Long-term Changes in Tropical Cyclone Activity

Observations, Theory and Modeling

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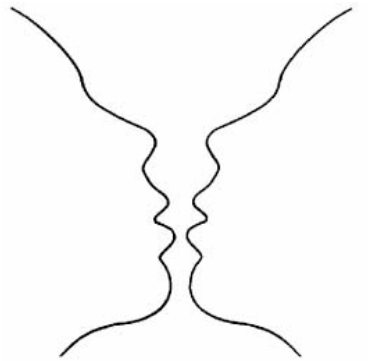
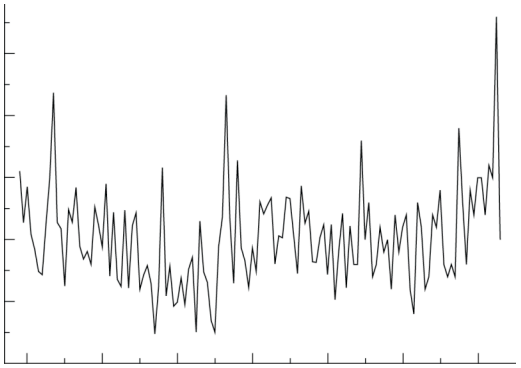
http://www.gfdl.noaa.gov/~gav





Some recent results from GFDL

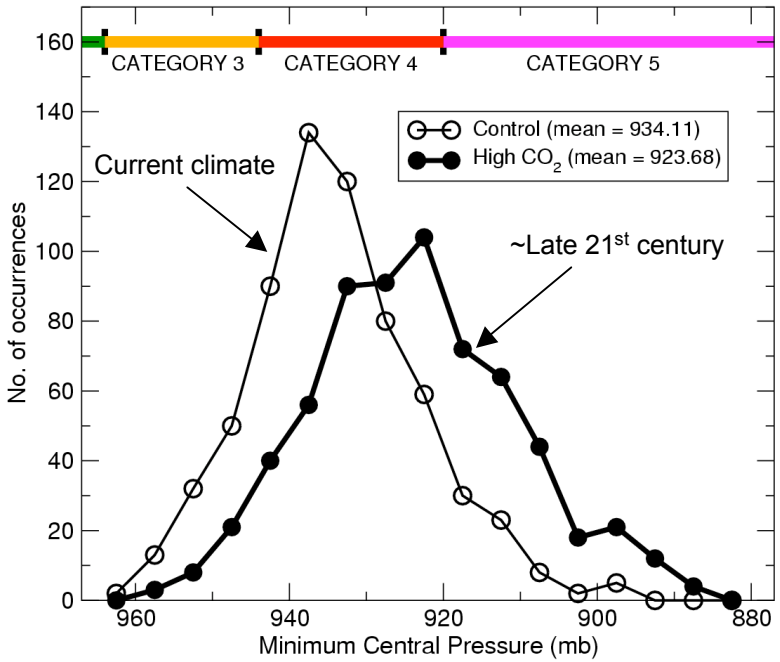
- Have Atlantic storms changed?
- How do we expect them to change?

Collaborators

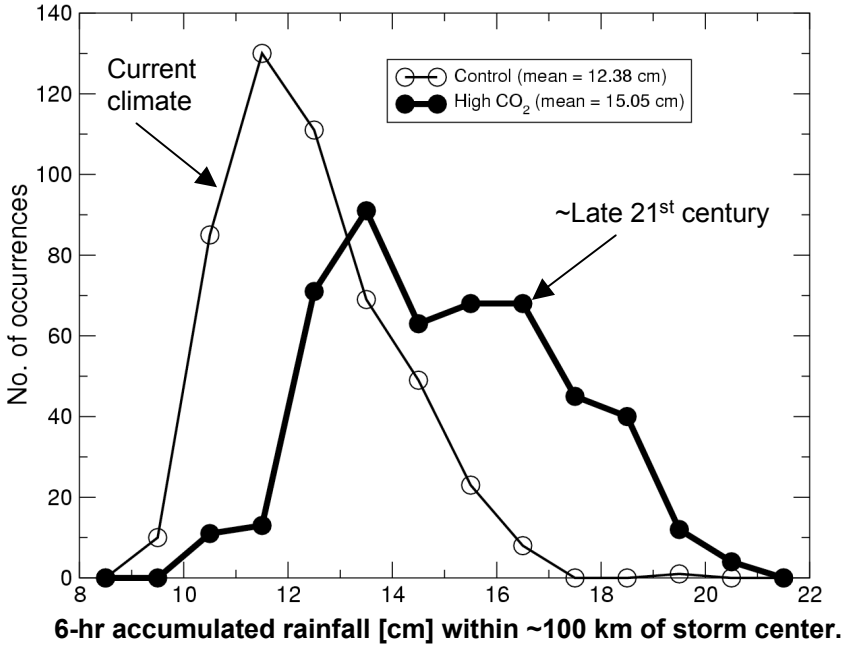
- Morris Bender (GFDL)
- Steve Garner (GFDL)
- Isaac Held (GFDL)
- Tom Knutson (GFDL)
- S-J Lin (GFDL)
- Ian Lloyd (Princeton/AOS)
- Joe Sirutis (GFDL)
- Brian Soden (U. Miami)
- Kyle Swanson (U. Wisc./Mil.)
- Bob Tuleya (GFDL/Old Dominion U.)
- Ming Zhao (GFDL)

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

Hurricane Intensity

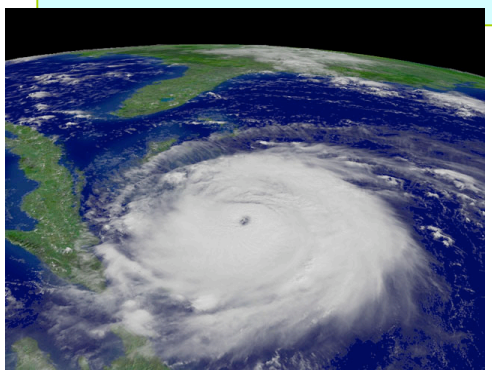


Hurricane Rainfall Rates

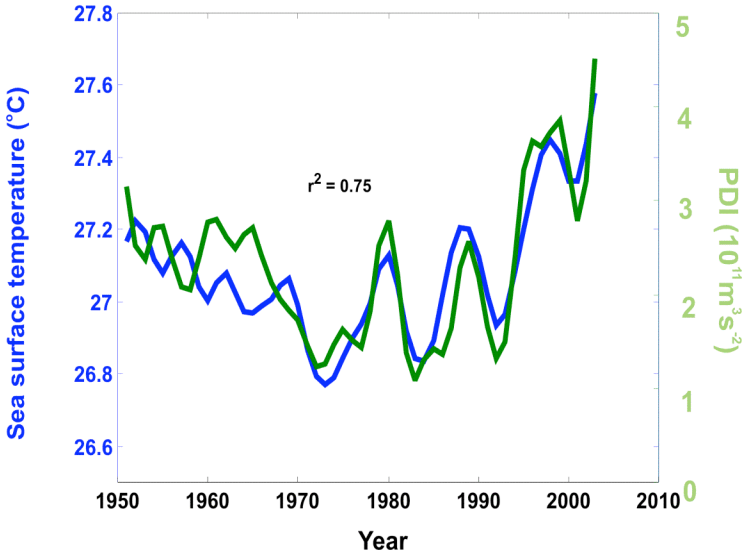


Sources: Knutson and Tuleya, *J. Climate*, 2004 (left);
Knutson and Tuleya, 2007; accepted for publication, Cambridge Univ Press (right).

North Atlantic tropical cyclones



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



Emanuel (2007, J. Clim.)

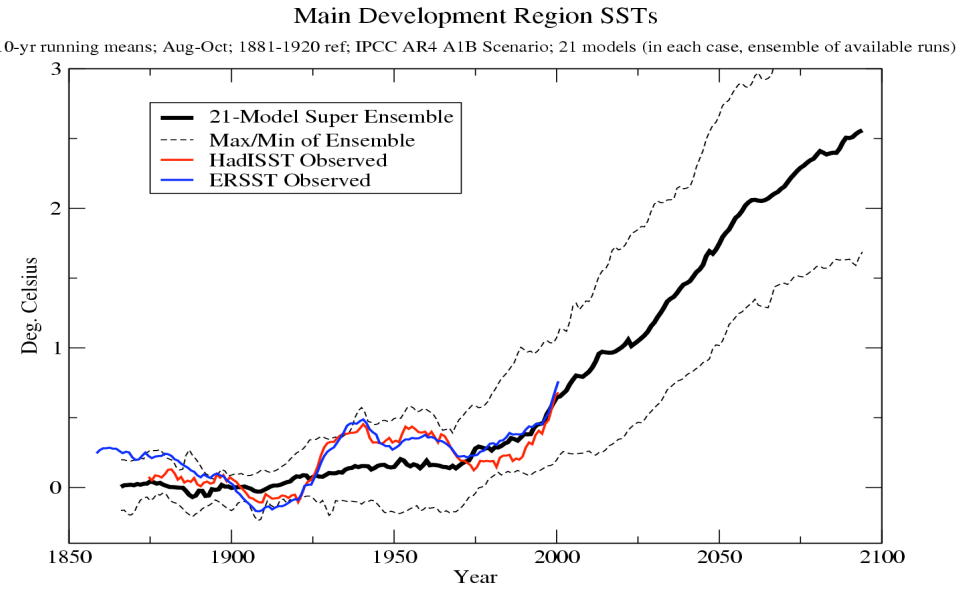


Figure: Tom Knutson

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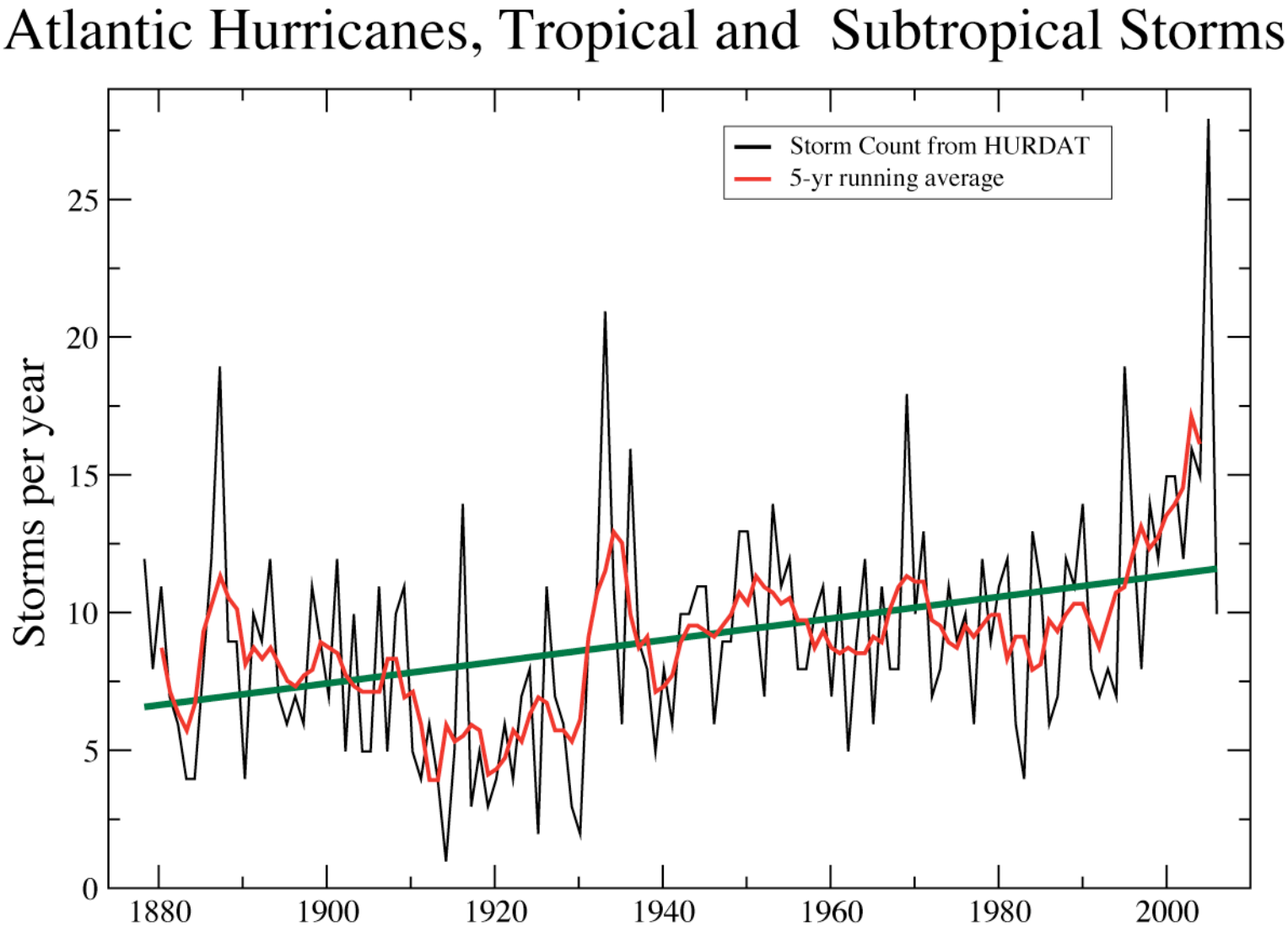
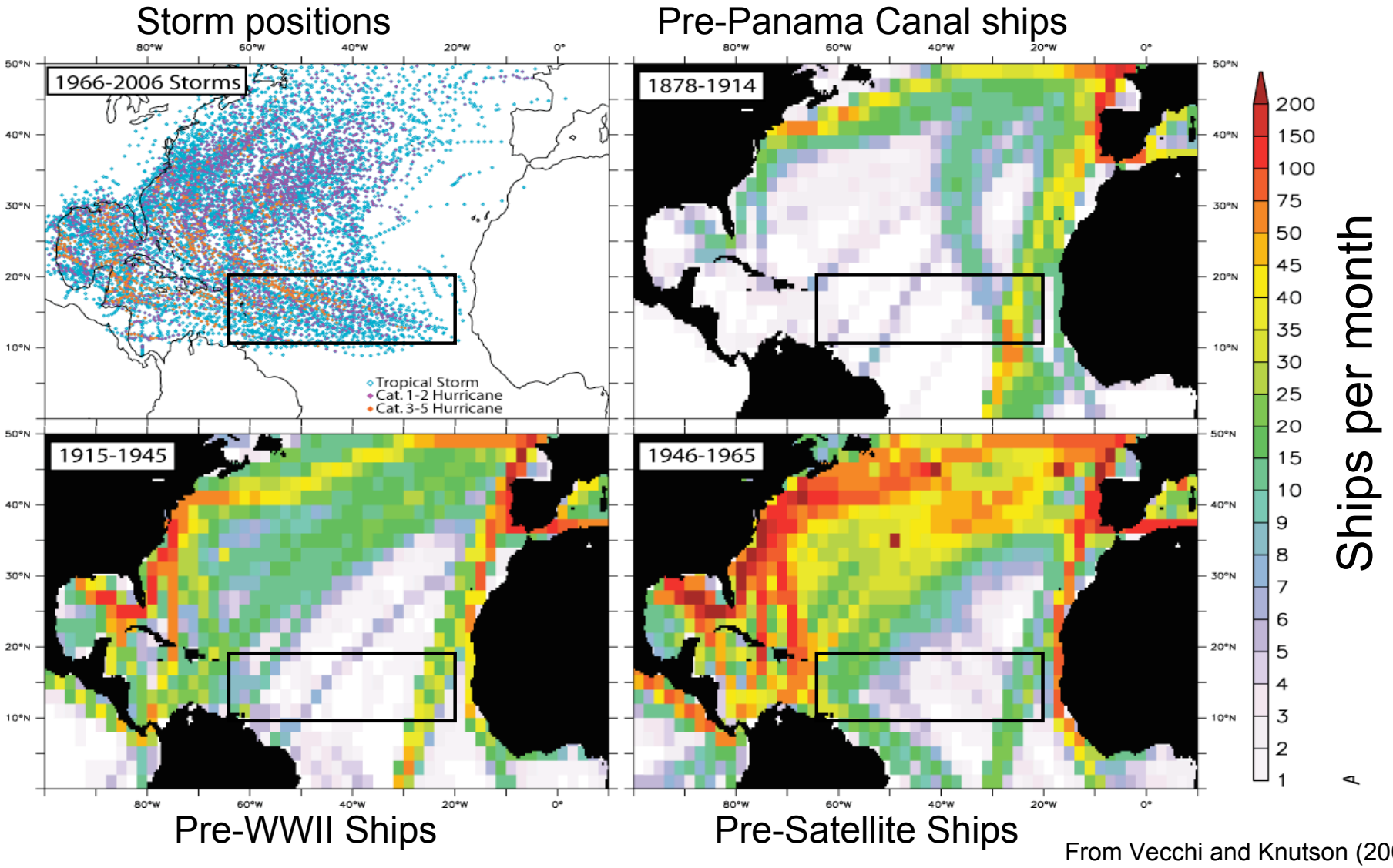
Observations

- Data problems
- Multiple possible interpretations of observations.

What does historical record of storms tell us?

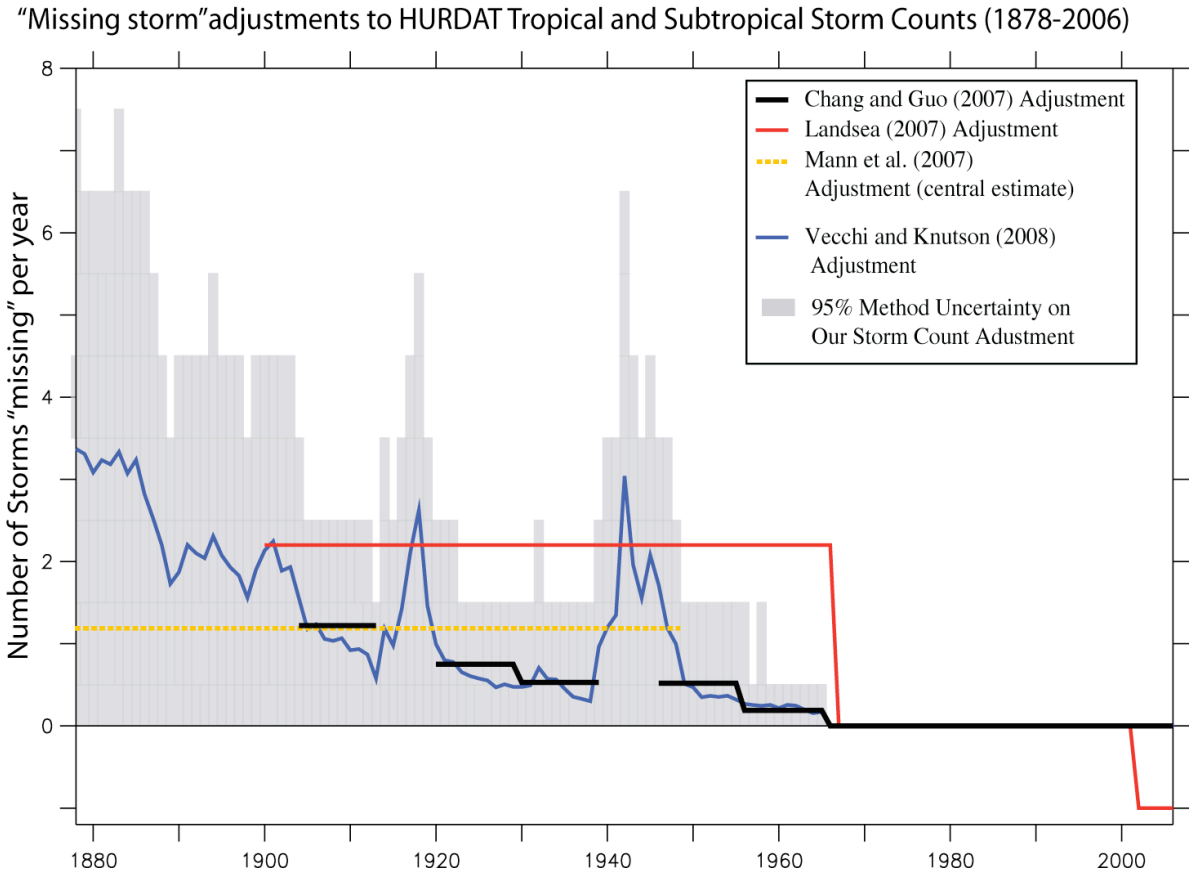


Can we be sure the long-term increase is real? Observational methods have changed with time….



From Vecchi and Knutson (2007)

…but we can estimate number of "missed" storms



- *Landsea (2007)*: Assumes constant landfall fraction.
  Is this justified (see *Holland, 2007*)?
- Mann *et al.* (2007): Based on statistical relationship to predictors (*e.g.* SST)
- *Chang and Guo (2007)*, *Vecchi and Knutson (2008)*:
  How many storms "slip" through ship tracks?

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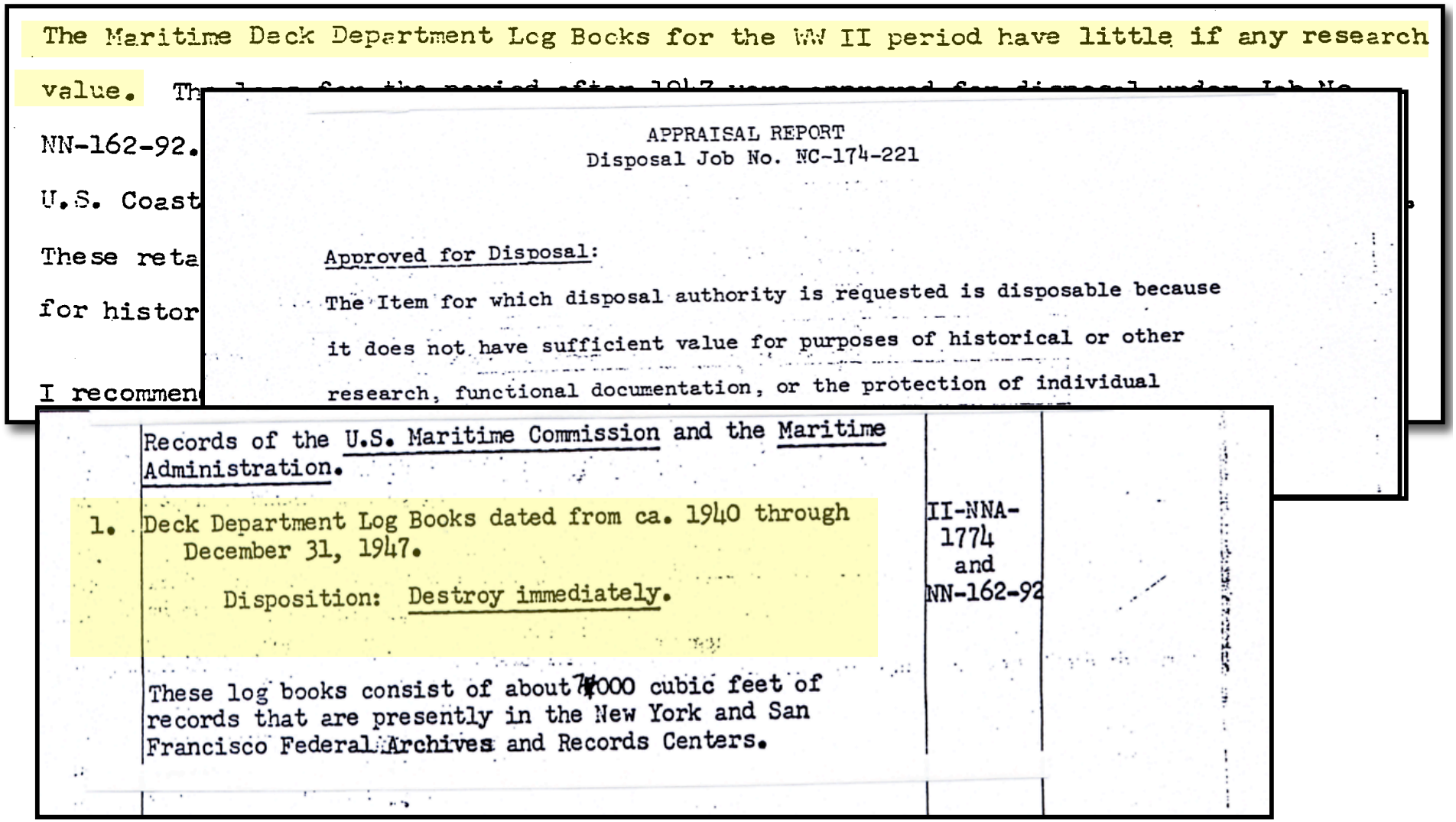
US WW II Merchant Marine Logbooks: Excerpts from Appraisal Reports & National Archives "Disposal Authority" (1974)



The Maritime Deck Department Log Books for the WW II period have little if any research value. Th

NN-162-92.

U.S. Coast

These reta

for histor

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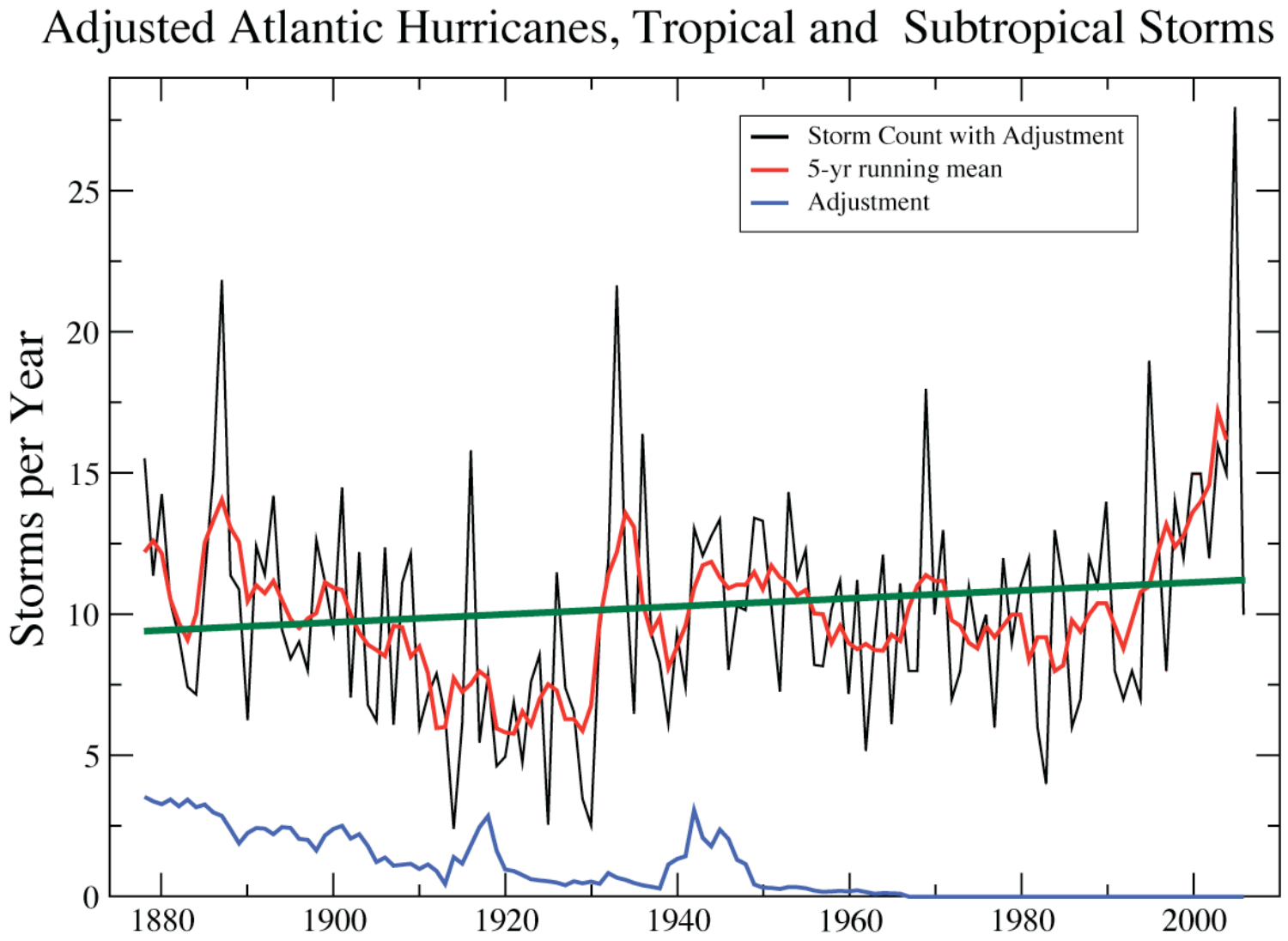
APPRAISAL REPORT
Disposal Job No. NC-174-221

Approved for Disposal:

The Item for which disposal authority is requested is disposable because it does not have sufficient value for purposes of historical or other research, functional documentation, or the protection of individual

	Records of the U.S. Maritime Commission and the Maritime Administration.	
1.	Deck Department Log Books dated from ca. 1940 through December 31, 1947. Disposition: Destroy immediately.	II-NNA-1774 and NN-162-92
	These log books consist of about 7000 cubic feet of records that are presently in the New York and San Francisco Federal Archives and Records Centers.	

from Scott Woodruff, NOAA/ESRL



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

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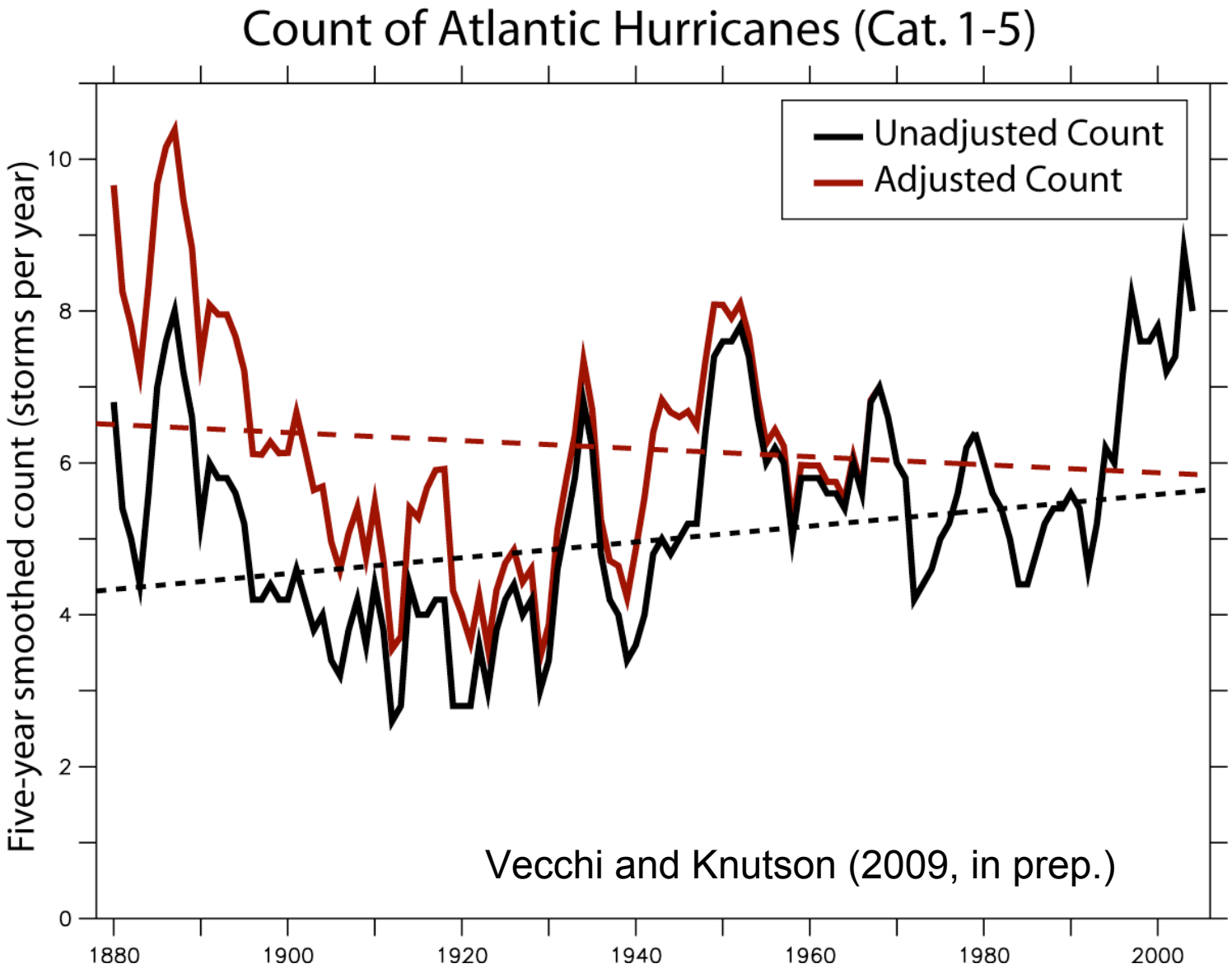

Adjustment changes sign of hurricane count trend

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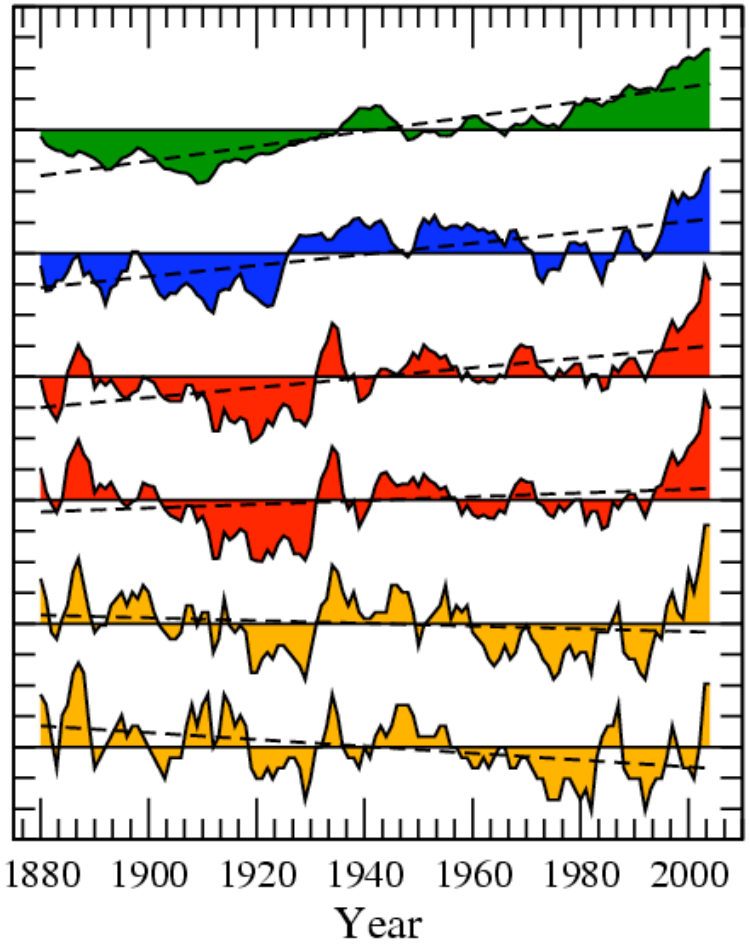
A comparison of several climate change metrics:



Global Mean Temperature

Tropical Atlantic Sea Surface Temperature

Atlantic Tropical Storm Counts (unadj.)

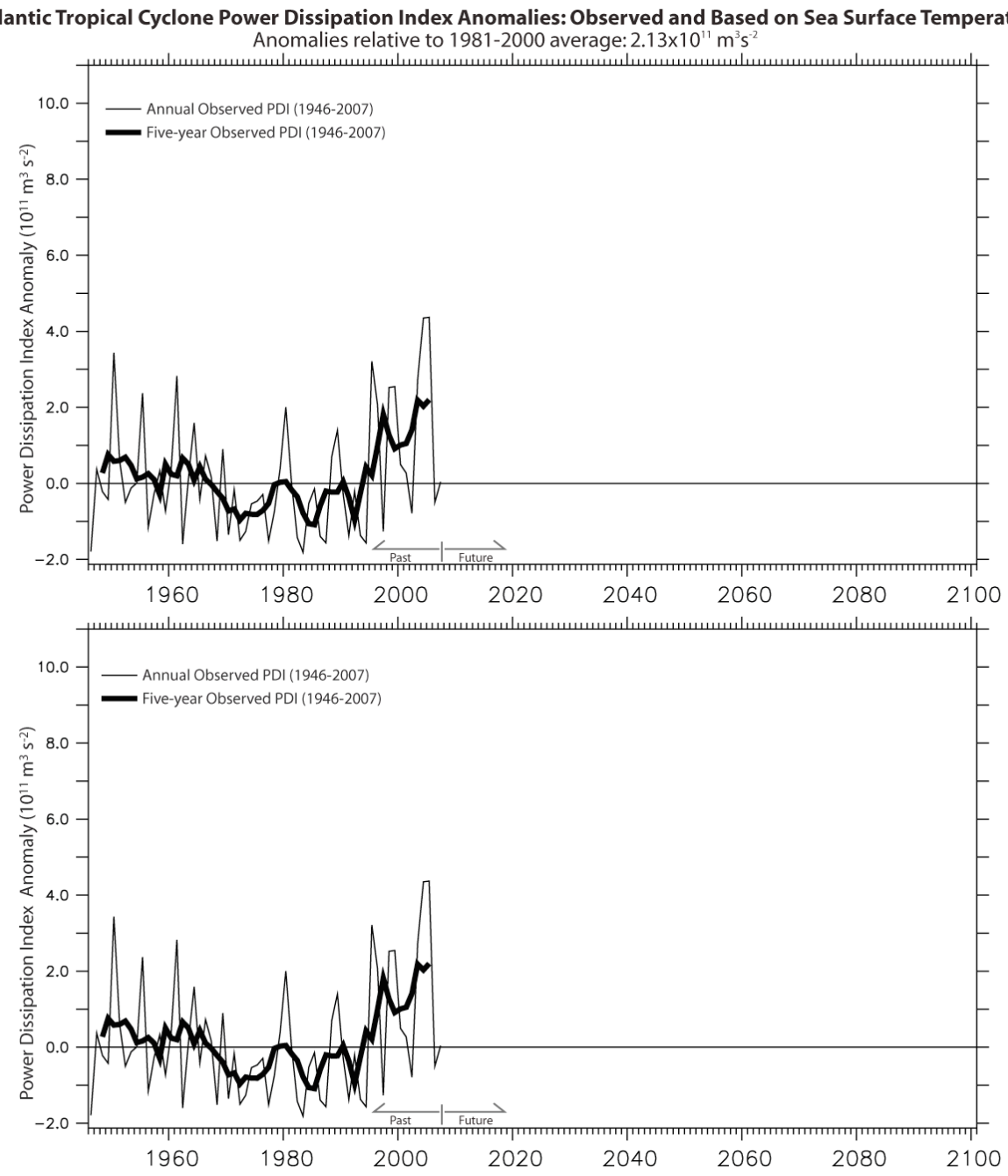
Atlantic Trop. Storm Counts (Vecchi/Knut. Adj.)

U.S. Landfalling Tropical Storms (unadj.)

U.S. Landfalling Hurricanes (unadj.)

Vecchi and Knutson (2008, J. Clim.)

Note: All time series are low-pass filtered (5-yr mean) and normalized to unit standard deviation (y-axis tic marks: 1 st. dev).

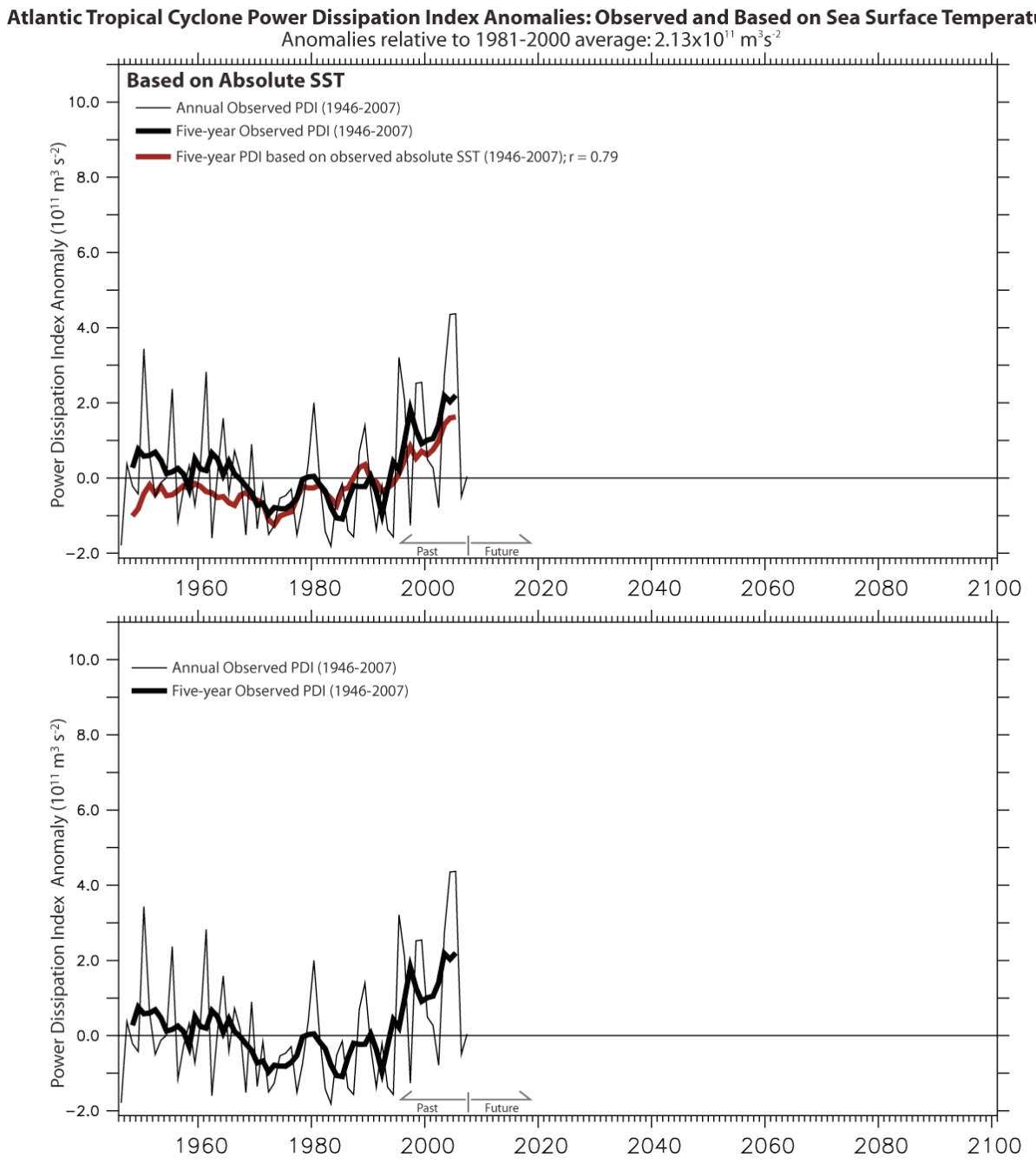


Observed PDI

Power Dissipation Index: sum of cube of max. wind over all storms in a season.

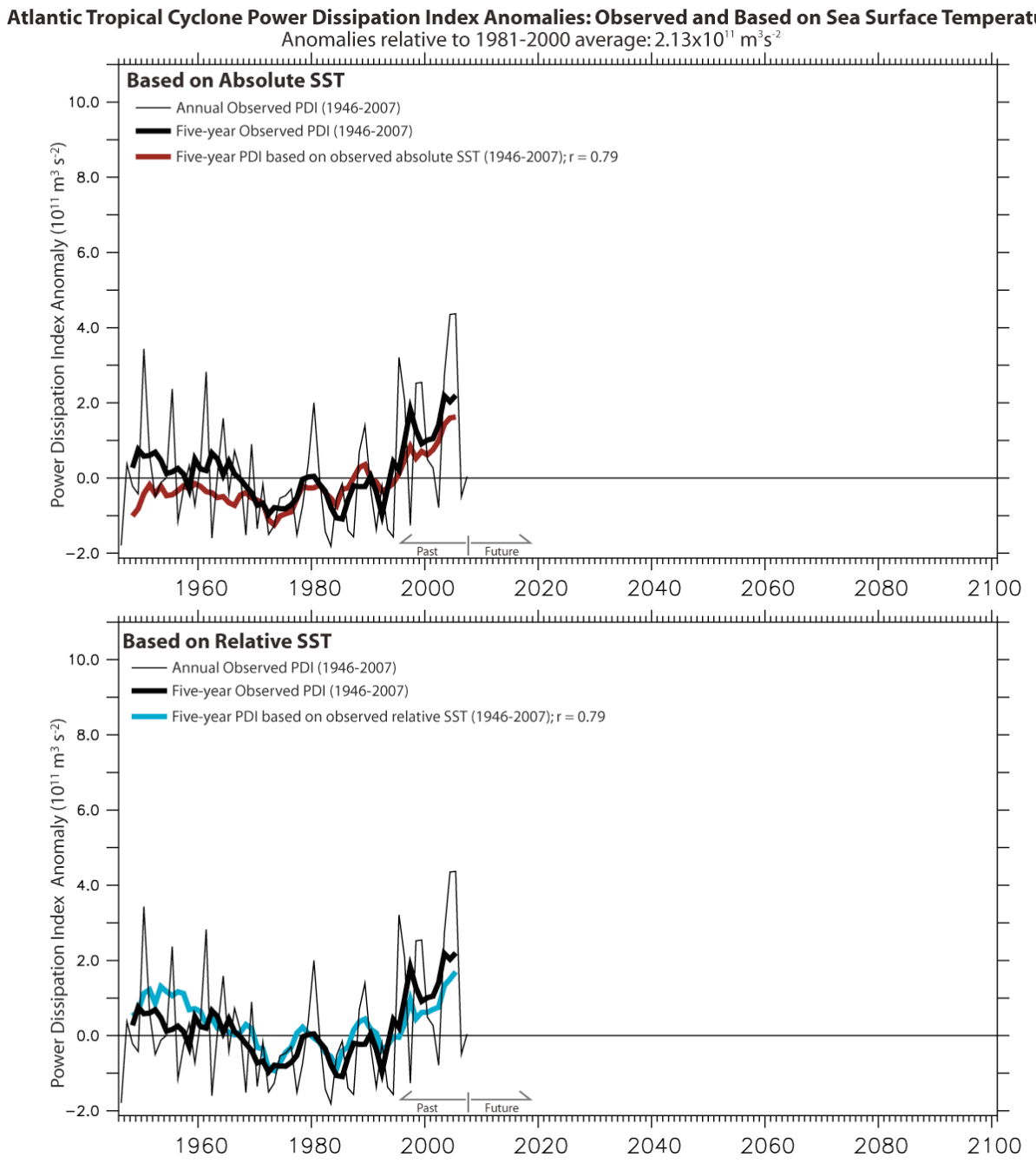
Affected by intensity, duration and number.

Vecchi, Swanson and Soden (2008, *Science*)



Observed Activity
Absolute SST

Vecchi, Swanson and Soden (2008, *Science*)



Observed Activity

Absolute SST

Relative SST

Vecchi, Swanson and Soden (2008, *Science*)

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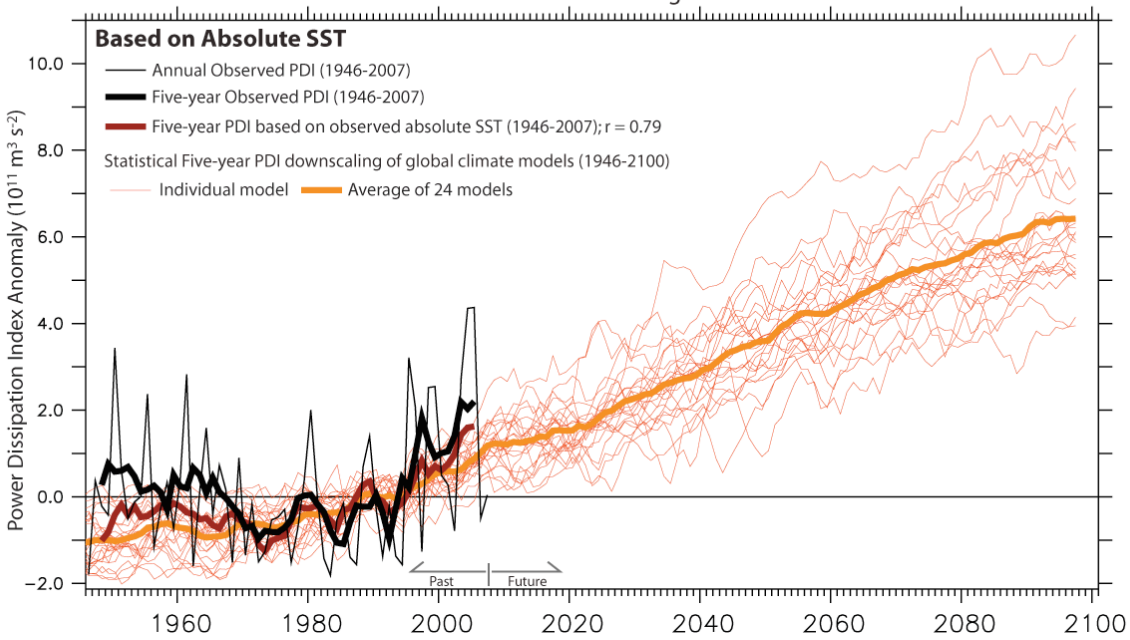
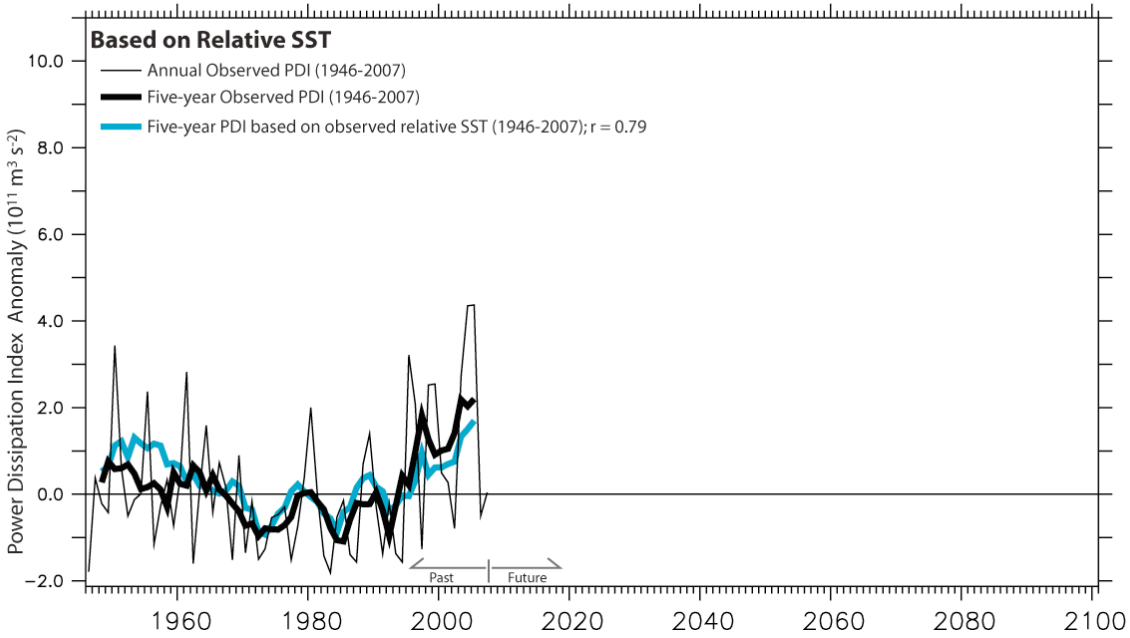
Atlantic Tropical Cyclone Power Dissipation Index Anomalies: Observed and Based on Sea Surface Temperature

Anomalies relative to 1981-2000 average: 2.13×10^{11} $m^3 s^{-2}$





Observed Activity

Absolute SST

Model Abs. SST

Relative SST

Vecchi, Swanson and Soden (2008, *Science*)

Atlantic Tropical Cyclone Power Dissipation Index Anomalies: Observed and Based on Sea Surface Temperature

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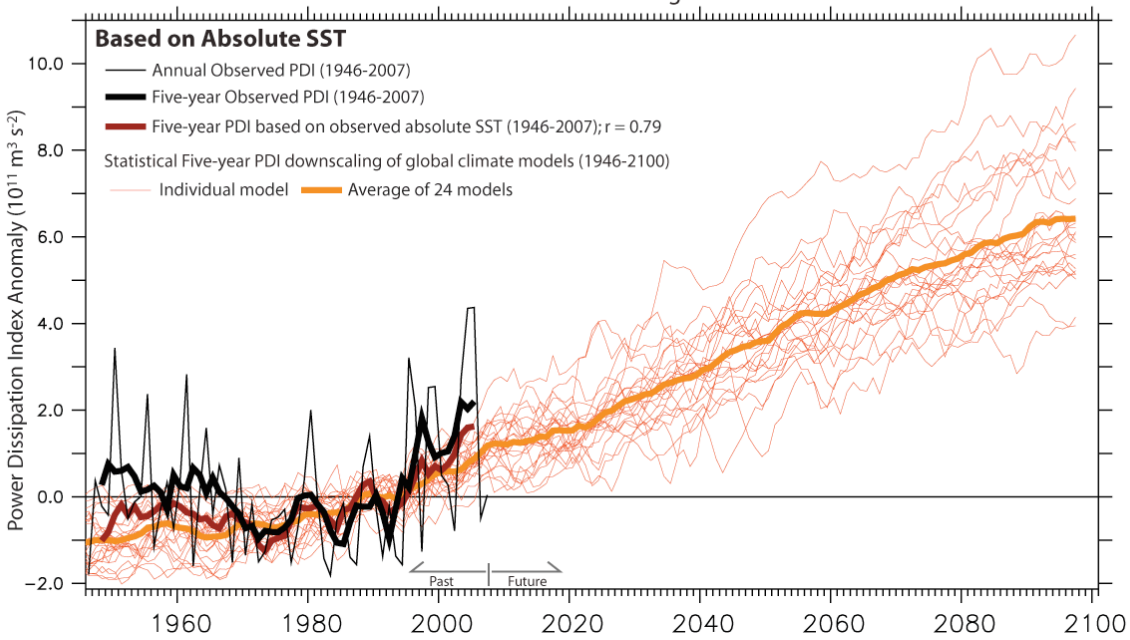
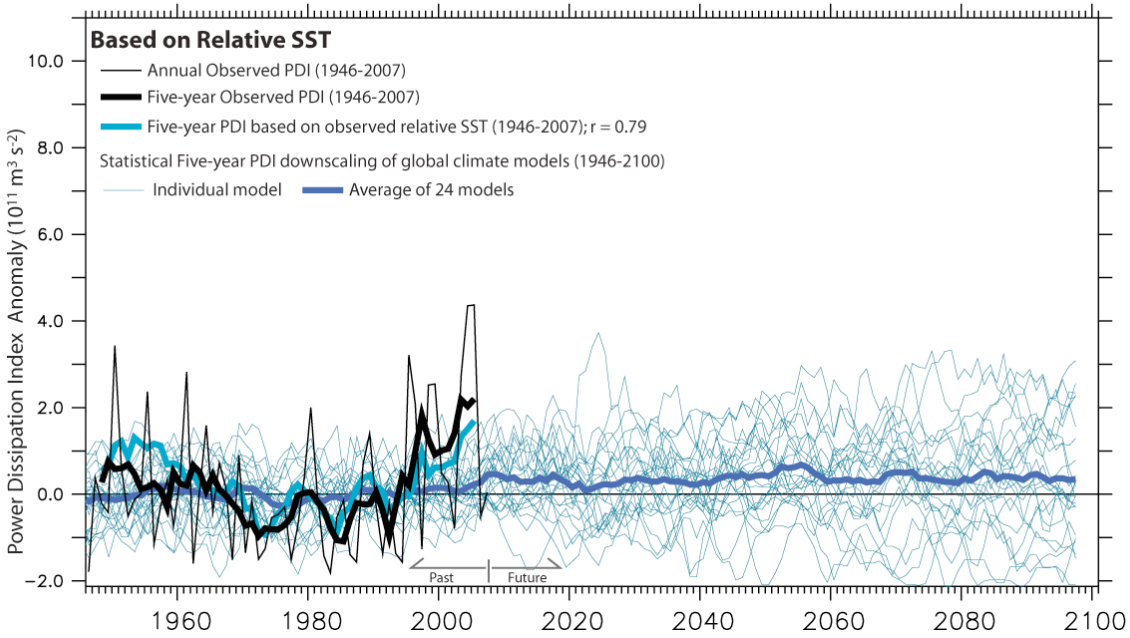




Observed Activity

Absolute SST

Model Abs. SST

Relative SST

Model Rel. SST

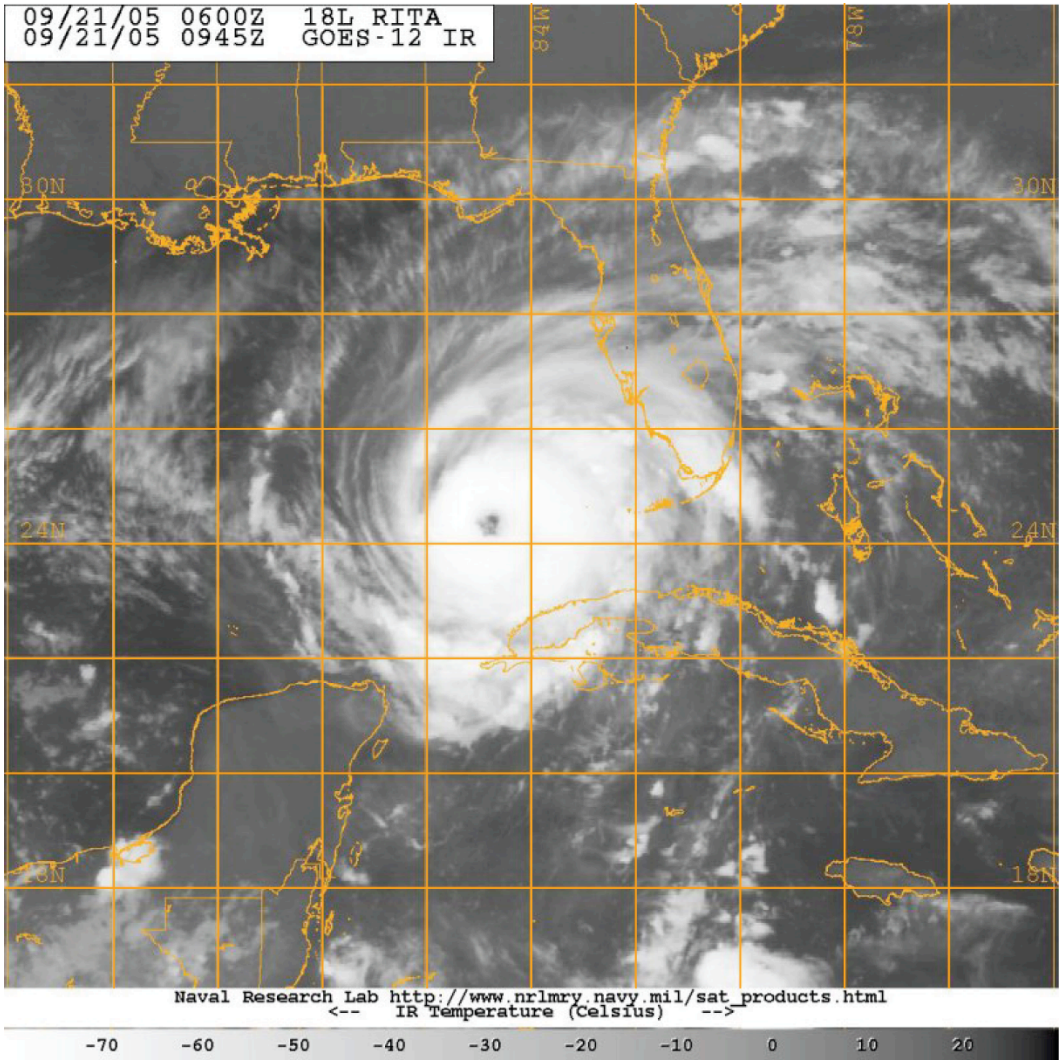
Vecchi, Swanson and Soden (2008, *Science*)

Theory

Current theory on seasonal cyclone activity is limited.

Theoretical understanding developed on individual storms can be applied to large-scale conditions.

Current computing power limits ability of global climate models to represent hurricanes



Hurricane Rita (2005): orange grid is representative of typical IPCC-AR4 ***global*** climate model resolution.

Size of grid limited by power of computers.

Gabriel Vecchi, NOAA/GFDL, Princeton, NJ

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

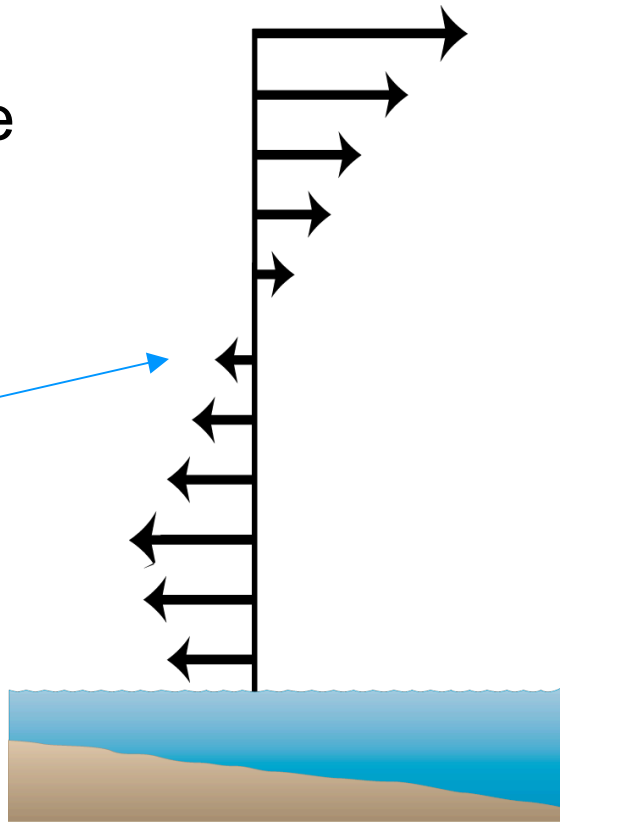
<u>Factors that favor storm development and intensification</u>:

- Warm ocean surface
- Cool upper atmosphere

} Help define potential intensity

cf. Emanuel, Holland

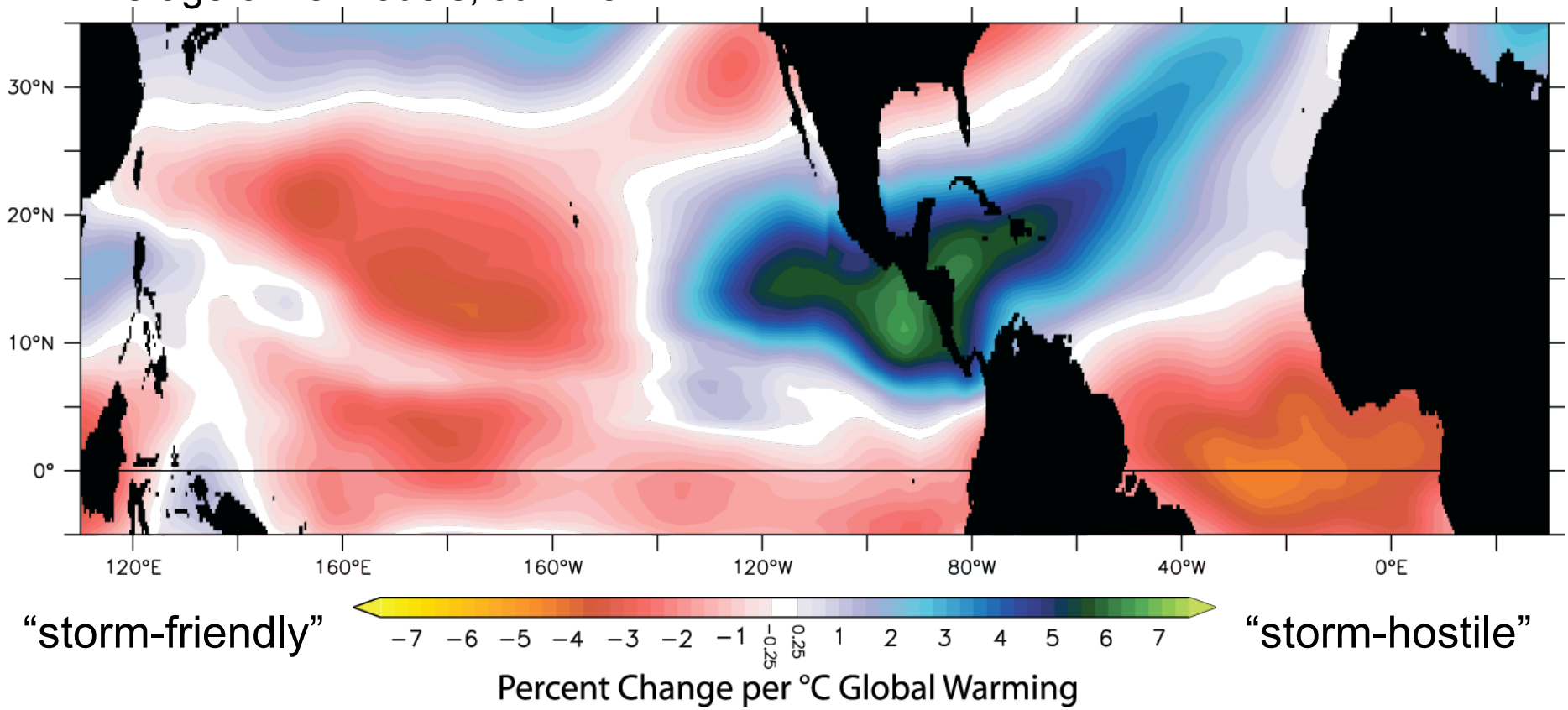
- Low vertical wind shear
- Moist middle atmosphere
- etc.



Projected 21st Century Changes in Vertical Wind Shear

from Vecchi and Soden (2007, GRL)

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?

Emanuel's Potential Intensity

$$PI^2 = V_{red}^2 \frac{c_k}{c_d} \frac{T_s - T_o}{T_o} \left(k_s^* - k_a \right) \Big|_{r_{\max}}$$

Scale factor

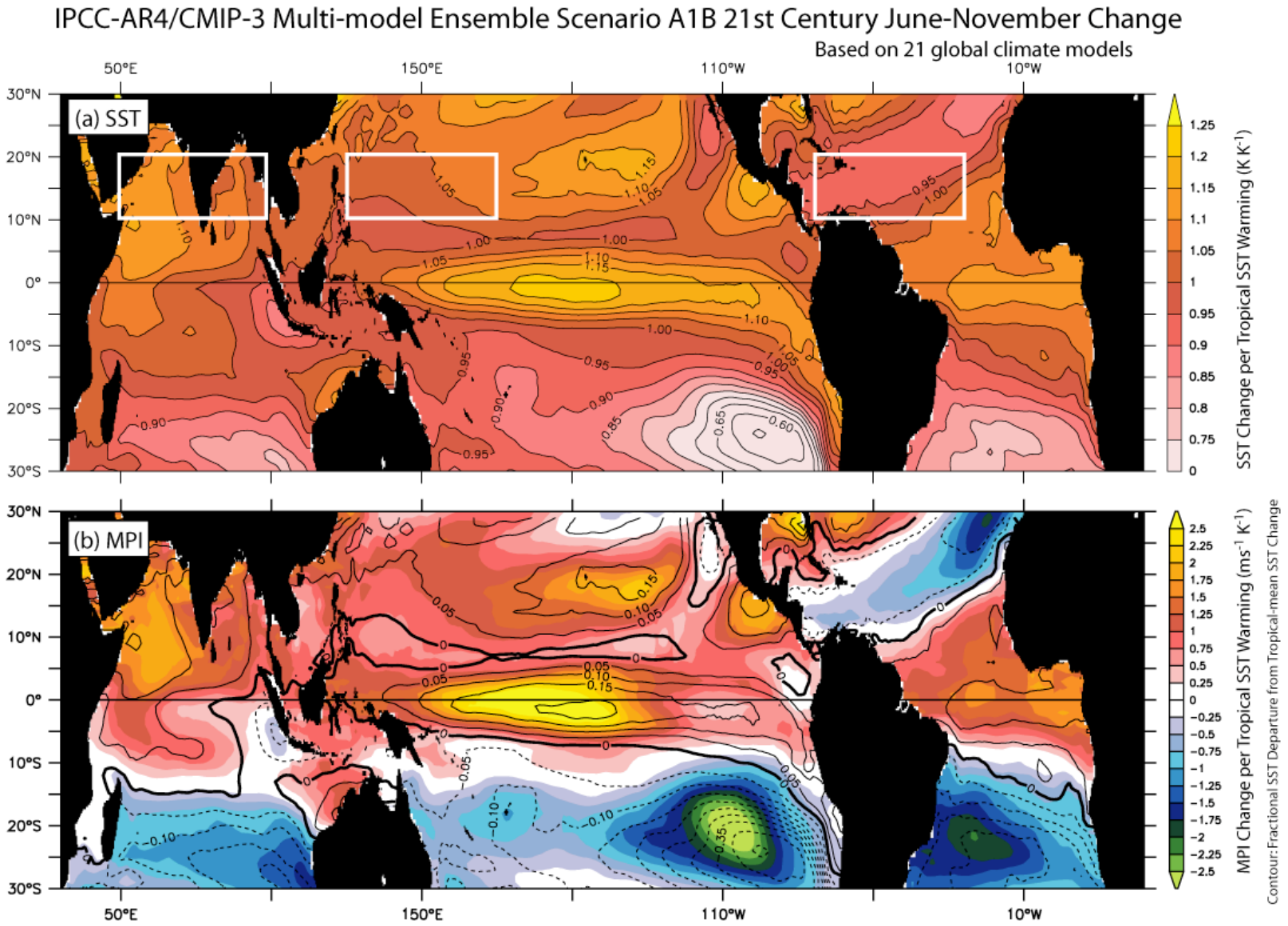
Drag coefs.

Ts = SST
To = outflow temp

Enthalpy jump at surface.

- Theoretical upper bound of cyclone intensity from local thermodyn. env. (*Emanuel 1995, Bister and Emanuel 1998)*
- "Efficiency" and "Fuel" terms (Carnot Cycle analogue)
- All other things equal: SST increase-> PI increase

Potential intensity does not necessarily track SST



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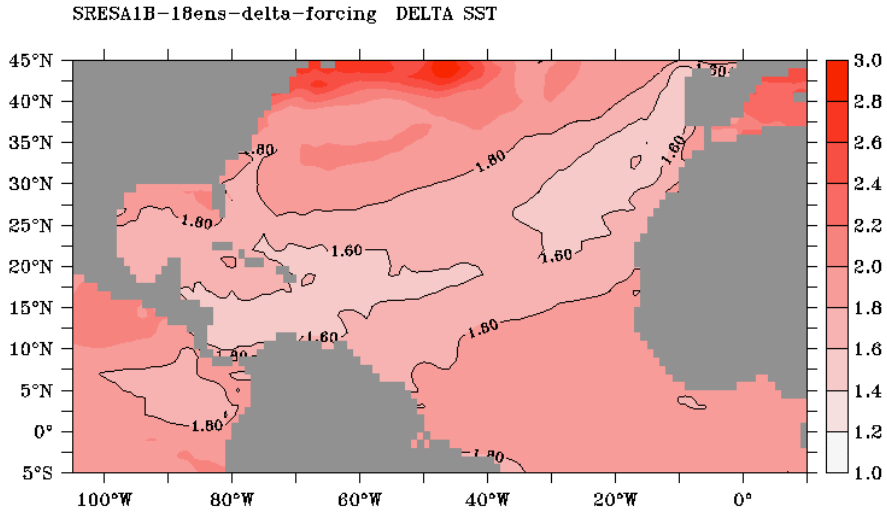
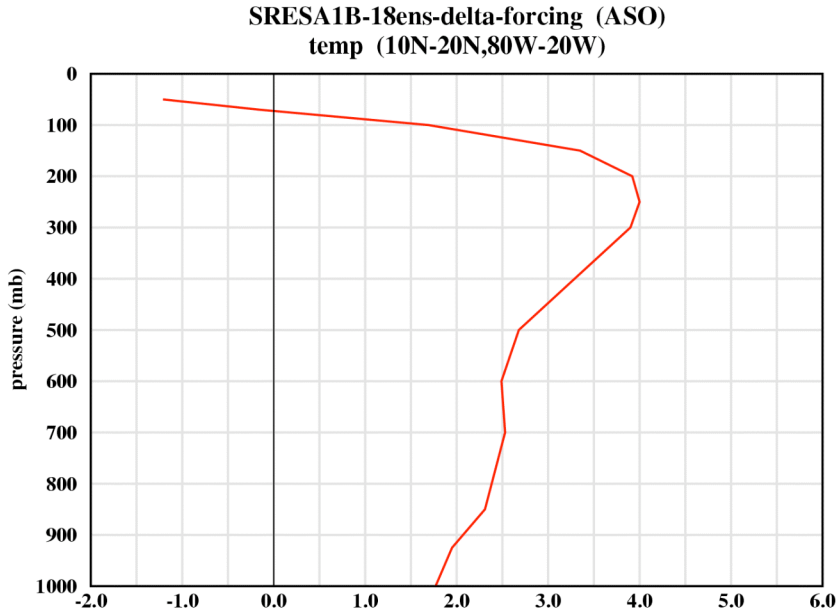


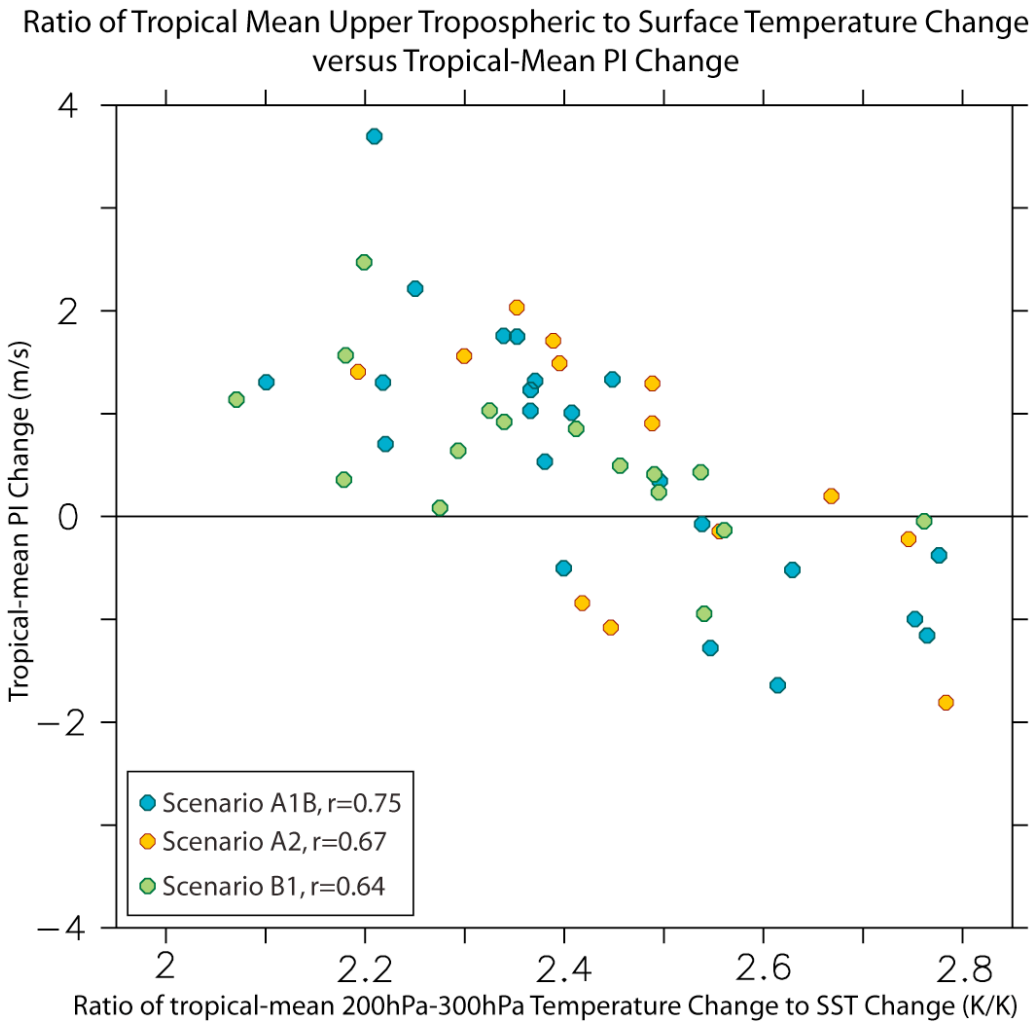


Large-scale tropical Atlantic climate changes projected for late 21st century by CMIP3 models (A1B scenario). Average SST change in MDR is 1.72°C with warming near 4°C in the upper troposphere.

Source: Knutson et al., *Nature Geoscience*, 2008.

What about tropical-mean PI?

- Not well constrained by SST changes.
- Related to vertical structure of warming (model/ parameterization dependent)



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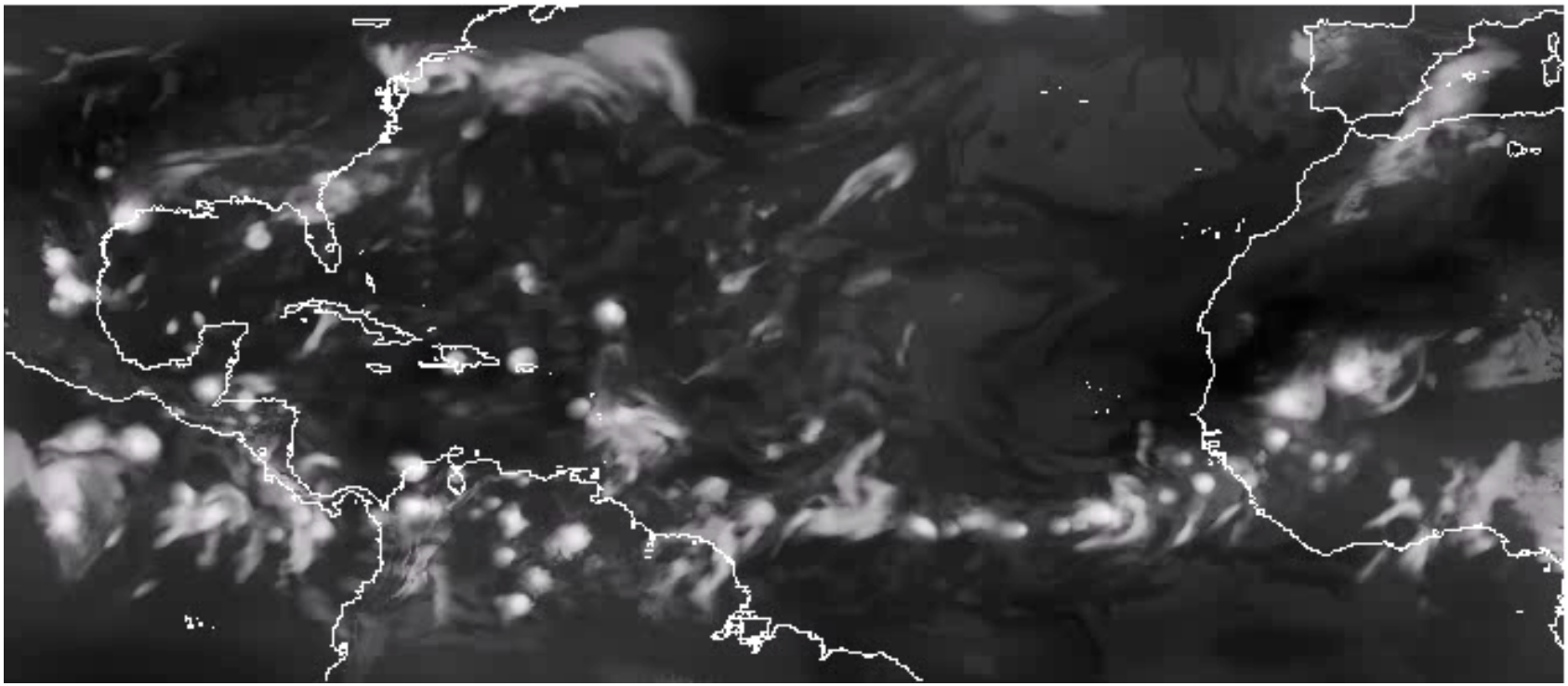
High-resolution models

- Regional 18-km model (Knutson et al 2007, 2008):
  - Explore sensitivity of storm frequency
- Global 100-km model:
  - Explore sensitivity to idealized forcing
- GFDL Hurricane forecast model:
  - Refined study of intensity response

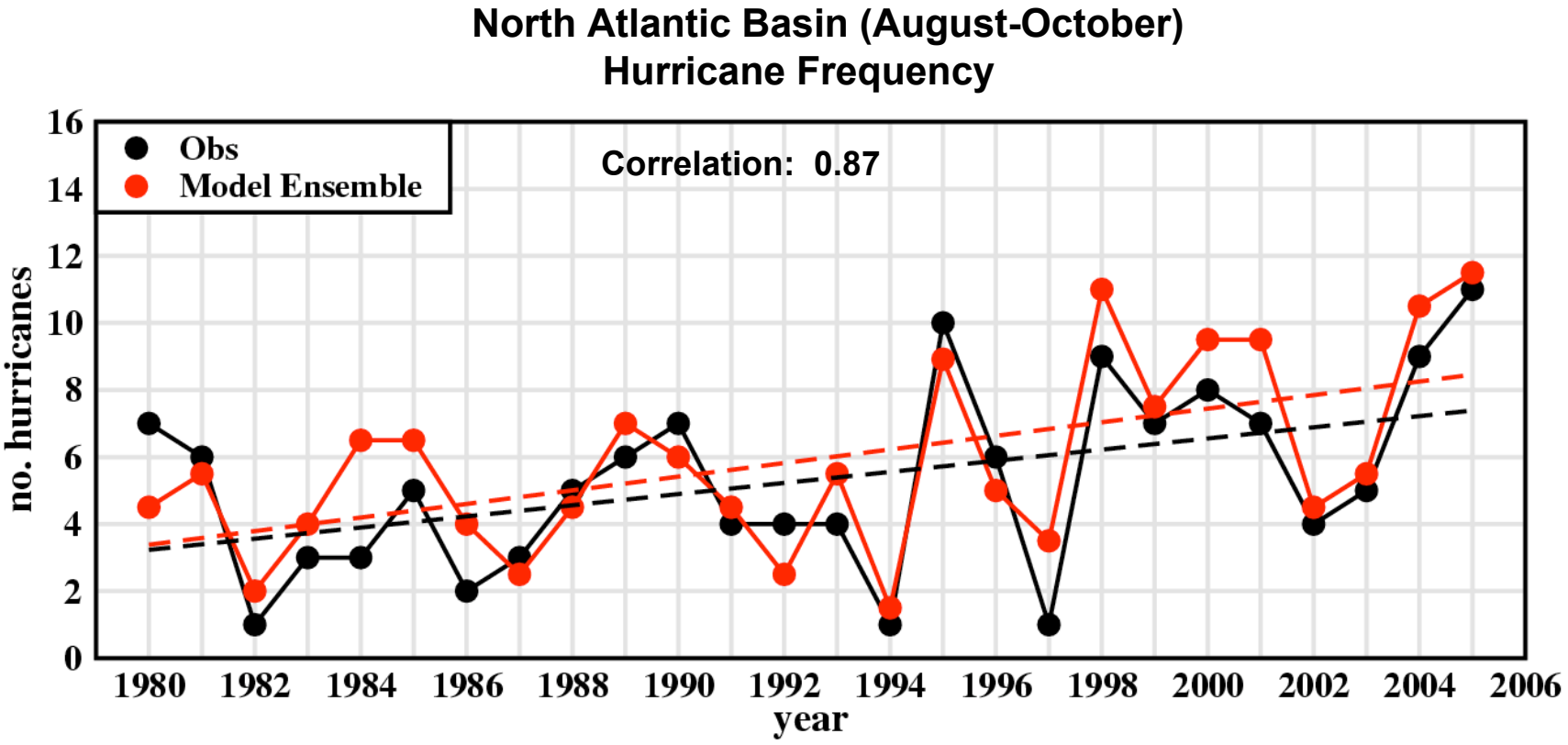
GFDL Zetac Model: A new high-resolution regional model for Atlantic hurricane season simulations…



Knutson et al (2007, BAMS)

- The model runs for entire hurricane seasons.
- The model generates its own sample of hurricanes during each season.
- These experiments push the limits of available computing resources.

The model captures both the increase in hurricane activity since the 1980s and the year-by-year fluctuations….



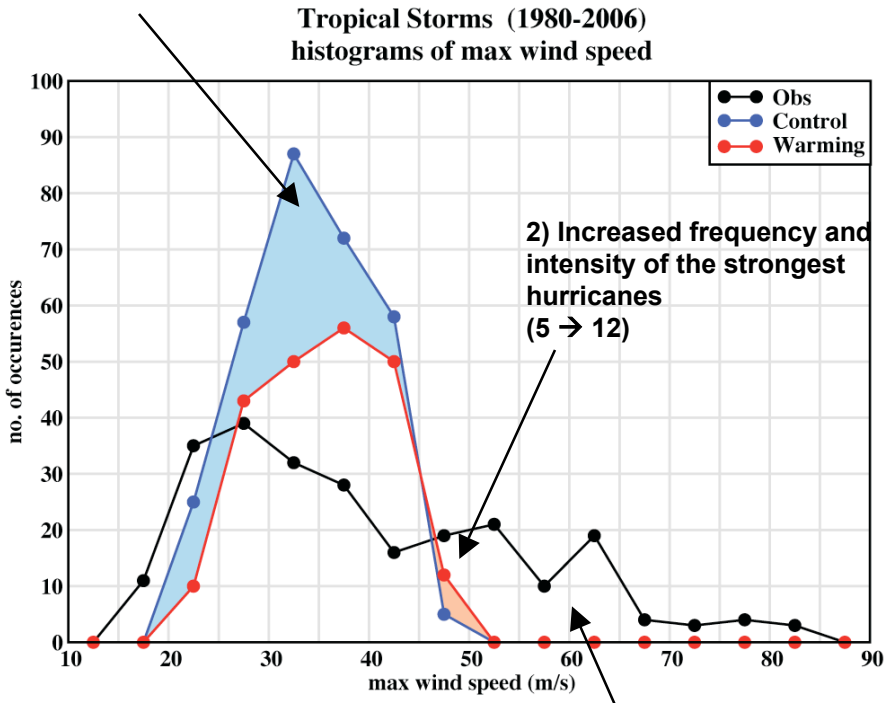
Source: Knutson et al. 2007 (BAMS)

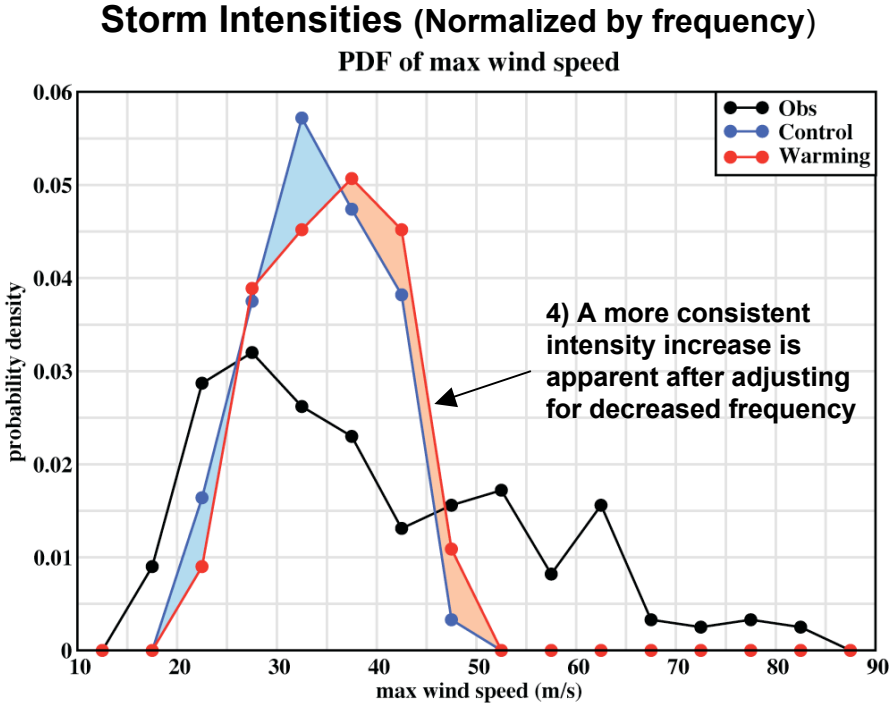
Note: Model uses large-scale interior nudging to NCEP Reanalysis

What is response to 21st Century climate change?

The model provides projections of Atlantic hurricane and tropical storm *frequency* changes for late 21st century, downscaled from a multi-model ensemble climate change (IPCC A1B scenario):

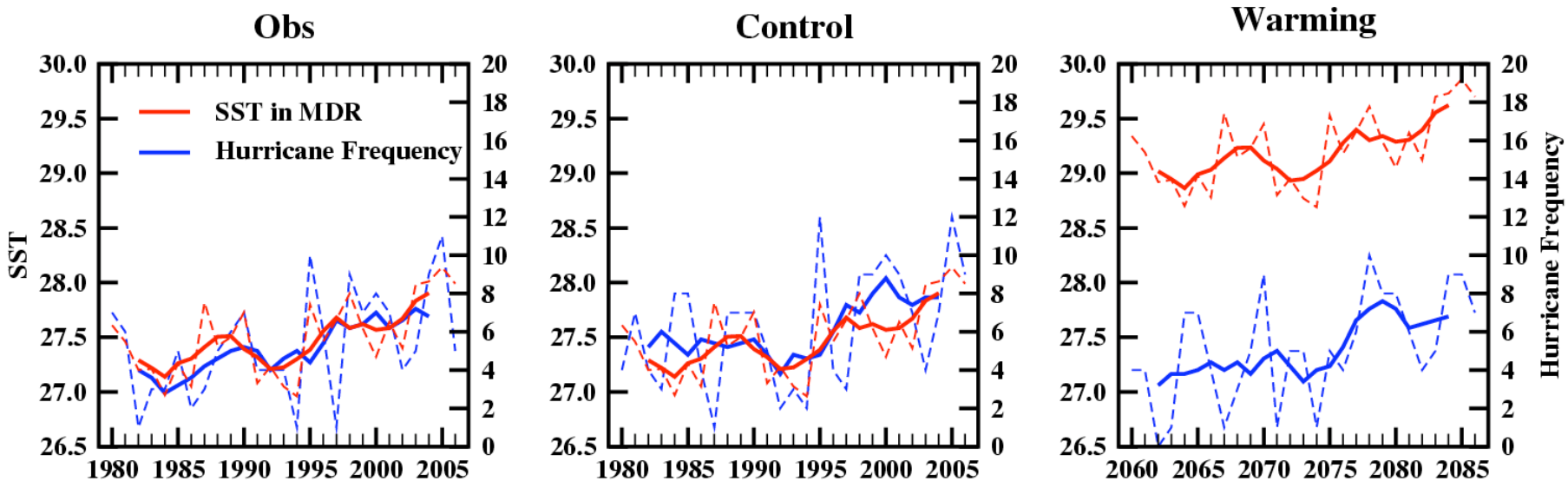
1) Decreased frequency of tropical storms (-27%) and hurricanes (-18%).





Source: Knutson et al., *2008*, Nature Geoscience.

The control model reproduces the observed close relationship between SST and hurricane frequency (1980-2006), but this statistical relationship does not hold for future human-caused warming in the model.



Hurricane frequency actually *decreases* by 18% in the warm climate case… although the model does not simulate hurricanes as intense as observed.

Lesson: Caution using correlations from the present climate to make future climate projections…

Source: Knutson et al., Nature Geoscience (2008).

Dependence on Climate Model: ZETAC model downscaling (Warm minus Control)

Control: 11.1 /yr

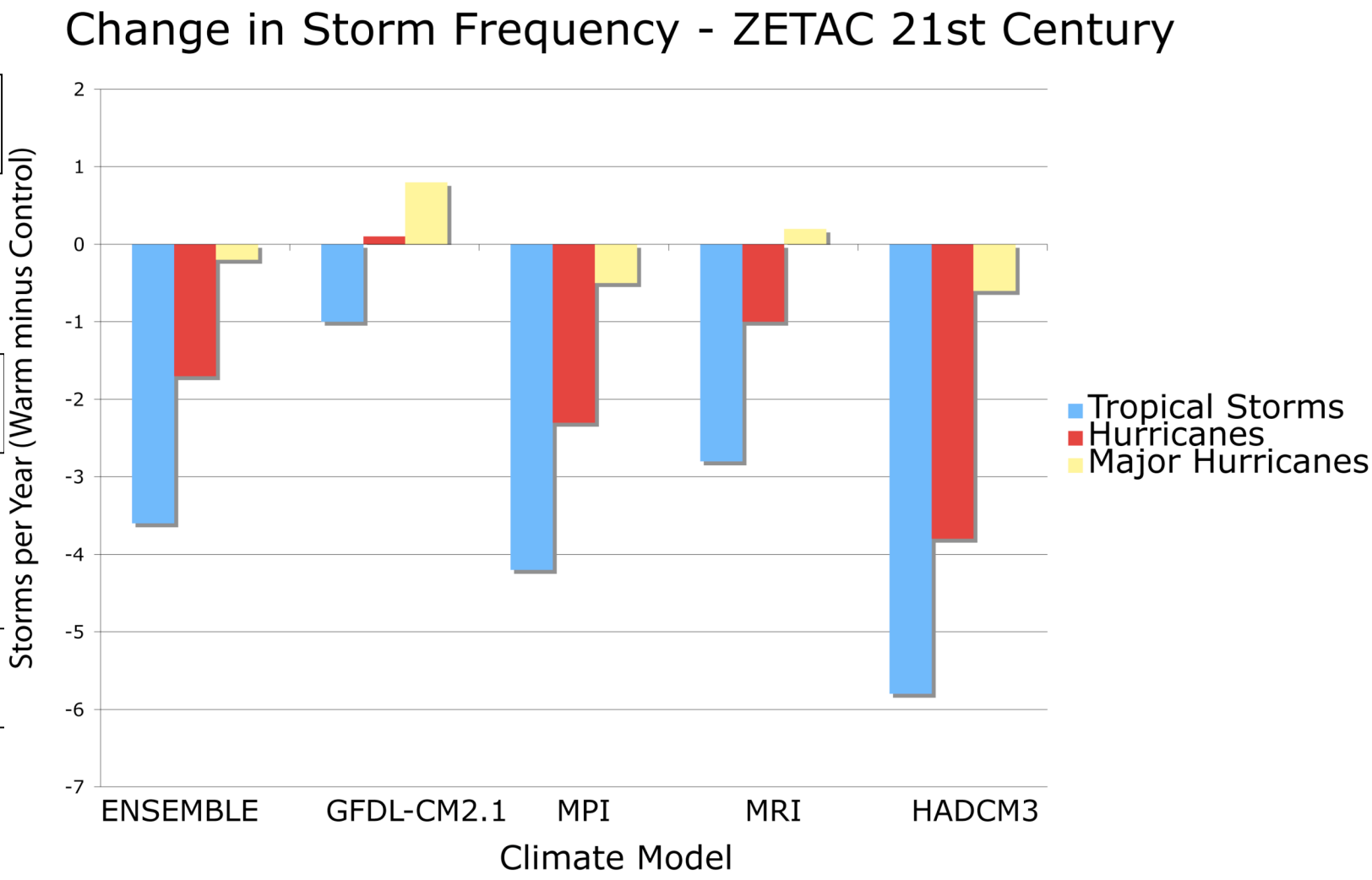
Tropical Storms:
Range: -9% to -52%
Ensemble: -20%

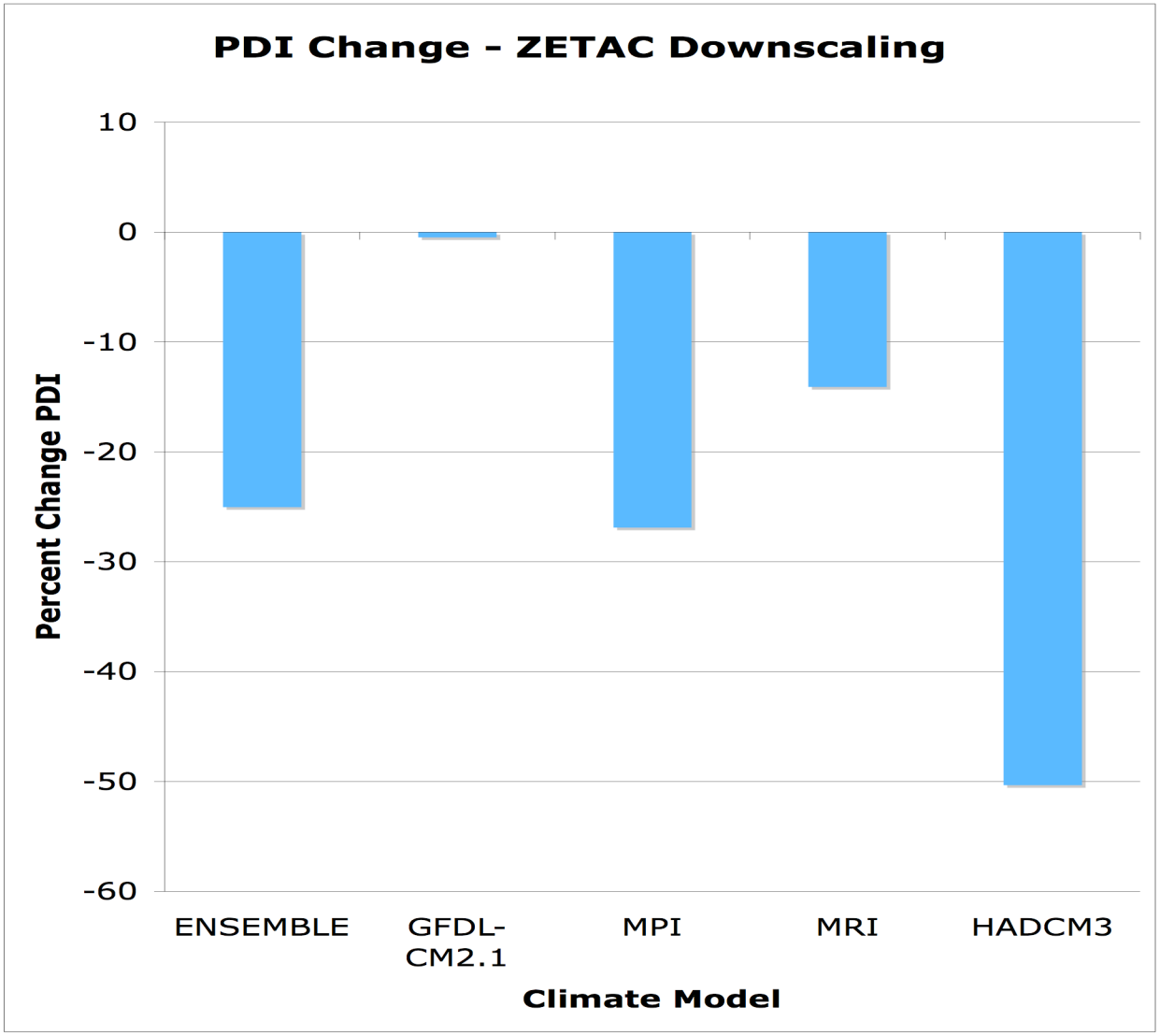
Control: 6.5 /yr

Hurricanes:
Range: +2% to -58%
Ensemble: -26%

Control:1.4 /yr

Major Hurricanes:
Range: +57% to -43%
Ensemble: -14%





Power Dissipation (PDI) decreases as the reduced storm frequency dominates over increase in strength of strongest storms.

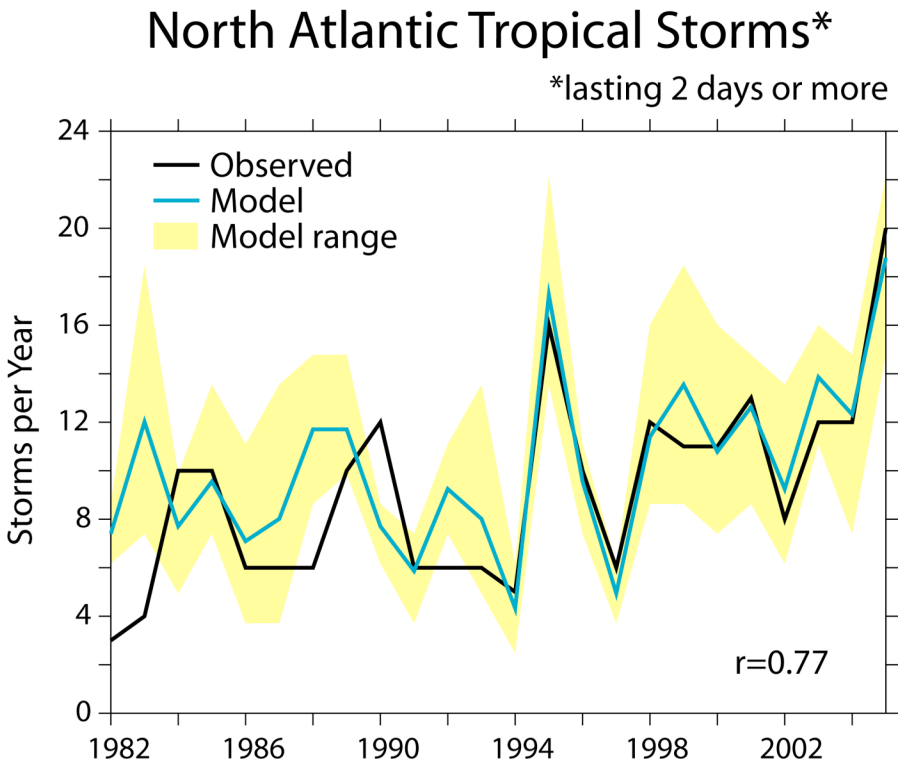
High-resolution models

- Regional 18-km model (Knutson et al 2007, 2008):
  - Explore sensitivity of storm frequency
- Global 100-km model:
  - Explore sensitivity to idealized forcing
- GFDL Hurricane forecast model:
  - Refined study of intensity response

GFDL C-X HiRAM GCMs

Family of global atmospheric models designed for better-representing tropical cyclone frequency. **C90 - 1°,** C180=1/2°, C360=1/4°, C720=1/8°

Ref. Ming Zhao, S-J Lin and Isaac Held.



Explore C90 Model

Adapted from AM2 with:

- Deep convection scheme adapted from Bretherton, McCaa and Grenier (MWR, 2004)
- Cubed sphere dynamical core
- Changes to parameterizations of cloud microphysics
- C90 Atm. resolution of 1°x1°

Unpublished: do not quote or cite

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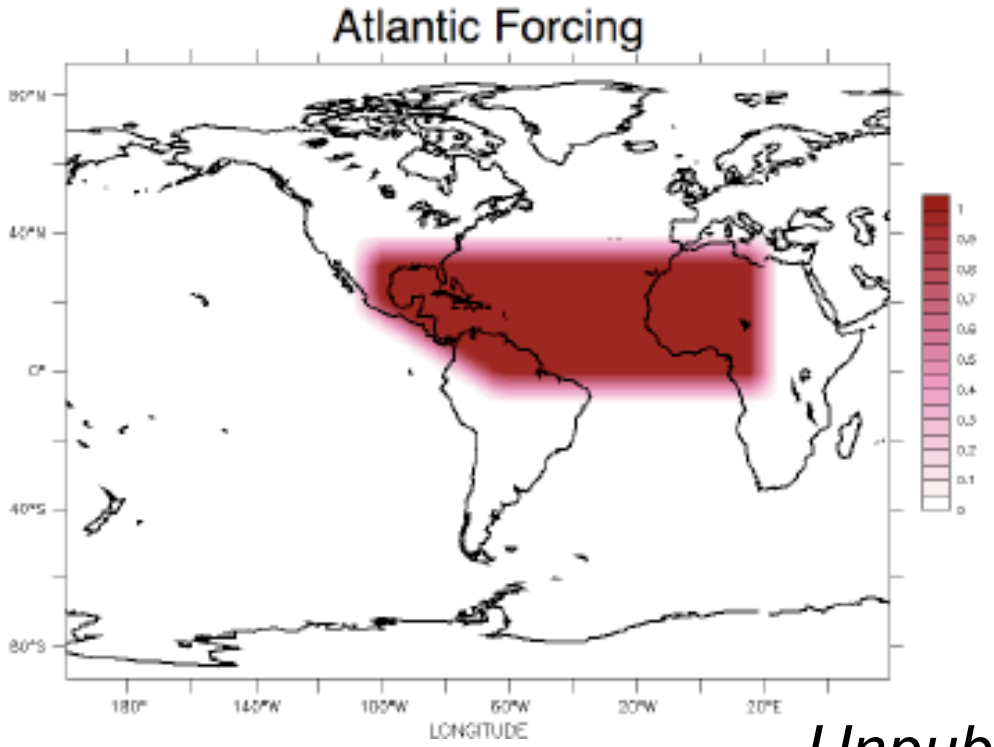
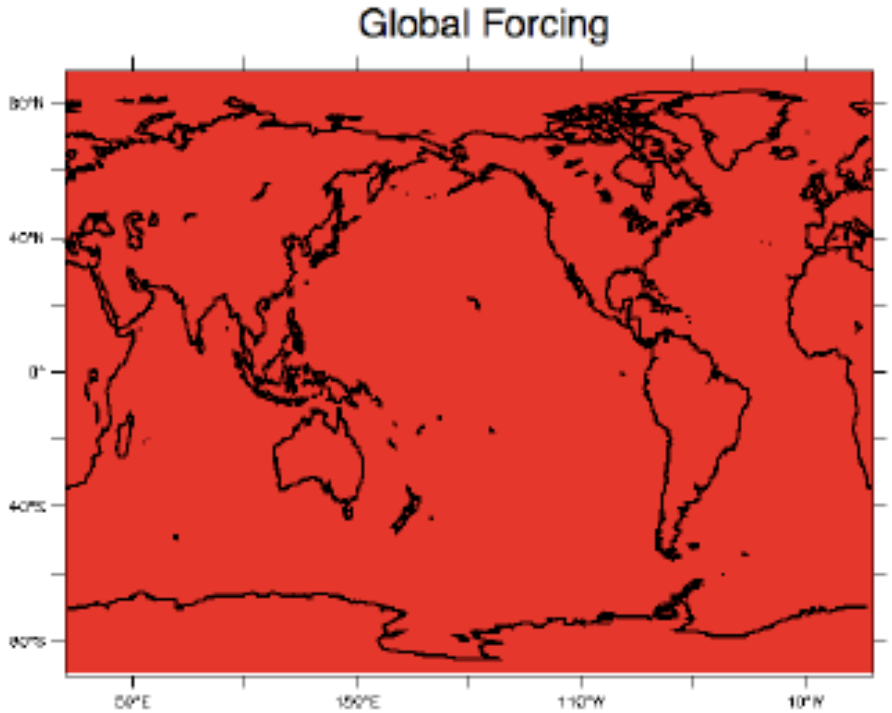
Idealized Forcing Experiments

If local SST the dominant control, as opposed to relative SST:

- Similar Atlantic Response to Atlantic and Uniform F'cing
- Little Pacific Response to Atlantic compared to Uniform





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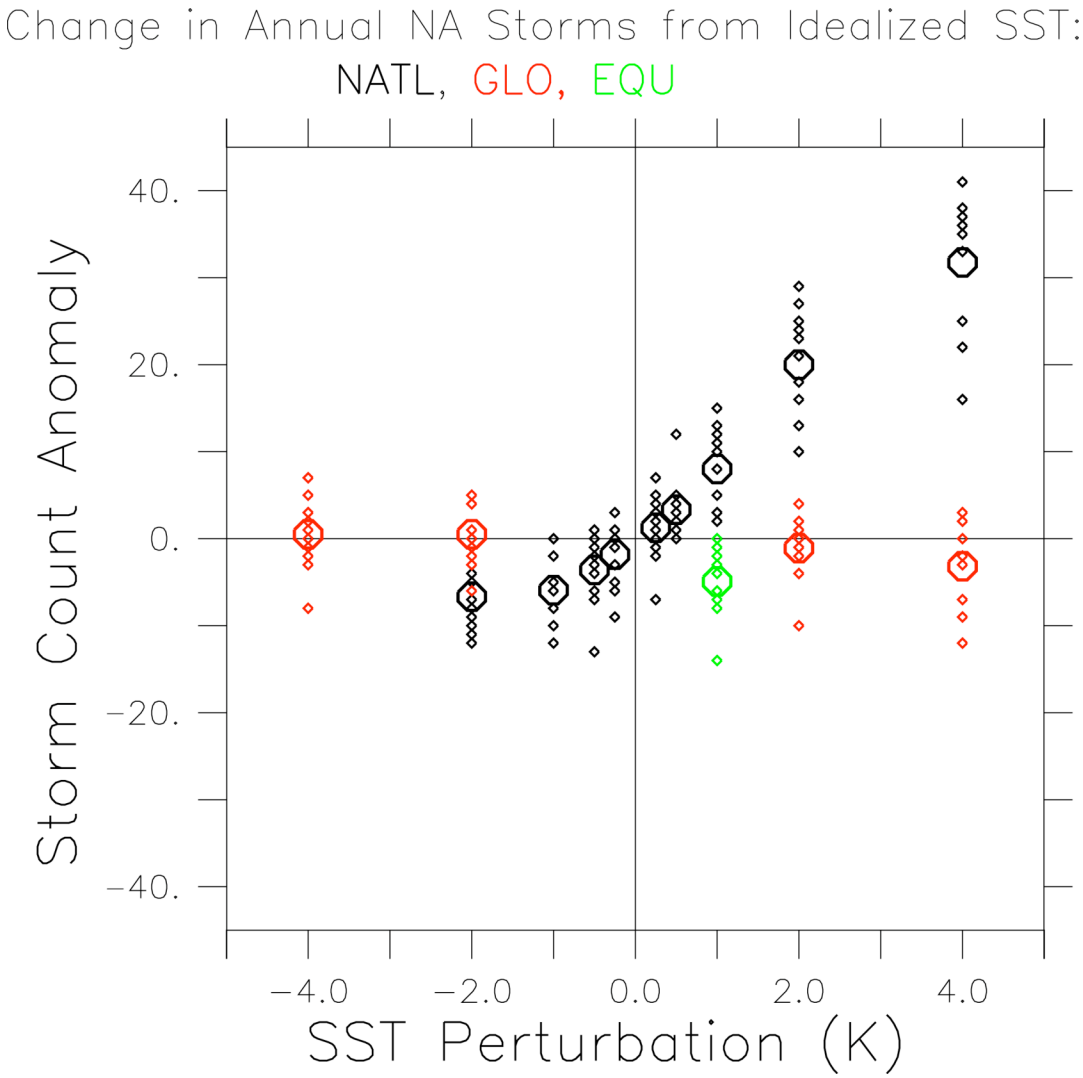
Response in North Atlantic



Atlantic Forcing

Uniform Forcing

Near-equatorial Forcing

Similar TS frequency response to:
0.25° local warming
4° global cooling

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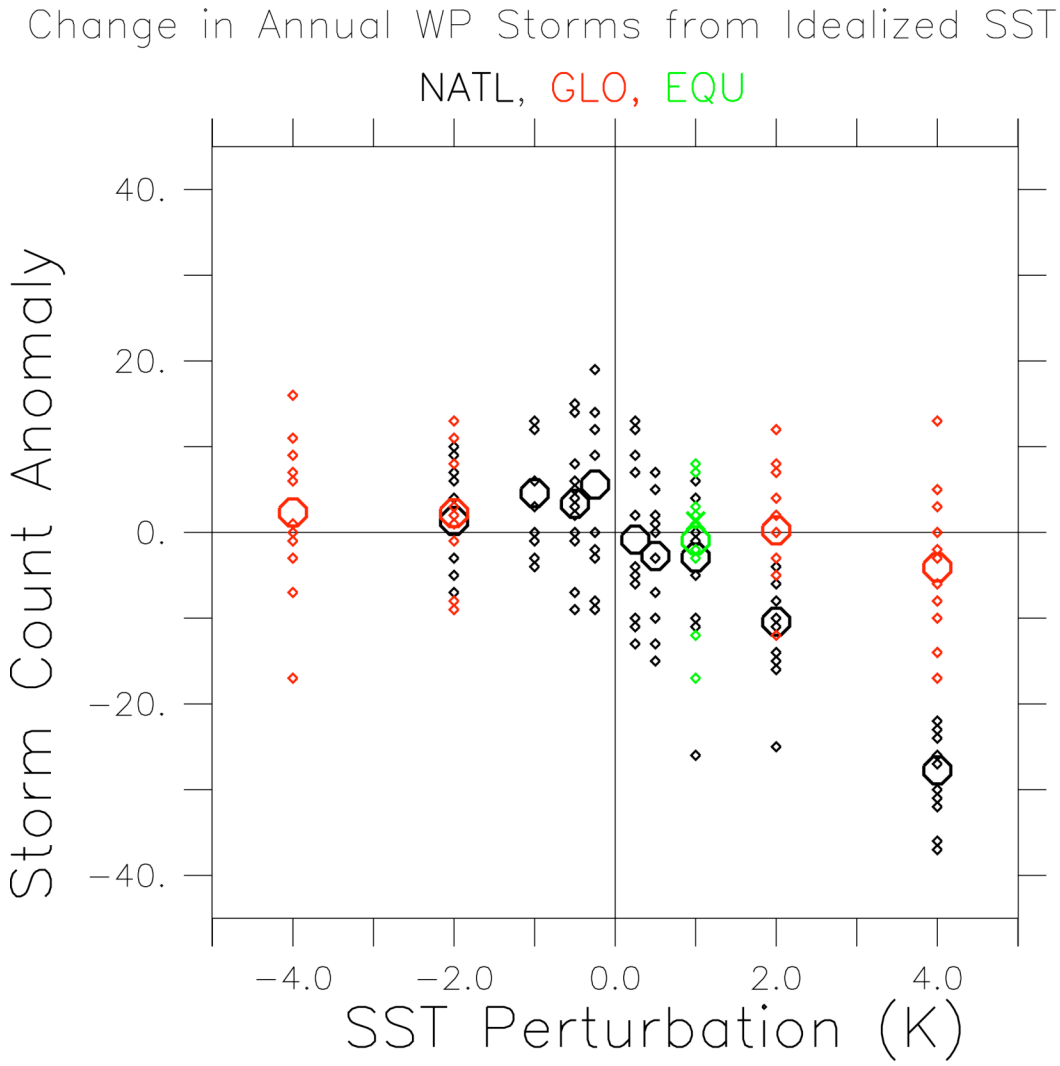
Response in Northwest Pacific



Atlantic Forcing

Uniform Forcing

Near-equatorial Forcing

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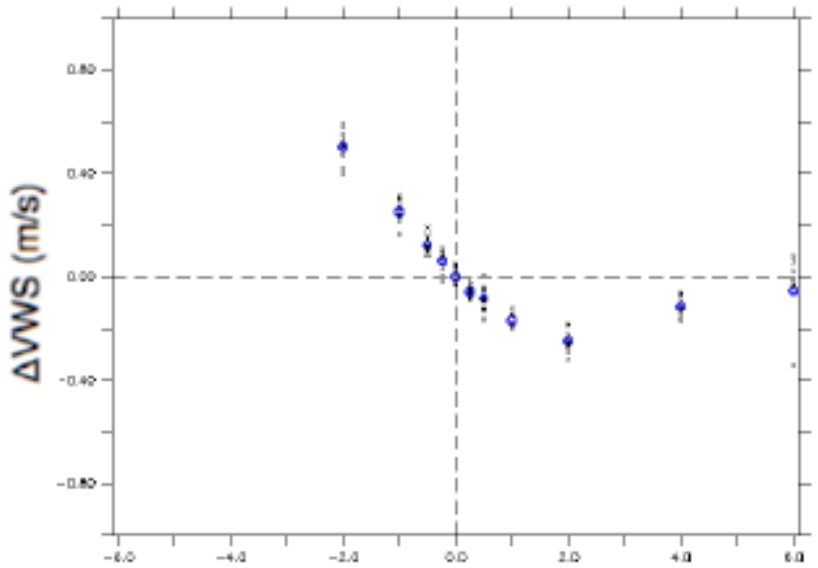
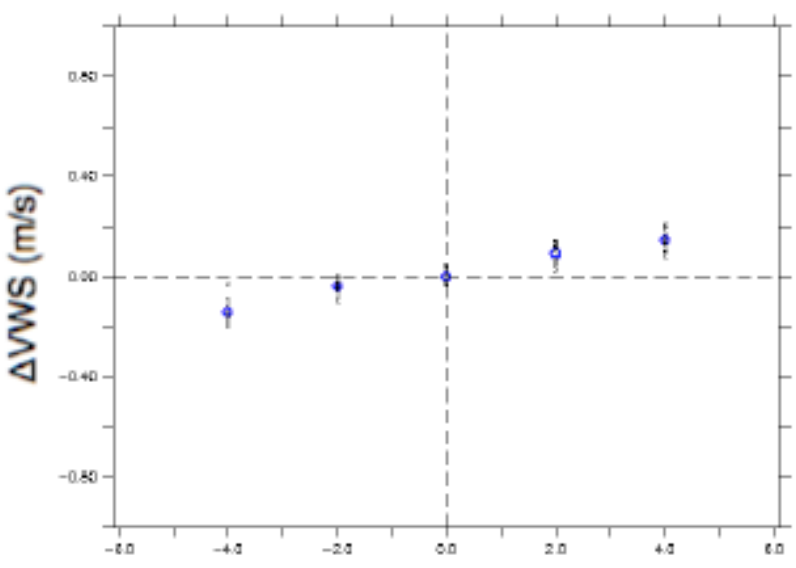
Atlantic Vertical Wind Shear Changes

Atlantic SST Forcing



Global SST Forcing



Localized warming in Atlantic decreases wind shear:
"storm friendly"

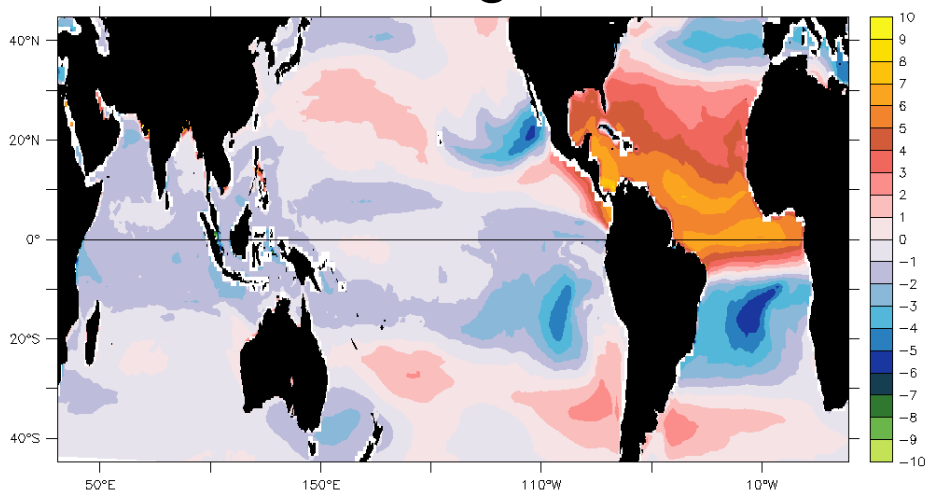
Uniform warming increases wind shear:
"storm hostile"

Gabriel Vecchi, NOAA/GFDL, Princeton, NJ

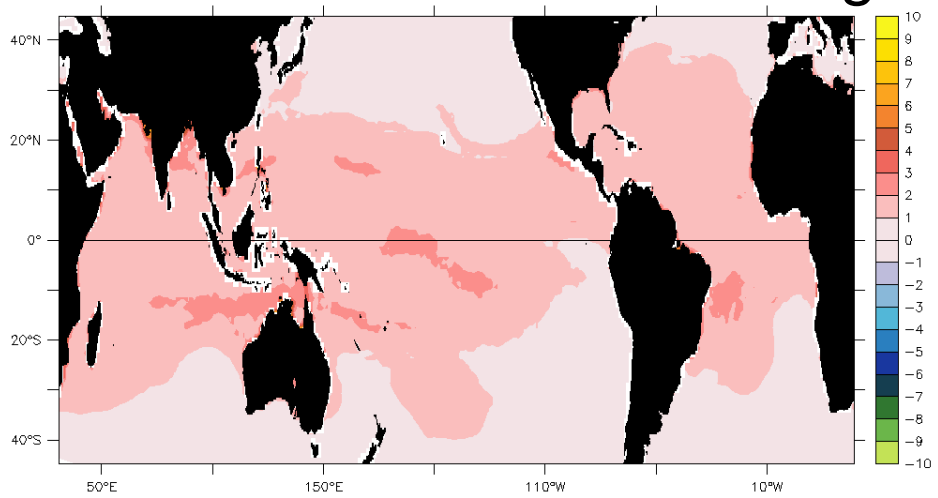
Potential Intensity Change

m/s per degree warming

Atlantic forcing



Uniform forcing



- In C90 HiRAM:
  - Localized SST forcing has large local impact on PI.
    - Remote decreases - consistent with Vecchi and Soden (2007, Nature)
  - Uniform SST forcing has smaller impact on PI.
- Change in PI does not explain change in Atlantic frequency.

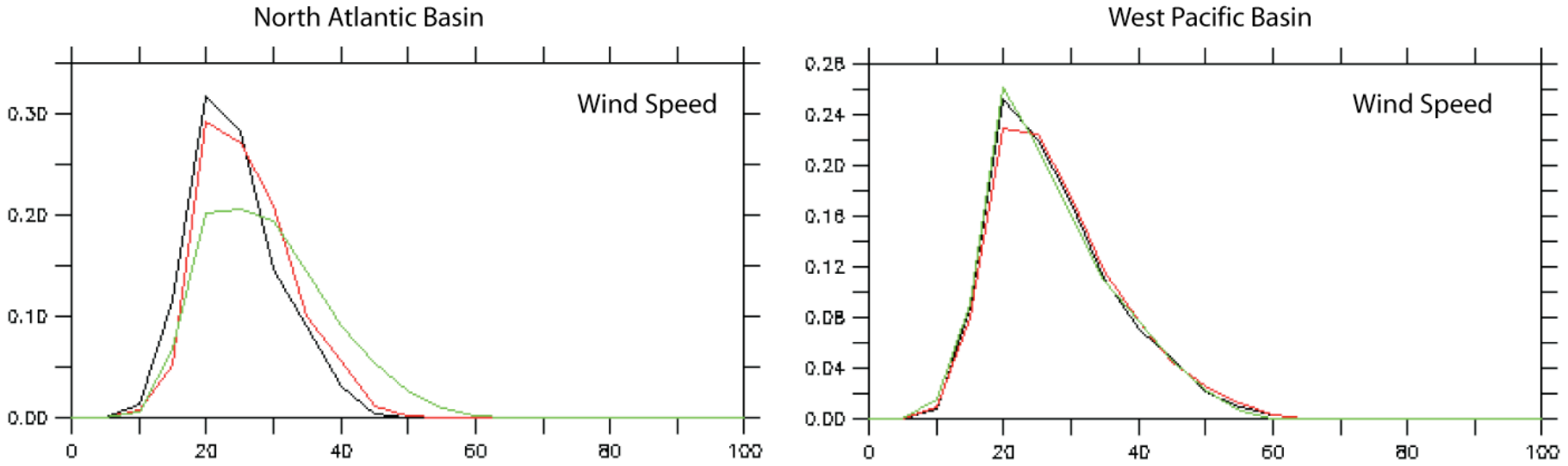
Unpublished: do not quote or cite

Impact on Intensity*

*Modest C90 model resolution limits confidence in intensity results

PDFs of Intensity (based on all 6-hour periods) for C90L32 Control (HADISST) and 2K Idealized Perturbation Runs (12-years, 1980-1991)

CONTROL **GLOBAL+2K** **NATL+2K**



Uniform warming: modest increase in intensity.

Localized Atlantic warming:

large intensification in Atlantic

modest weakening in Pacific

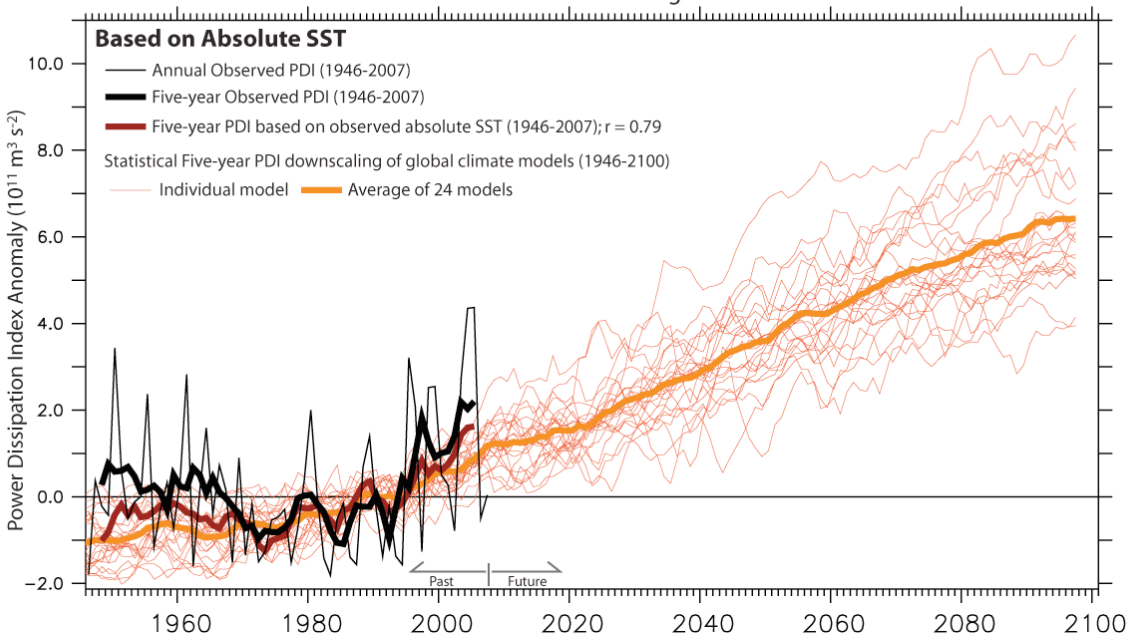
Unpublished: do not quote or cite

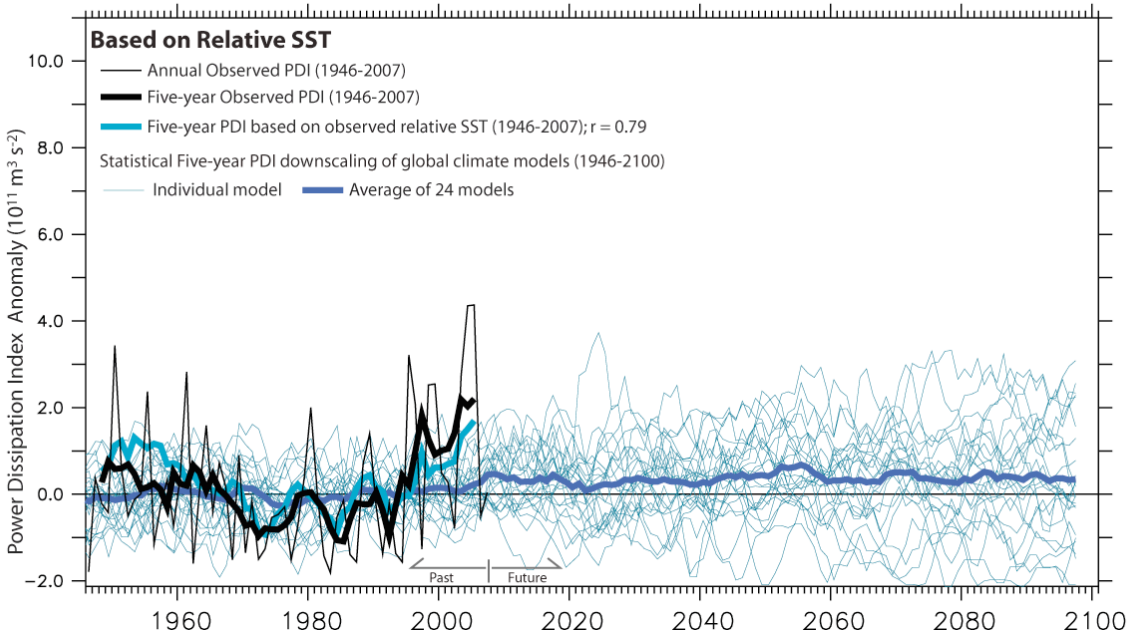
Gabriel Vecchi, NOAA/GFDL, Princeton, NJ

Summary

Atlantic Tropical Cyclone Power Dissipation Index Anomalies: Observed and Based on Sea Surface Temperature

Anomalies relative to 1981-2000 average: 2.13×10^{11} $m^3 s^{-2}$





Observed Activity

Absolute SST

Model Abs. SST

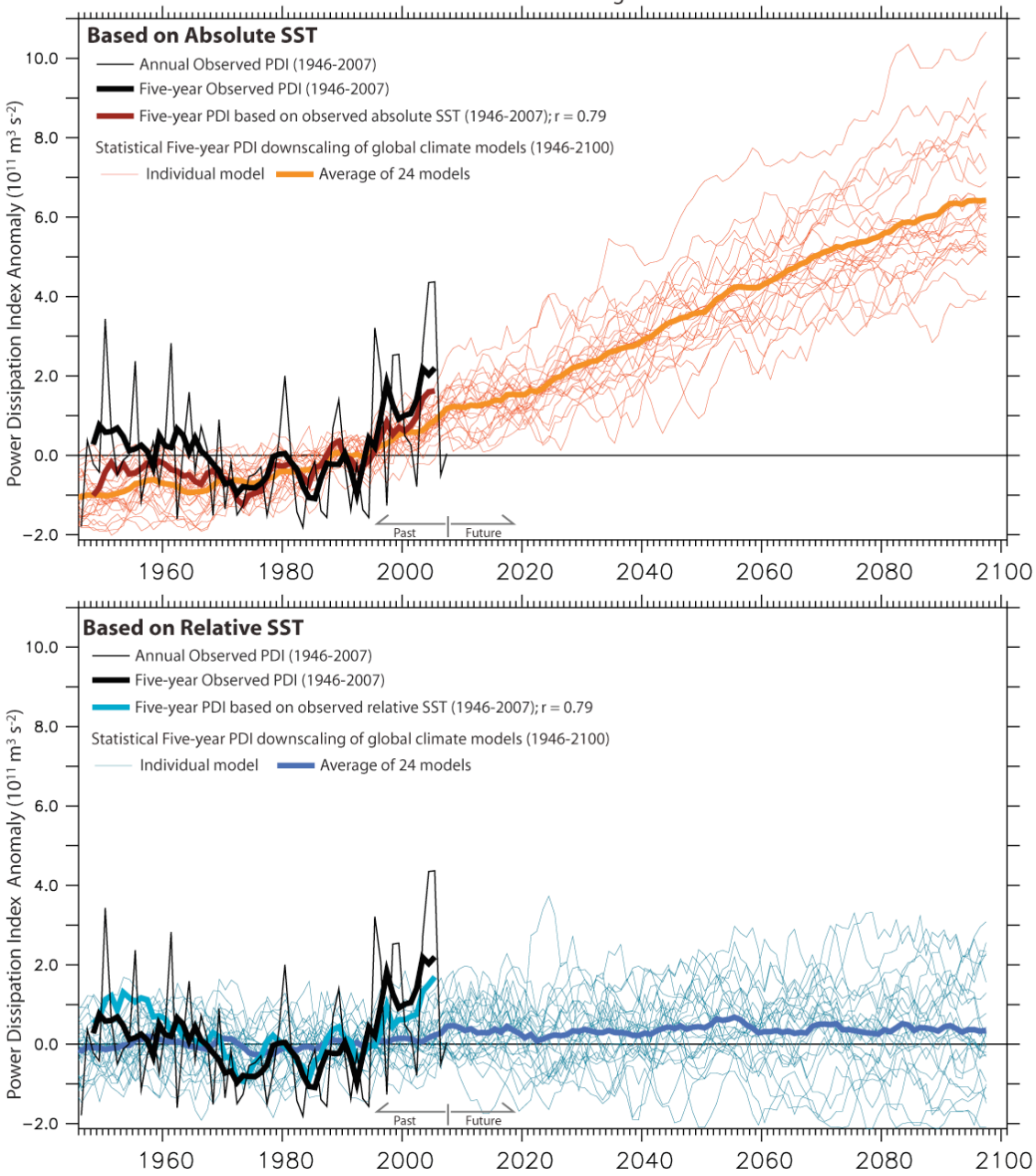
Relative SST

Model Rel. SST

Vecchi, Swanson and Soden (2008, *Science*)

Atlantic Tropical Cyclone Power Dissipation Index Anomalies: Observed and Based on Sea Surface Temperature

Anomalies relative to 1981-2000 average: 2.13×10^{11} $m^3 s^{-2}$



Observed Activity

Absolute SST

Model Abs. SST

Idealized C90 exps. **inconsistent** with absolute SST control.

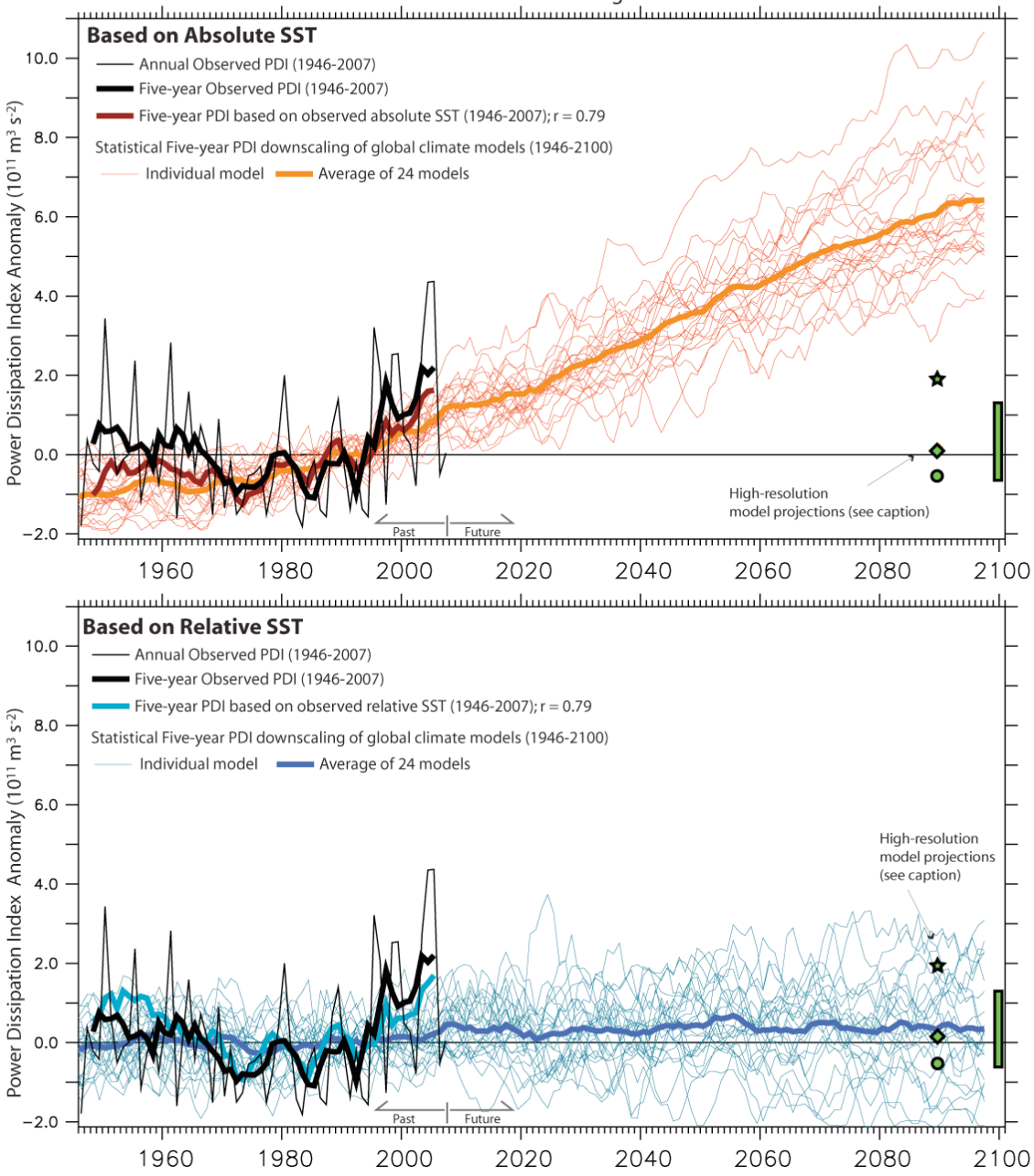
Relative SST

Model Rel. SST

Vecchi, Swanson and Soden (2008, *Science*)

Atlantic Tropical Cyclone Power Dissipation Index Anomalies: Observed and Based on Sea Surface Temperature

Anomalies relative to 1981-2000 average: 2.13×10^{11} $m^3 s^{-2}$



Observed Activity

Absolute SST

Model Abs. SST

High-resolution model activity change

Emanuel et al (08),Knutson et al (08)
Oouchi et al (06),Bengtsson et al (07)

Relative SST

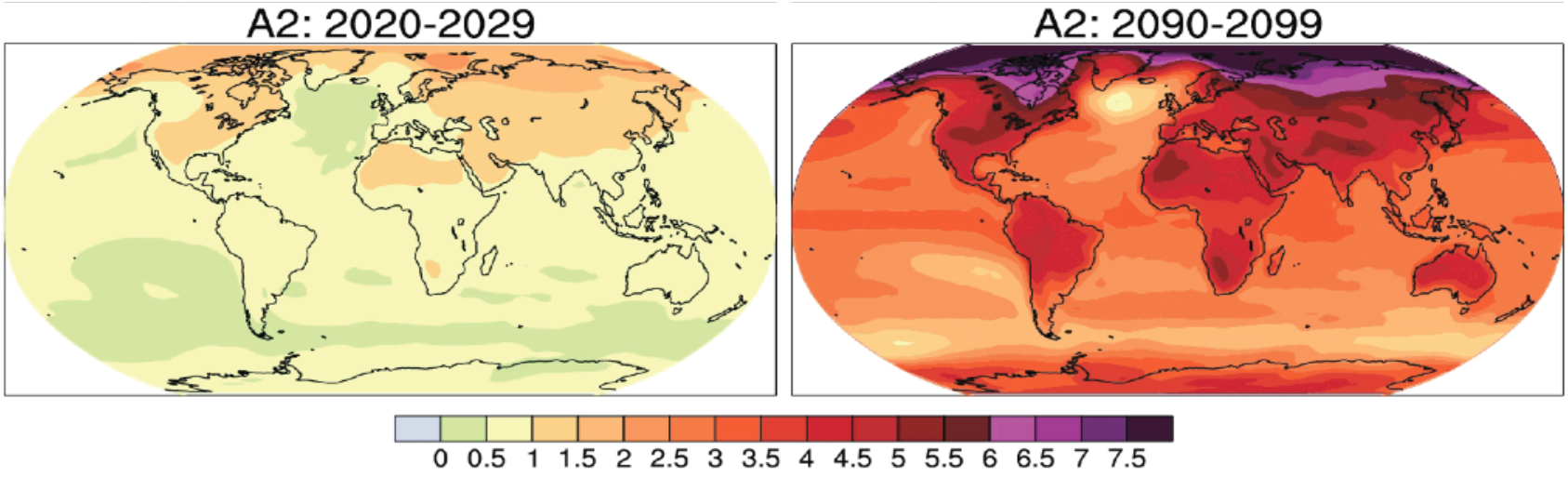
Model Rel. SST

Vecchi, Swanson and Soden (2008, *Science*)

Gabriel Vecchi, NOAA/GFDL, Princeton, NJ

Projections of Future Changes in Climate

Projected warming in 21st century expected to be greatest over land and at most high northern latitudes and least over the Southern Ocean and parts of the North Atlantic Ocean…



Source: IPCC 4th Assessment Report. Used with permission.

Summary

- Since 1980s: unambiguous Atlantic activity increase. Since late-19th Century, results are mixed.
  - Efforts ongoing to improve historical database.
  - Human-forcing or natural variations?
    It's not an "either…or" question.
- Does absolute or relative SST control basin-wide cyclone activity:
  - Observations consistent with either.
  - Current theory and models suggest relative SST control.
  - Need to focus on patterns on SST change:
    - What controls patterns of SST change? How confident are we on future SST patterns? How do we gain confidence?
- 21st Century climate model projections:
  - Response of intensity and frequency not same
    - stronger but fewer?
  - Details in large-scale conditions impact response.
- Need to continue investing in: observations, computer power, "brainpower".