Hurricanes and Climate Change

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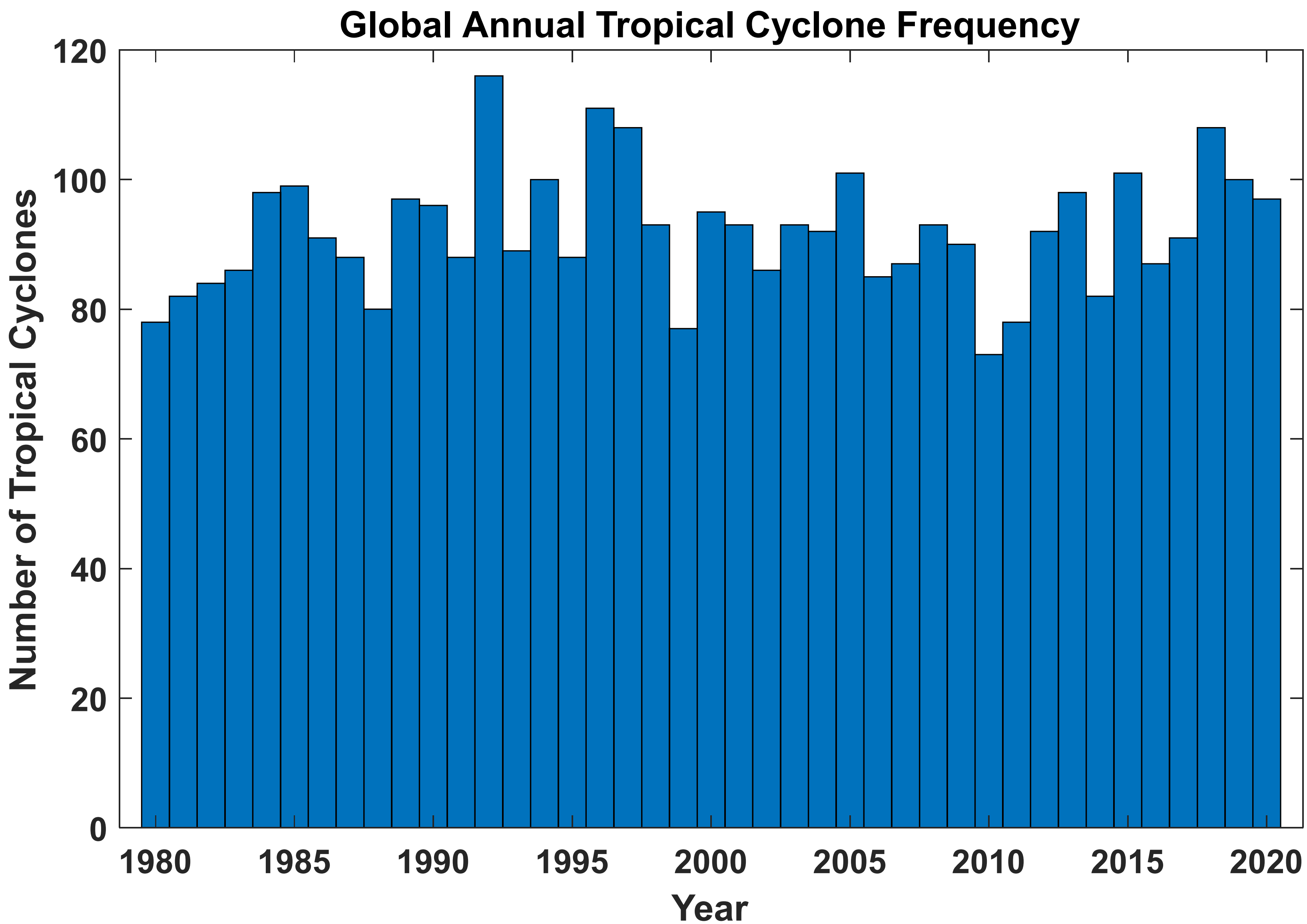
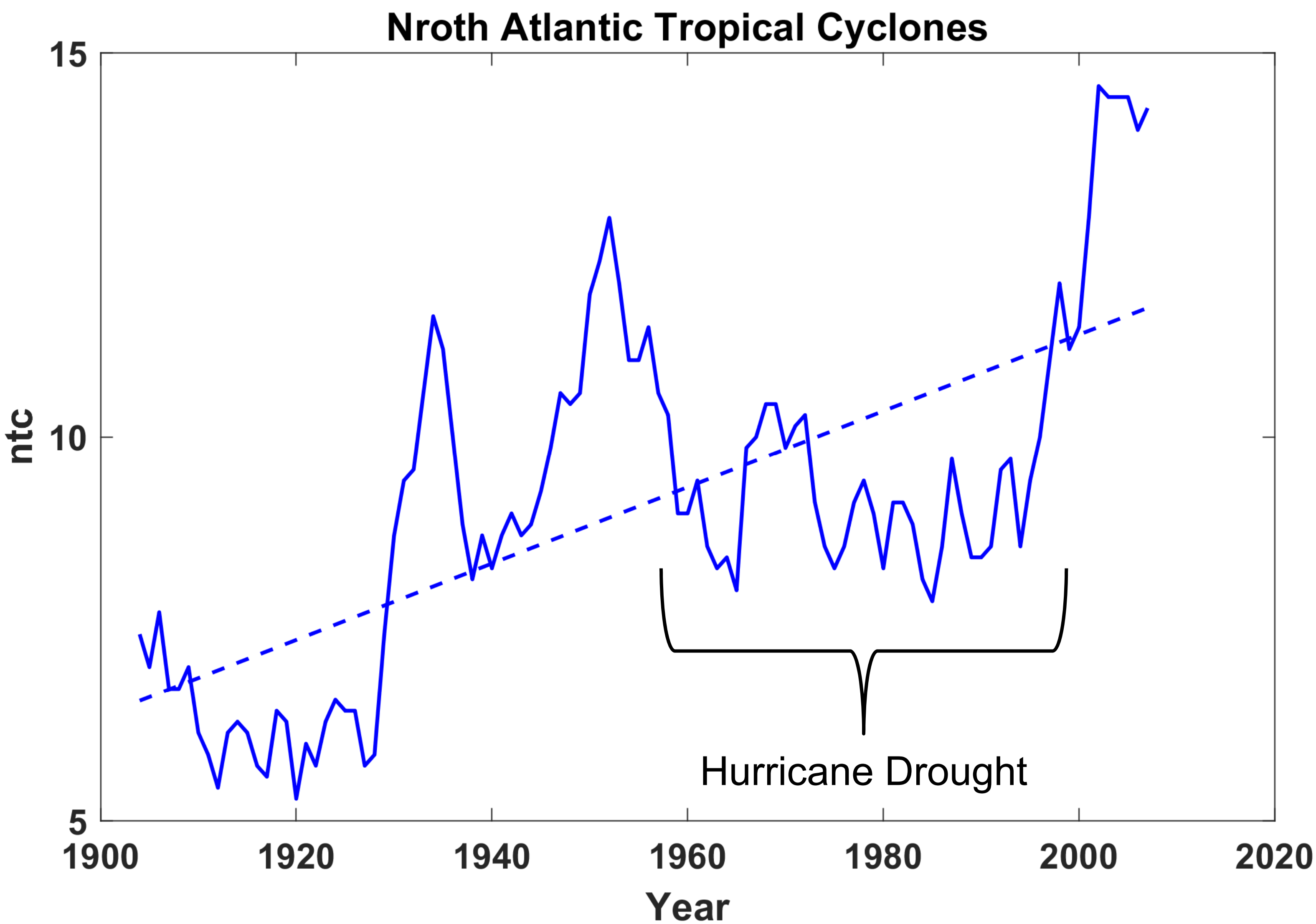
Program

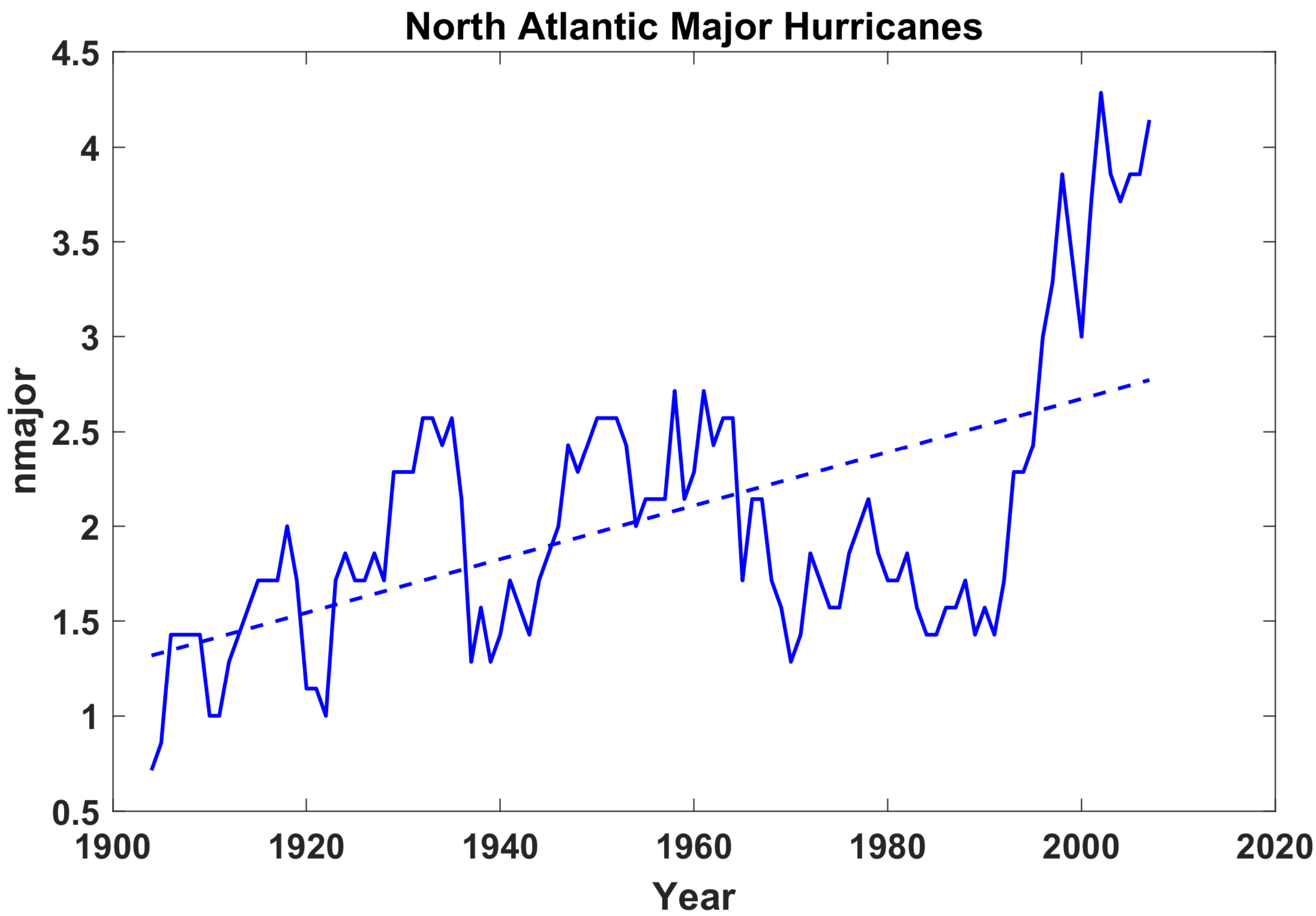
- The historical record of tropical cyclones
- Downscaling reanalyses and models
- Application to 20th century reanalyses
- Feedbacks of tropical cyclones on climate



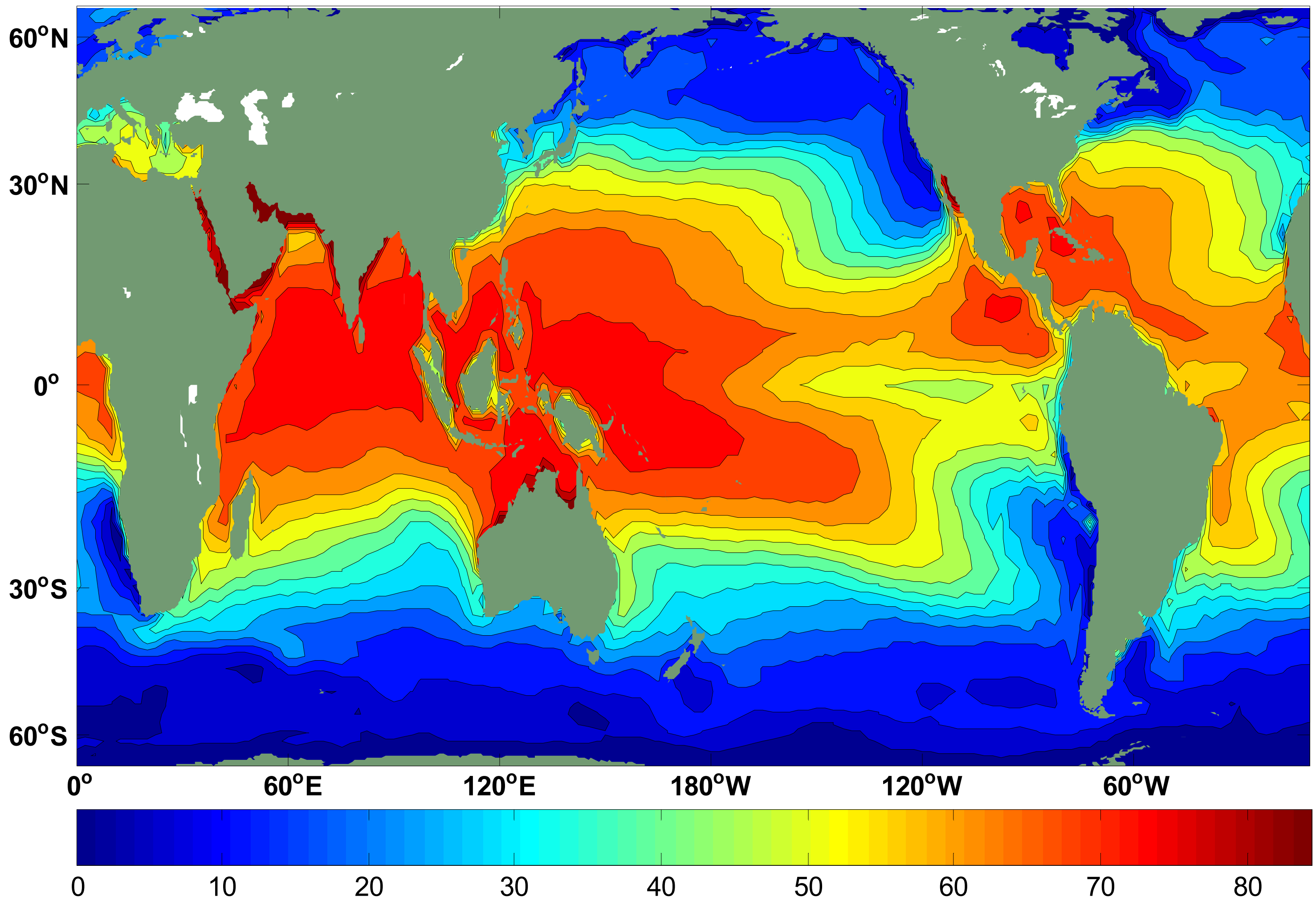
Global records prior to ~1980 are unreliable

North Atlantic tropical cyclone database extends back to 19th century

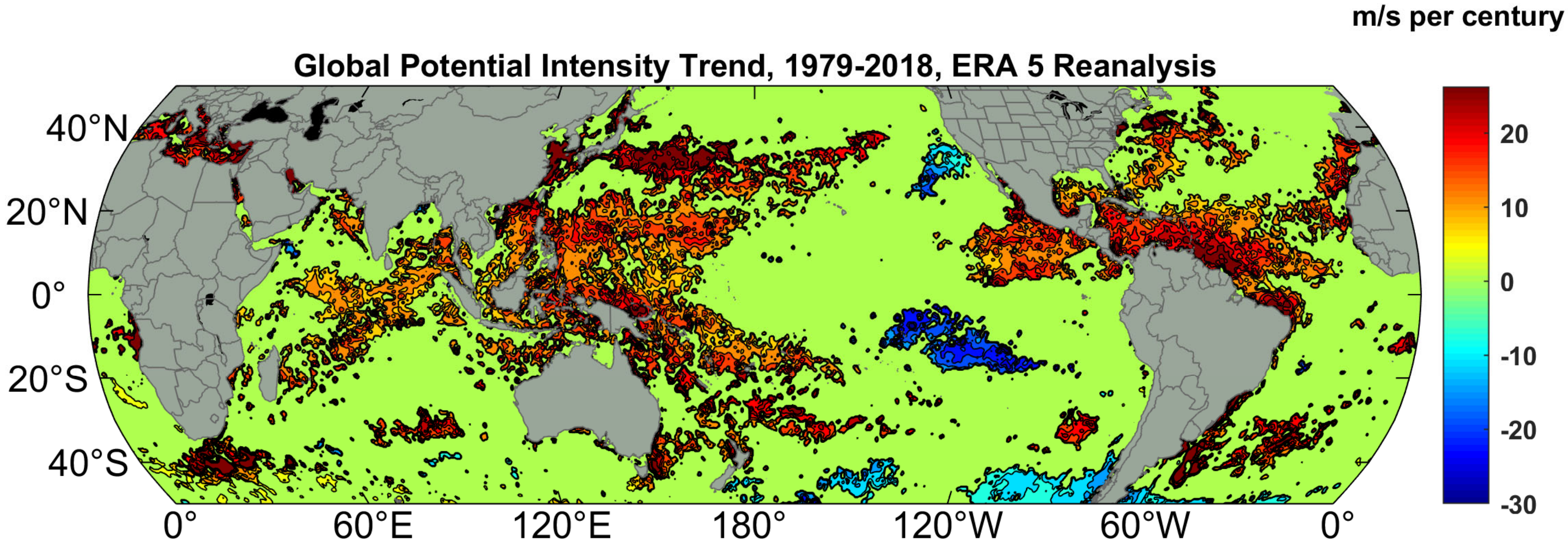



North Atlantic Major Hurricanes
4.5
4
3.5
3
2.5
2
1.5
1
0.5
nmajor
1900
1920
1940
1960
1980
2000
2020
Year

Annual Maximum Potential Intensity (m/s)

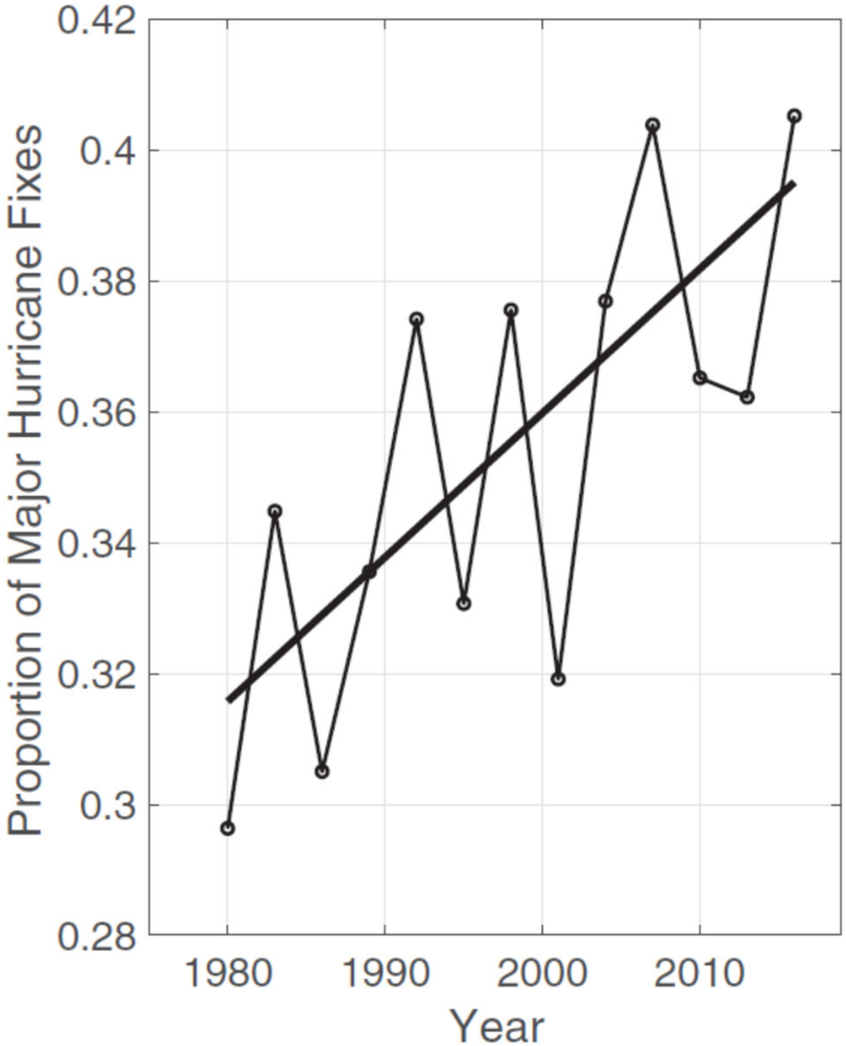


Potential Intensity Trend, 1979-2018, ERA 5 Reanalysis



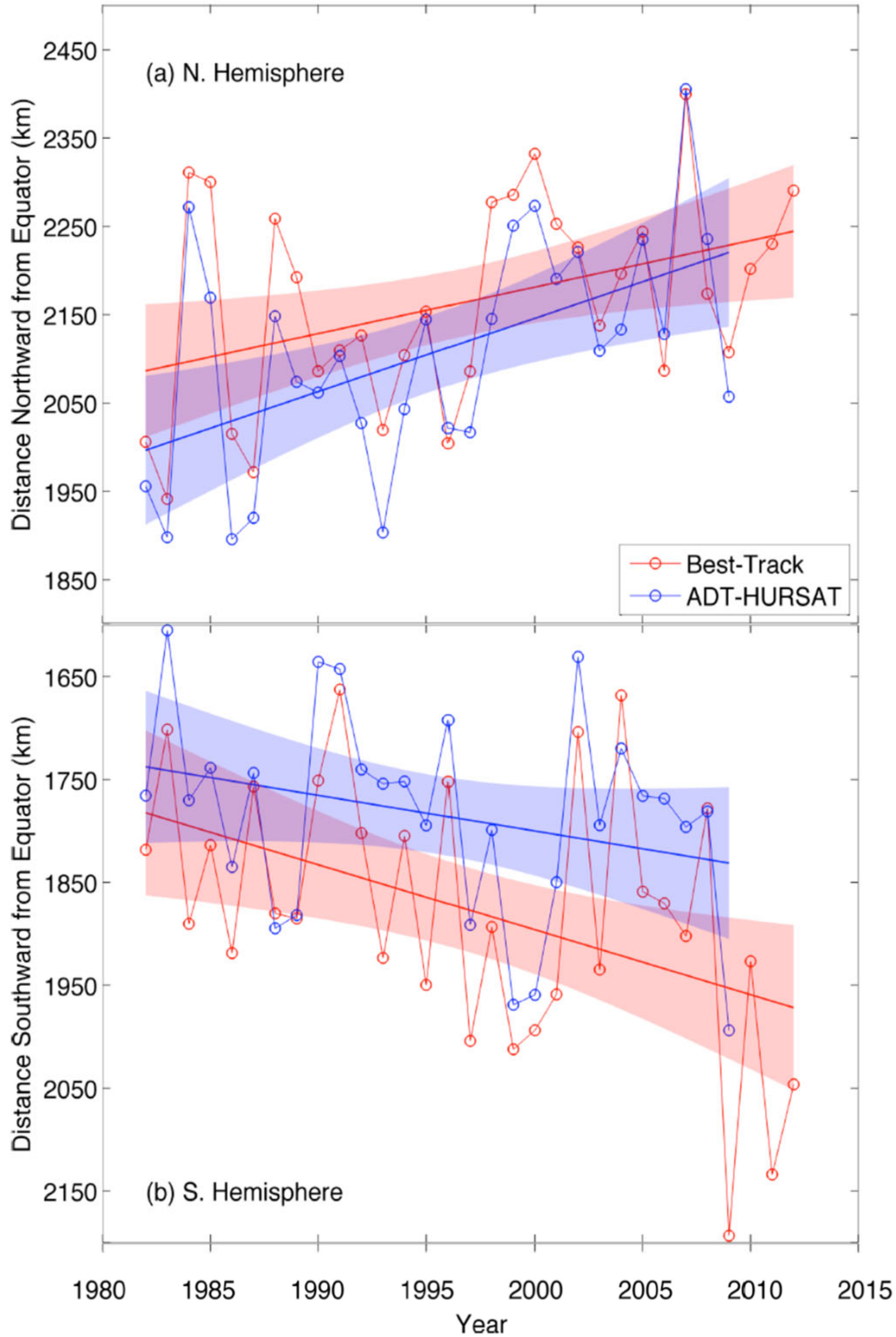
(Trend shown only where p value < 0.05)

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

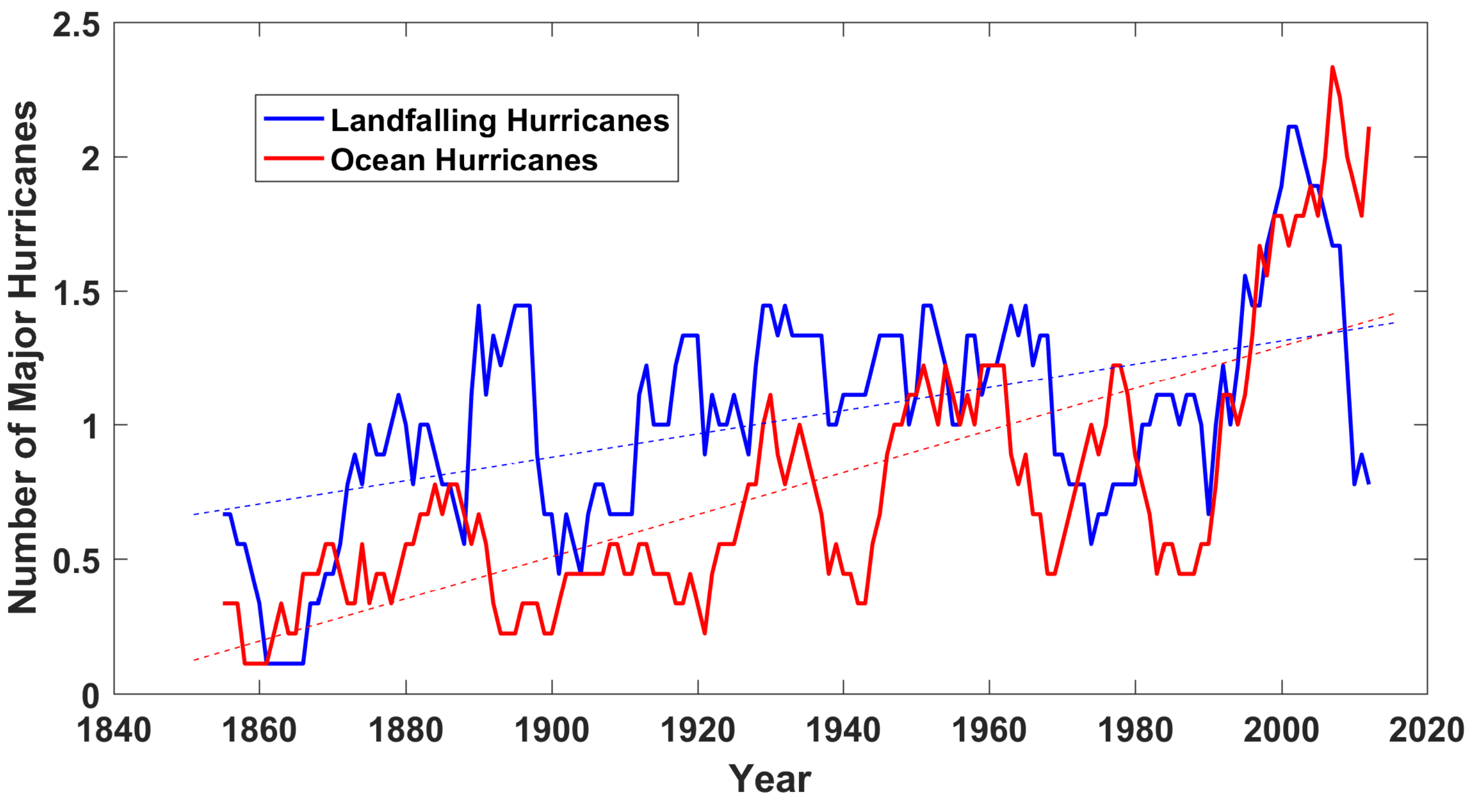


Hurricanes are reaching peak intensity at higher latitudes

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

From *Kossin et al. (2014)*

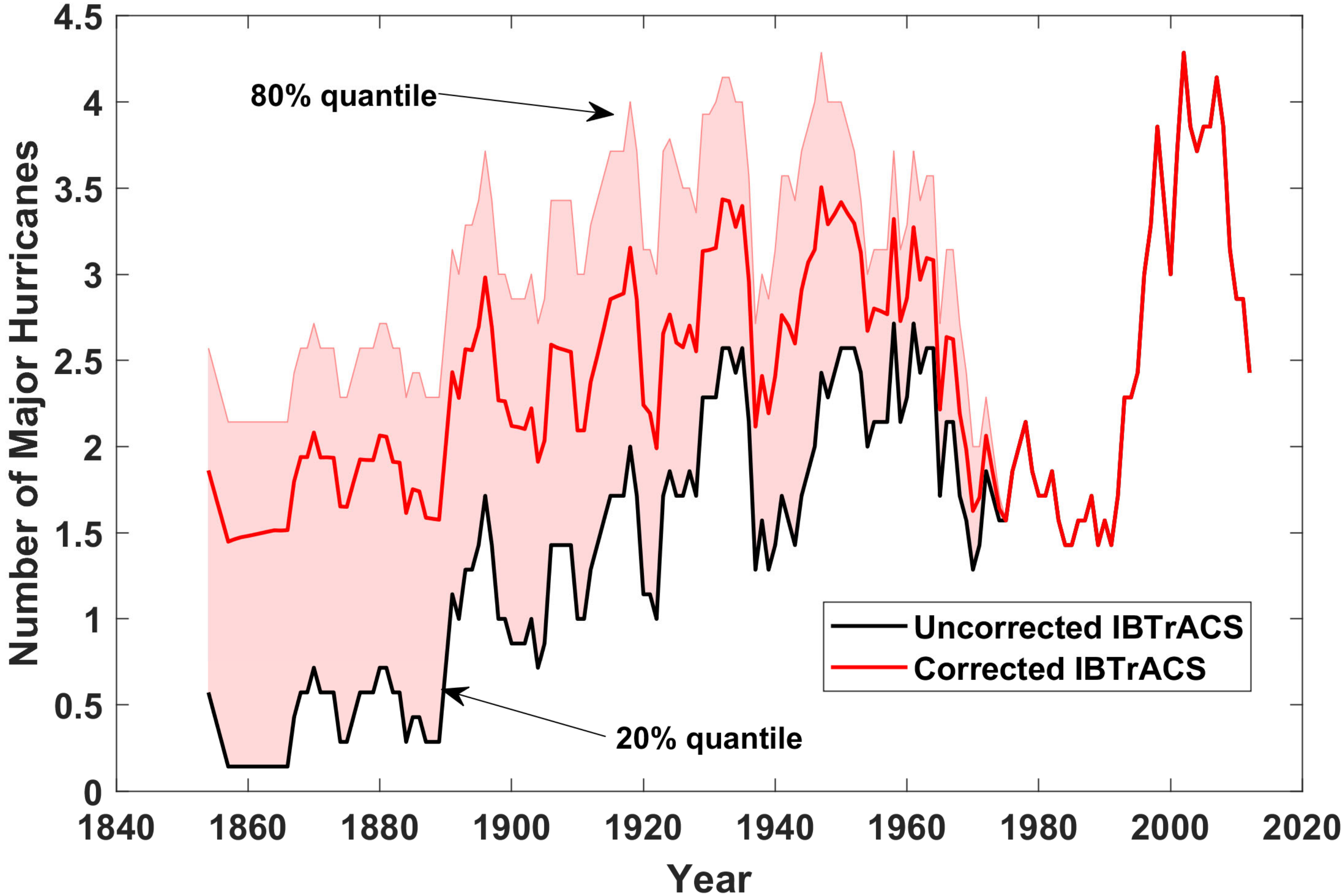
North Atlantic standard database extends back to 1851 but there are problems



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.

Statistical Corrections to Early Record

- Vecchi et al., *Nature Comm*., 2021
- Resample post-1971 historical record with digitized ship tracks (ICOADS) before 1971 to estimate number of missing storms
- Add estimated number of missing storms to original historical record



Note: ~20% of the bootstrapped samples agree with the historical record

Data from Vecchi et al., *Nature Comm.*, 2021

Potential problems with corrections

- Weights the null hypothesis of no change. For example, an early year that actually had no cyclones but some ship tracks would be corrected to a number equal to the number missed in sampling of modern storms by those ship tracks

- ICOADS only contains ship logs that have been digitized. Many have not. Historical track reconstructions relied on other data sources, such as newspaper reports of ship encounters with storms at sea

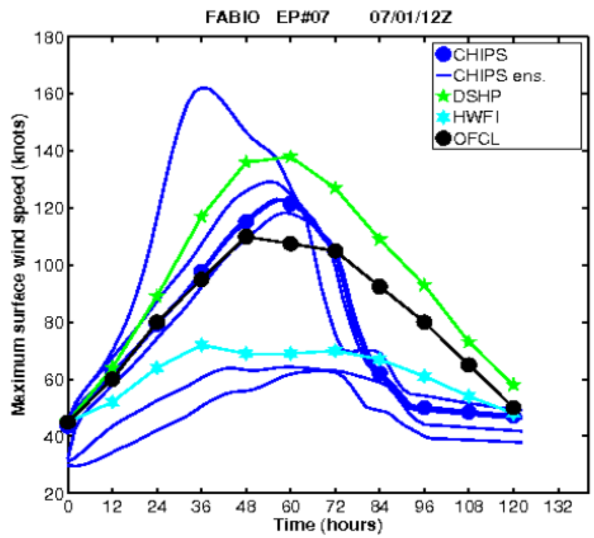
An Alternative Approach

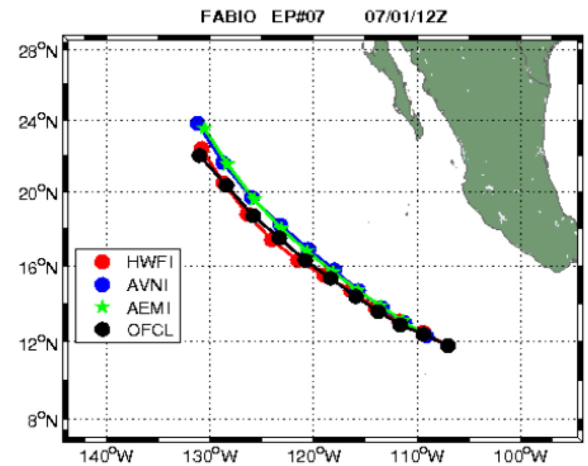
- Apply dynamical tropical cyclone downscaling to 20th century reanalyses
- These reanalyses, in contrast with standard reanalyses (like ERA 5) assimilate ONLY sea surface temperature, sea level pressure, and sea ice
- We use three 20th century reanalyses: NOAA v. 2c (1851-2014), NOAA v.3 (1836-2015), and CERA 20c (1901-2010).
- CERA 20c assimilates marine surface winds and uses a coupled model with SSTs relaxed back to HadISST 2

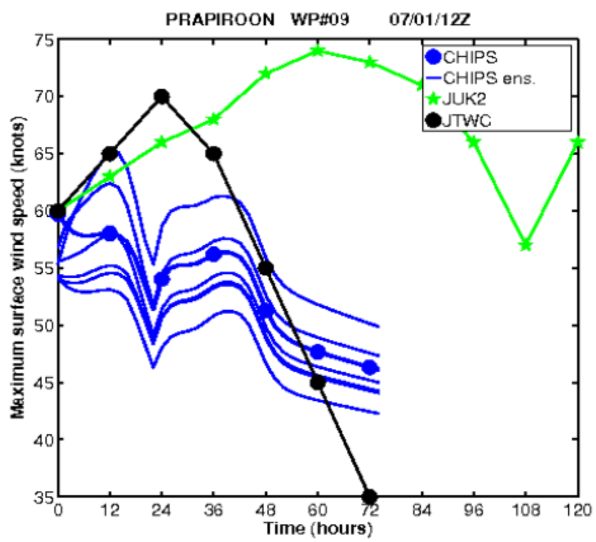
MIT Synthetic Hurricanes

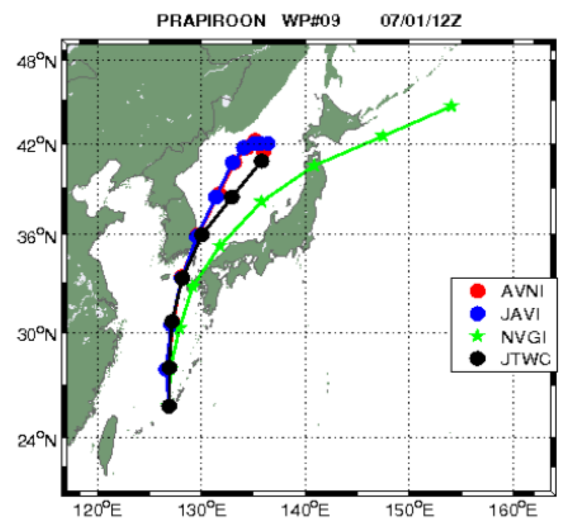
- **Embed high-resolution, fast coupled ocean-atmosphere hurricane model in global climate model or climate reanalysis data**
- **Coupled Hurricane Intensity prediction Model (CHIPS) has been used for 20 years to forecast real hurricanes in near-real time**

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









Risk Assessment Approach:

- **Step 1**: Seed each ocean basin with a very large number of weak, randomly located cyclones

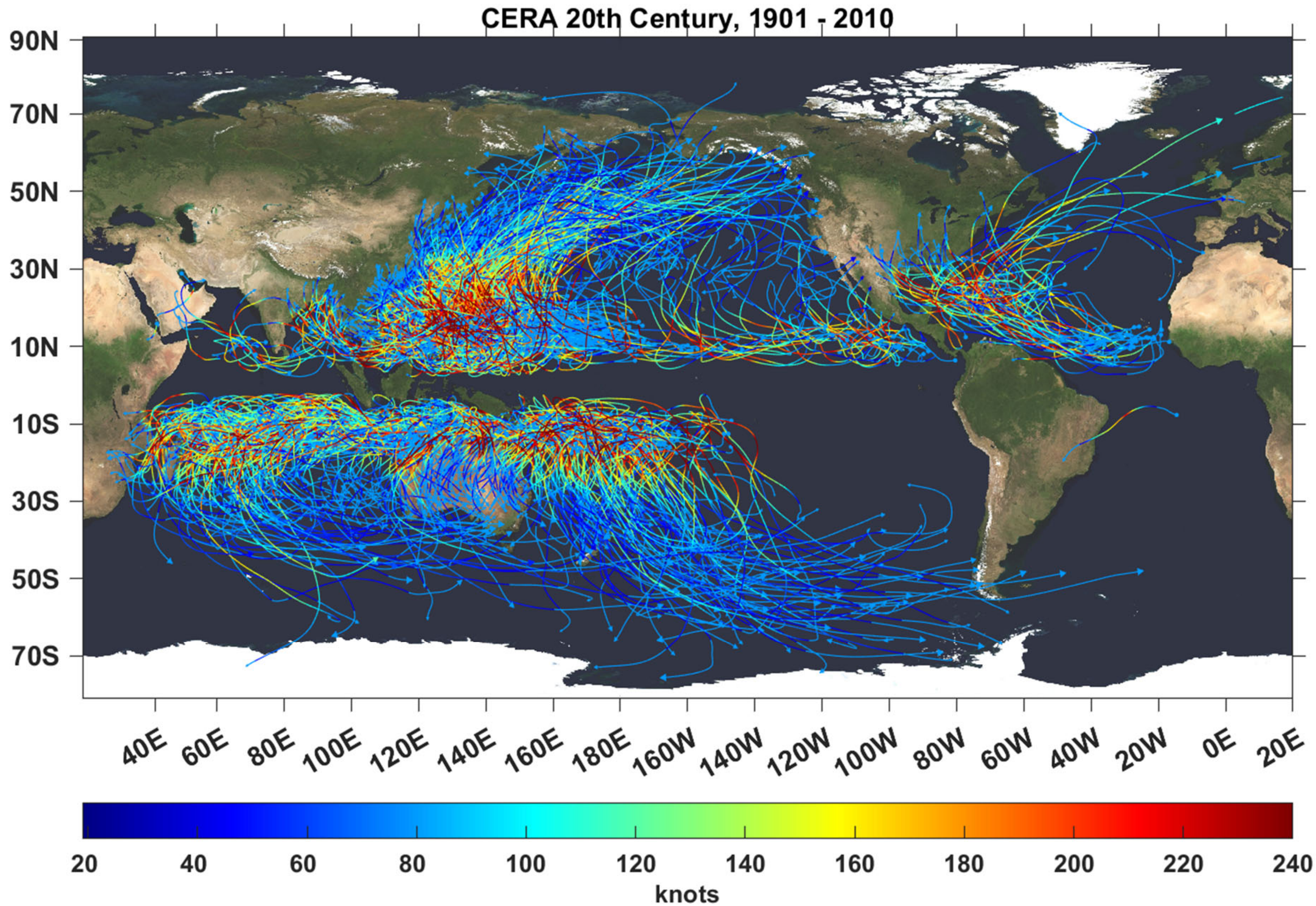
- **Step 2**: Cyclones are assumed to move with the large scale atmospheric flow in which they are embedded, plus a correction for the earth's rotation and sphericity (beta-drift)

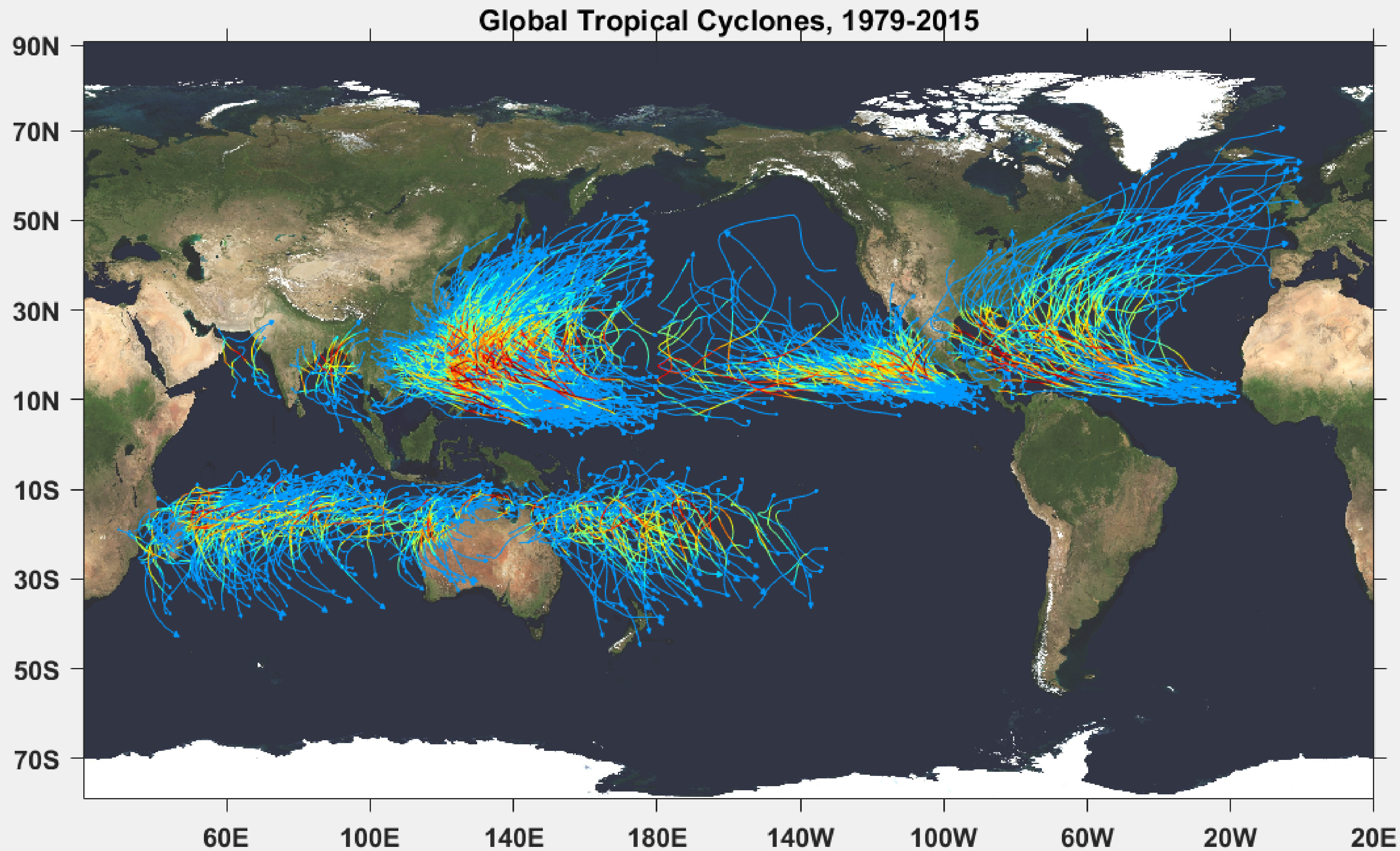
- **Step 3**: Run the CHIPS coupled intensity model for each cyclone, and note how many achieve at least tropical storm strength

- **Step 4:** Using the small fraction of surviving events, determine storm statistics. Can easily generate 100,000 events

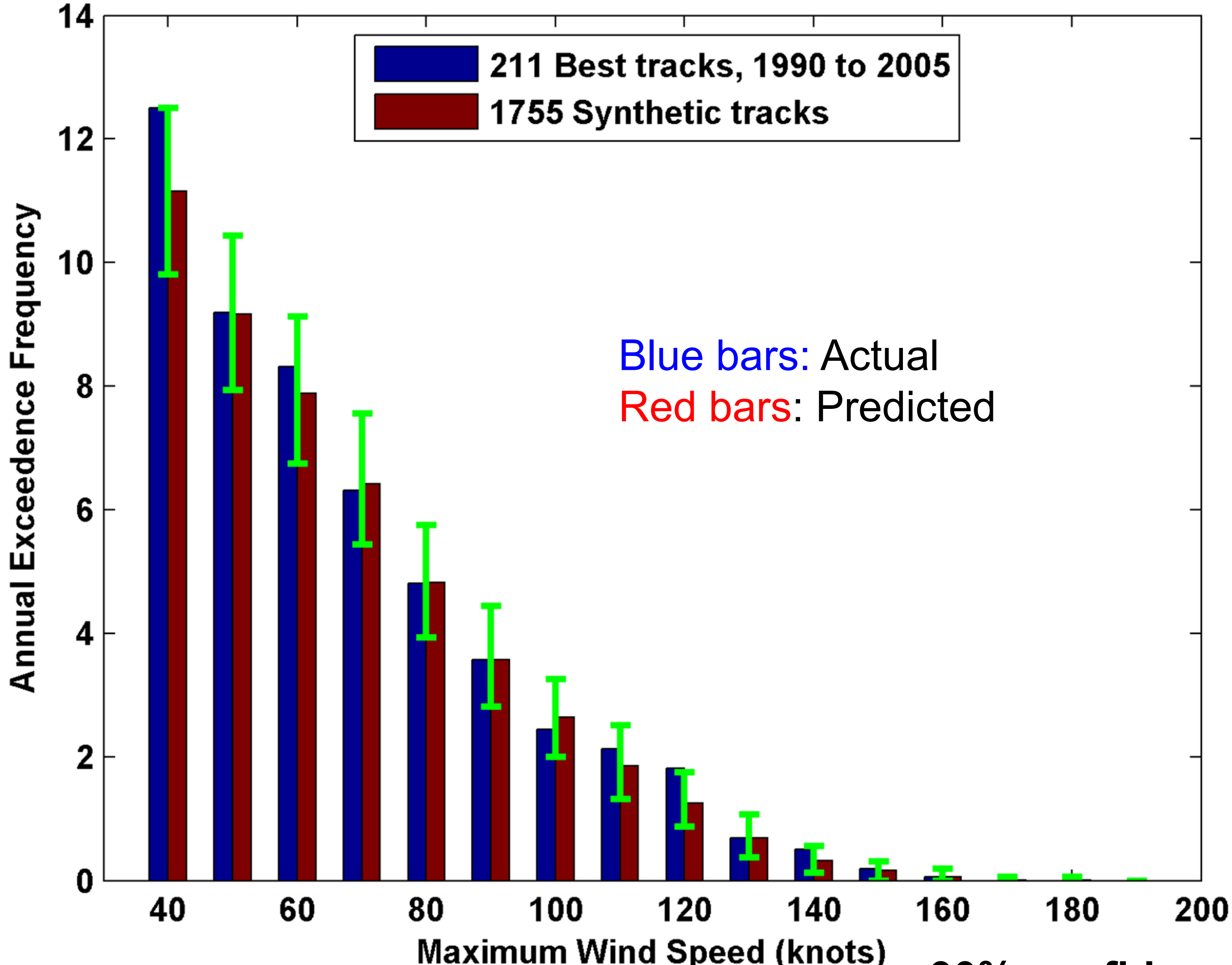
Details: Emanuel et al., *Bull. Amer. Meteor. Soc*, 2008

Top 1,000 storms Downscaled from CERA 29th Century Reanalysis



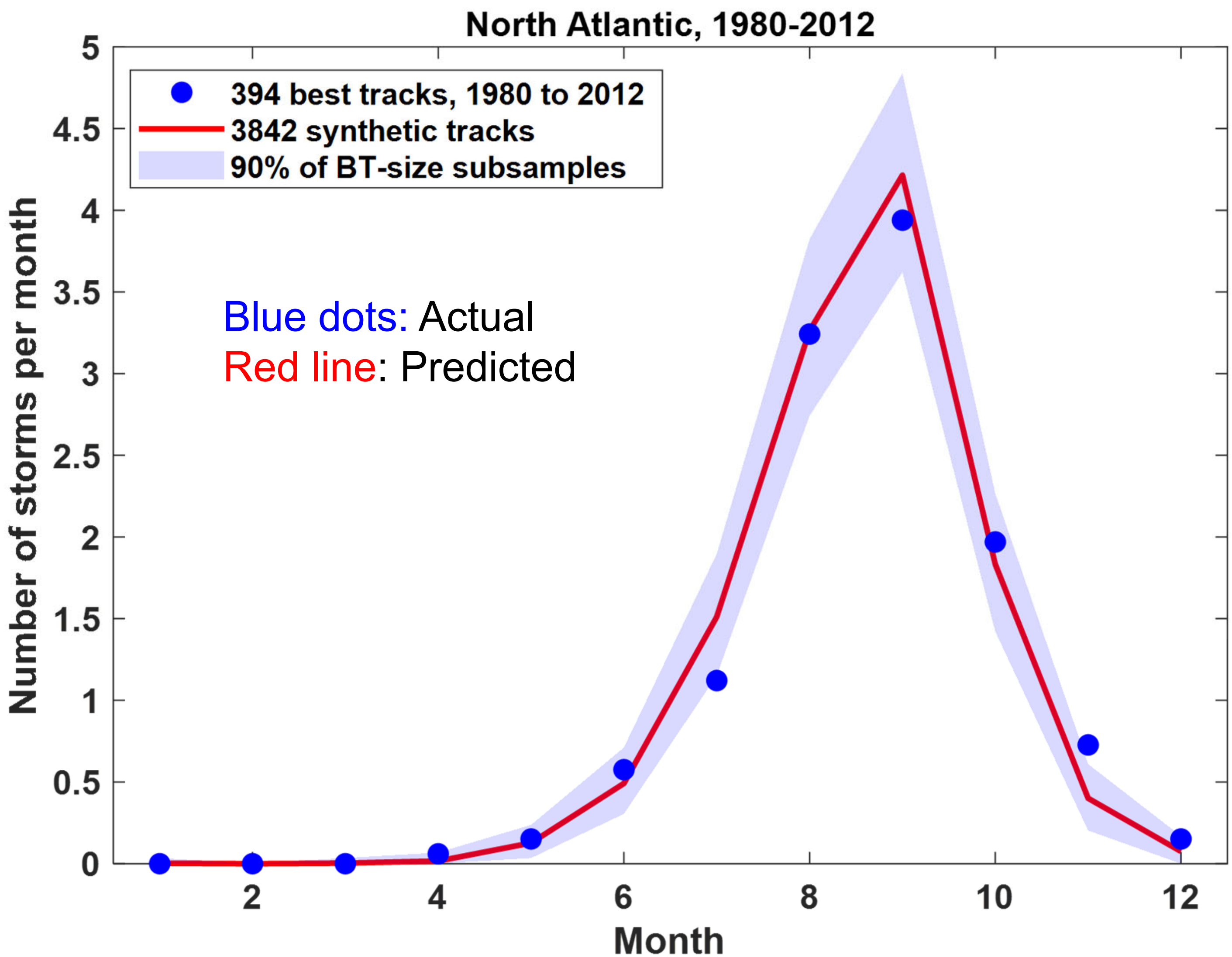

Global Tropical Cyclones, 1979-2015
90N
70N
50N
30N
10N
10S
30S
50S
70S
60E
100E
140E
180E
140W
100W
60W
20W
20E

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

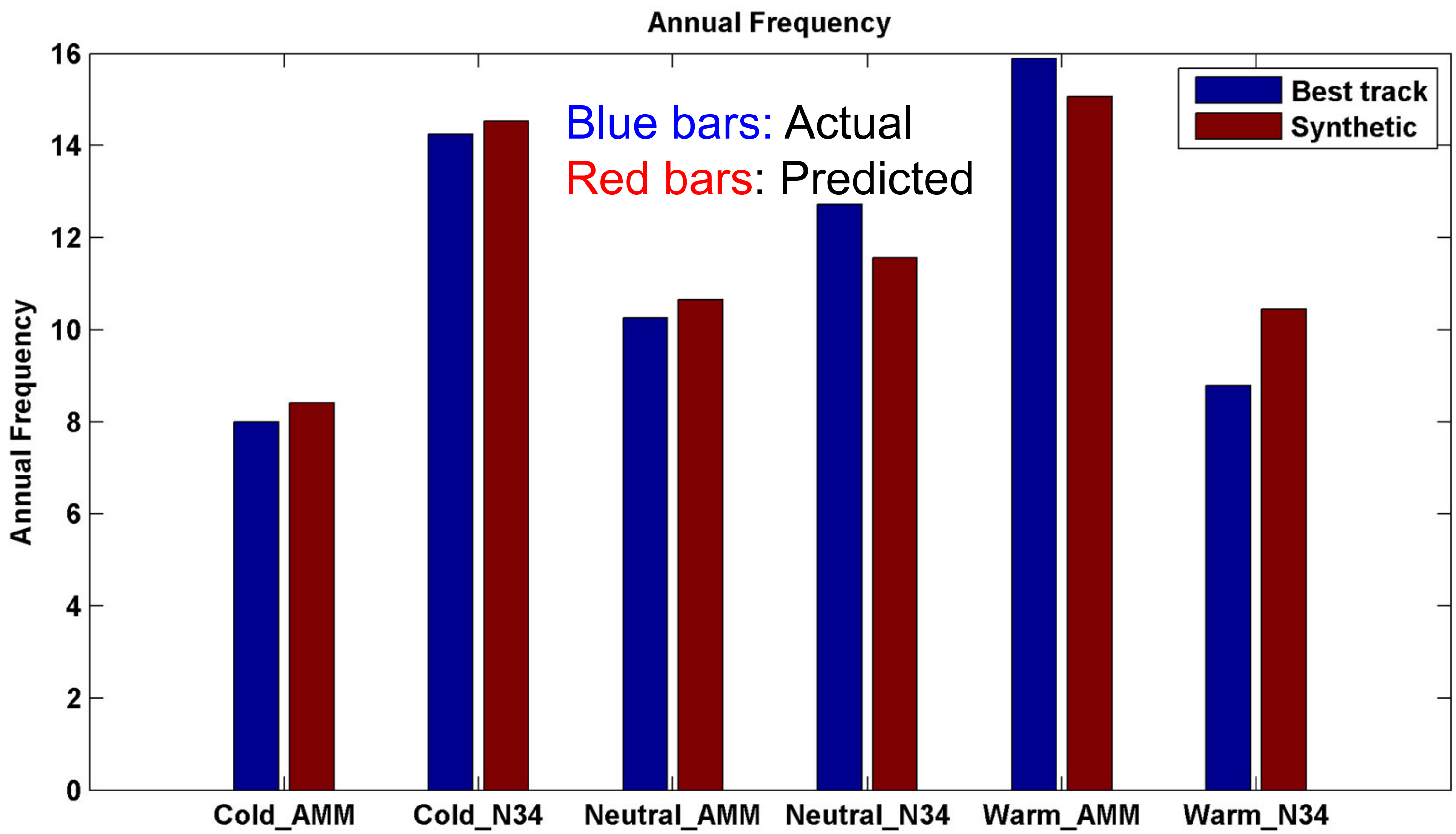


90% confidence bounds

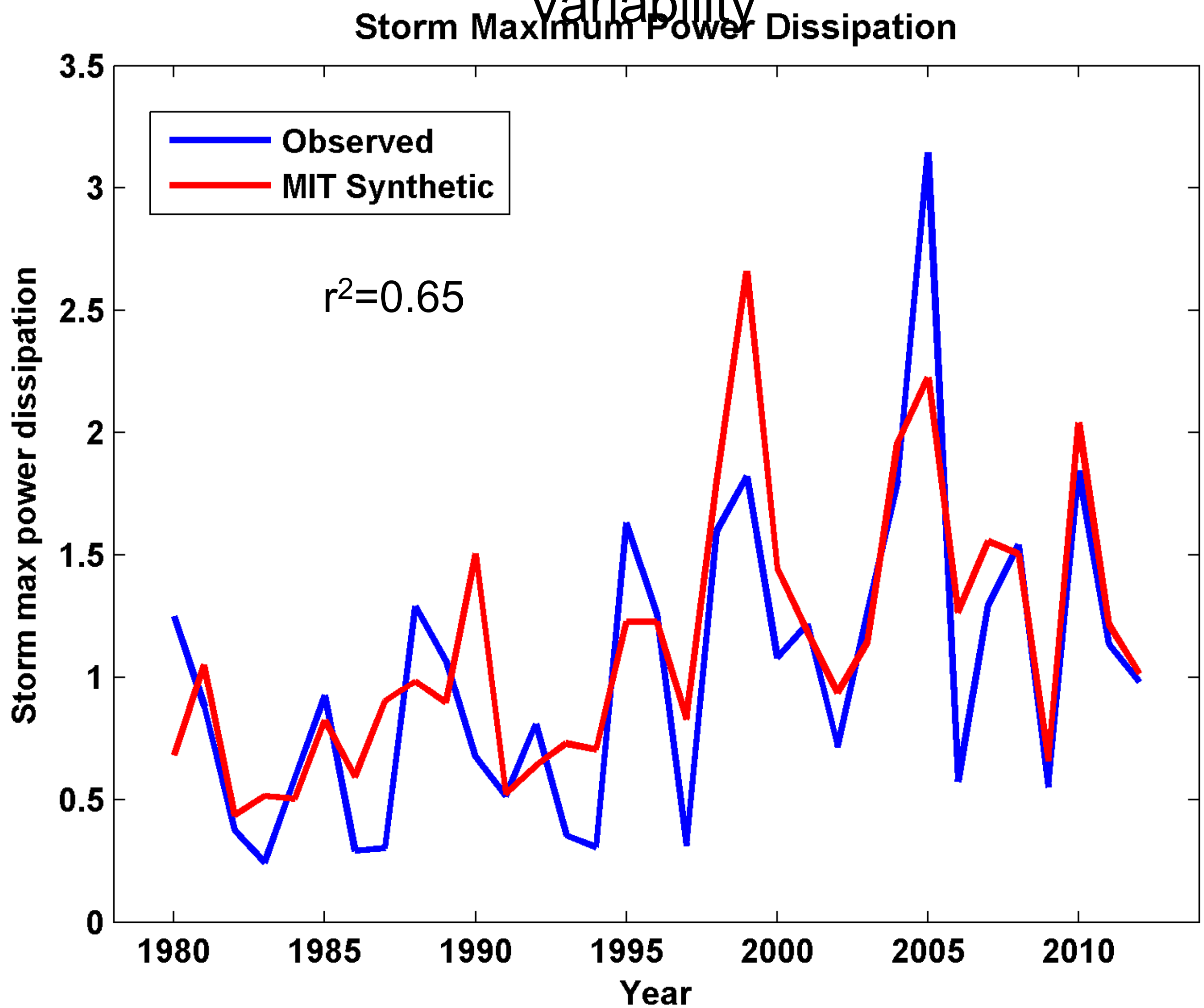
Atlantic Annual Cycle



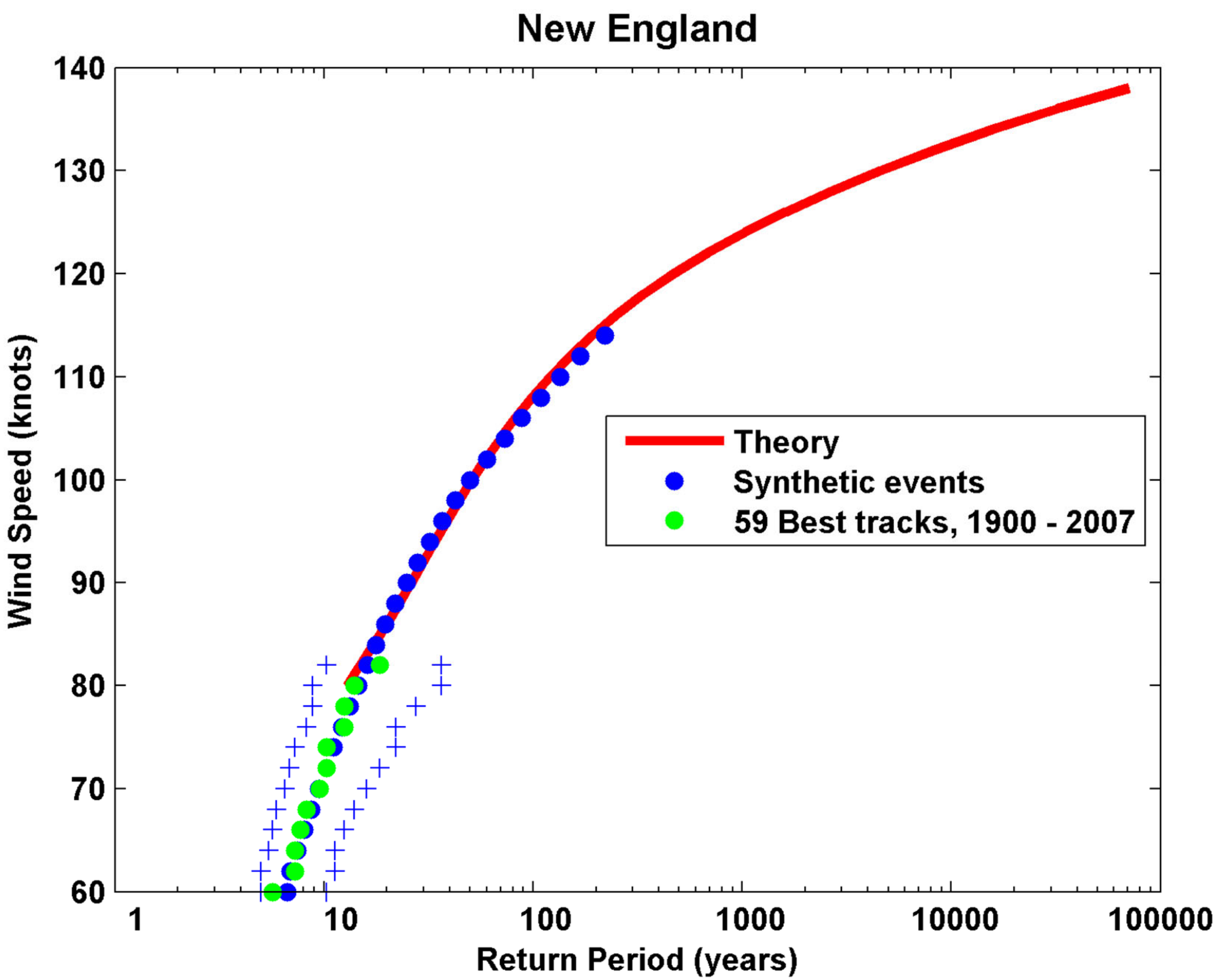
Captures effects of regional climate phenomena (e.g. ENSO, AMM)



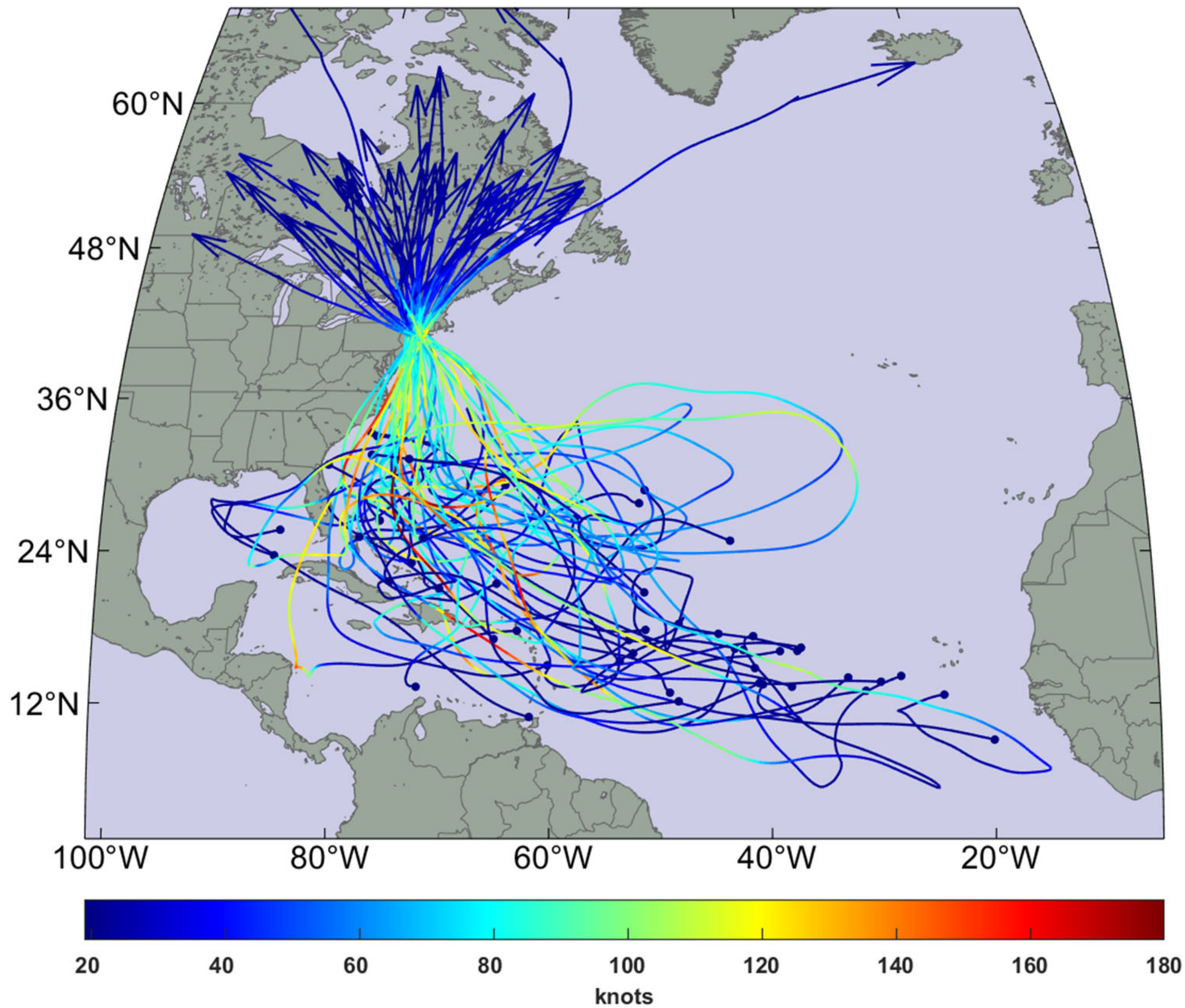
Captures Much of the Observed North Atlantic Interannual Variability



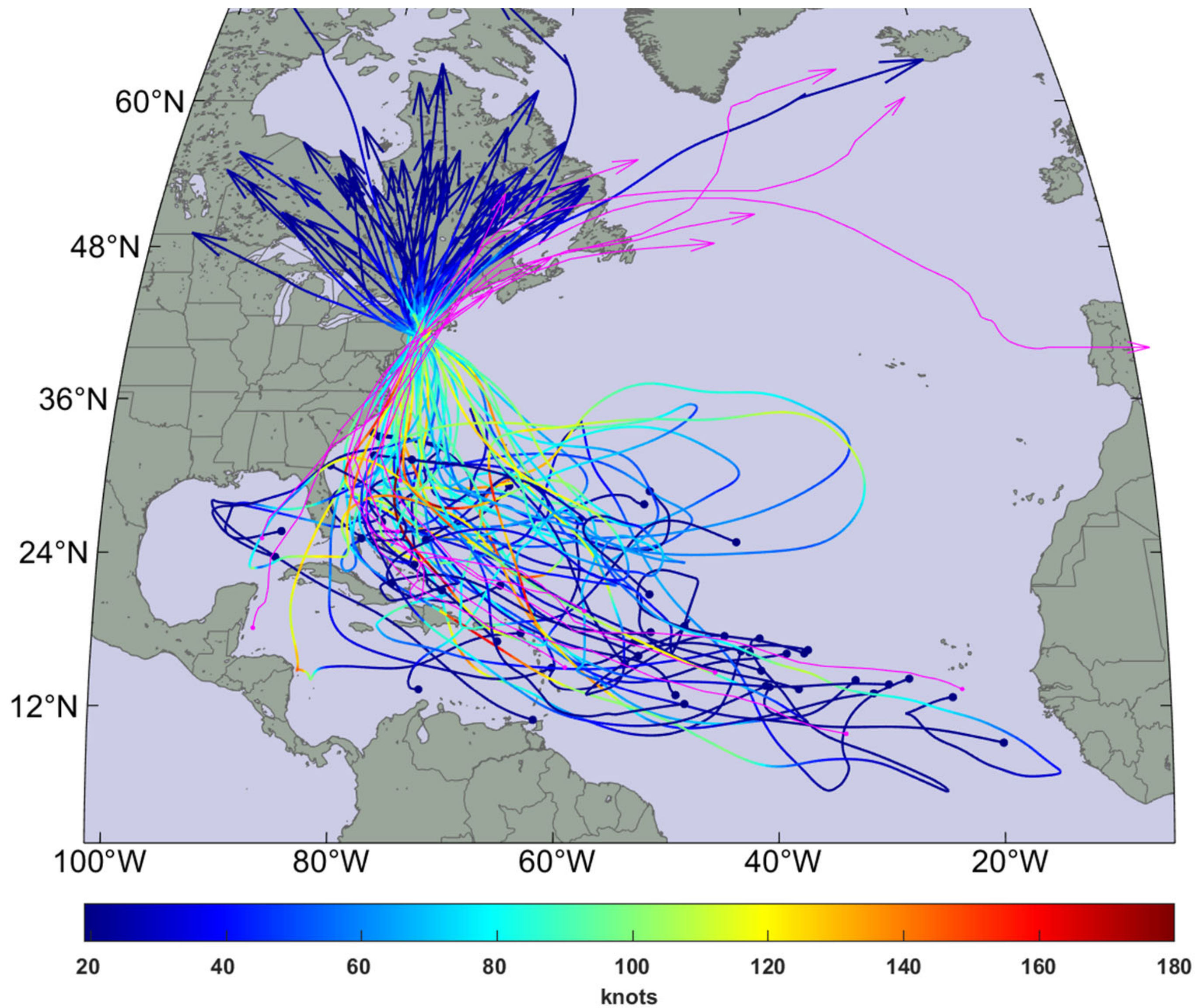
Return Periods



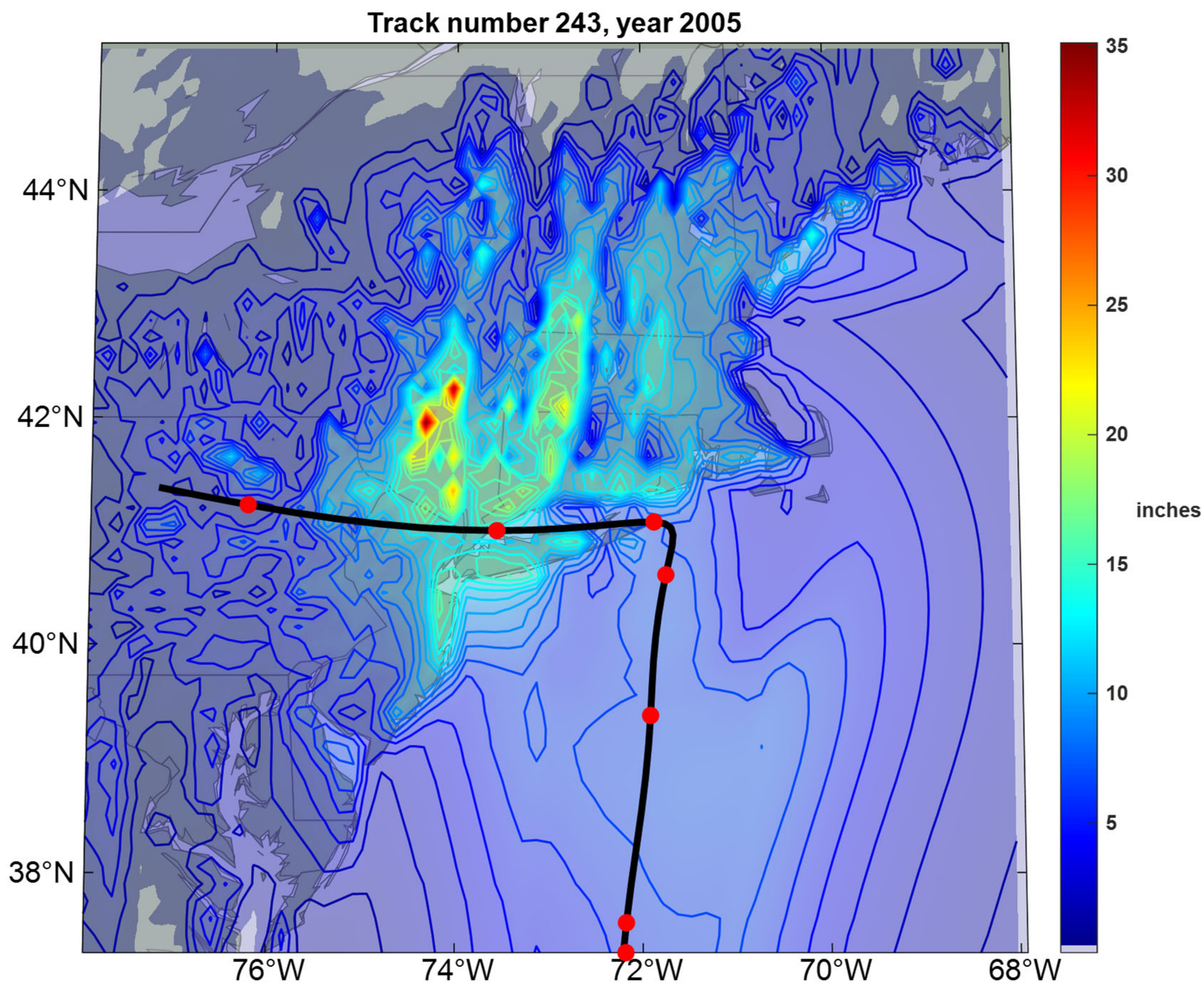
Top 50 out of 380 TCs Affecting New Haven



Same but with top 8 historical tracks

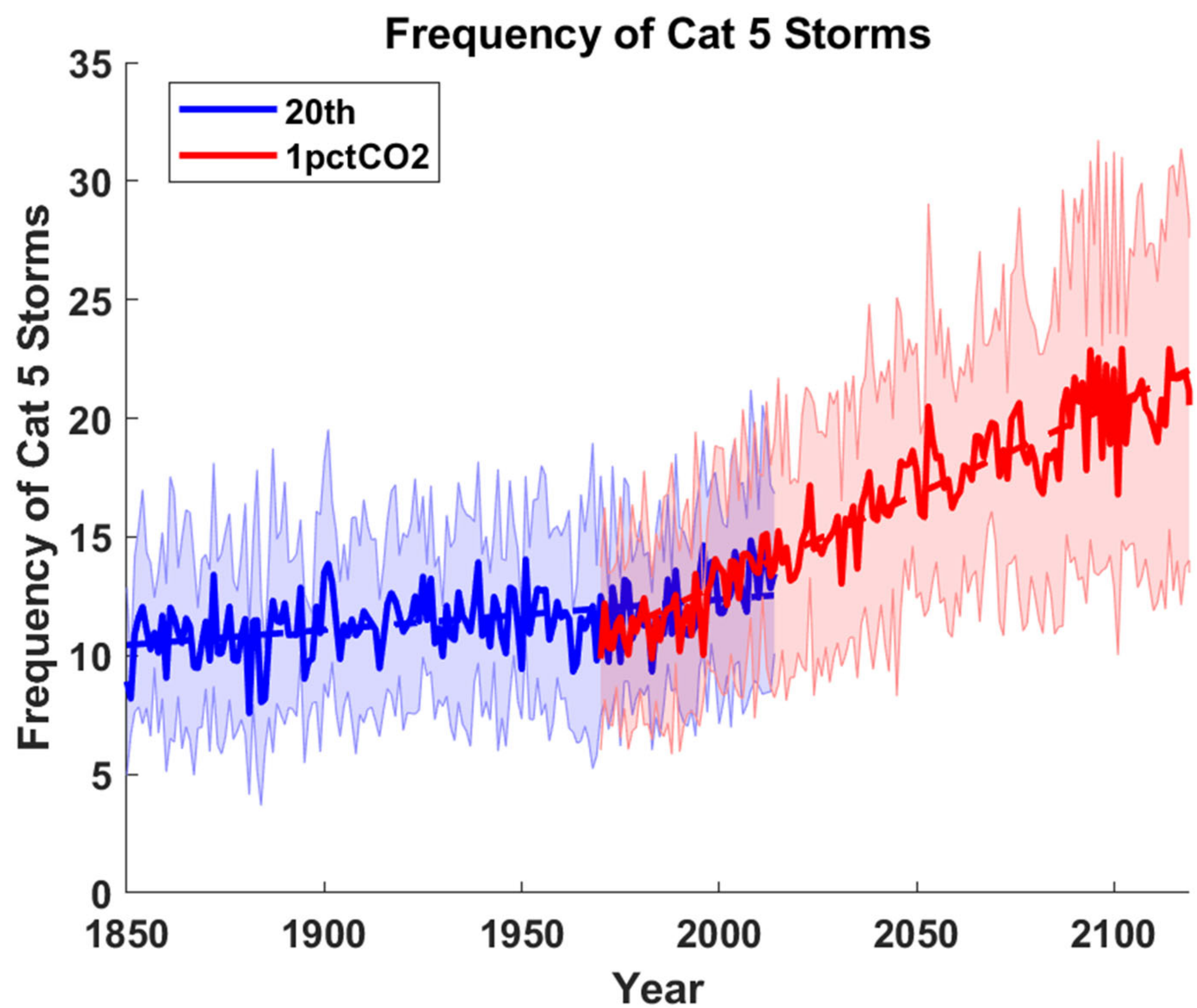


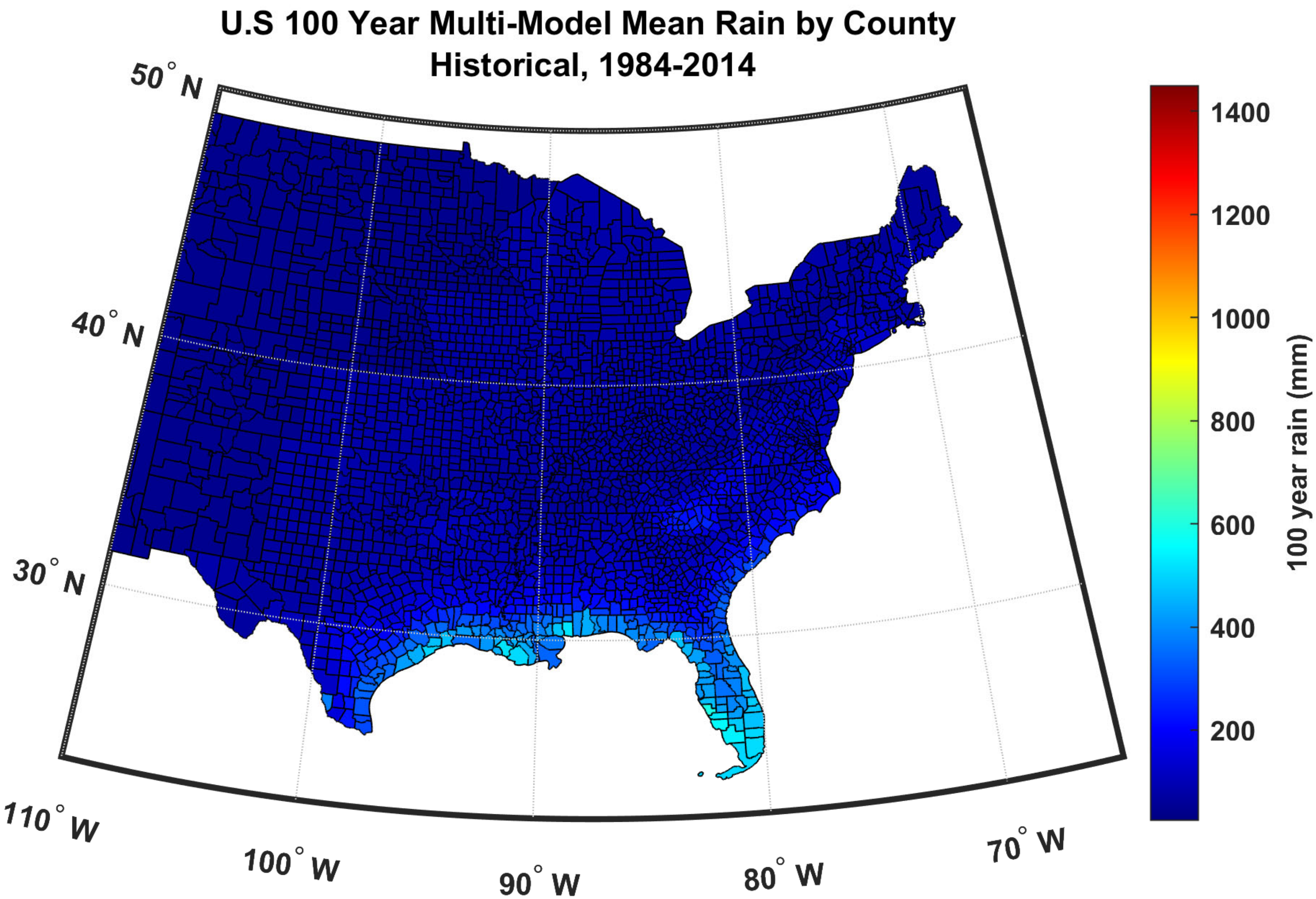
Example of Storm Total Rainfall



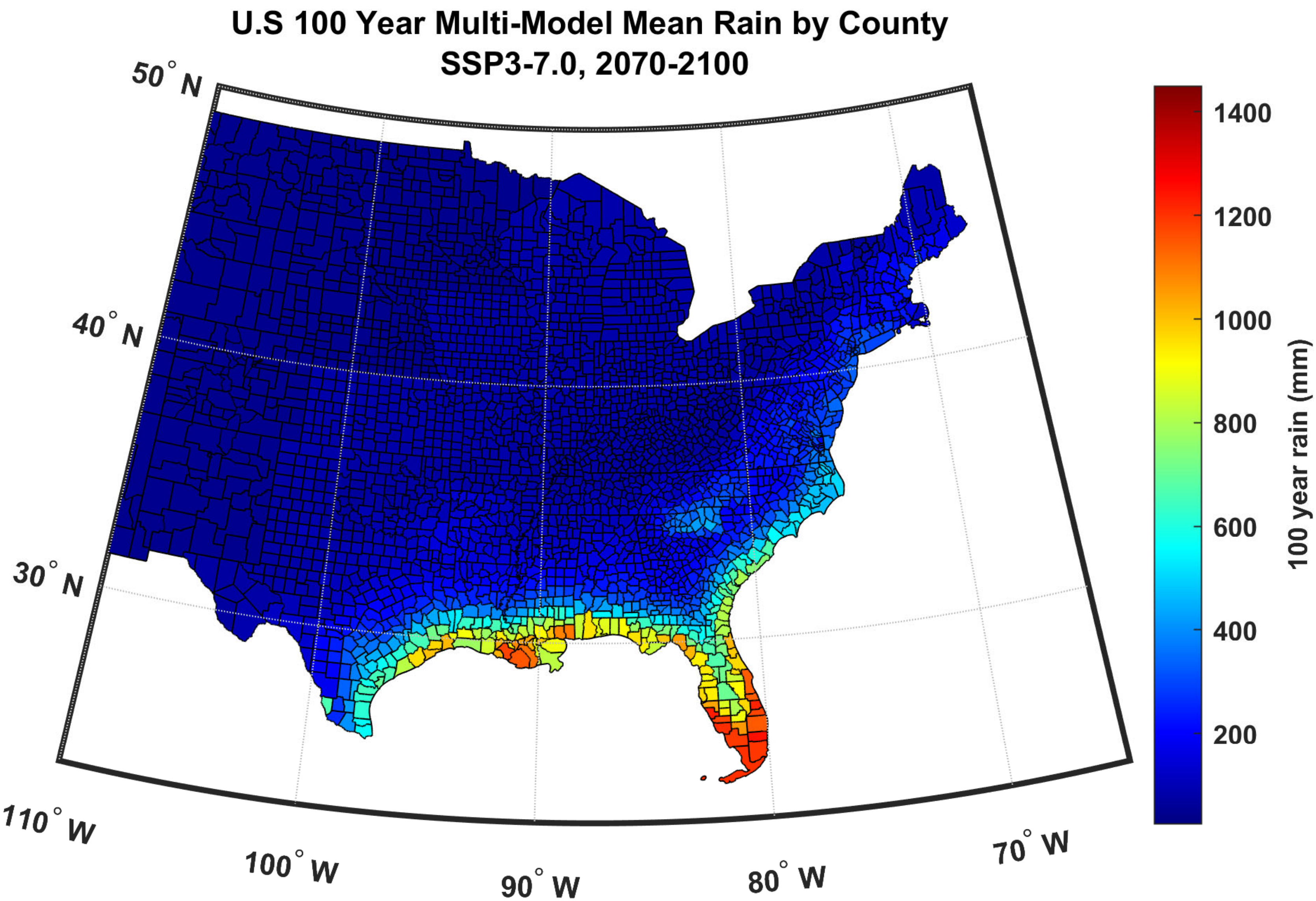
Taking Climate Change Into Account

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

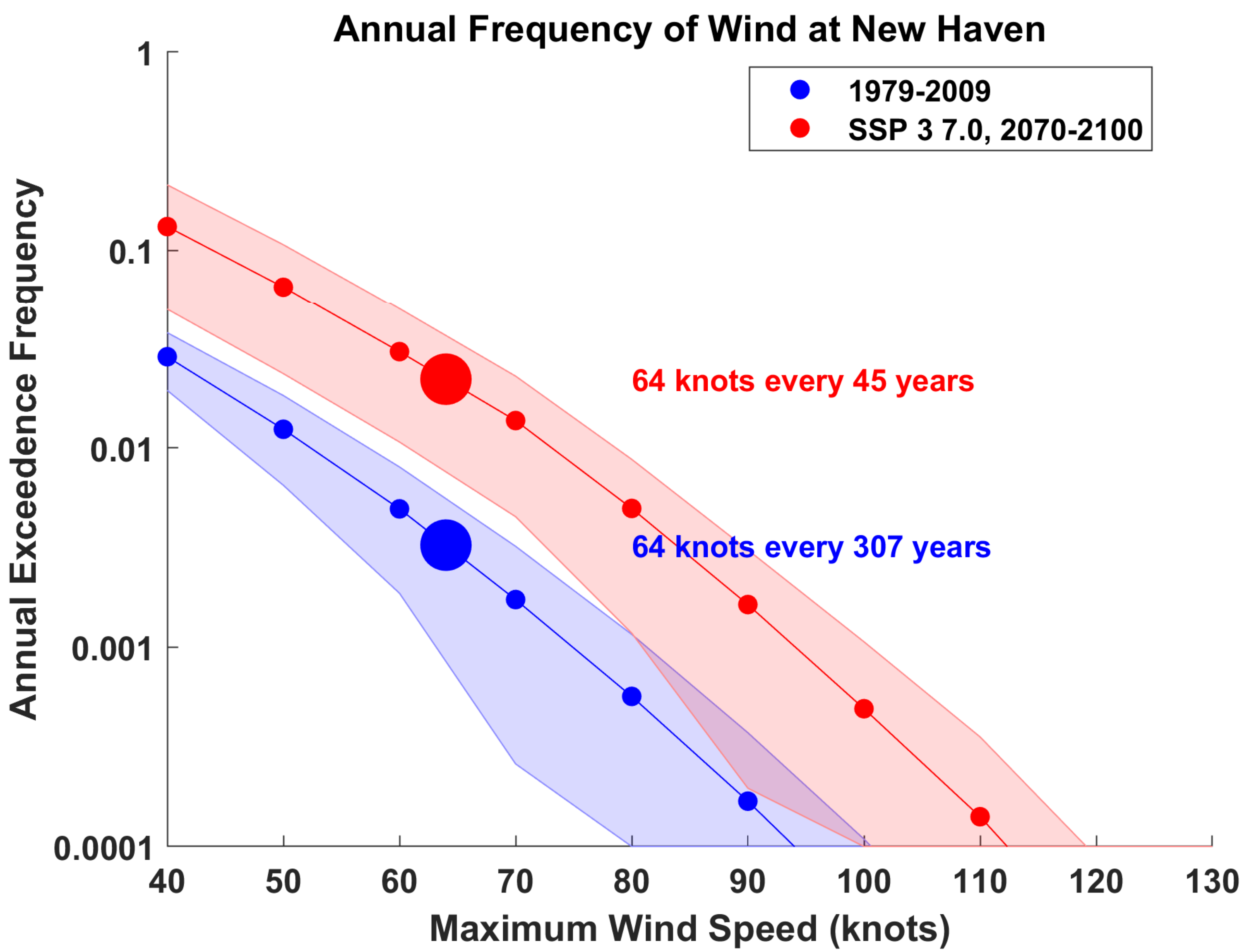


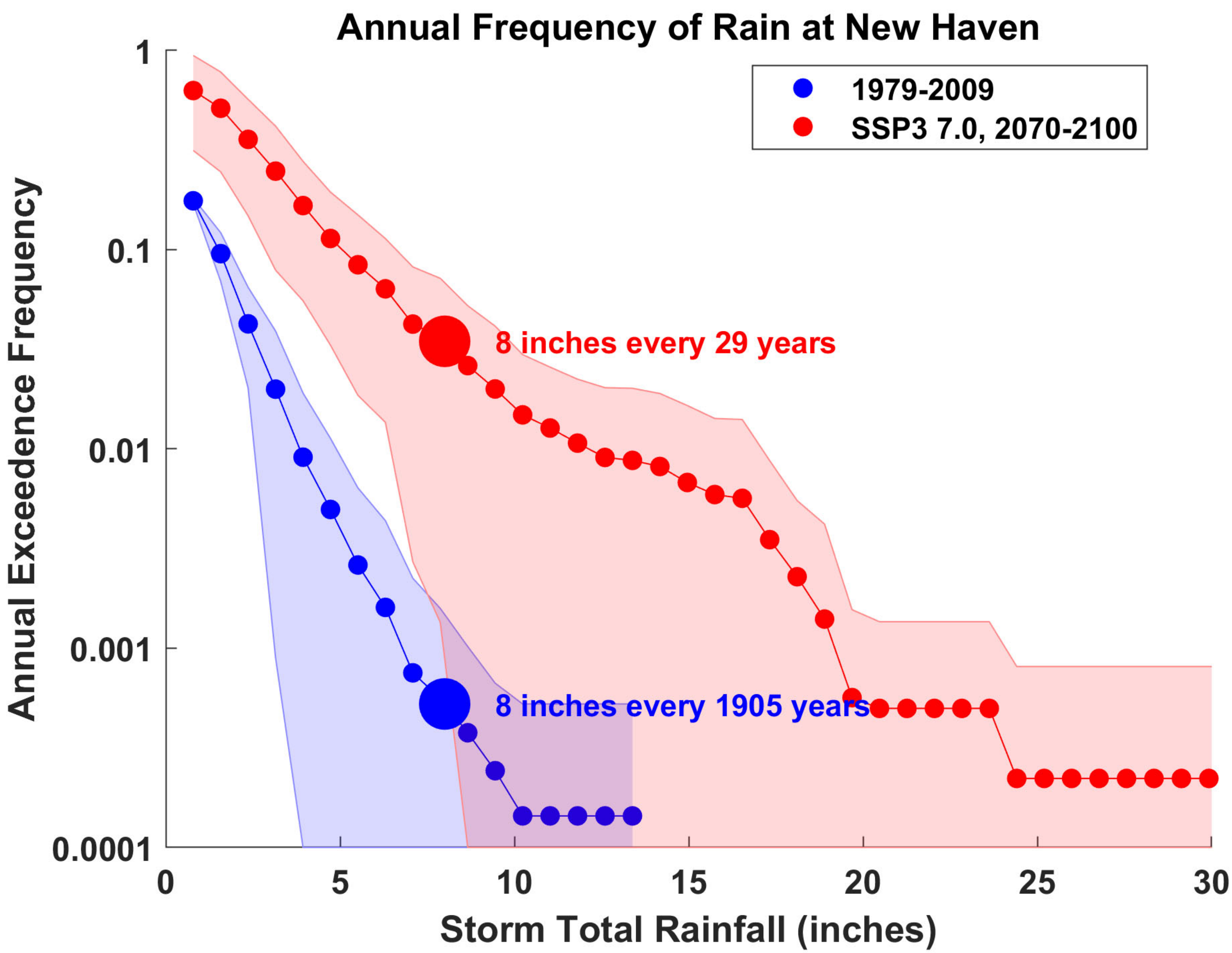


U.S 100 Year Multi-Model Mean Rain by County
Historical, 1984-2014
50° N
40° N
30° N
110° W
100° W
90° W
80° W
70° W
1400
1200
1000
800
600
400
200
100 year rain (mm)


U.S 100 Year Multi-Model Mean Rain by County
SSP3-7.0, 2070-2100
50° N
40° N
30° N
110° W
100° W
90° W
80° W
70° W
1400
1200
1000
800
600
400
200
100 year rain (mm)

Effects of Climate Change using 7 CMIP 6 Models



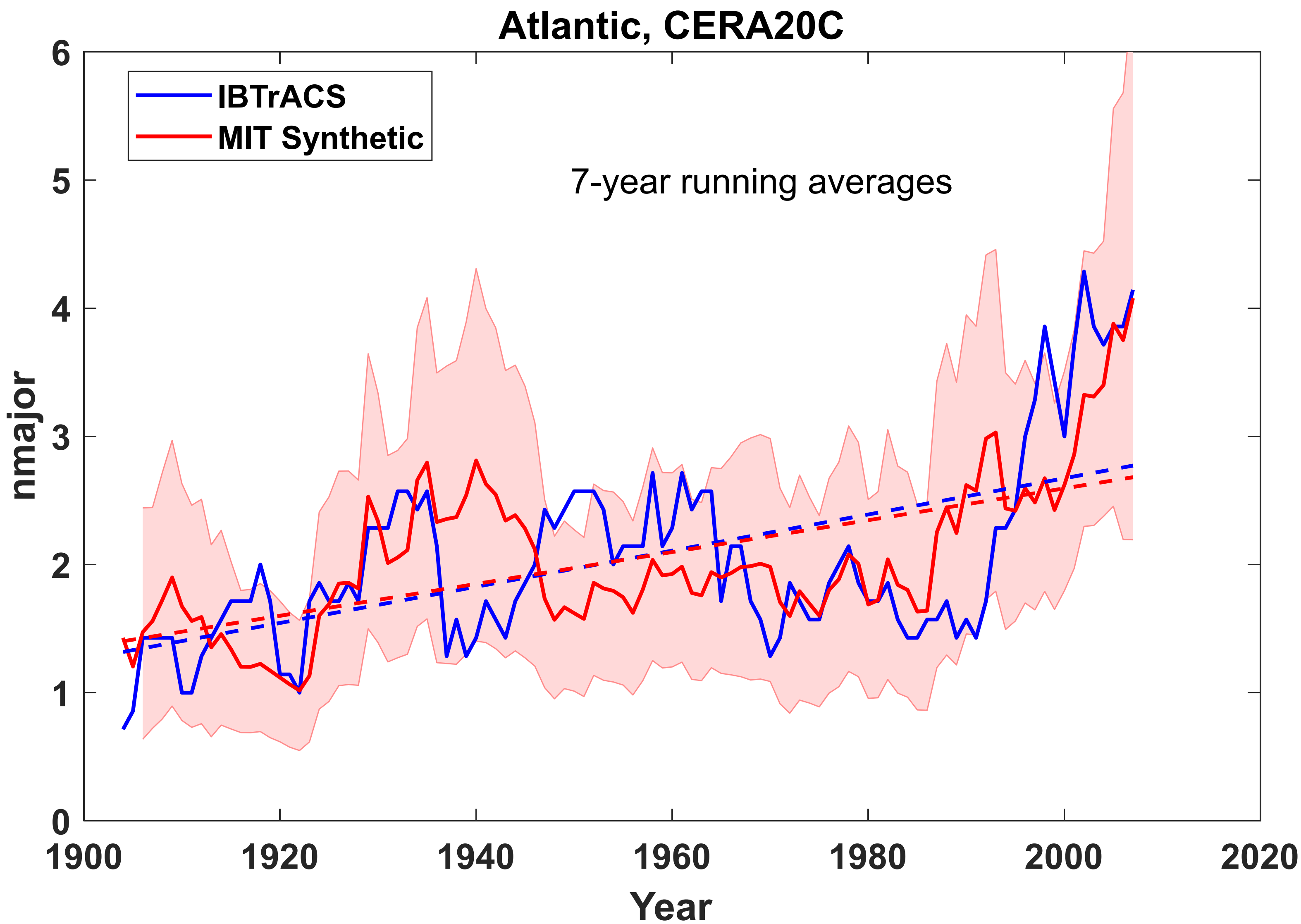


Annual Frequency of Rain at New Haven
1979-2009
SSP3 7.0, 2070-2100
8 inches every 29 years
8 inches every 1905 years
Annual Exceedence Frequency
1
0.1
0.01
0.001
0.0001
0
5
10
15
20
25
30
Storm Total Rainfall (inches)

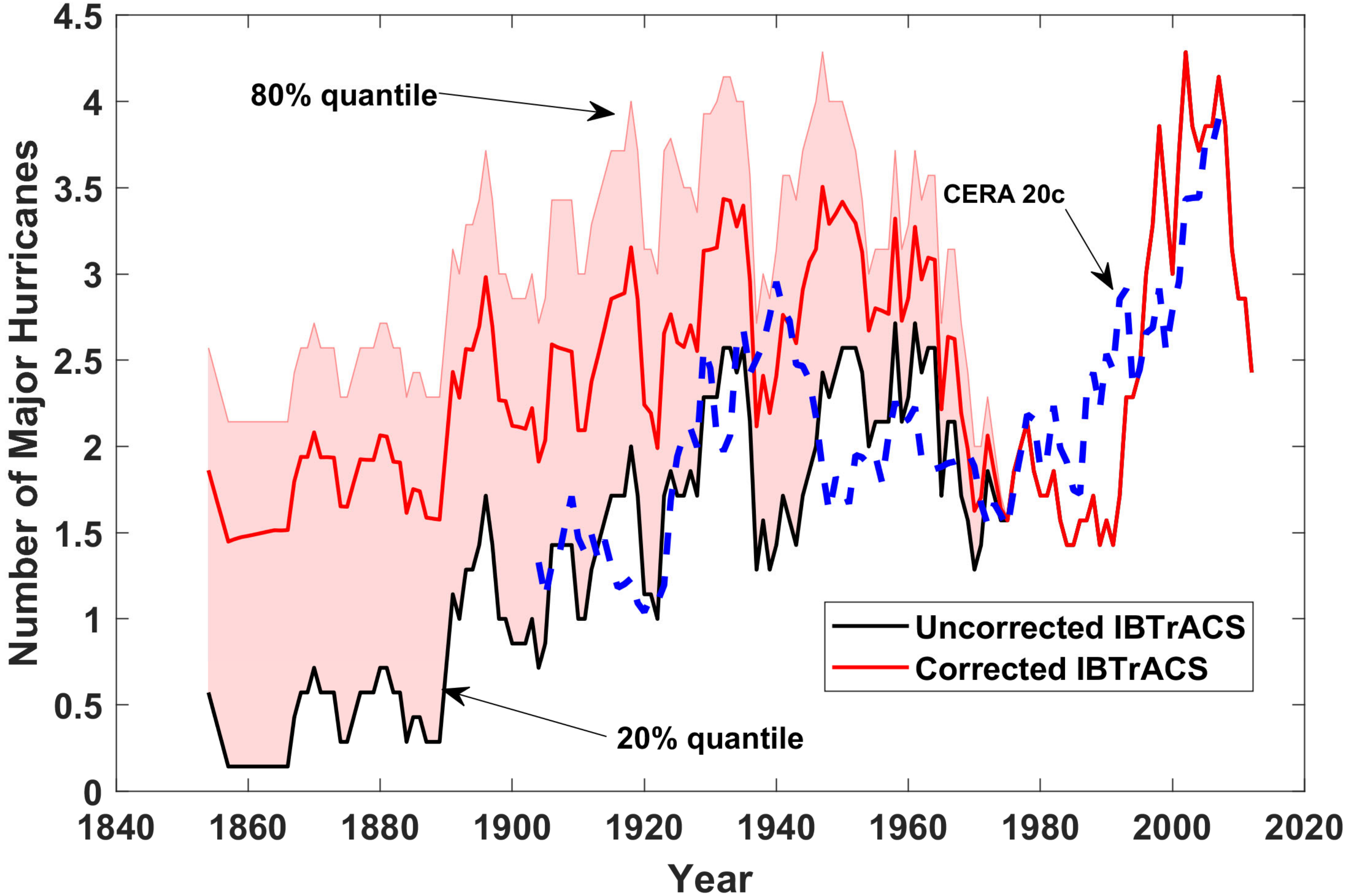
Application to Three 20th Century Reanalyses: NOAA v.2c, NOAA v.3 and CERA 20c

- Run 100 synthetic TCs for each year of the reanalysis data record
- Retain only storms whose lifetime maximum intensity exceeds 40 kts
- Do this for the North Atlantic and separately for the world

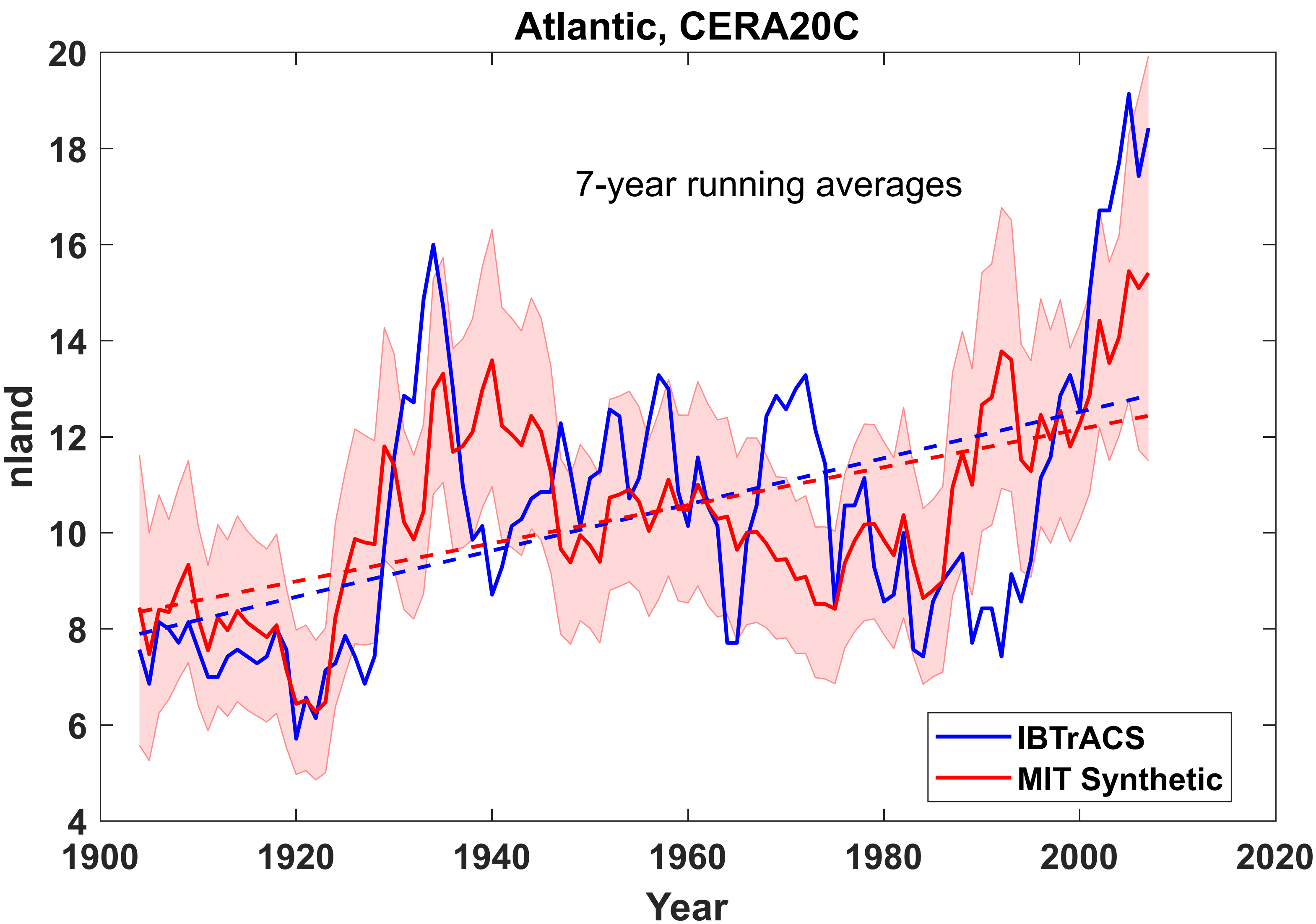
Major Hurricanes



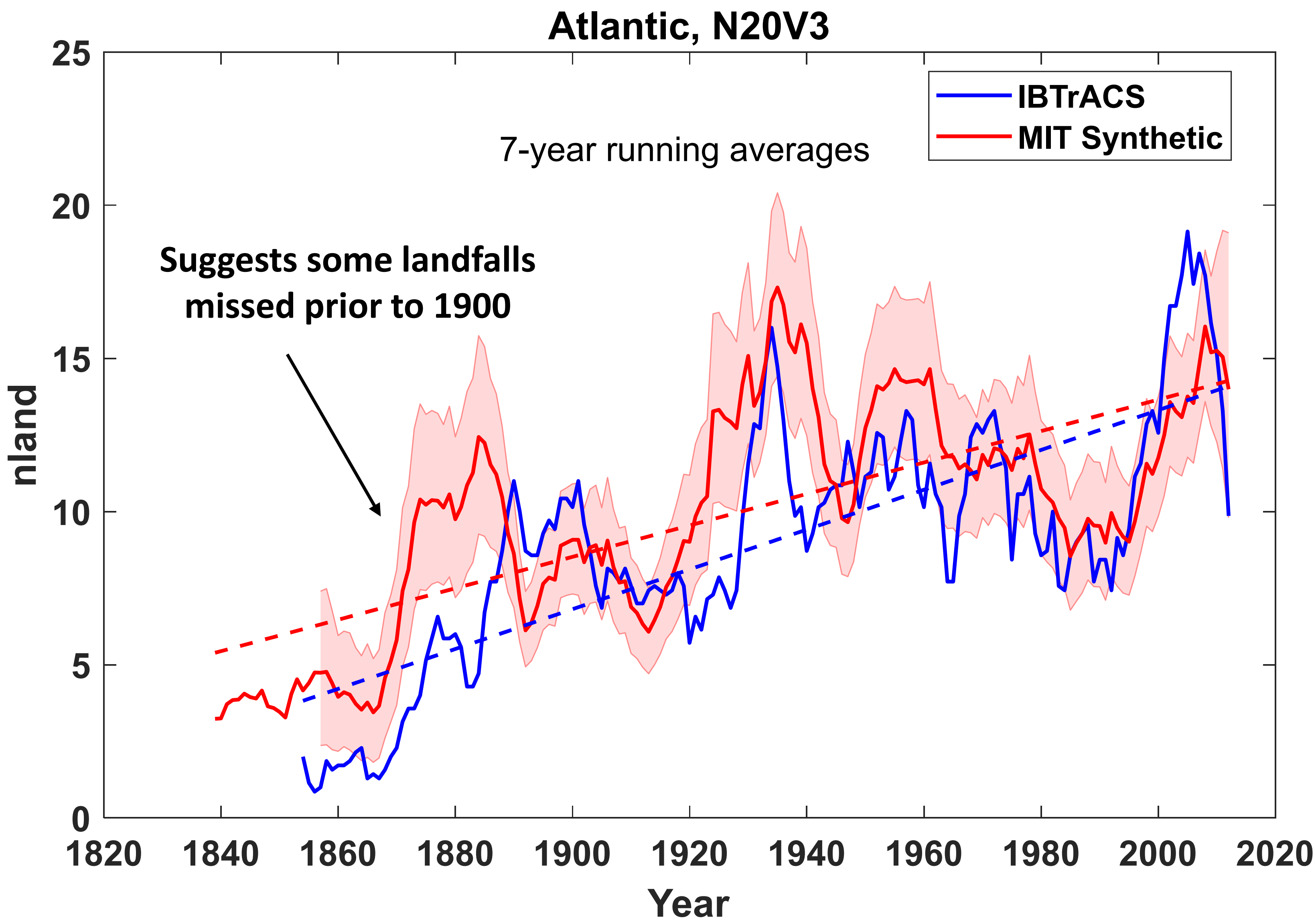
Number of North Atlantic Major Hurricanes



All landfalls (not just USA)



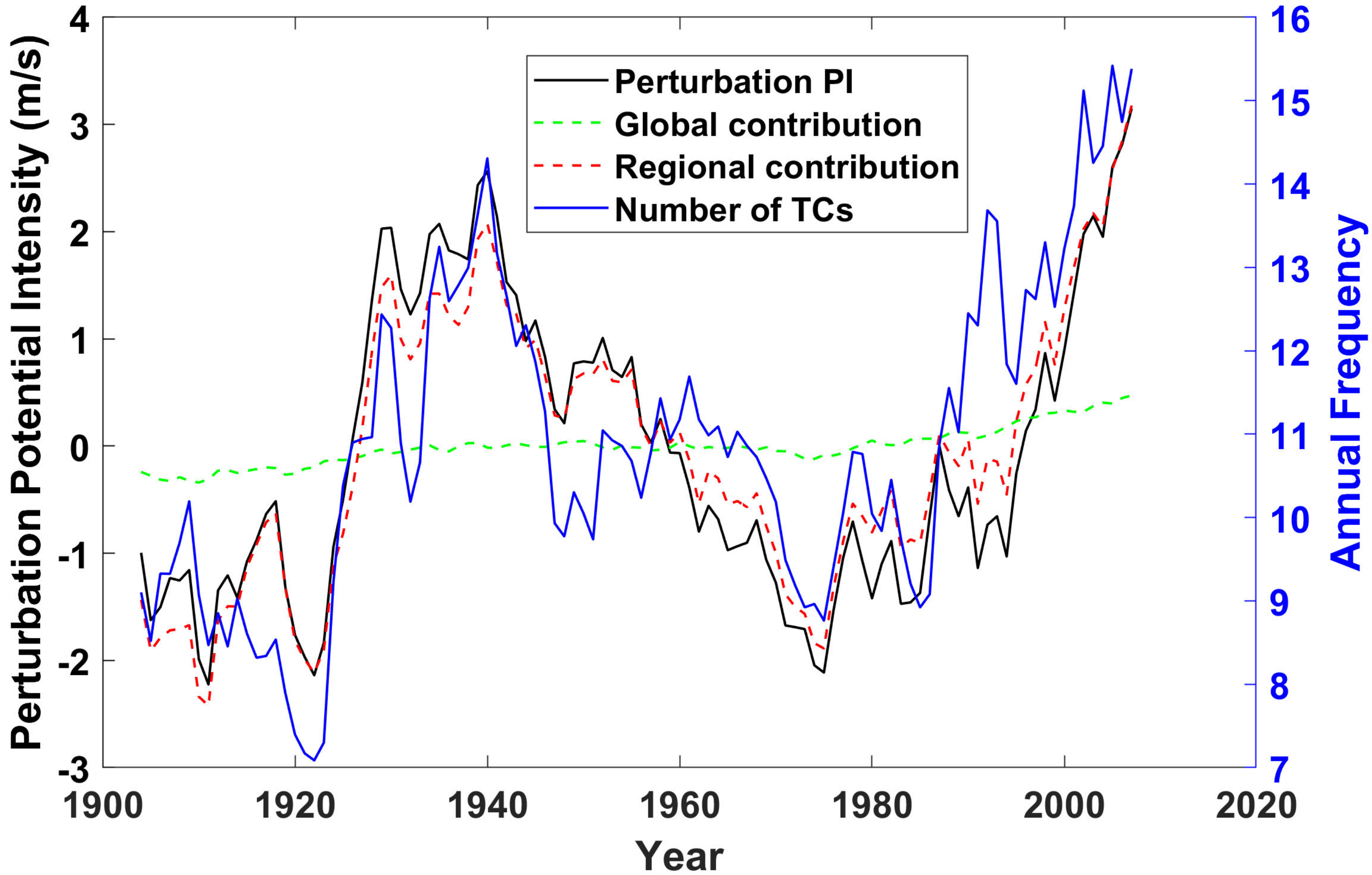
All Landfalls, NOAA 20th Century v.3

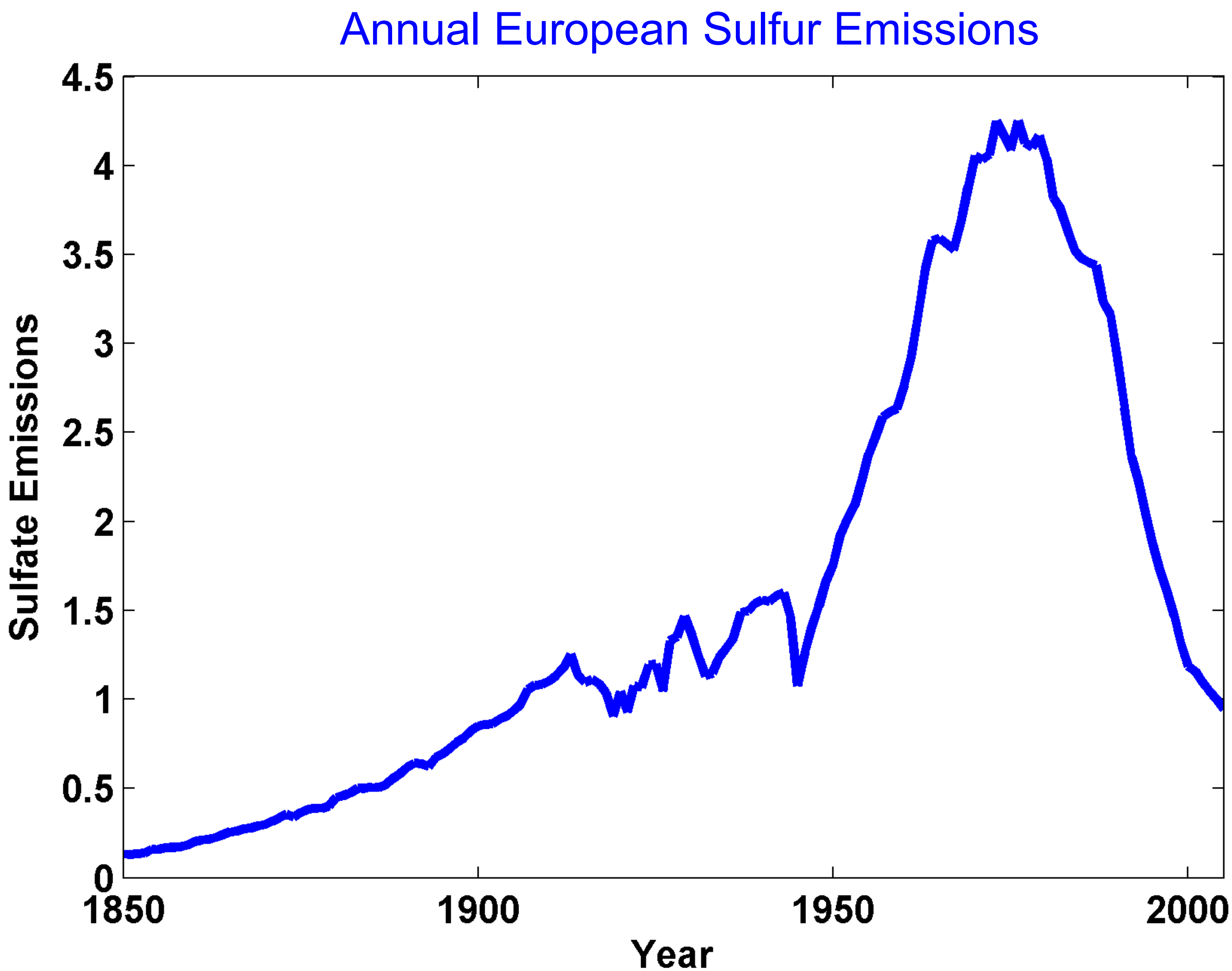


What may have caused the North Atlantic TC trends and variability?

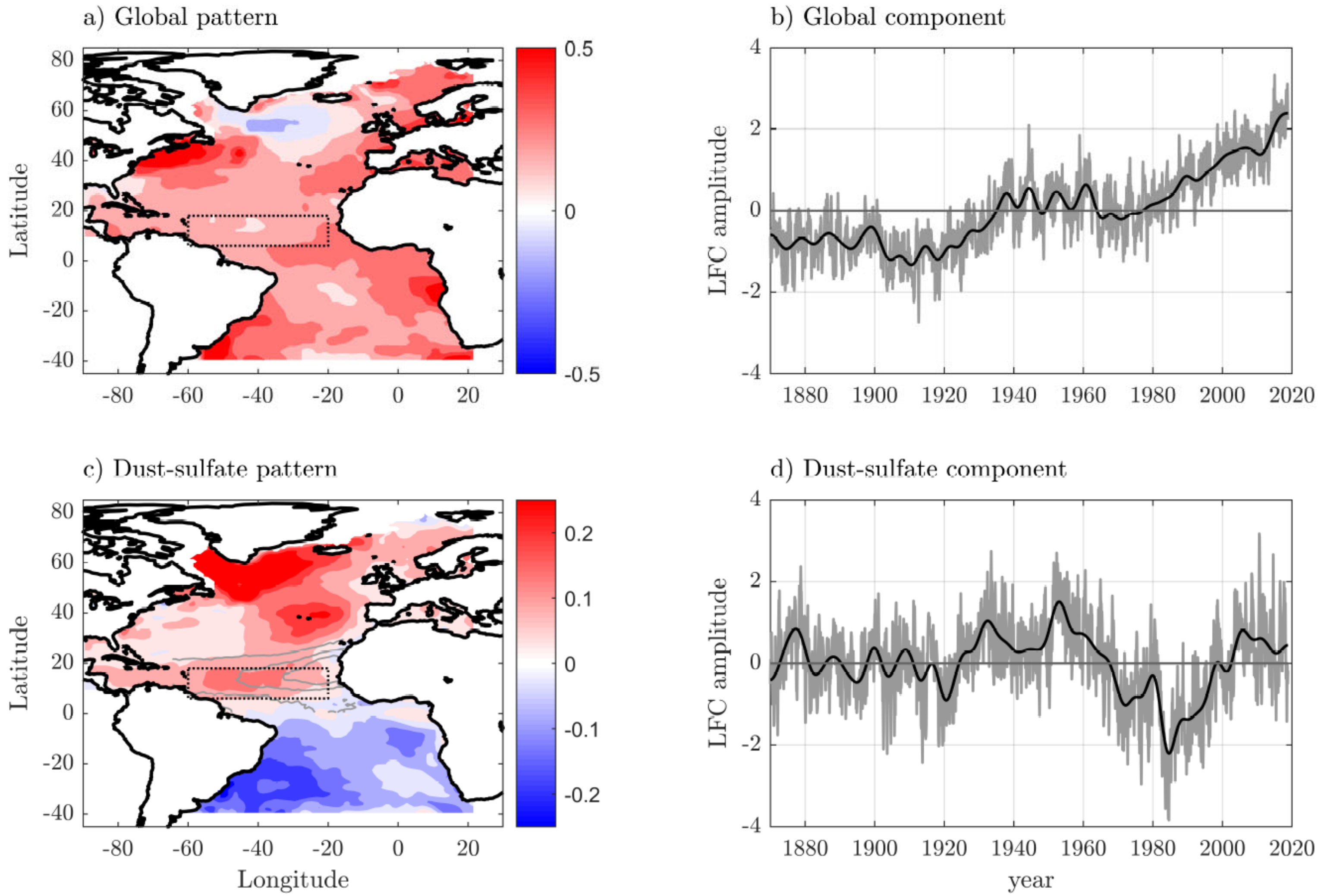
- North Atlantic tropical cyclone frequency strongly correlated with potential intensity (PI), the theoretical upper bound on TC intensity that can be calculated from coarse climate data.
- Technique developed by R. Rousseau-Rizzi partitions PI change into a part owing to global climate change and a separate part due to local or regional climate change
- We apply this technique to the North Atlantic main genesis region using the reanalysis data to calculate PI and the mean temperature of the tropical free troposphere

Results:


Perturbation PI
Global contribution
Regional contribution
Number of TCs
Perturbation Potential Intensity (m/s)
4
3
2
1
0
-1
-2
-3
Annual Frequency
16
15
14
13
12
11
10
9
8
7
1900
1920
1940
1960
1980
2000
2020
Year



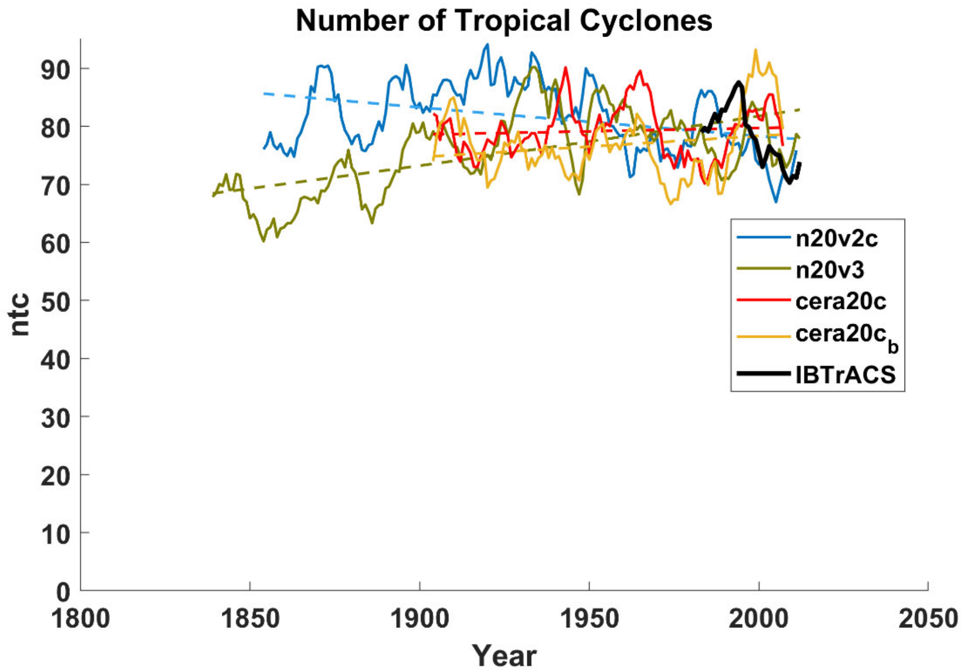
Annual European Sulfur Emissions
Sulfate Emissions
Year
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
1850
1900
1950
2000



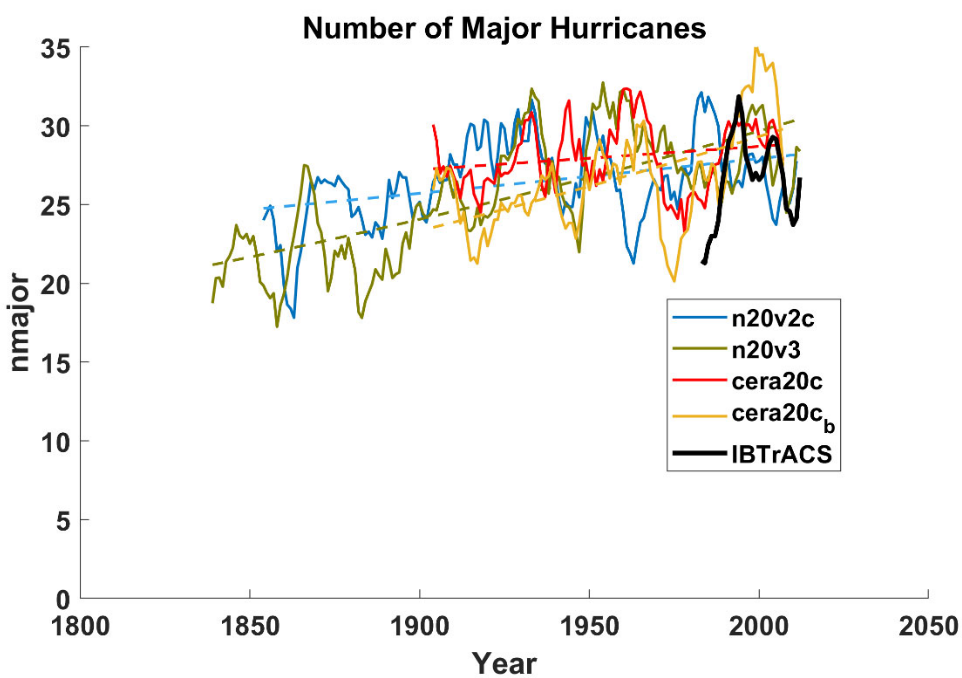
Patterns of sea-surface temperature (color shading) associated with the global mode (a) and the dust-sulfate mode (c). The dust-sulfate pattern is plotted along with dust aerosol optical depth contours from [14] for τ = [0:150:30:45] (gray contours), and the main development region is indented (dotted black box). Associated components for the global mode (b) and the dust-sulfate mode (d), including variability at all frequencies (gray) and only at low frequencies (black).

From R. Rousseau-Rizzi Ph.D thesis, MIT, 2021

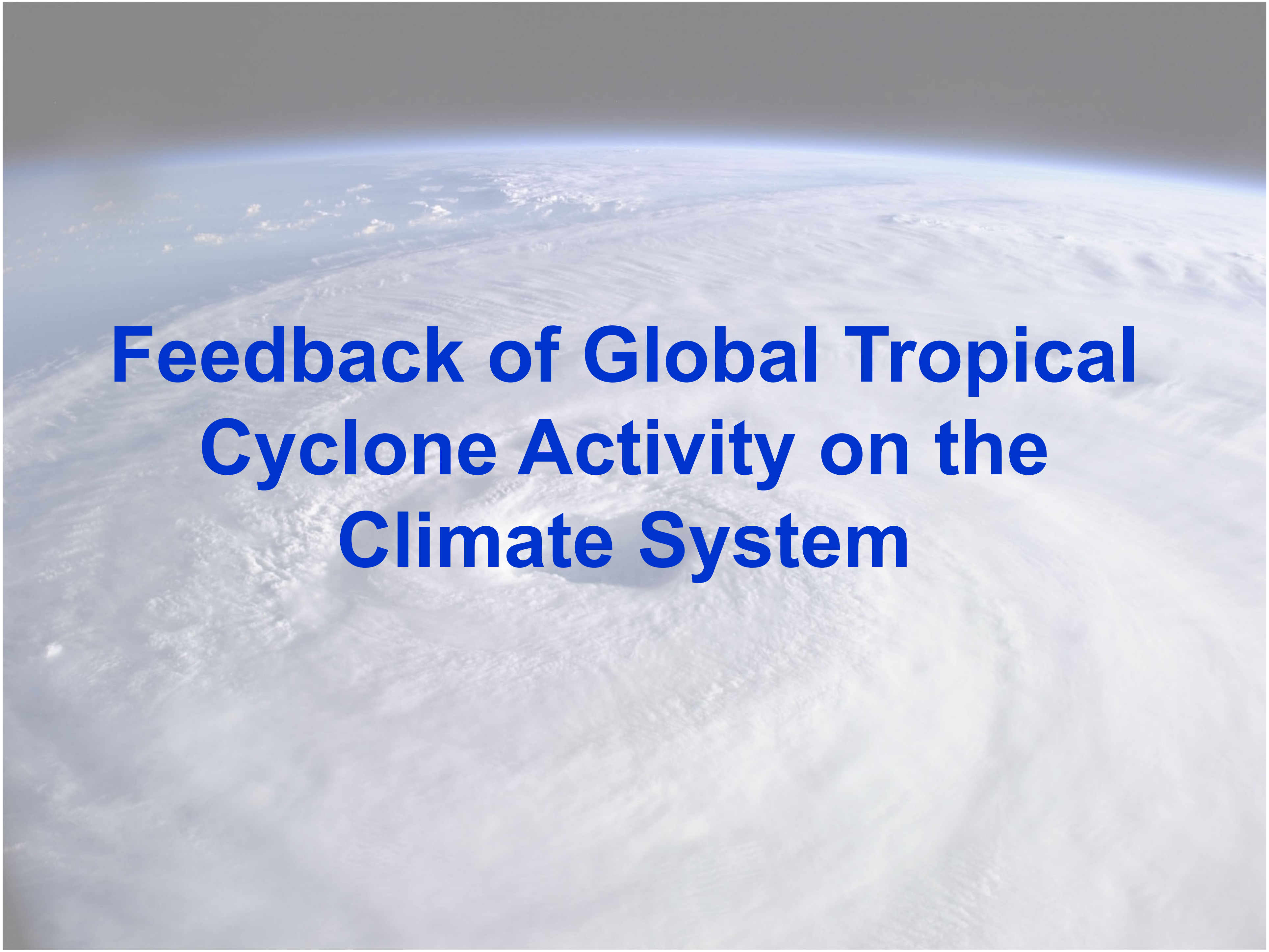
But the general upward trends in North Atlantic TC metrics are not explained. They are mostly owing to regional SST increases, not the global increase. It is possible that this is related to a trend in the Atlantic sector meridional overturning circulation of the ocean; this may be natural and/or a response to anthropogenic forcing.



No significant trends in global downscaled tropical cyclone frequency!



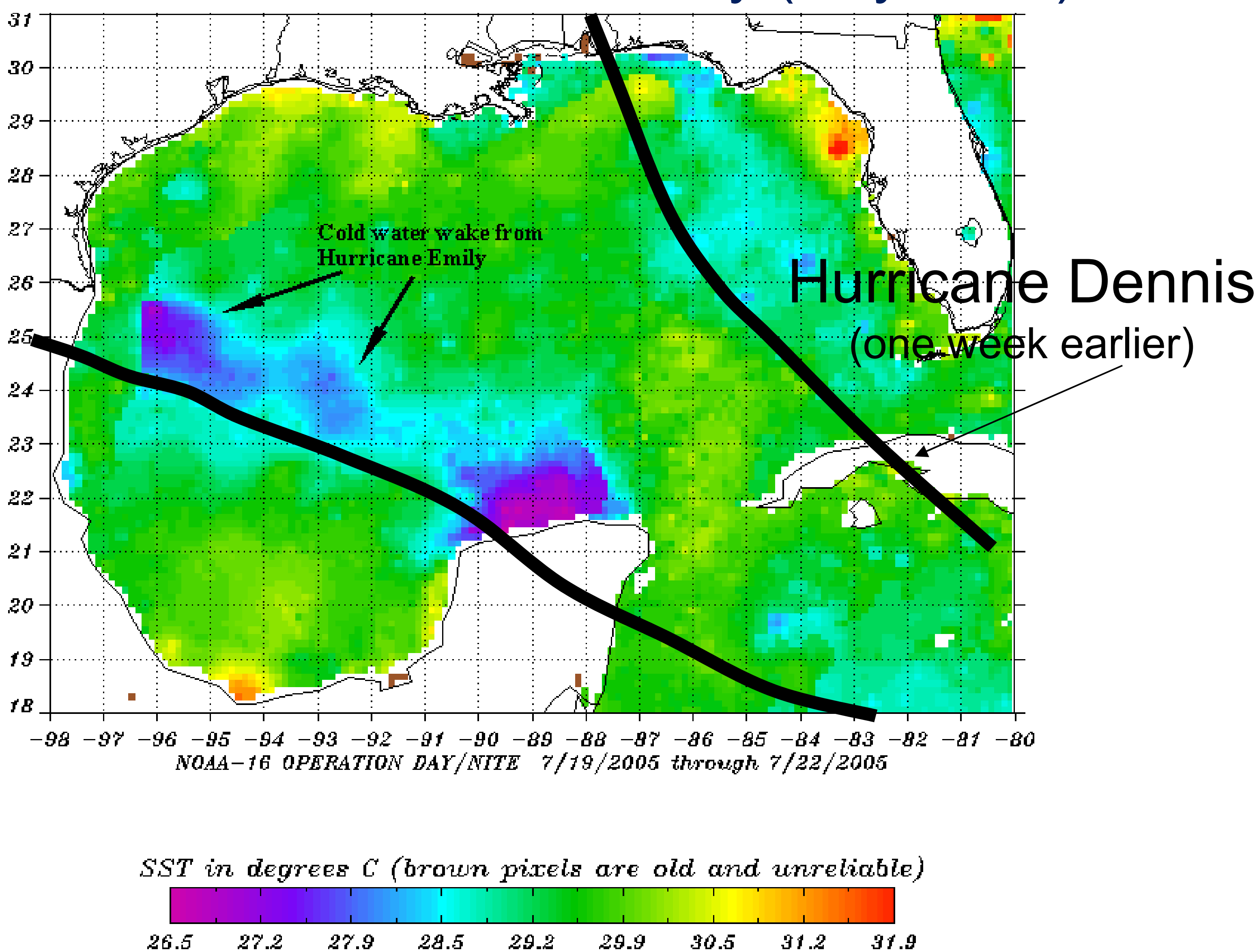
Some upward trend in global downscaled major hurricanes



Feedback of Global Tropical Cyclone Activity on the Climate System

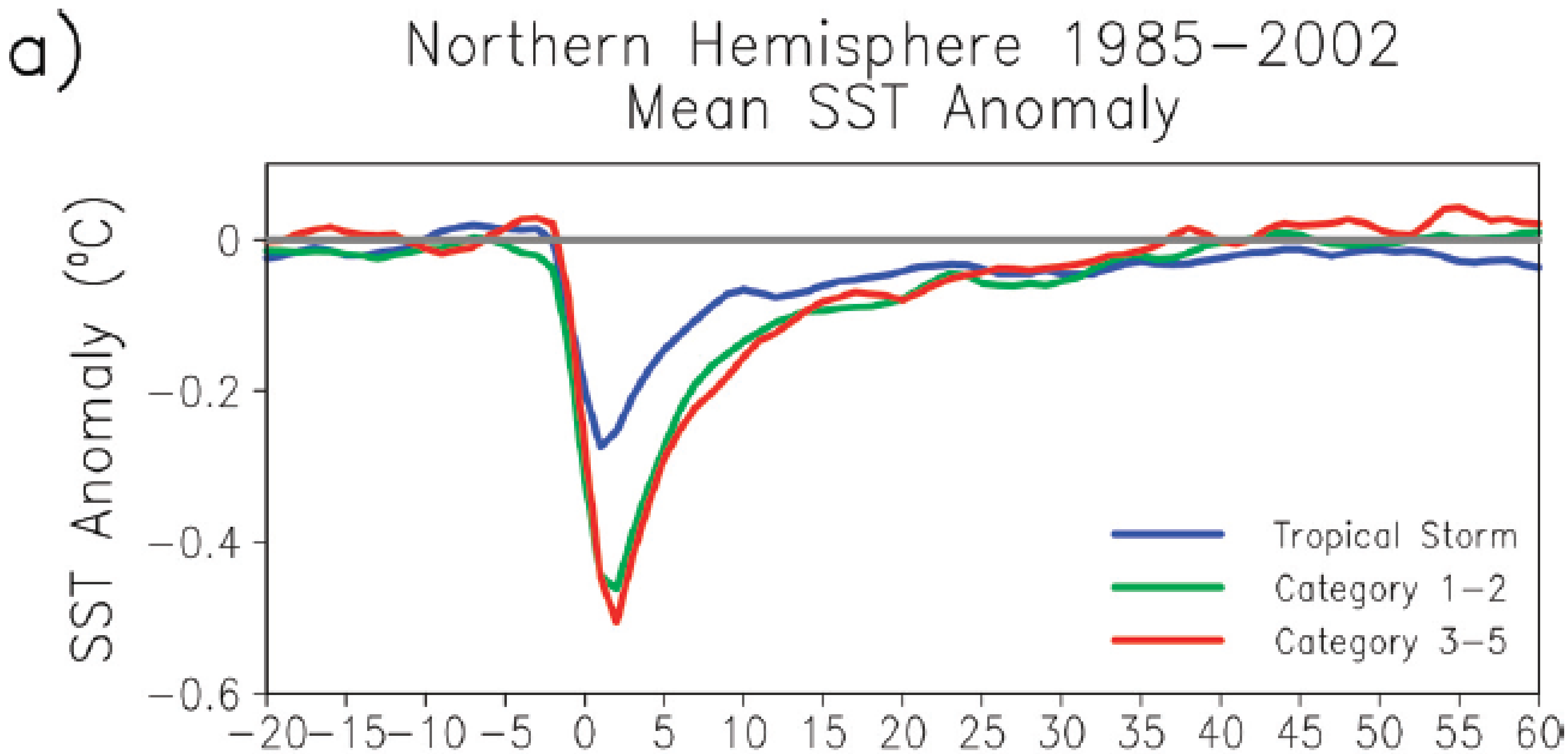
The wake of Hurricane Emily (July 2005)

Sea Surface Temperature in the Wakes of Hurricanes



Source: Rob Korty, CalTech

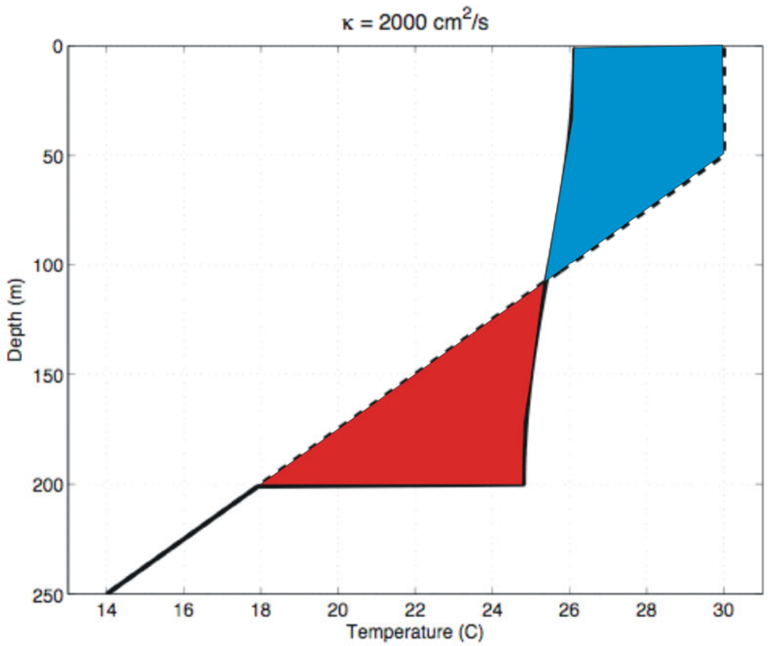
Wake Recovery



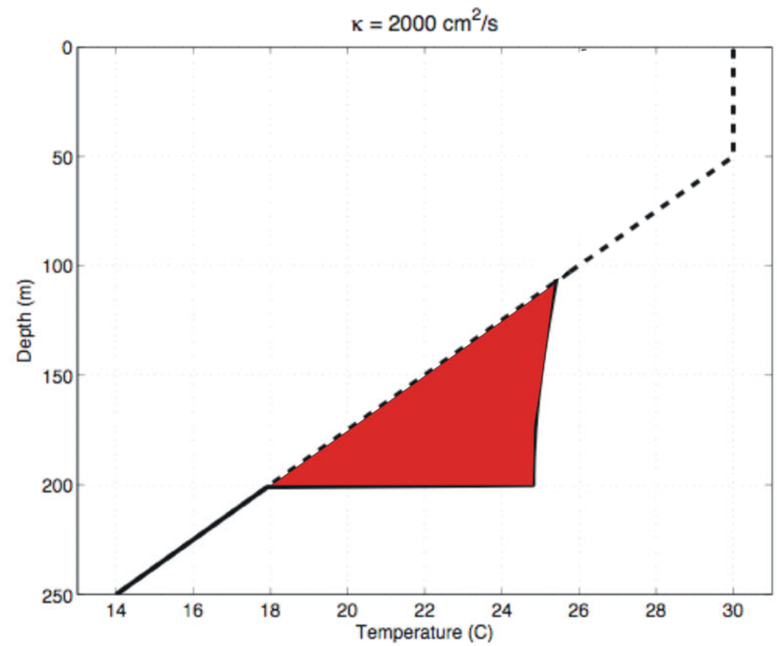
Hart, Maue, and Watson, *Mon. Wea. Rev.*, 2007

Direct mixing by tropical cyclones

Stage 1:
Enthalpy-conserving mixing



Stage 2:
Wake recovery

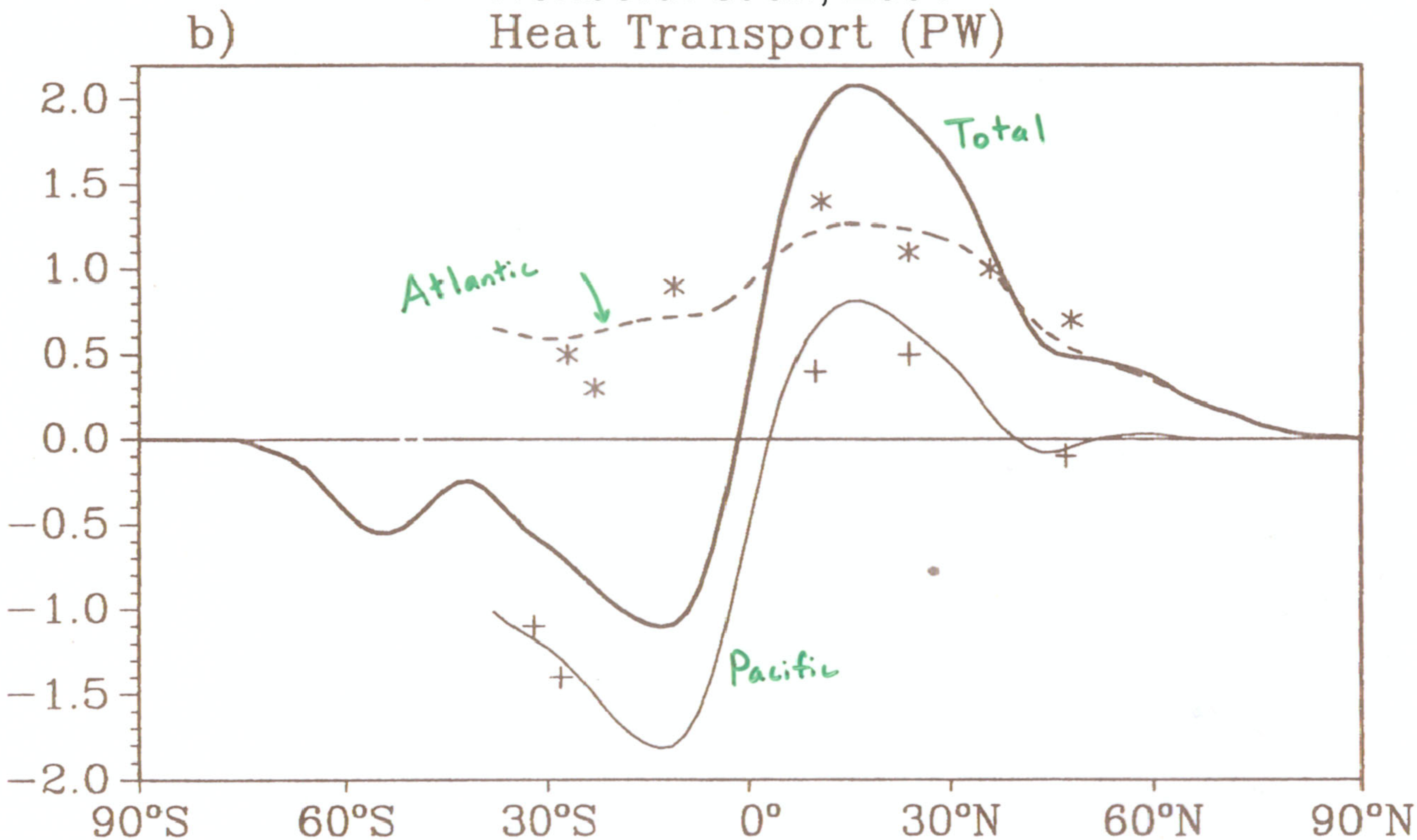


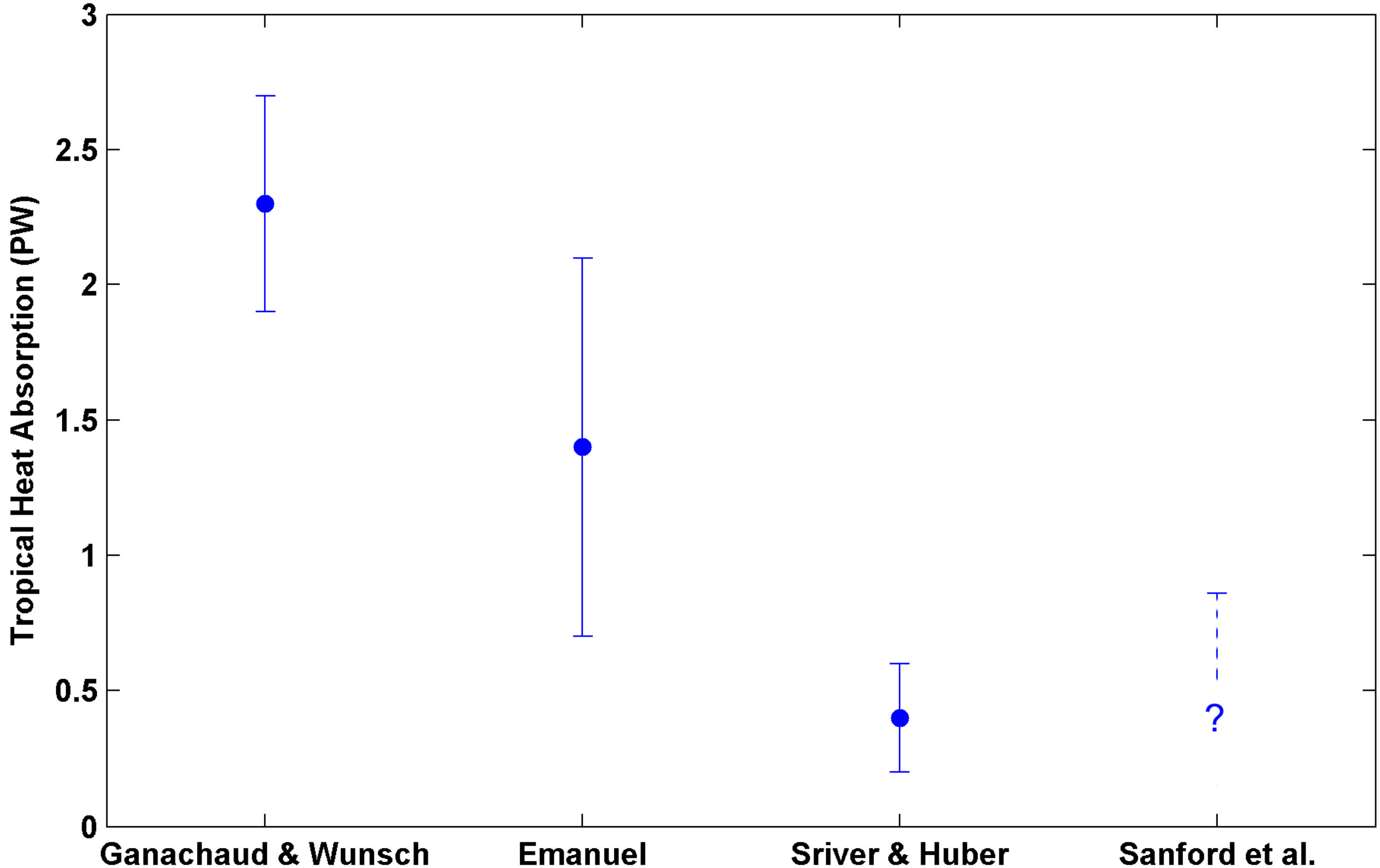
Emanuel (2001) estimated global rate of heat input as 1.4 X 10^{15} Watts

Source: Rob Korty, CalTech

TC Mixing May Induce Some of the Observed Poleward Heat Flux by the Oceans

Trenberth et al., 2001



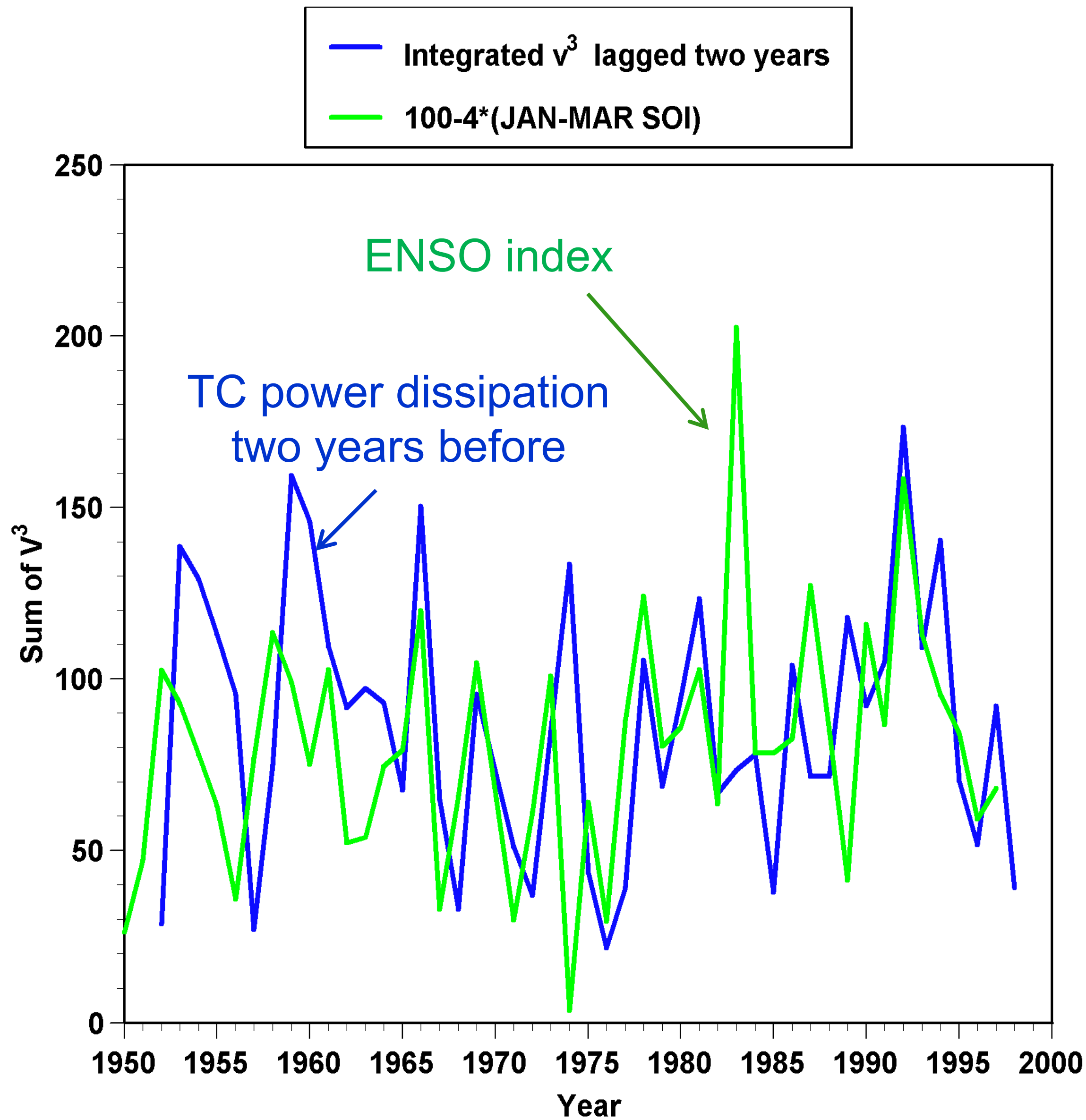


Estimate of total heat uptake by tropical oceans

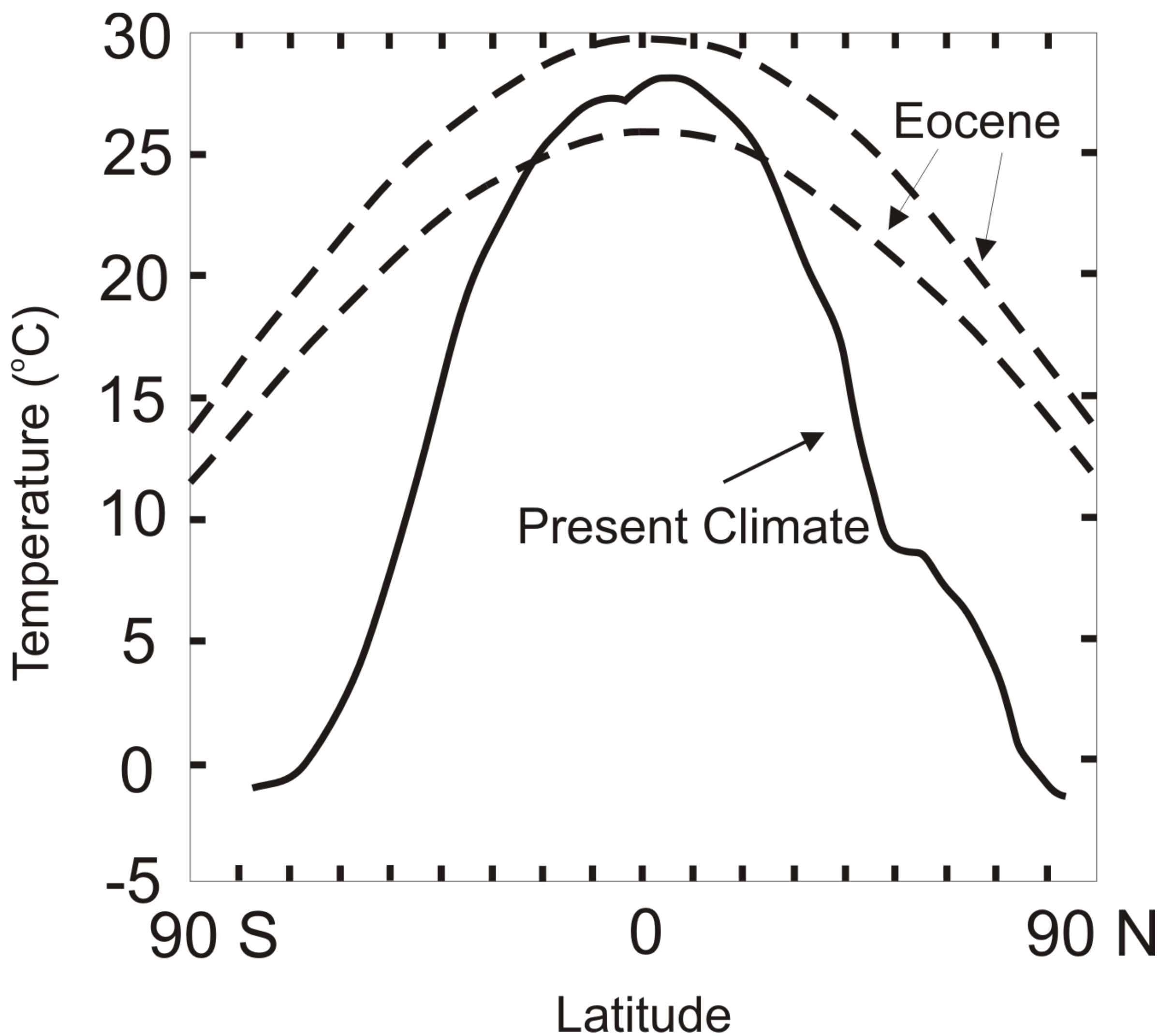
Estimate from satellite-derived wake recoveries

Extrapolation from detailed ocean measurements of one storm

This plot shows a measure of El Niño/La Niña (green) and a measure of the power put into the far western Pacific Ocean by tropical cyclones (blue). The blue curve has been shifted rightward by two years on this graph. There is the suggestion that powerful cyclones in the western Pacific can trigger El Niño/La Niña cycles.



TC-Mixing may be Crucial for High-Latitude Warmth and Low-Latitude Moderation During Warm Climates, such as that of the Eocene



Summary

- Historical observations and synthetic tropical cyclones both show substantial upward trends in the North Atlantic, interrupted by a prominent “hurricane drought” in the 1970s and 80s
- Previous work may have overestimated the number of missing storms earlier in the record

- Hurricane drought was probably caused by Saharan dust anomalies associated with drought caused by European sulfate aerosol-induced cooling
- No detectable frequency trend in global tropical cyclones
- Upward trend in the Atlantic may be related to changes in the meridional overturning circulation of the ocean.

- Tropical cyclones dry the atmosphere and may thereby cool the tropics through increase in OLR
- While TCs operate by extracting heat from the ocean, their net effect is to export heat away in ocean currents, thus cooling the tropics