Predicting the Evolution of Hurricane Risk with Climate Change

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Hurricane Risks
Average of 10,000 deaths per year globally

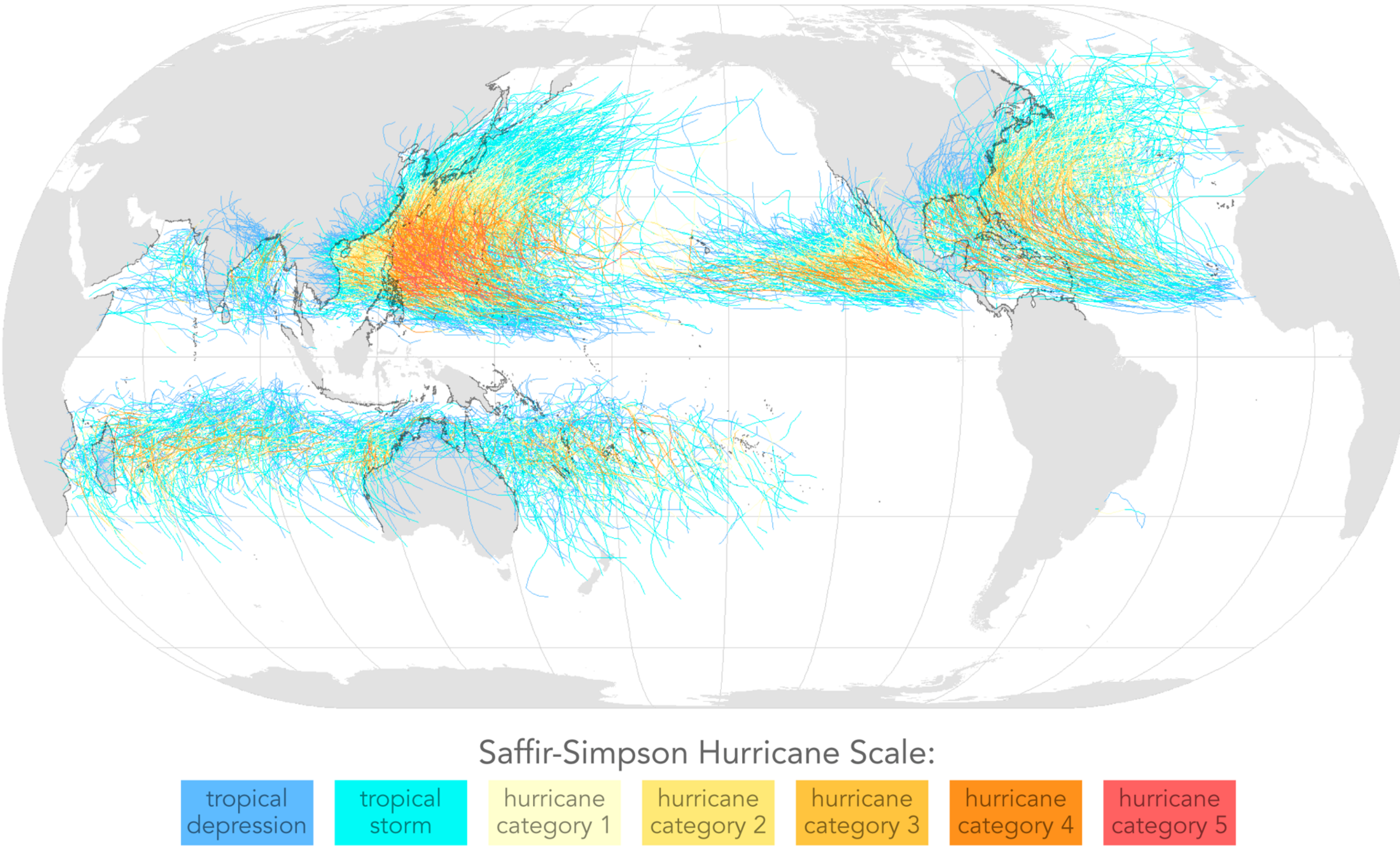
- Wind

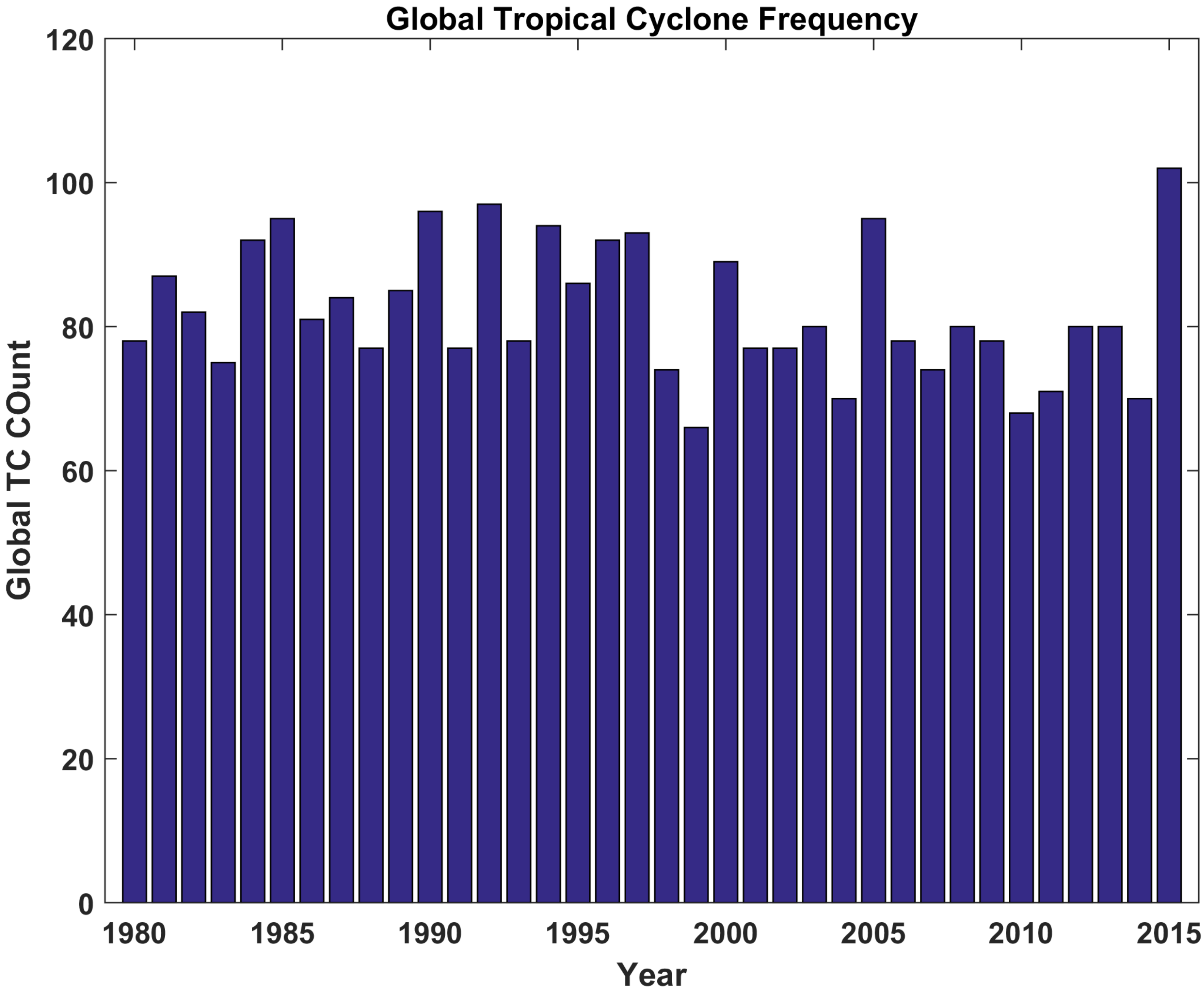
- Storm Surge

- Rain

Tropical Cyclone Climatology

Tropical Cyclones, 1945–2006

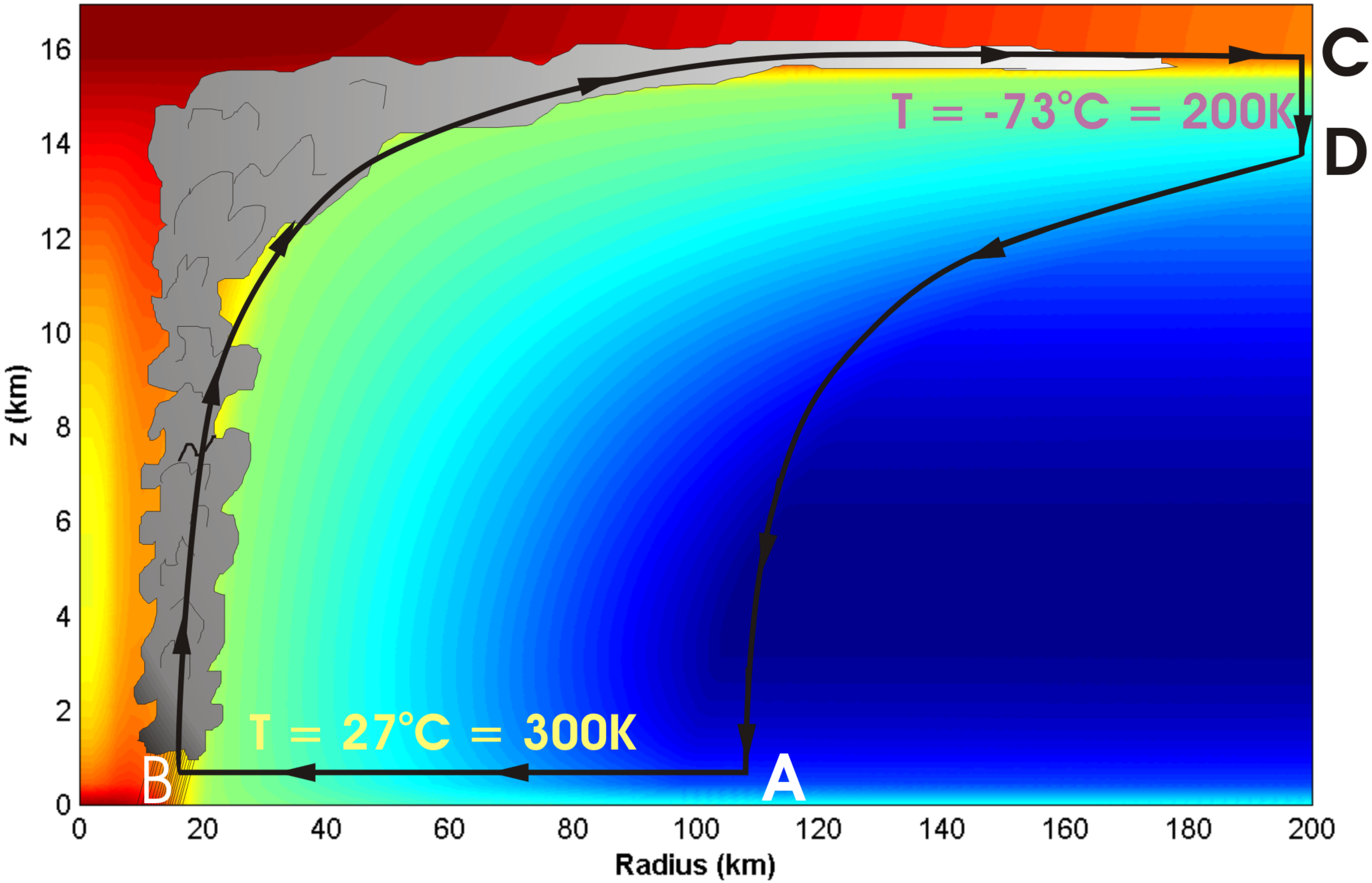




Global Tropical Cyclone Frequency
120
100
80
60
40
20
0
Global TC COunt
1980
1985
1990
1995
2000
2005
2010
2015
Year

Basic Theory: Implications for Hurricane and Climate Change

Energy Production



See, e.g., Emanuel, K., 2006: Hurricanes: Tempests in a greenhouse. *Physics Today*, **59**, 74-75

Theoretical Steady-State Maximum Hurricane Wind Speed:

Surface temperature

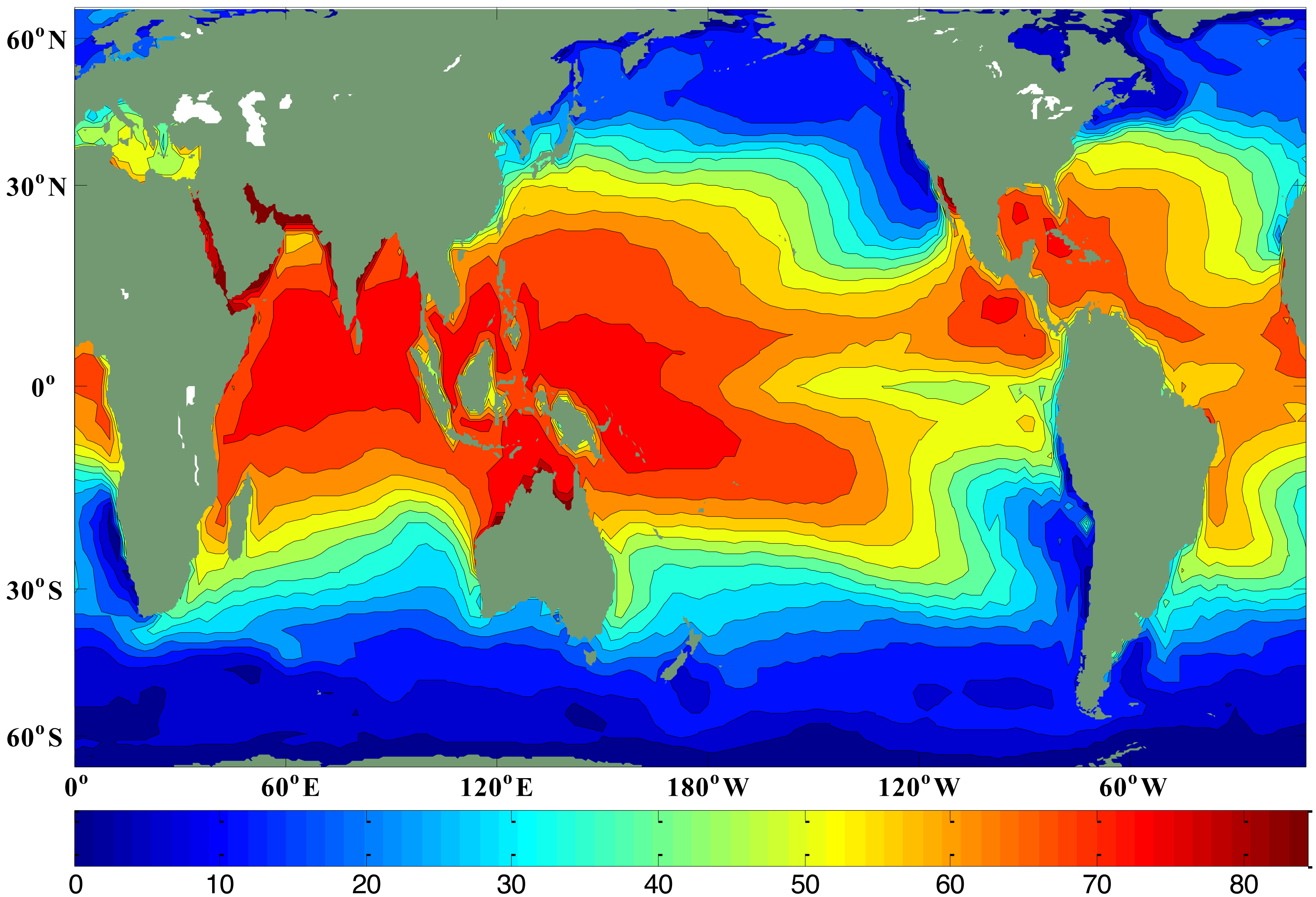
$$V_{pot}^{2} = \boxed{\frac{C_k}{C_D}} \frac{T_s - T_o}{T_0} \left(h_0^* - h_e^* \right)$$

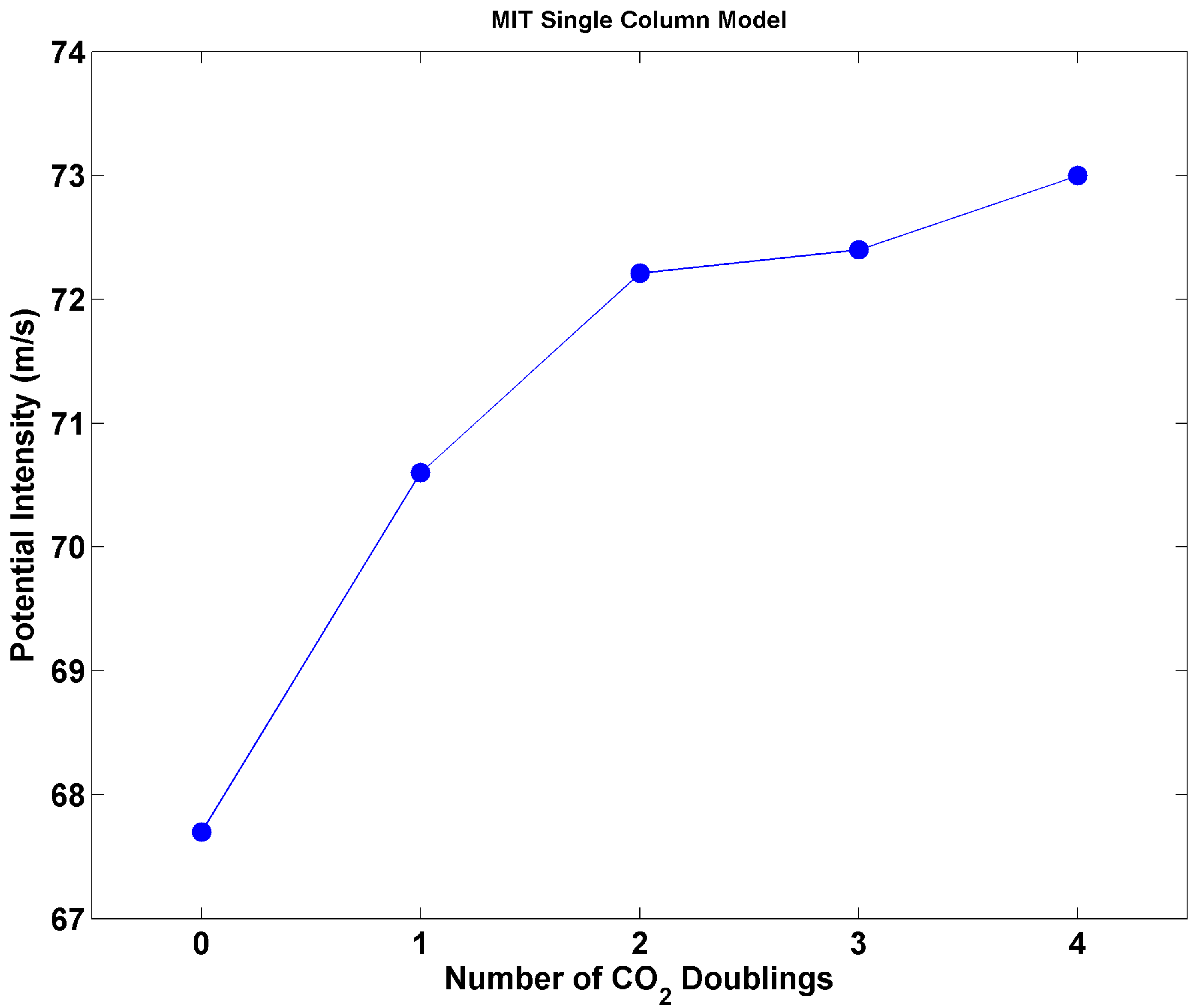
Ratio of exchange coefficients of enthalpy and momentum

Outflow temperature

Air-sea enthalpy disequilibrium of moist static energy

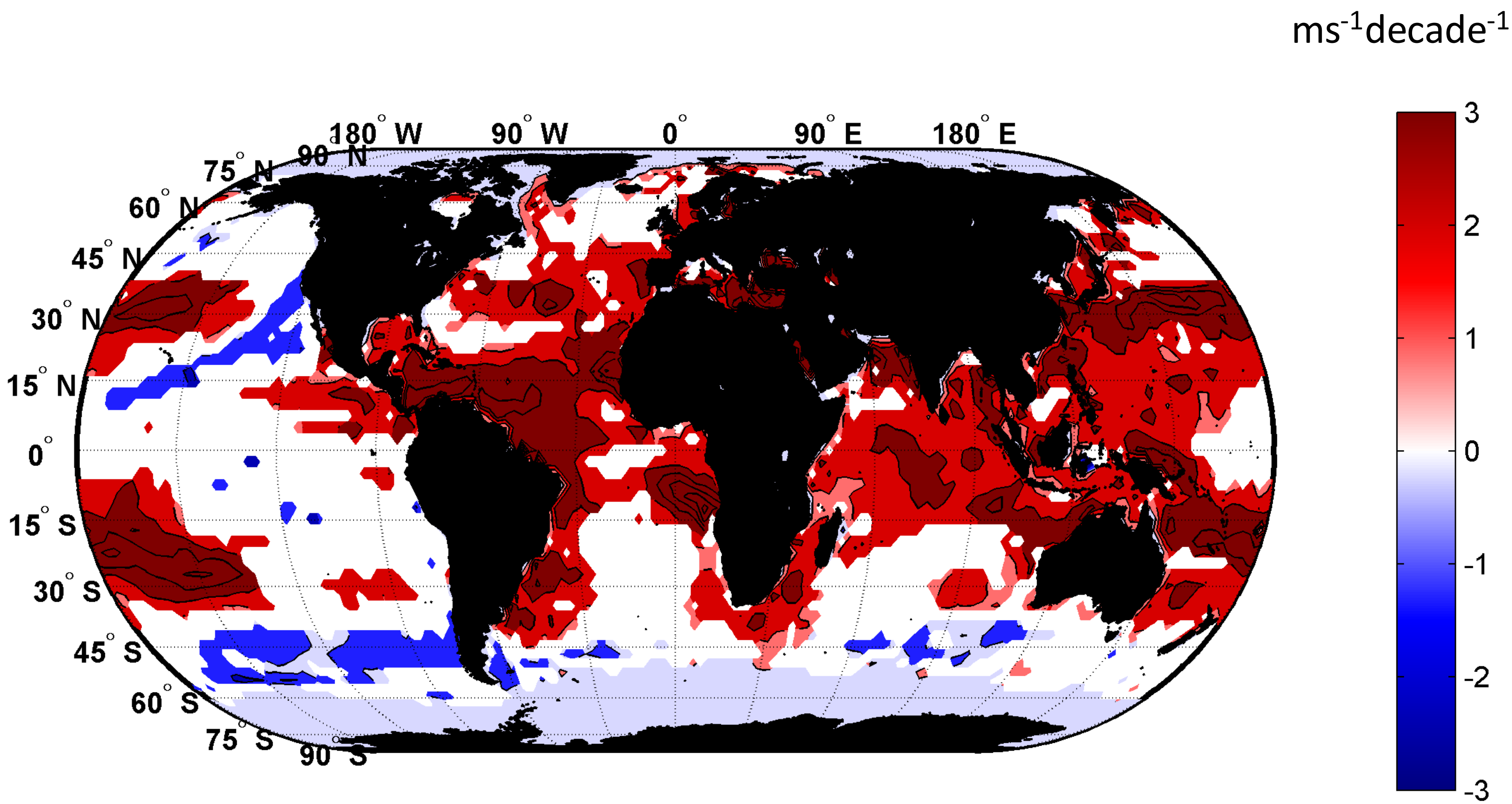
Annual Maximum Potential Intensity (m/s)



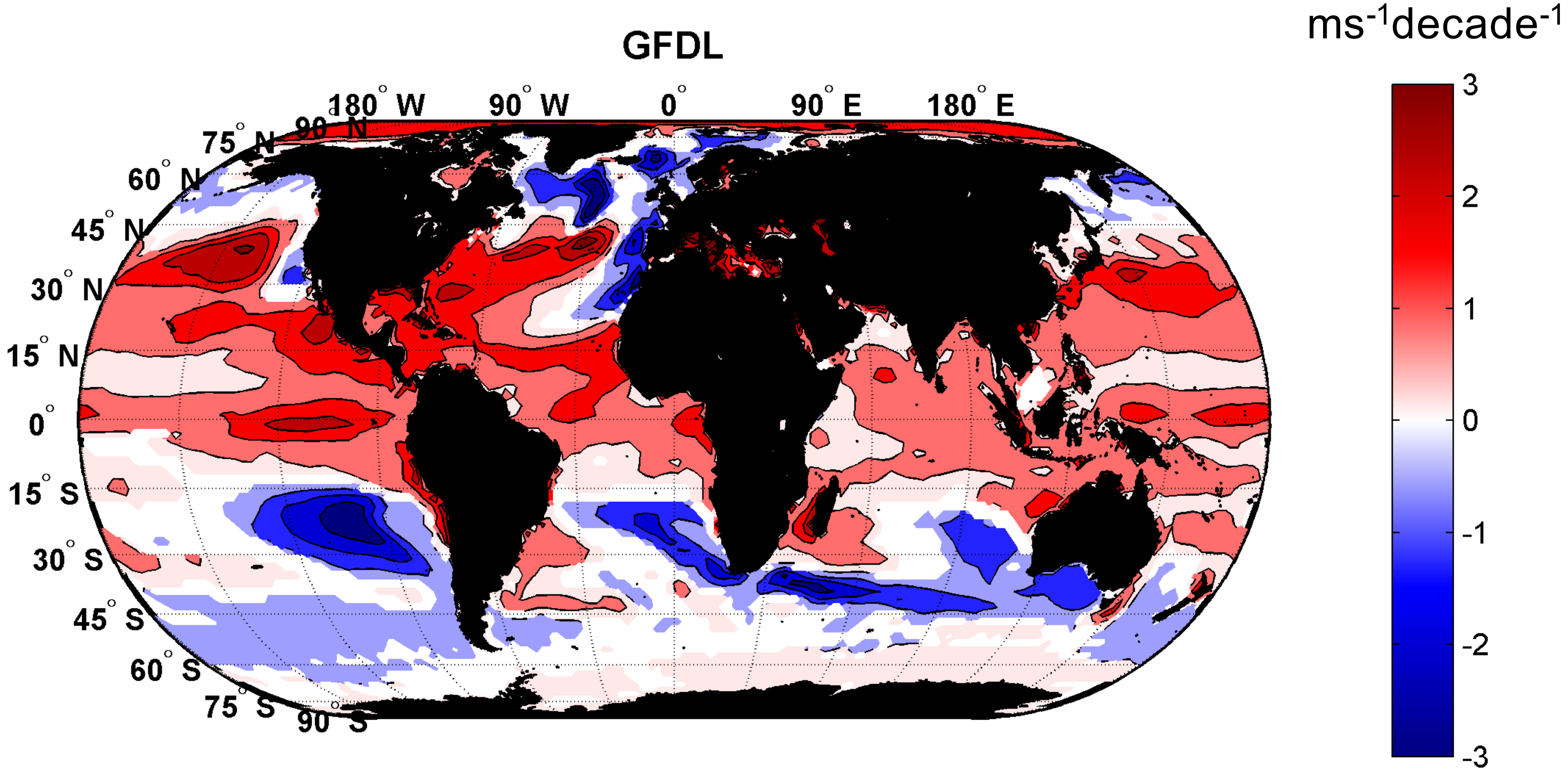


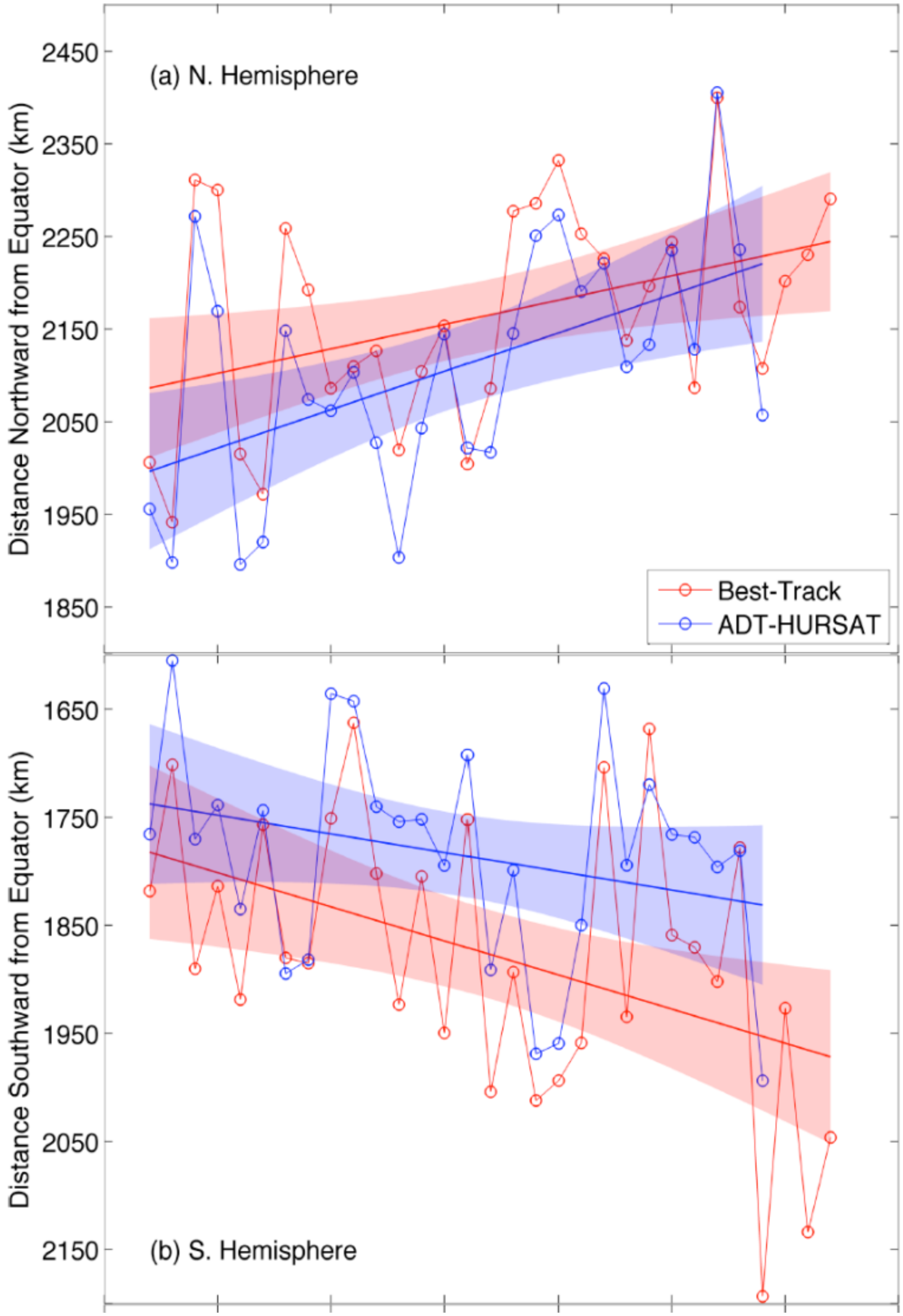
MIT Single Column Model
74
73
72
71
70
69
68
67
0
1
2
3
4
Potential Intensity (m/s)
Number of CO_2 Doublings

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



Projected Trend, 2006-2100: GFDL model
RCP 8.5



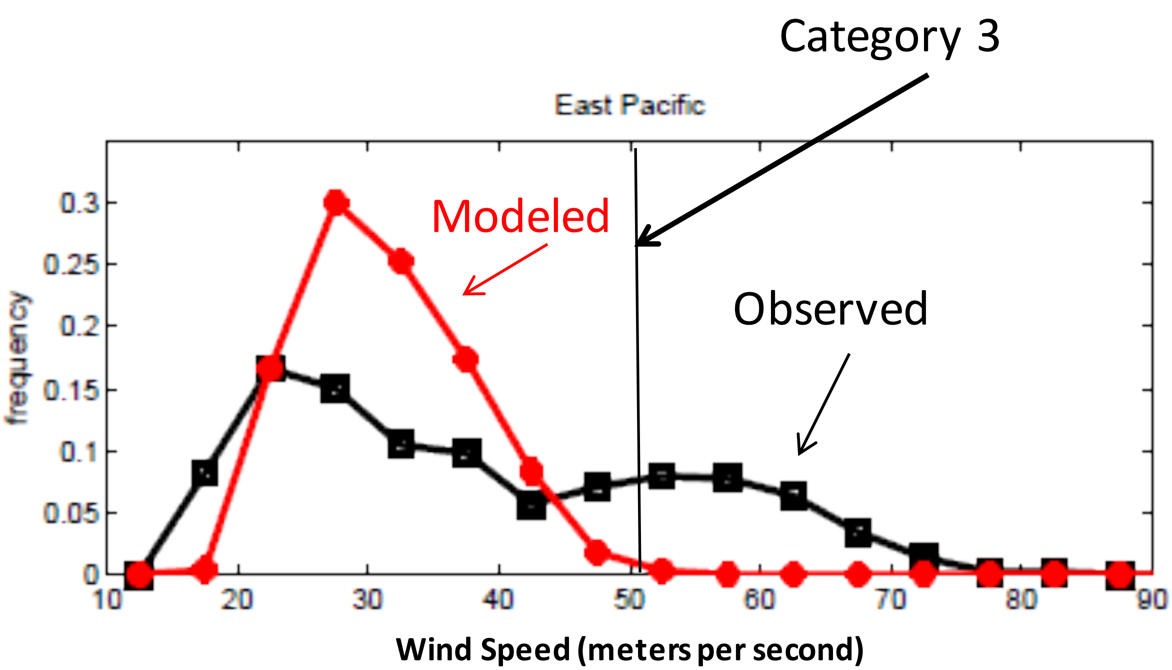


Time series of the latitudes at which tropical cyclones reach maximum intensity.

From Kossin et al., *Nature,* (2014)

Projections of Future Hurricane Risk

Problems with direct numerical simulation of tropical cyclones globally



Histograms of Tropical Cyclone Intensity as Simulated by a Global Model with 30 mile grid point spacing.

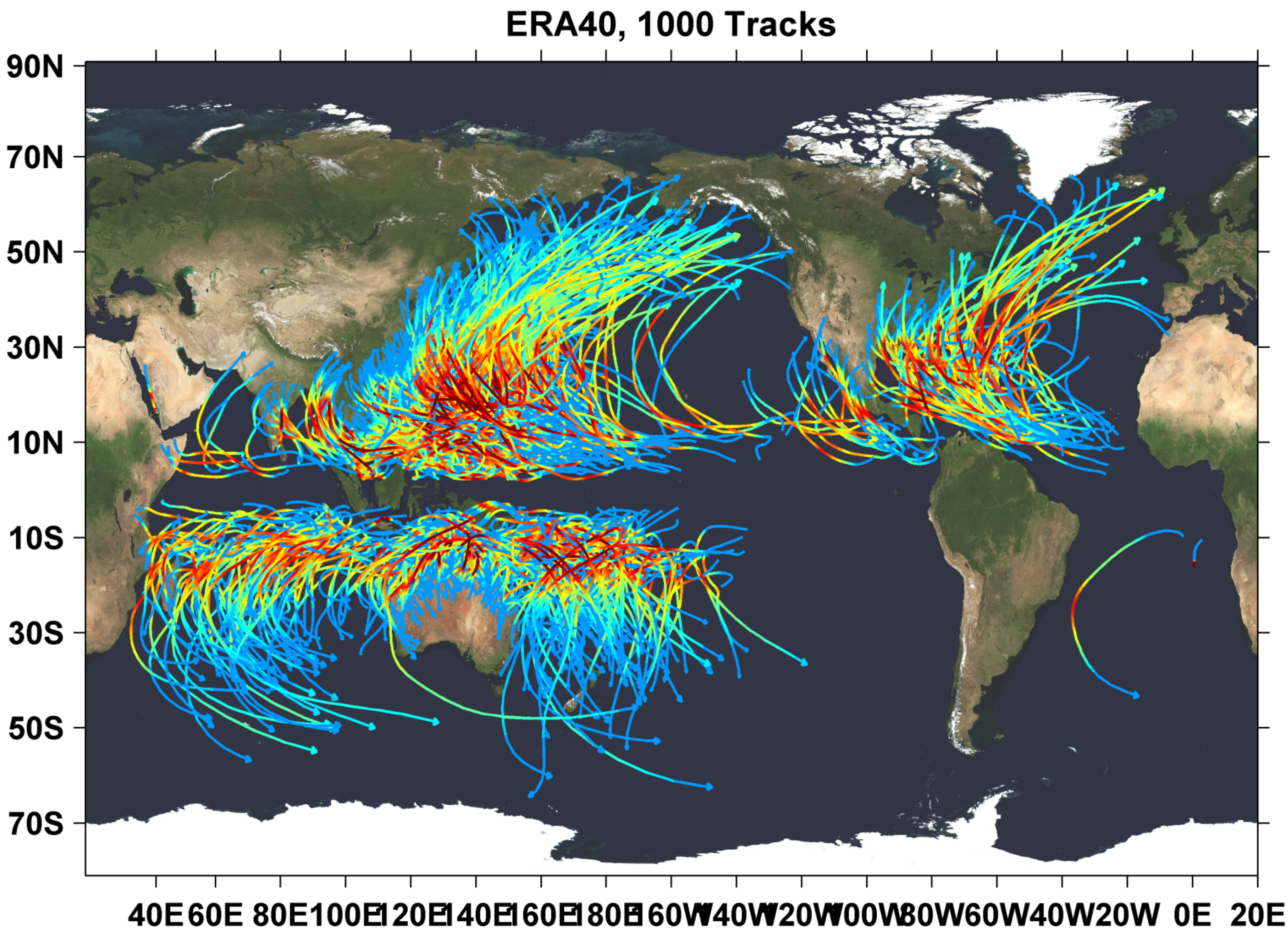
Global models do not simulate the storms that cause destruction

(Courtesy Isaac Held, GFDL)

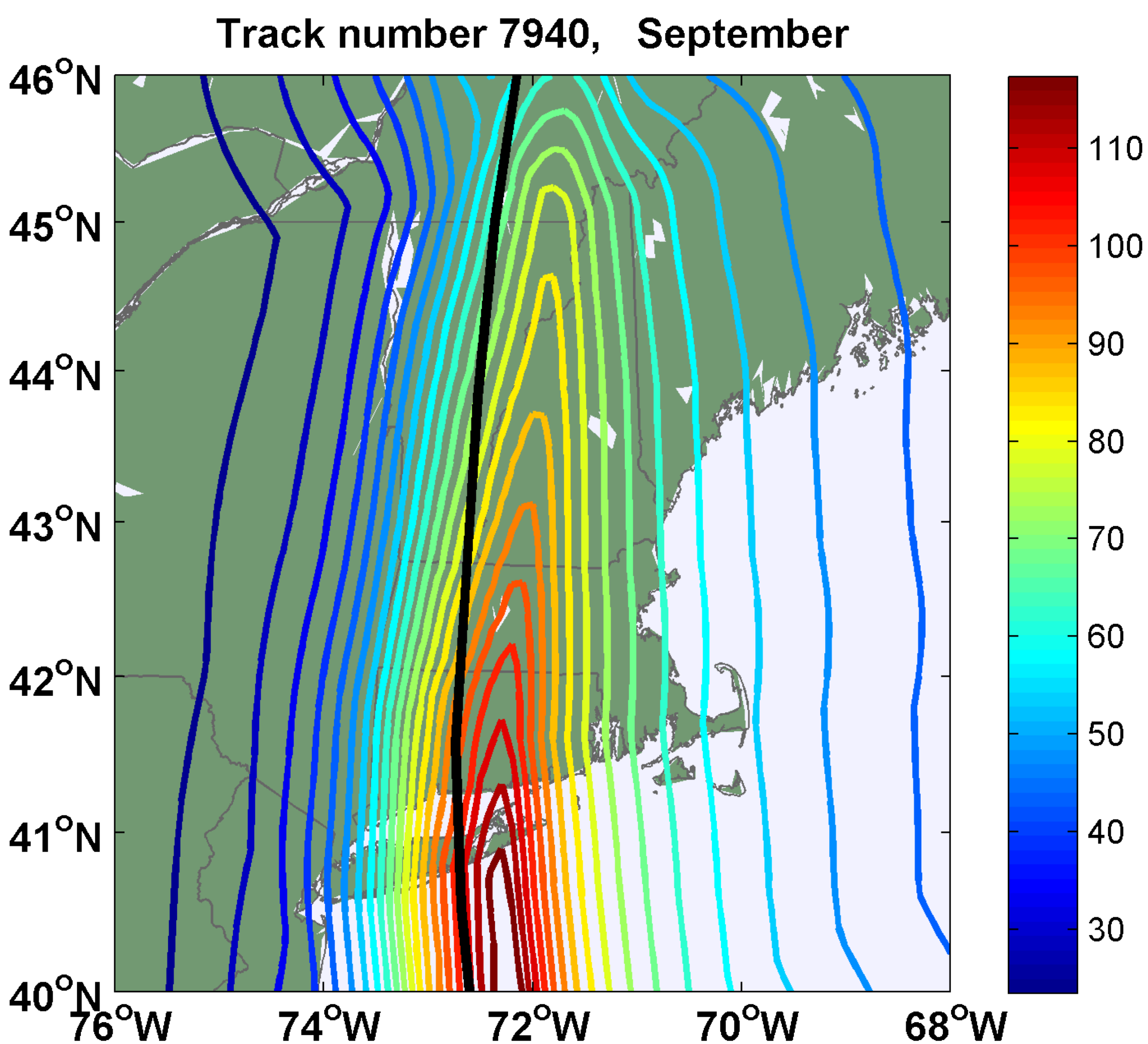
Our Approach:

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

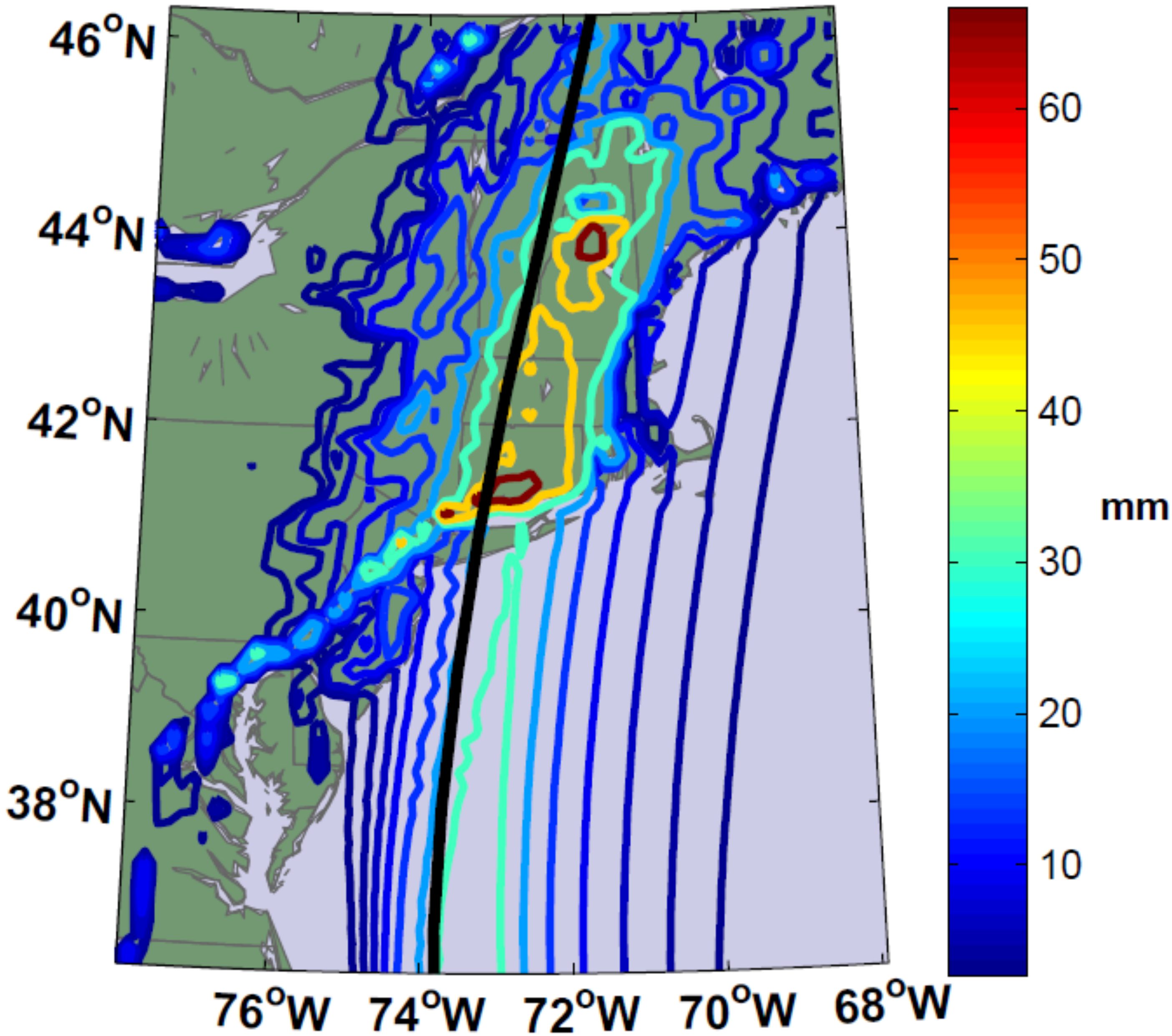
Emanuel, K., R. Sundararajan, and J. Williams, 2008: Hurricanes and global warming: Results from downscaling IPCC AR4 simulations. *Bull. Amer. Meteor. Soc,*, **89**, 347-367


ERA40, 1000 Tracks
90N
70N
50N
30N
10N
10S
30S
50S
70S
40E 60E 80E 100E 120E 140E 160E 180E 160W 140W 120W 100W 80W 60W 40W 20W 0E 20E

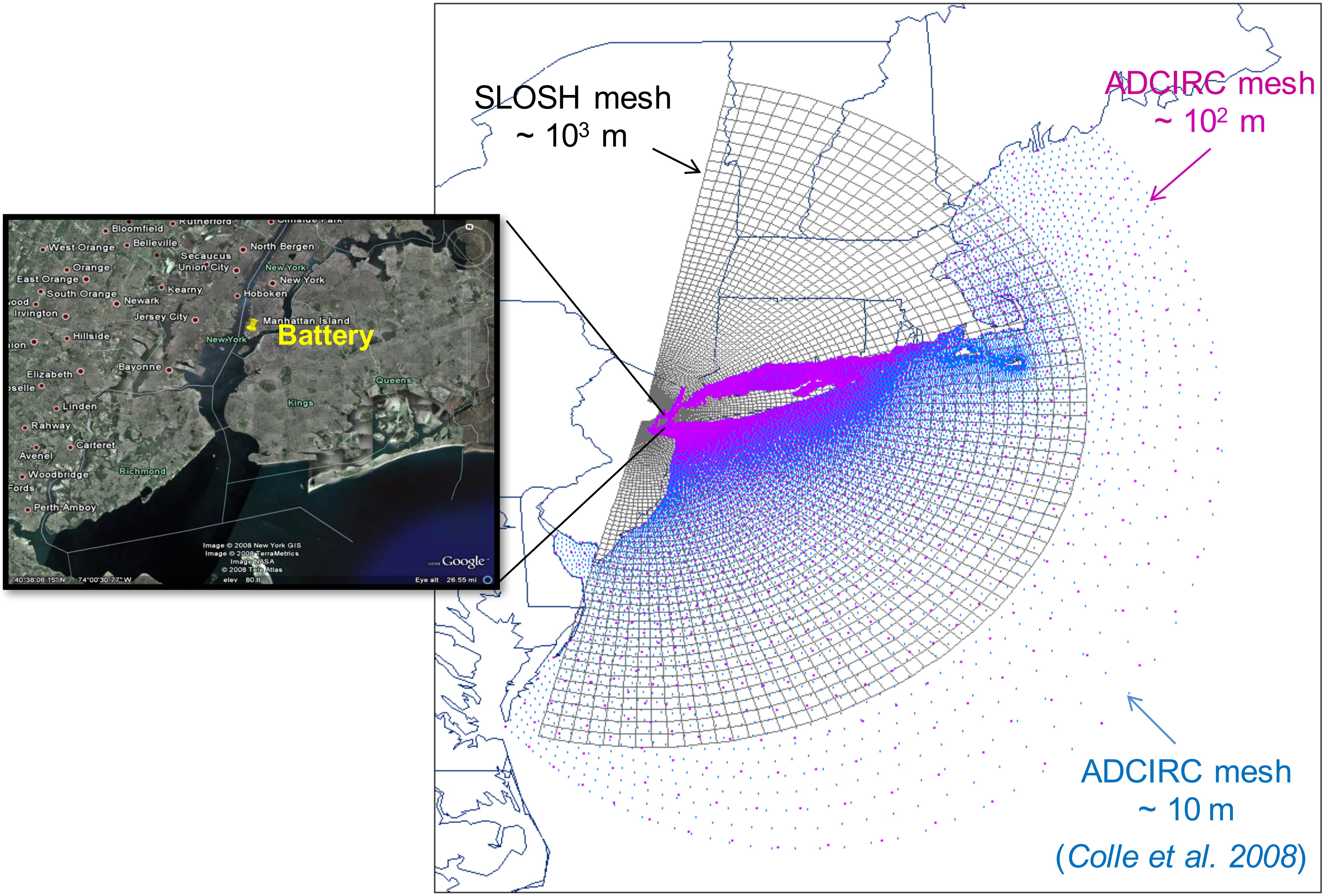
Sample Storm Wind Swath



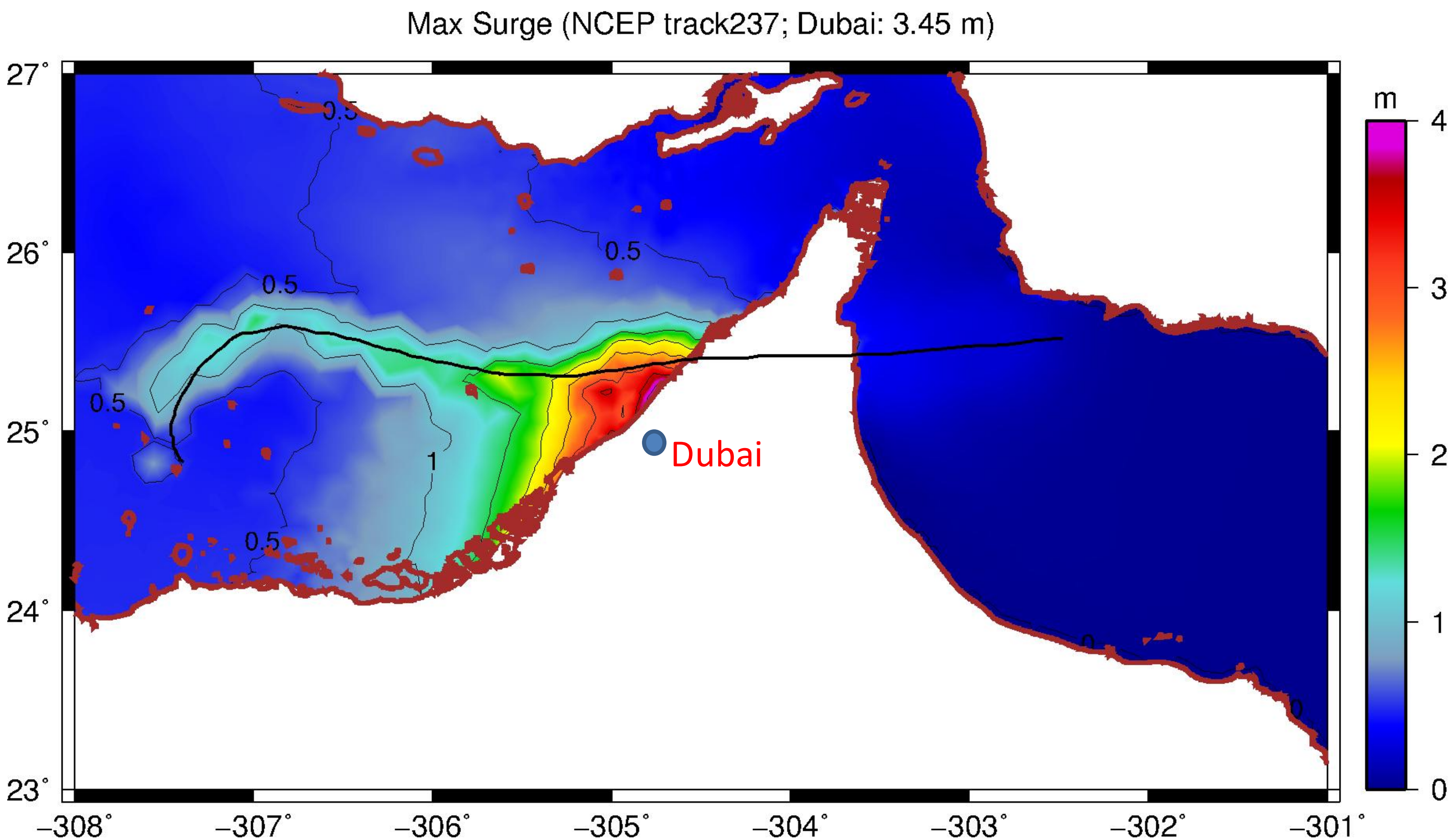
Accumulated Rainfall (mm)



Storm Surge Simulation (Ning Lin)

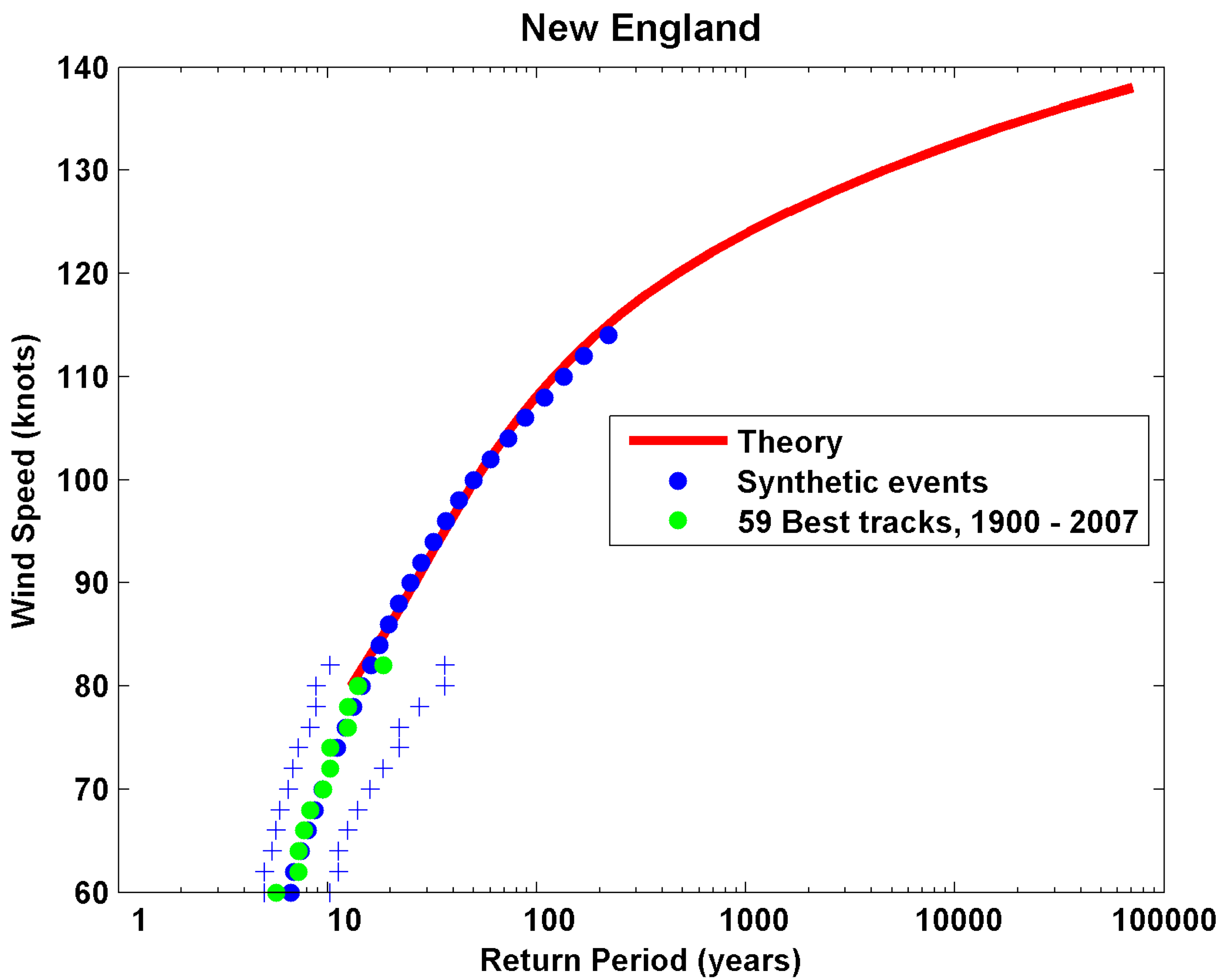


A Grey Swan: Dubai

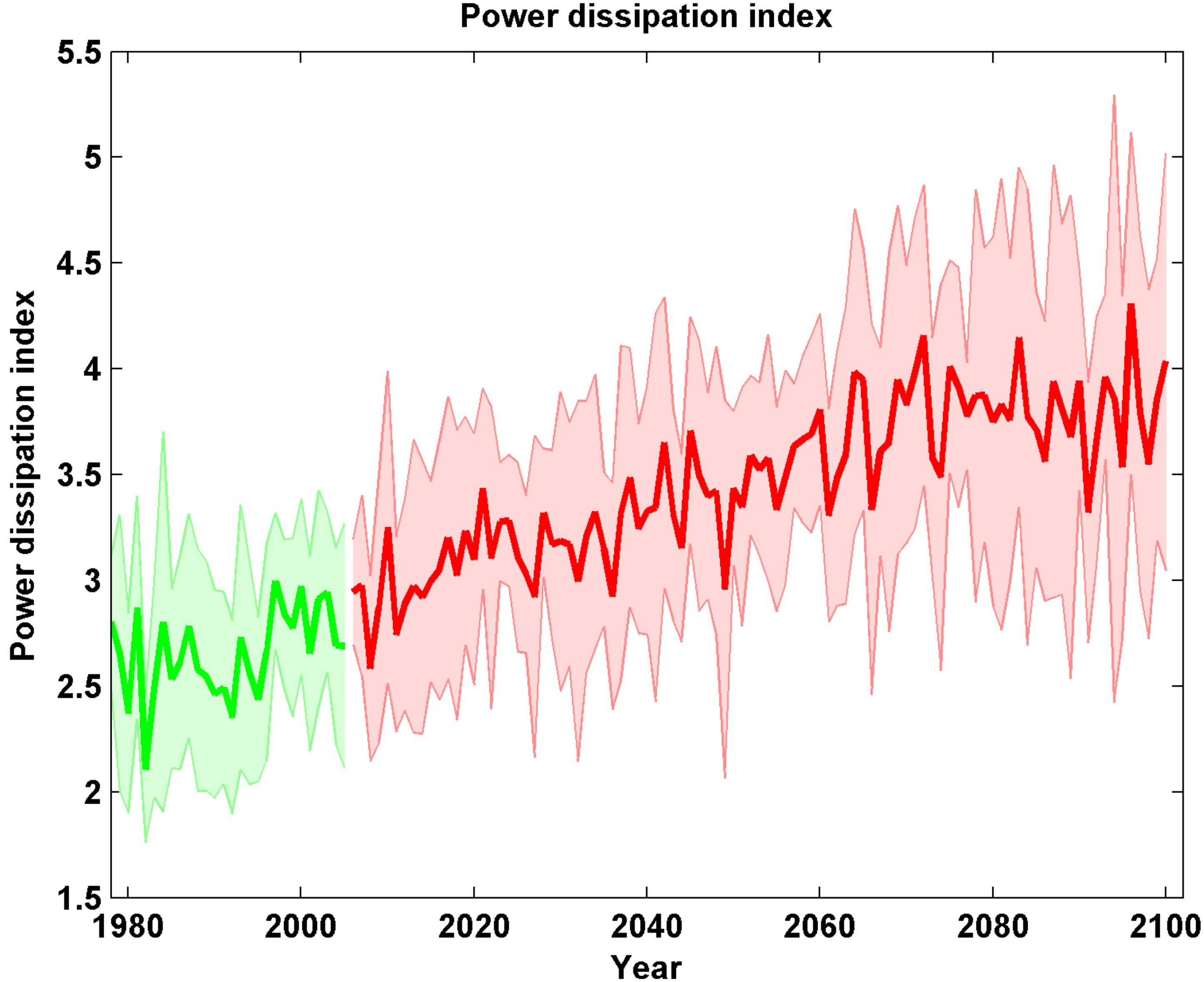


Lin, N. and K. Emanuel, 2015: Grey swan tropical cyclones. *Nature Clim. Change*, doi: 10.1038/NCLIMATE2777

Return Periods

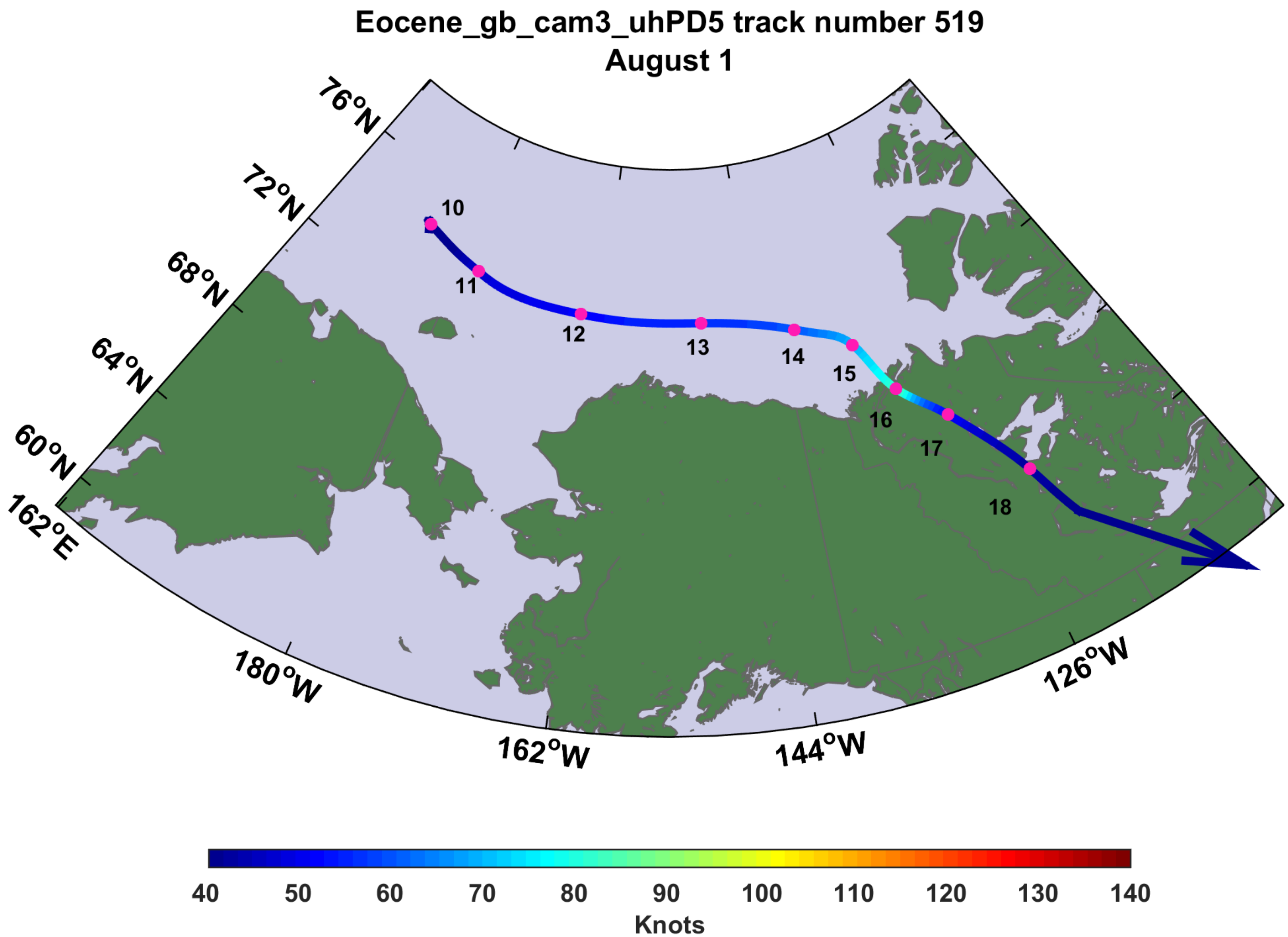


Projections of Global TC Power Dissipation using 6 CMIP5 Climate Models

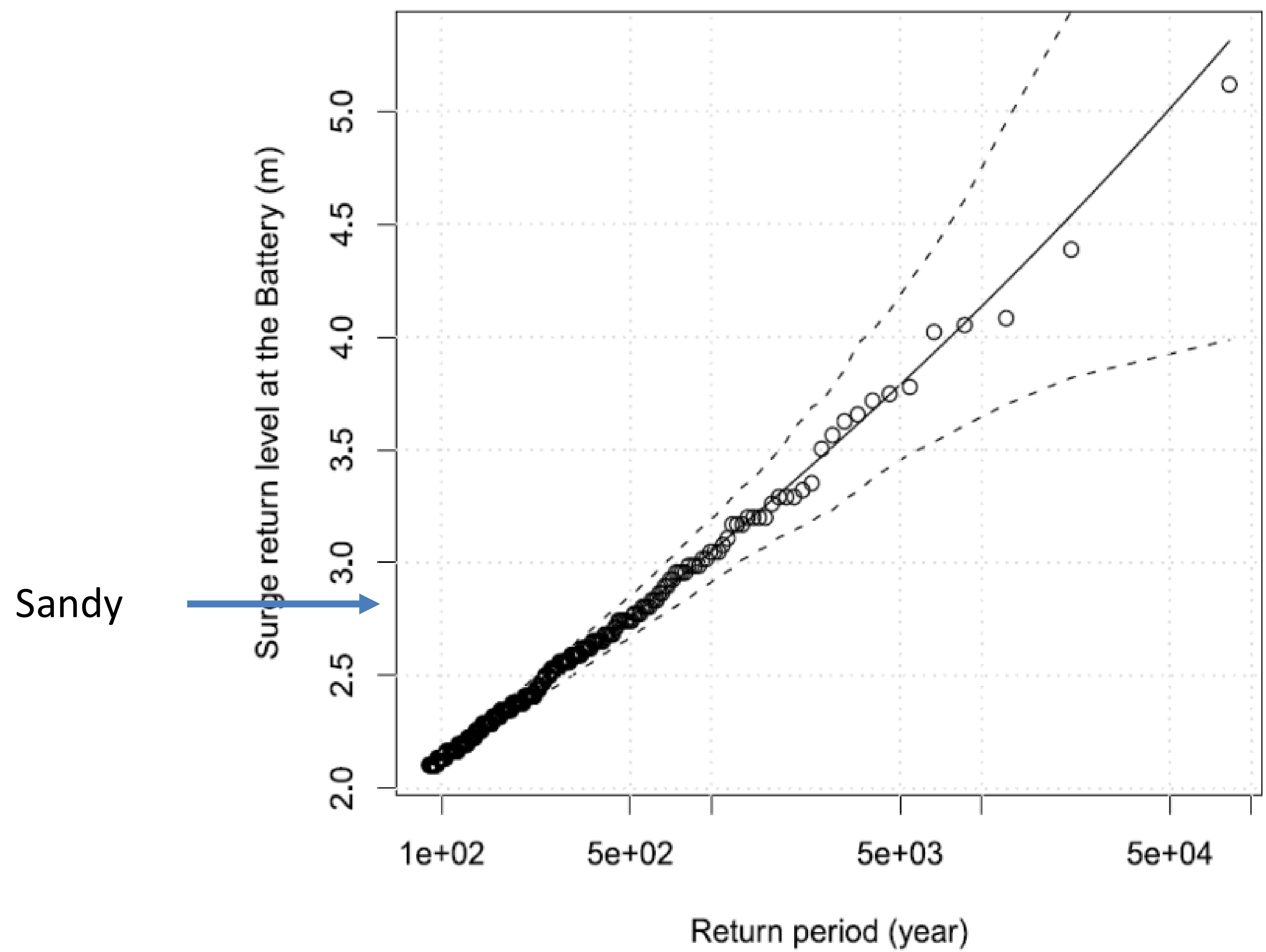


Emanuel, K.A., 2013: Downscaling CMIP5 climate models shows increased tropical cyclone activity over the 21st century. *Proc. Nat. Acad. Sci.*, **110**, doi/10.1073/pnas.1301293110

Eocene hurricane making landfall in the Yukon



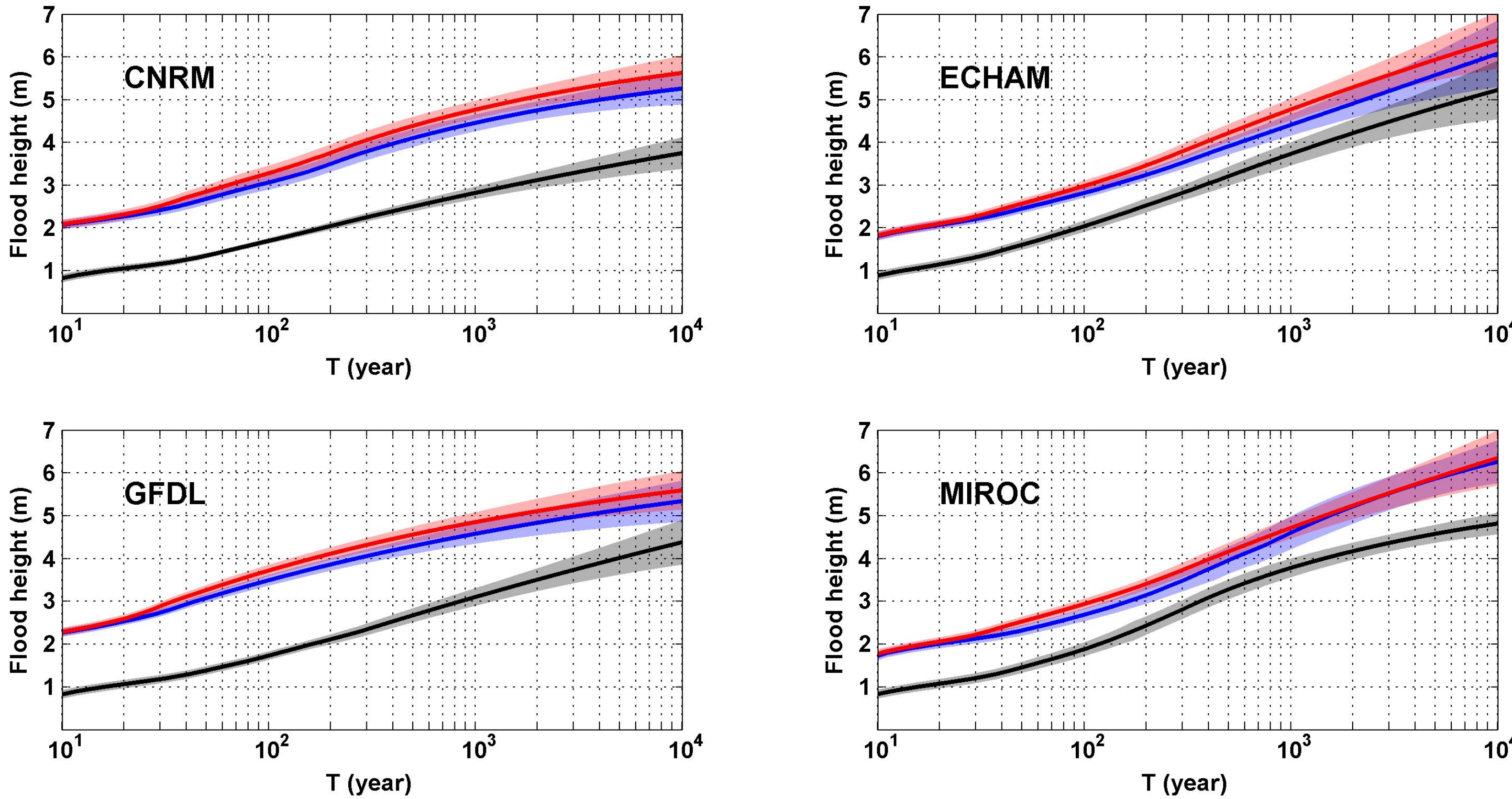
Surge Return Periods for The Battery, New York



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

GCM flood height return level, Battery, Manhattan

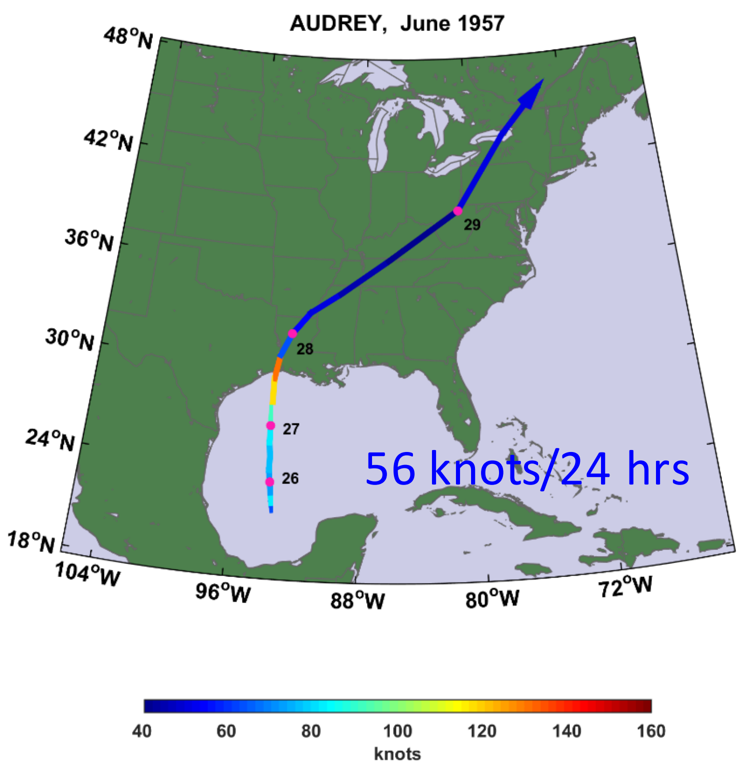
(assuming SLR of 1 m for the future climate)

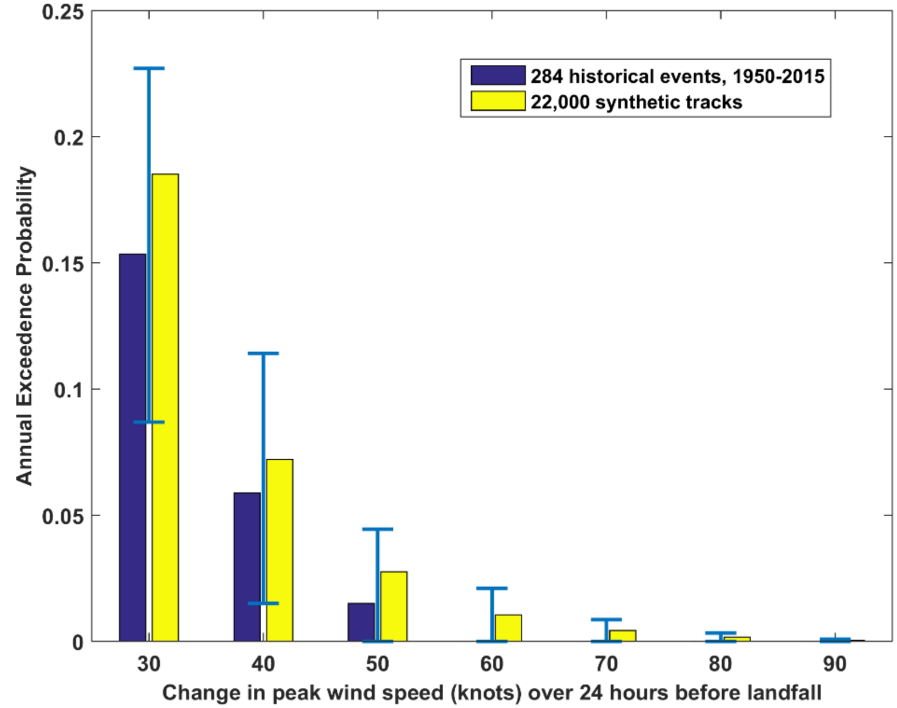


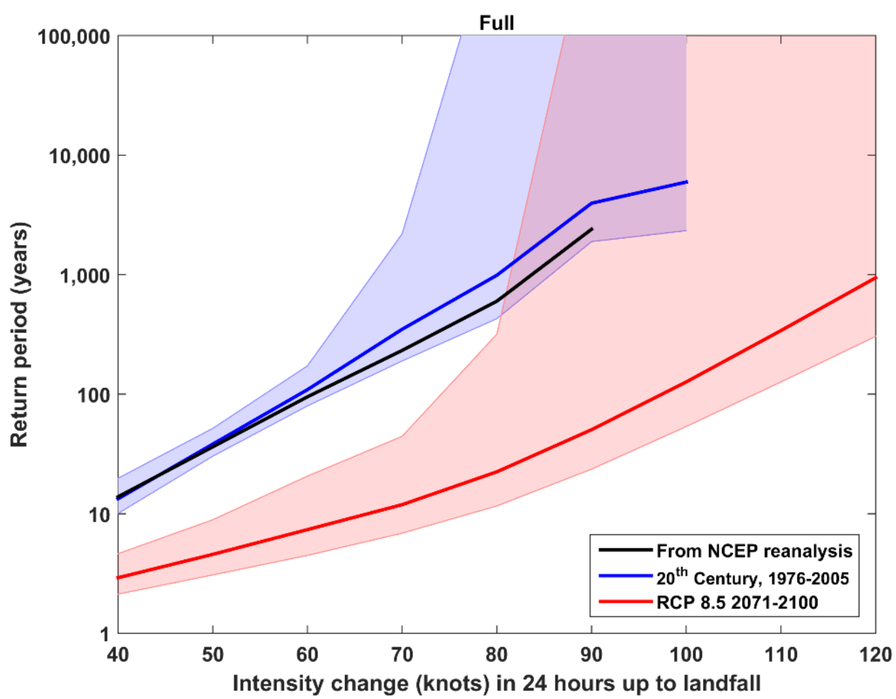
Black: Current climate (1981-2000)
Blue: A1B future climate (2081-2100)
Red: A1B future climate (2081-2100) with R_0 increased by 10% and R_m increased by 21%

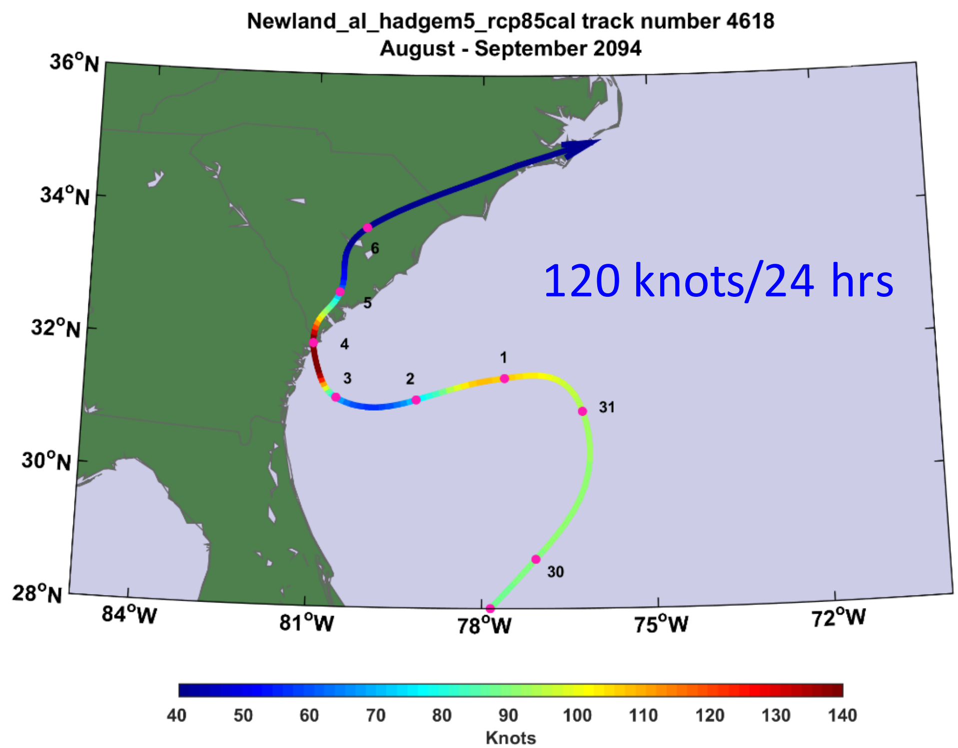
Lin, N., K. Emanuel, M. Oppenheimer, and E. Vanmarcke, 2012: Physically based assessment of hurricane surge threat under climate change. *Nature Clim. Change*, doi:10.1038/nclimate1389

TC Intensity Forecast Nightmares


AUDREY, June 1957
48°N
42°N
36°N
30°N
24°N
18°N
104°W
96°W
88°W
80°W
72°W
29
28
27
26
56 knots/24 hrs
40
60
80
100
120
140
160
knots


284 historical events, 1950-2015
22,000 synthetic tracks
Annual Exceedence Probability
0.25
0.2
0.15
0.1
0.05
0
30
40
50
60
70
80
90
Change in peak wind speed (knots) over 24 hours before landfall


Full
Return period (years)
100,000
10,000
1,000
100
10
1
40
50
60
70
80
90
100
110
120
Intensity change (knots) in 24 hours up to landfall
From NCEP reanalysis
20th Century, 1976-2005
RCP 8.5 2071-2100


Newland_al_hadgem5_rcp85cal track number 4618
August - September 2094
36°N
34°N
32°N
30°N
28°N
84°W
81°W
78°W
75°W
72°W
6
5
4
3
2
1
31
30
120 knots/24 hrs
40
50
60
70
80
90
100
110
120
130
140
Knots

Summary

- The weight of existing evidence supports the conclusion that unmitigated climate warming presents significant risk to future generations
- Scientific uncertainty about the nature and magnitude of climate change entails a low but not tiny risk of catastrophic outcomes
- Among the myriad risks posed by climate change are changes in extreme events, including hurricanes
- There is now a strong consensus that the frequency of high category events should rise, producing a greater number of storms (like Haiyan) that exceed empirical tolerance levels

- There is also a strong consensus that tropical cyclone rainfall and associated flood hazards will increase with temperature

- Increased high category events coupled with sea level indicate a strong risk of increased storm surge hazard