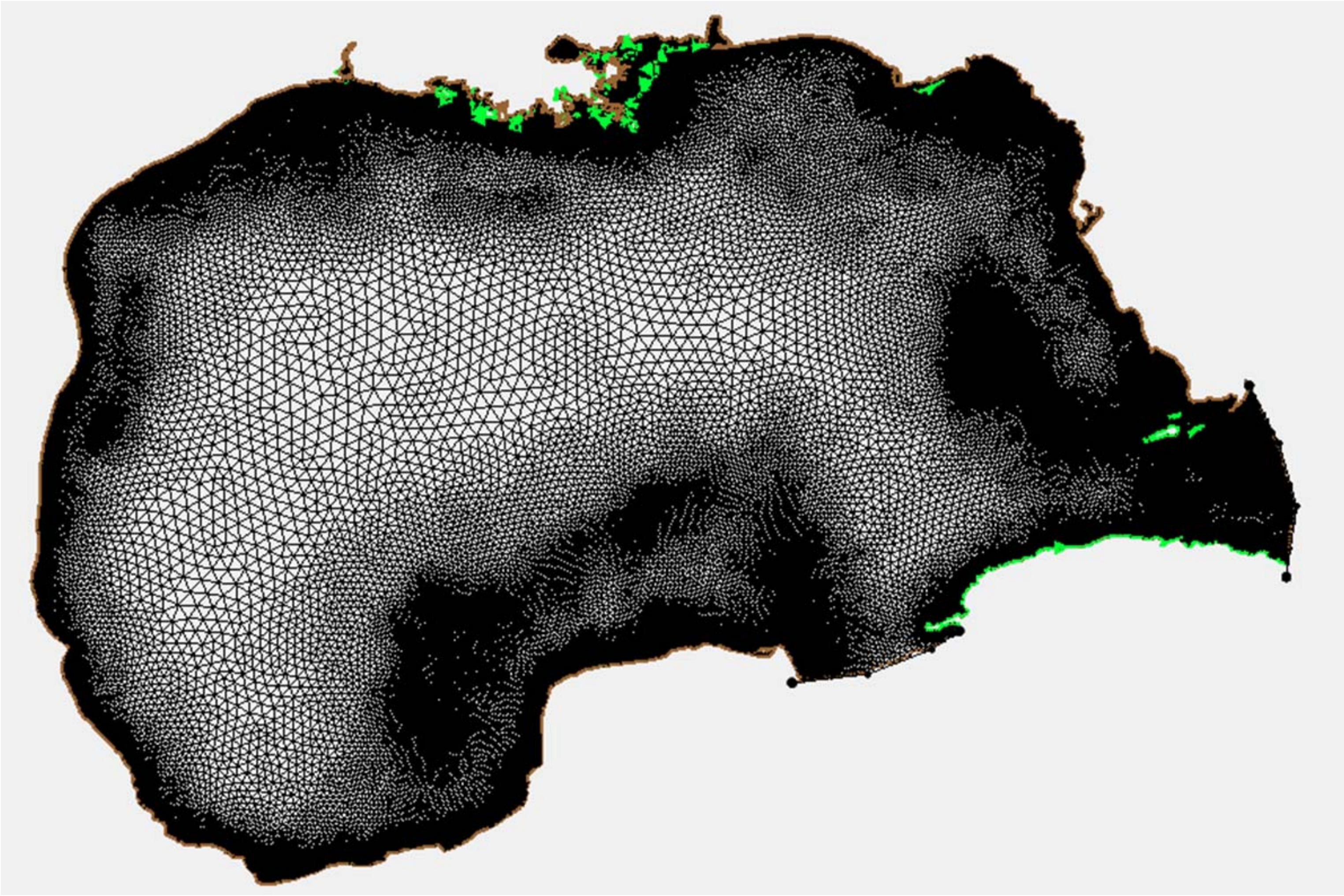



Storm Surge Prediction

# Storm Surge Simulation (Ning Lin)

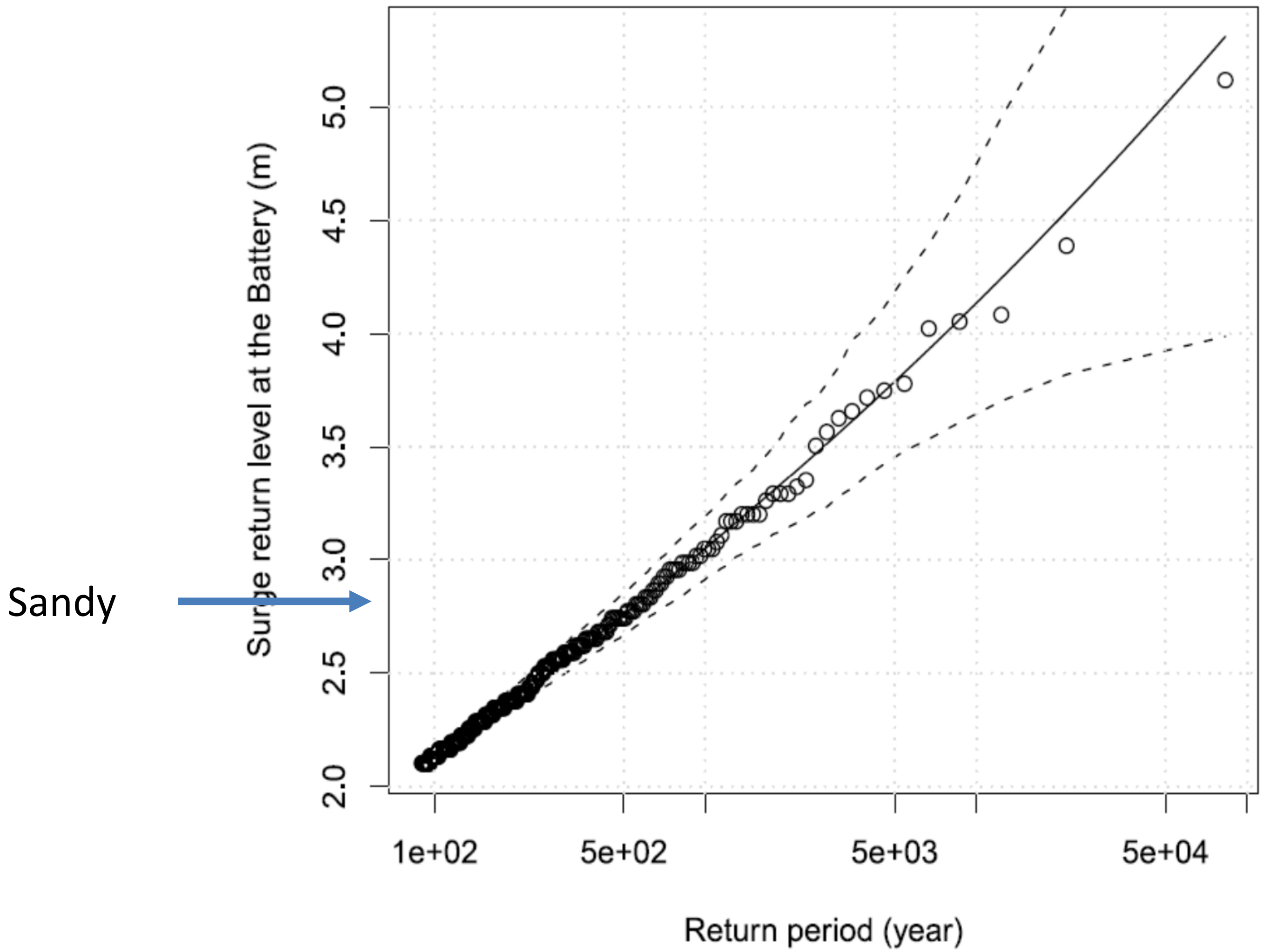


# Computer Simulation of Storm Surges



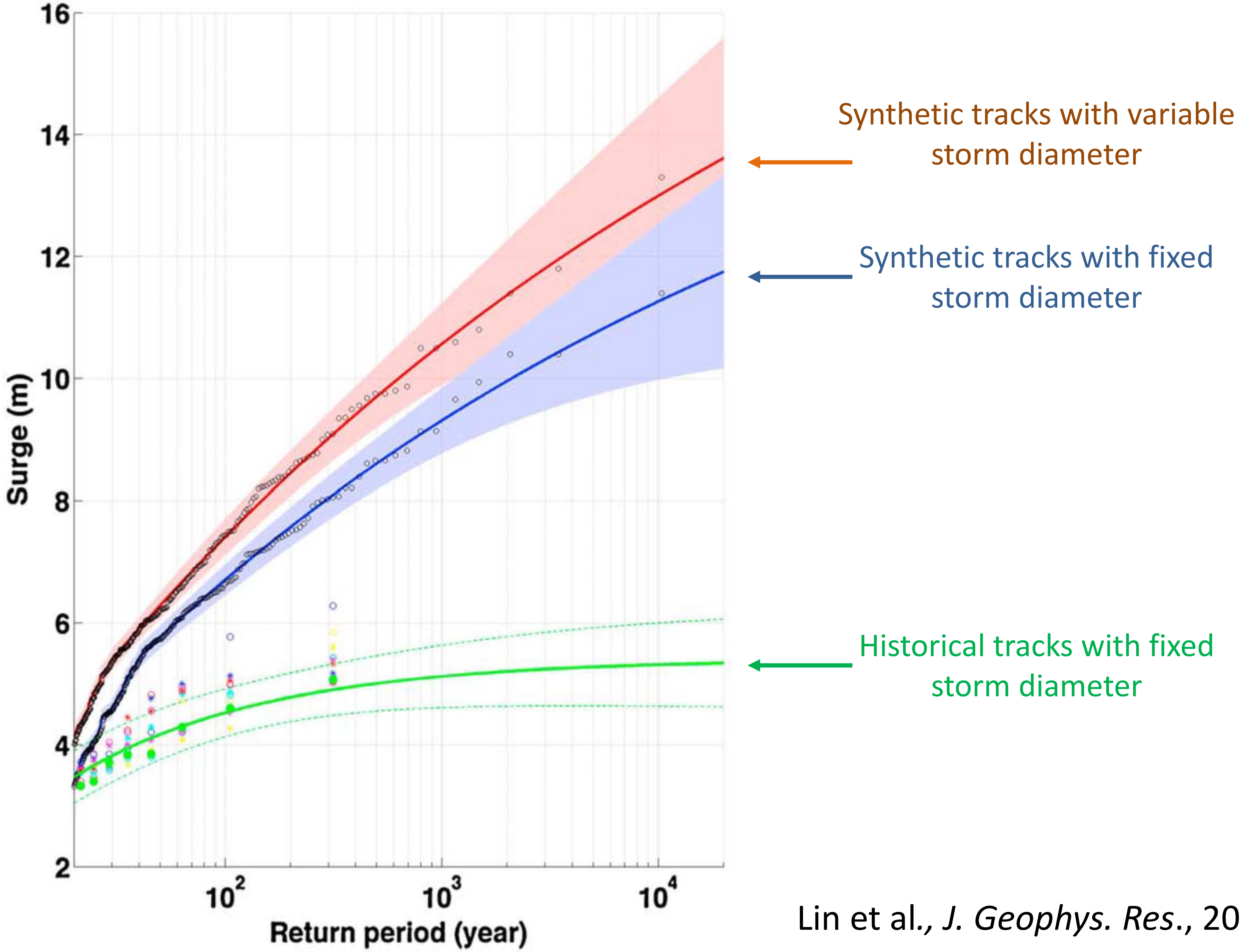
ADCIRC grid for the Gulf of Mexico, courtesy Ning Lin, Princeton

# Surge Return Periods for The Battery, New York



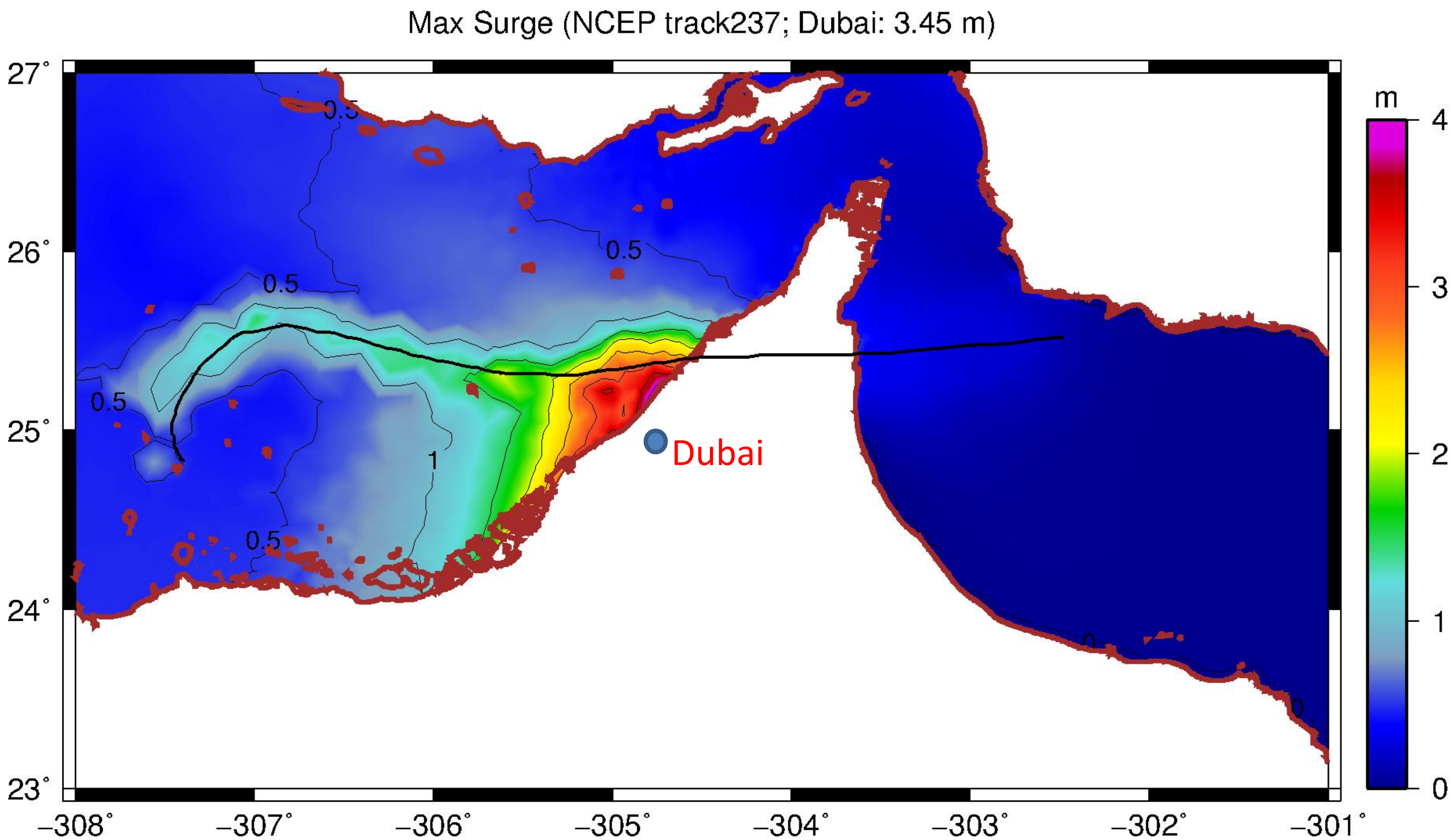

Lin, N., K. A. Emanuel, J. A. Smith, and E. Vanmarcke, 2010: Risk assessment of hurricane storm surge for New York City. *J. Geophys. Res.*, **115**, D18121, doi:10.1029/2009JD013630

# Assessment of Surge Risk, St. Marks, Apalachee Bay




Lin et al., *J. Geophys. Res.*, 2014

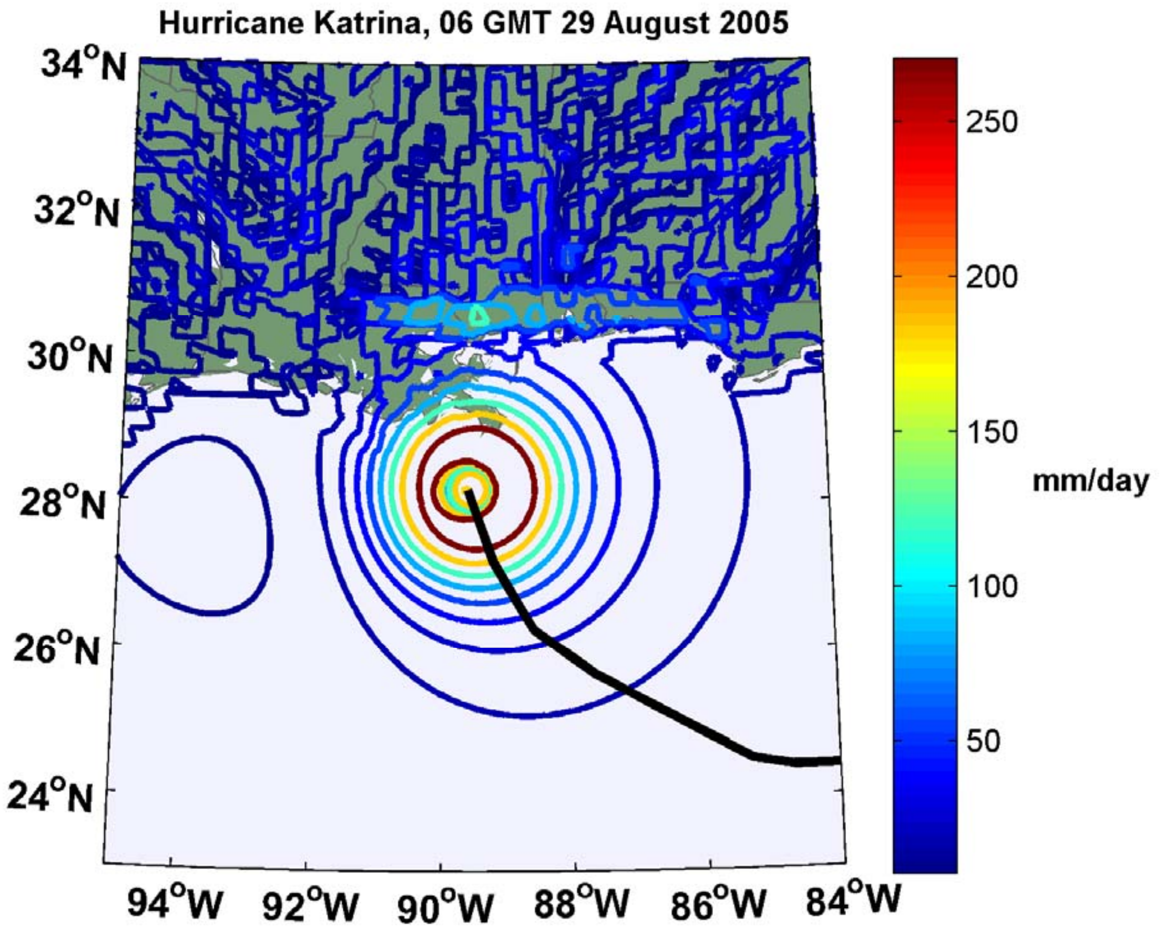
# A Grey Swan: Dubai



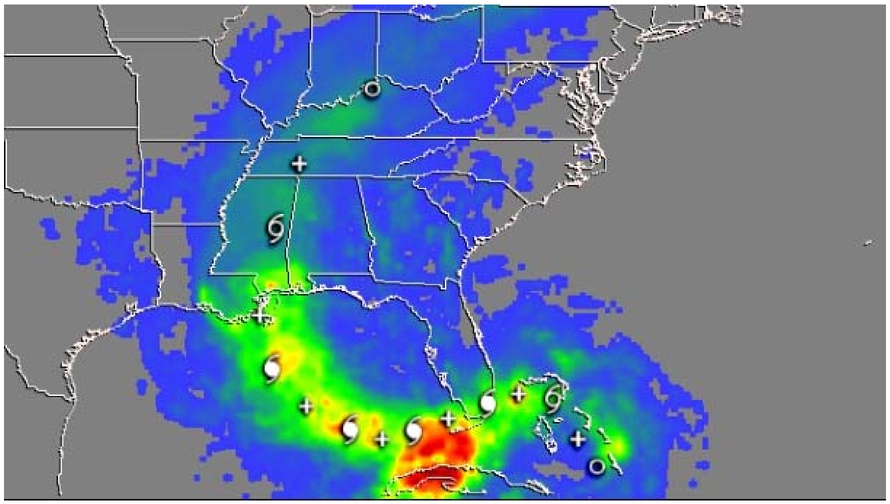

Lin, N. and K. Emanuel, 2015: Grey swan tropical cyclones. *Nature Clim. Change*, doi: 10.1038/NCLIMATE2777

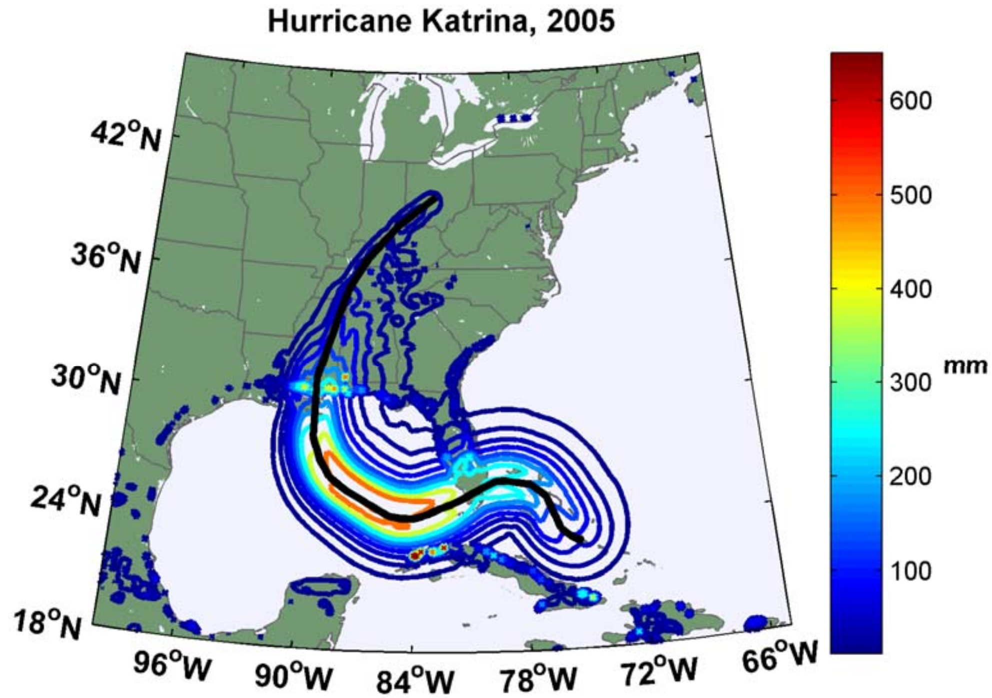
# Rain Prediction

# Rainfall Rates



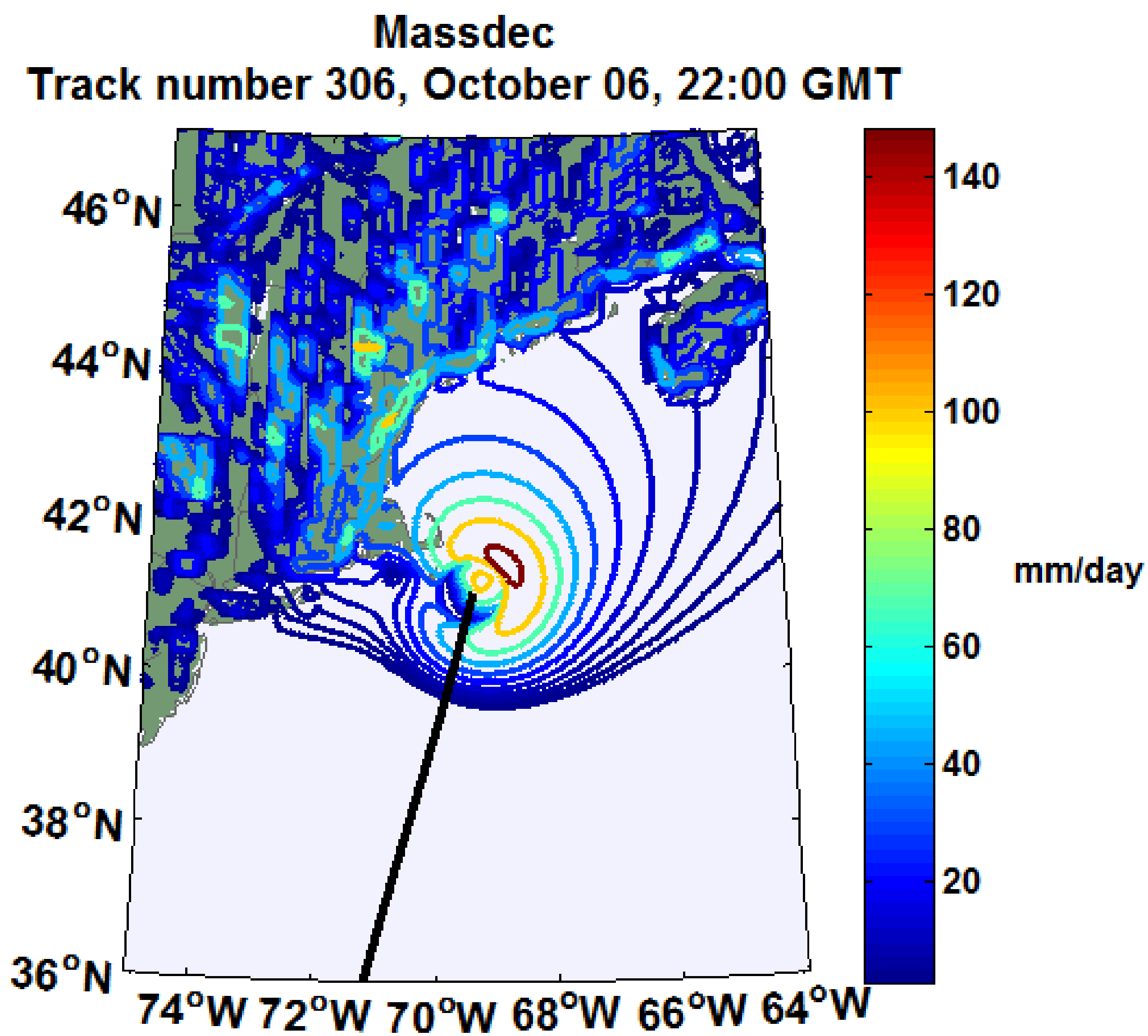

**Instantaneous rainfall rate (mm/day) associated with Hurricane Katrina at 06 GMT 29 August 2005 predicted by the model driven towards Katrina's observed wind intensity along its observed track**



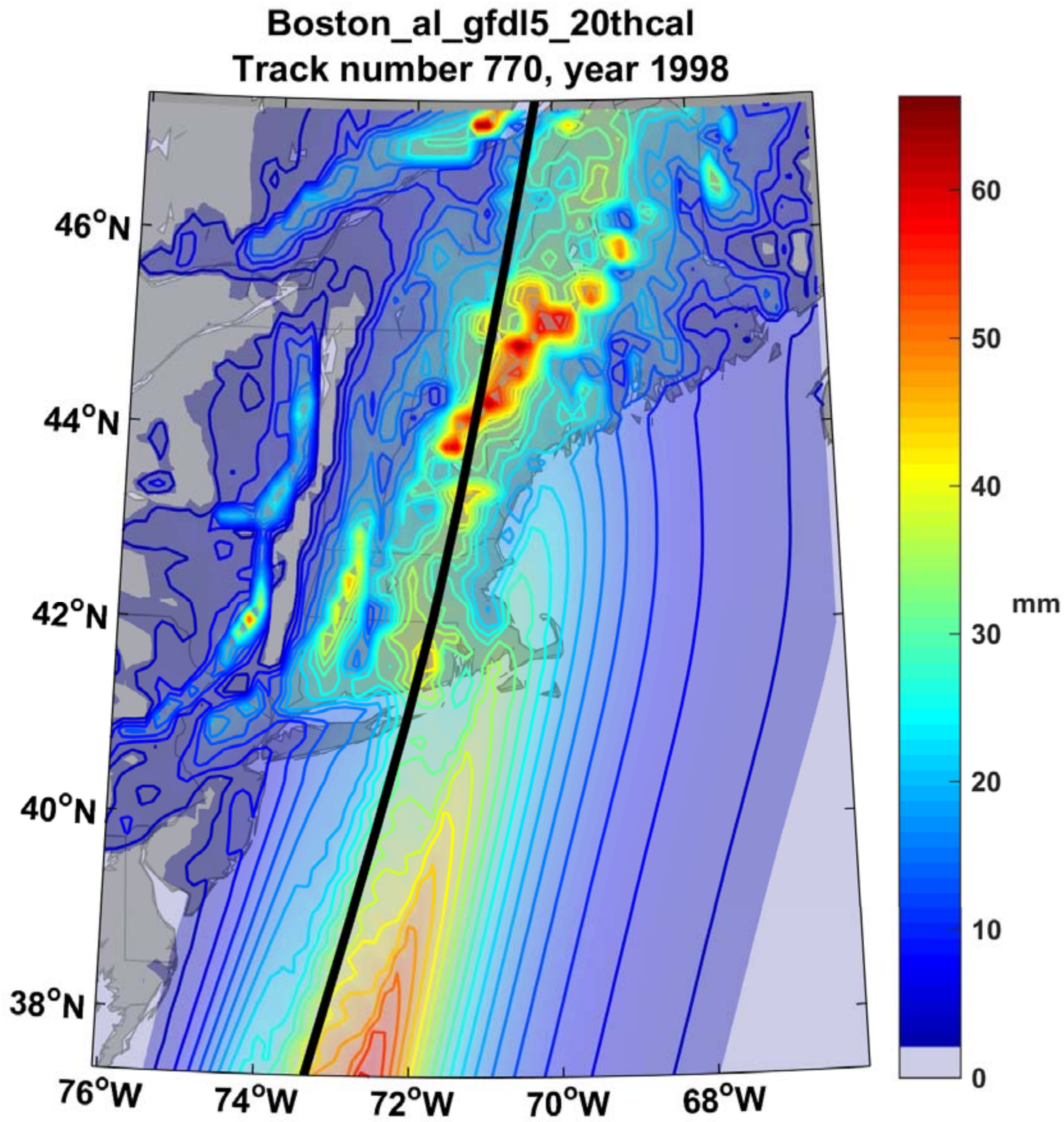



**Observed (left) and simulated storm total rainfall accumulation during Hurricane Katrina of 2005. The plot at left is from NASA's Multi-Satellite Precipitation Analysis, which is based on the Tropical Rainfall Measurement Mission (TRMM) satellite, among others. Dark red areas exceed 300 mm of rainfall; yellow areas exceed 200 mm, and green areas exceed 125 mm**

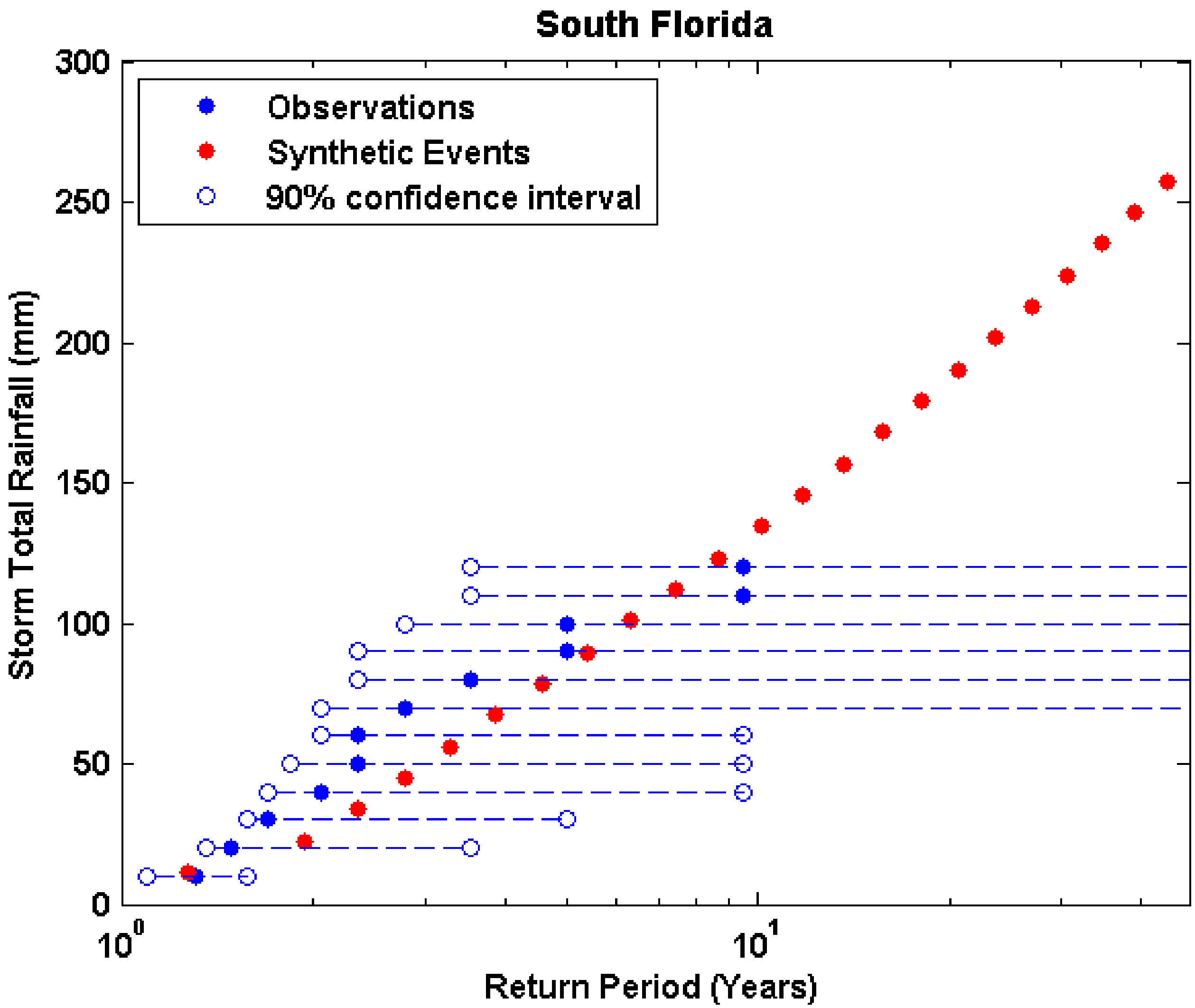
Example showing baroclinic and topographic effects

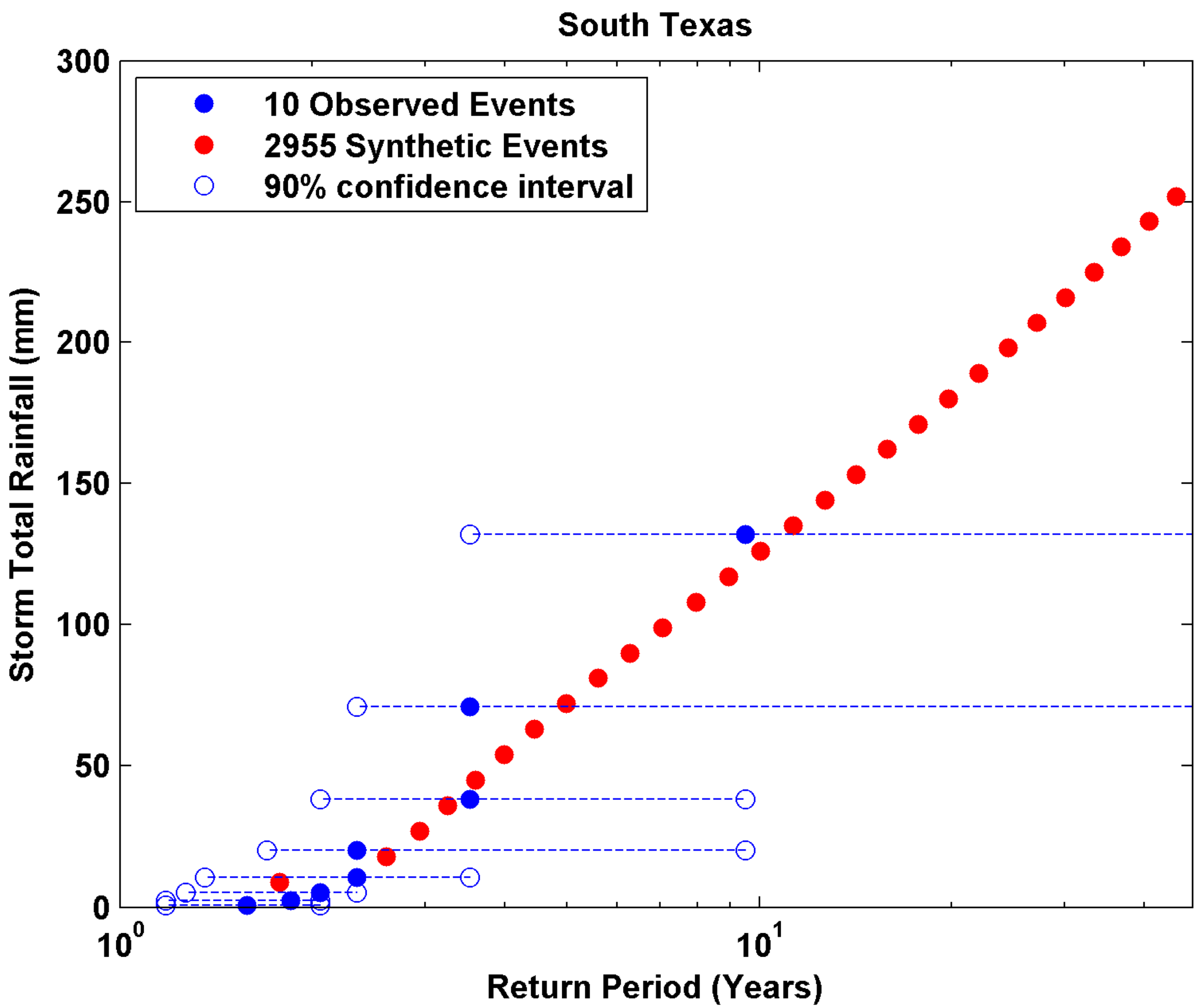


# Accumulated Rainfall



# Comparison to inferences based on NEXRAD data (work of Casey Hilgenbrink)




South Texas
10 Observed Events
2955 Synthetic Events
90% confidence interval
Storm Total Rainfall (mm)
Return Period (Years)
300
250
200
150
100
50
0
$10^0$
$10^1$

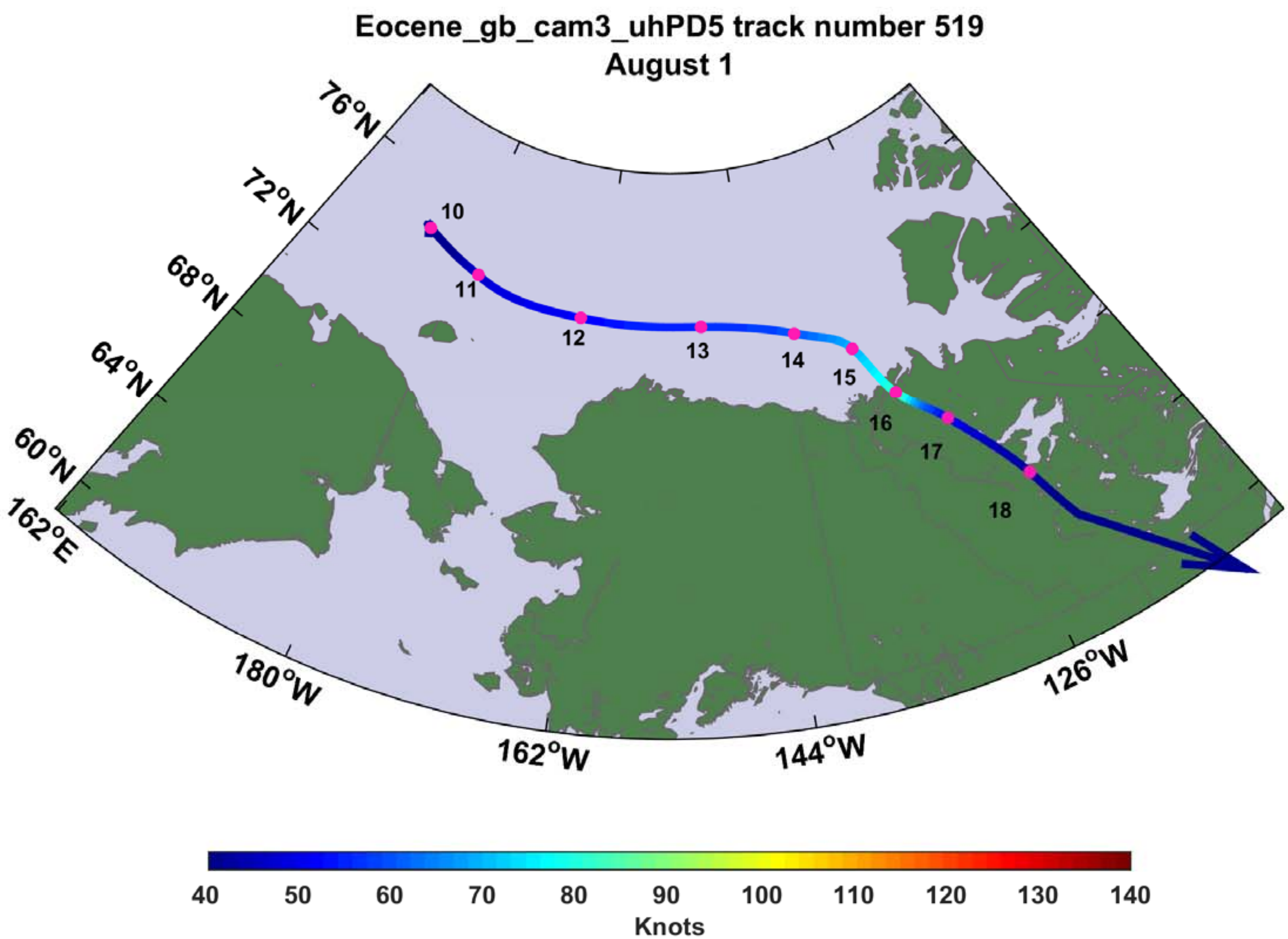
# Effects of Climate Change

- More moisture in boundary layer
- Stronger storms but more compact inner regions
- Possibly larger storm diameters

Global warming leads to fewer but heavier rain events. Rain intensity in the tropics goes up exponentially with temperature.

(Global mean precipitation rises much more slowly.)

# Eocene hurricane making landfall in the Yukon



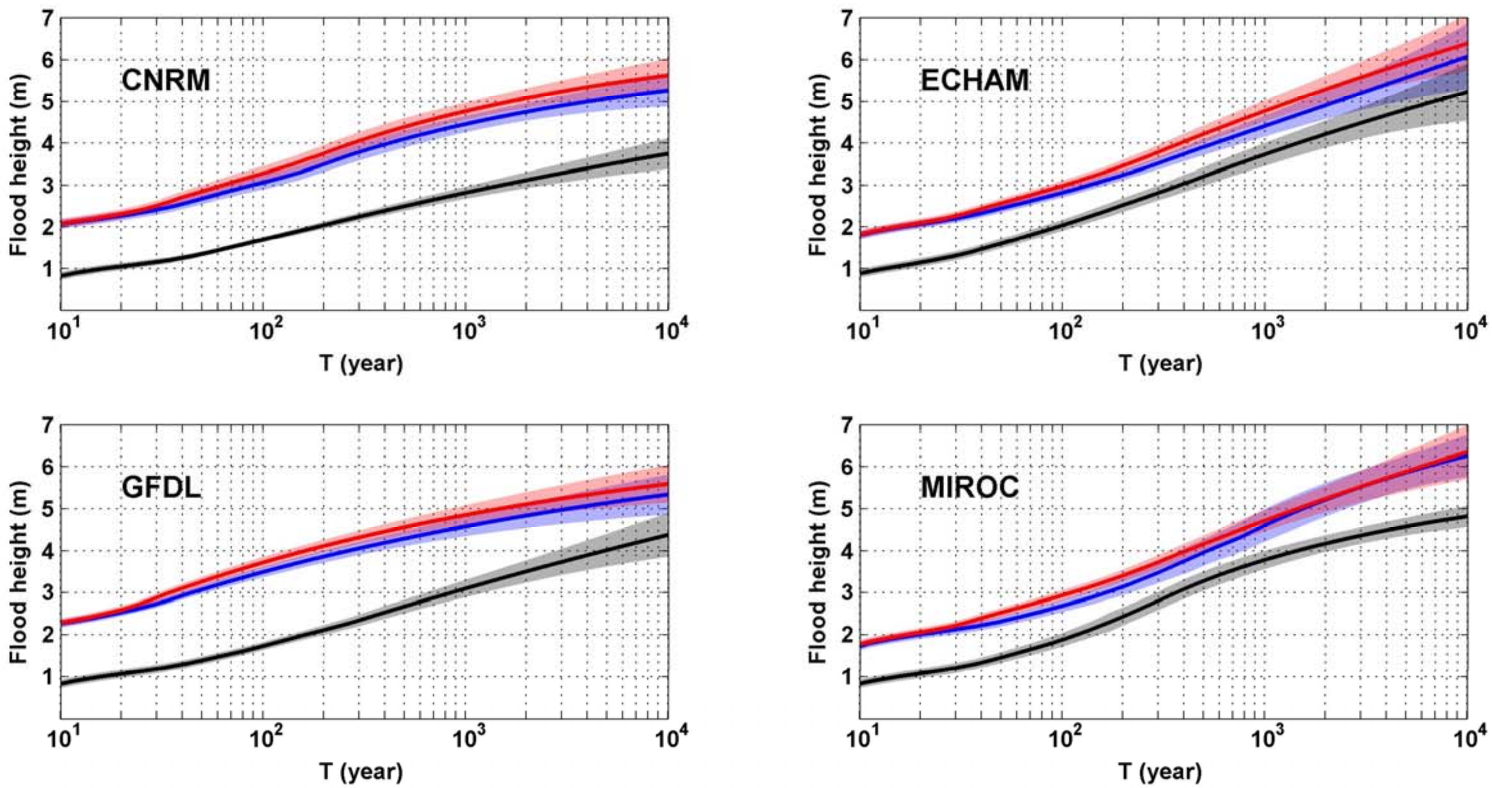
# Downscaling of AR5 GCMs

- CCSM4
- GFDL-CM3
- HadGEM2-ES
- IPSL CM5A-LR
- MPI-ESM-MR
- MIROC-5
- MRI-CGCM3

**Historical:** 1950-2005, **RCP8.5** 2006-2100

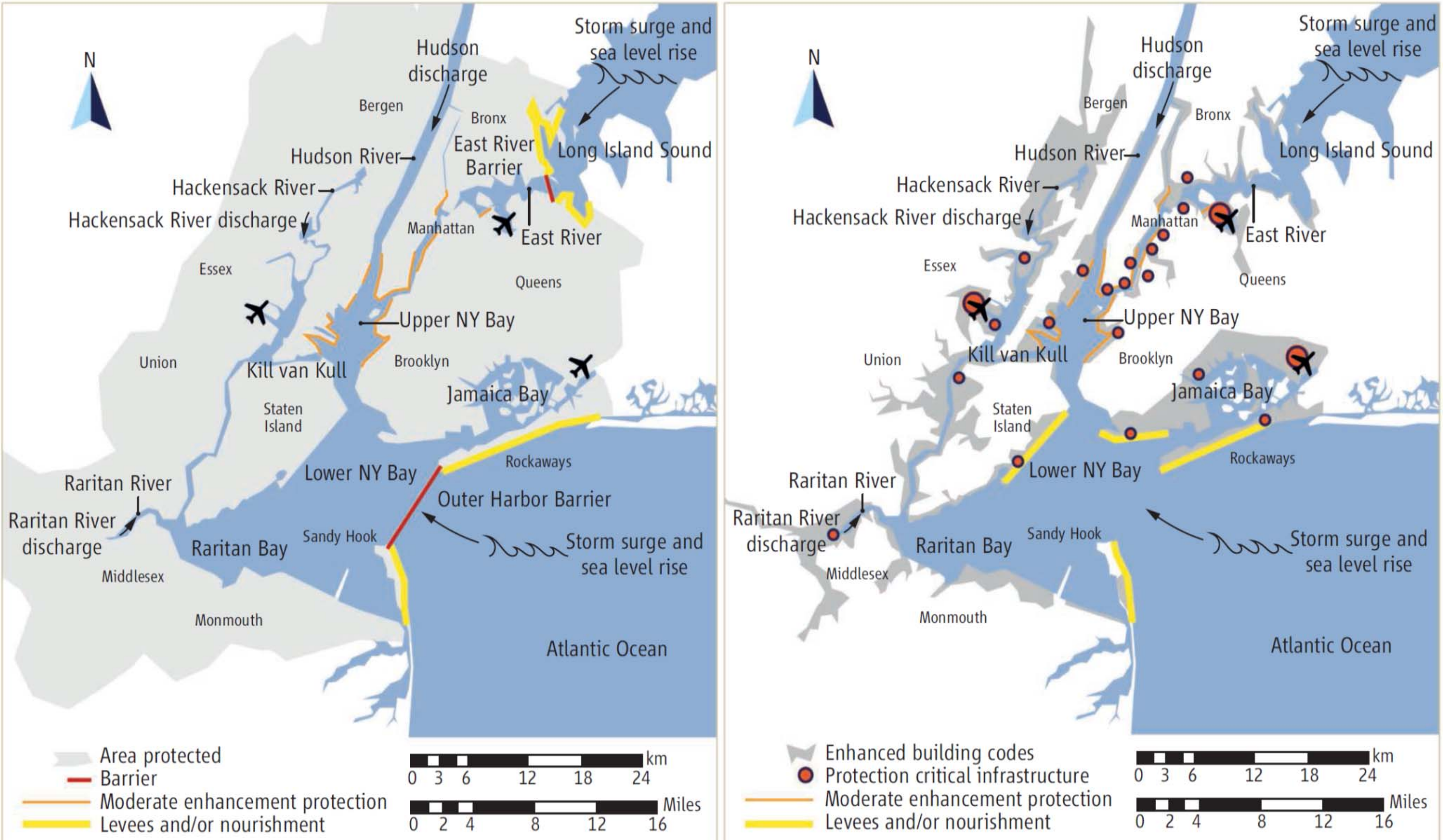
# GCM flood height return level, Battery, Manhattan

## (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, N., K. Emanuel, M. Oppenheimer, and E. Vanmarcke, 2012: Physically based assessment of hurricane surge threat under climate change. *Nature Clim. Change*, doi:10.1038/nclimate1389




**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.

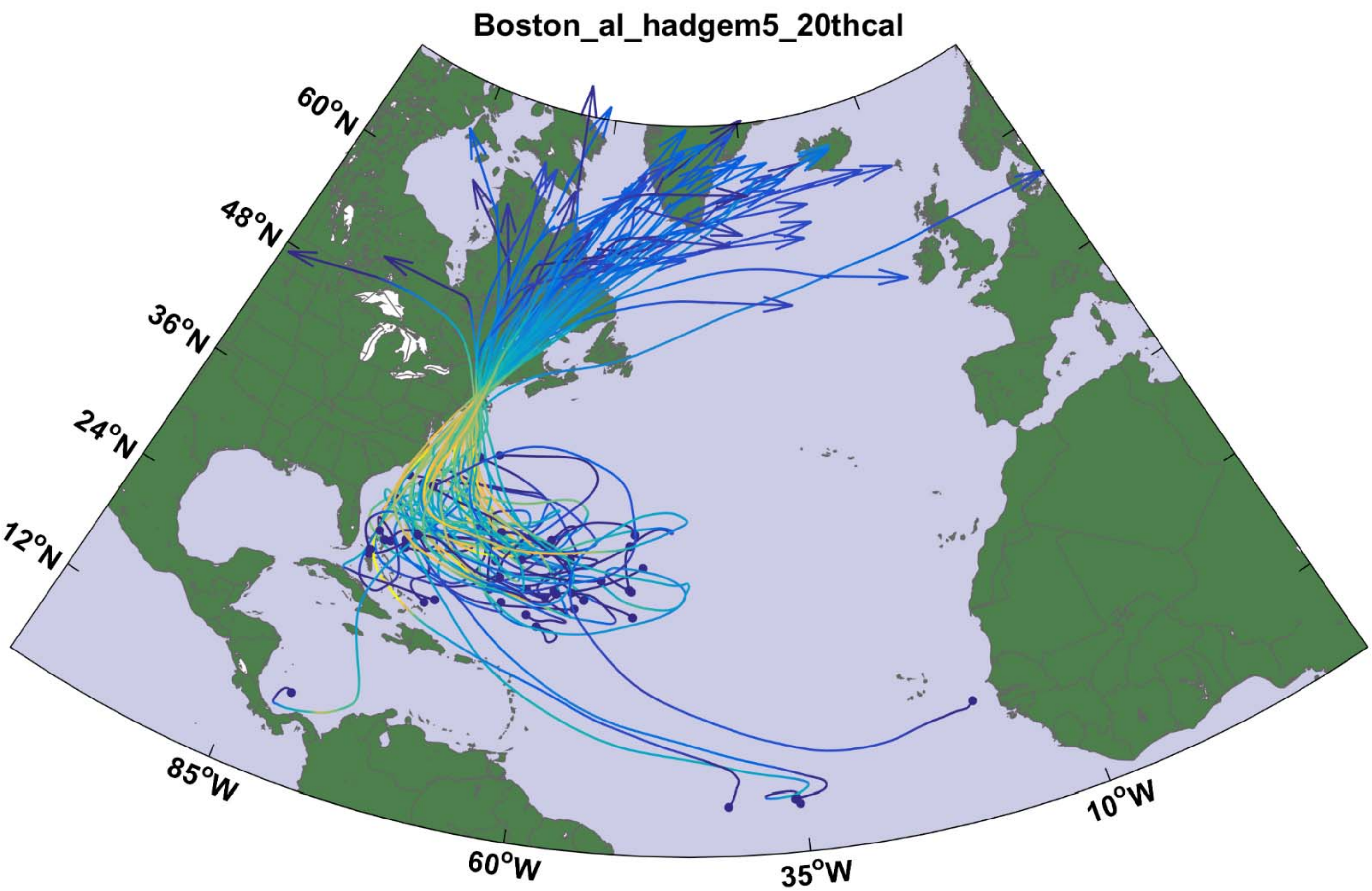
Aerts, C. J. H. J., W. J. W. Botzen, K. Emanuel, N. Lin, H. de Moel, and E. O. Michel-Kerjan, 2014: Evaluating flood resilience strategies for coastal megacities. *Science*, **344**, 473-475.

# Benefit-Cost Ratios

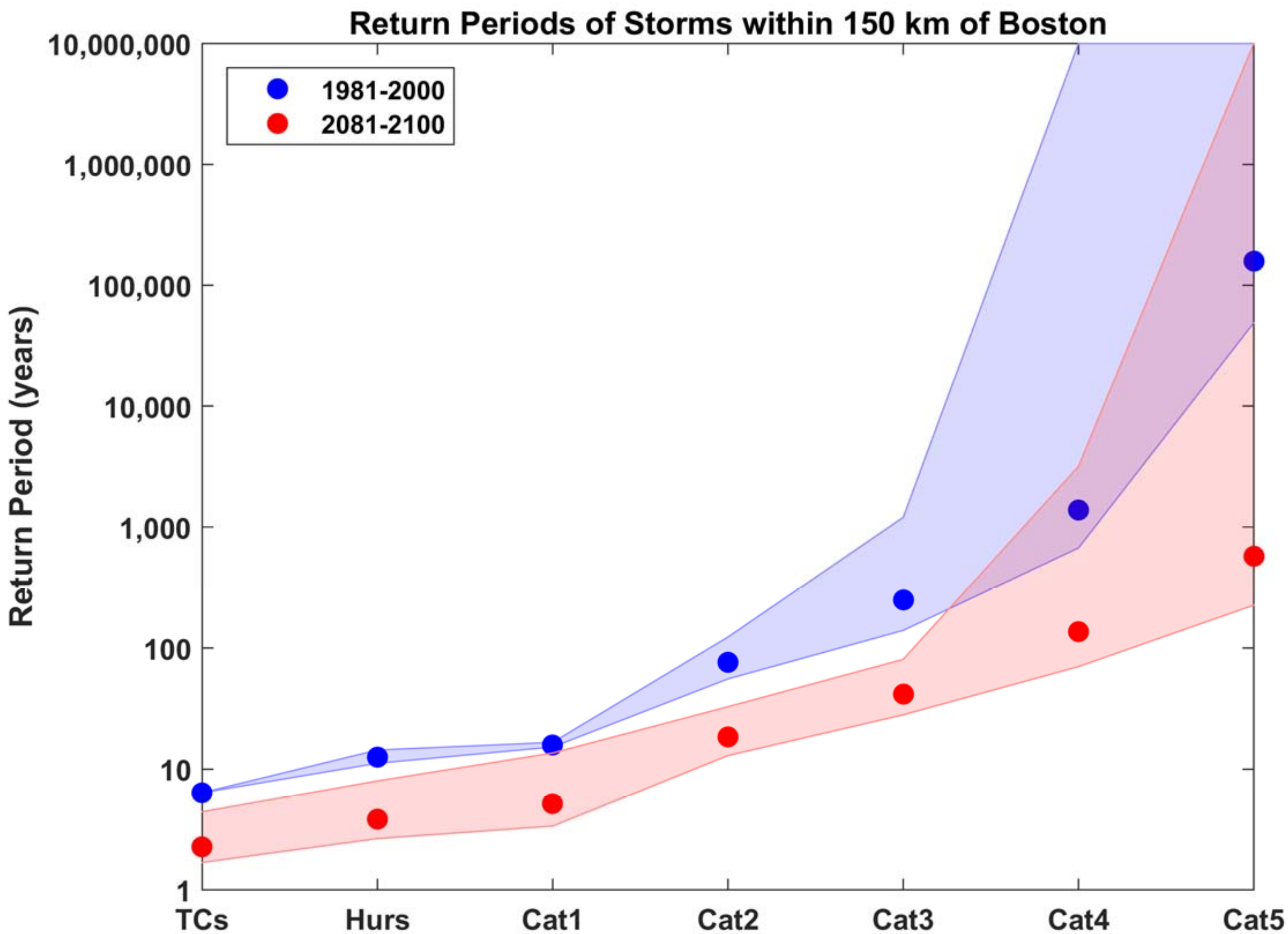
| | Where/ how much | Environ.dyn. S2a | Bay closed S2b | NJ-JY connect S2c | Hybrid solution S3 |
|---|---|---|---|---|---|
| **Costs** | | | | | |
| Total investment | NYC | $16.9–21.1 billion | $15.9–21.8 billion | $11.0–14.7 billion | $6.4–7.6 billion |
| Total investment | NJ | $2 billion | $2 billion | 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.

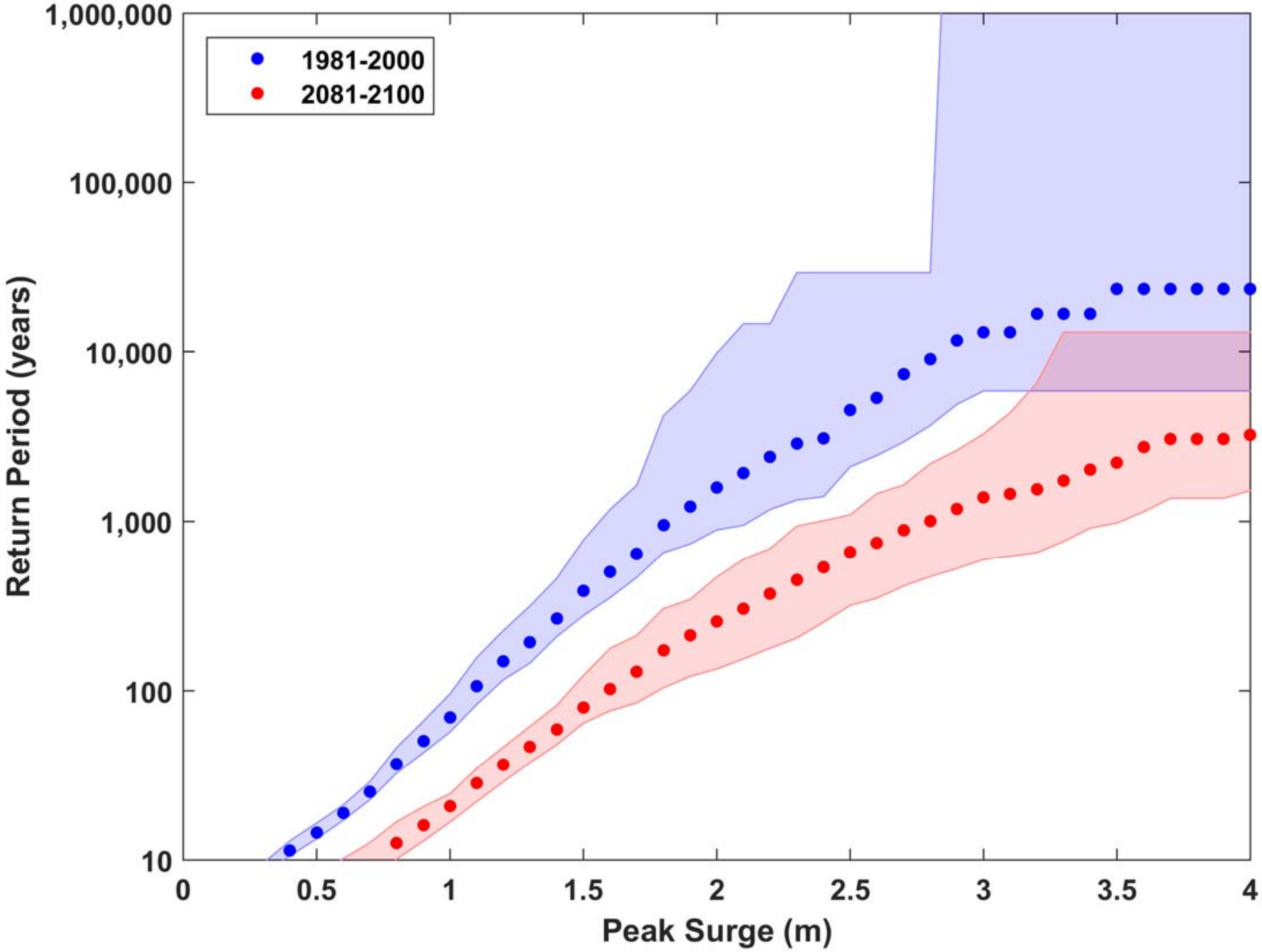
# Top 50 of 5,000 events affecting Boston



# Hurricanes Passing within 150 km of Boston Downscaled from 5 climate models

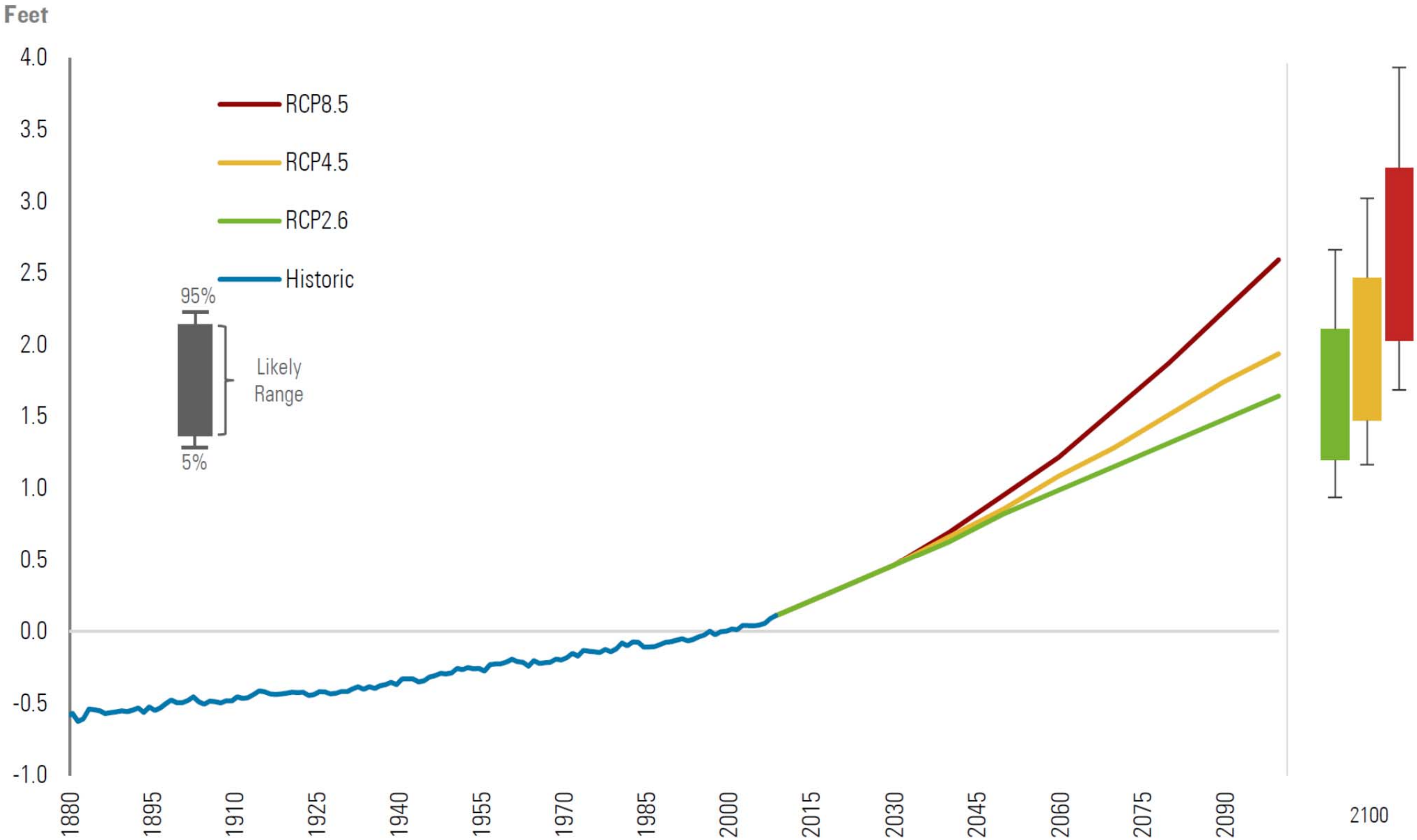


# Surge Risk

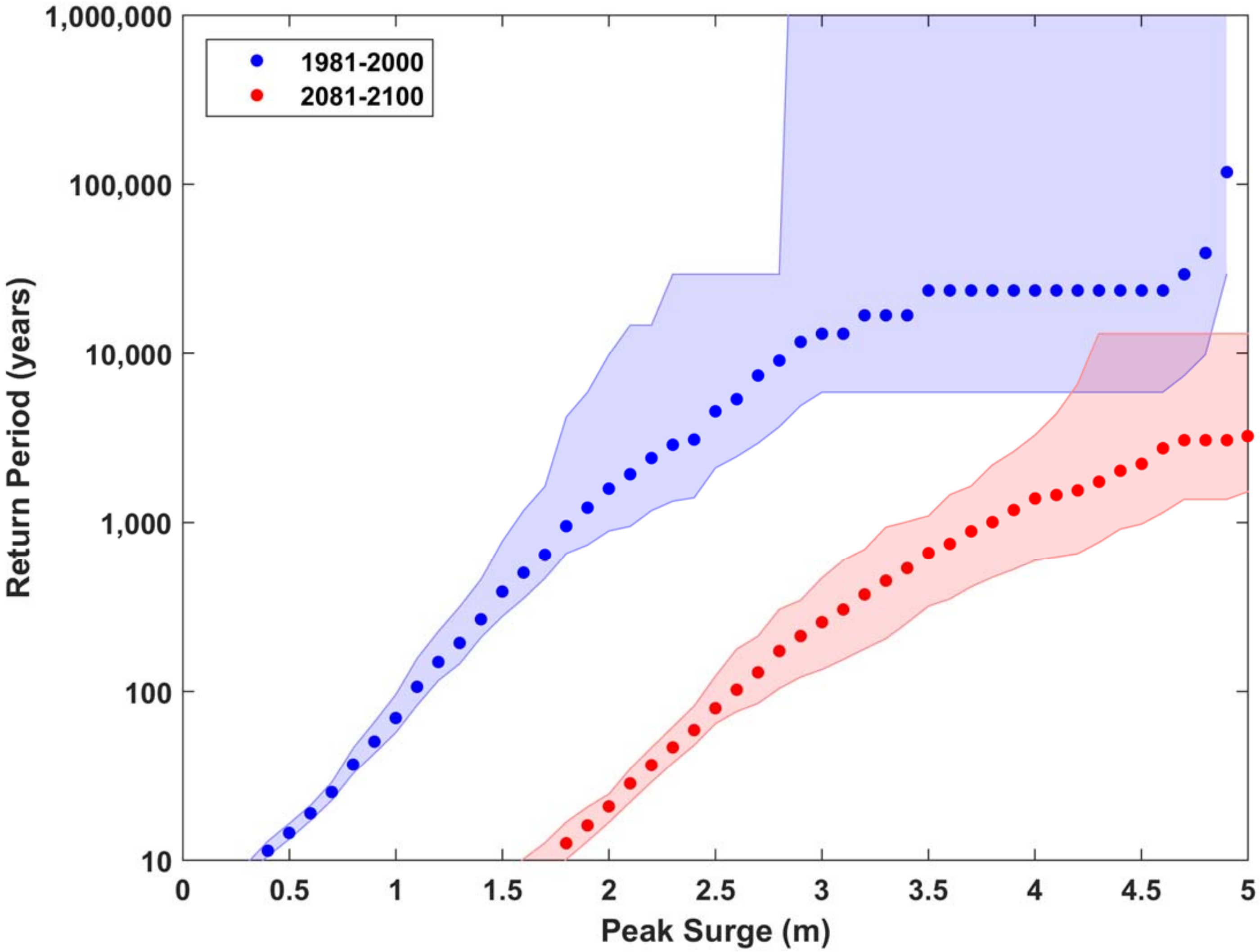


1,000,000
100,000
10,000
1,000
100
10
Return Period (years)
1981-2000
2081-2100
0
0.5
1
1.5
2
2.5
3
3.5
4
Peak Surge (m)

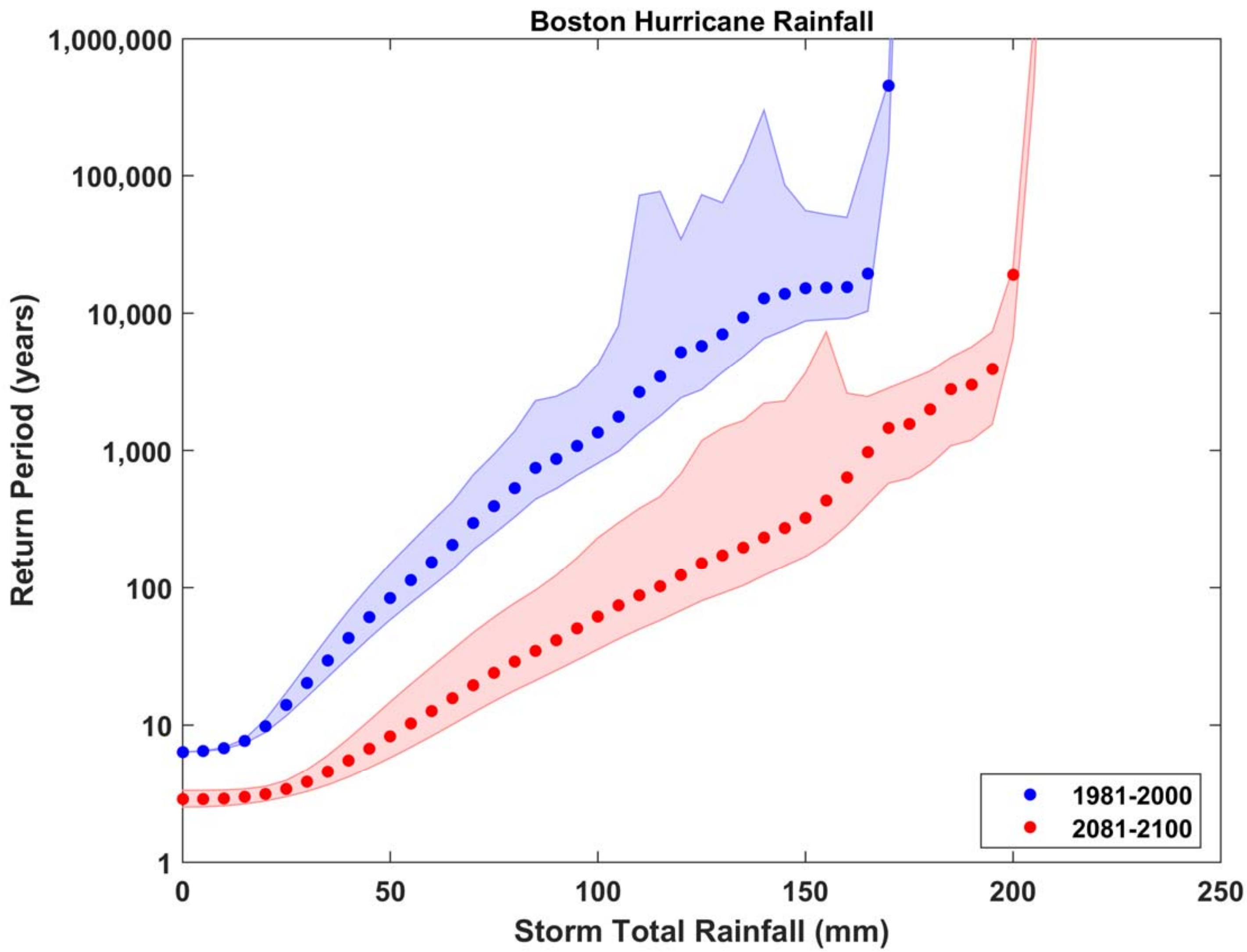
**Figure 4.11: Global mean sea level rise**



# Surge Risk with 1 meter sea level rise

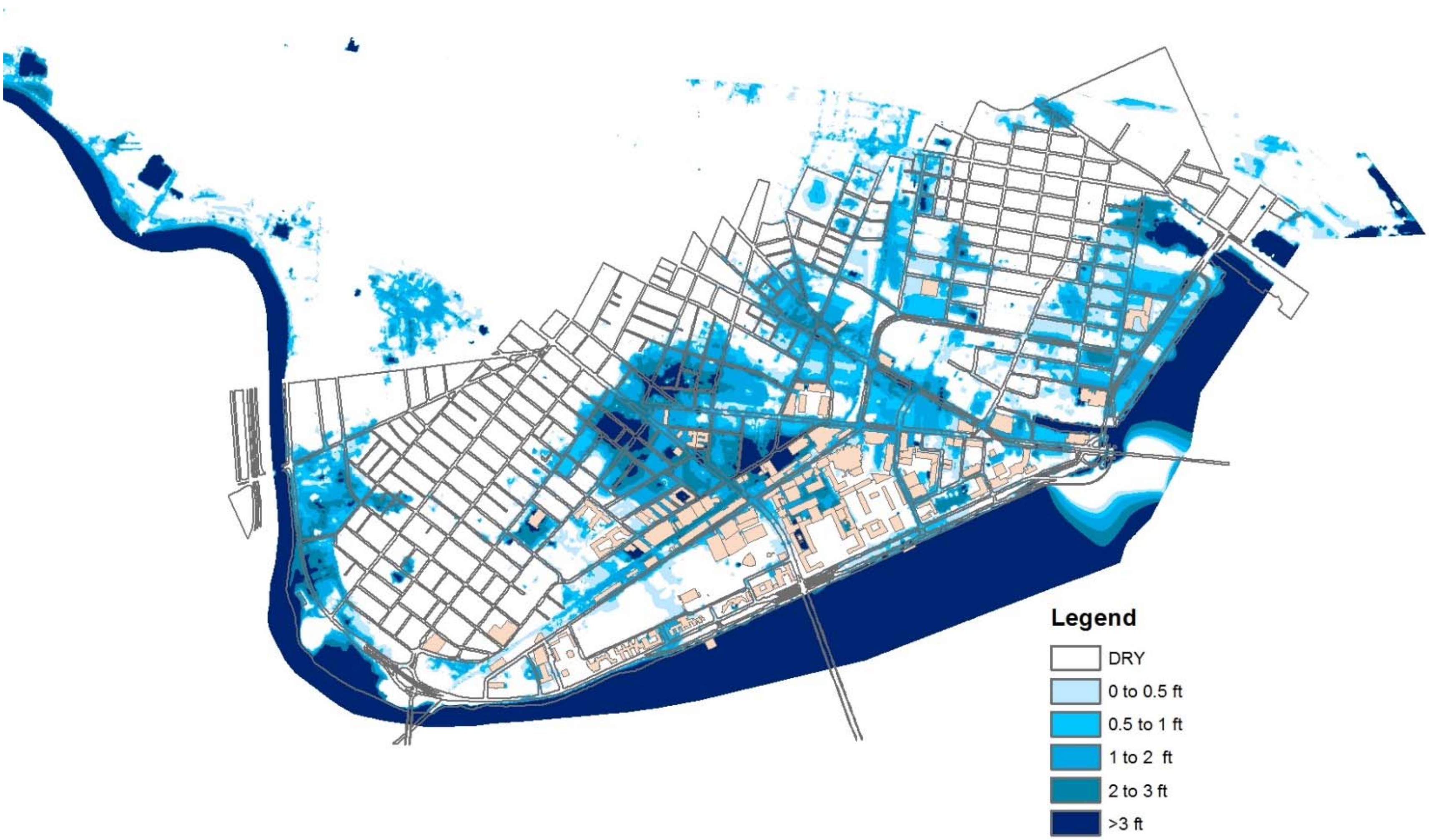


# Rain Risk



Boston Hurricane Rainfall
1,000,000
100,000
10,000
1,000
100
10
1
Return Period (years)
0
50
100
150
200
250
Storm Total Rainfall (mm)
1981-2000
2081-2100

# Depth of 100-Year Flooding of the MIT Campus in the year 2070 (with Ken Strzepek)



# Storm Total Rainfall, College Station

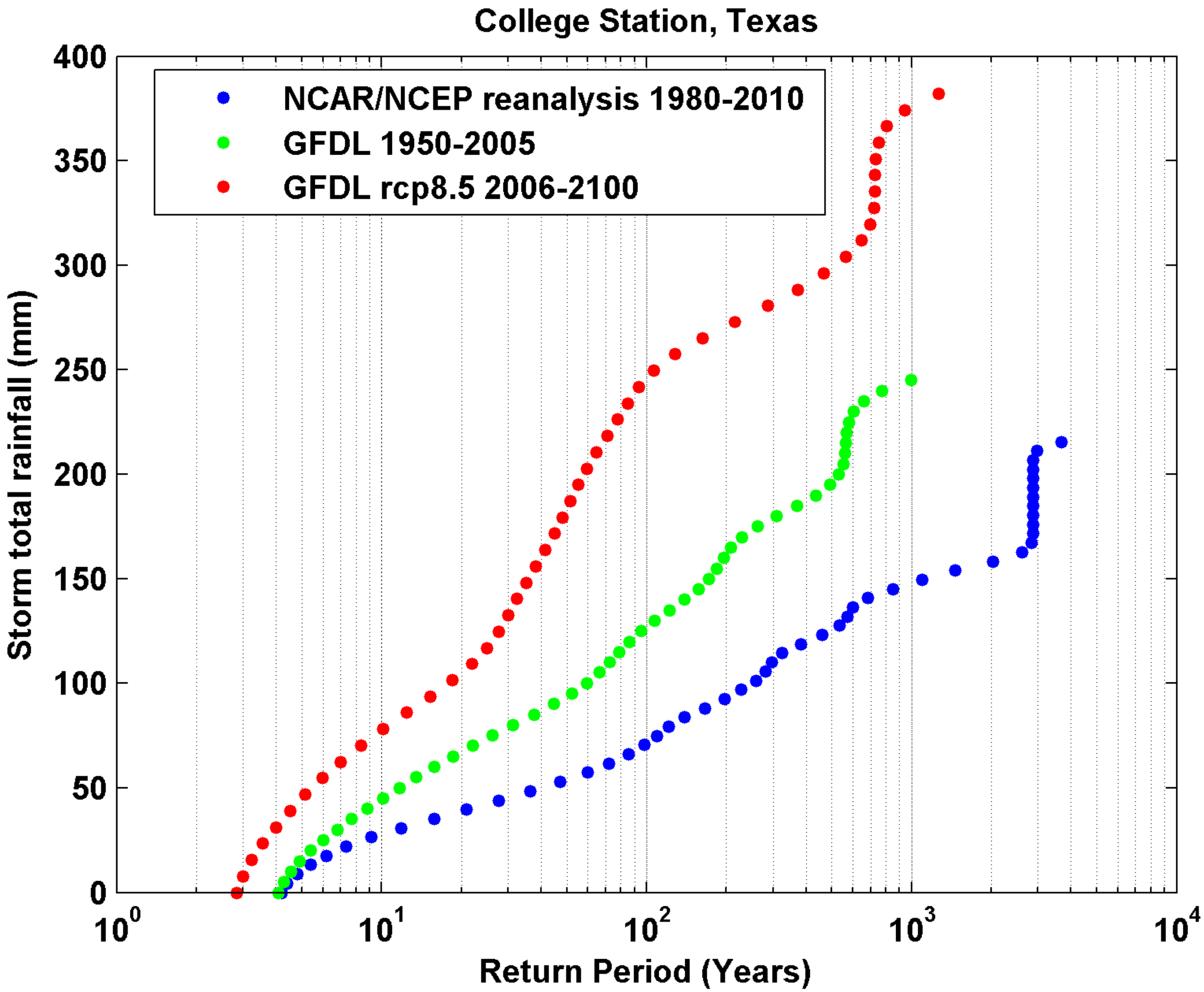
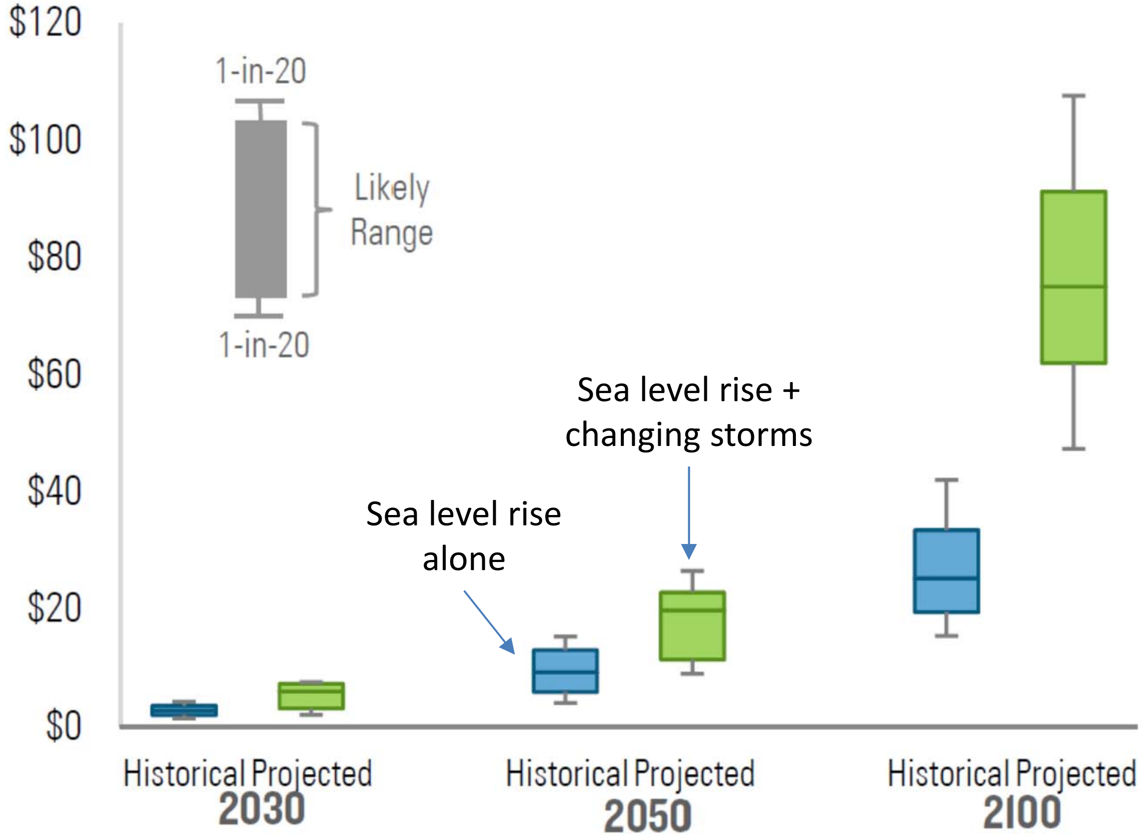


**Figure 11.17: Increase in average annual losses with historical and projected hurricane activity**

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



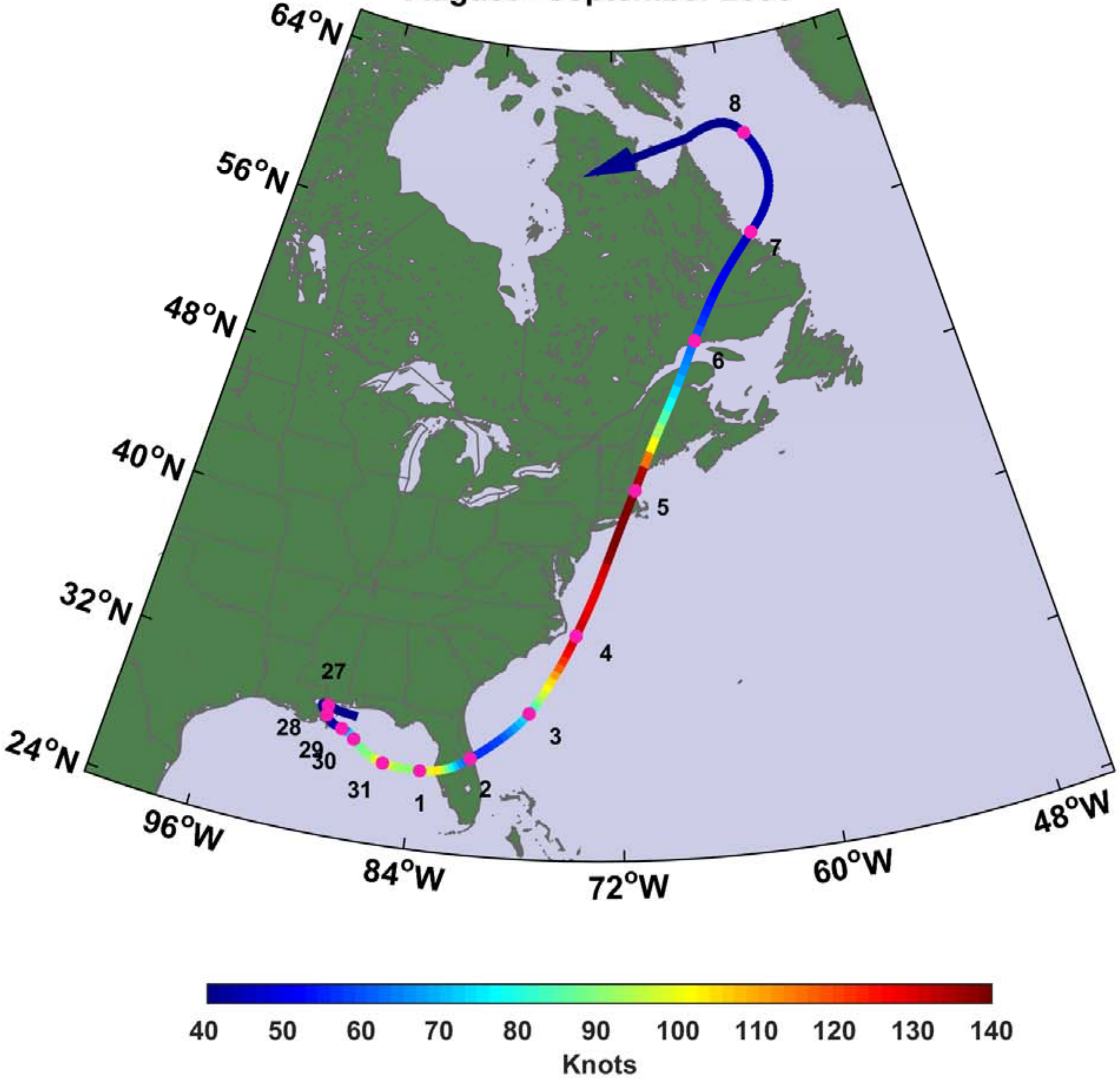

From: *American Climate Prospectus Economic Risks in the United States*

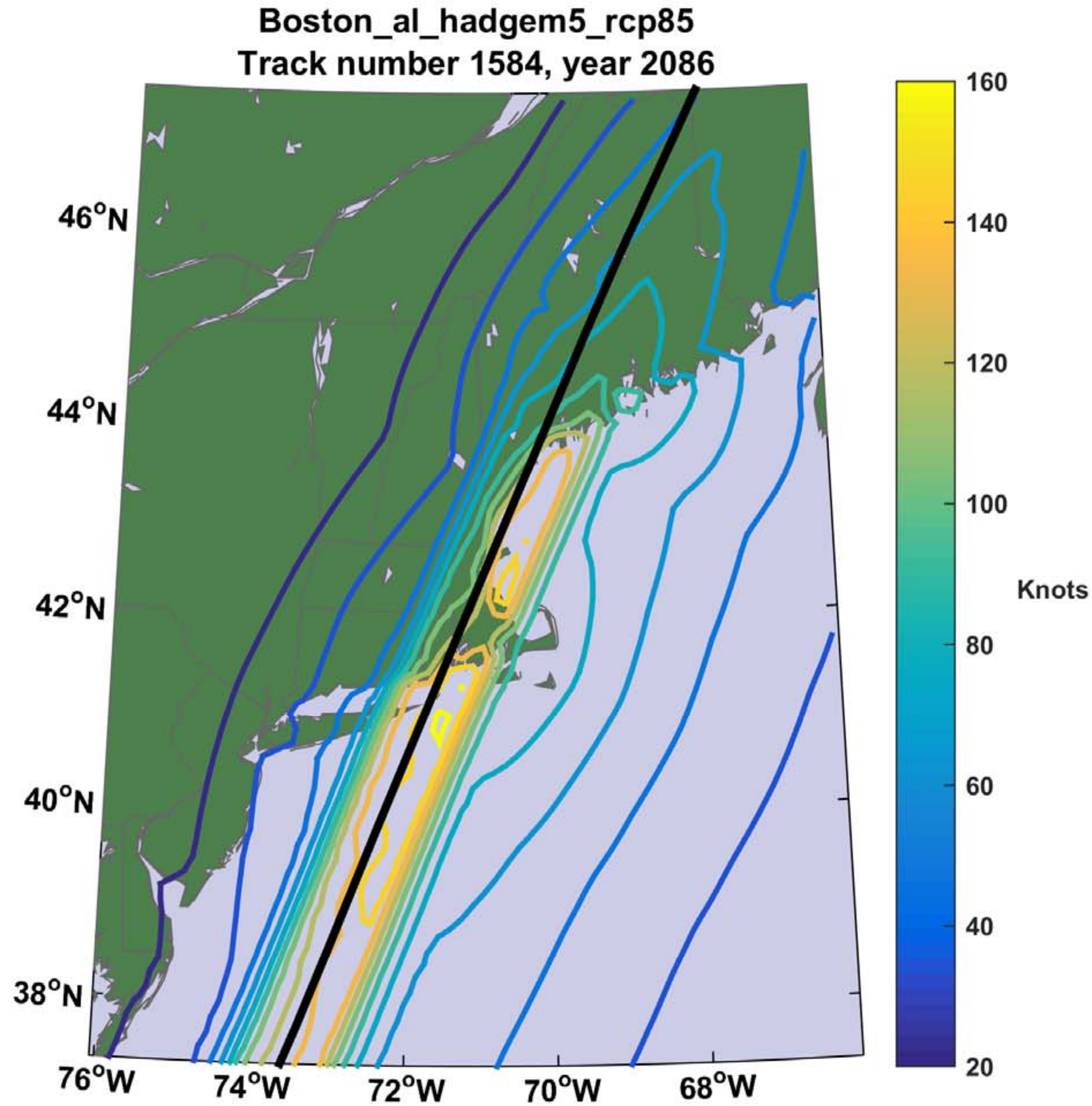
# Summary

- Tropical cyclone history is too short, sparse, and imperfect to estimate hurricane risk
- Better estimates can be made by downscaling hurricane activity from climatological or global model output
- Hurricanes clearly vary with climate and there is a decided risk that hurricane threats will increase over this century

# Spares

**Boston_al_hadgem5_rcp85 track number 1584**
**August - September 2086**




Boston_al_hadgem5_rcp85
Track number 1584, year 2086
46°N
44°N
42°N
40°N
38°N
76°W
74°W
72°W
70°W
68°W
160
140
120
100
80
60
40
20
Knots

# Wind speed and direction at Logan Airport