Past and Future Tropical Cyclone Activity

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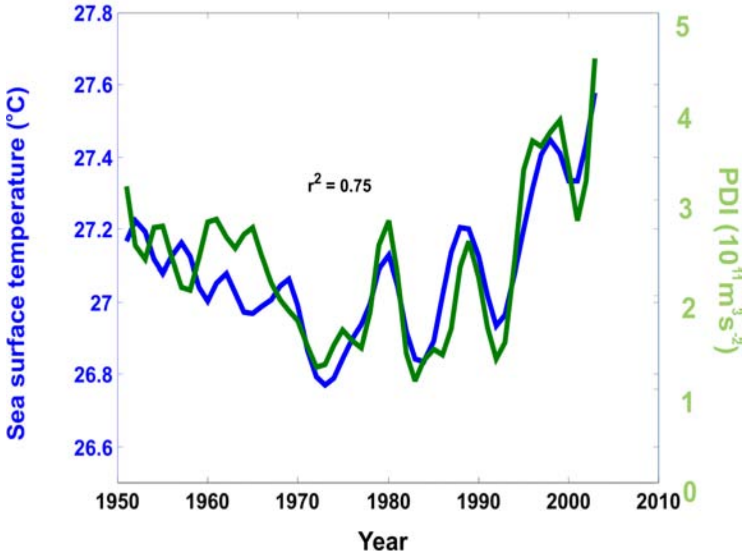
- What is a tropical cyclone?
- What is cyclone "activity"?
- How has activity changed in the past? Why?
- How do we expect it to change in future? Why?

Miami After Hurricane Andrew

Source: wikimedia.org

North Atlantic tropical cyclones

- Recent increase in activity
  - Including extreme 2004-2005 seasons
- Why? Implications for future?



Emanuel (2007, J. Clim.)

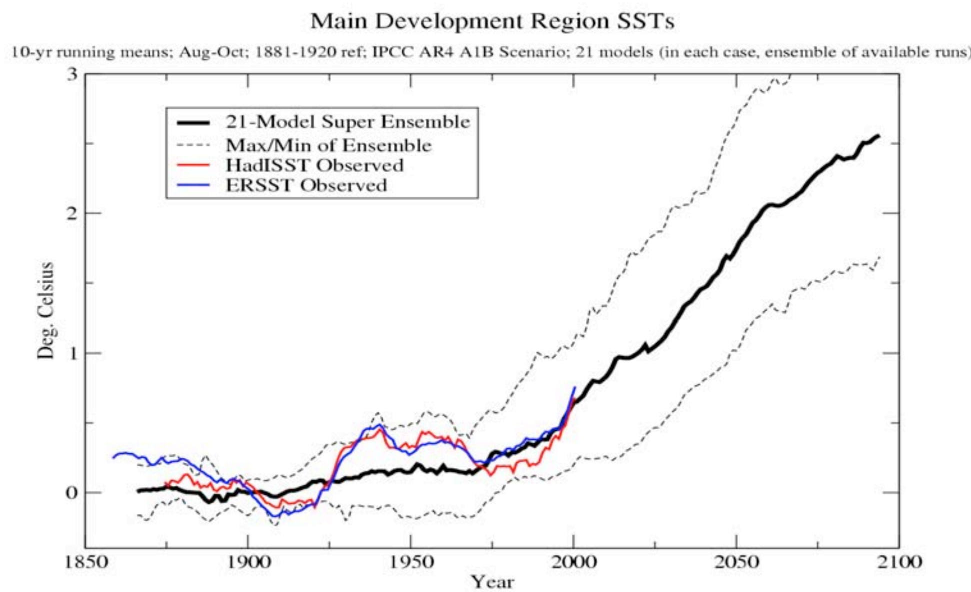


Figure: Tom Knutson

Key concepts

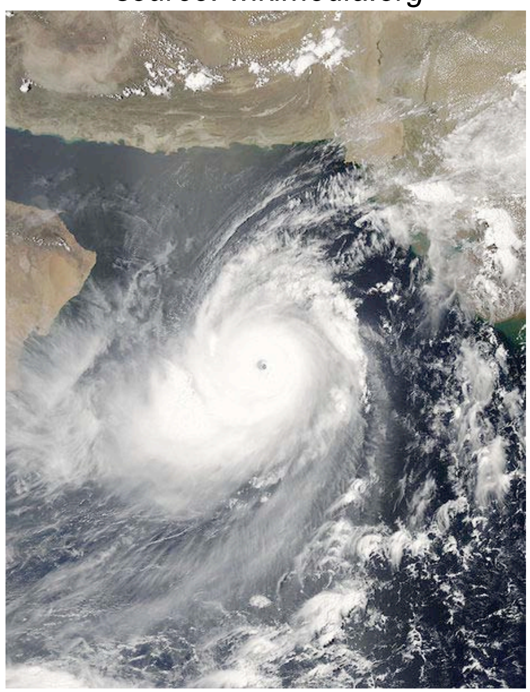
- Established vs. Developing understanding
  - Multiple factors impact hurricanes
  - Observational uncertainties
  - Pushing the limits of our theory and computers
- False choice: global warming **OR** climate variability
- Not about one storm or one season (“Katrina effect”).
- How do we develop our understanding?
  - Observations
  - Theoretical understanding
  - Numerical Modeling
- As we learn more the interpretation of total evidence changes: this is how science works
- Interpretations of sum of evidence can differ between scientists: not a “debate” - an ongoing inquiry

Tropical cyclones

- Tropical cyclone not a big tornado
- Tropical cyclone, hurricane and typhoon same phenomenon, different location.

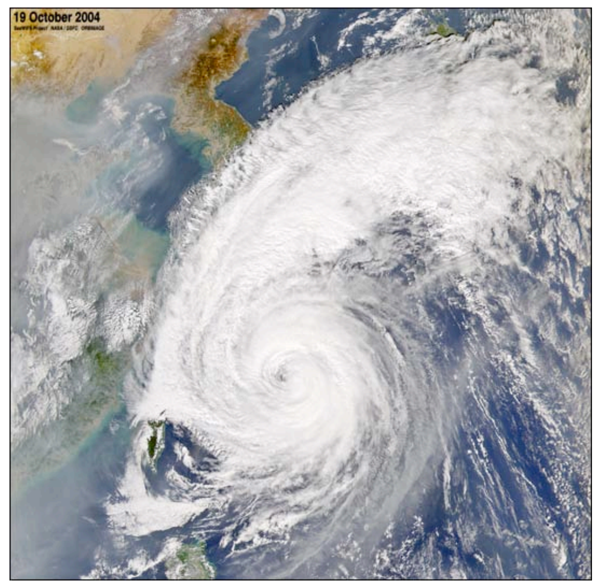
Hurricane Isabel (2003)
Atlantic Ocean
source: wikimedia.org

Cyclone Gonu (2007)
North Indian Ocean
source: wikimedia.org



Cyclone Tokage (2004)
Northwest Pacific Ocean

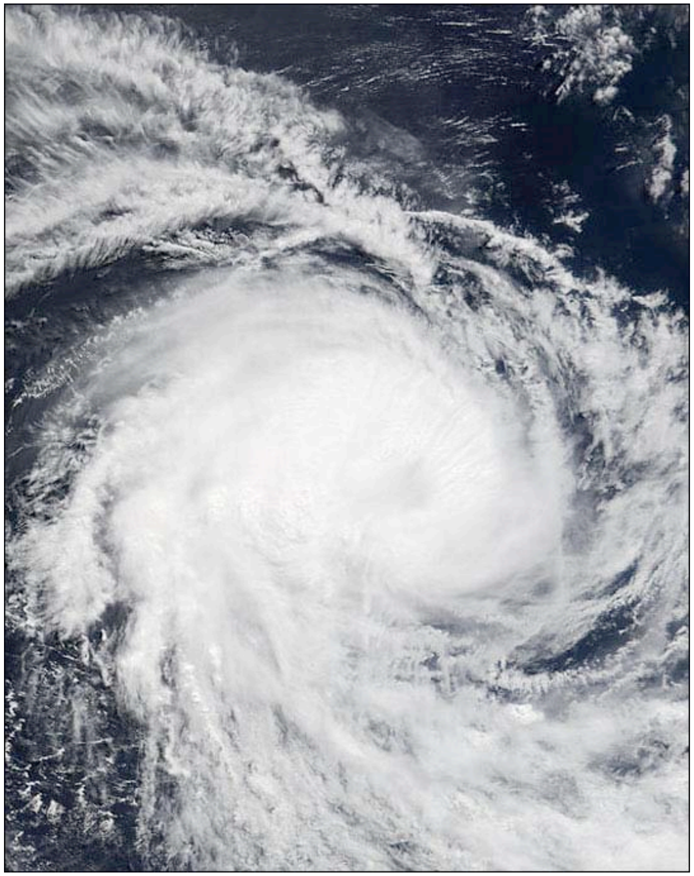
source: NASA

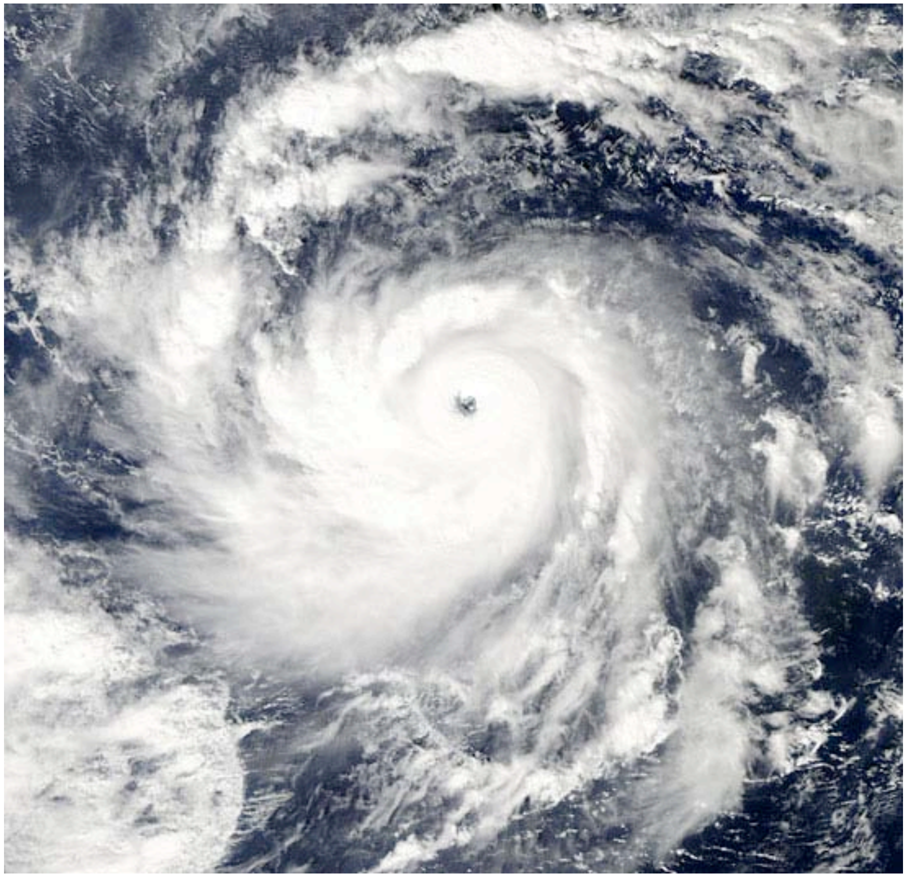


Cyclones spin "cyclonically"

TC Kessiny (2002)
South Indian Ocean

Supertyphoon Nida (2009)
Northwest Pacific Ocean





source: NASA

Cyclones spin “cyclonically”

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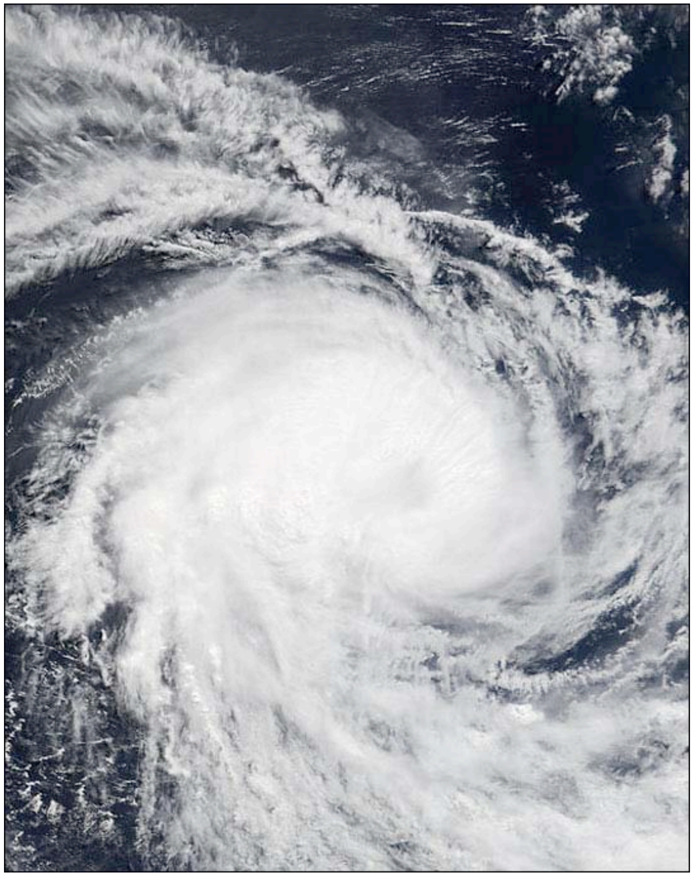

Supertyphoon Nida (2009)
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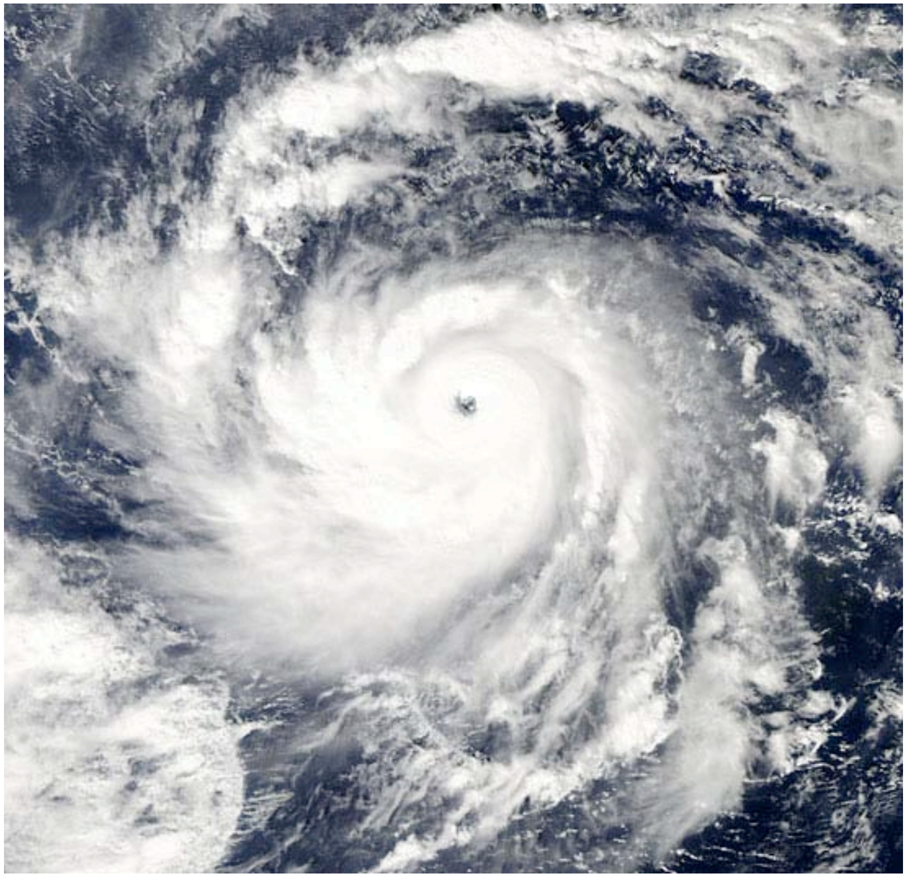


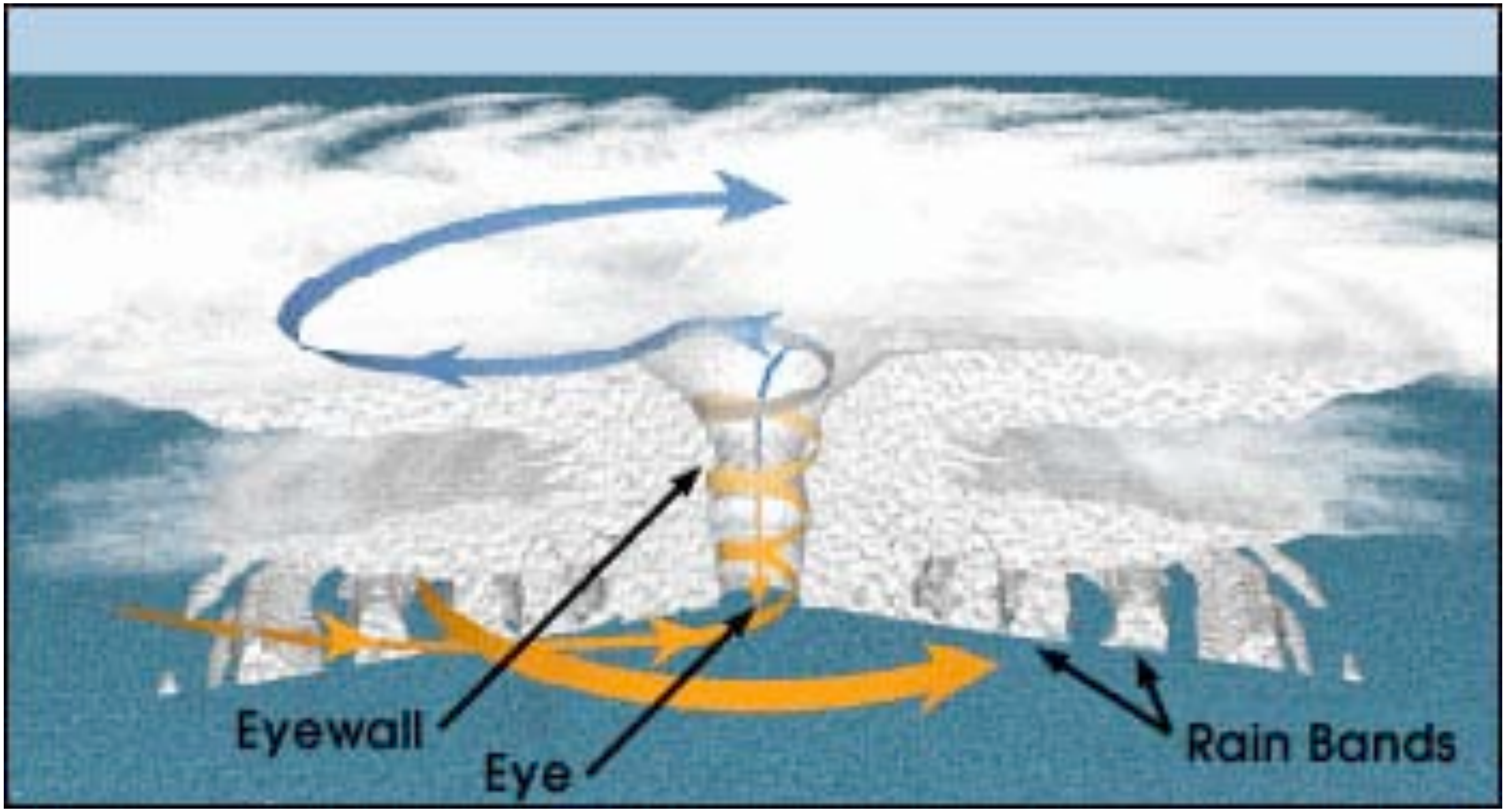
source: NASA

Saffir-Simpson Hurricane Scale

Category	Wind speed mph (km/h)	Storm surge ft (m)
5	≥156 (≥250)	>18 (>5.5)
4	131–155 (210–249)	13–18 (4.0–5.5)
3	111–130 (178–209)	9–12 (2.7–3.7)
2	96–110 (154–177)	6–8 (1.8–2.4)
1	74–95 (119–153)	4–5 (1.2–1.5)
Additional classifications		
Tropical storm	39–73 (63–117)	0–3 (0–0.9)
Tropical depression	0–38 (0–62)	0 (0)

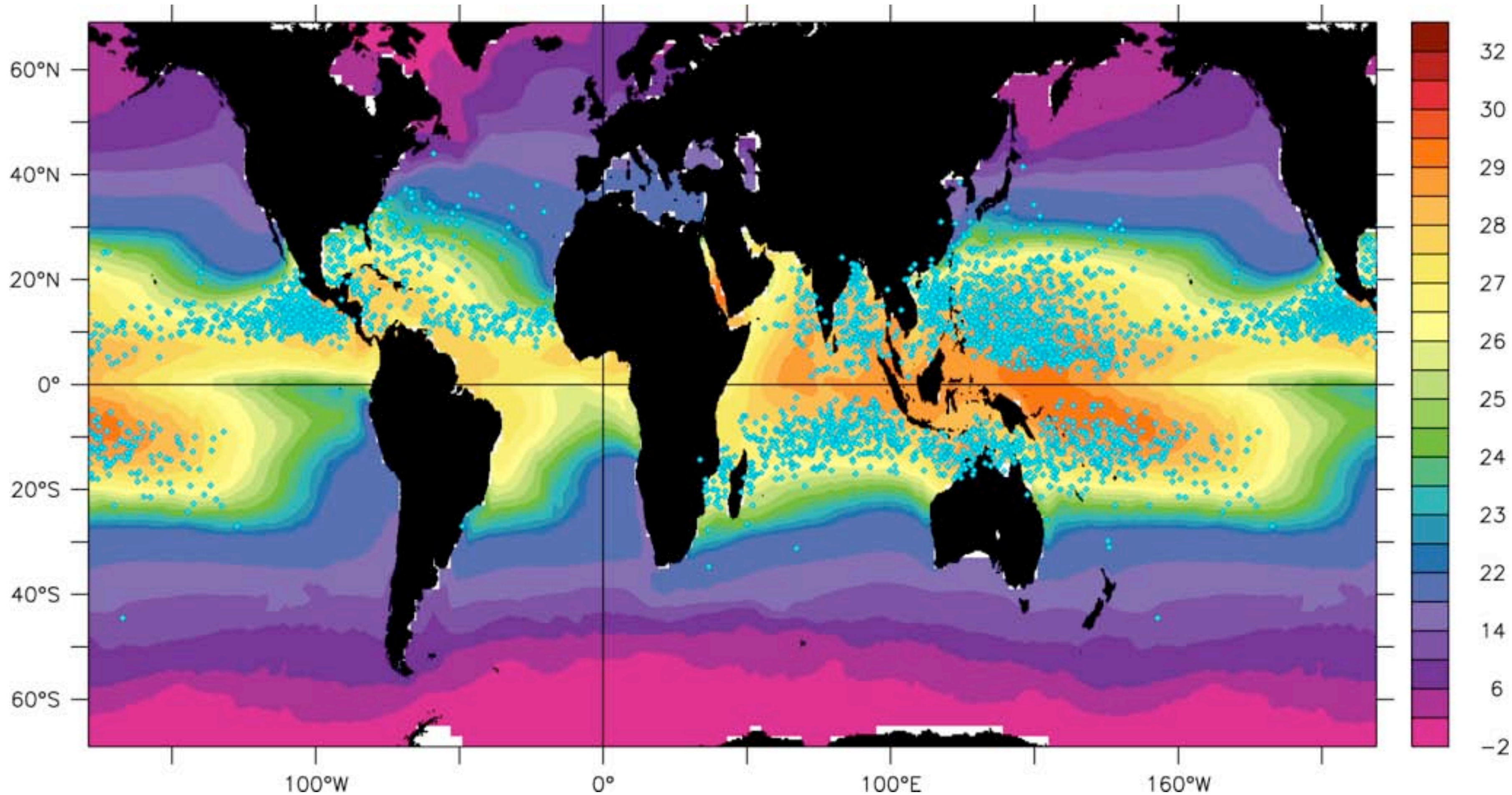
source: NOAA

Conceptual view of a tropical storm



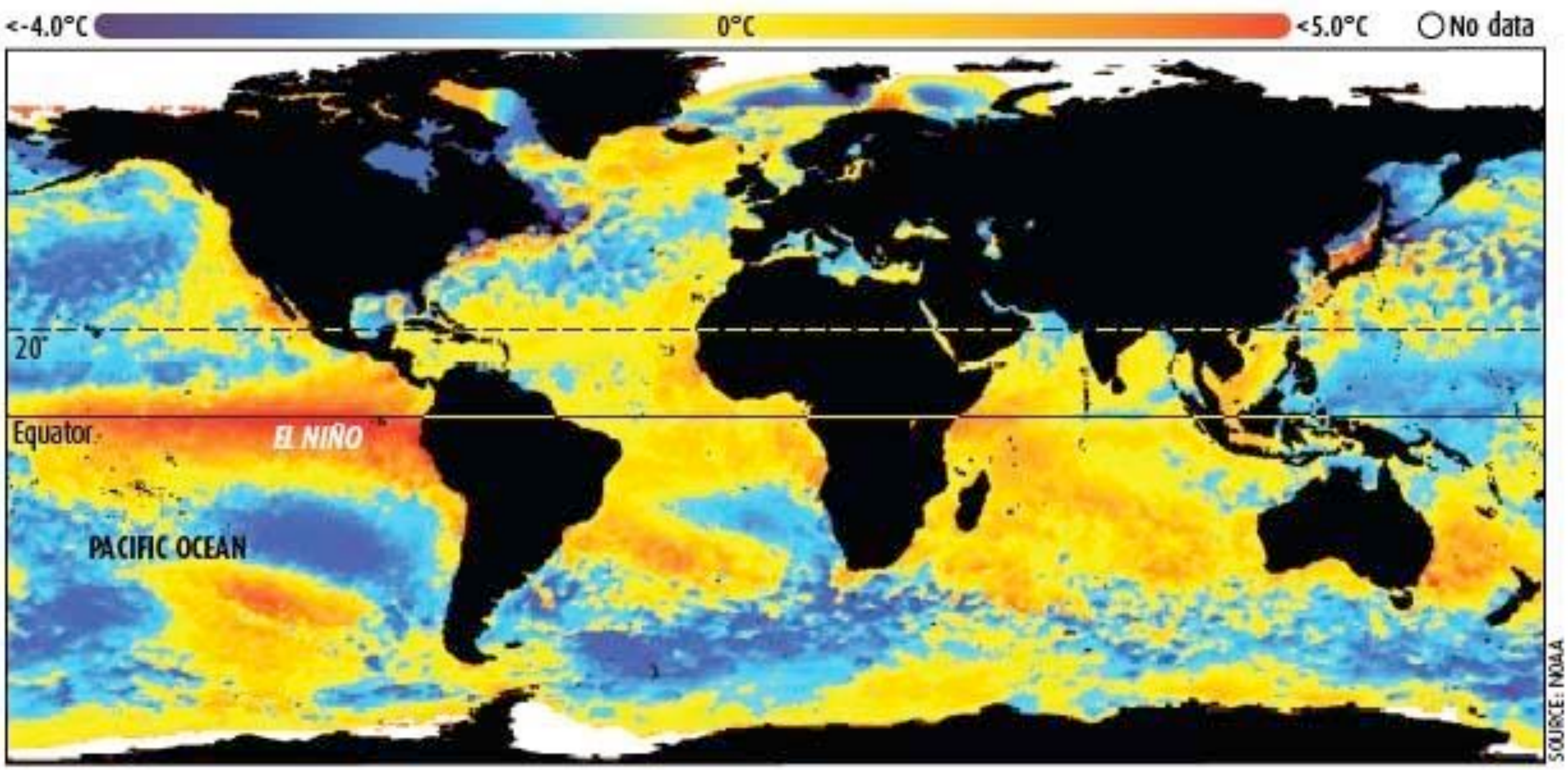
source: wikimedia.org
http://upload.wikimedia.org/wikipedia/commons/a/a9/Hurricane_structure_graphic.jpg

Warm water necessary for storm formation.

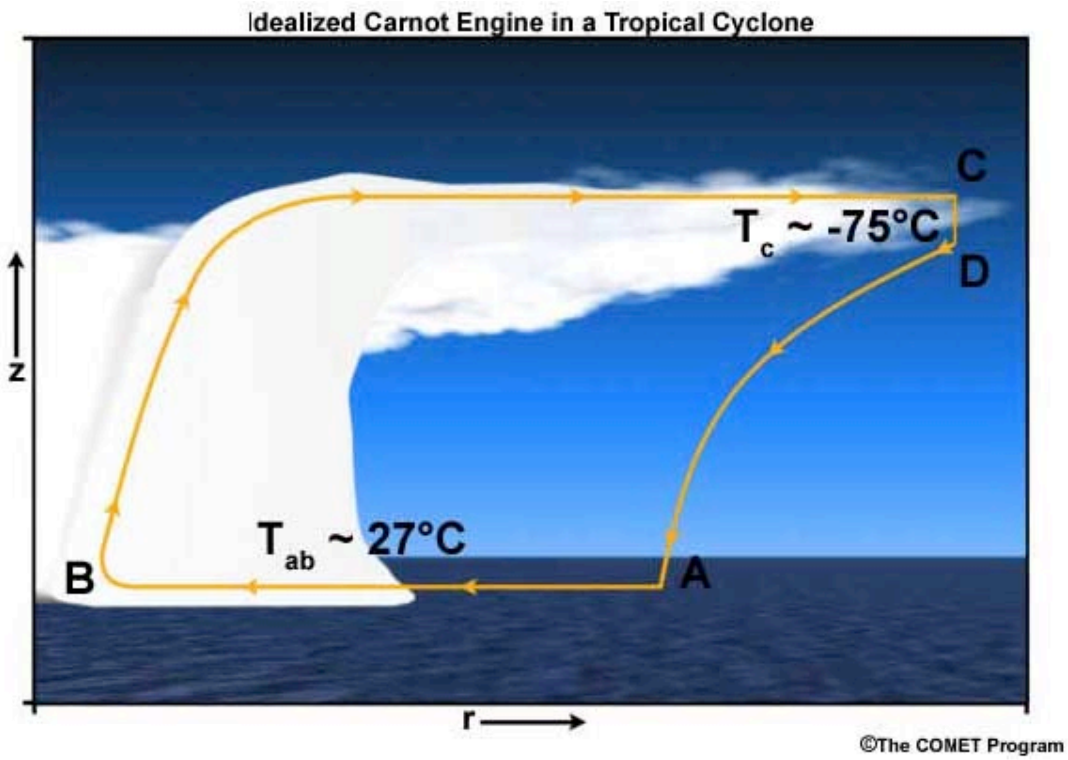


But warm water not enough, *e.g.* cyclones need a "calm" environment (without strong "wind shear" to disrupt them)

It’s not all local: El Niño events are associated with fewer Atlantic hurricanes, but warmer Atlantic



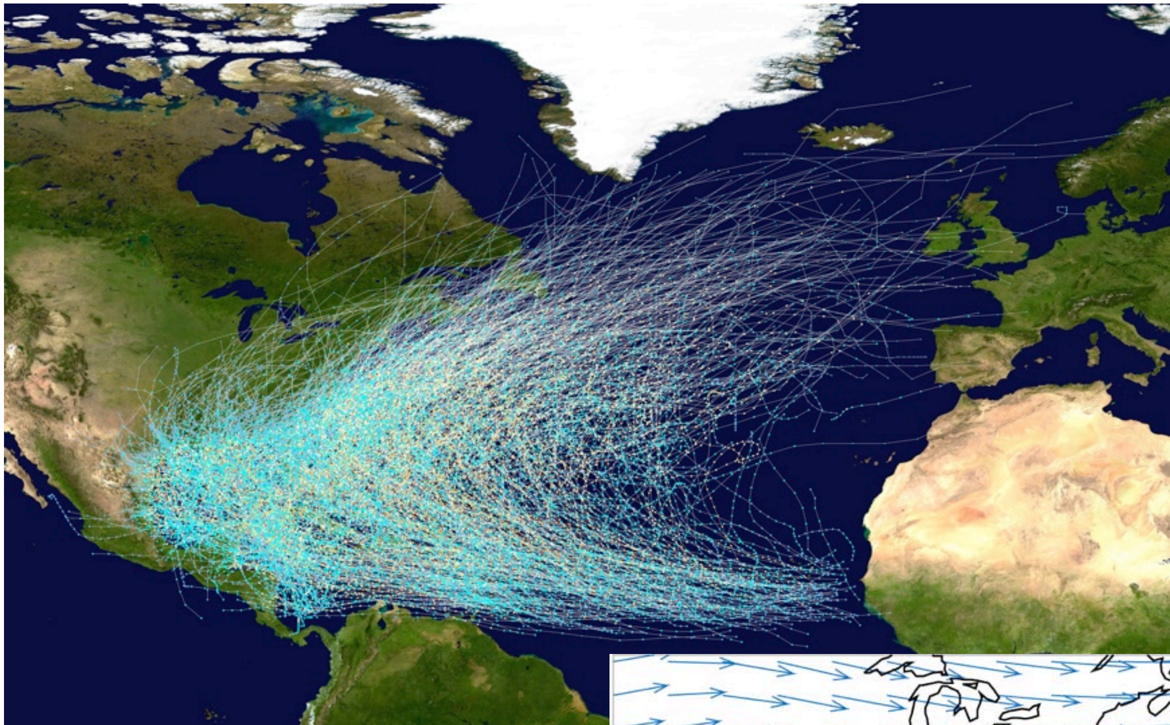
Theory of Maximum Potential Intensity



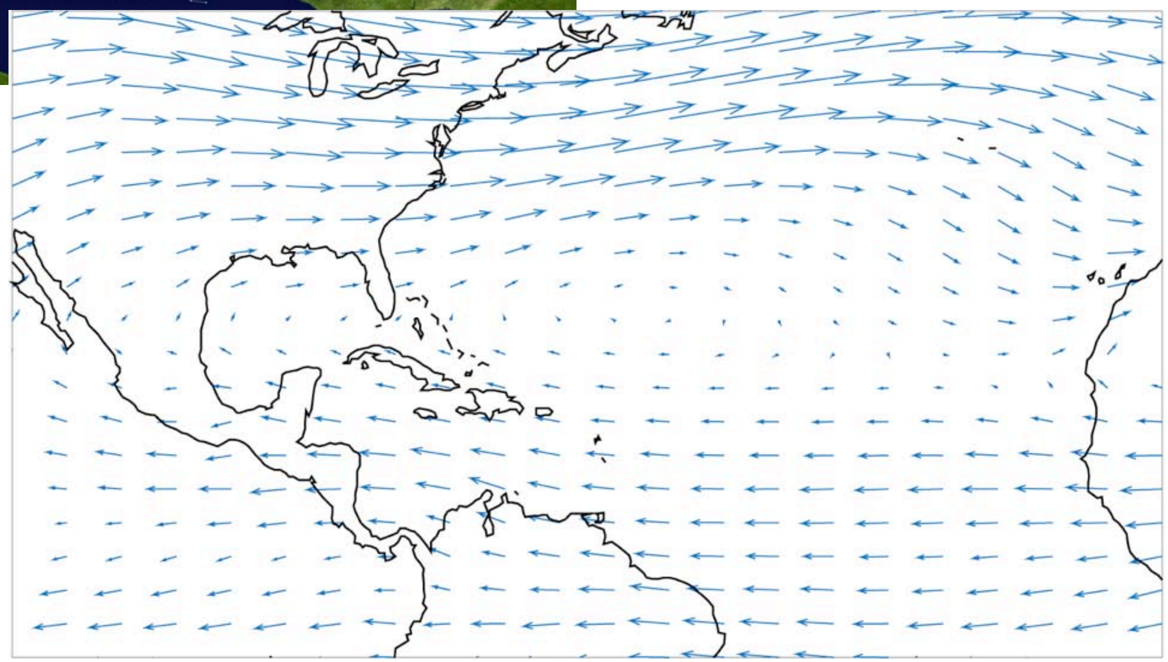
cf. Bister and Emanuel (1998)

Potential Intensity = "Fuel" * "Efficiency"

"Fuel" increases as ocean warms
"Efficiency" increases as ocean warms, decreases as upper atmosphere warms



Tracks of known Atlantic Tropical Storms (1850-2008)

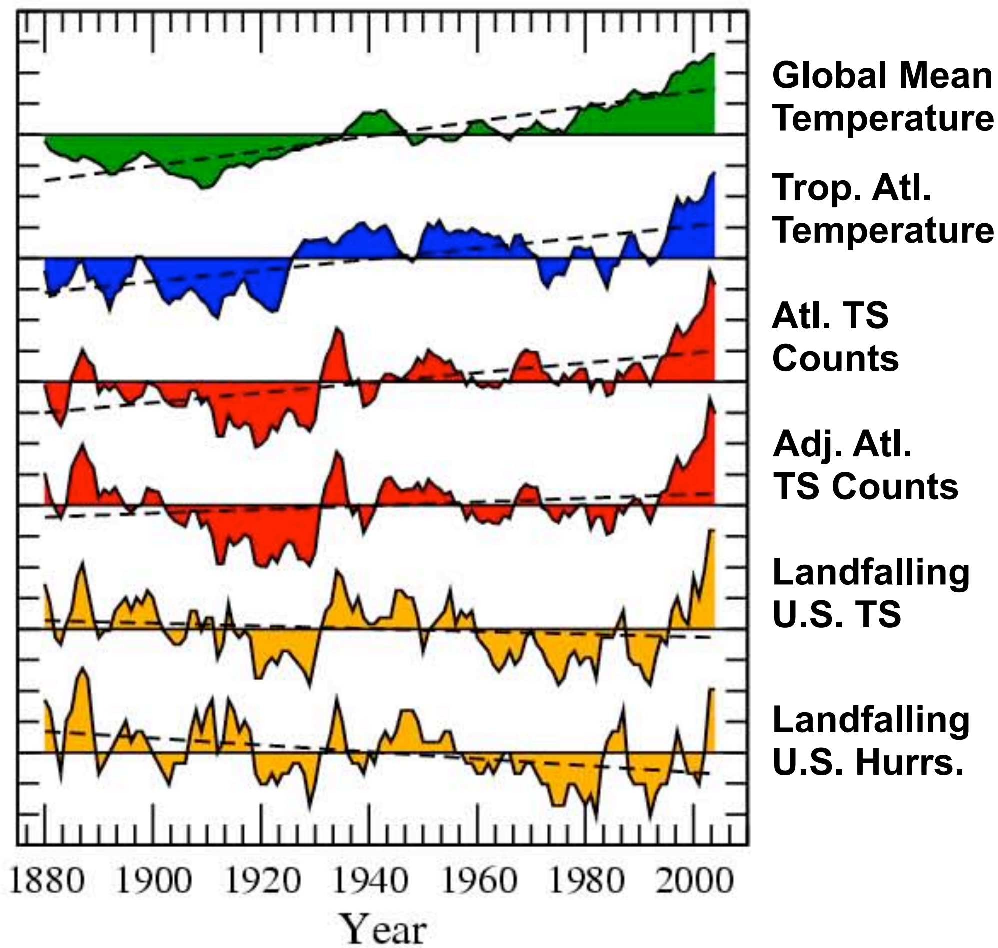


Winds averaged over lower atmosphere June-November

Measure of Activity

Measure of Activity

- Which measure?
  - Hurricane count
  - Landfalling storm count
  - Extremes in intensity
  - Shifts in average intensity
  - Sum of intensity
- Must balance demand with current understanding
  - Obs, models and theory limit.
- Differences must be communicated and understood



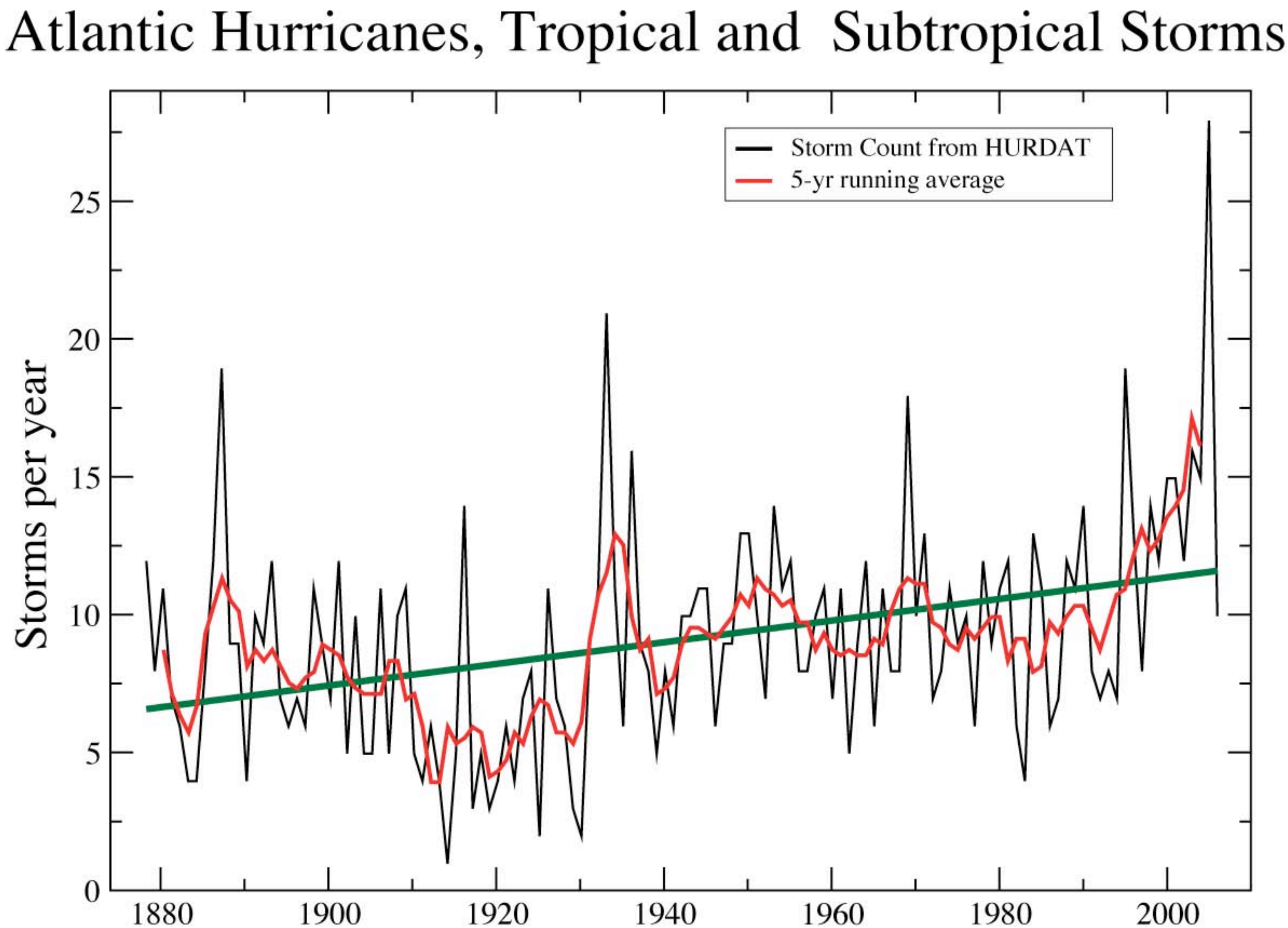
Source: Vecchi and Knutson (2008, J. Clim.)

How can we know what hurricanes did in the past?

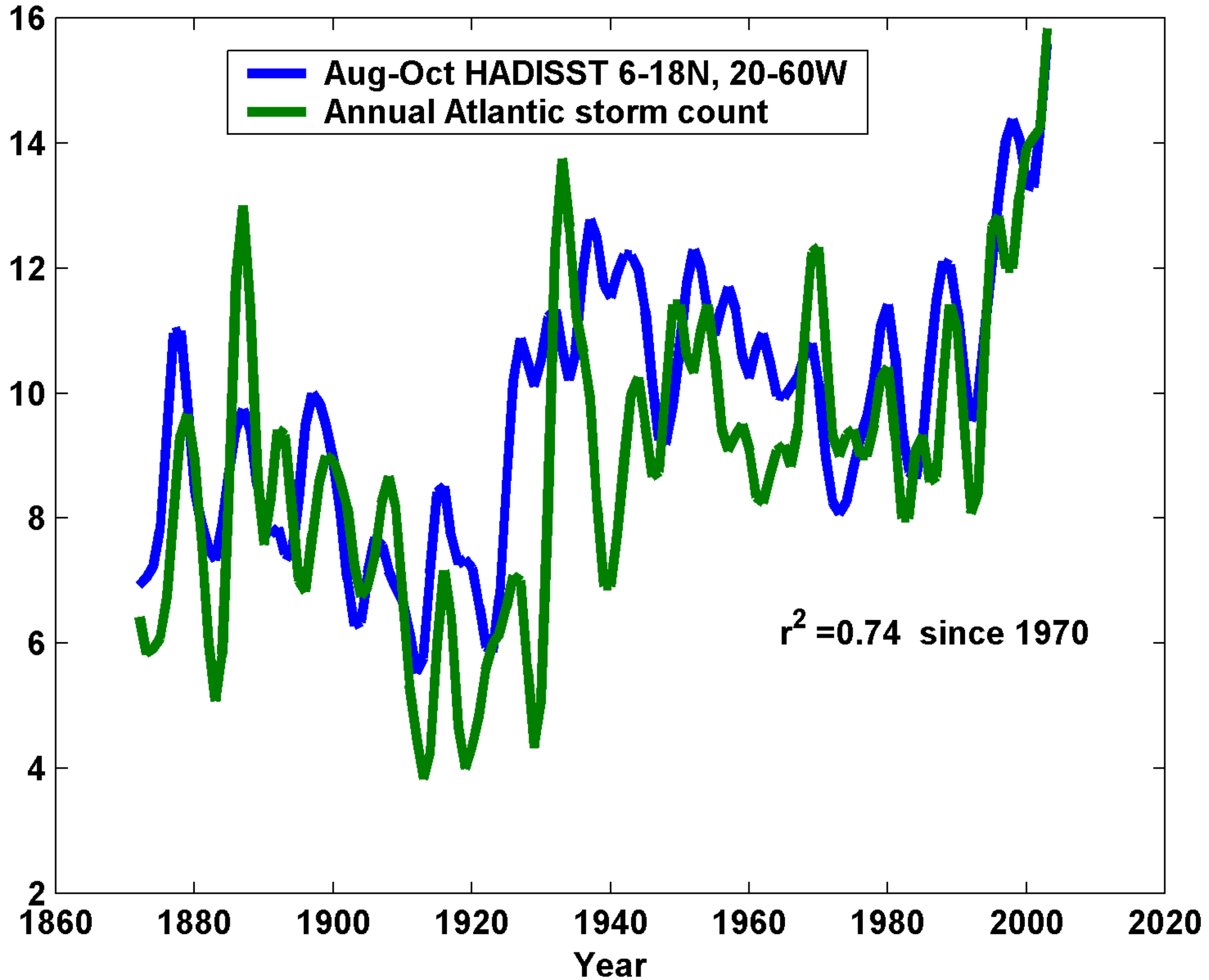
How can we estimate what hurricanes did in the past?

- Weather maps and reports
- Satellites
- Historical records (newspapers, etc)
- Sediments in marshes

Raw record of Atlantic tropical storms shows strong century-scale increase



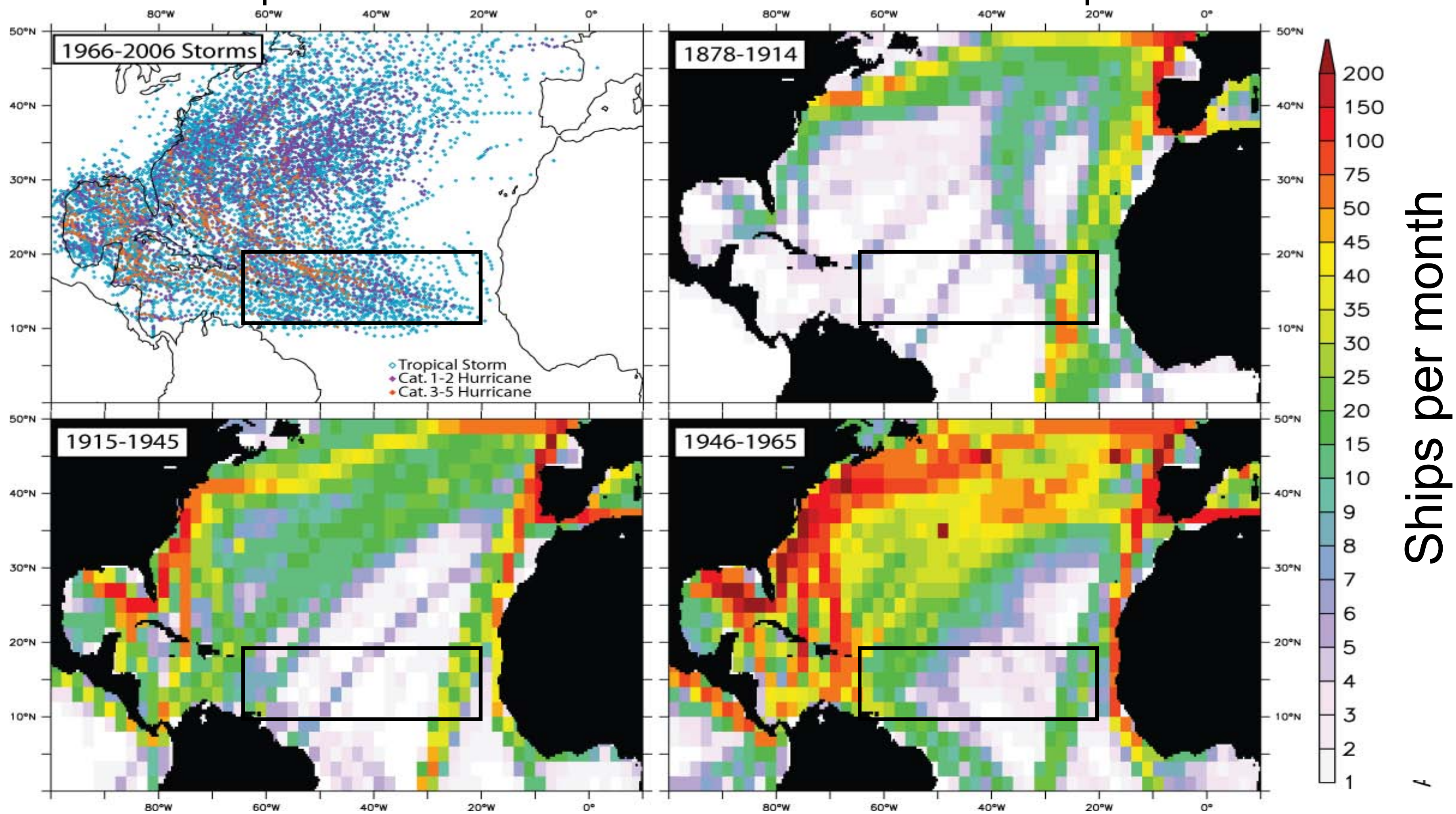
Source: Vecchi and Knutson (2008, J. Climate)



Source: Emanuel (2006); Mann and Emanuel (2006) EOS.
See also Holland and Webster (2007) Phil.Trans. R. Soc. A

Can we be sure the long-term increase is real?
Observational methods have changed with time….

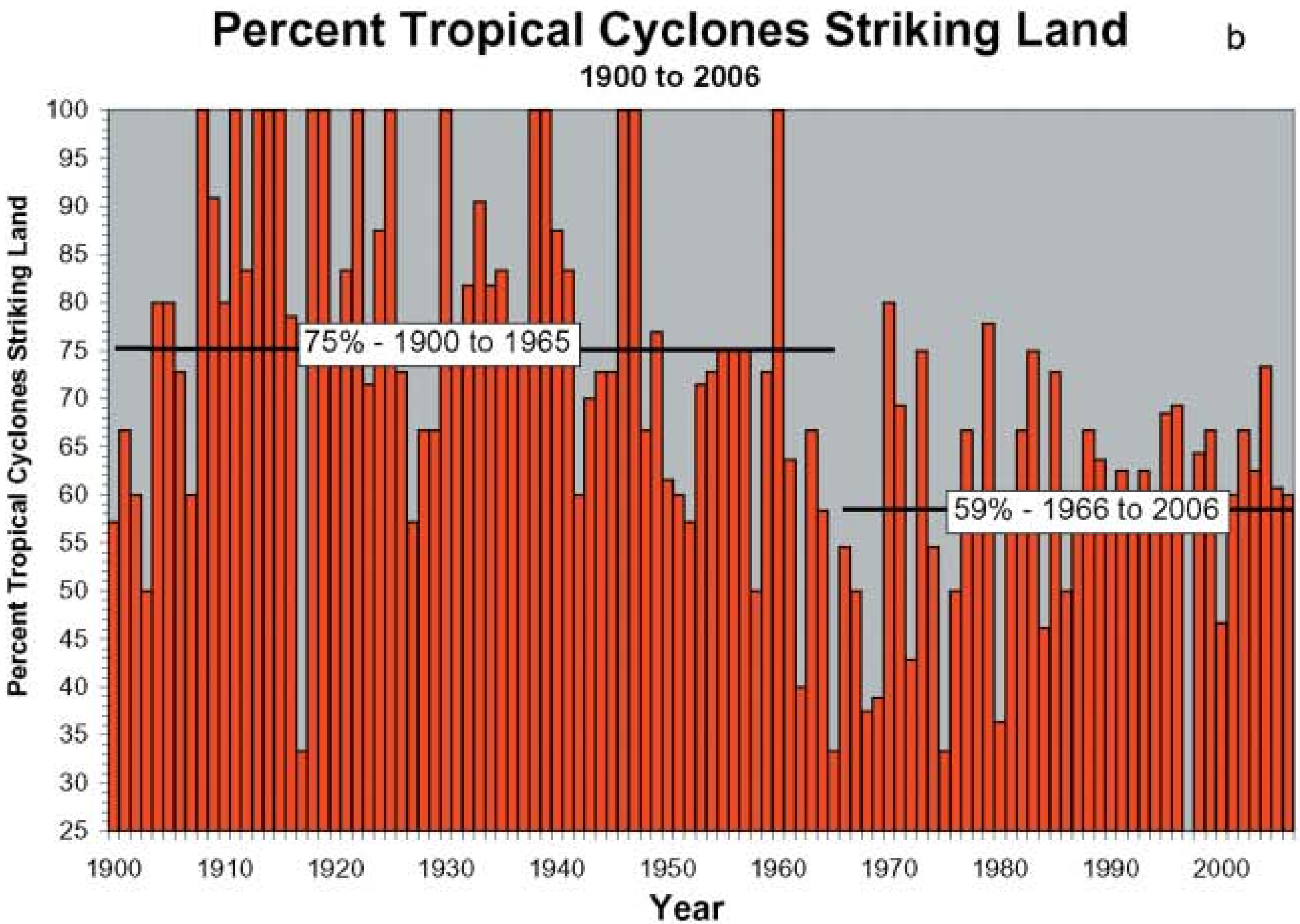
Storm positions | Pre-Panama Canal ships



Pre-WWII Ships | Pre-Satellite Ships

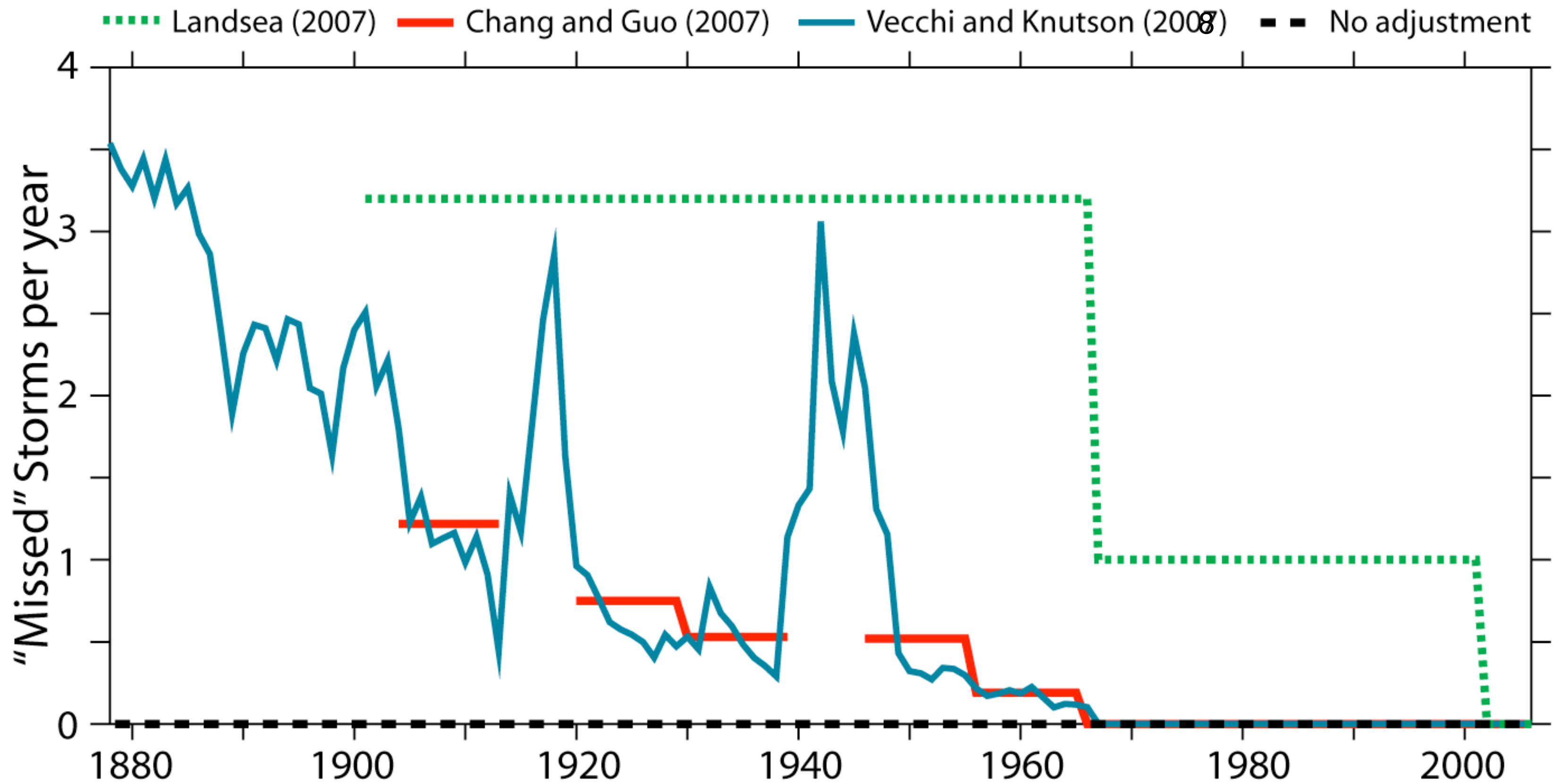
Vecchi and Knutson (2008)

Characteristics of recorded storms exhibit strong secular changes, e.g., fraction of storms hitting land



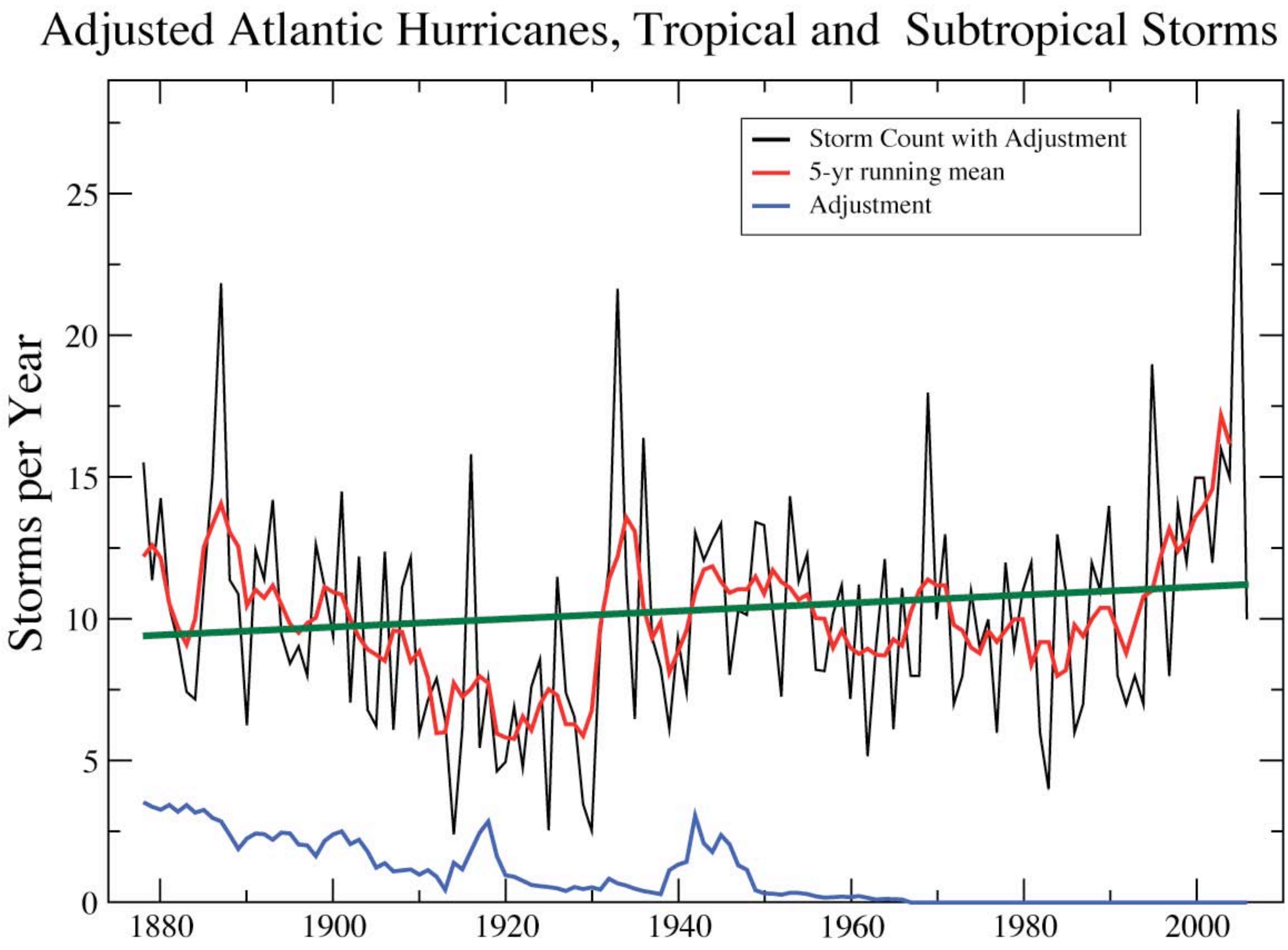
Source: Landsea, EOS, 2007.

…but we can estimate number of “missed” storms



Landsea (2007): Assumes constant landfall fraction.
Is this justified (see *Holland, 2007*)?

Chang and Guo (2007), *Vecchi and Knutson (2008)*:
How many storms “slip” through ship tracks?



-Adjusted storm count trend since 1878 **not** distinct from "noise"
-Decadal swings ***not*** a simple "cycle", either.

Estimating Atlantic tropical storm counts using historical document

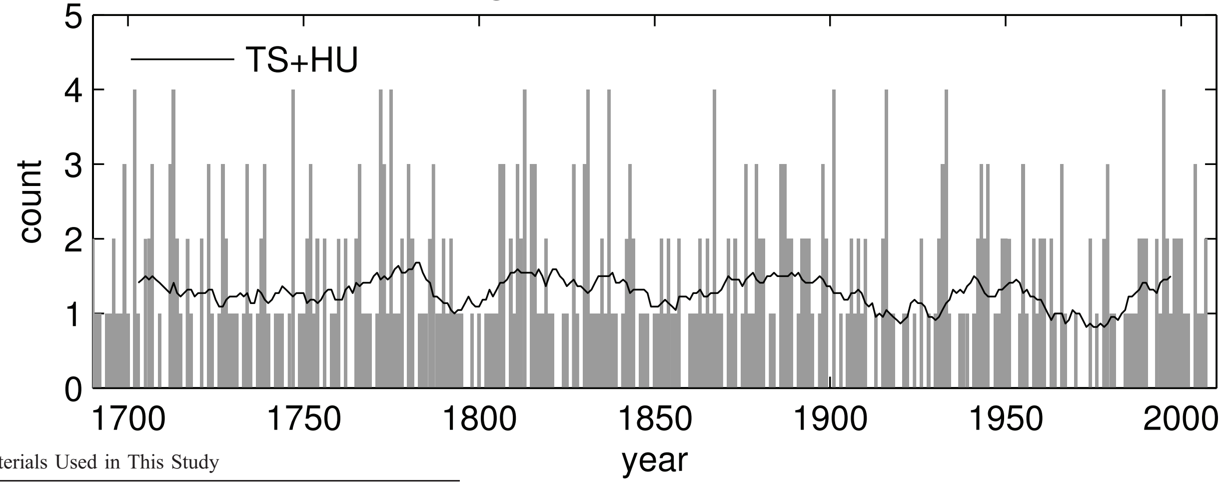


Table 1. Institutions Holding the Main Primary Source Materials Used in This Study

Institution	Source	Years Data Available
	Denmark	
Staatsbiblioteket (State and University Library), Aarhus	Danish West Indies newspapers	1817–1916
	United Kingdom	
National Archives (formerly Public Record Office), London	Royal Navy logbooks	1690–1823
National Archives (formerly Public Record Office), London	Caribbean region newspapers	1820–1855
British Library Newspaper Library, London	Caribbean region newspapers	1779–1872
	United States	
National Archives, Washington, DC	Reports of U.S. Consul Generals	1785–1905
National Archives, College Park, MD	Record Group 27, Records of the Weather Bureau: operational records; surface land observations made outside the United States	1843–1887
U.S. Library of Congress, Washington DC, Newspaper and Current Periodicals Library	US, Canada, Caribbean region newspapers	1703–1949
University of Maryland, College Park, MD, McKeldin Library	Early English newspaper collection and U.S. newspapers	1665–1870
American Antiquarian Society, Worcester, MA	Caribbean Newspaper Collection	1770–1870
University of Florida, Gainesville, FL	Latin American newspaper collection; Caribbean region newspapers	1766–1949
Harvard University, Cambridge, MA, Widener Library	Jamaica newspapers	1718–1895 (discontinuous series)
Columbia University, New York City, Butler Library	Danish West Indies newspapers	1770–1791
Mariner's Museum, Newport News, Virginia	Complete set of extant issues of *Lloyd's List* for the 18th century	

Source: Cenoweth and Divine et al (2008, G3)

Using sediment overwashes to estimate tropical cyclones

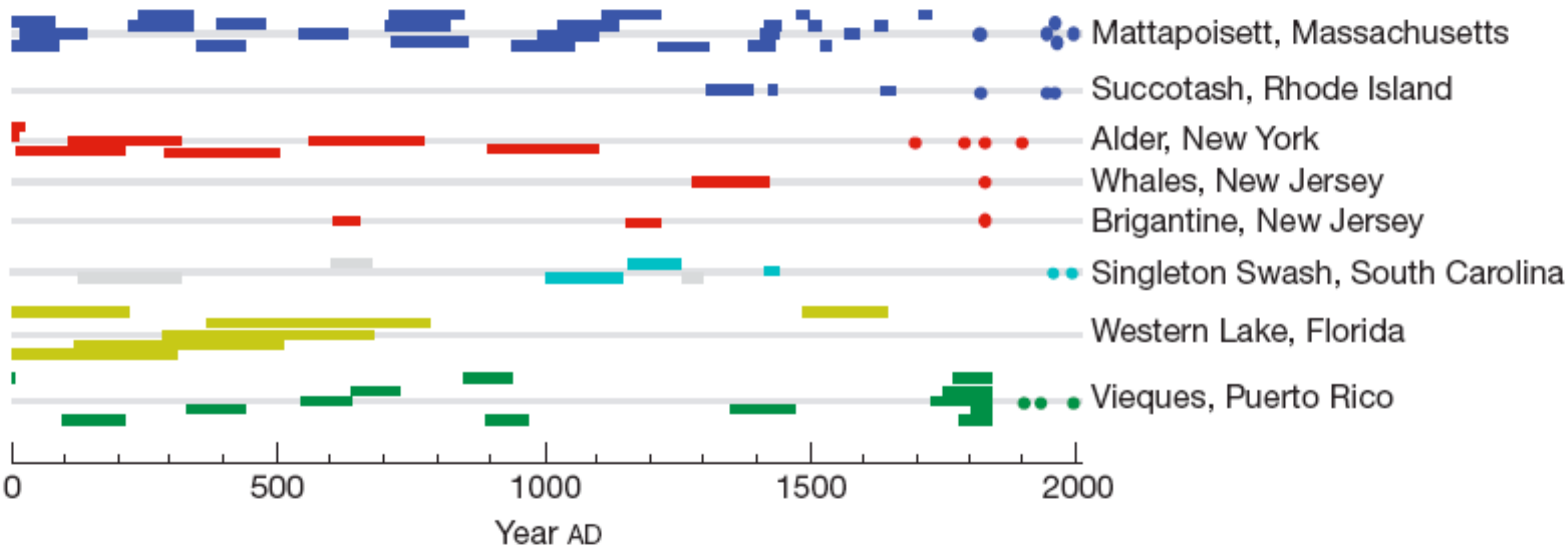


Figure 1 | Overwash sediment records of landfalling hurricanes. Event histories are shown for New England (blue), Mid-Atlantic (red), the southeastern US coast (turquoise; grey denotes oyster-bed events not used for reasons discussed by ref. 28 and in the Supplementary Information), the Gulf Coast (yellow) and the Caribbean (green). The horizontal width of shaded rectangles indicates the $\pm 1\sigma$ age model uncertainties. Circles indicate historical hurricane events.

Source: Mann et al (2009, Nature)

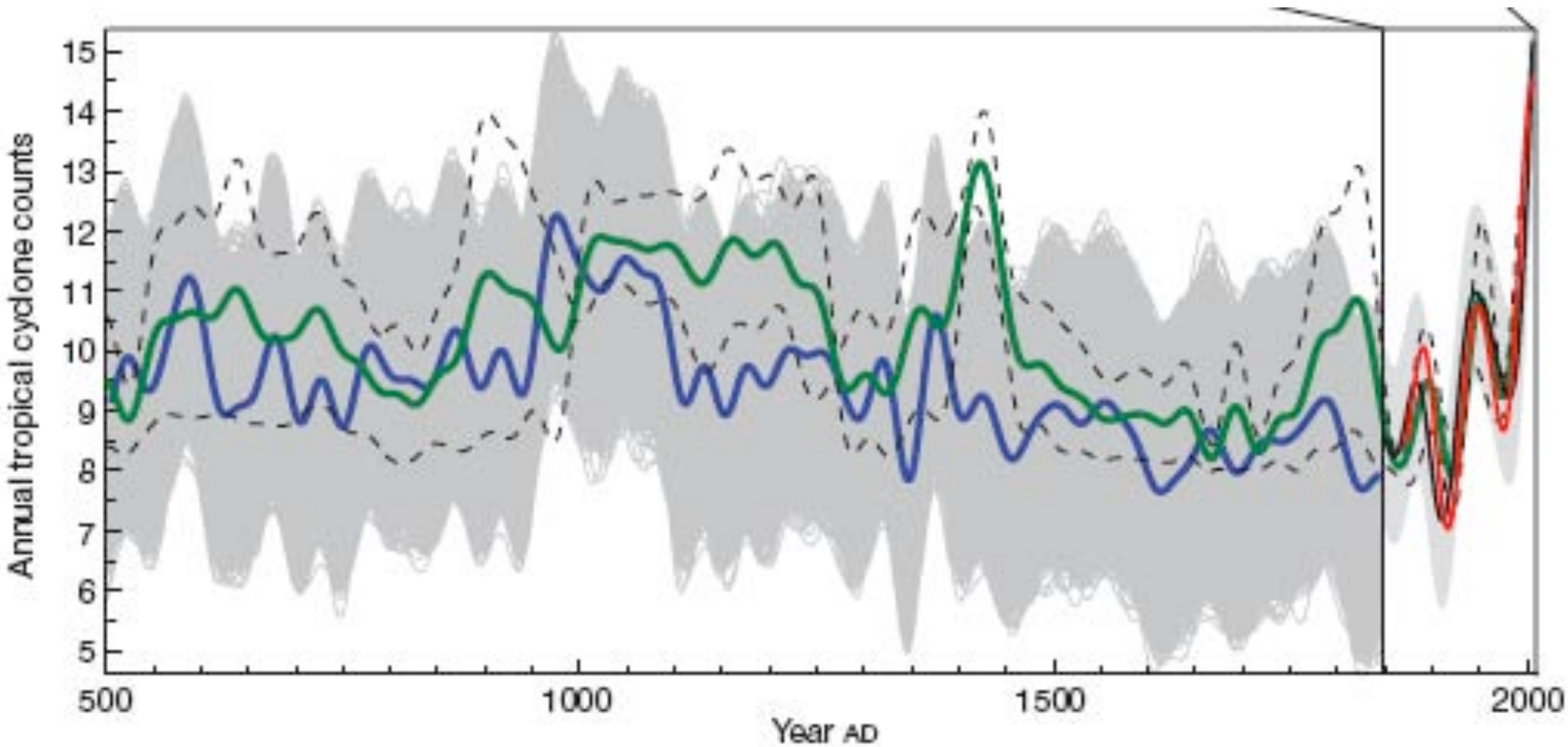
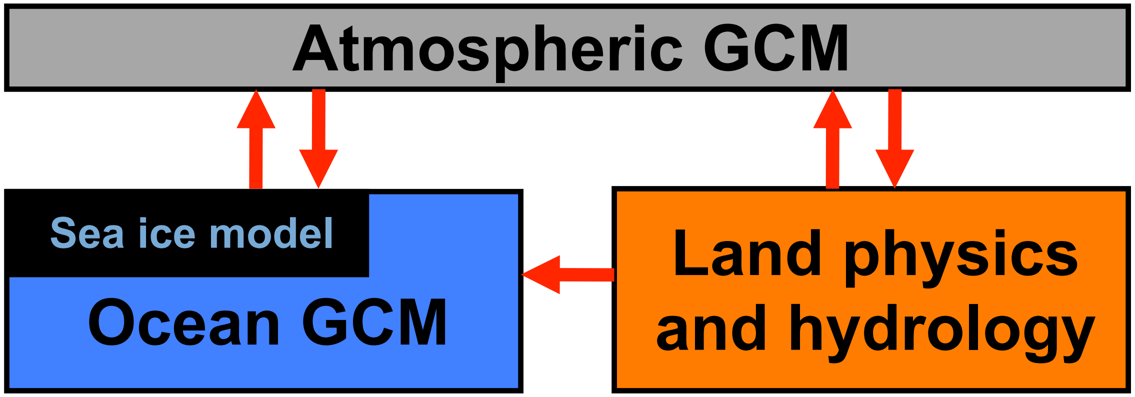


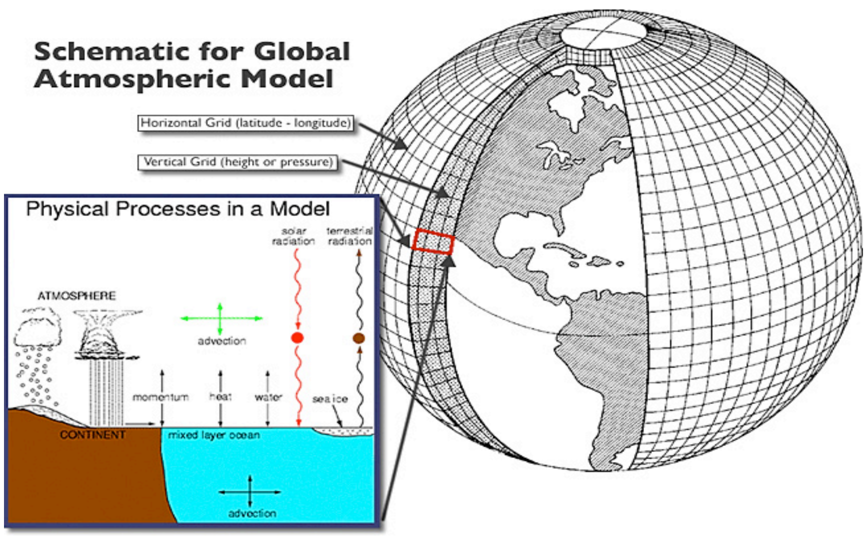
Figure 3 | Long-term Atlantic tropical cyclone counts. Modern Atlantic tropical cyclone counts (red) compared both with statistical model estimates of tropical cyclone activity based on modern instrumental (AD 1851–2006; black) and proxy-reconstructed (AD 500–1850; blue) climate indices and an estimate of basin-wide landfalling Atlantic hurricane activity (AD 500–1991) derived from regional composites of overwash sediments (green). All series were smoothed[30] at multidecadal (>40-year) timescales. The sediment composite record was standardized to have the same mean and multidecadal variance as the statistical model estimates. Uncertainties for the statistical model estimates (grey shading, indicating 95% confidence intervals) take into account the uncertainty in the statistical model itself (grey shading), and—in the case of the proxy-reconstructed indices (grey shading), the additional uncertainty due to the uncertainties in the proxy-reconstructed climate indices. Uncertainties for the sediment composite record (thin dashed black curves indicating upper and lower limits of the 95% confidence interval) are derived from jackknifing of the full composite with respect to each of the five contributing regional estimates, as discussed in the text.

Source: Mann et al (2009, Nature)

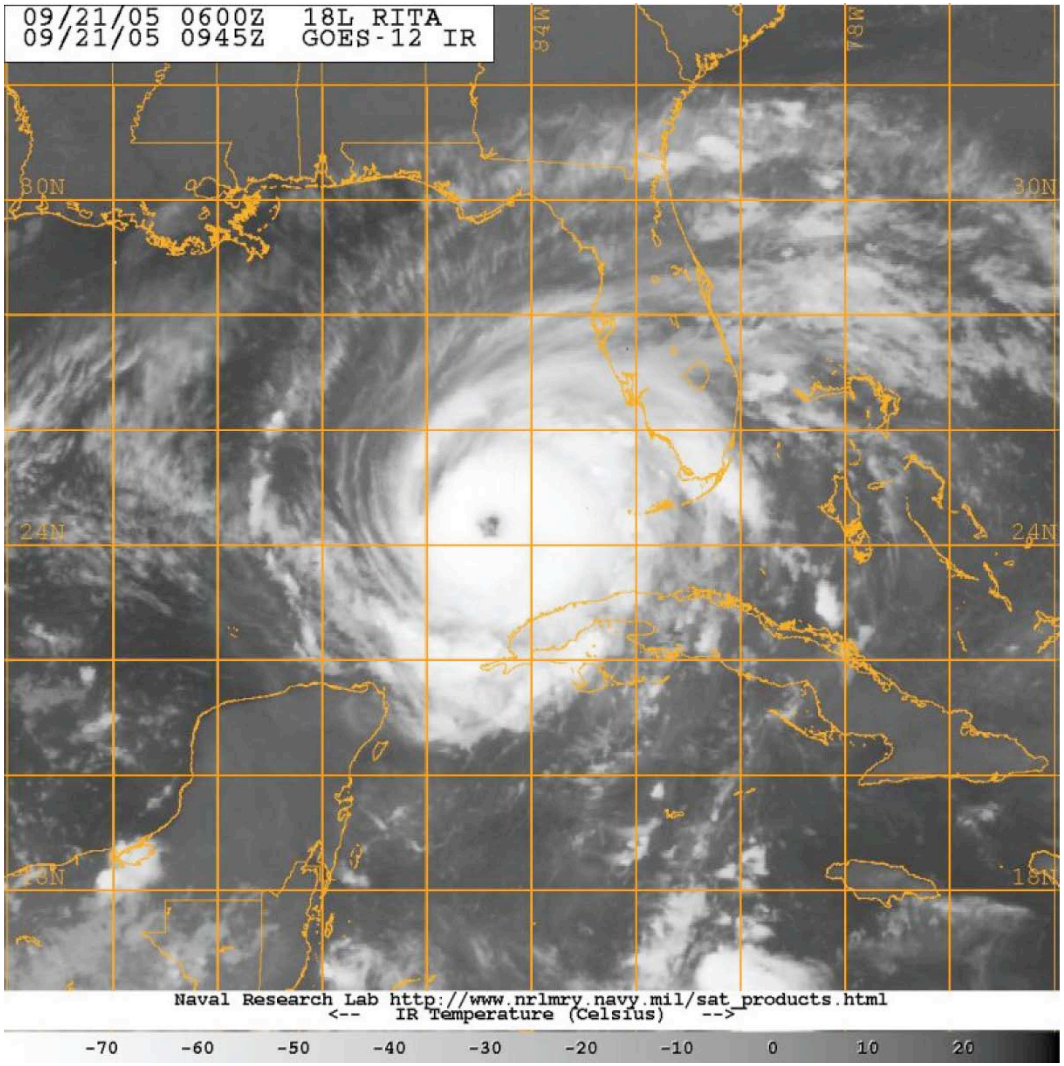
How do we expect hurricane activity to change?



Can global climate models give guidance about changes in Atlantic storm activity?



But, current computing power limits ability of global climate models to represent hurricanes



Hurricane Rita (2005): orange grid is representative of current ***global*** climate model resolution.

Size of grid limited by power of computers.

Nonetheless, tropical storms are affected by ***large-scale*** conditions that today's climate models ***can*** represent.

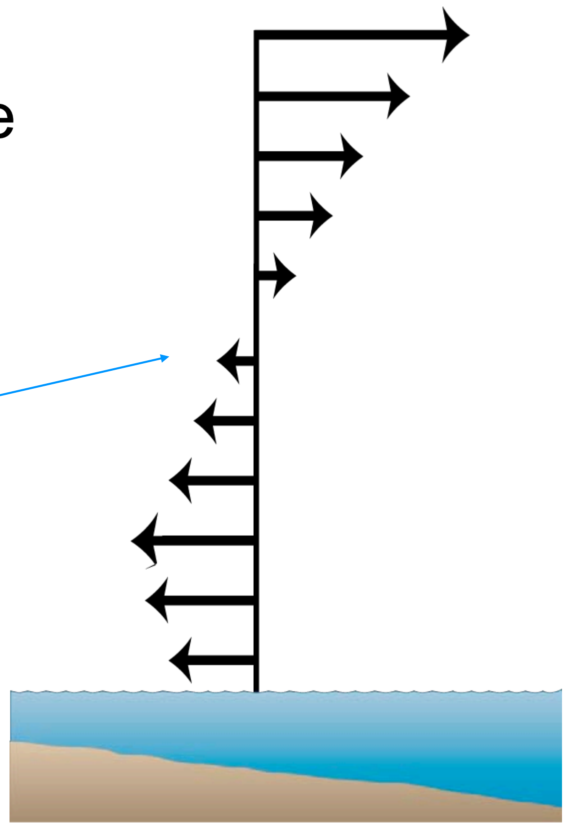
<u>Factors that favor storm development and intensification</u>:

- Warm ocean surface
- Cool upper atmosphere

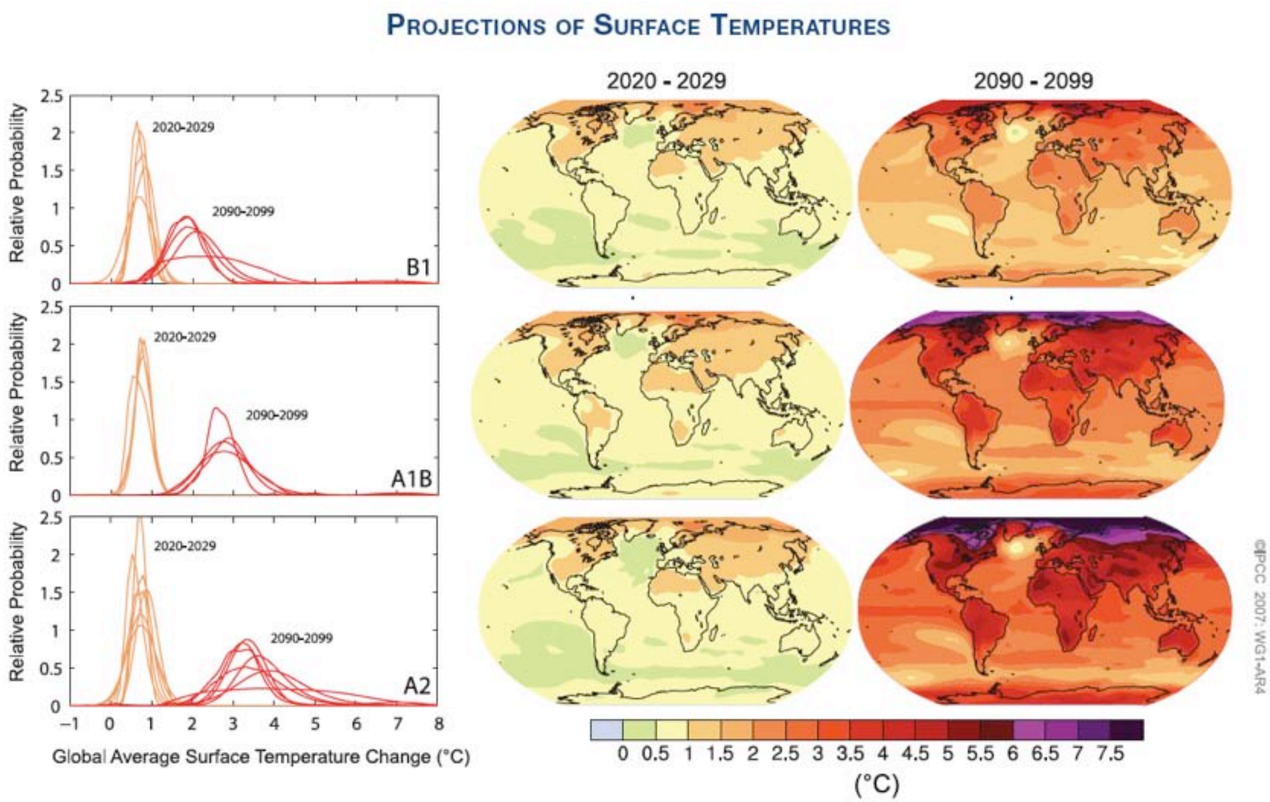
} Help define potential intensity

cf. Emanuel, Holland

- Low vertical wind shear
- Moist middle atmosphere
- etc.



From increasing greenhouse gases, we expect tropics to warm over current century



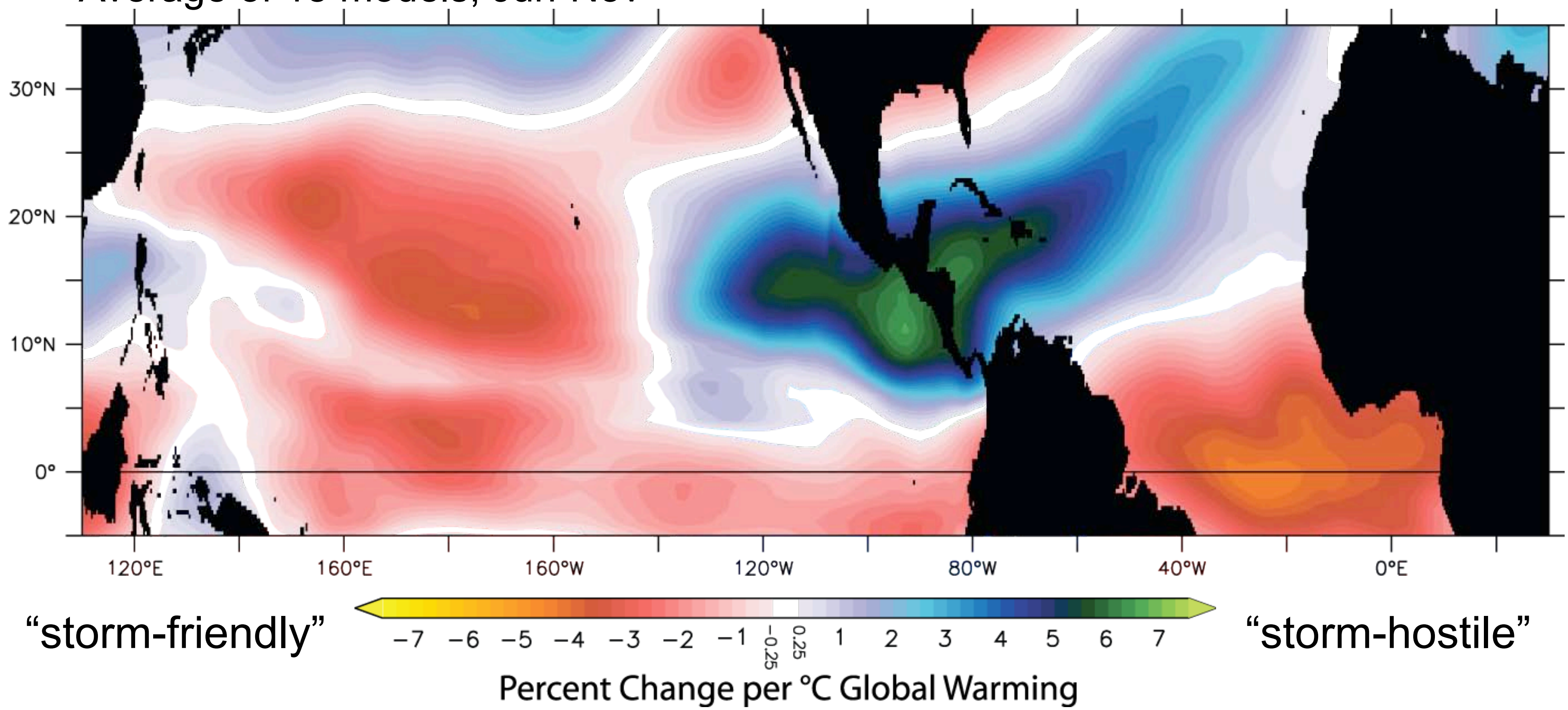
IPCC-AR(2007)

Models also indicate that upper atmosphere should warm much more than the surface.

What is net effect?

Projected 21st Century Changes in Vertical Wind Shear

Average of 18 models, Jun-Nov

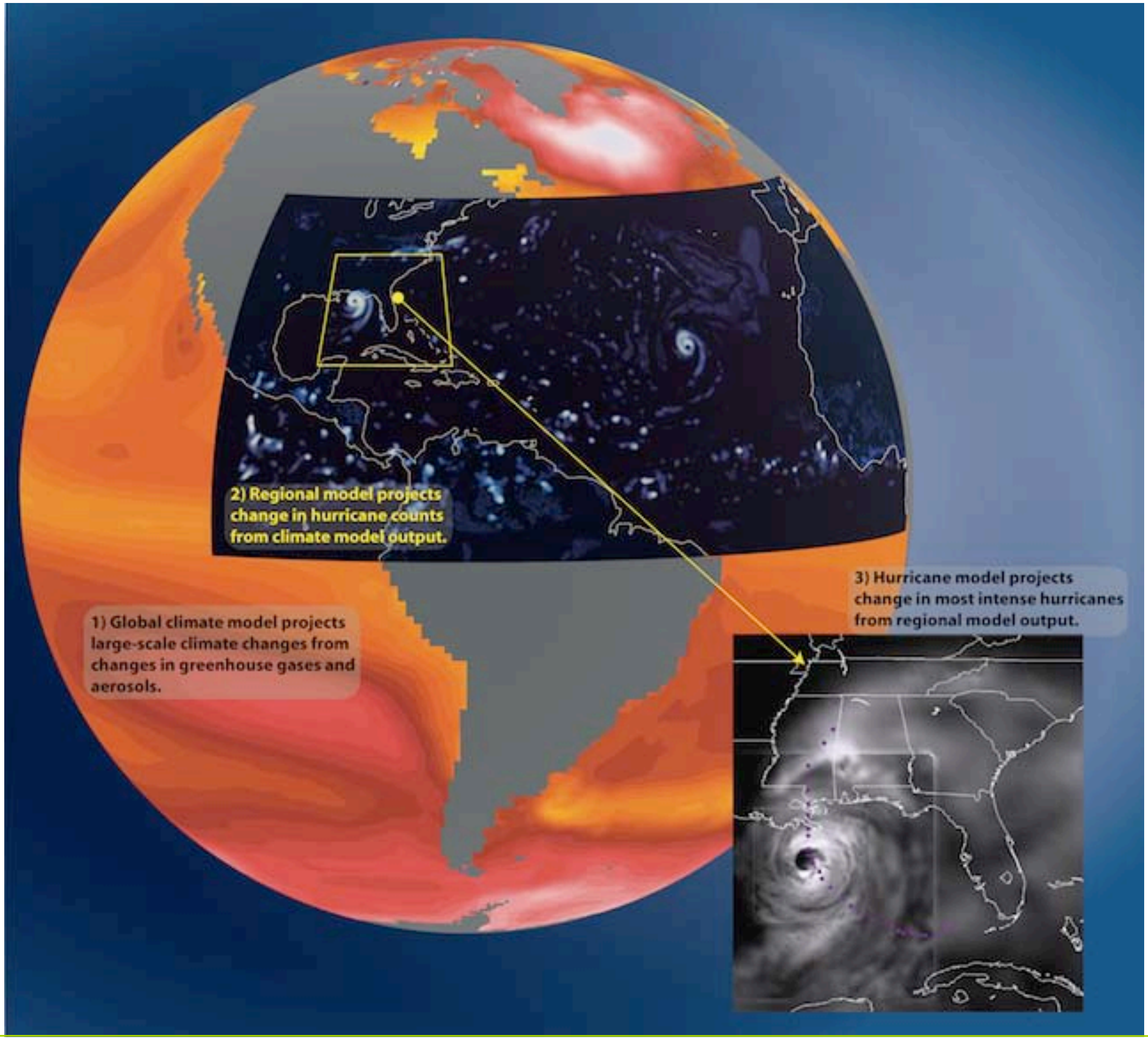


Over swath of tropical Atlantic and East Pacific, increased wind-shear.

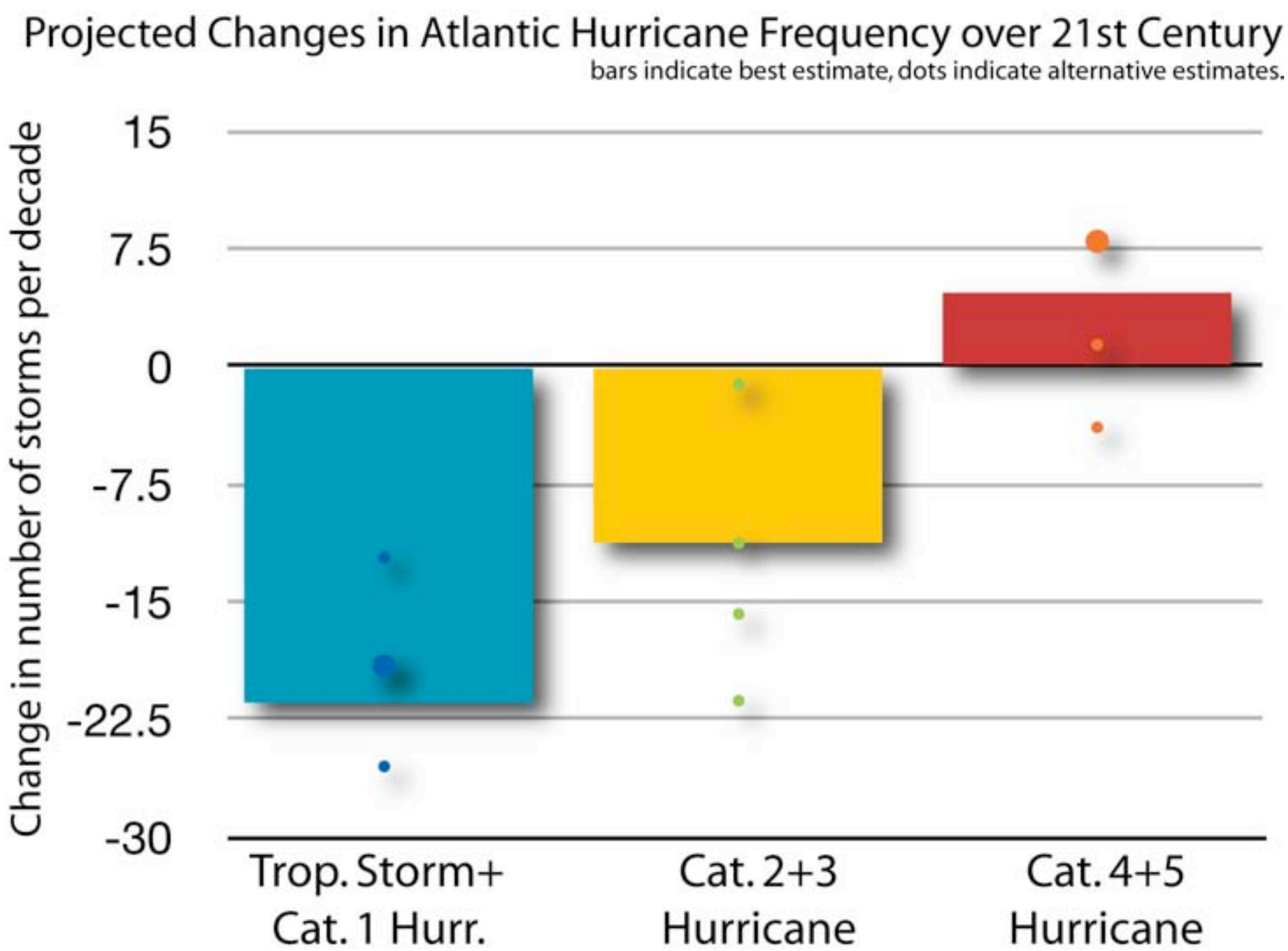
What is net effect of increased potential intensity and wind shear?

Vecchi and Soden (2007, GRL)

Three-step assessment of impact of global warming on strongest storms



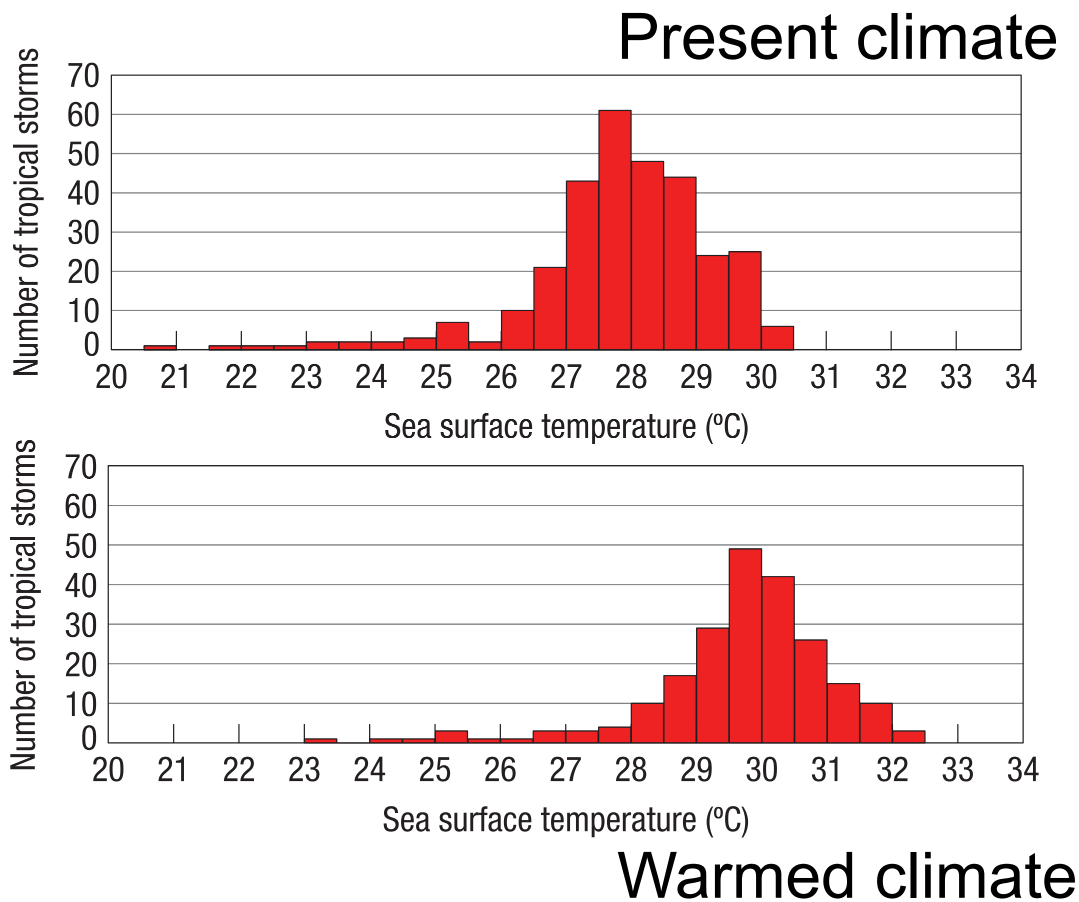
Frequency of weakest storm projected to decrease.
Frequency of strongest storms may increase.



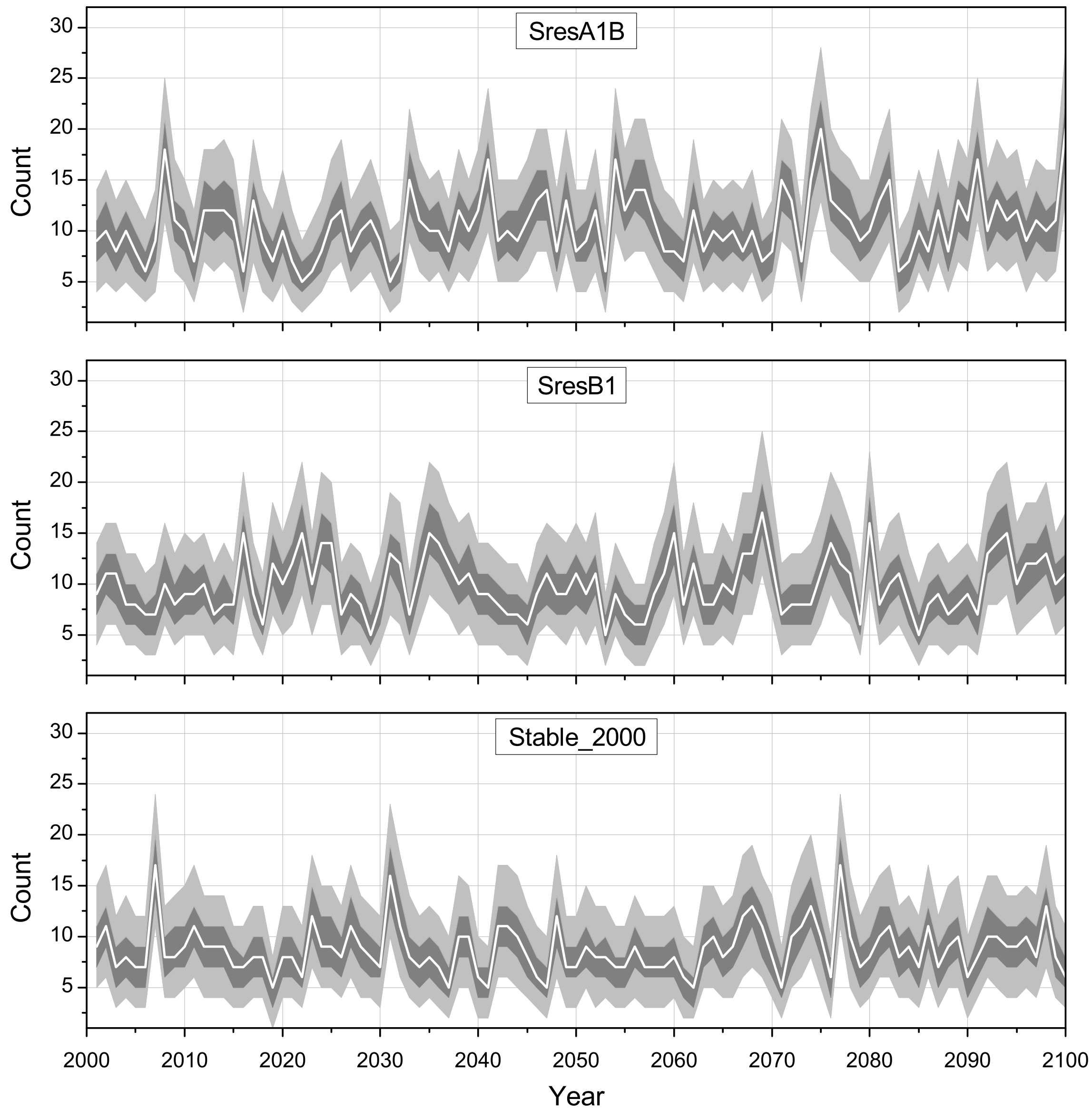
Adapted from Knutson et al (2008, Nature Geosci.), Bender et al (2010 Science)

Temperature "threshold" of TC formation increases with global warming

Ocean temperature when cyclone forms:



We expect continued variation of tropical storm frequency



Projected Atlantic Tropical Storm Frequency

(statistical downscaling of GFDL-CM2.1)

source: Villarini et al (2010)

My current interpretation of evidence

- Observations: can't reject possibility of no change in frequency
  - Data issues and short records
  - We will never know how many storms we didn't see, or what they were like. We can only estimate it.
- Multiple factors affect change in hurricane activity:
  - Pattern of temperature changes is key.
- Projected changes depend on measure chosen, *e.g.:*
  - Atlantic TC Frequency: small change, possible **decrease**
  - Atlantic TC Intensity: projected **increase**
- Year-to-year and decade-to-decade variations will still exist.
- Increased coastal population and wealth: increased vulnerability
- Sea level rise: same storm greater potential impact.
- This is a topic of vigorous scientific inquiry.

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Key concepts

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  - Pushing the limits of our theory and computers
- False choice: global warming **OR** climate variability
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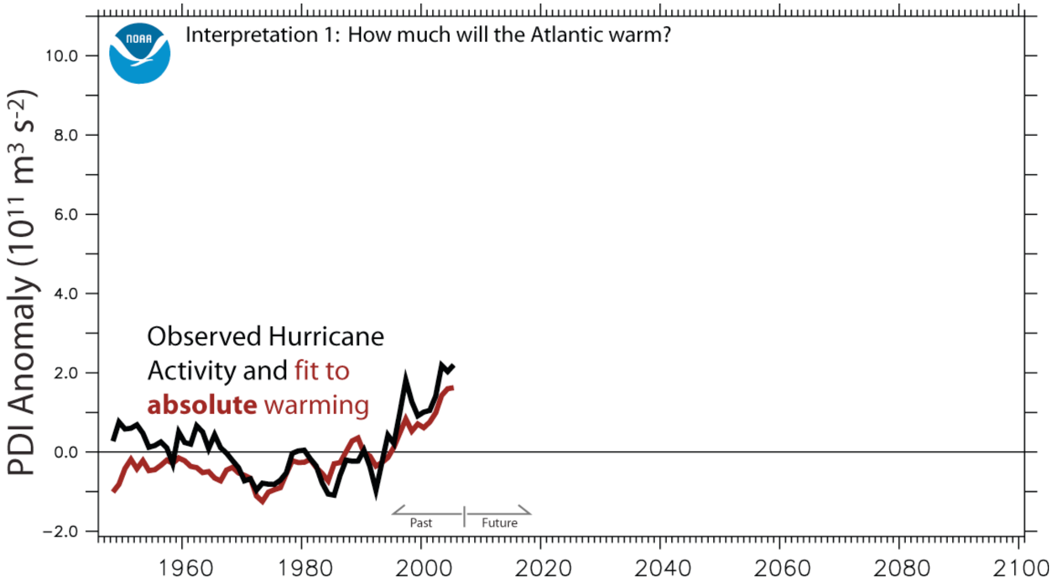
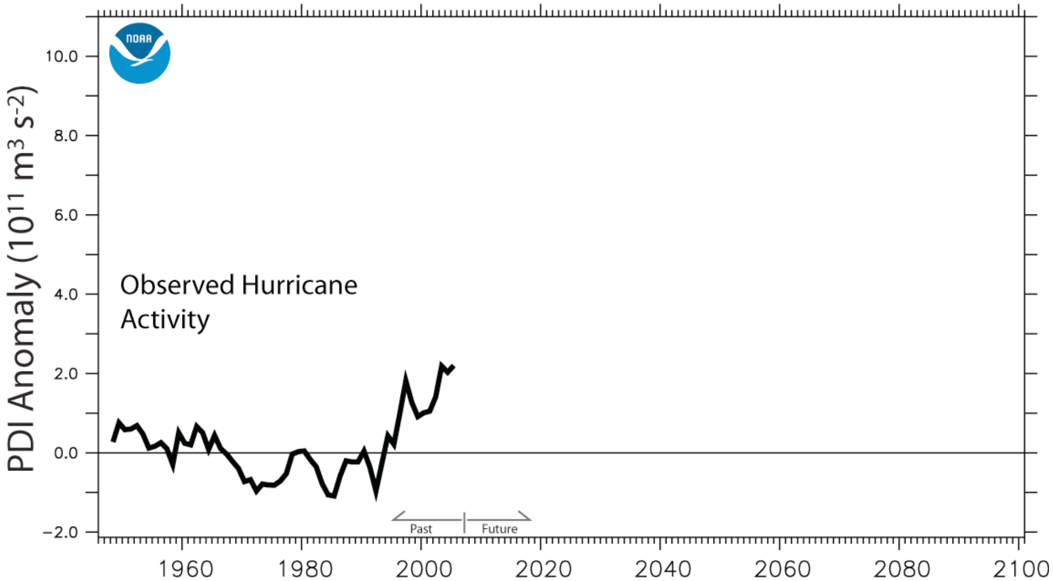
One Temperature Predictor of Atlantic Hurricane Activity



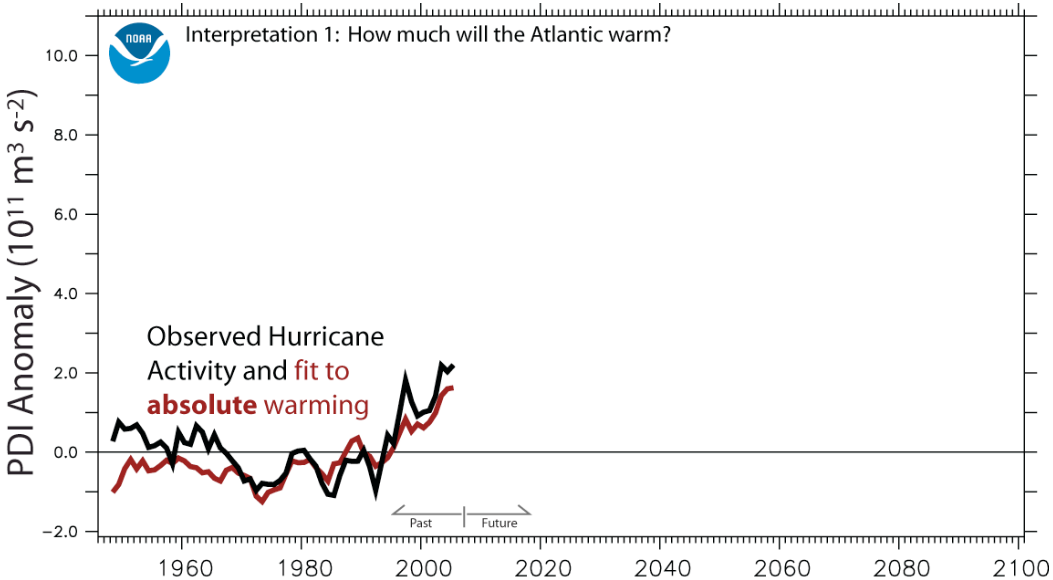


Observed Activity

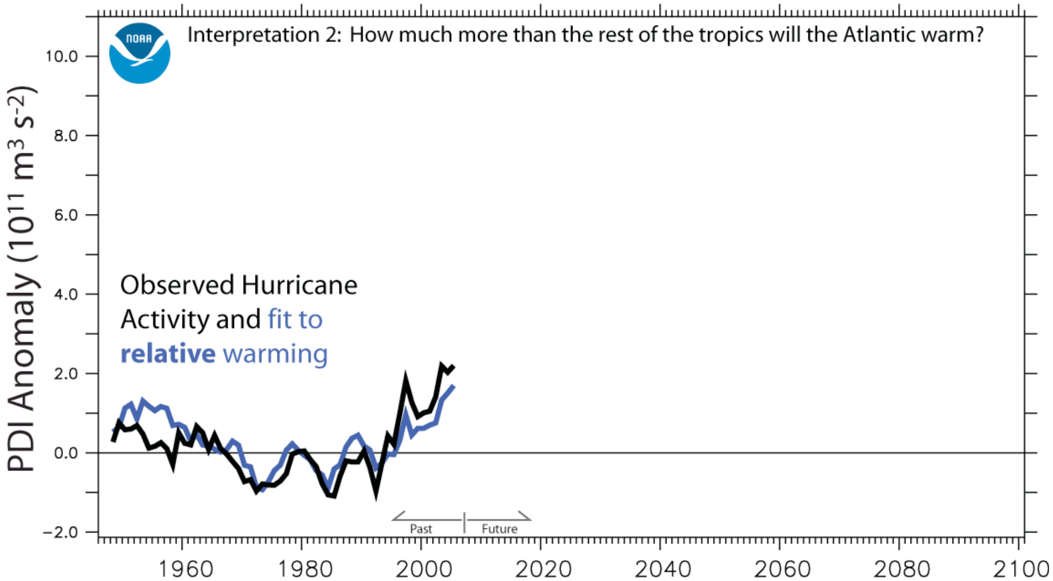
Absolute Atlantic Temperature

Vecchi, Swanson and Soden (2008, Science)

Two Temperature Predictors of Atlantic Hurricane Activity



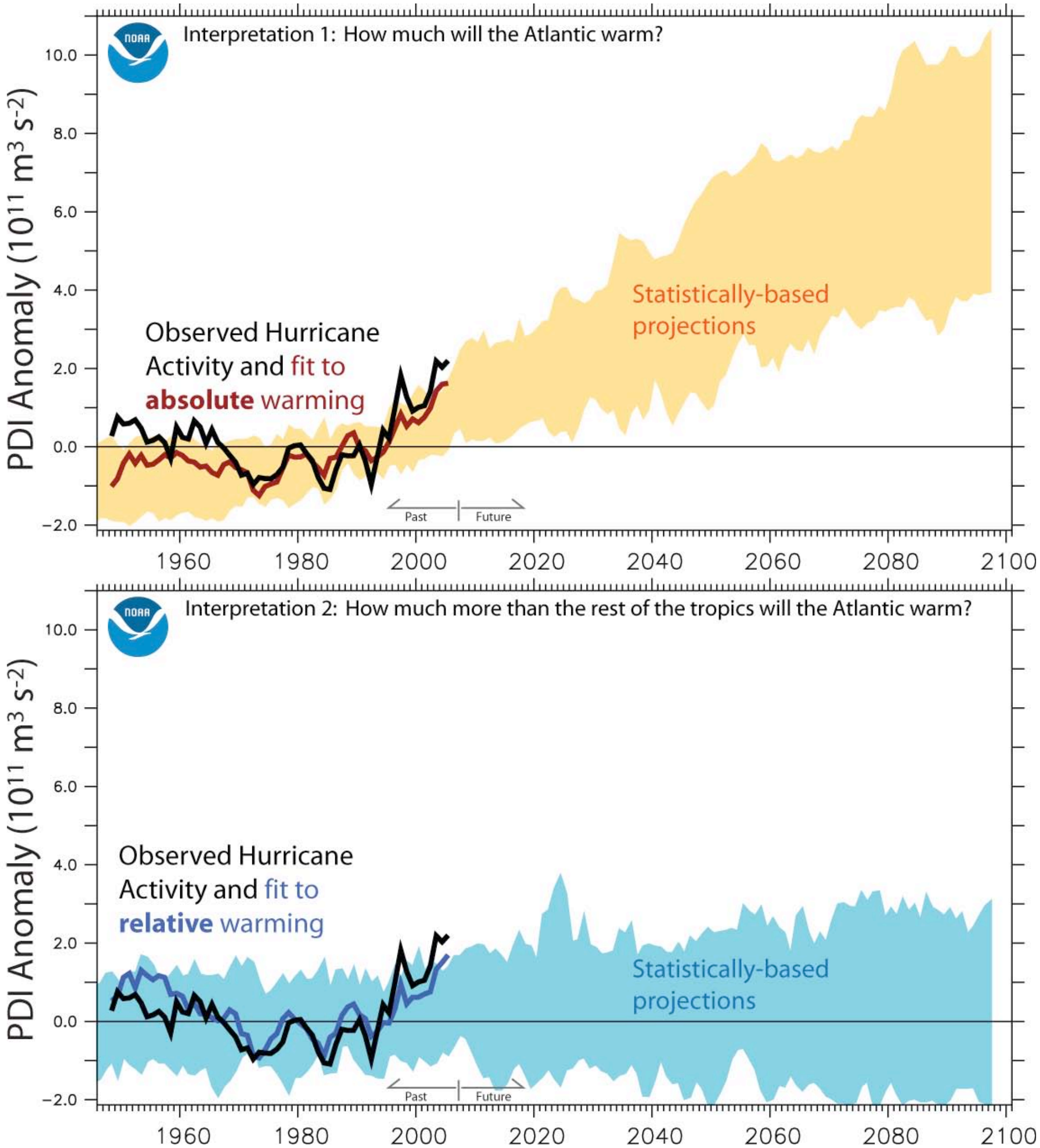
Observed Activity
Absolute Atlantic Temperature



Observed Activity
Relative Atlantic Temperature

Vecchi, Swanson and Soden (2008, Science)

Two Statistical Projections of Atlantic Hurricane Activity

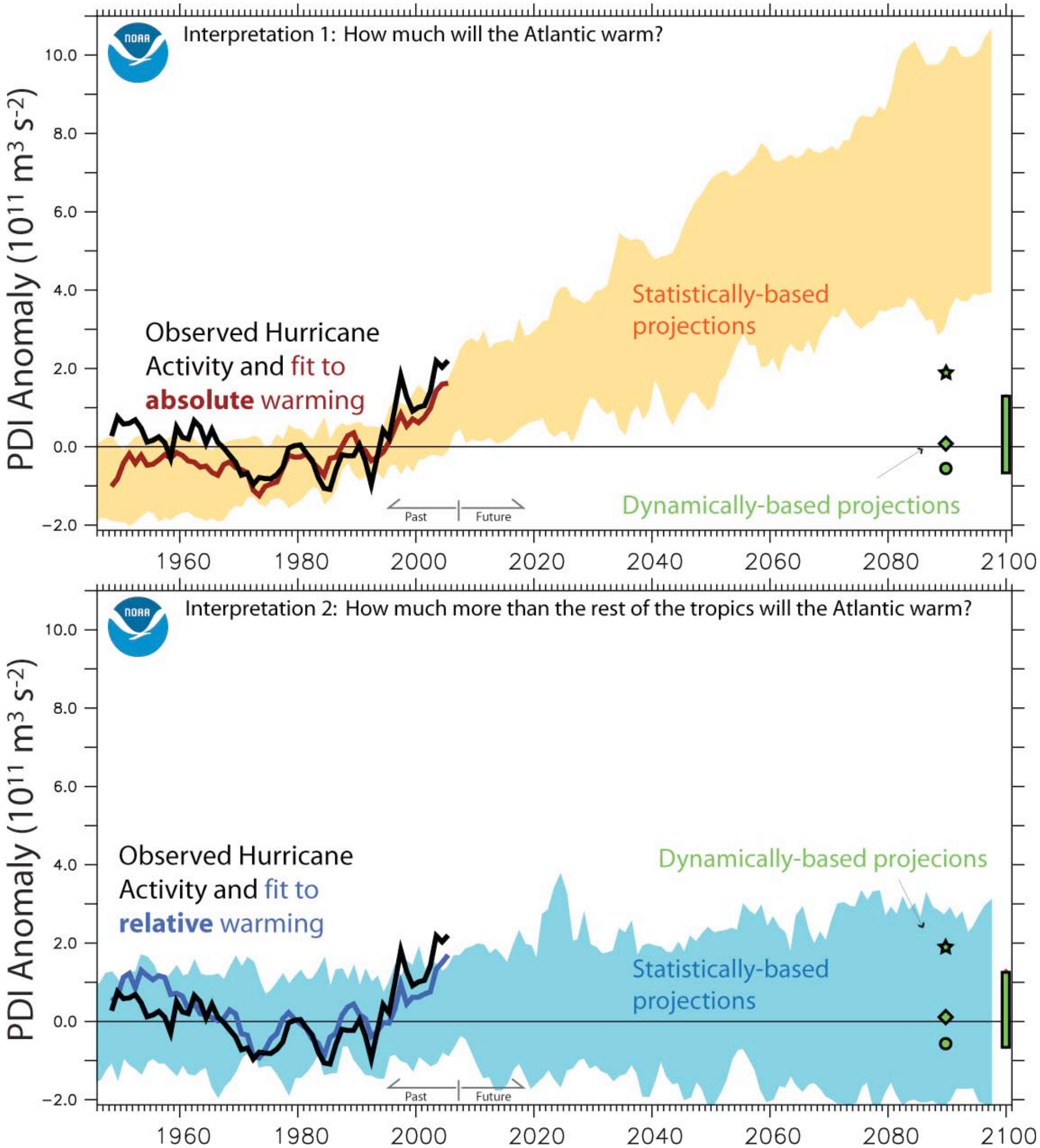


Observed Activity
Absolute Atlantic Temperature

Observed Activity
Relative Atlantic Temperature

Vecchi, Swanson and Soden (2008, Science)

…Add Dynamical Projections of Atlantic Hurricane Activity



Observed Activity
Absolute Atlantic Temperature

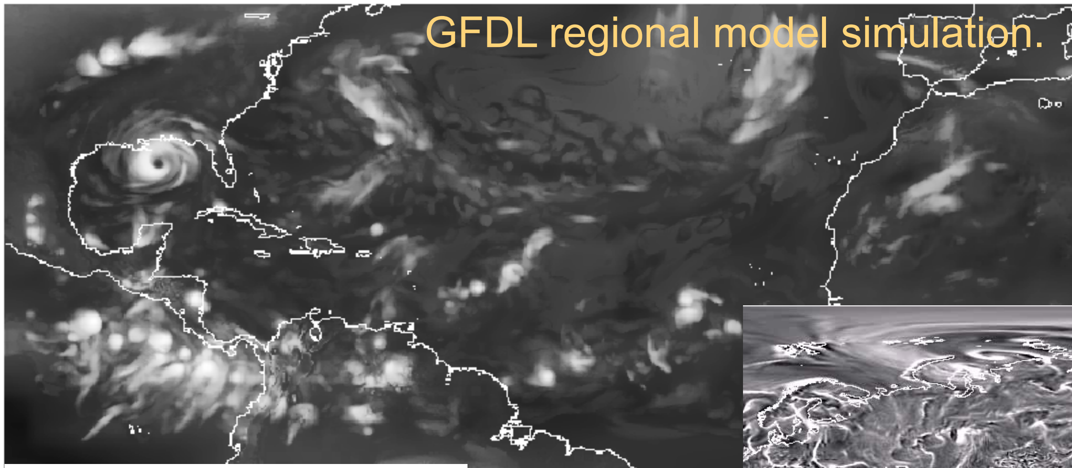
Dynamical Model Projections

Observed Activity
Relative Atlantic Temperature

Vecchi, Swanson and Soden (2008, Science)

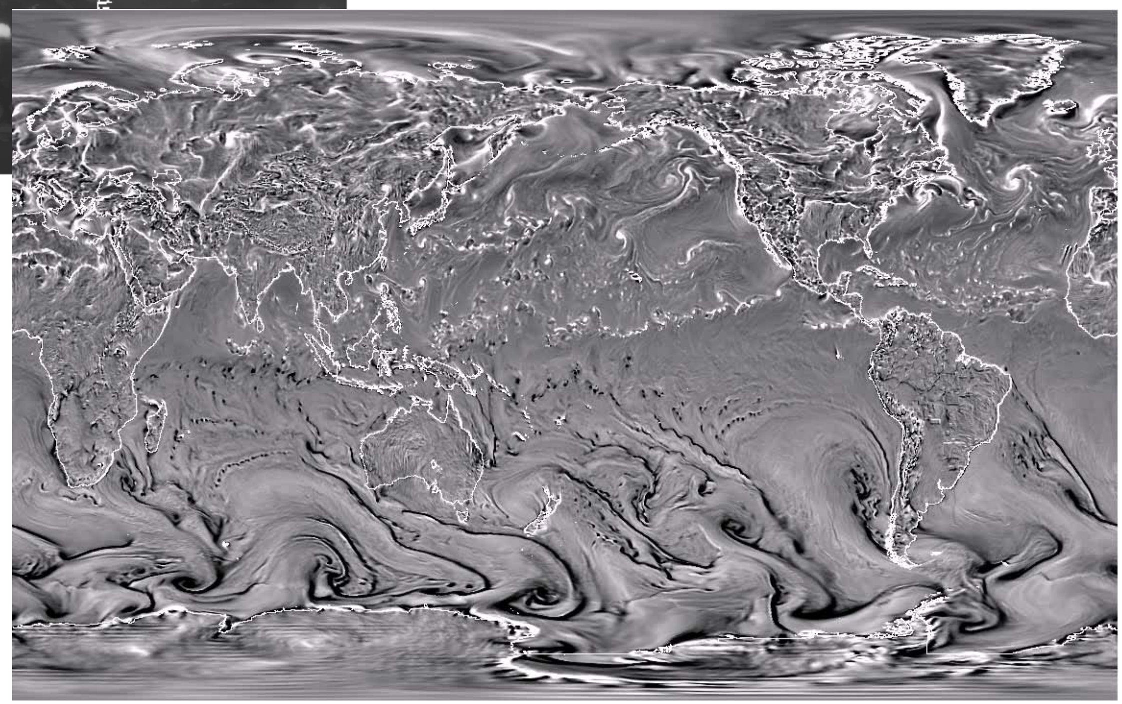
High-Resolution Comprehensive models

Assess TC sensitivity to climate change in a physically-consistent manner



Knutson et al (2007, BAMS)

Models ranging in 100km to 18km resolution.



Zhao, Held, Lin and Vecchi (2009, J. Climate)

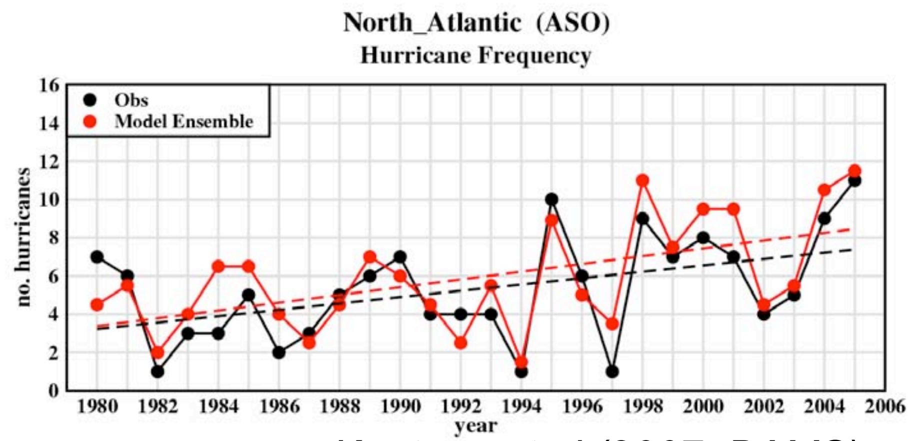
GFDL global model simulation.

Comprehensive models

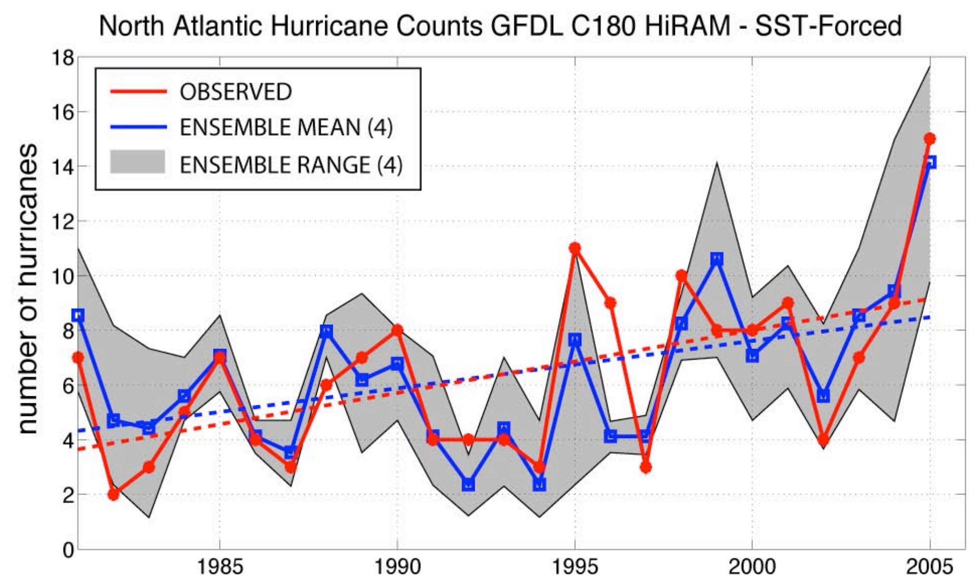
Given "large-scale" conditions, high-resolution models can reproduce observed changes in hurricane frequency.

Use these models to assess impact of model-projected large-scale response to doubled CO2.

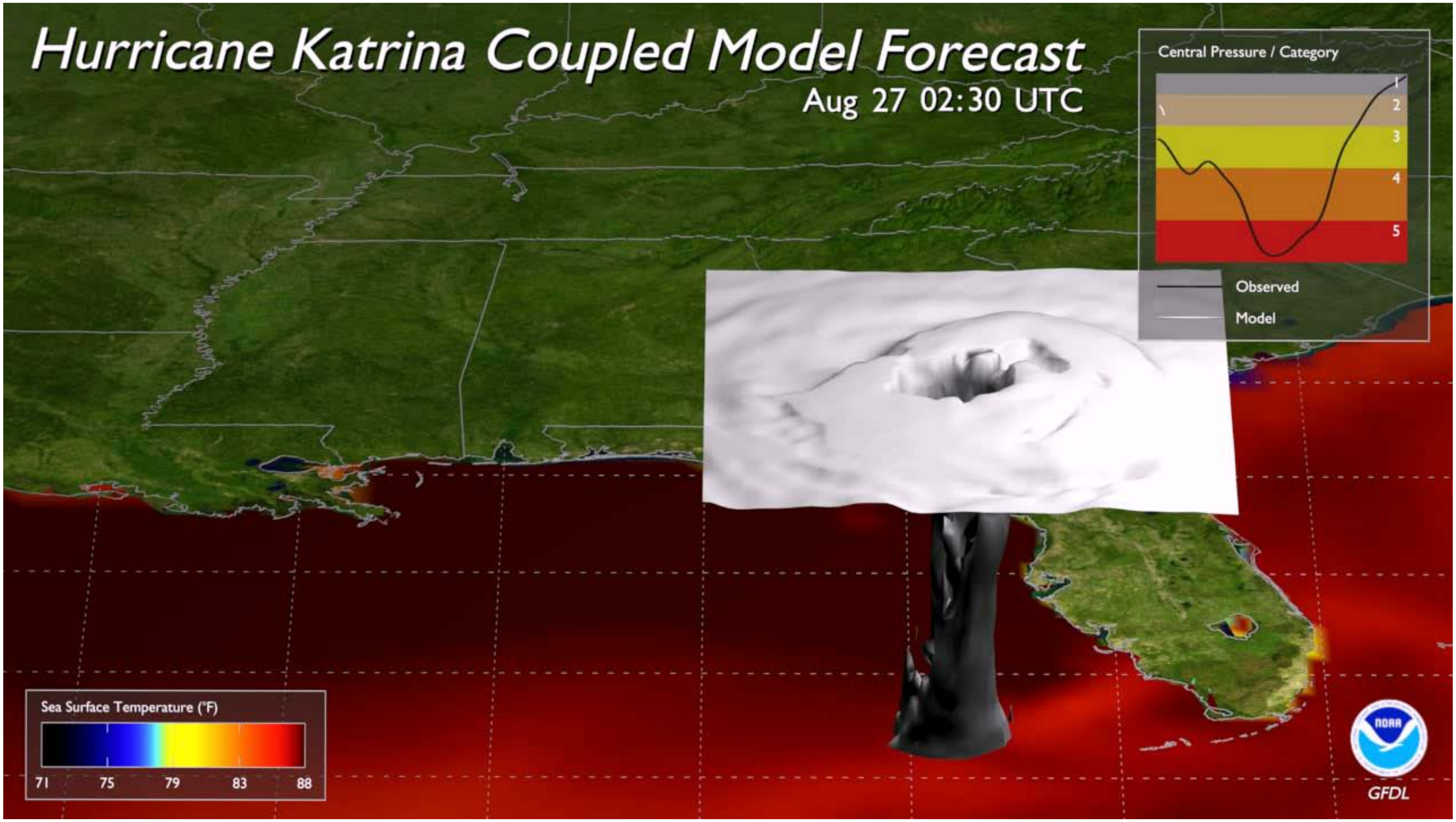
(e.g. Oouchi et al 2005, Bengtsson et al 2007, Emanuel et al 2008, Knutson et al 2008, Zhao et al 2009 ….)



Knutson et al (2007, BAMS)



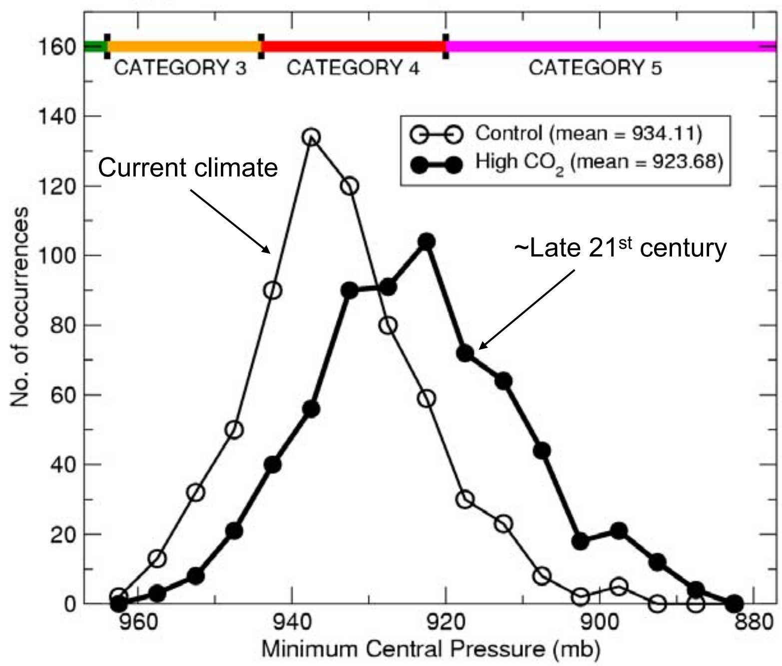
Zhao et al (2009, J. Clim.)



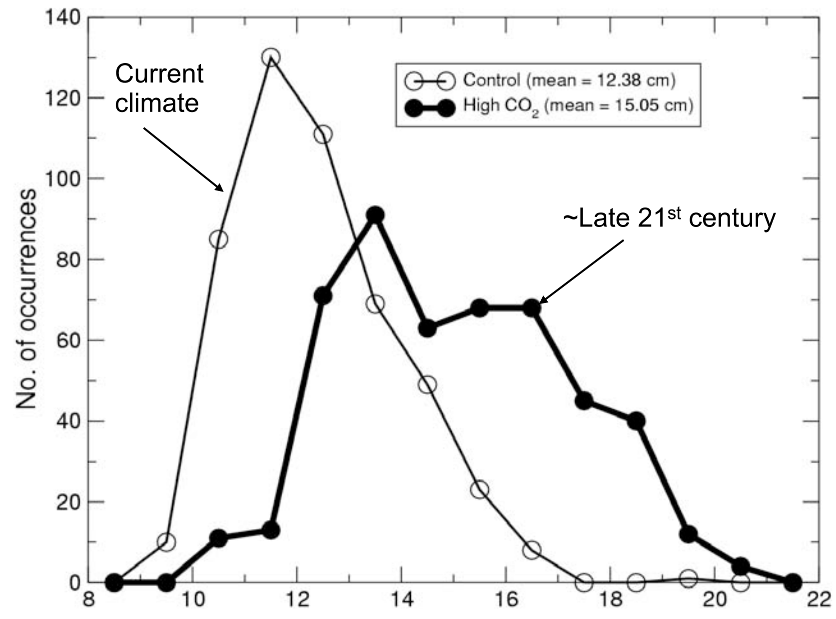
Courtesy Morris Bender and Tim Marchok, NOAA/GFDL

Hurricane models project increasing hurricane intensities and rainfall rates with greenhouse climate warming …

Hurricane Intensity



Hurricane Rainfall Rates



Sources: Knutson and Tuleya, *J. Climate*, 2004 (left);
Knutson and Tuleya, 2008; Cambridge Univ Press (right).