Past and Future Tropical Cyclone Activity

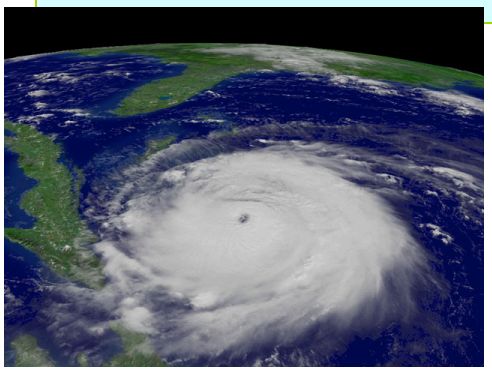
Gabriel A. Vecchi
NOAA/Geophysical Fluid Dynamics Laboratory
Princeton, NJ 08540

- 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?

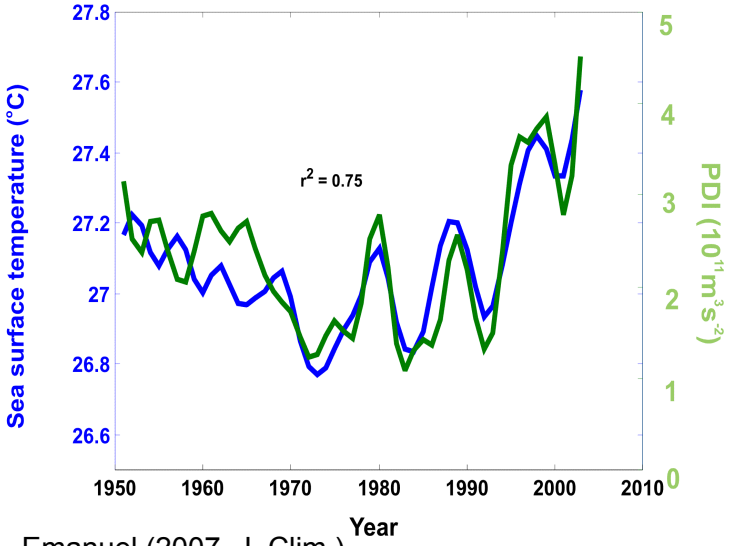
Miami After Hurricane Andrew

Source: wikimedia.org

North Atlantic tropical cyclones



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



Emanuel (2007, J. Clim.)

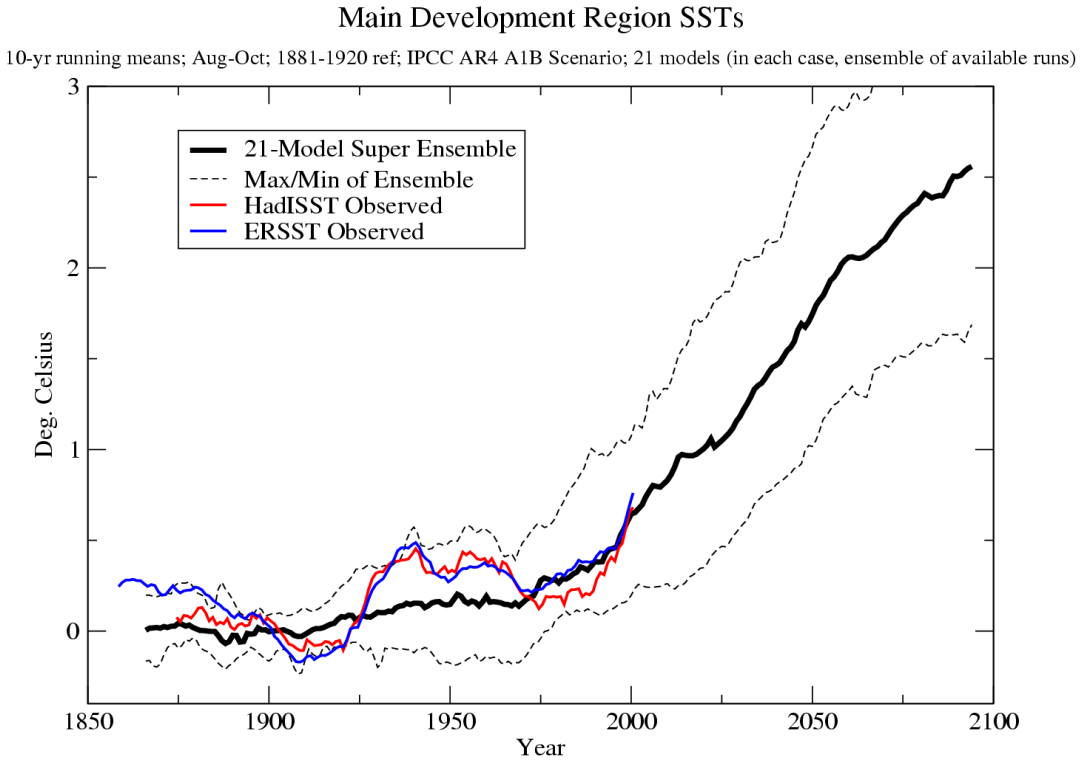


Figure: Tom Knutson

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

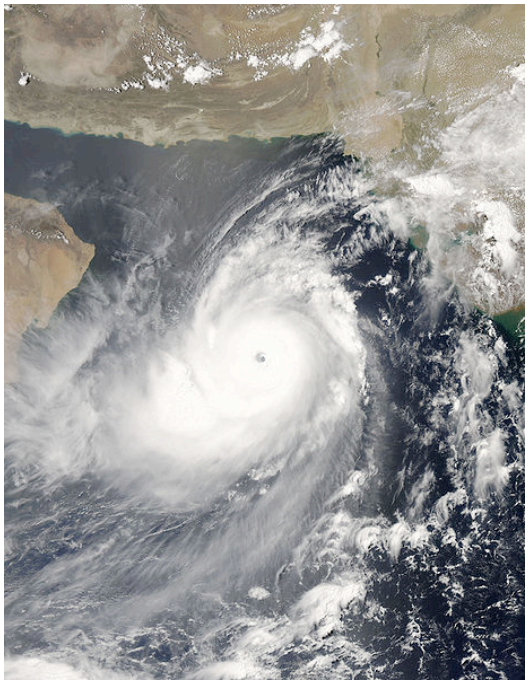
- Tropical cyclone not a big tornado
- Tropical cyclone, hurricane and typhoon same phenomenon, different location.

Hurricane Isabel (2003)
Atlantic Ocean

source: wikimedia.org

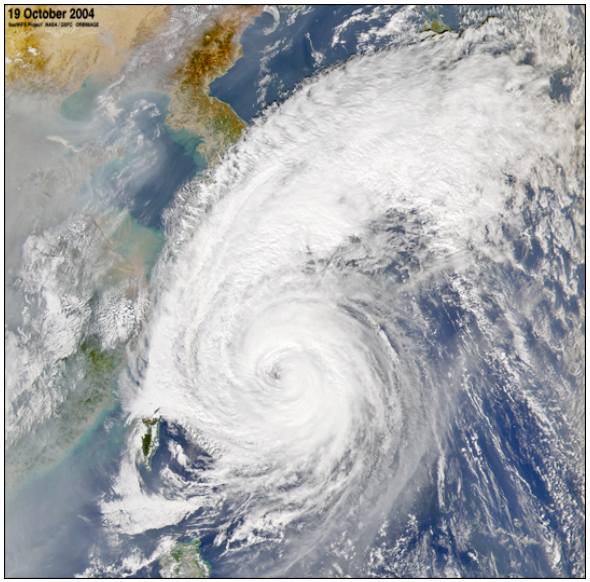
Cyclone Gonu (2007)
North Indian Ocean

source: wikimedia.org



Cyclone Tokage (2004)
Northwest Pacific Ocean

source: NASA

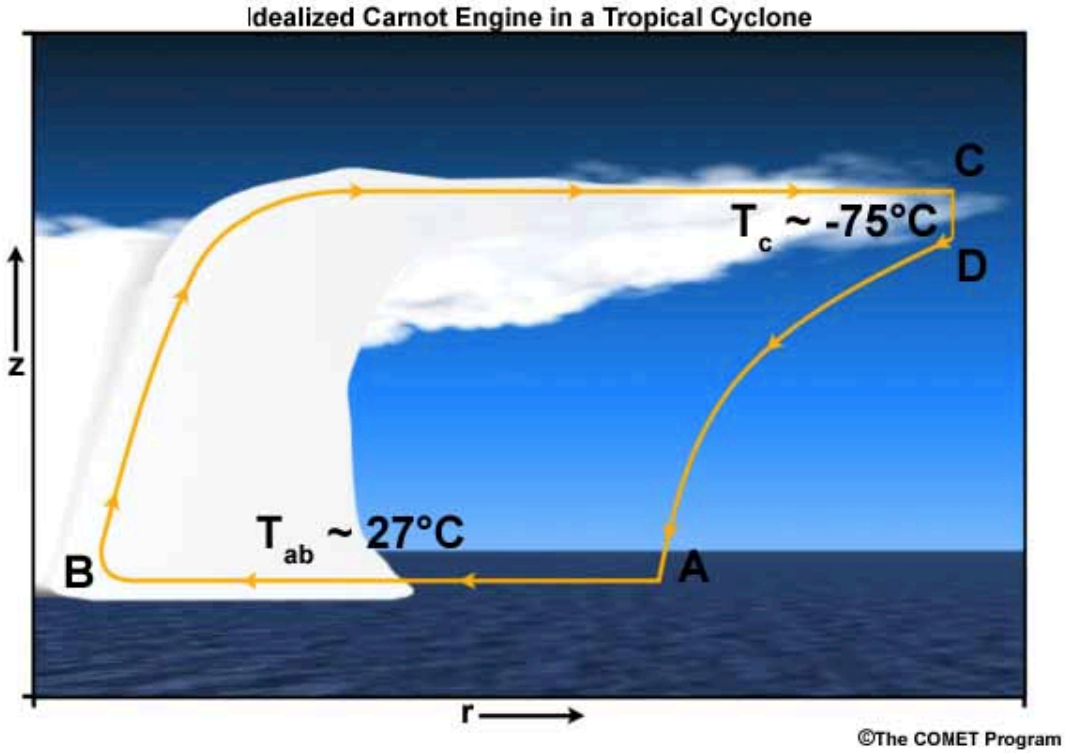


Saffir-Simpson Hurricane Scale

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

Theory of Maximum Potential Intensity

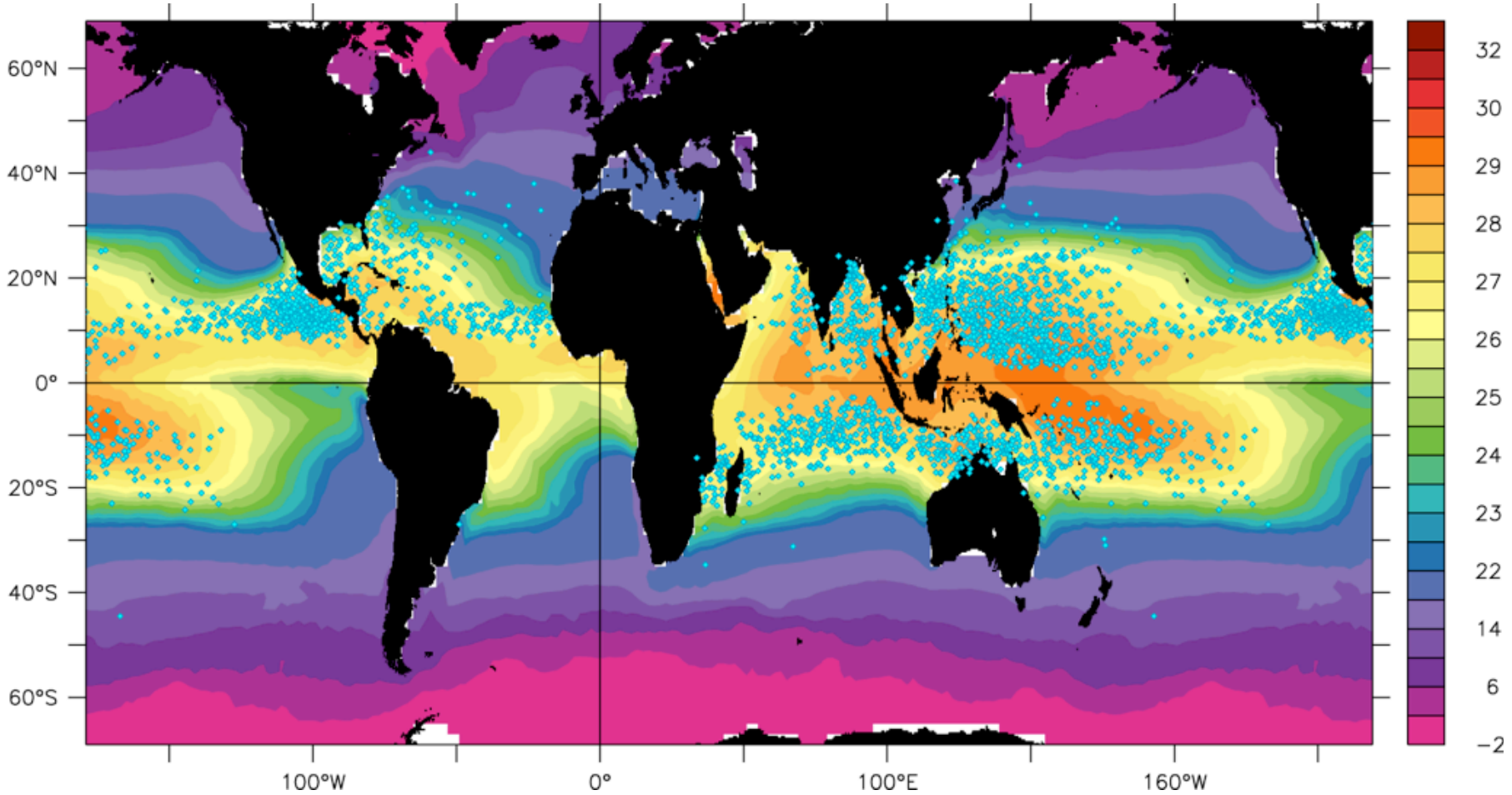


cf. Bister and Emanuel (1998)

Potential Intensity = "Fuel" * "Efficiency"

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

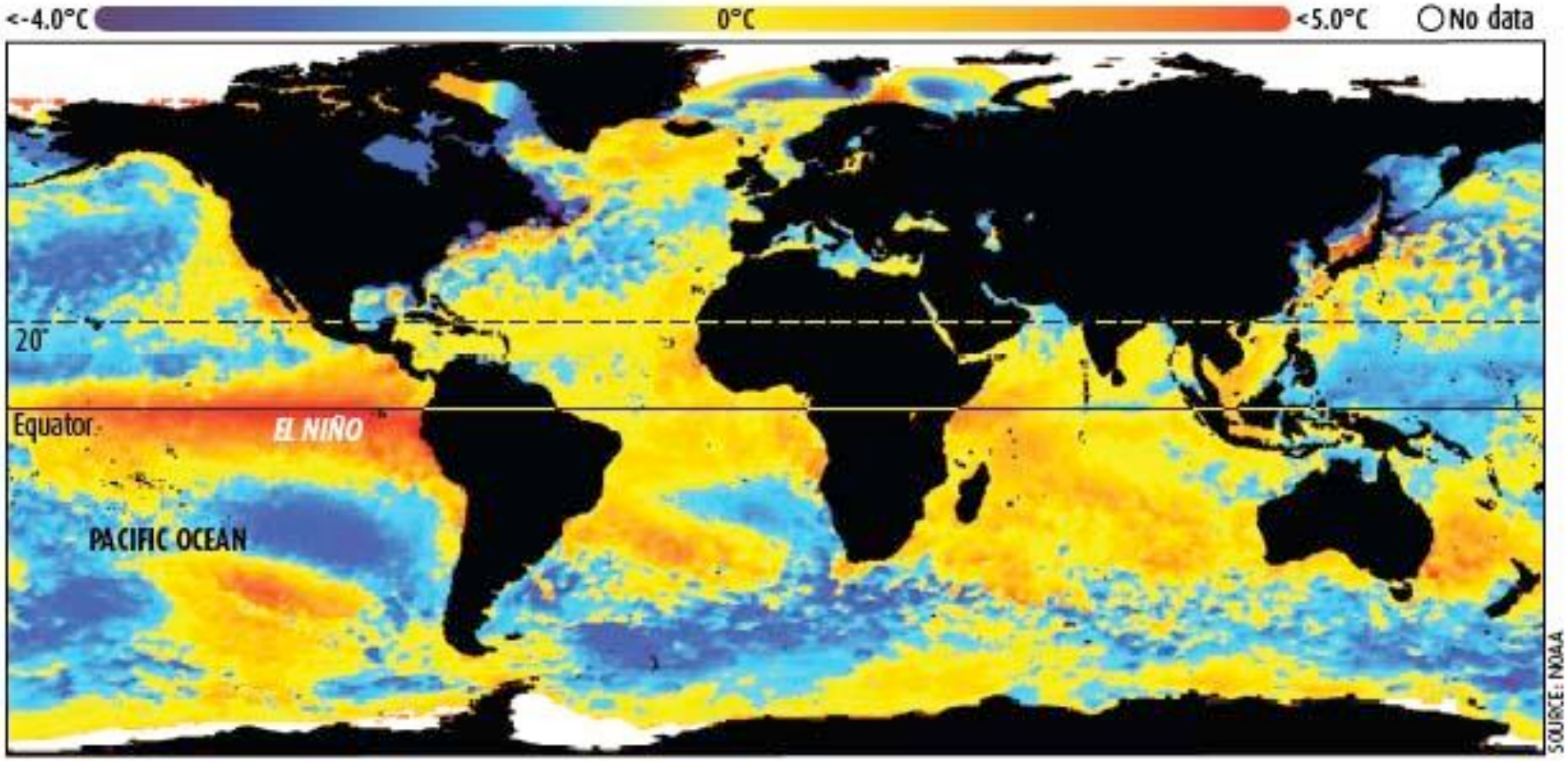
Warm water necessary for storm formation.



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

Gabriel Vecchi, NOAA/GFDL, Princeton, NJ

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



Measure of Activity

Measure of Activity

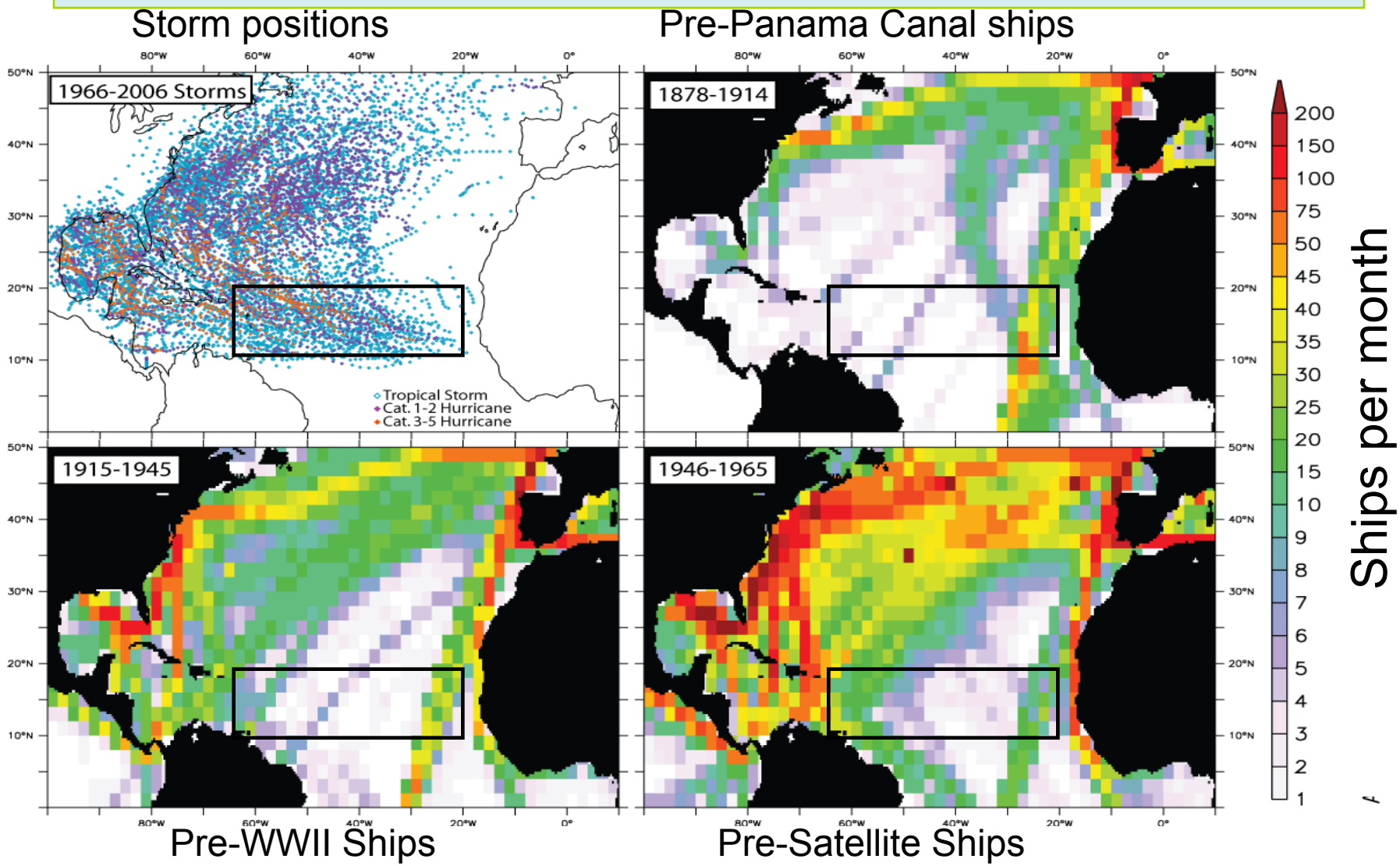
- Which measure?
  - Hurricane count
  - Landfalling storm count
  - Extremes in intensity
  - Shifts in average intensity
  - Sum of intensity
- Must balance demand with current understanding
  - Obs, models and theory limit.
- Differences must be communicated and understood

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
- Etc.

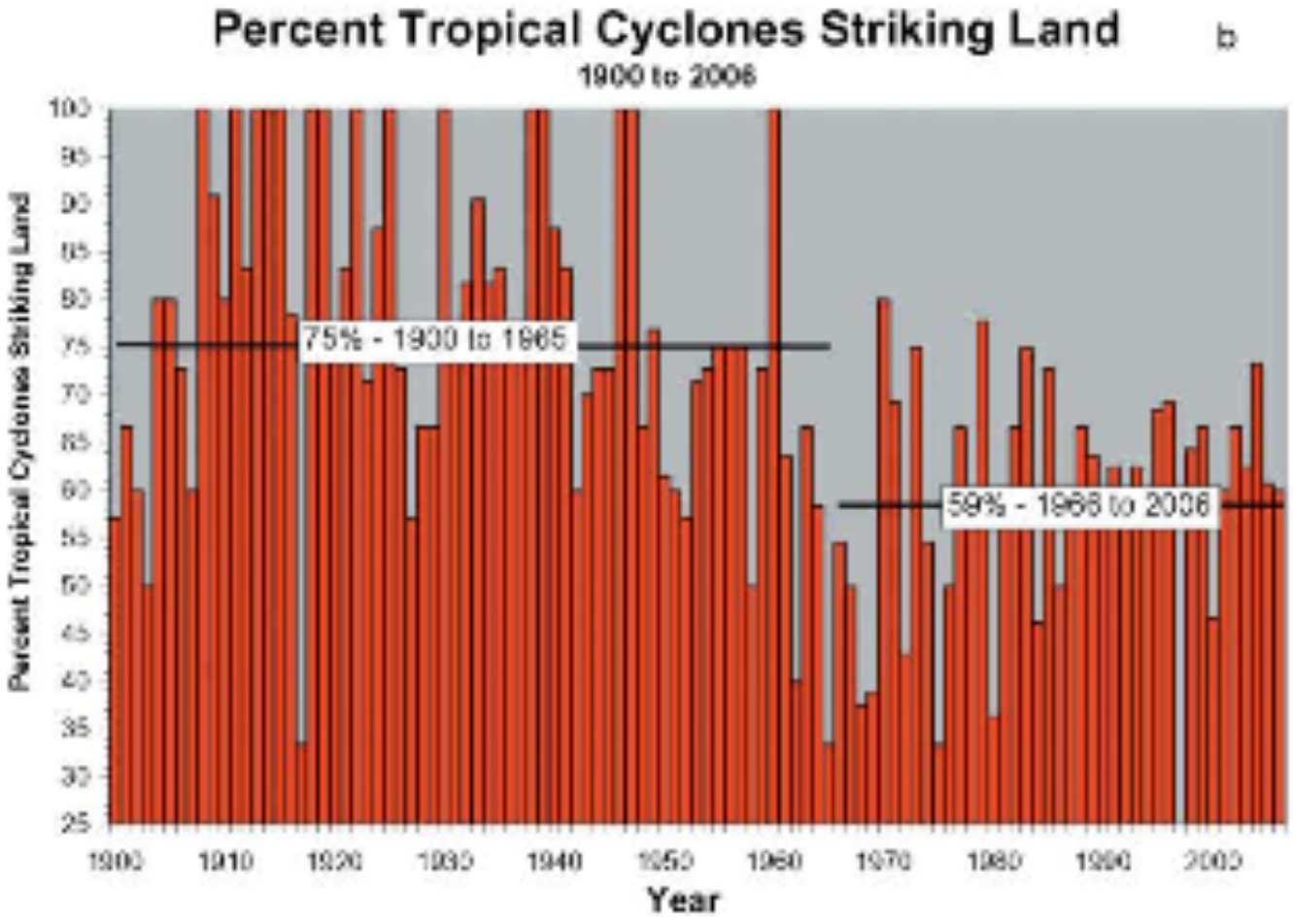
Can we be sure the long-term increase is real? Observational methods have changed with time….



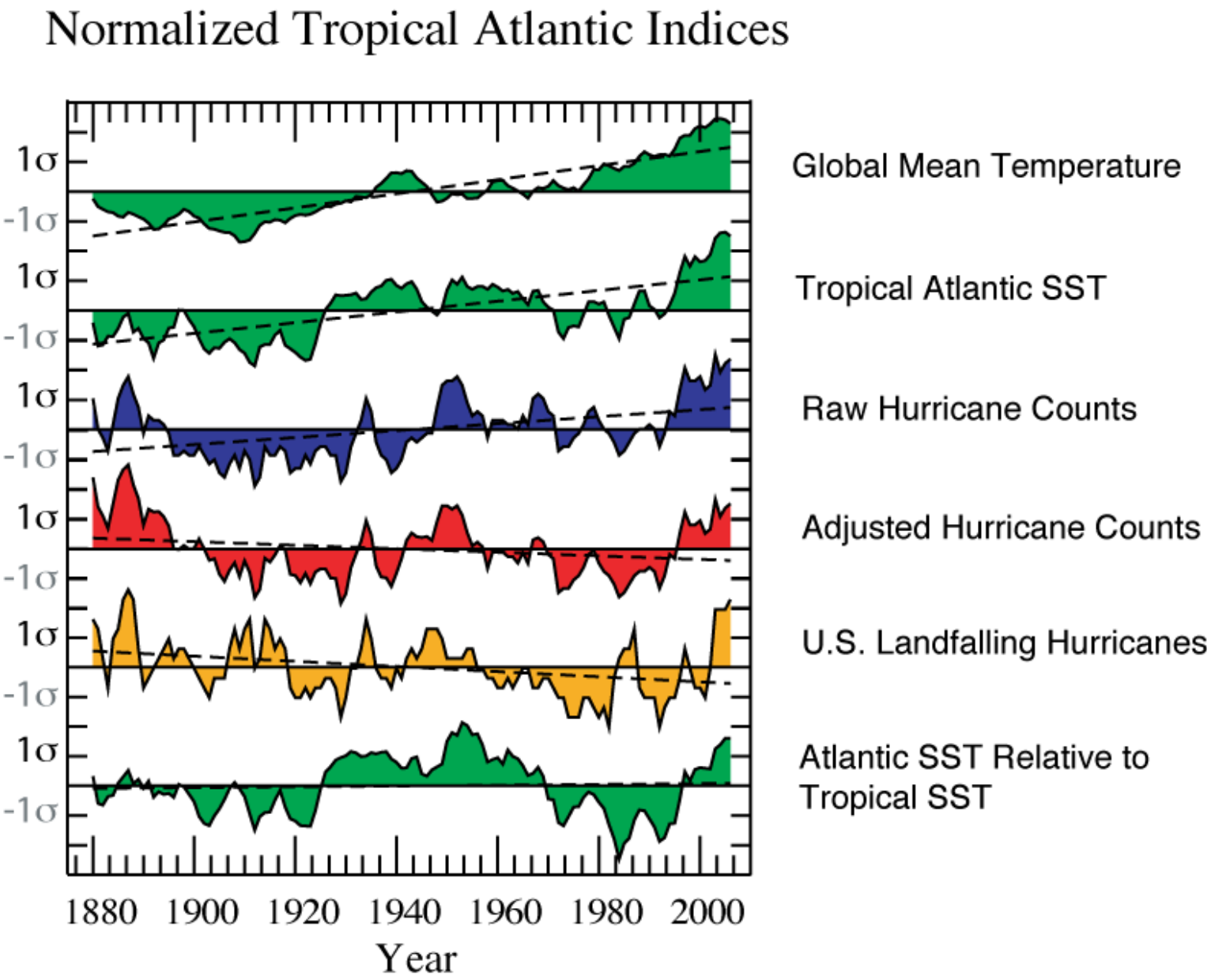
Vecchi and Knutson (2008)

Gabriel Vecchi, NOAA/GFDL, Princeton, NJ

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

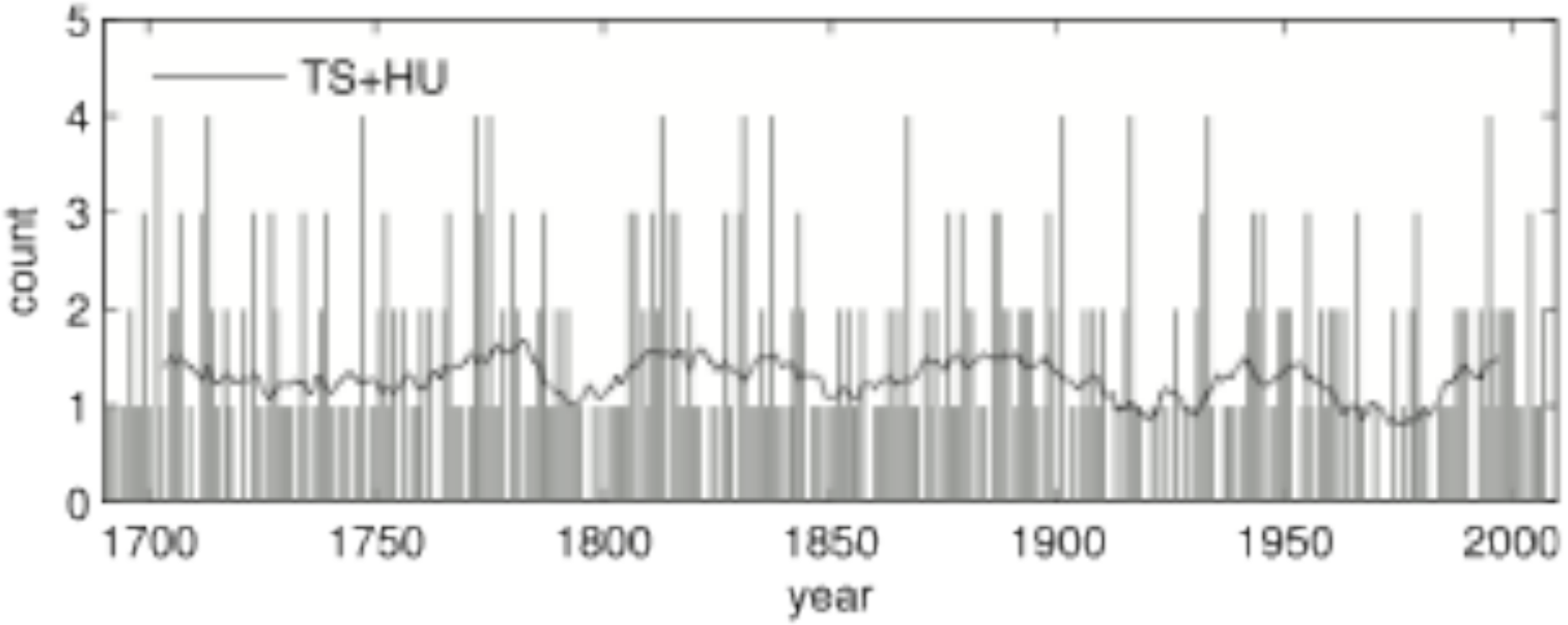


Source: Landsea, EOS, 2007.



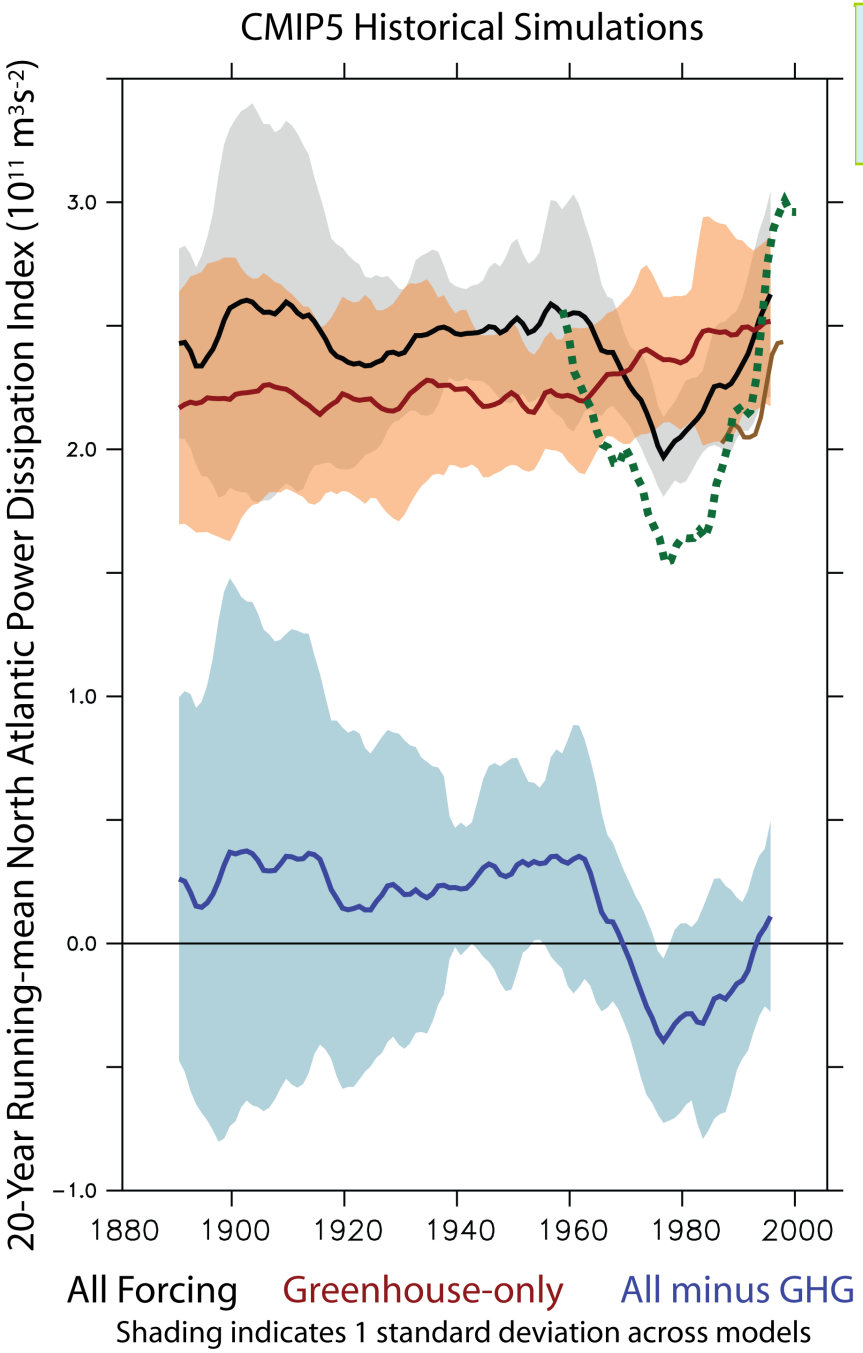
Vecchi and Knutson (2008, J. Clim.); Landsea et al. (2009, J. Clim.); Vecchi and Knutson (2011, J. Clim.)

Estimating Atlantic tropical storm counts using historical document. Number of hurricanes and TS passing over Antilles.



Explored historical newspaper archives in various islands in the Antilles.

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



Greenhouse gases not only factor in past (or future) TC activity

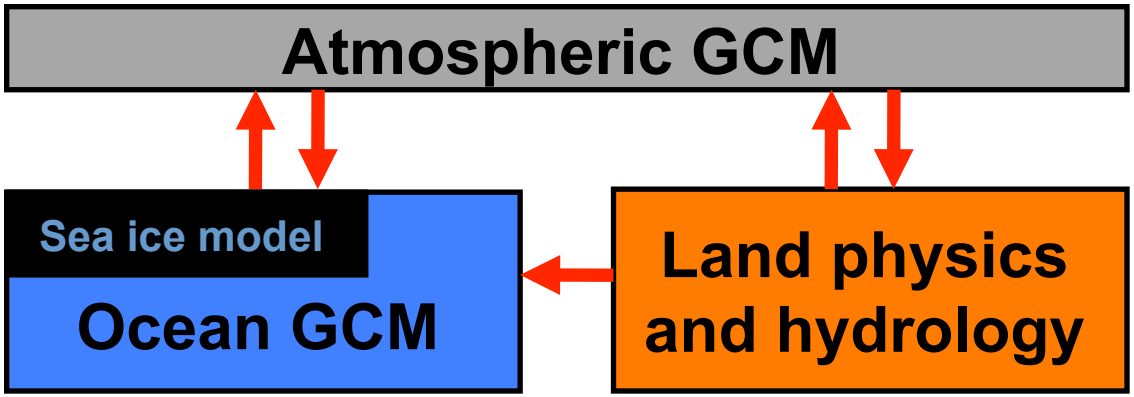
Models estimate that for Atlantic TC intensity over 20th century:

- Increase from GHGs
- But that non-GHG forcing should have led to a decrease, with a minimum in 1970s-1980s.
  - Likely due to "aerosols" – particulate pollution, more pollution before 1970s, less after.

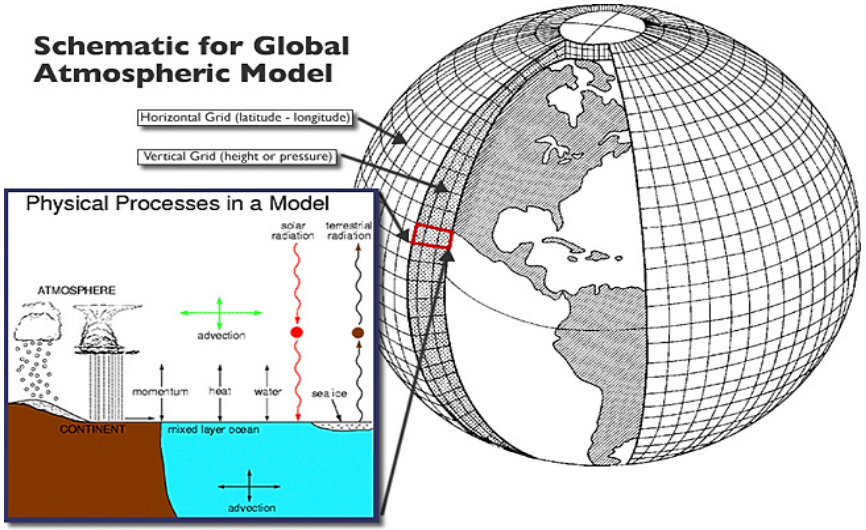
Villarini and Vecchi (2012, J. Climate)

How do we expect hurricane activity to change?

Gabriel Vecchi, NOAA/GFDL, Princeton, NJ

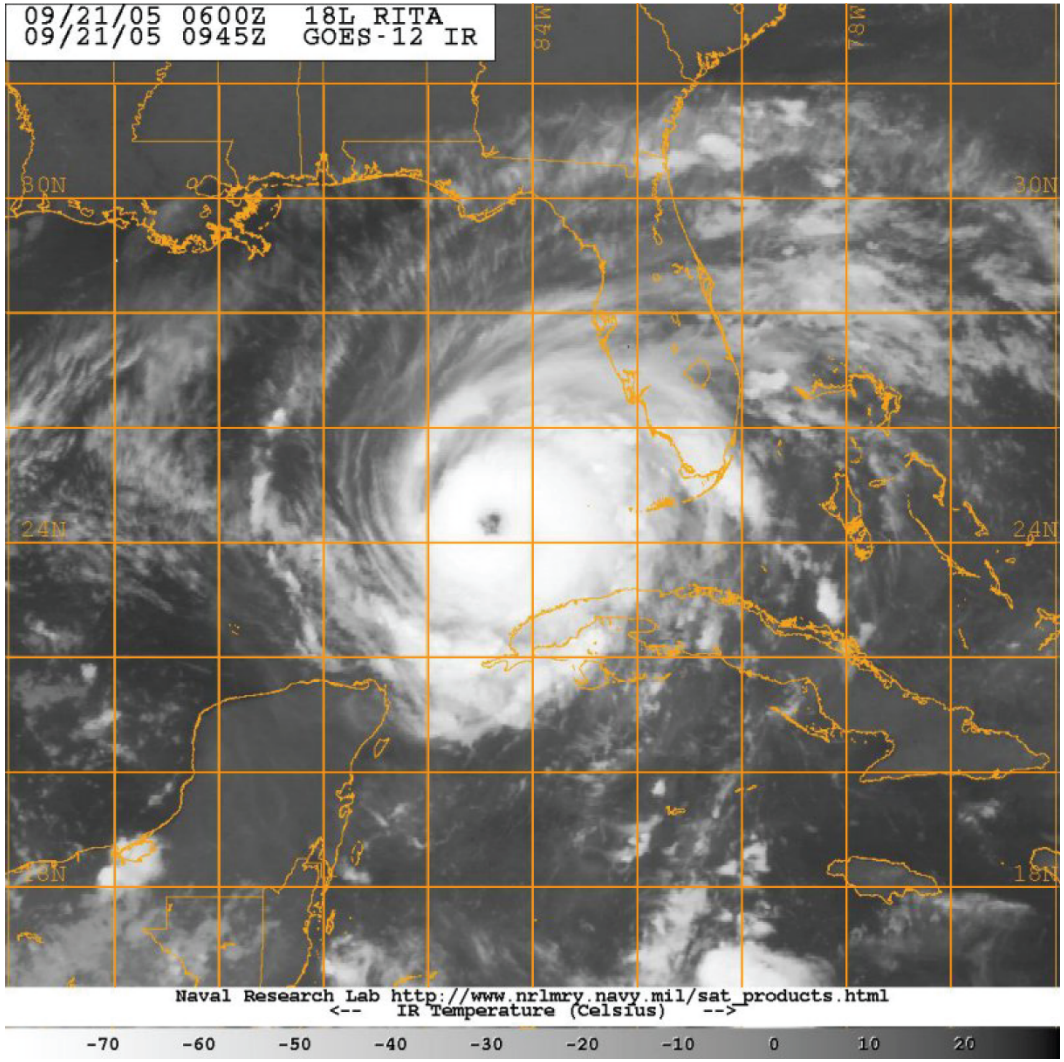


Can global climate models give guidance about changes in Atlantic storm activity?



Gabriel Vecchi, NOAA/GFDL, Princeton, NJ

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.

Factors that favor storm development and intensification:

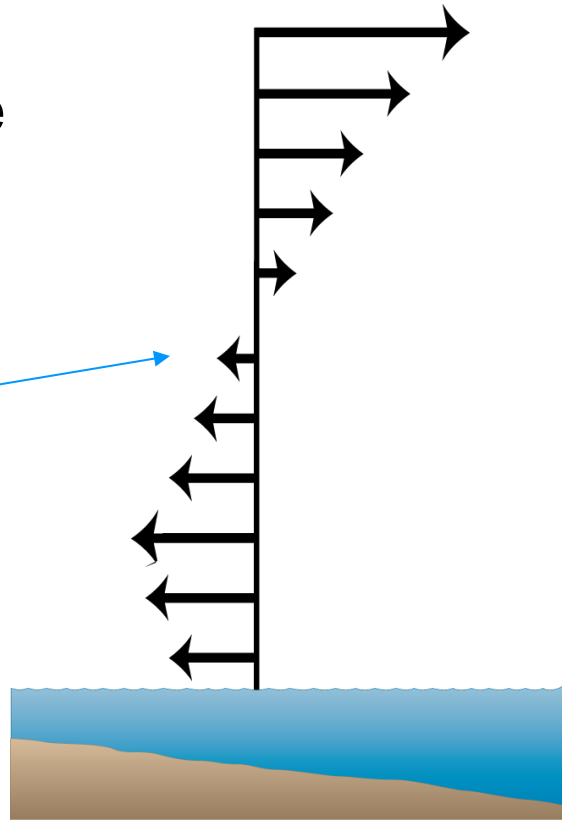
- Warm ocean surface
- Cool upper atmosphere

} Help define potential intensity

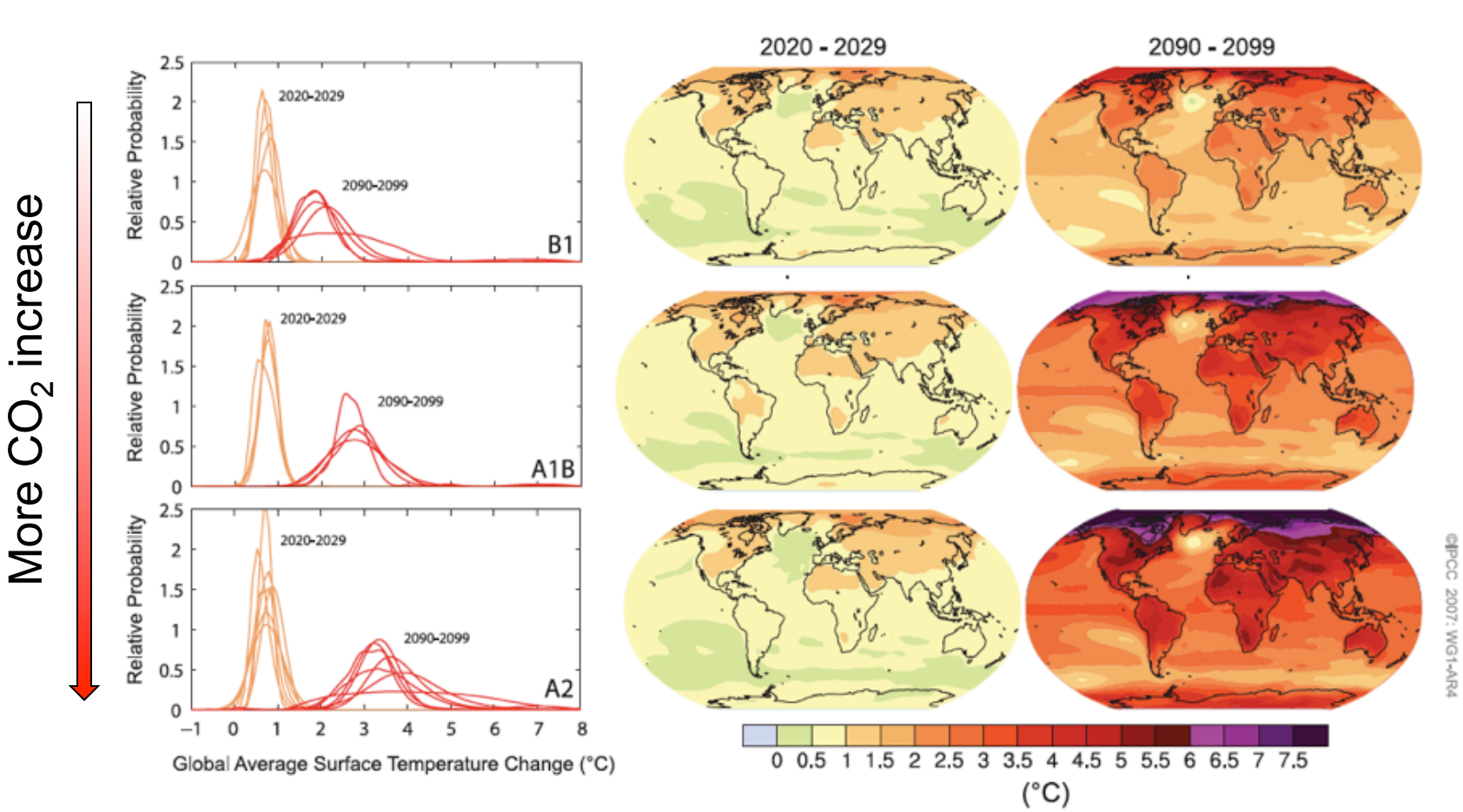
cf. Emanuel, Holland

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

Vertical wind shear



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



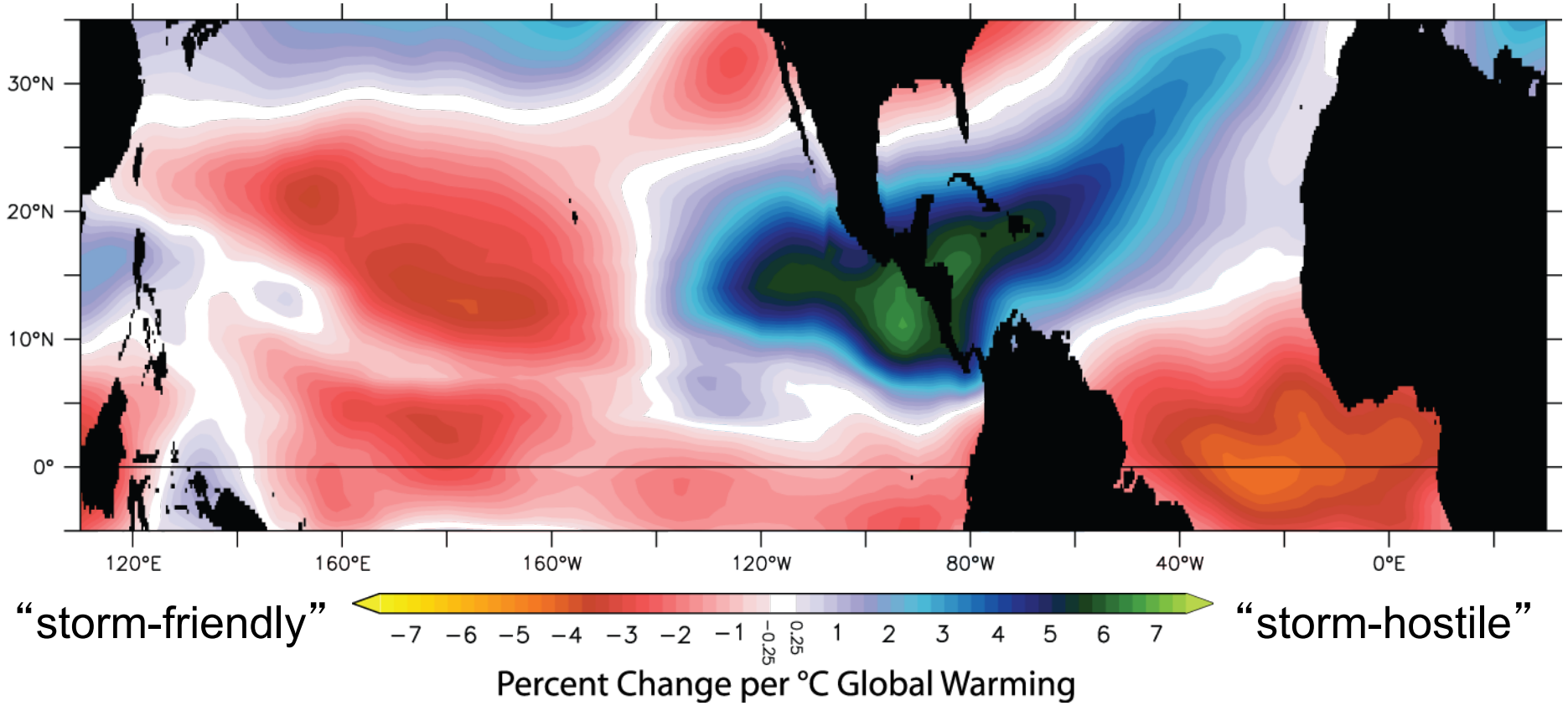
Models also indicate that upper atmosphere should warm much more than the surface.

What is net effect?

IPCC-AR(2007)

Projected 21st Century Changes in Vertical Wind Shear

Average of 18 models, Jun-Nov



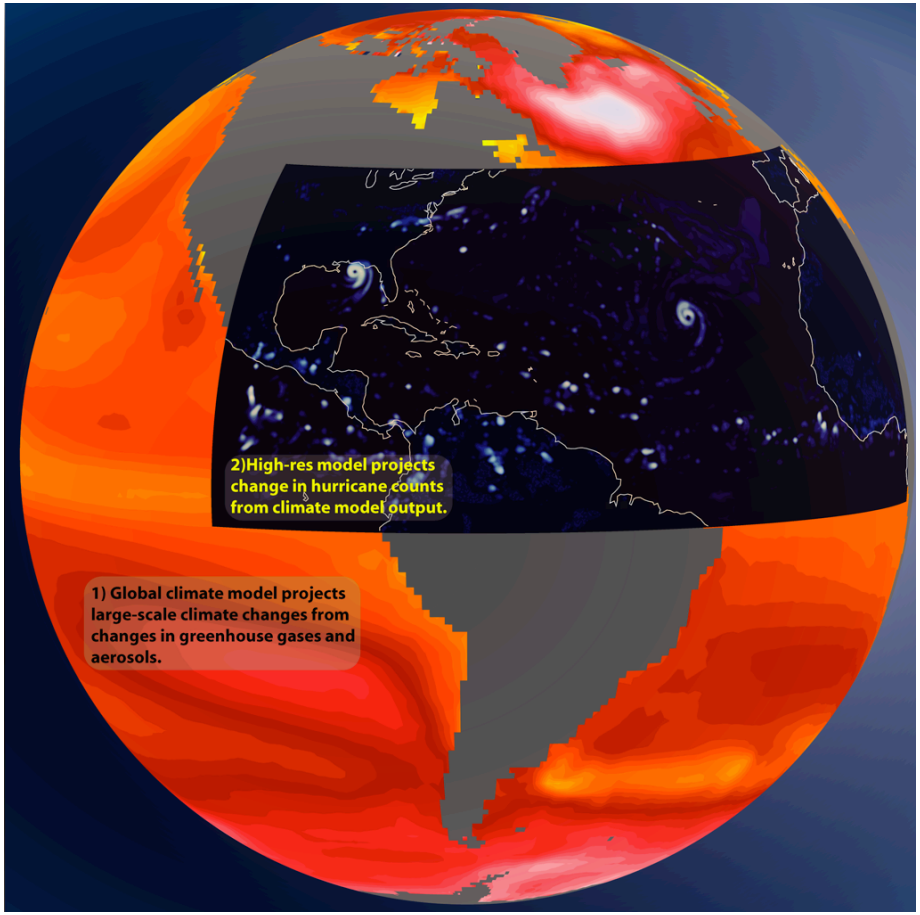
Over swath of tropical Atlantic and East Pacific, increased wind-shear.

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

Vecchi and Soden (2007, GRL)

Gabriel Vecchi, NOAA/GFDL, Princeton, NJ

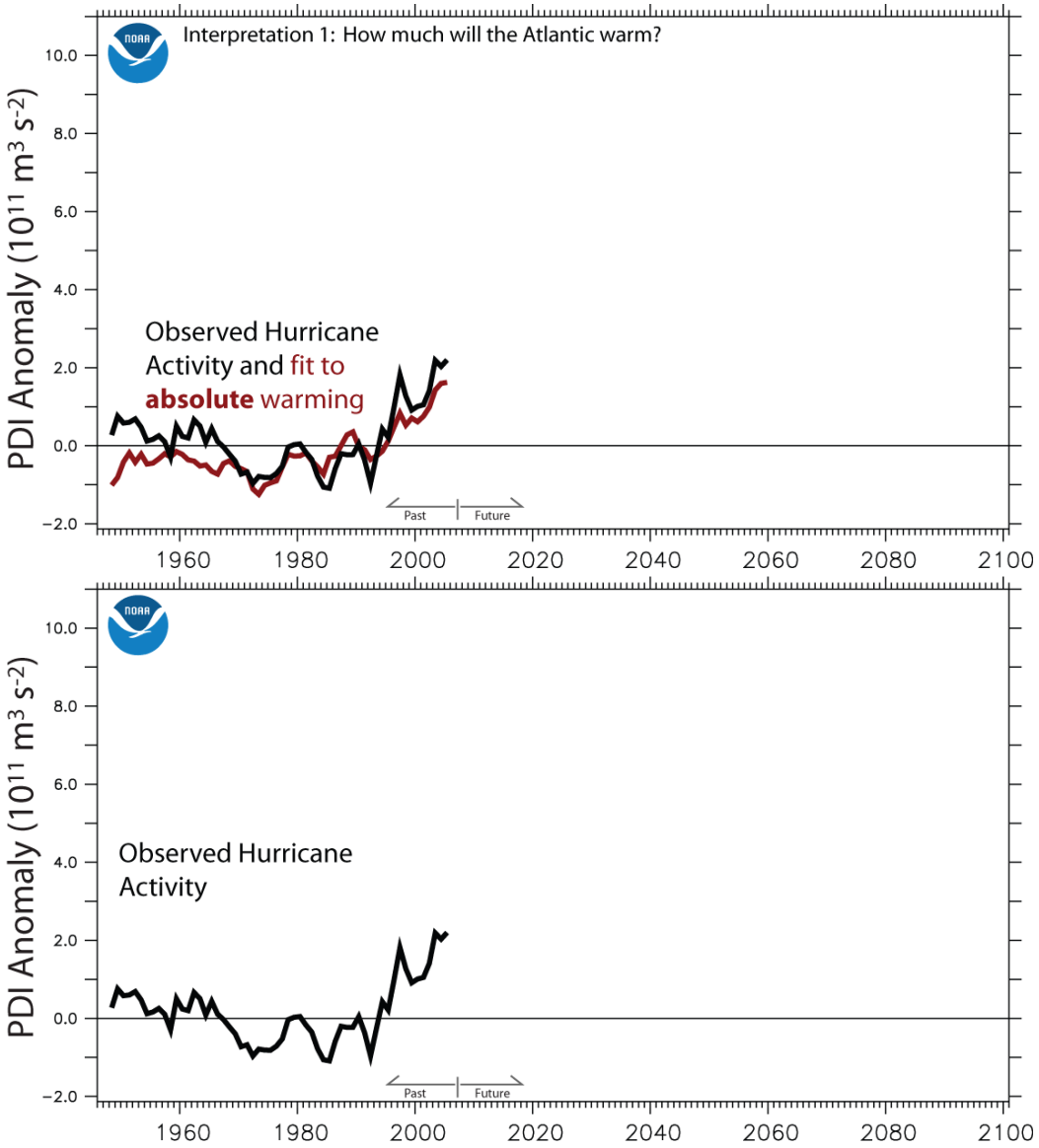
“Downscale” Climate Model Projections With High-Resolution or Statistical Models



Global Climate Models -> High-resolution Model

Large-scale TS Frequency

One Temperature Predictor of Atlantic Hurricane Activity



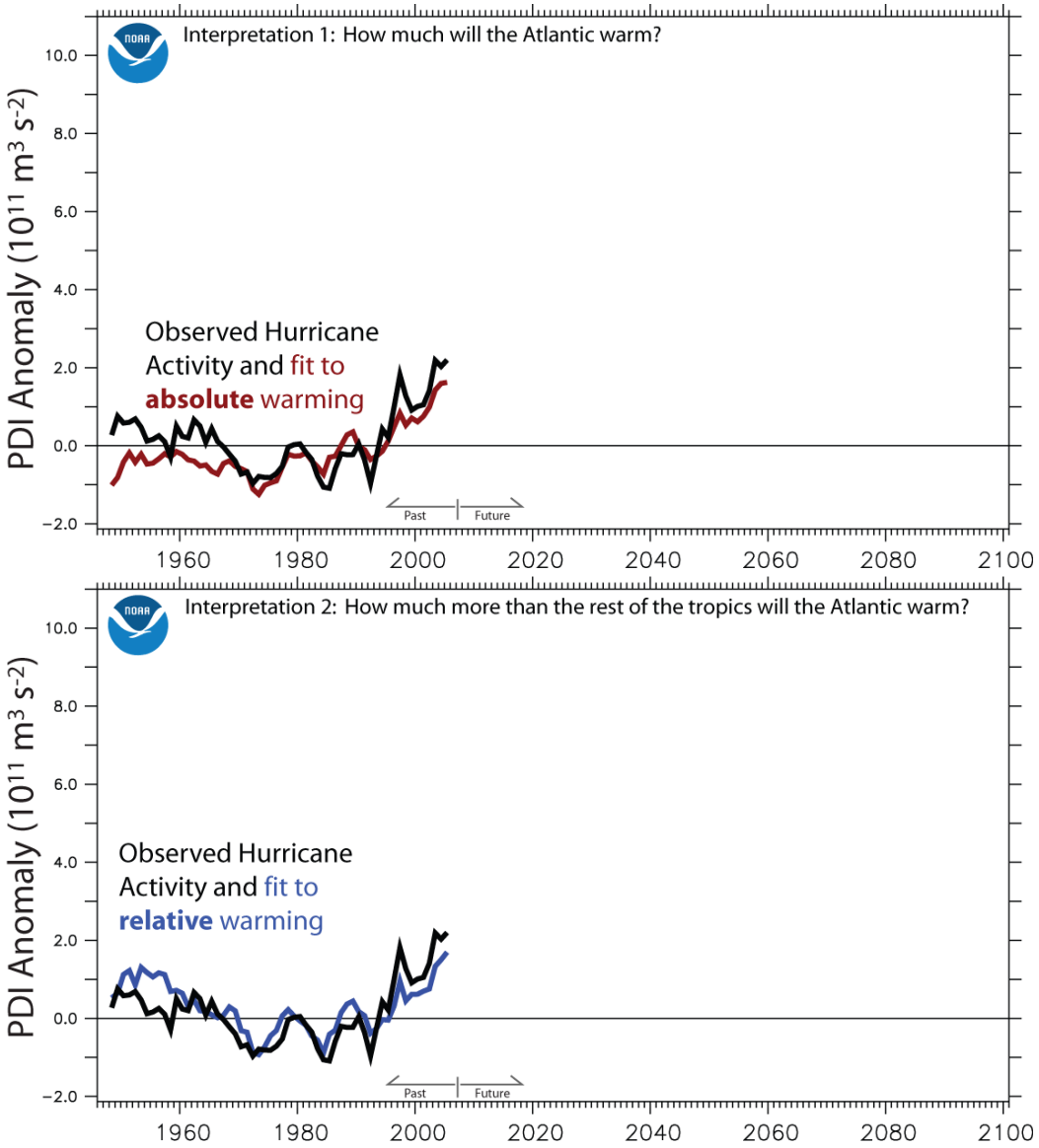
Observed Activity

Absolute Atlantic Temperature

Vecchi, Swanson and Soden (2008, Science)

Gabriel Vecchi, NOAA/GFDL, Princeton, NJ

Two Temperature Predictors of Atlantic Hurricane Activity



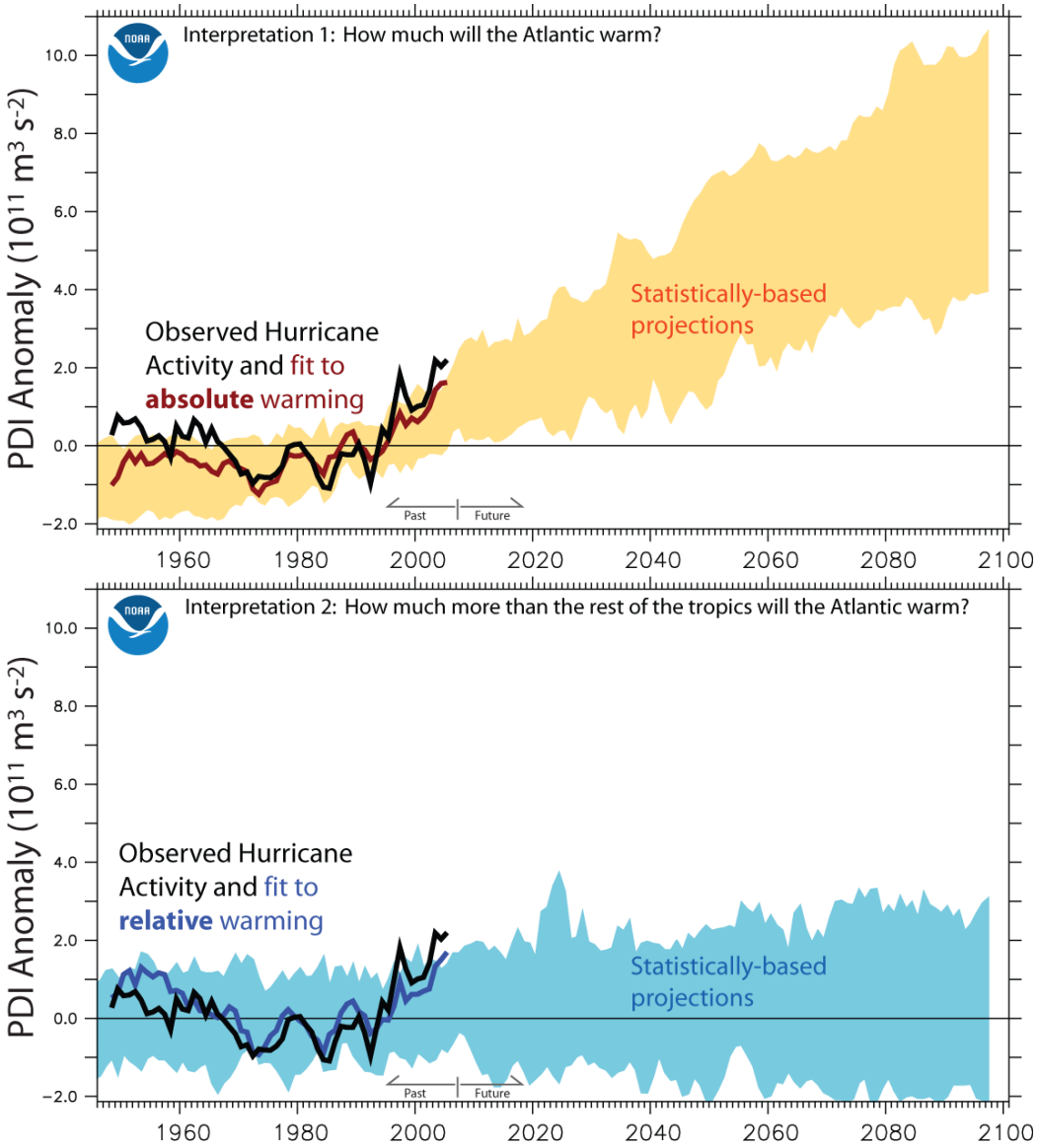
Observed Activity
Absolute Atlantic Temperature

Observed Activity
Relative Atlantic Temperature

Vecchi, Swanson and Soden (2008, Science)

Gabriel Vecchi, NOAA/GFDL, Princeton, NJ

Two Statistical Projections of Atlantic Hurricane Activity



Observed Activity
Absolute Atlantic Temperature

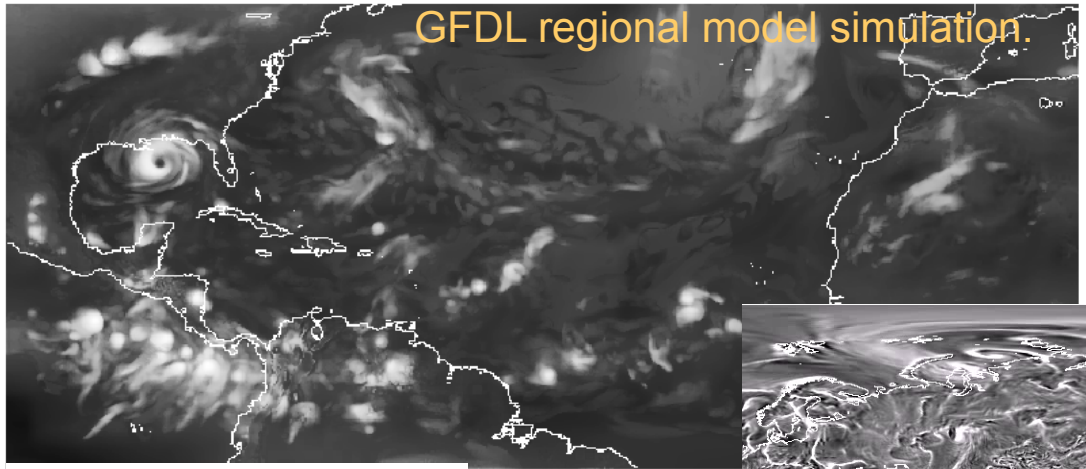
Observed Activity
Relative Atlantic Temperature

Vecchi, Swanson and Soden (2008, Science)

Gabriel Vecchi, NOAA/GFDL, Princeton, NJ

High-Resolution Comprehensive models

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



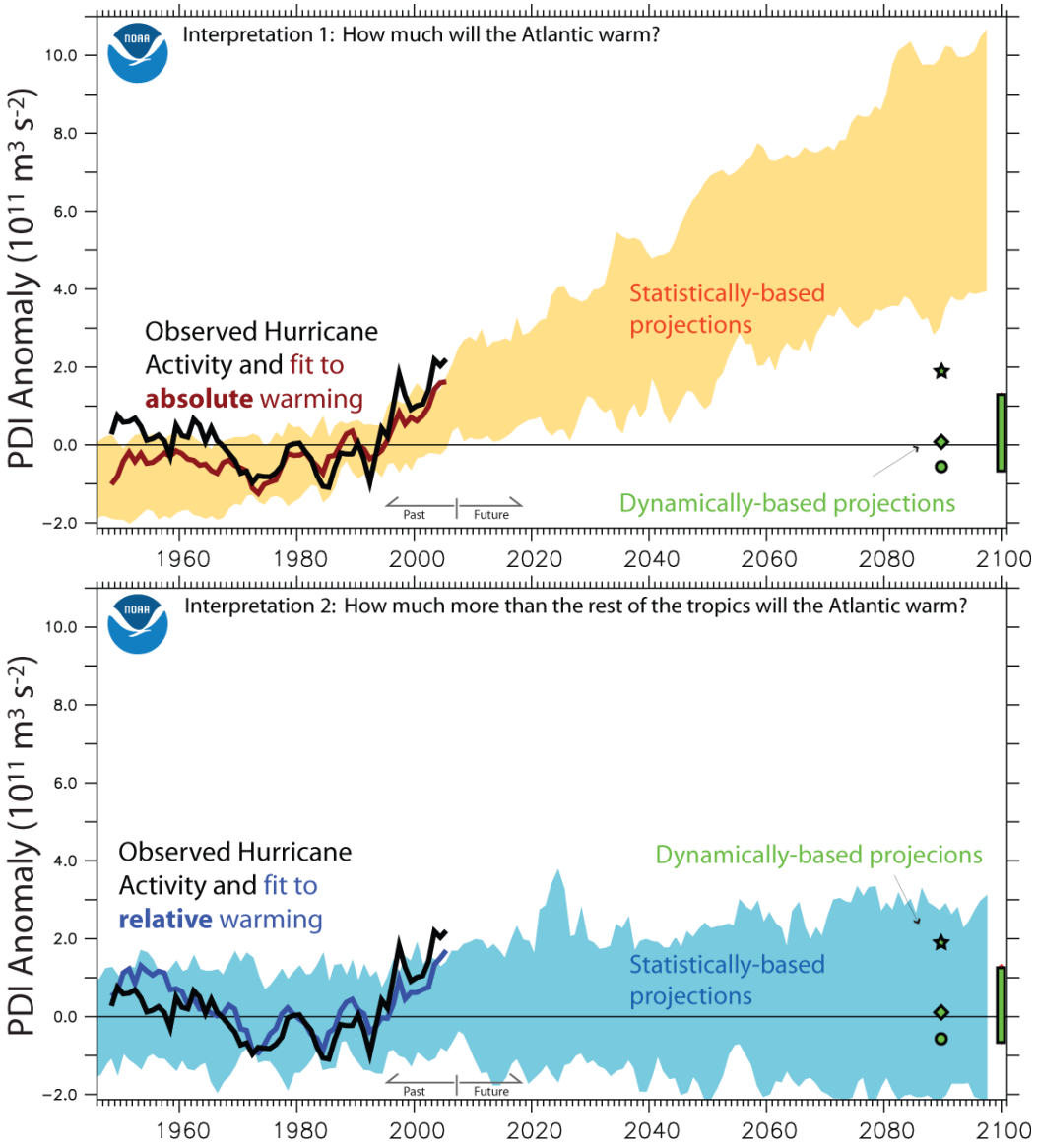
Knutson et al (2007, BAMS)

Models ranging in 100km to 18km resolution.

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

GFDL global model simulation.

…Add Dynamical Projections of Atlantic Hurricane Activity



Observed Activity
Absolute Atlantic Temperature

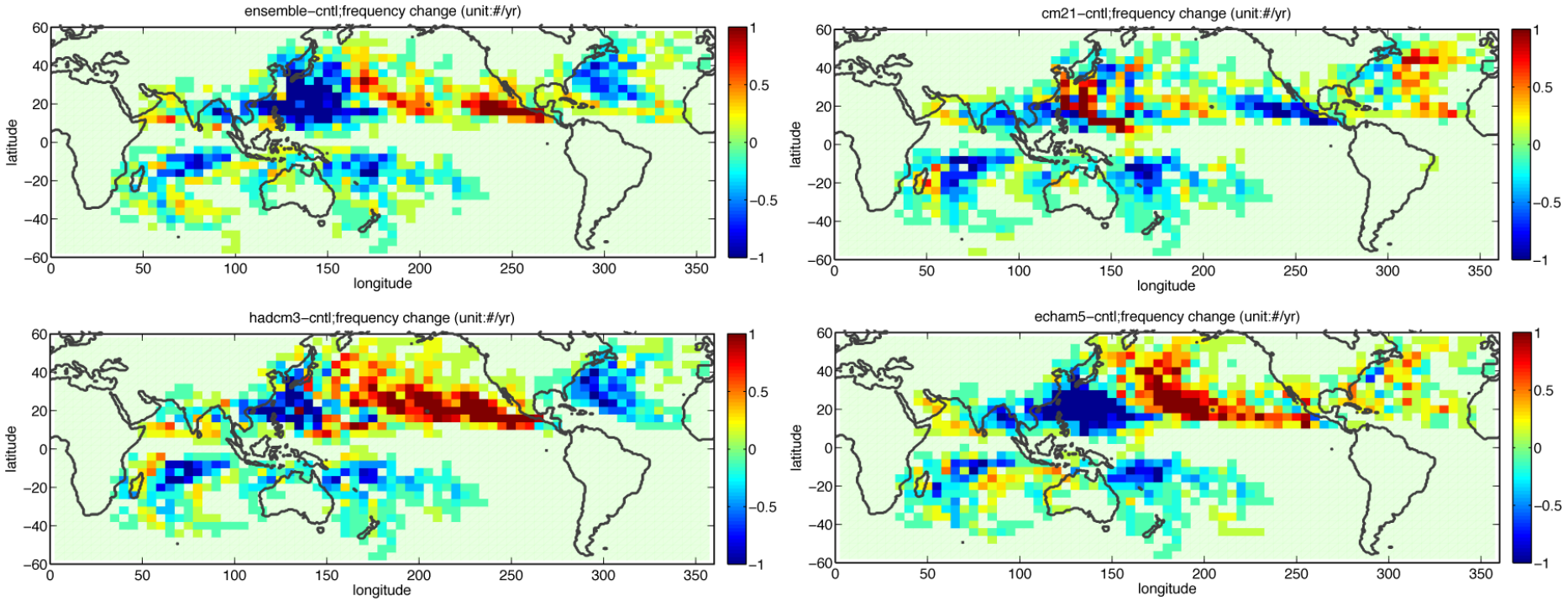
Dynamical Model Projections

Observed Activity
Relative Atlantic Temperature

Vecchi, Swanson and Soden (2008, Science)

Gabriel Vecchi, NOAA/GFDL, Princeton, NJ

Response of TC frequency in single 50km global atmospheric model forced by four climate projections for 21st century



Red/yellow = increase
Blue/green = decrease

Adapted from Zhao et al. (2009, J. Climate)

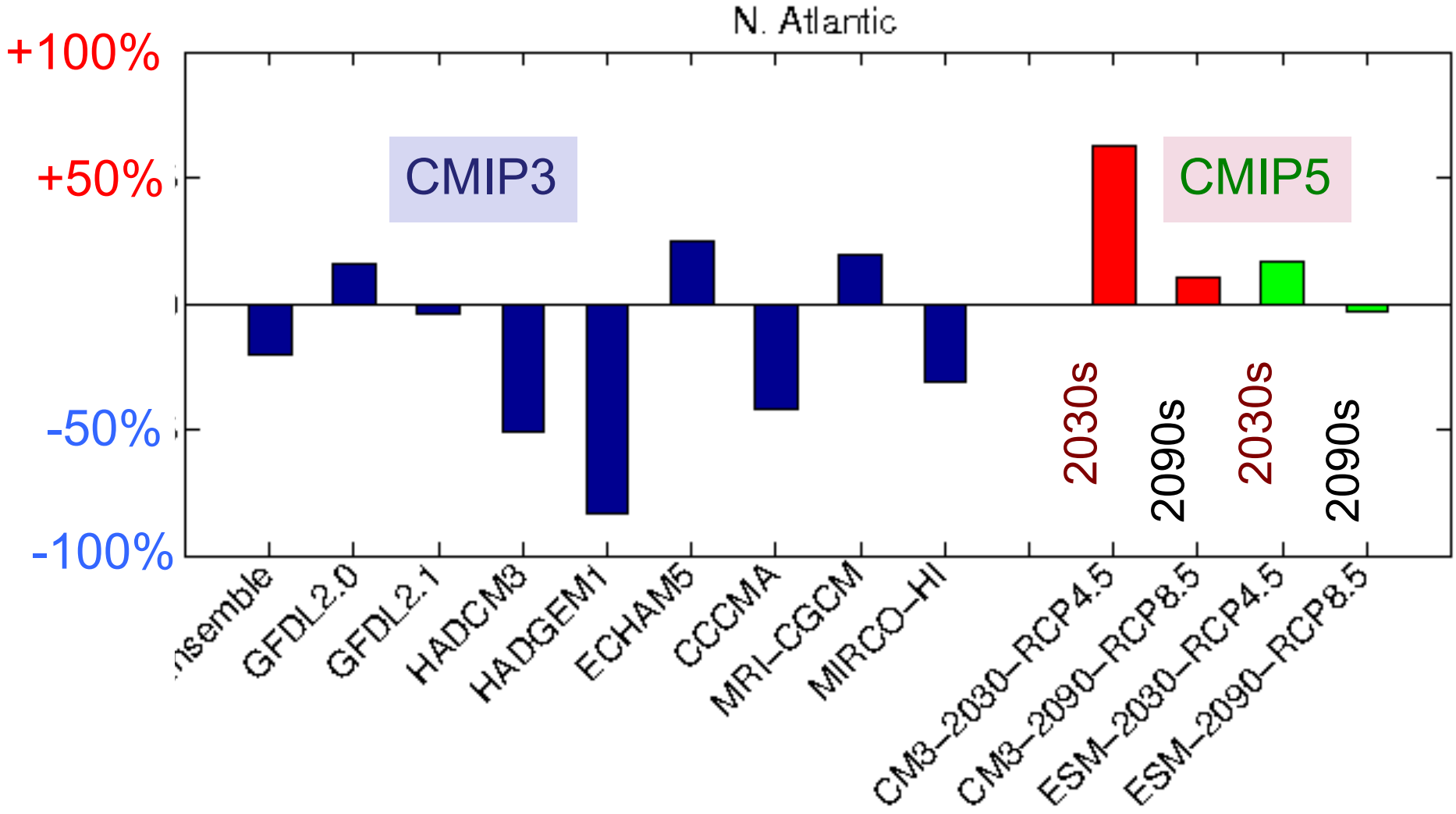
Regional increase/decrease much larger than global-mean.

Pattern depends on details of ocean temperature change.

Sensitivity of response seen in many studies

e.g., Emanuel et al. 2008, Knutson et al. 2008, Sugi et al. 2010, Villarini et al. 2011, etc.

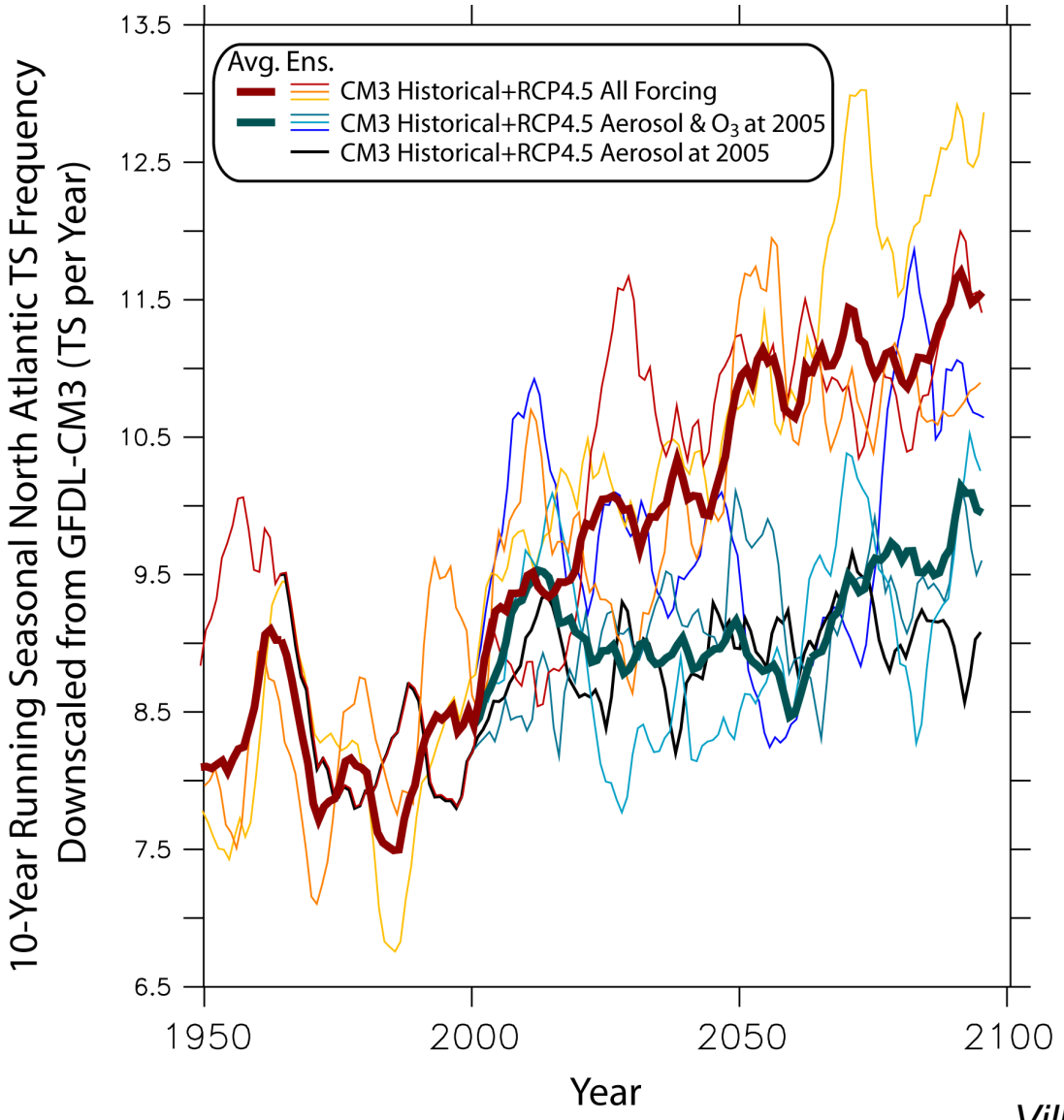
Dynamical Projections of Atl. Hurricanes for end of 21st Century



Using GFDL-HiRAM

Adapted from Zhao et al. (2009, J. Clim.) and Held et al. (2012, in prep)

GFDL-CM3 indicates aerosols key for NA TS projections (projected aerosol clearing -> more storms)



All Forcing

No future aerosol or O_3

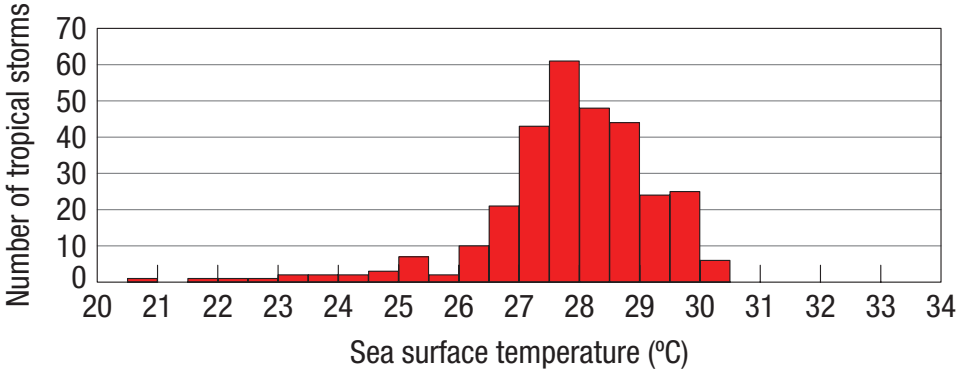
No future aerosol

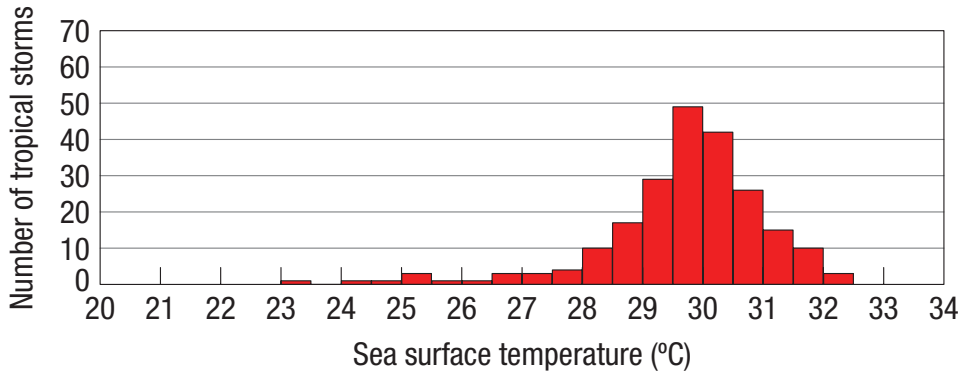
Villarini and Vecchi (2012, Nature C.C.)

Temperature “threshold” of TC formation increases with global warming

Ocean temperature when cyclone forms:

Present climate

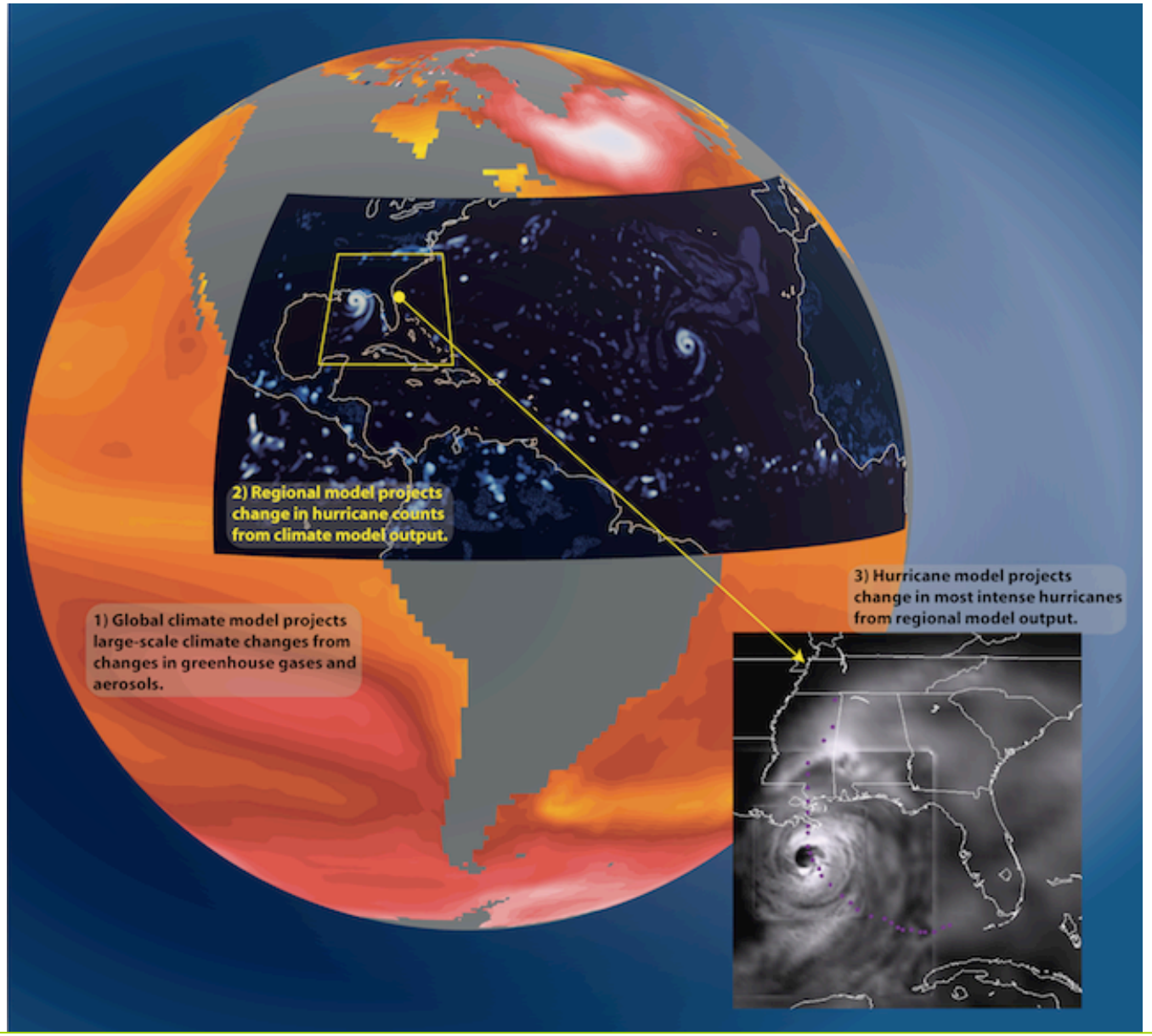




Warmed climate

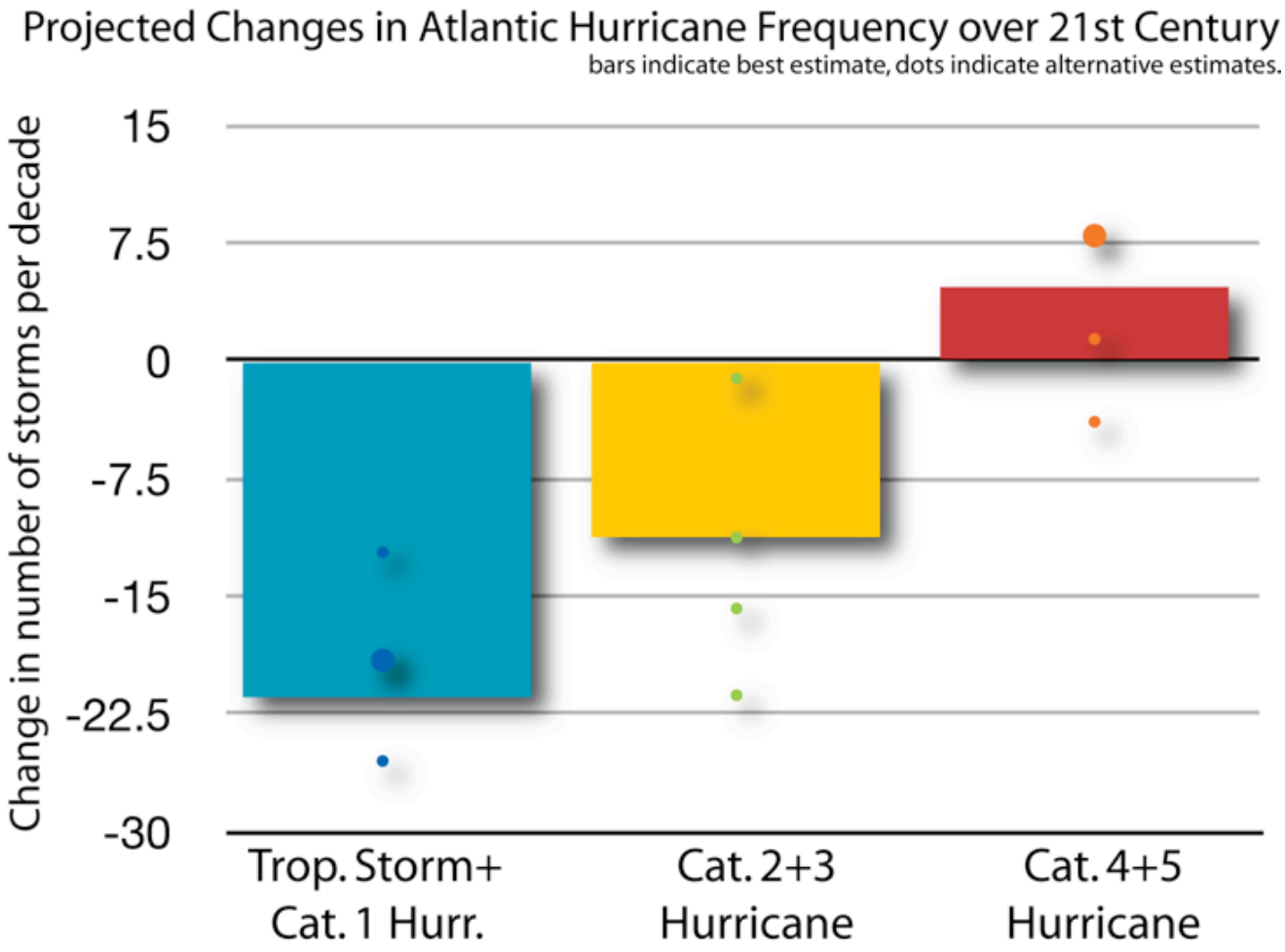
Gabriel Vecchi, NOAA/GFDL, Princeton, NJ

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



Gabriel Vecchi, NOAA/GFDL, Princeton, NJ

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

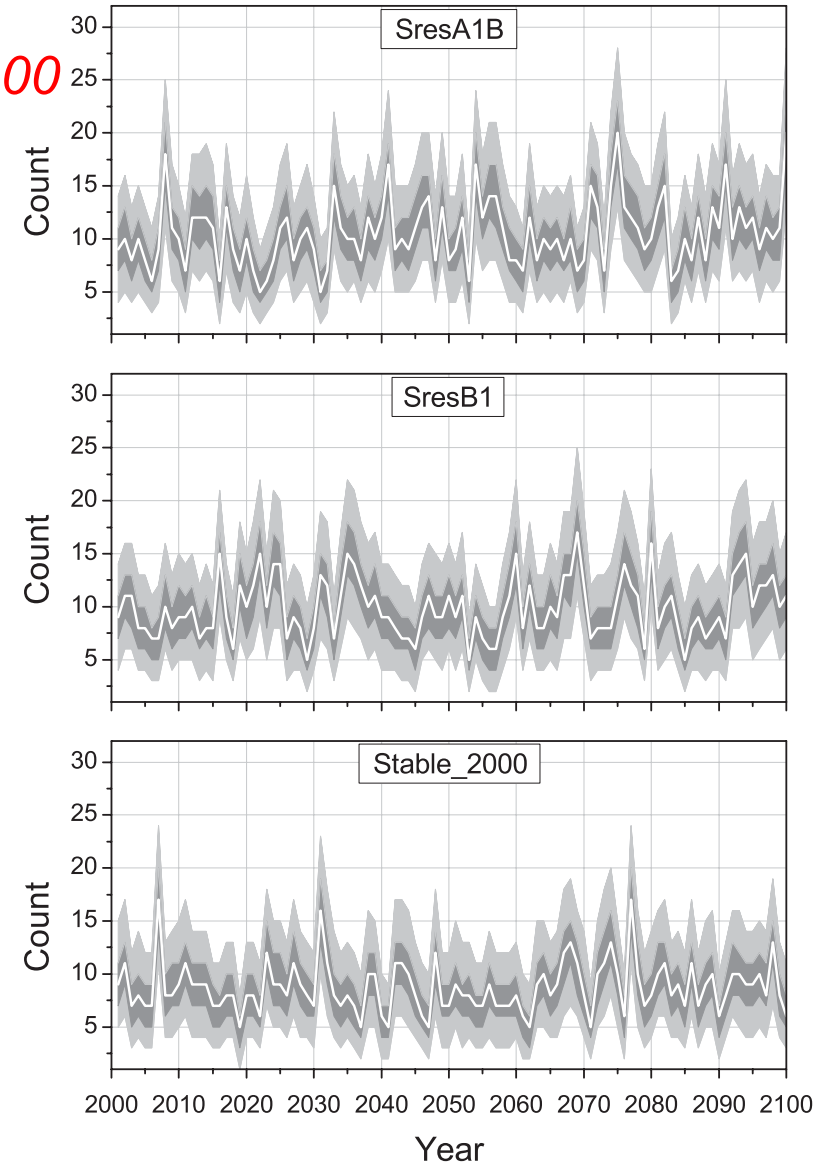


Adapted from Knutson et al (2008, Nature Geosci.), Bender et al (2010 Science)

Gabriel Vecchi, NOAA/GFDL, Princeton, NJ

We expect continued variation of tropical storm frequency

2x CO_2 by 2100



Stable CO_2 by 2000

Projected Atlantic Tropical Storm Frequency

(statistical downscaling of GFDL-CM2.1)

source: Villarini et al (2010)

Gabriel Vecchi, NOAA/GFDL, Princeton, NJ

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.

www.gfdl.noaa.gov
Gabriel.A.Vecchi@noaa.gov

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