Attribution, Prediction and Projection of Hurricane Activity Changes

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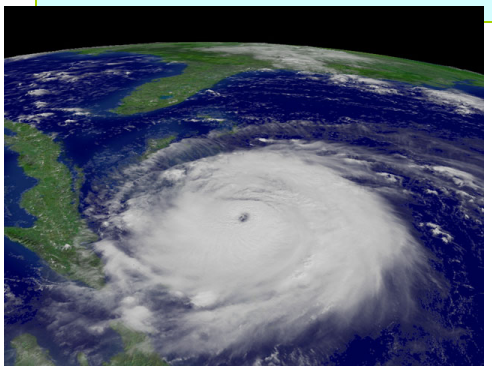
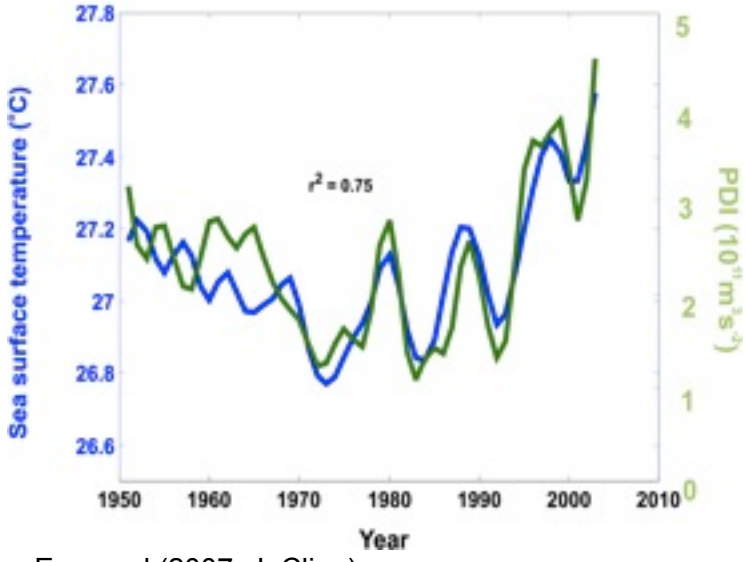
1-GFDL; 2-Princeton/AOS; 3-U. Miami; 4-U. Wisc.-Milw.; 5-Princeton U.; 6 - Old Dominion U.

- How has hurricane activity changed?
- What has driven changes in hurricane activity?
- Tools to predict/project and understand hurricane activity changes

North Atlantic tropical cyclones



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



Emanuel (2007, J. Clim.)

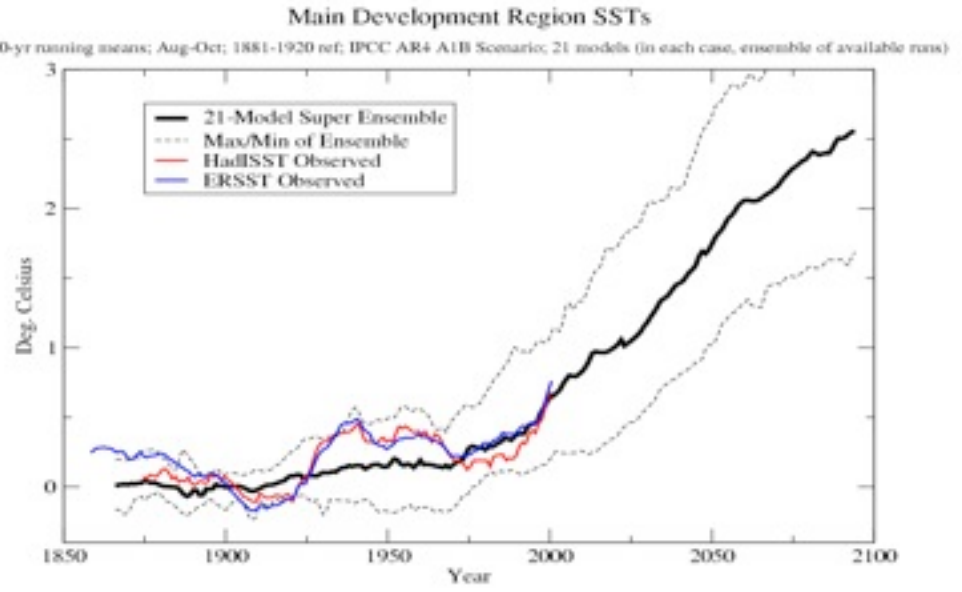
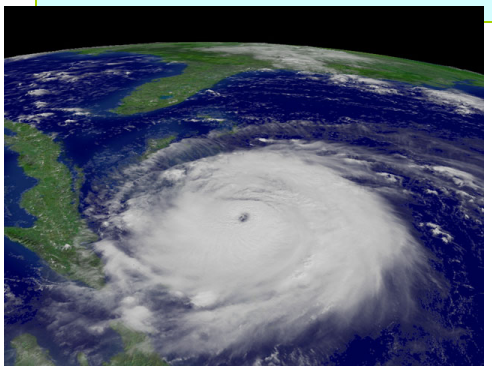


Figure: Tom Knutson

North Atlantic tropical cyclones



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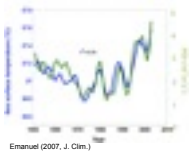

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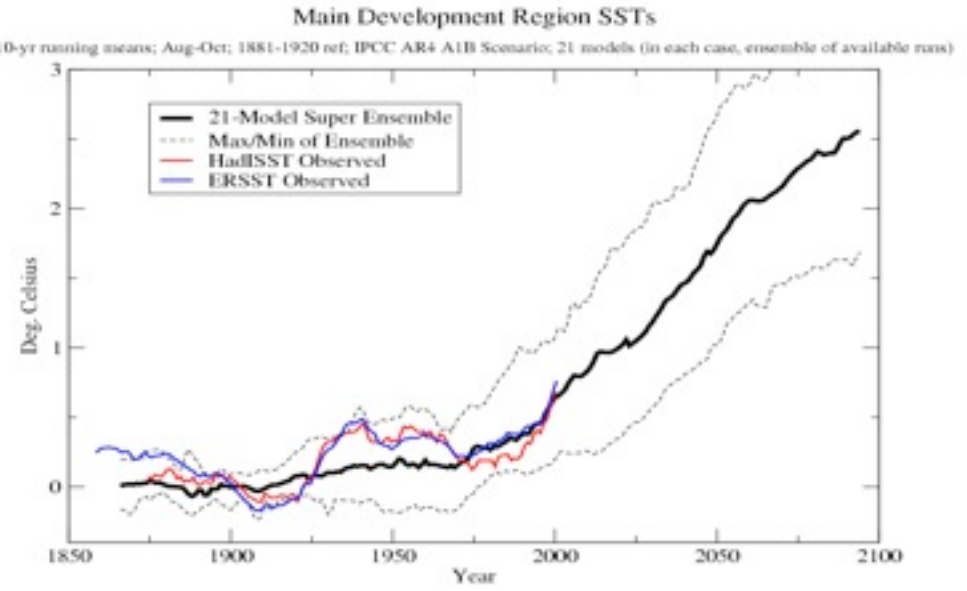
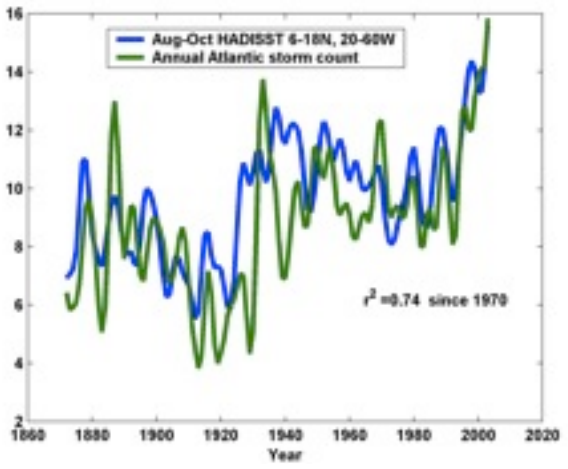
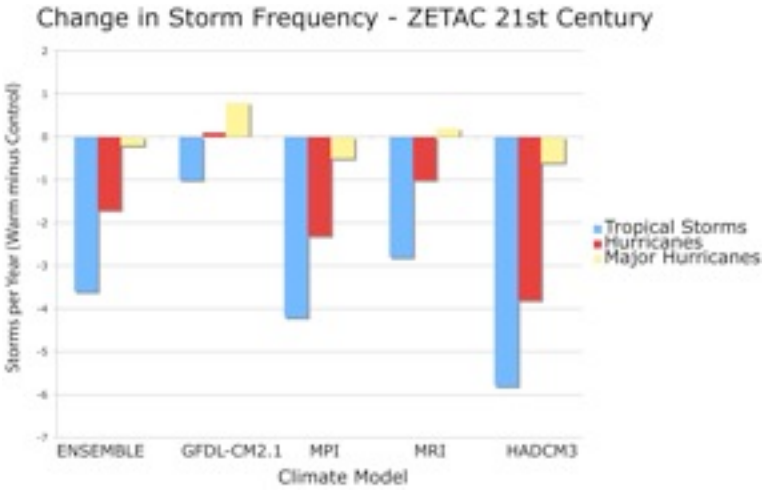


Figure: Tom Knutson

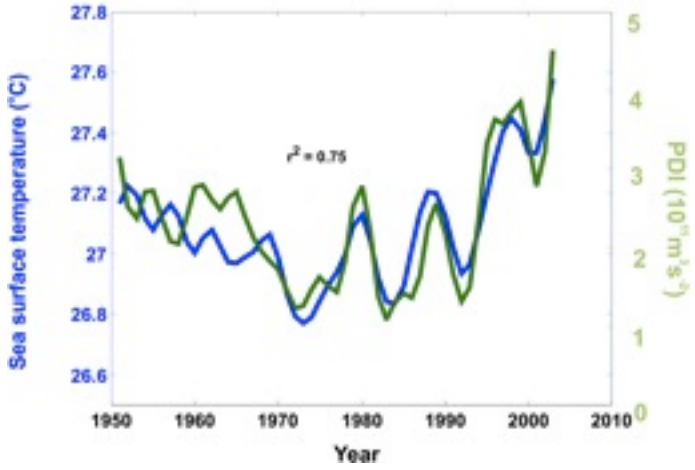
Is the historical Atlantic TS record consistent with dynamical model projections of a weak (and possibly negative) sensitivity to warming?



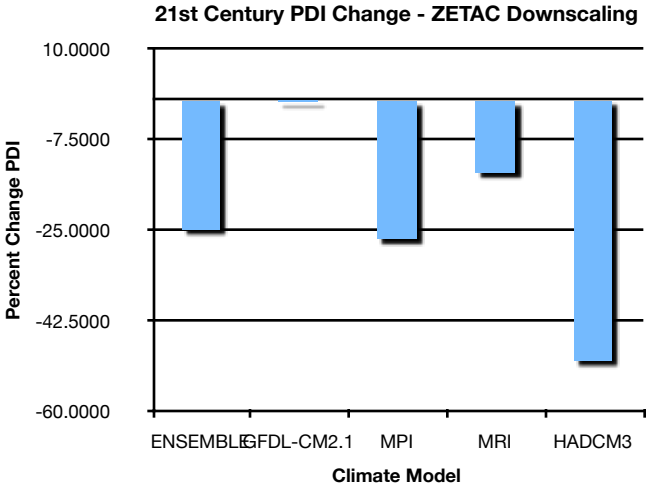
Source: Emanuel (2006); Mann and Emanuel (2006) EOS. See also Holland and Webster (2007) Phil. Trans. R. Soc. A



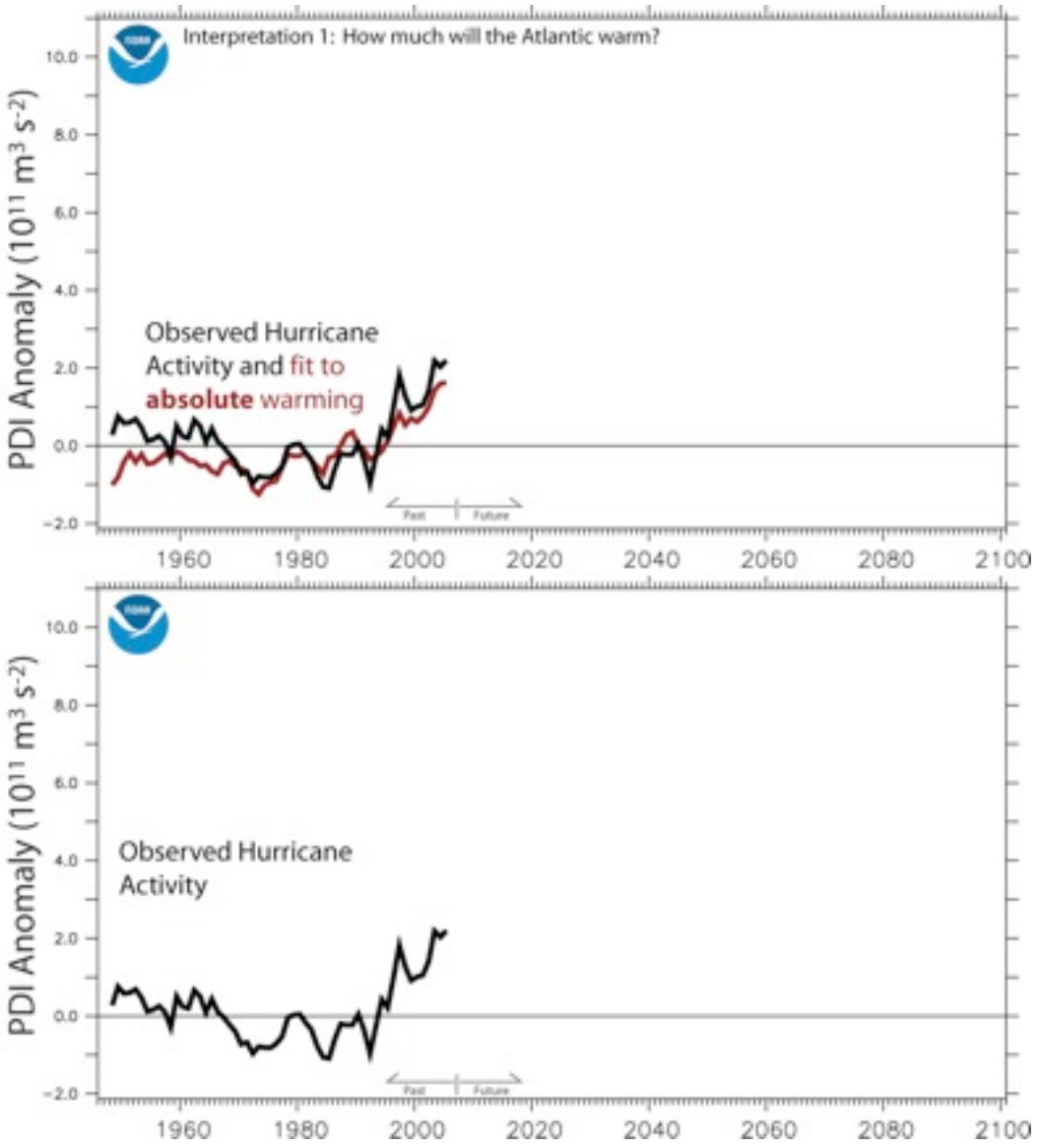
Source: Knutson et al (2008, Nature Geosci.) Knutson et al (2010, in prep.)



Emanuel (2007, J. Clim.)



One Temperature Predictor of Atlantic Hurricane Activity

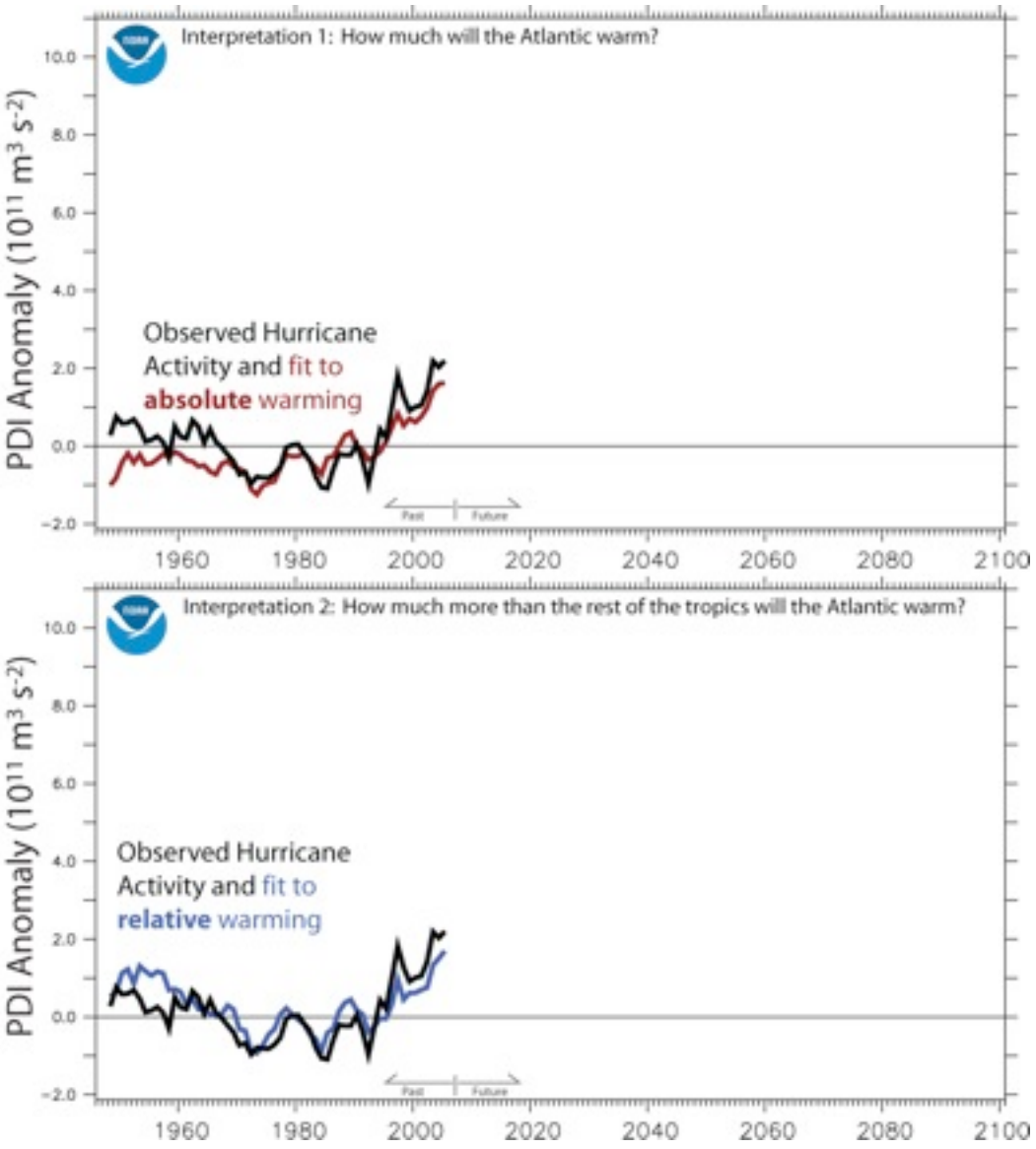


Observed Activity

Absolute Atlantic Temperature

Vecchi, Swanson and Soden (2008, Science)

Two Temperature Predictors of Atlantic Hurricane Activity



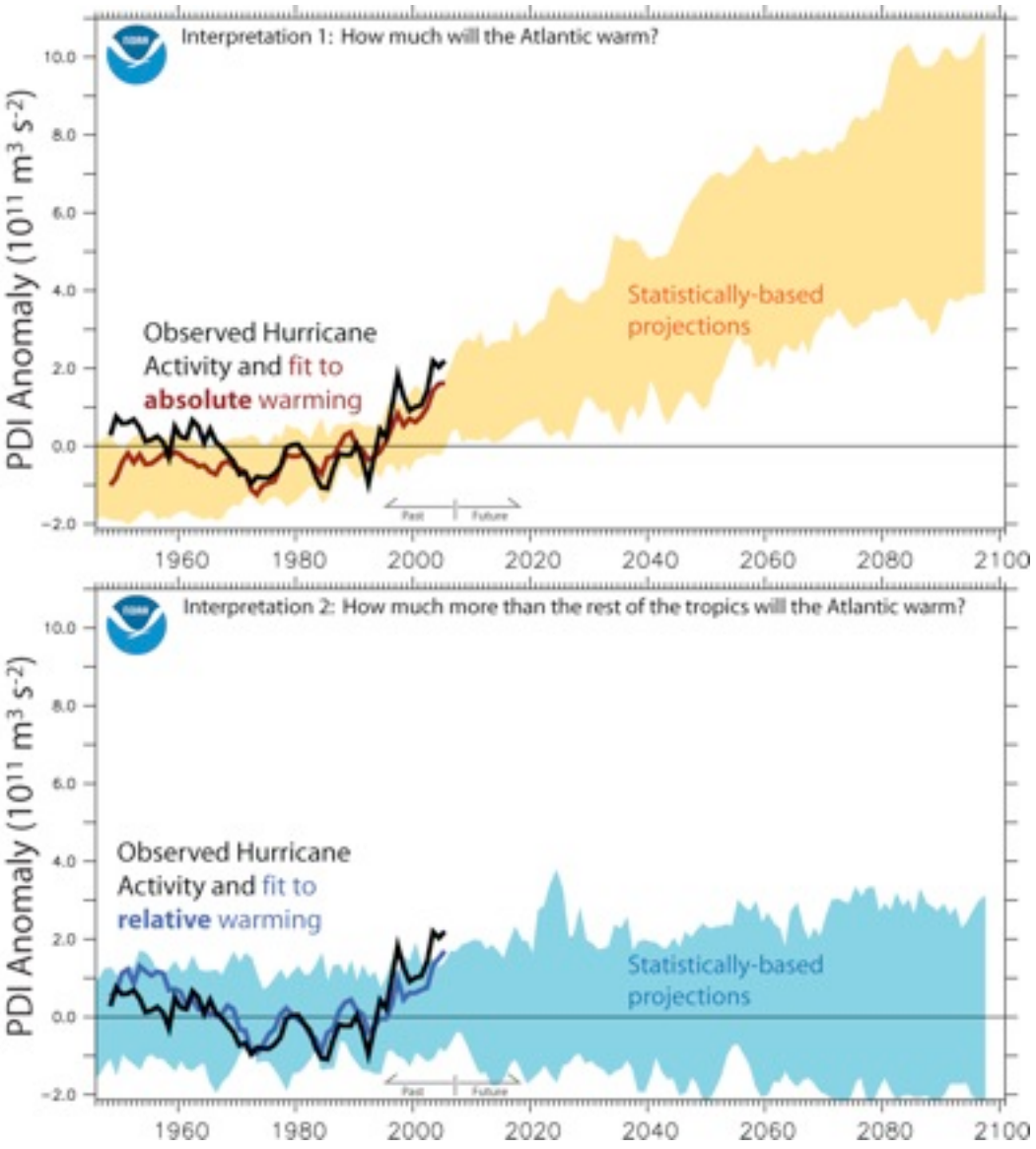
Observed Activity
Absolute Atlantic Temperature

Observed Activity
Relative Atlantic Temperature

Vecchi, Swanson and Soden (2008, Science)

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)

Outline

- Tools:
  - Global climate models (with aside into lapse-rates)
  - High-resolution dynamical models
  - Observational records
  - Statistical models

- Attribution of recent increase in Atlantic activity
- Predictions of seasonal activity
- Century-scale projections

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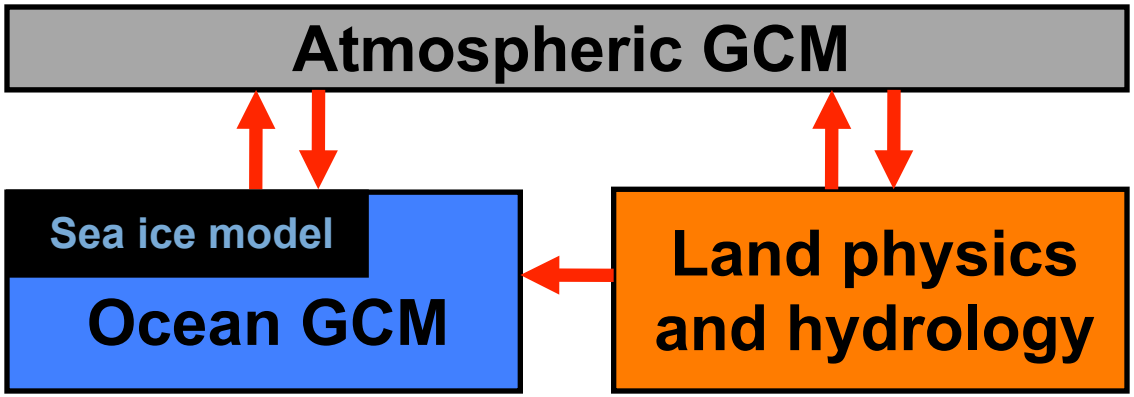
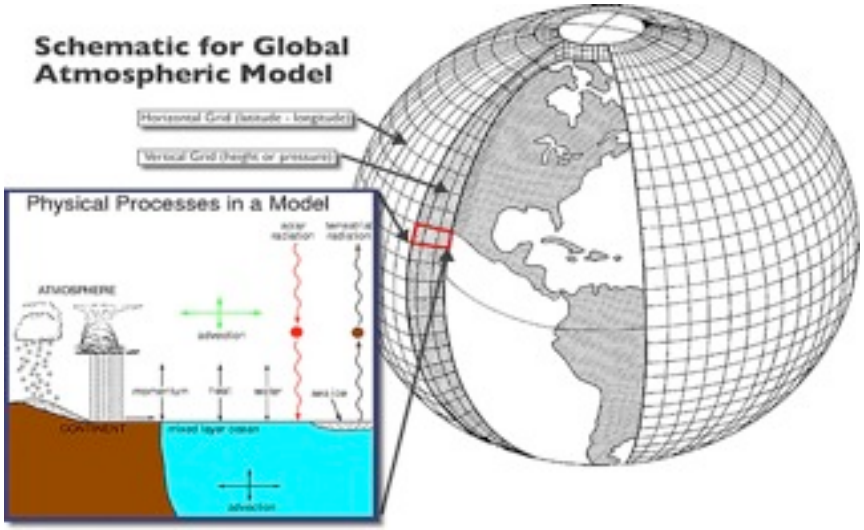
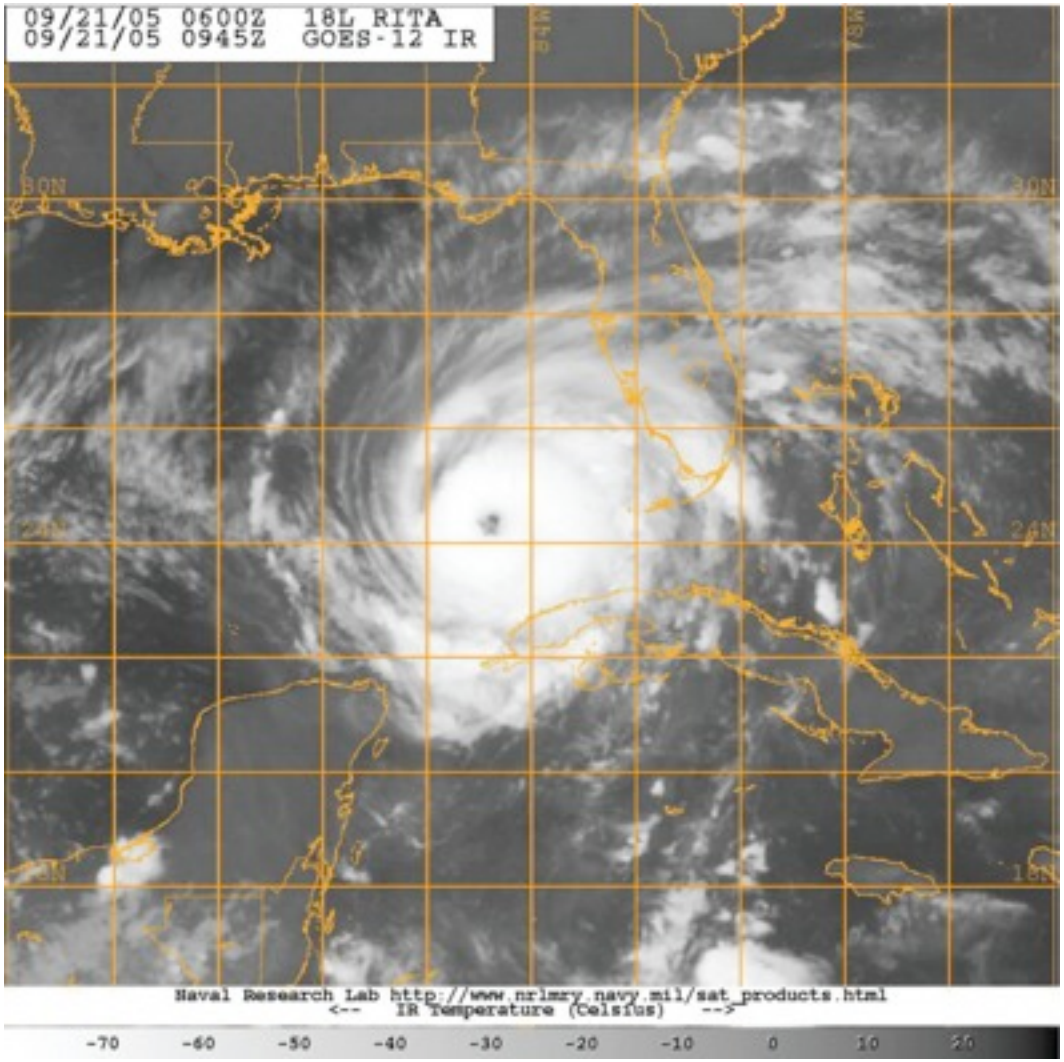


Can global climate models give guidance about changes in Atlantic storm activity?



Not directly: Current computing power limits ability of global climate models to represent hurricanes...

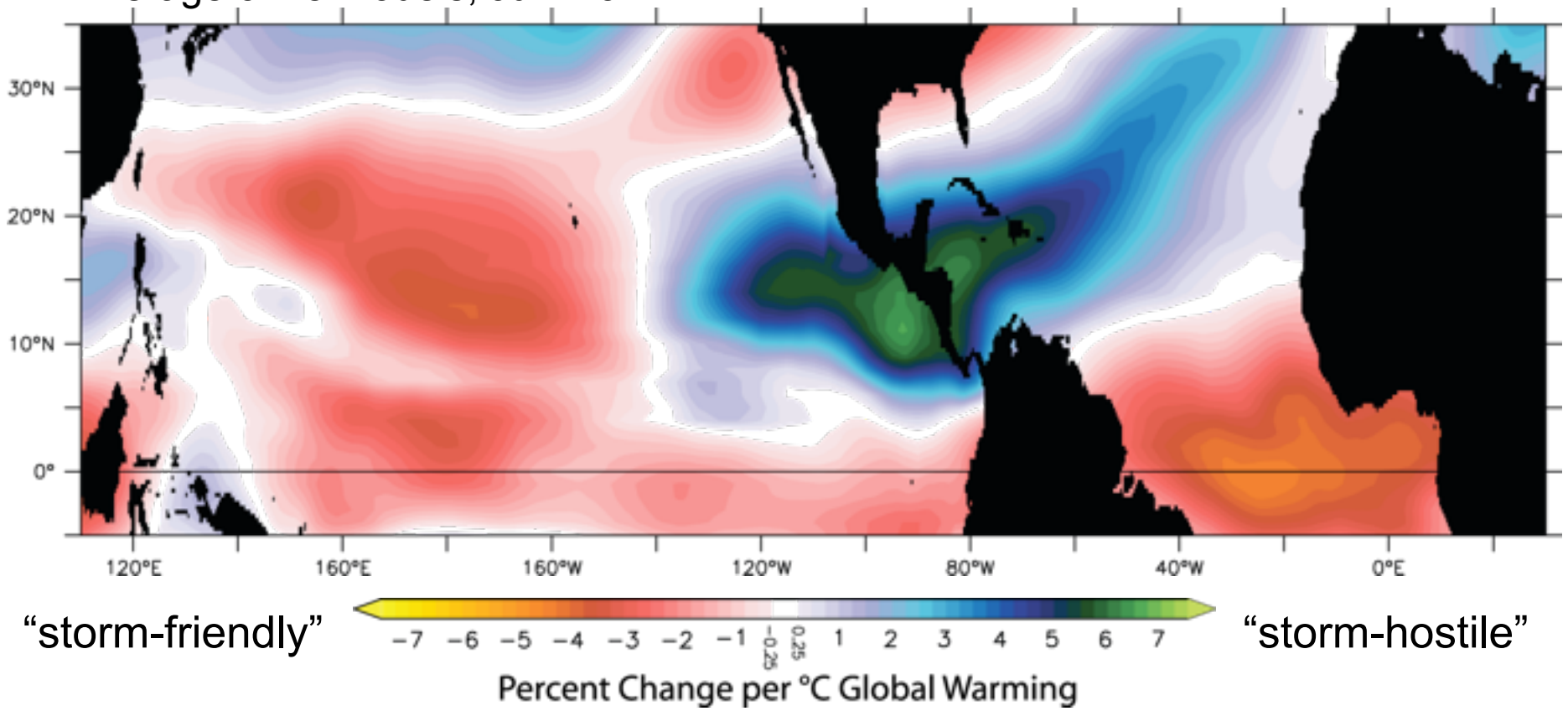


But GCMs can give large-scale conditions that influence hurricane activity (e.g., shear, potential intensity (PI), SST, etc)

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

Projected 21st Century Changes in Vertical Wind Shear

Average of 18 models, Jun-Nov



"storm-friendly" "storm-hostile"

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)

Bister and Emanuel (1998) Potential Intensity

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

- Defined locally from a sounding and SST.
- All other things equal: SST increase-> PI increase

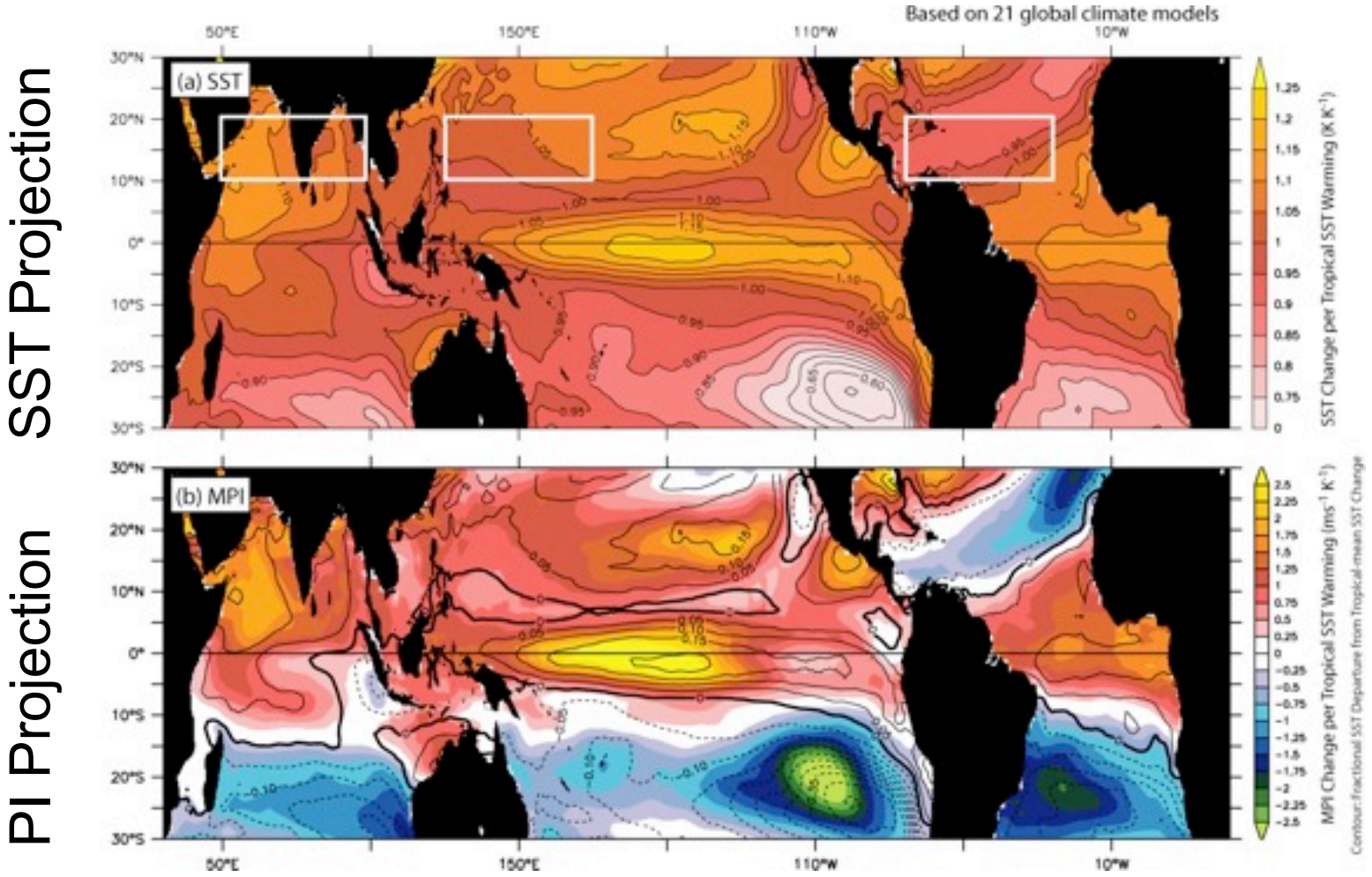
  Both through direct impact on T_s and k*, as well as indirectly impacting T_o and k_a
- However, **remote SST changes impact upper tropospheric temperature** (e.g., Sobel et al 2002) changing T_o directly and indirectly, and enthalpy diff. indirectly: remote warming acts to reduce PI.

  See also Shen *et al* (2000), Tang and Neelin (2004) and Ramsay and Sobel (2010, submitted)

From GCMs, PI'-<PI'> ~ 8·(SST'-<SST'>)
In GCMs, |<PI'>| smaller than |PI'|, so PI' ~ 8·(SST'-<SST'>)

Potential intensity tracks SST relative to tropical-mean, not local SST*

*global-mean PI changes still need to be explained, more soon.



Vecchi and Soden (2007, Nature)

Bister and Emanuel (1998) Potential Intensity

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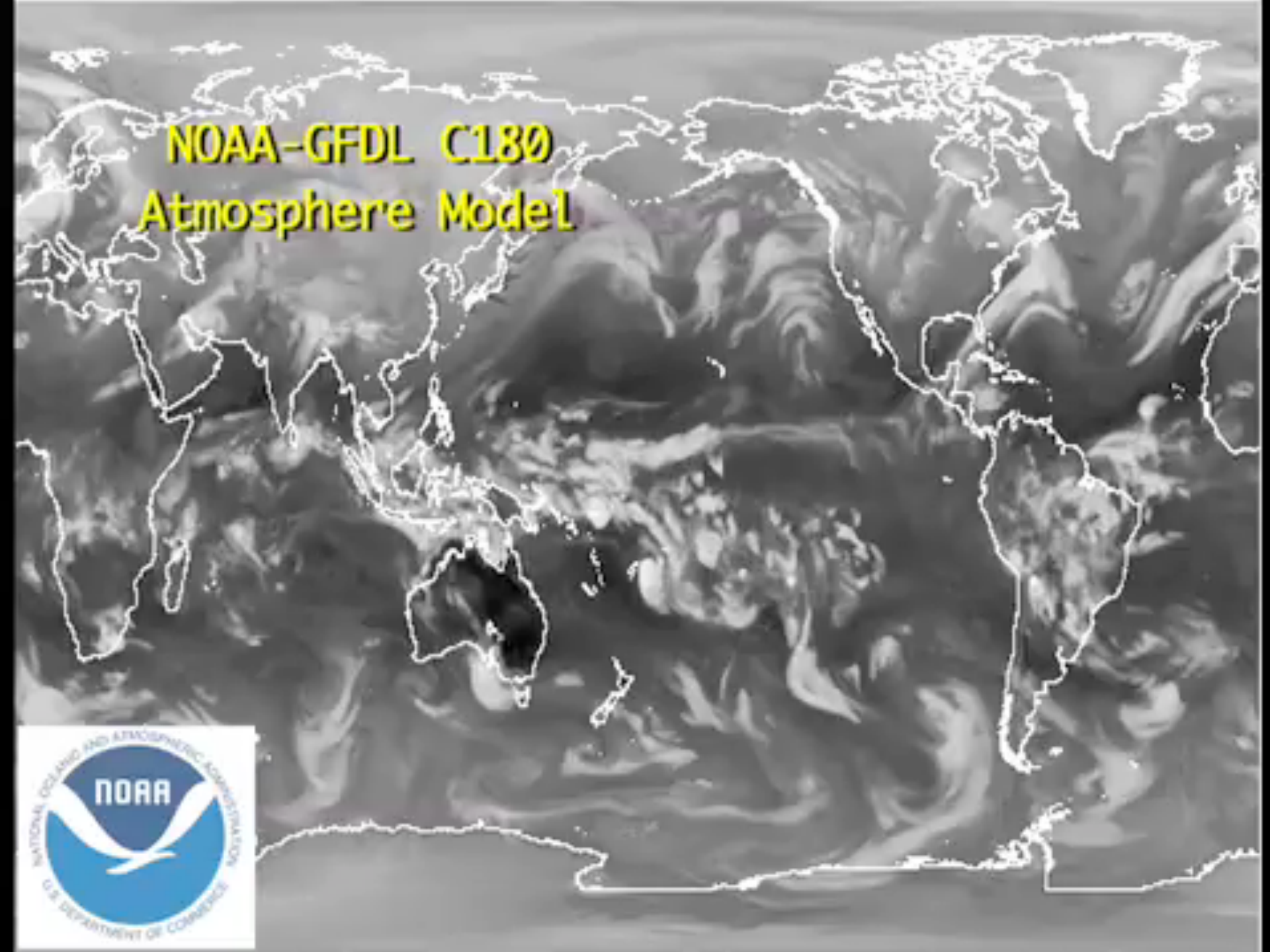
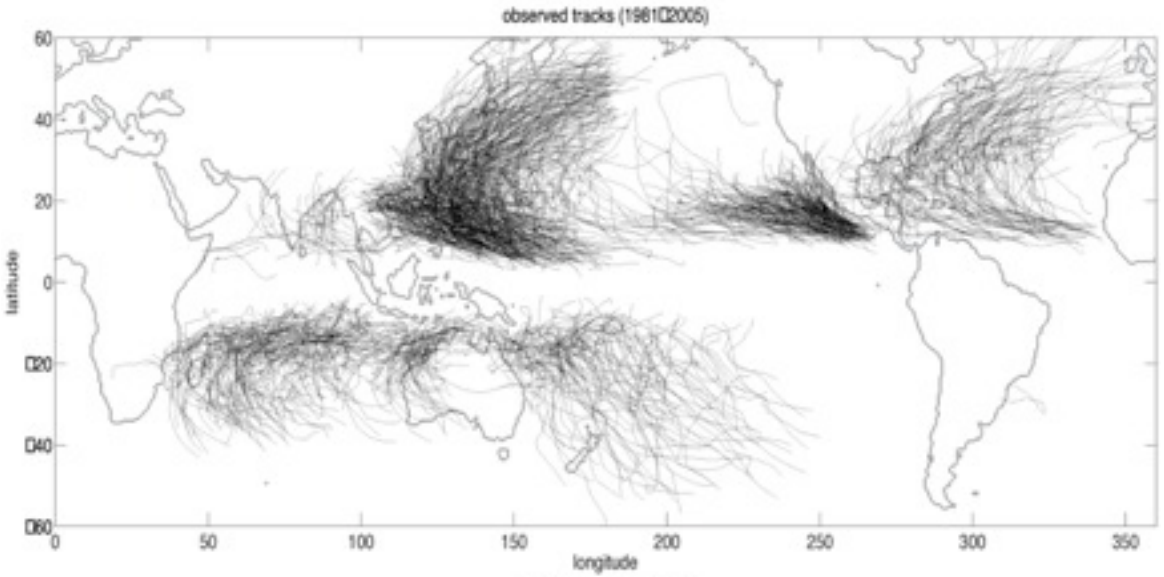
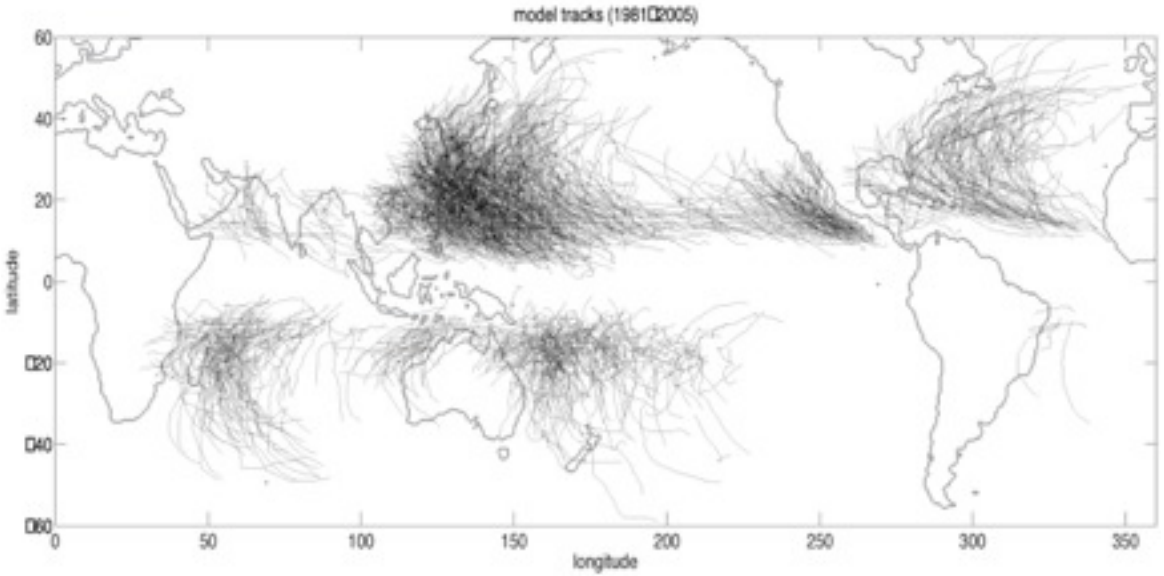

NOAA-GFDL C180
Atmosphere Model
NOAA

Model recovers many aspects of observed hurricane tracks

Observed



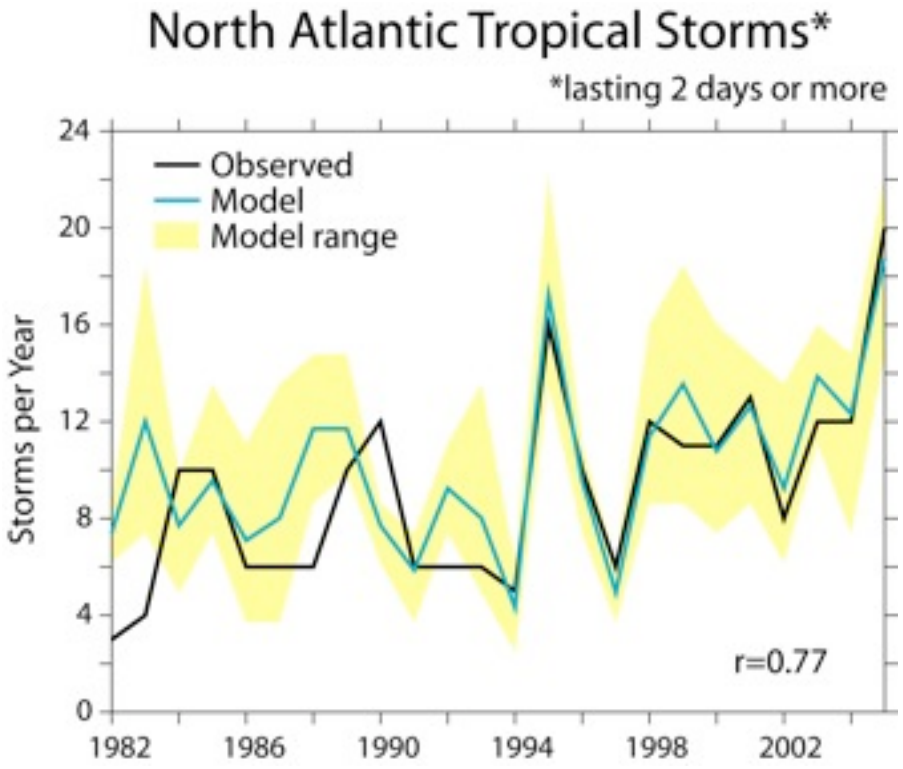
C180 Model



Zhao et al (2009, J. Climate)

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. Zhao et al (2009, J. Climate)



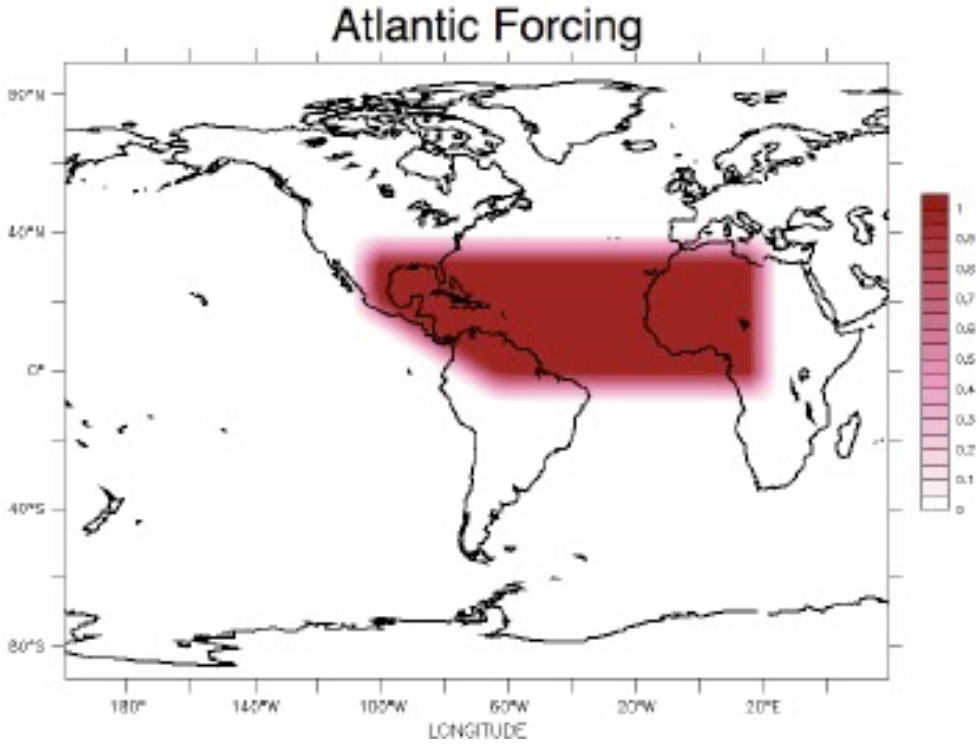
Adapted from AM2 with:

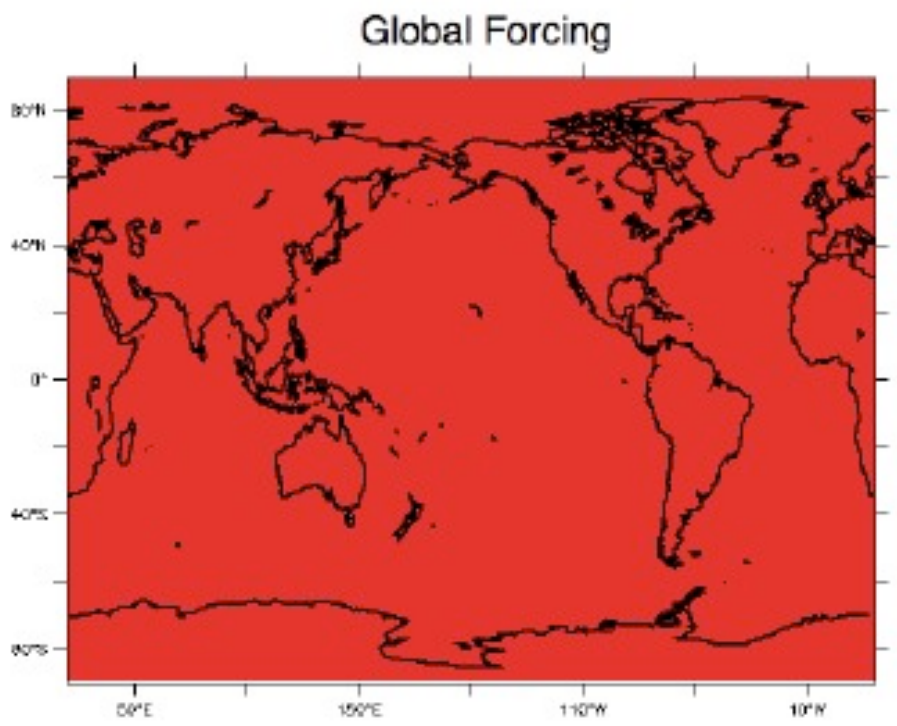
- Deep convection scheme adapted from Bretherton, McCaa and Grenier (MWR, 2004)
- Cubed sphere dynamical core
- Changes to parameterizations of cloud microphysics
- C90 Atm. resolution of 1°x1°

Idealized Forcing Experiments

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

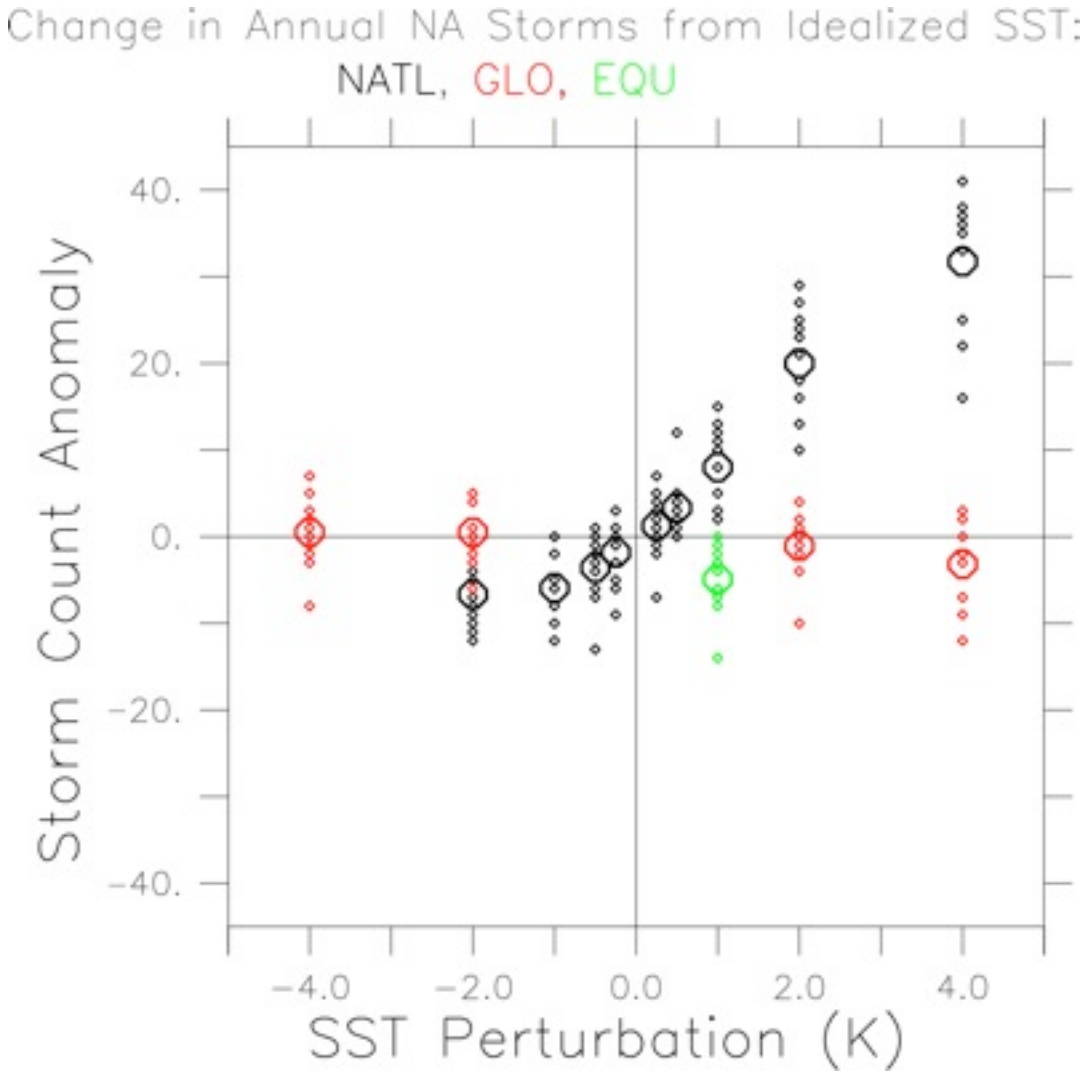
- Similar Atlantic Response to Atlantic and Uniform F'cing
- Little Pacific Response to Atlantic compared to Uniform





Gabriel Vecchi, NOAA/GFDL, Princeton, NJ

North Atlantic Response to Idealized SST



Atlantic Forcing

Uniform Forcing

Near-equatorial Forcing

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

Vecchi et al (2010, in prep.)

Gabriel Vecchi, NOAA/GFDL, Princeton, NJ

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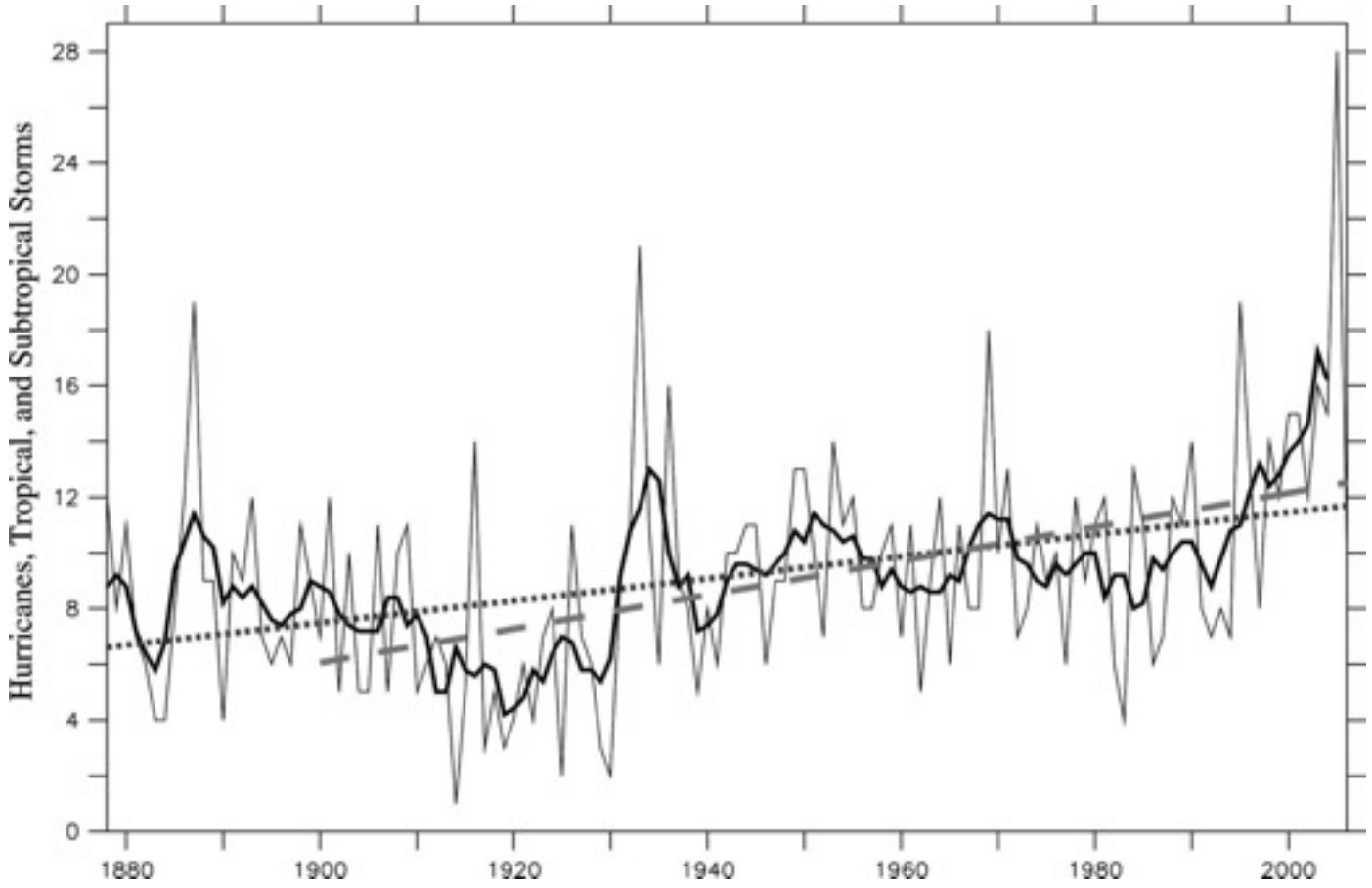
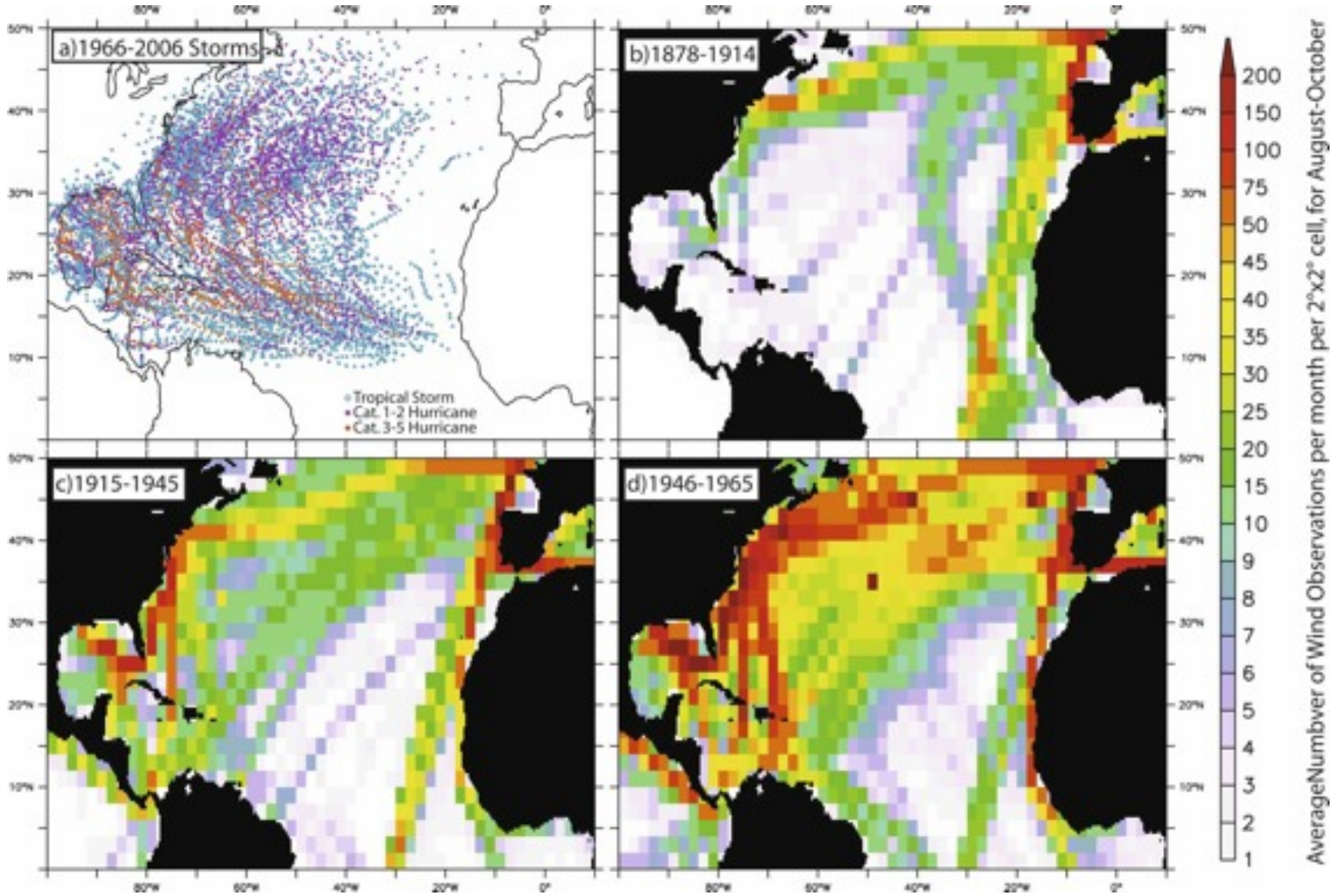
Clear increase in recorded number of Atlantic tropical storms since late-19th century



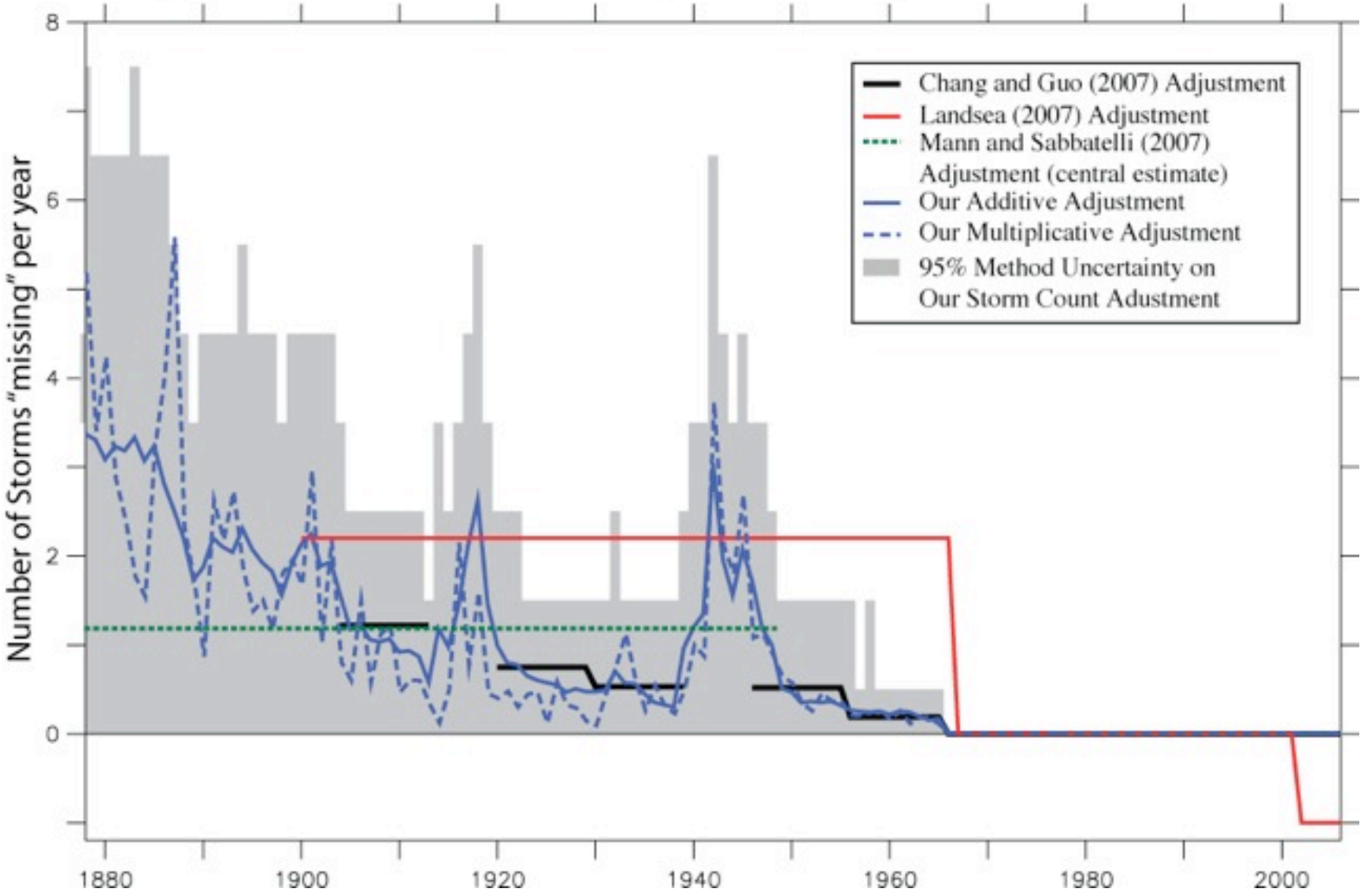
Vecchi and Knutson , J. Climate, 2008.

Ability to observe cyclones has also changed with time: e.g., ship track density



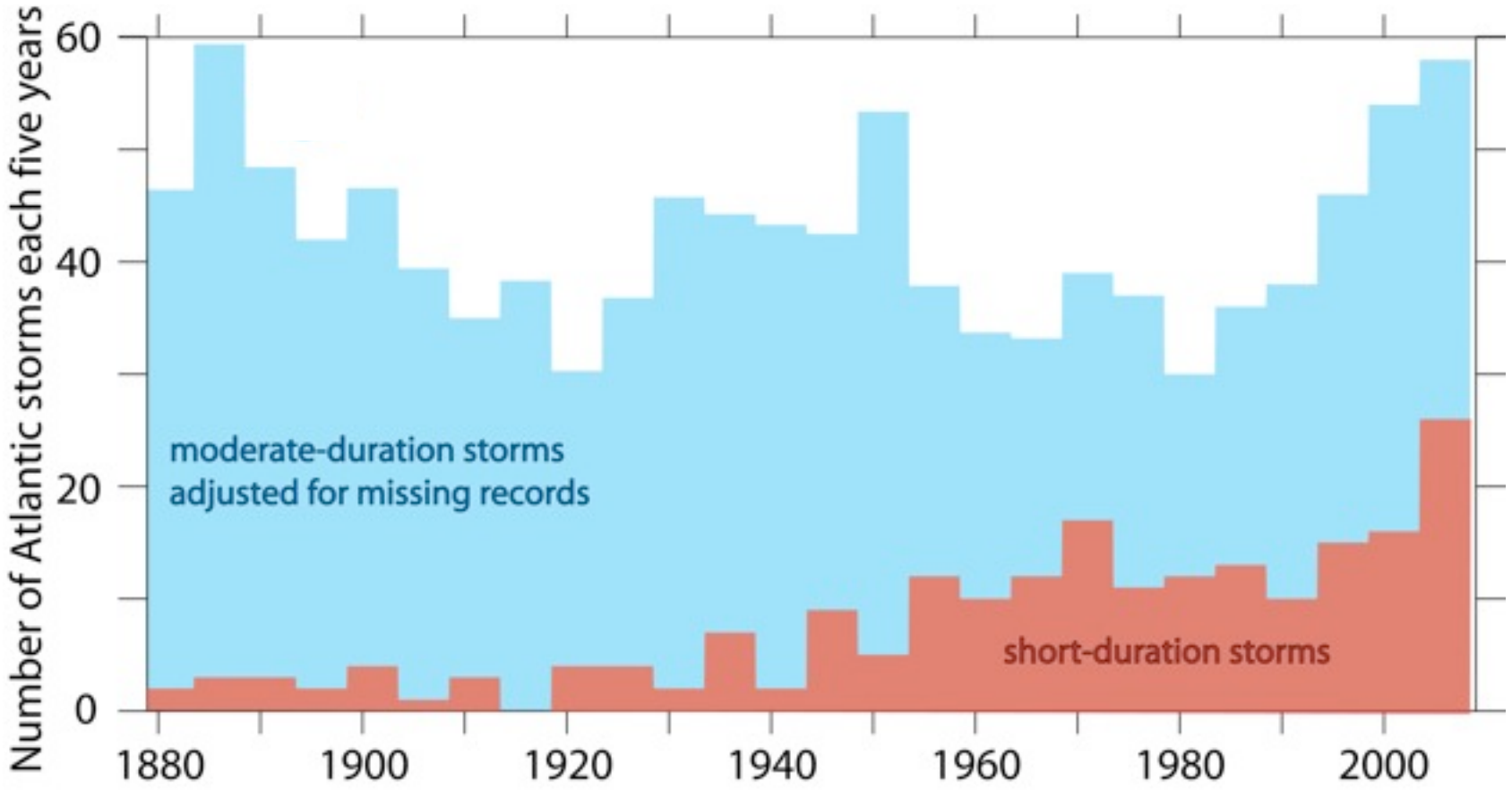
Vecchi and Knutson , J. Climate, 2008.

“Missing storm” adjustments to HURDAT storms (1878-2007)



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

Atlantic tropical storms (< 2 day duration) show a strong trend. Storms of >2 day duration - adjusted for “missing storms” - do not show a trend.



Adapted from Landsea et al (2010, J. Climate)

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Statistical models of TS frequency

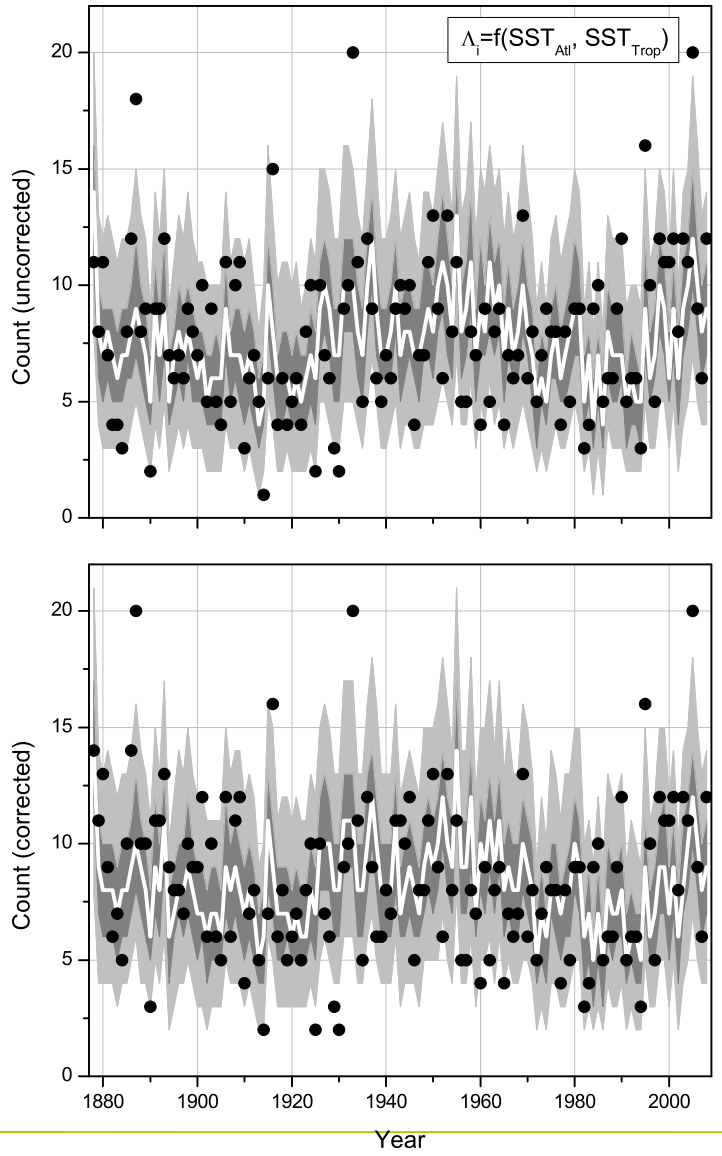
Villarini, Vecchi and Smith (2010, MWR, Submitted)

- Build statistical models of TS frequency:
  - >2 day duration basin-wide with and without adjustment
  - Landfalling
- Explore range of models, sensitivity to:
  - Possible covariates:
    (NAO, SOI, **Atlantic SST, Tropical SST**)
  - Model structure (Poisson vs. Negative Binomial).
  - Penalizing criterion for extra predictors (SBC vs. AIC).
  - SST dataset (Extended NOAA vs. HadISST)
- Apply to GCM projections and other runs.

Tropical SST as predictor of cyclone activity?

- Remote SST changes impact Atlantic wind shear:
  - During El Niño (e.g., Gray 1975)
  - Warming-induced weakening of Walker circulation increases shear (Vecchi and Soden 2007)
  - Warming of Indo-West Pacific increases shear (Latif et al 2007, GRL)
- Remote warming acts to increase thermodynamic stability:
  - WTG hypothesis (Sobel et al 2002)
  - During El Niño, remote thermodynamic stabilization acts to damp NA Activity (Tang and Neelin 2004)
  - Potential intensity strongly influenced by warming relative to tropical-mean (Vecchi and Soden 2007, Ramsay and Sobel 2010-submitted)
- High-resolution studies indicate warming relative to tropical-mean relevant quantity:
  - Knutson et al (2008), Zhao et al (2010), Vecchi et al (2010, in prep)

Build statistical model of basin-wide tropical storms using Atlantic and Tropical-mean SST as covariates



Atlantic SST increases frequency.

Tropical-mean SST reduces frequency.

Factors in fit (w/standard error)

	Uncorrected	Corrected
Intercept	2.03 (0.03) 2.03 (0.03)	2.11 (0.03) 2.10 (0.03)
SST_{Atl}	1.13 (0.20) 1.05 (0.15)	1.05 (0.15) 1.02 (0.14)
SST_{Trop}	-0.98 (0.23) -0.91 (0.20)	-1.22 (0.22) -1.05 (0.19)

Villarini, Vecchi and Smith (2010, MWR, Submitted)

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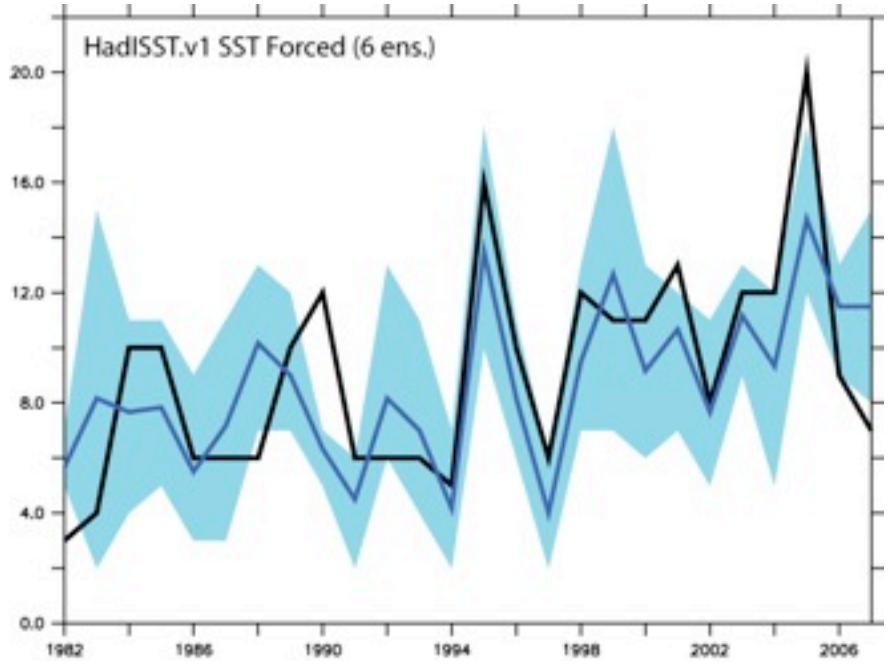
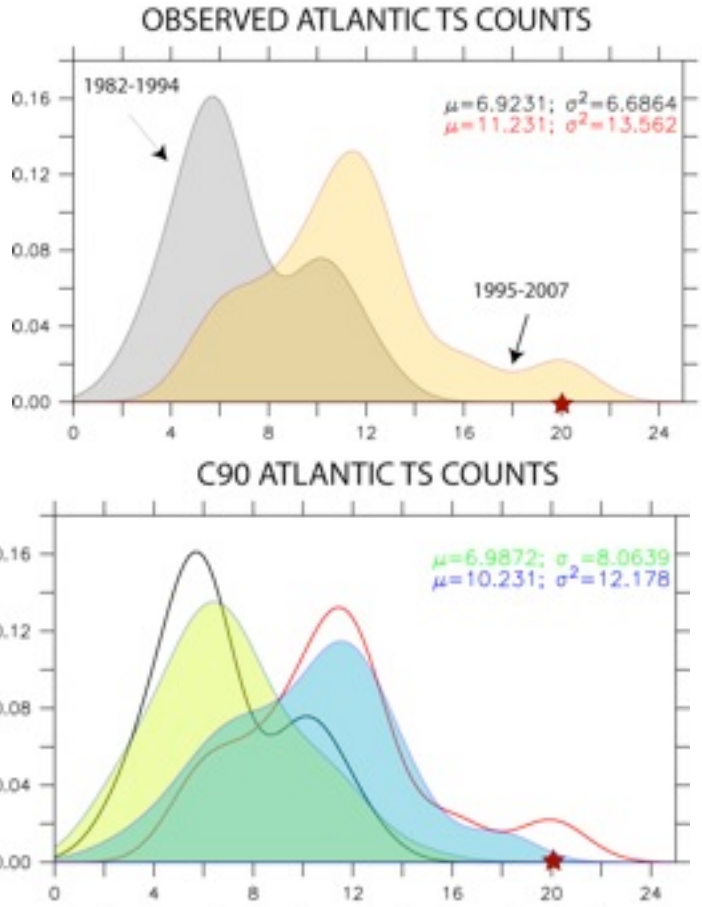
Change in Atlantic TS Frequency* Since 1982

* lasting two days or more

- TS Frequency and Variance has unambiguously increased since 1982.
- Shift in PDF across 1994-1995.
- HiRAM AGCM Captures shift



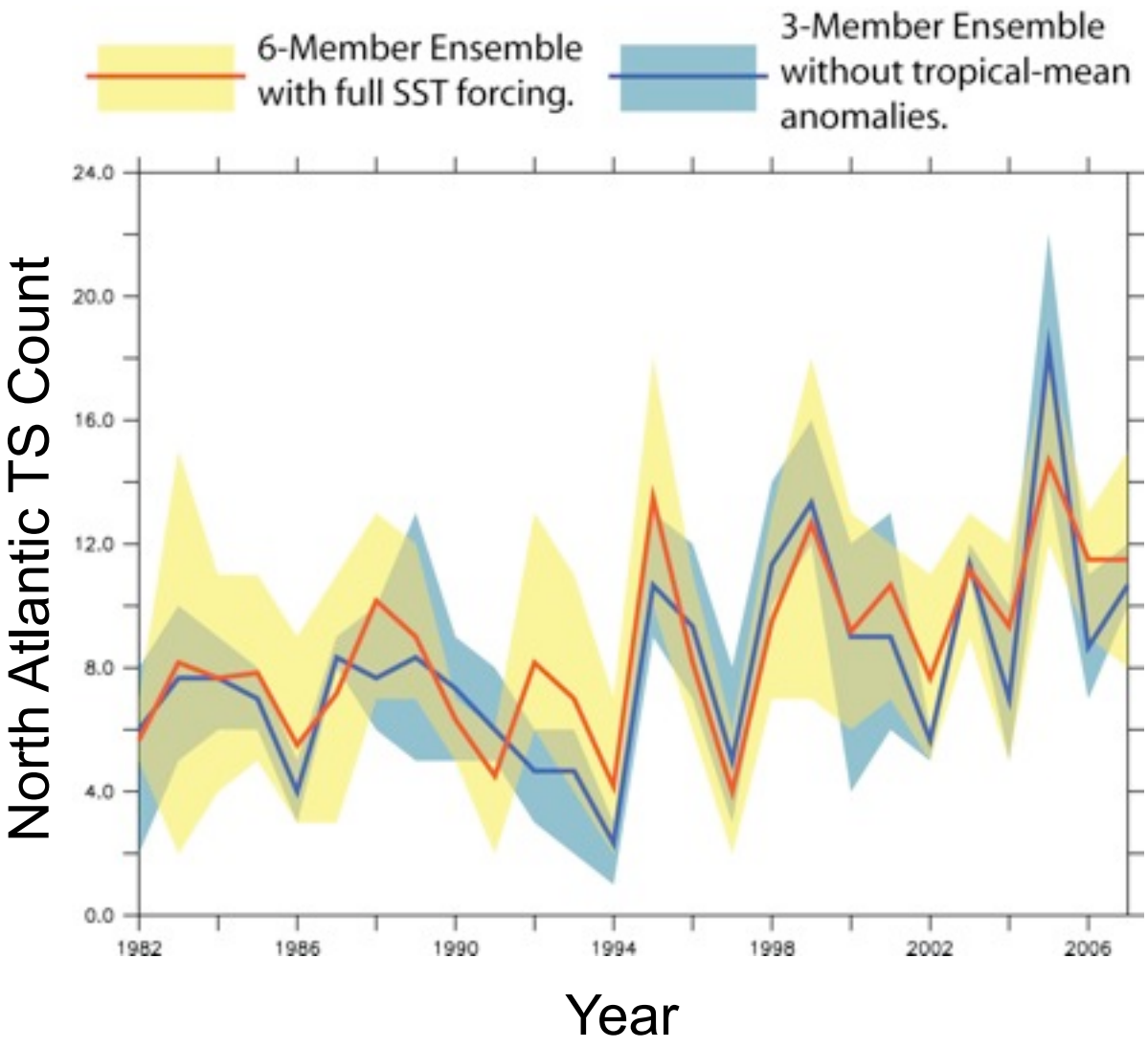


Vecchi et al (2010, in prep.)

★ 2005 Observed

Gabriel Vecchi, NOAA/GFDL, Princeton, NJ

AGCM with and without tropical-mean SST change



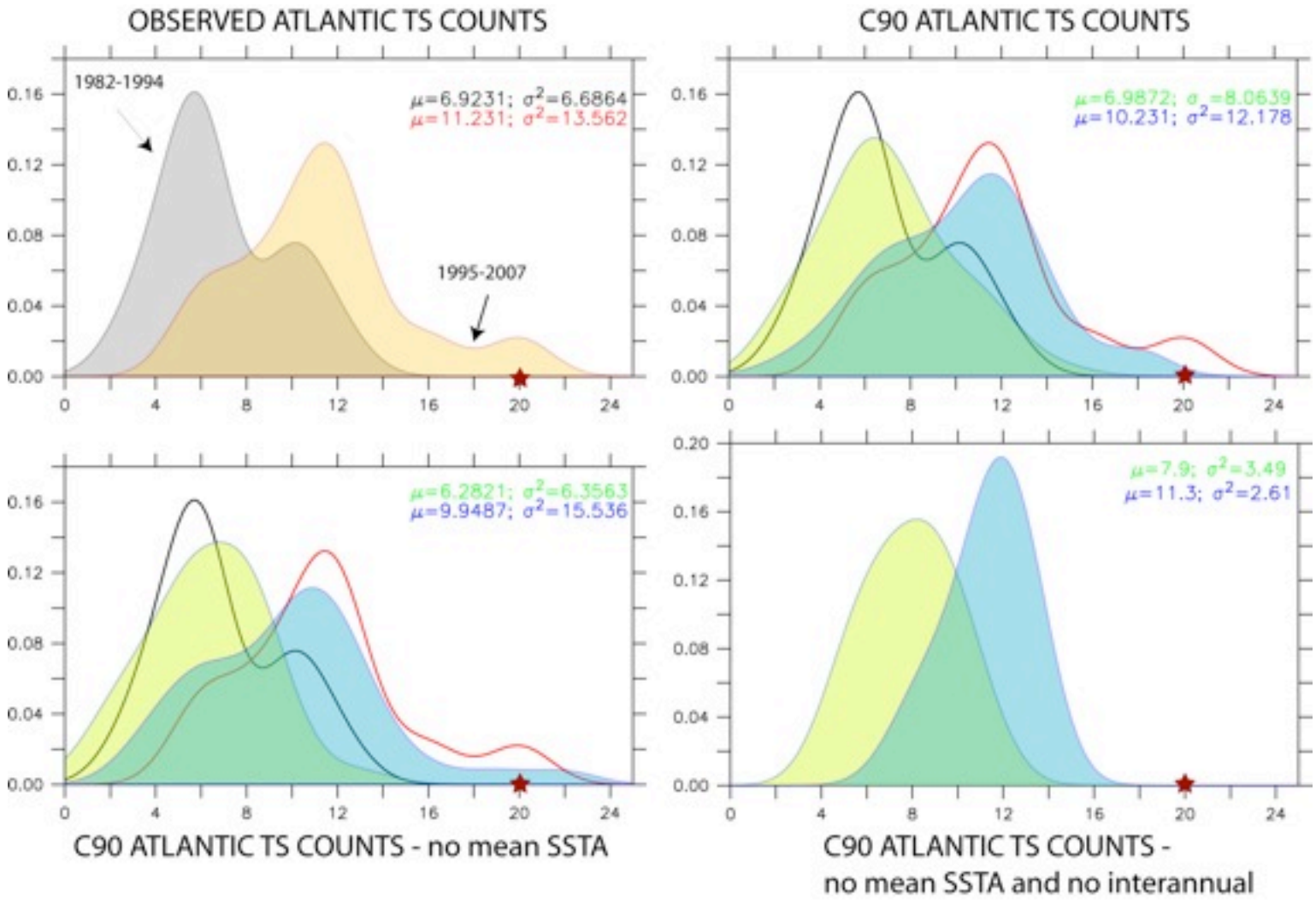
100km AGCM 1982-2007 North Atlantic tropical storm count not sensitive to removing tropical-mean SSTA forcing.

Vecchi et al (2010, in prep.)

1982-94 and 1995-2007 PDFs of NA TS Count*

* lasting two days or more

★ 2005 Observed



Vecchi et al (2010, in prep.)

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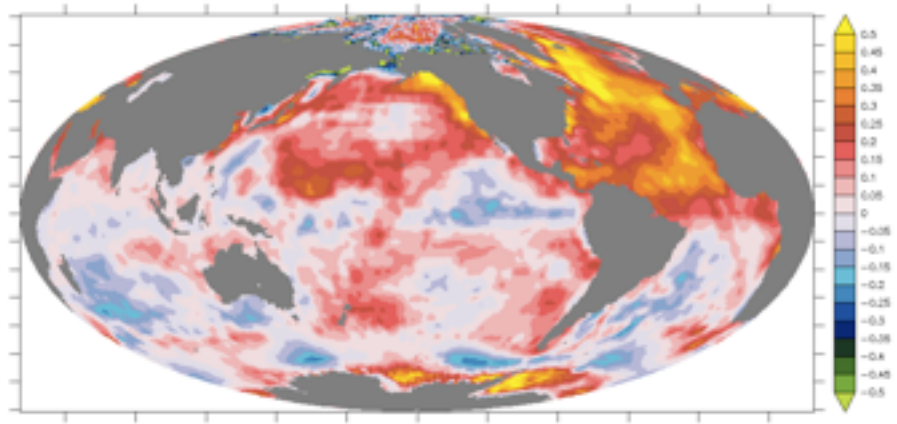
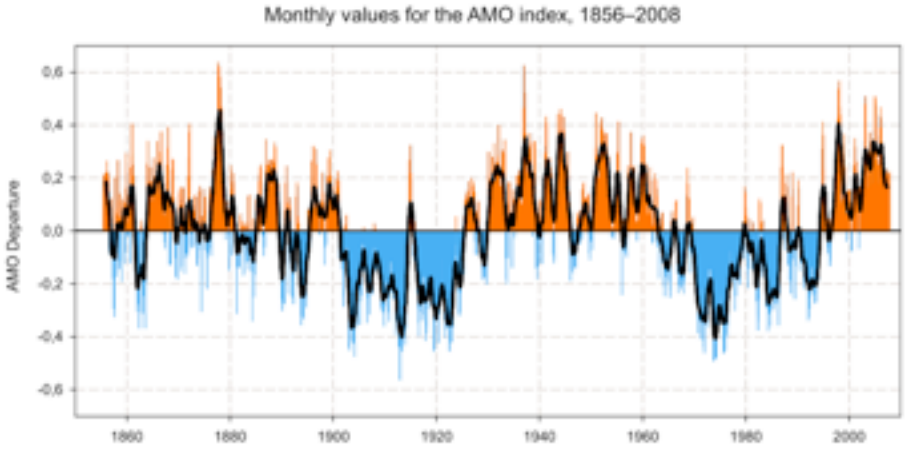
Shift in mean TS counts attributable to “AMO” SST change across 1994-1995

What drove this SST change? Internal variability? Aerosols? Combination?

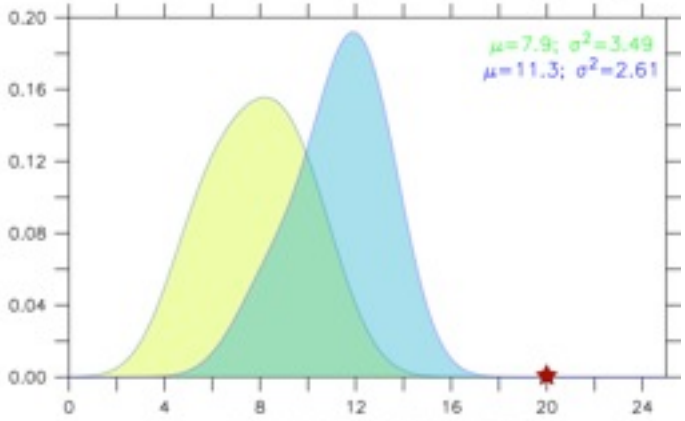
1995-2007 minus 1982-1994 “AMO” SSTA Forcing



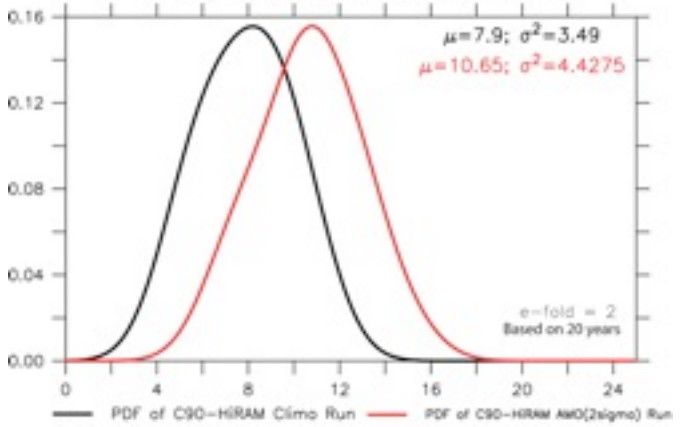


AMO Index: Regression of SST onto NA SST

Response to decadal shift



Response to “AMO” forcing



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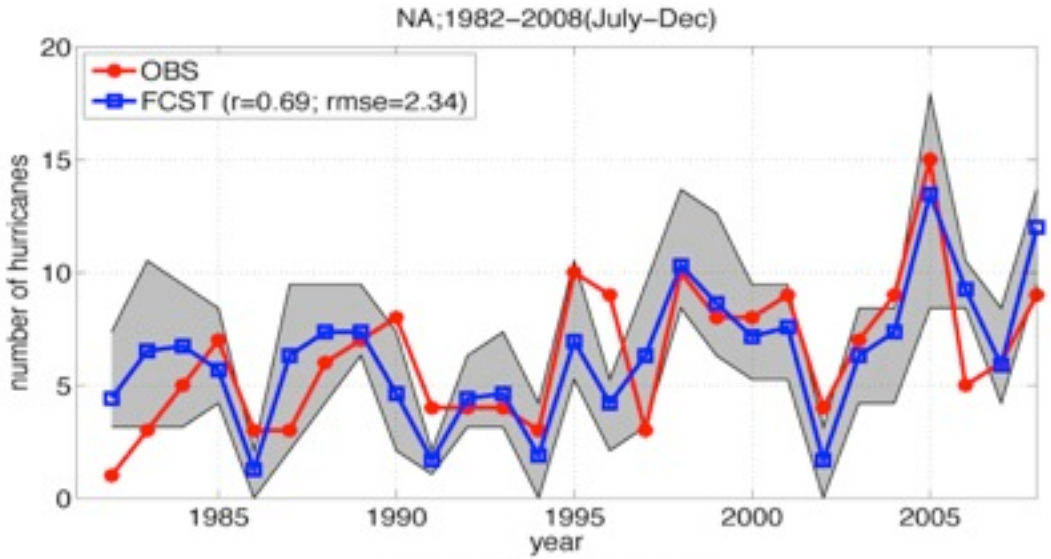
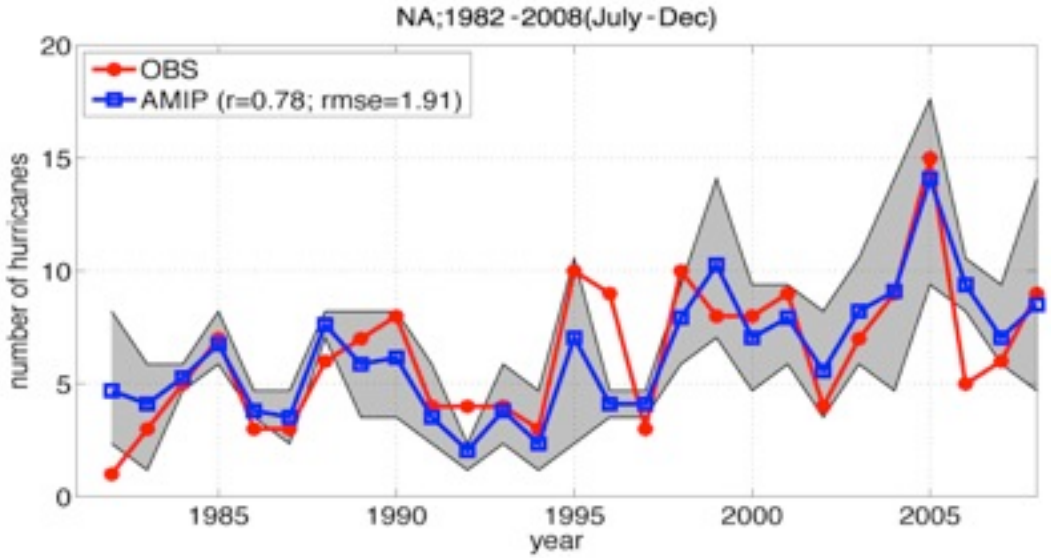
Retrospective NA Hurricane Forecast With Persisted June SSTA

FCST
r=0.69

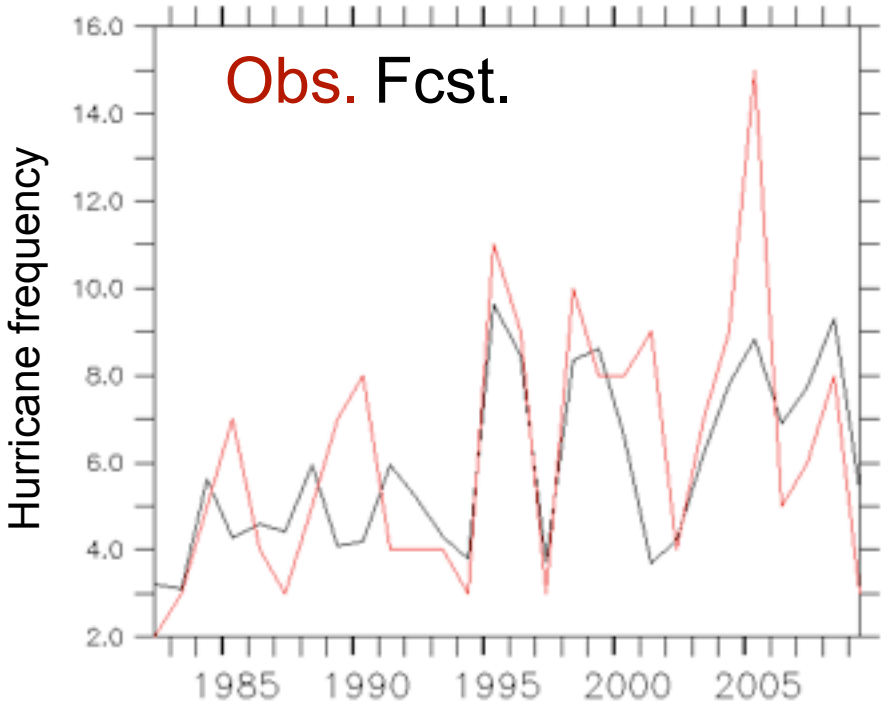


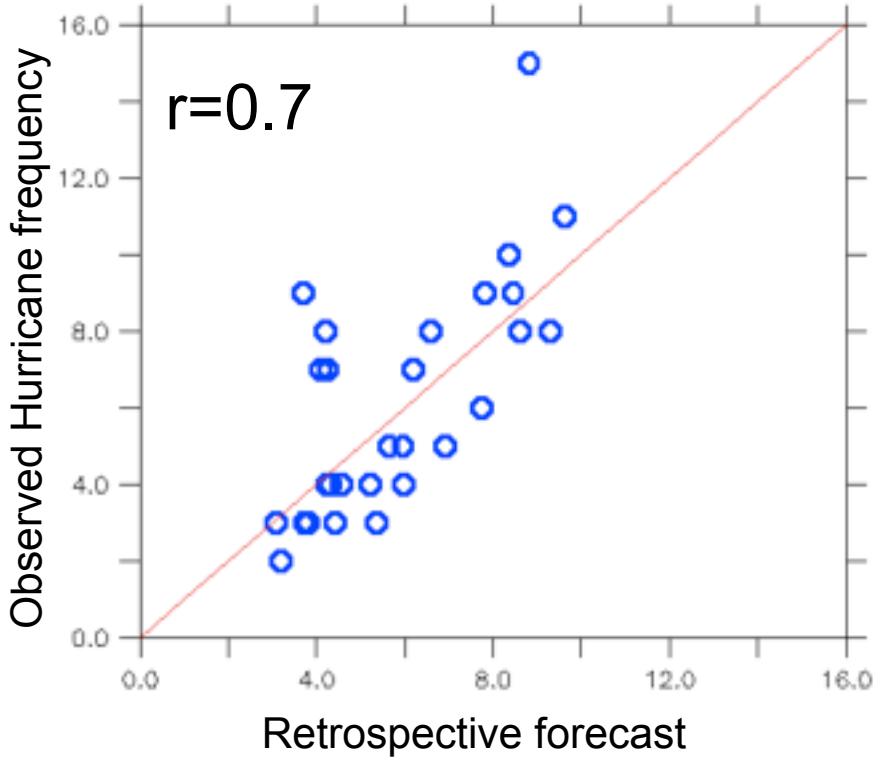
AMIP
r=0.78



Zhao, Held and Vecchi (2010, MWR Submitted)

Statistical downscale using SST-<SST> of GFDL experimental seasonal forecast system built on CM2.1: Initialized January





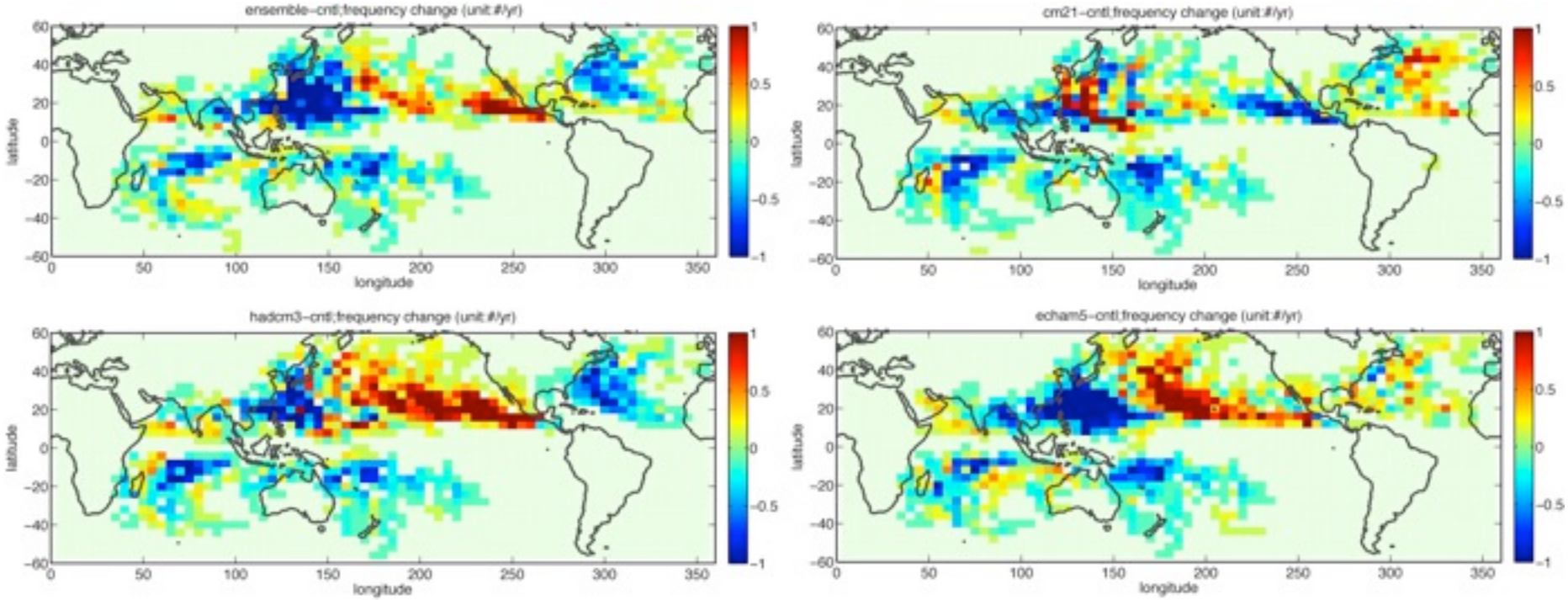
Gabriel Vecchi, NOAA/GFDL, Princeton, NJ

Outline

- Tools:
  - Global climate models
  - High-resolution dynamical models
  - Observational records
  - Statistical models

- Attribution of recent increase in Atlantic activity
- Predictions of seasonal activity
- Century-scale projections

21st Century Hurricane Activity Change: Four possibilities



Red/yellow = increase
Blue/green = decrease

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

Regional increase/decrease much larger than global-mean.

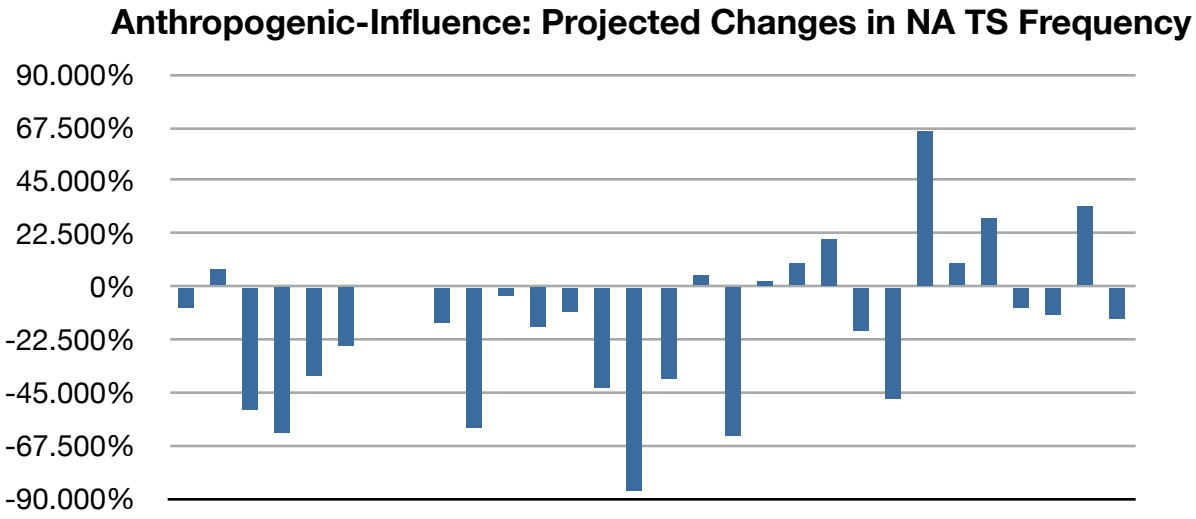
Pattern depends on details of ocean temperature change.

Sensitivity of response seen in many studies

e.g., Emanuel et al 2008, Knutson et al 2008, etc

Divergence of 21st Century projections of TS Frequency Change

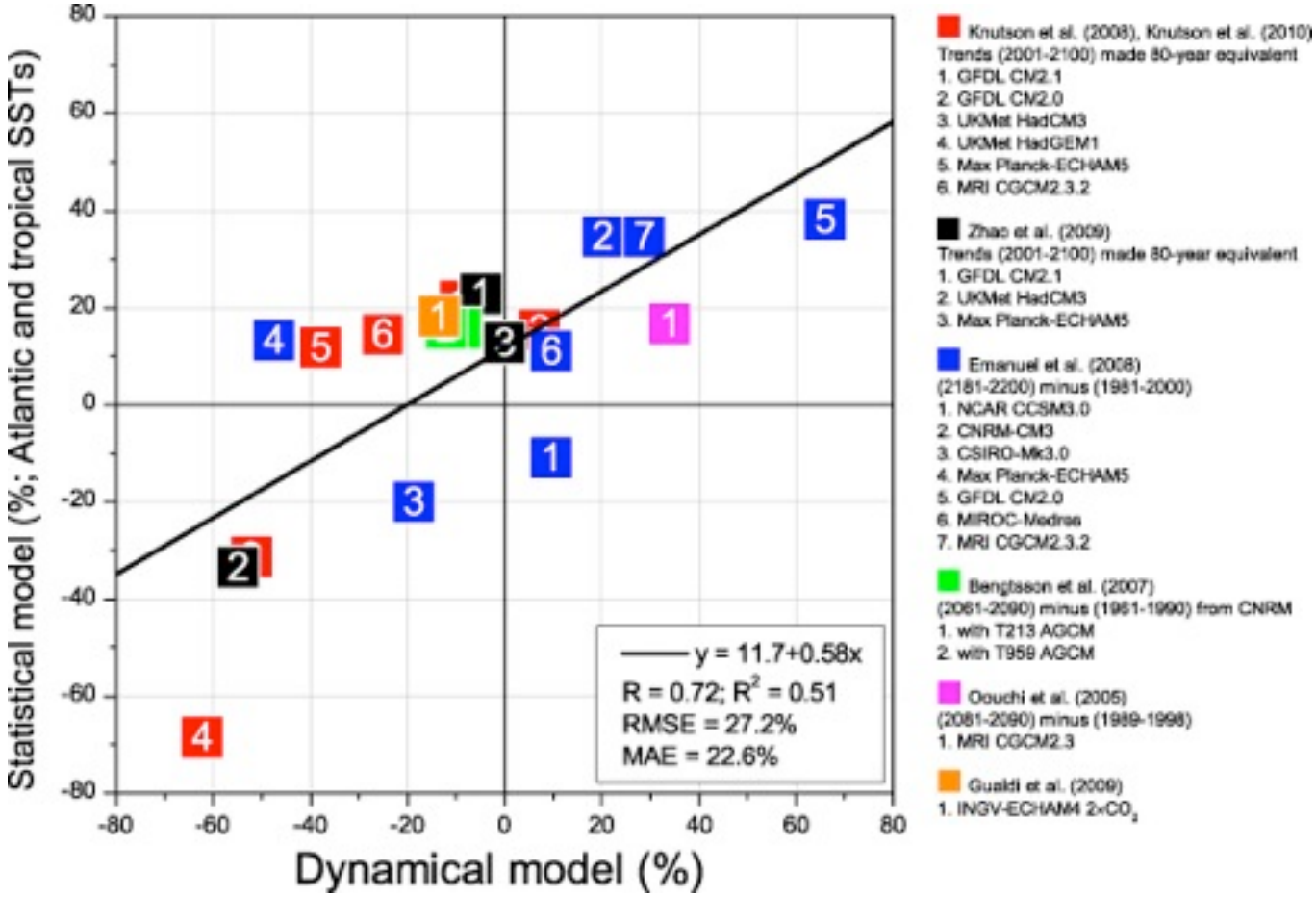
- Even sign of relationship between GHG and NA TS frequency unclear:
  - Not big help in decadal predictability



Oouchi et al (2005), Bengtsson et al (2007), Emanuel et al (2008), Knutson et al (2008), Zhao et al (2008)

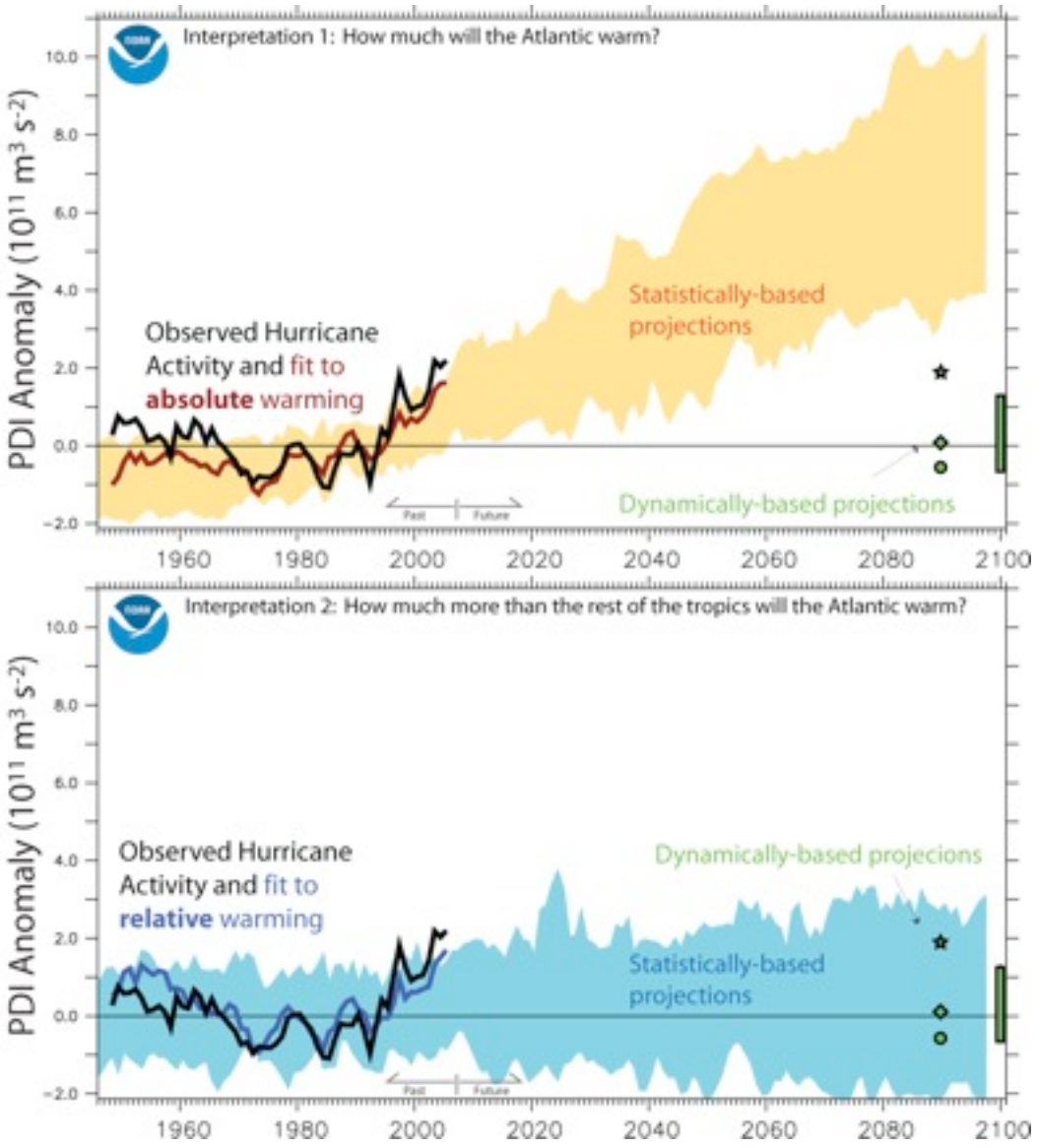
Is there any consistency in the various projections?

Dynamical models exhibit consistent relationship to MDR and tropical SSTs - all consistent with observations



Poisson model of 2-day duration TS (vertical) vs. dynamical downscaling results (horizontal)

…Add Dynamical Projections of Atlantic Hurricane Activity



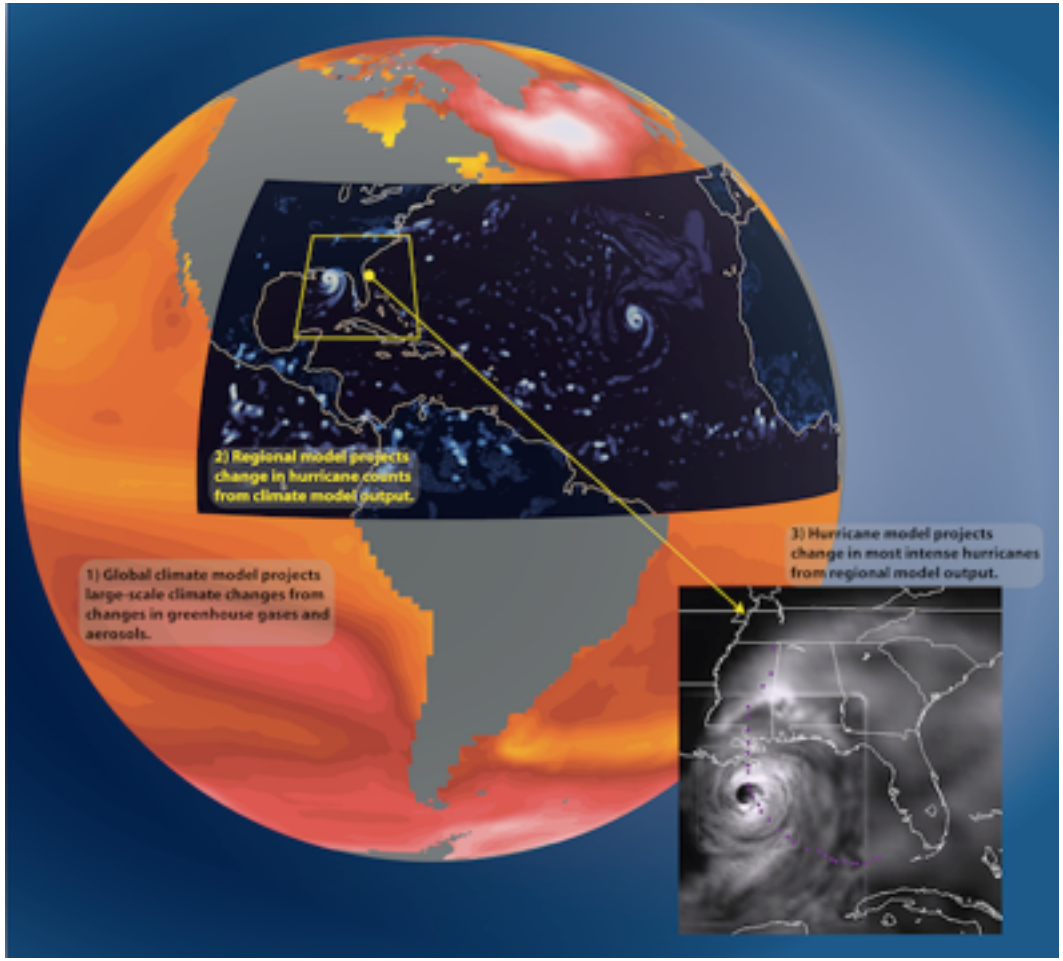
Observed Activity
Absolute Atlantic Temperature

Dynamical Model Projections

Observed Activity
Relative Atlantic Temperature

Vecchi, Swanson and Soden (2008, Science)

Strongest cyclones projected with double downscaling

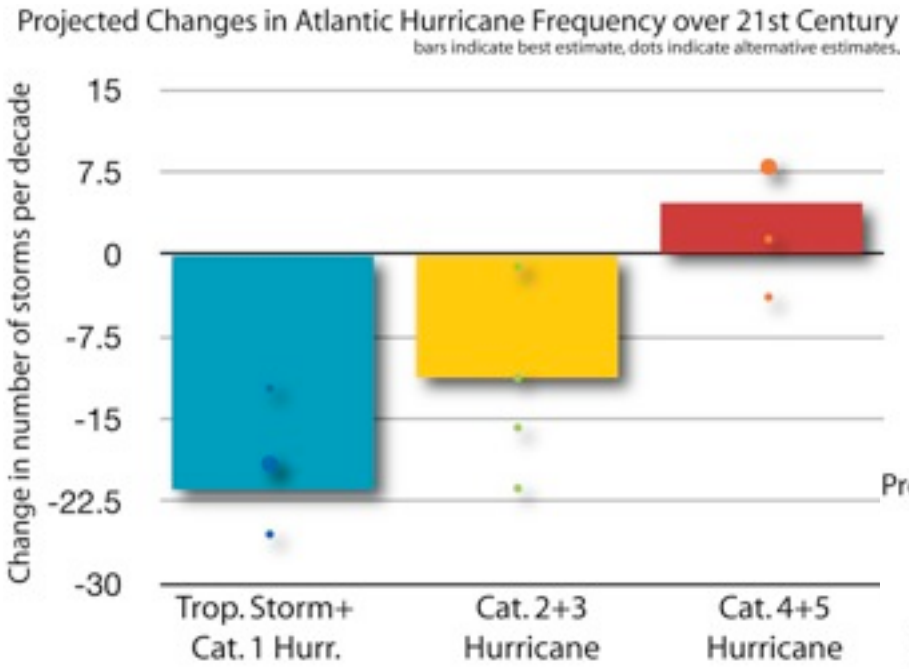


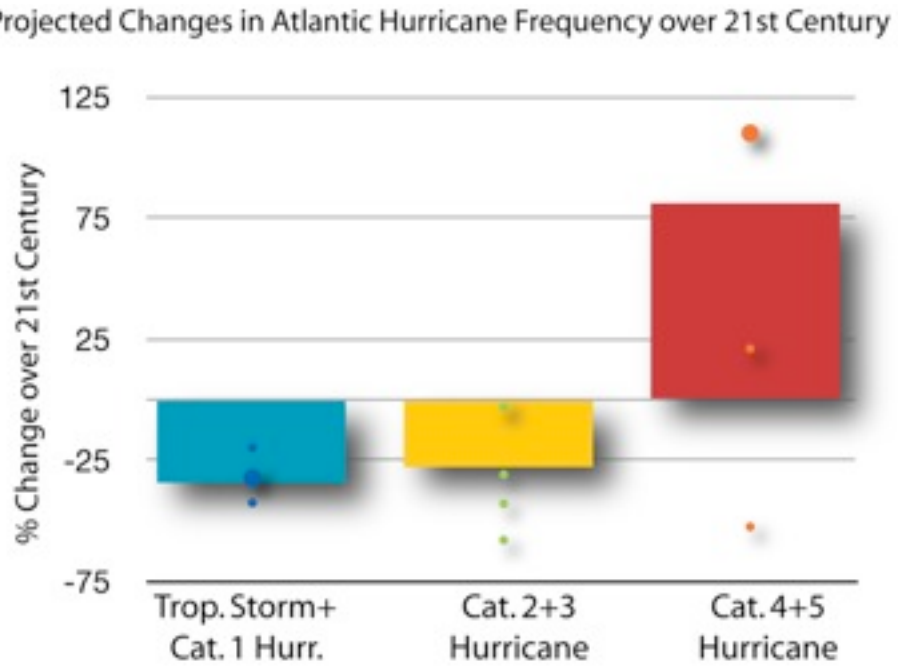
Adapted from
Bender et al (2010, Science)

Global Climate Models -> Regional Model -> Hurricane model

Large-scale TS Frequency Intensity

Overall frequency decrease, but strongest storms may become more frequent



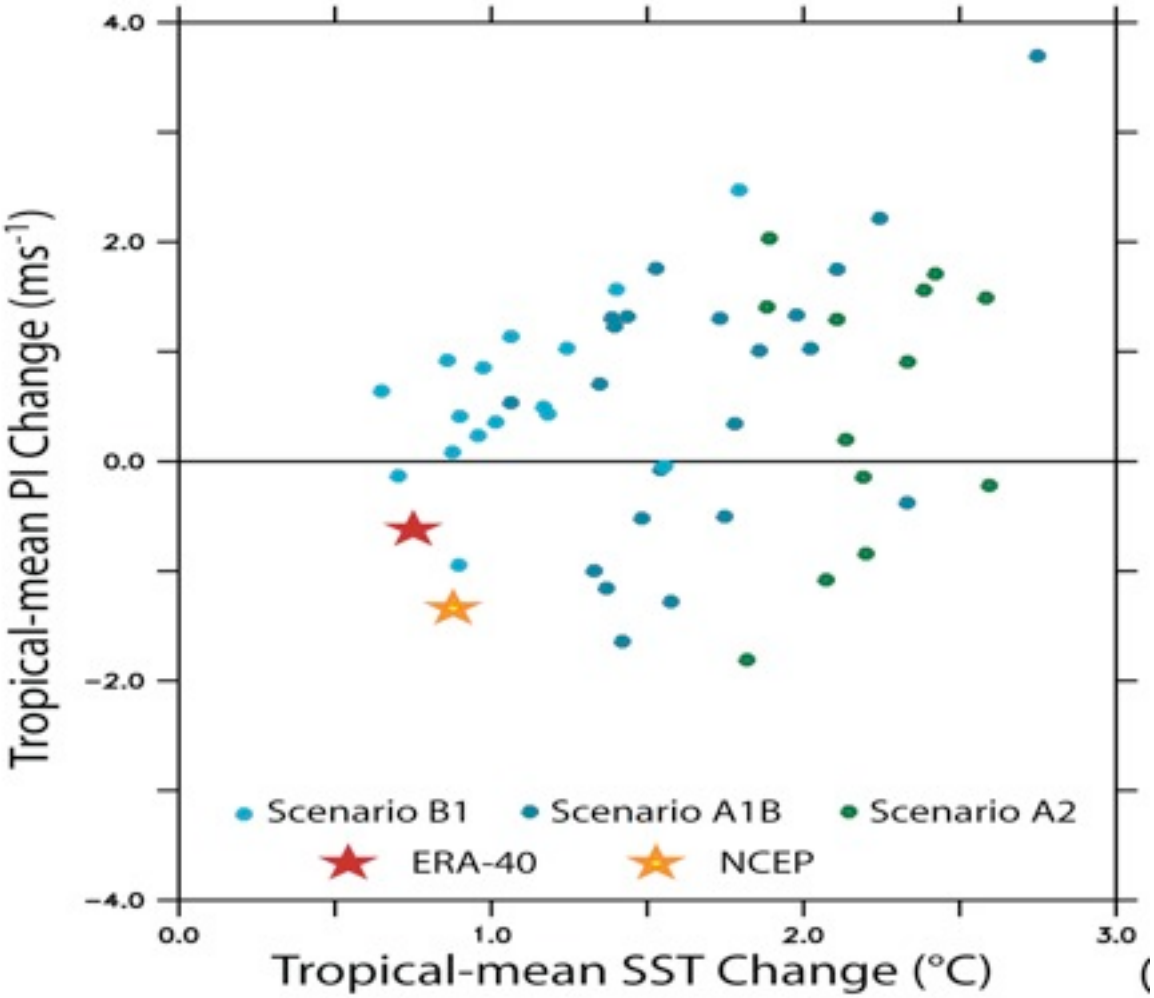


Adapted from Bender et al (2010, Science)

Summary

- It is premature to conclude that human activity (particularly CO2) has already had an impact on Atlantic TS/HU frequency or PDI.
  - Cannot reject null that frequency has not changed over century-scale (no detection)
  - Competing dependence on SST (local and remote) prevents two-step attribution
  - Not clear that “committed warming” adds to decadal TC predictability
- Atlantic basin-wide activity controlled by SST changes in the Atlantic relative tropics:
  - Need to attribute and predict pattern of SST change
  - To develop confidence in predictions must understand mechanisms:
    what controls regional SST patterns? (for CO2 response see LeLoup and Clement 2009 GRL, Xie et al 2010 J. Clim.).
- 1994-95 change in mean TS freq. attributable to “AMO-ish” SST change
  - What drove SST?
  - When can we expect it to swing back (or even further out)? Are last few years sign of end?
  - What about shift in variance?
- Forecasts feasible using rel-SSTA from June (persistence) and January (using CGCM)
- Dynamical projections disagree largely due to different large-scale inputs:
  - Consistent sensitivity to relative warming and with historical record
- Atlantic: Little change to frequency (possibly fewer) but increase in intensity.
- Big question remains: what about vertical changes in atmospheric temperature?

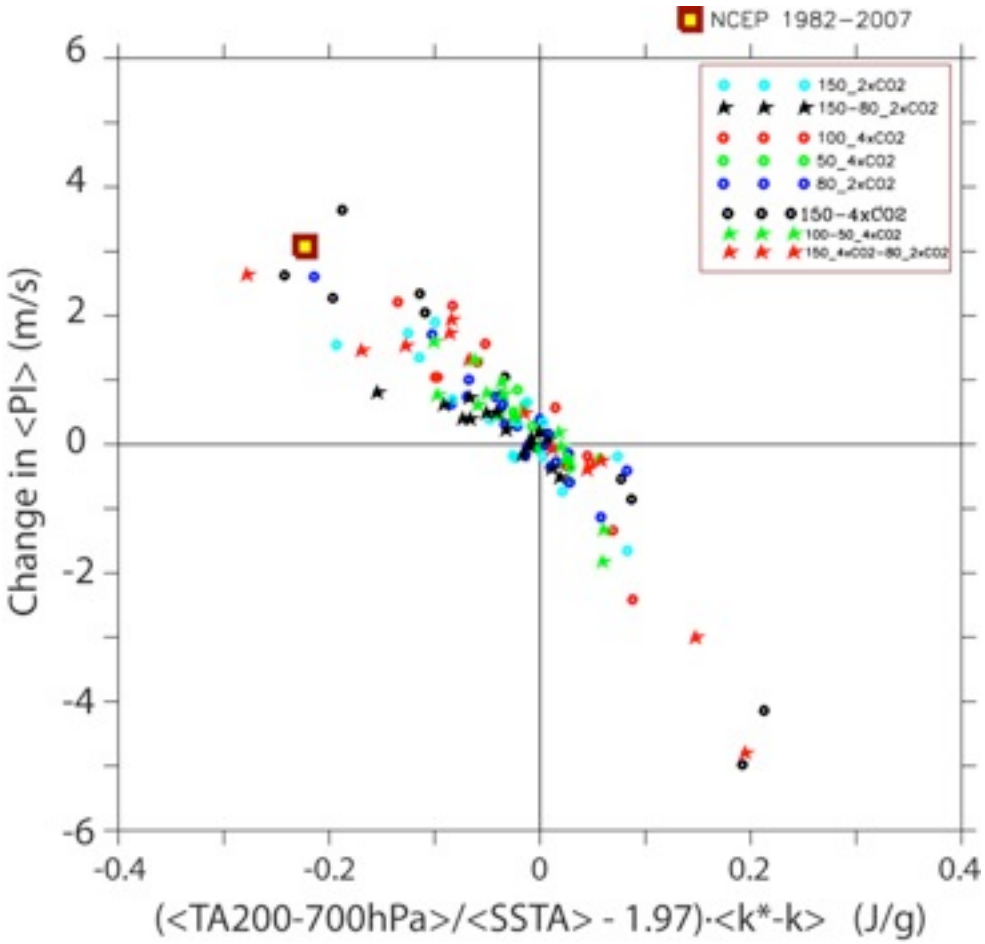
What about tropical-mean PI change?



Not well constrained by SST changes

Vecchi and Soden (2007, Nature)

Tropical-mean surface enthalpy disequilibrium seems to set scale



PI =<k*-k>·(<TA>/<SST>-1.97)

Relationship explains:

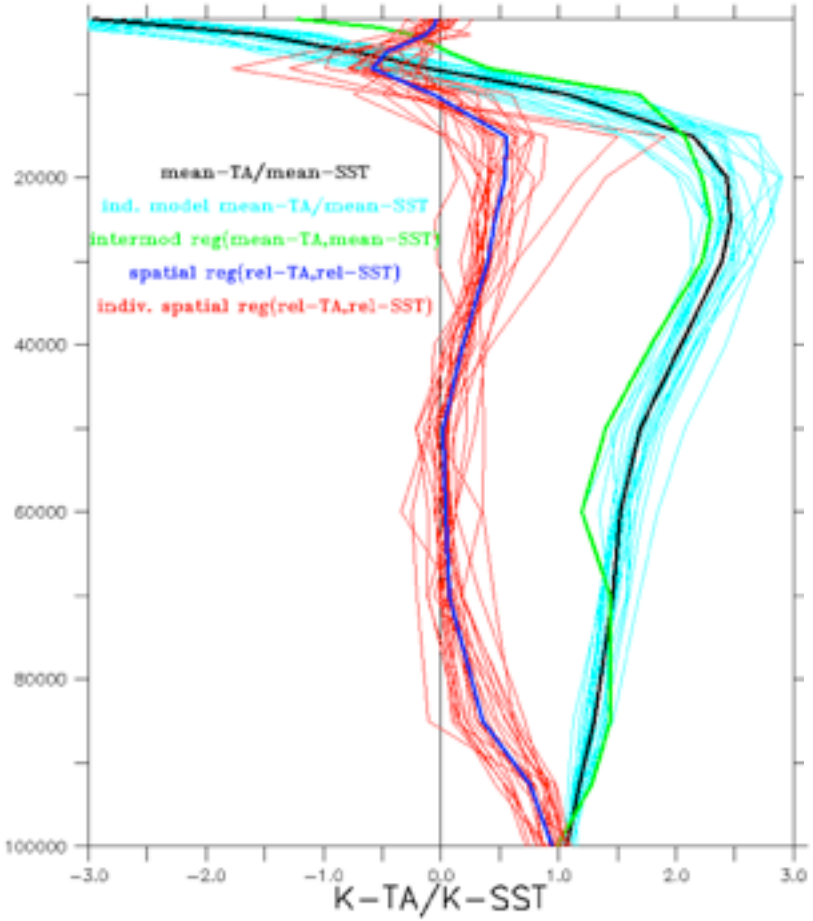
- IPCC-AR4 model decadal noise and response to 2xCO2, 4xCO2.

- NCEP Reanalysis trend.

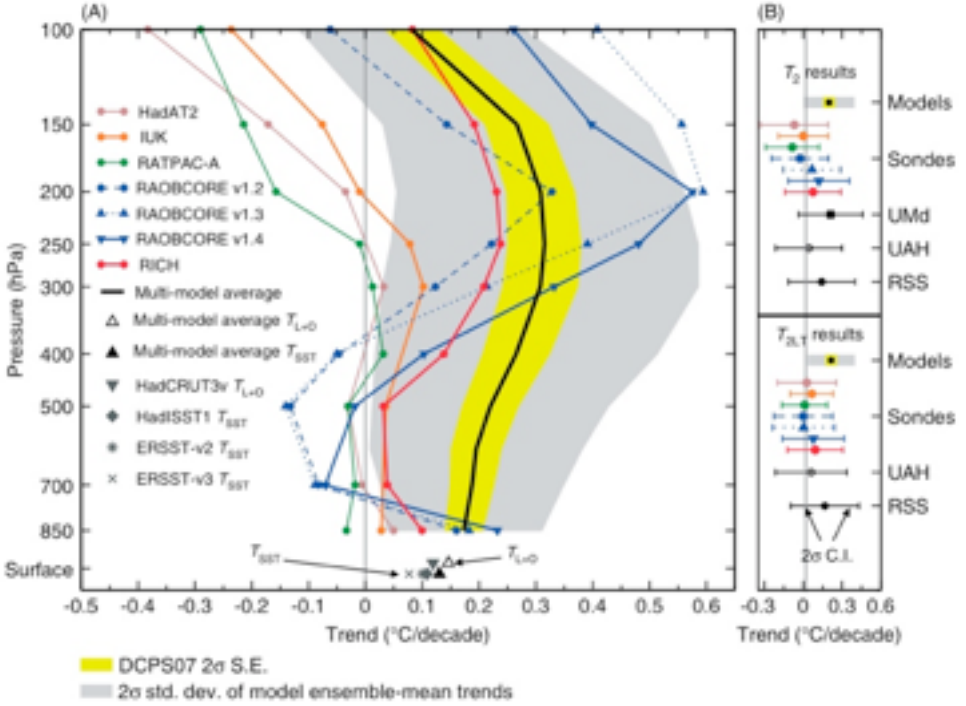
Do we know vertical structure of warming well enough?
Relatively small inter-model TA trend spread still gives large <PI'> spread (±2m/s)

For now: assume GCM lapse rate response "reasonable" estimate.

IPCC-AR4 21st Cy model response

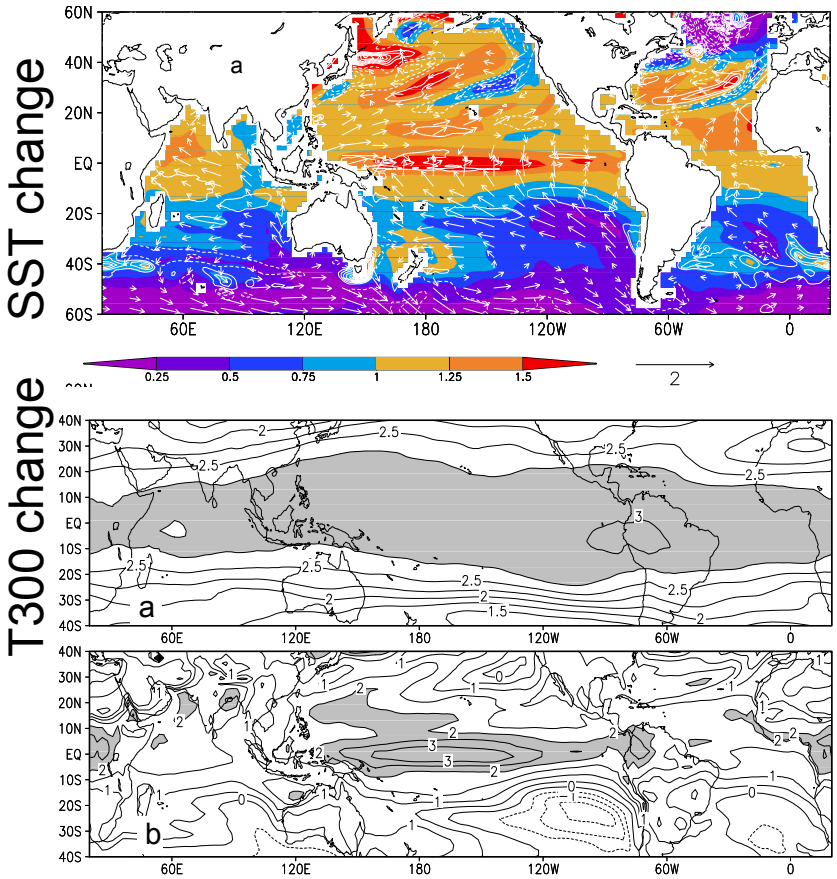


Observational estimates and
IPCC-AR4 historical runs

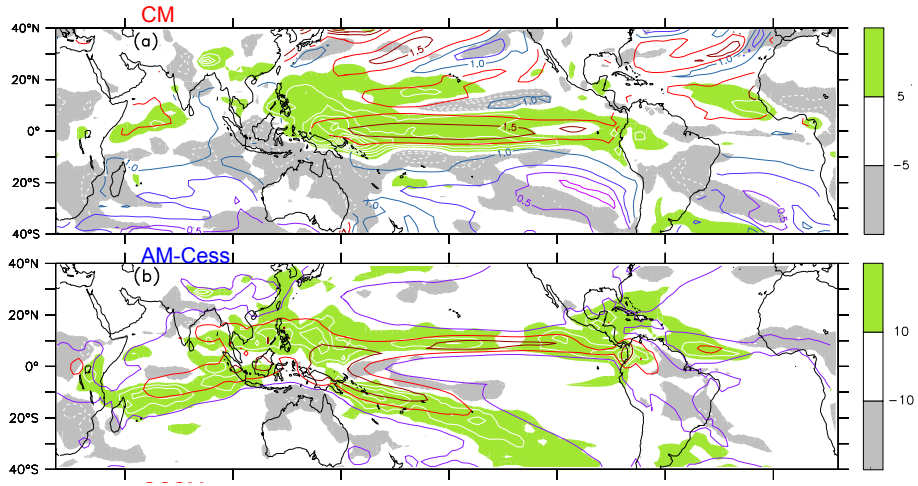


Santer et al (2008)

Relative warming impacts precipitation: GFDL CM2.1 21st Century Projection



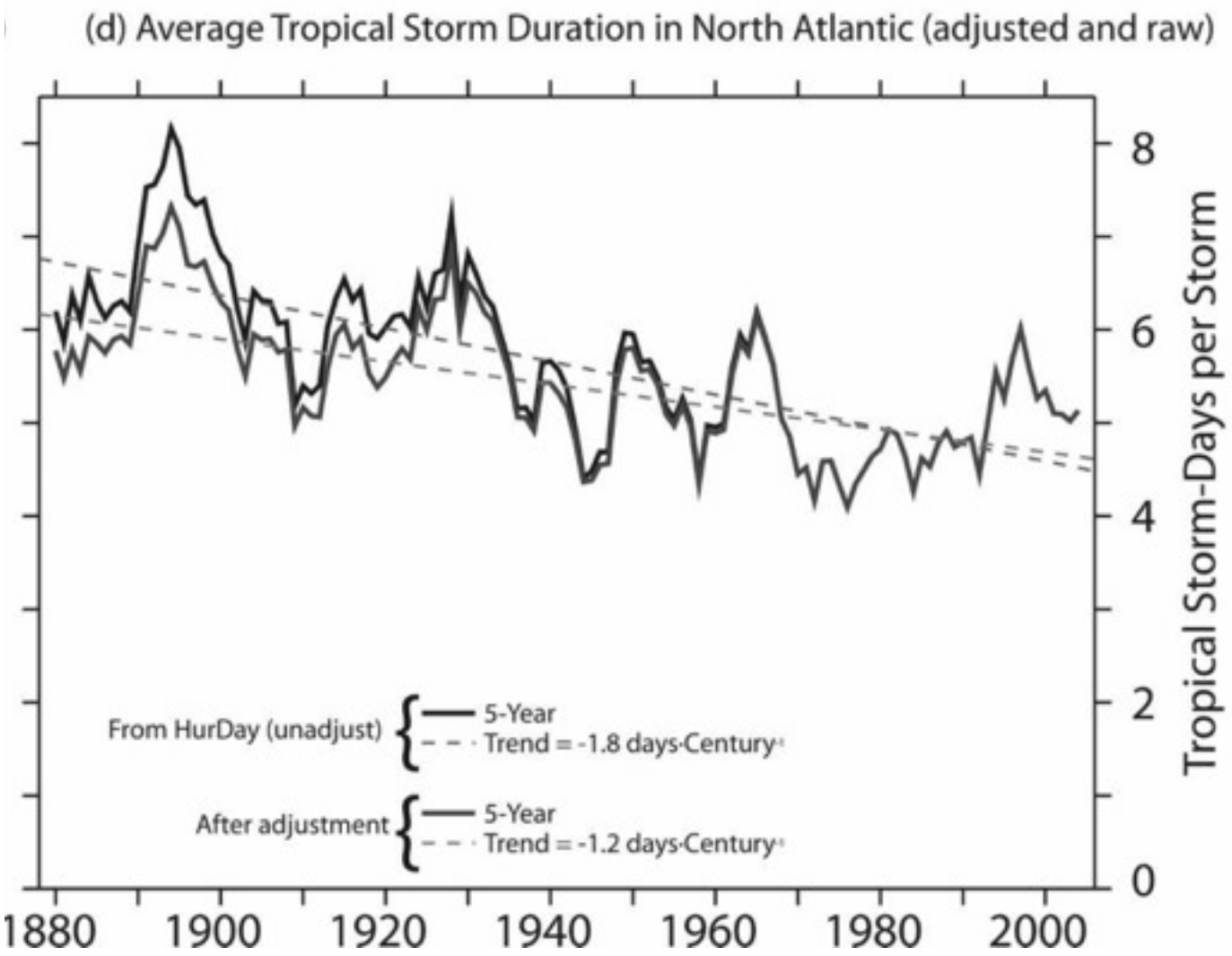
Precip change from non-uniform warming looks like SST pattern.



Precip change from uniform warming looks like mean precip.

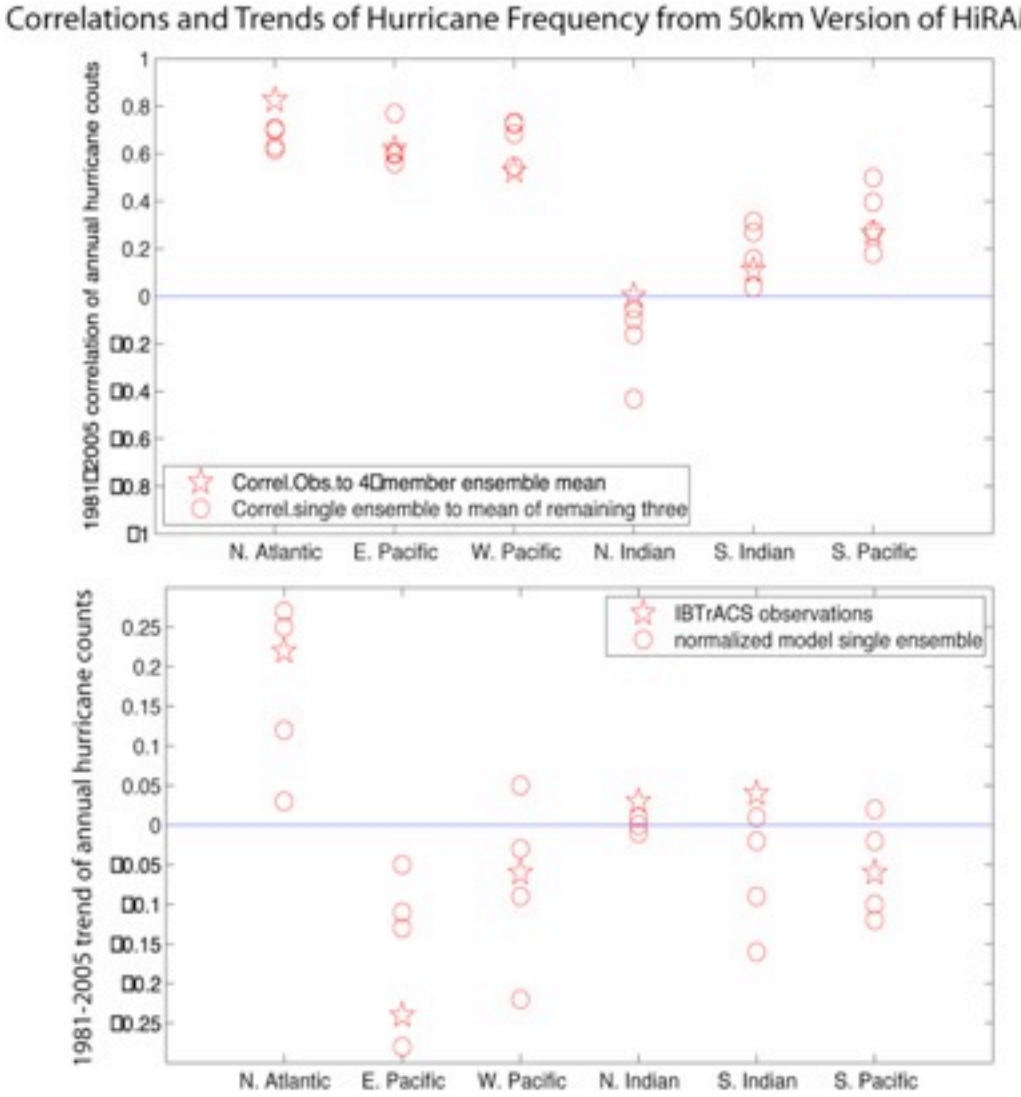
Xie et al (2010)

Tropical storm duration exhibits a large decrease, even with adjustment: why?



Vecchi and Knutson, J. Climate, 2008.

HiRAM models can recover trends and variations in hurricane and TS frequency when forced with SST.



Correlation to obs. similar to that of model to itself.

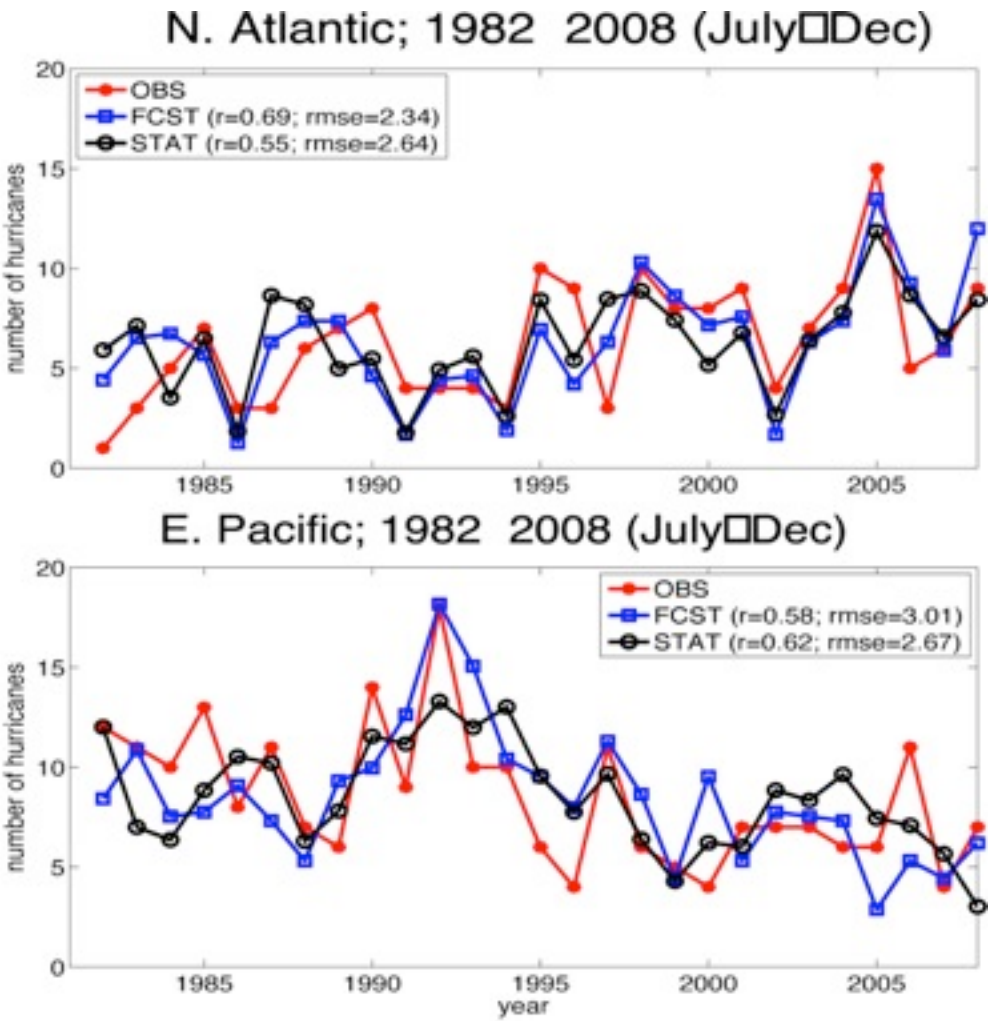
For each basin:

$$N'(t) = N_m(t) \cdot \langle N_o \rangle / \langle N_m \rangle$$

Trend of normalized model counts not distinguishable from obs.

Zhao et al (2010, J. Climate)

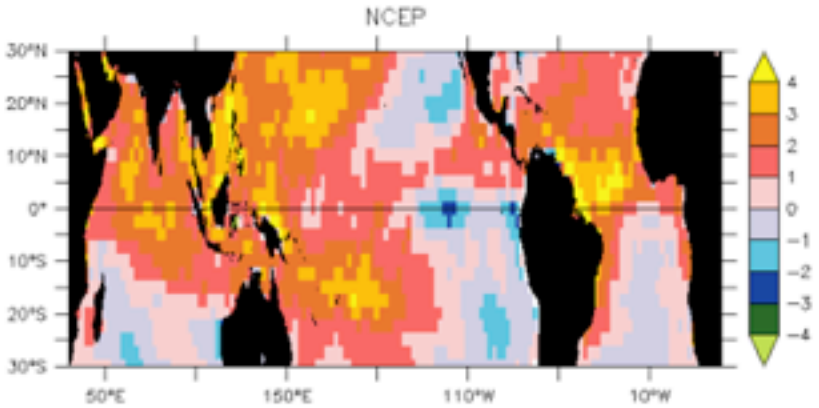
Simple statistical seasonal forecast persisting June relative SSTA performs well

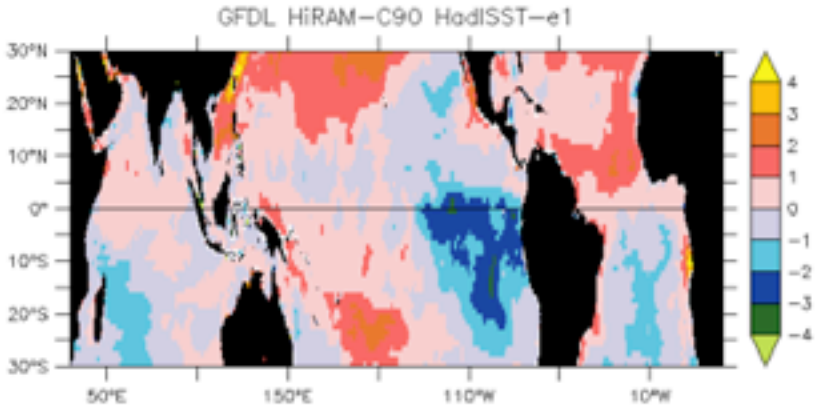


Linear regression on June relative SSTA recovers much of persisted SSTA GCM hurricane frequency predictions.

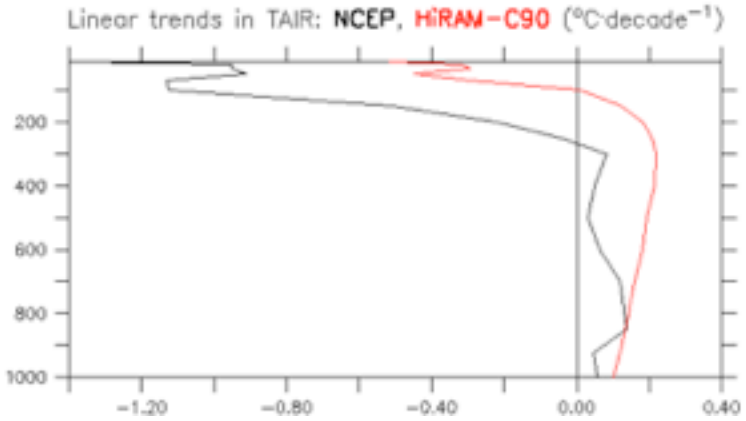
Zhao, Held and Vecchi (2010, MWR Submitted)

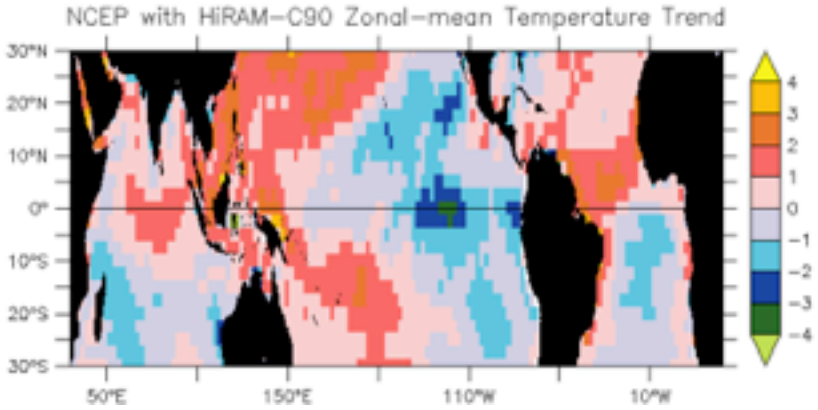
NCEP and GCMs exhibit different lapse rate and PI trends





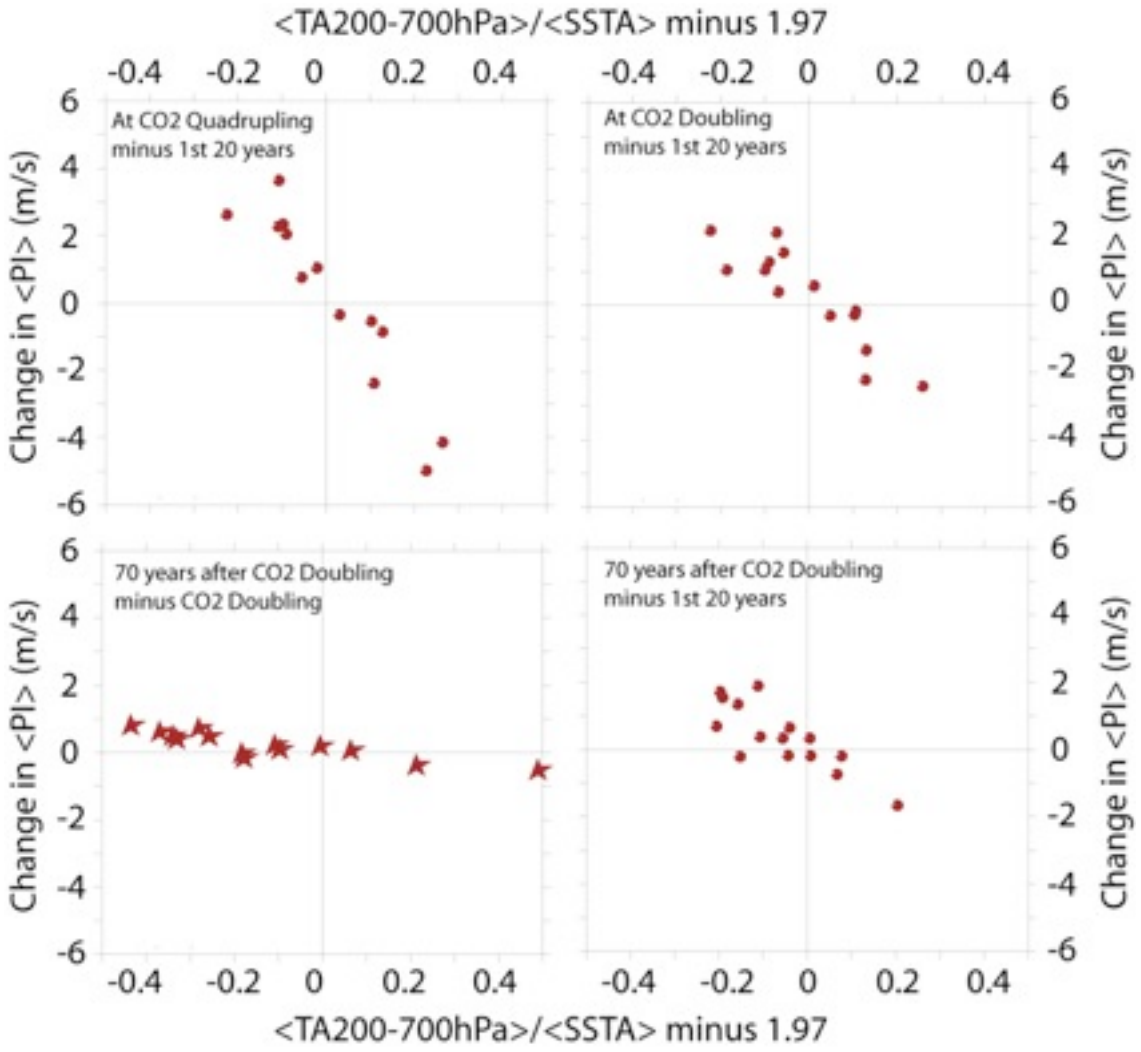
Linear trends in annual PI 1980–2005 ($m \cdot s^{-1} \cdot decade^{-1}$)





Gabriel Vecchi, NOAA/GFDL, Princeton, NJ

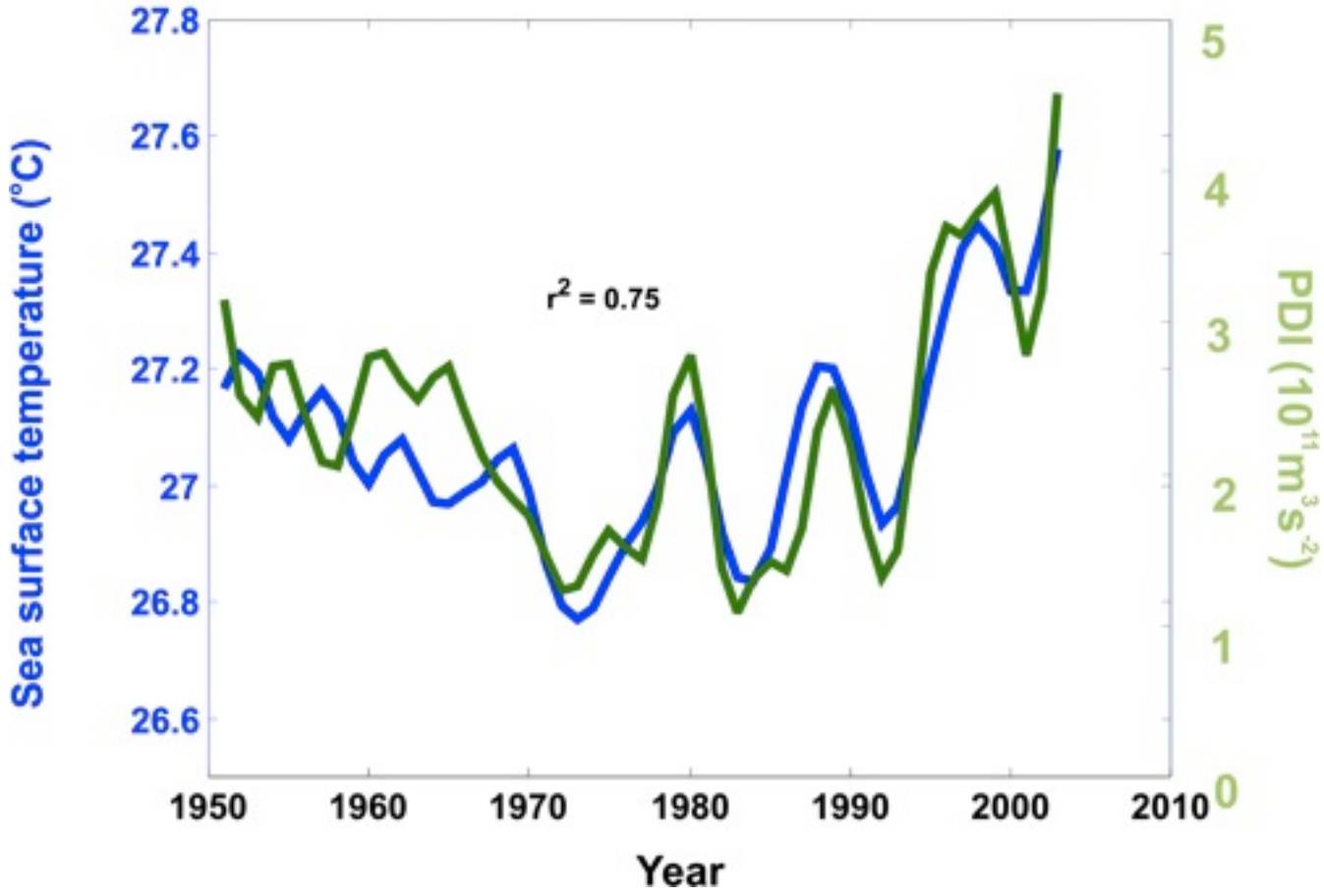
In GCMs, sign of sensitivity of tropical-mean PI scales with ratio of Tropospheric TA to SSTA



PI = K·(<TA>/<SST>-1.97)

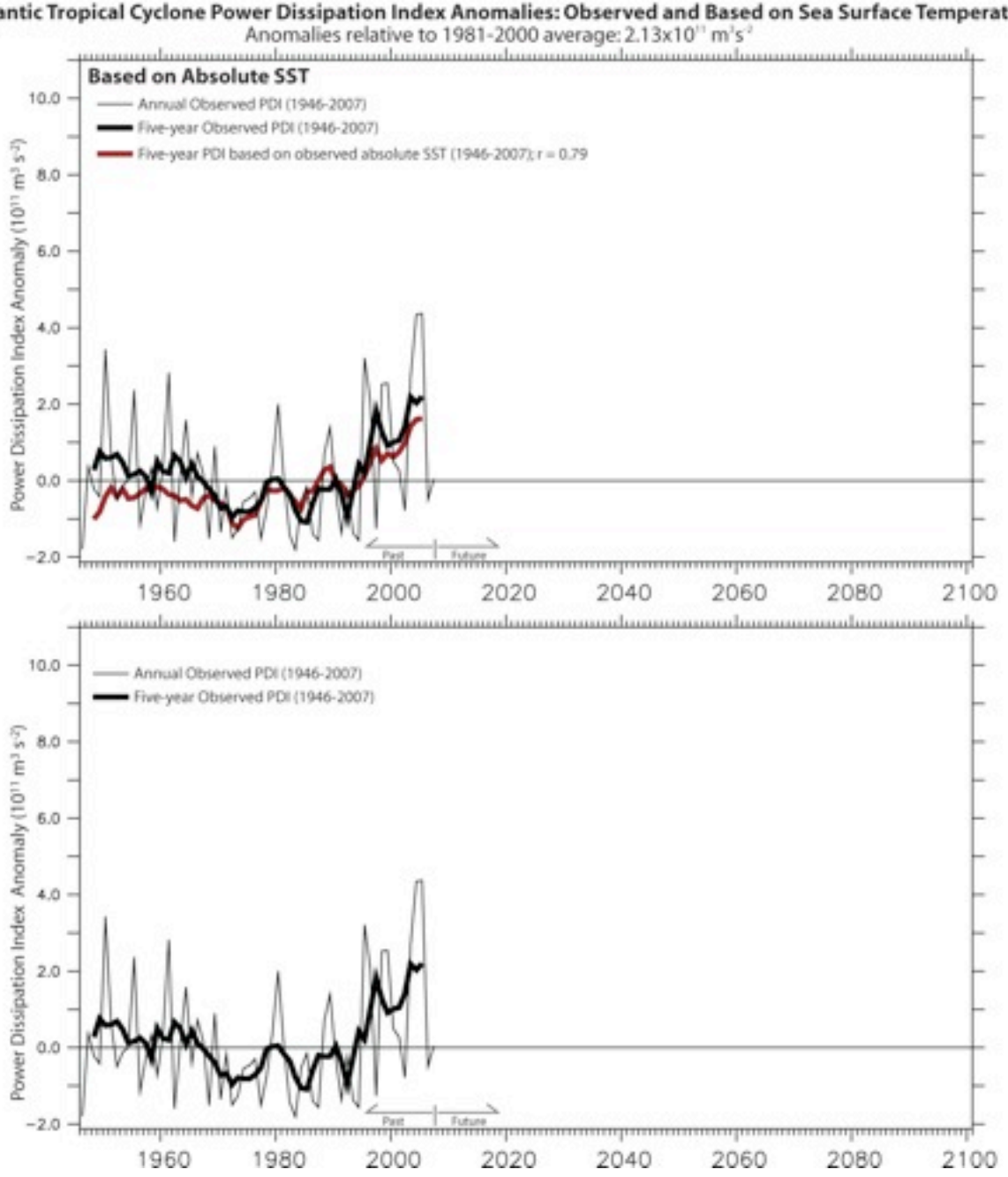
Where does magnitude (K) come from? Not a constant.

There is some recent evidence that overall Atlantic hurricane activity may have increased since in the 1950s and 60s in association with increasing sea surface temperatures…



PDI is proportional to the time integral of the cube of the surface wind speeds accumulated across all storms over their entire life cycles.

Source: Emanuel (2007)



see also Emanuel (2005, 2007)

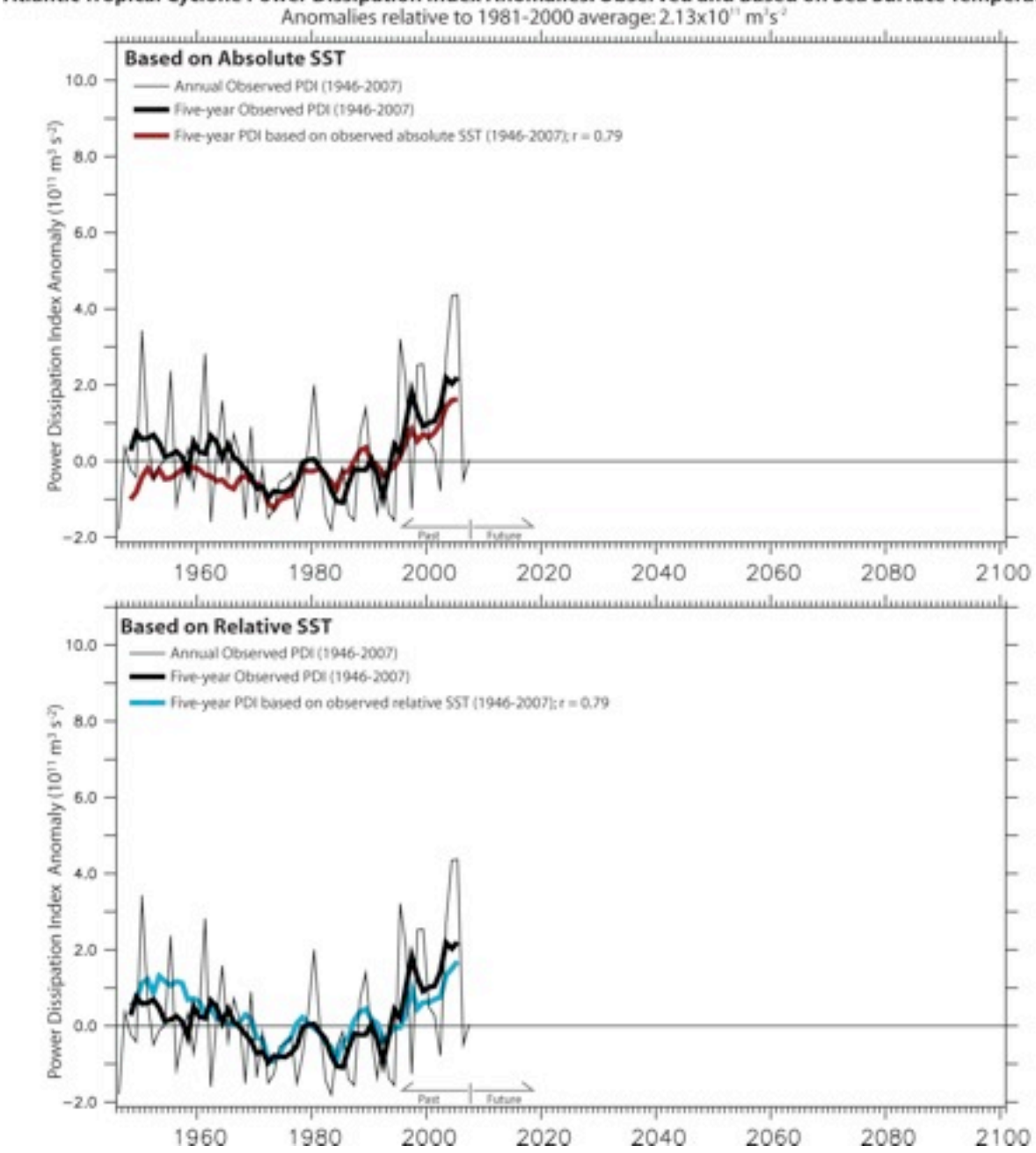
Observed Activity
Absolute MDR SST

If causal, can attribute to GHG.

e.g. CCSP-3.3

Storm count*duration has been a control of historical PDI changes (Maue and Hart (2007))

Vecchi, Swanson and Soden (2008, Science)



see also Emanuel (2005, 2007)

Observed Activity

Absolute MDR SST

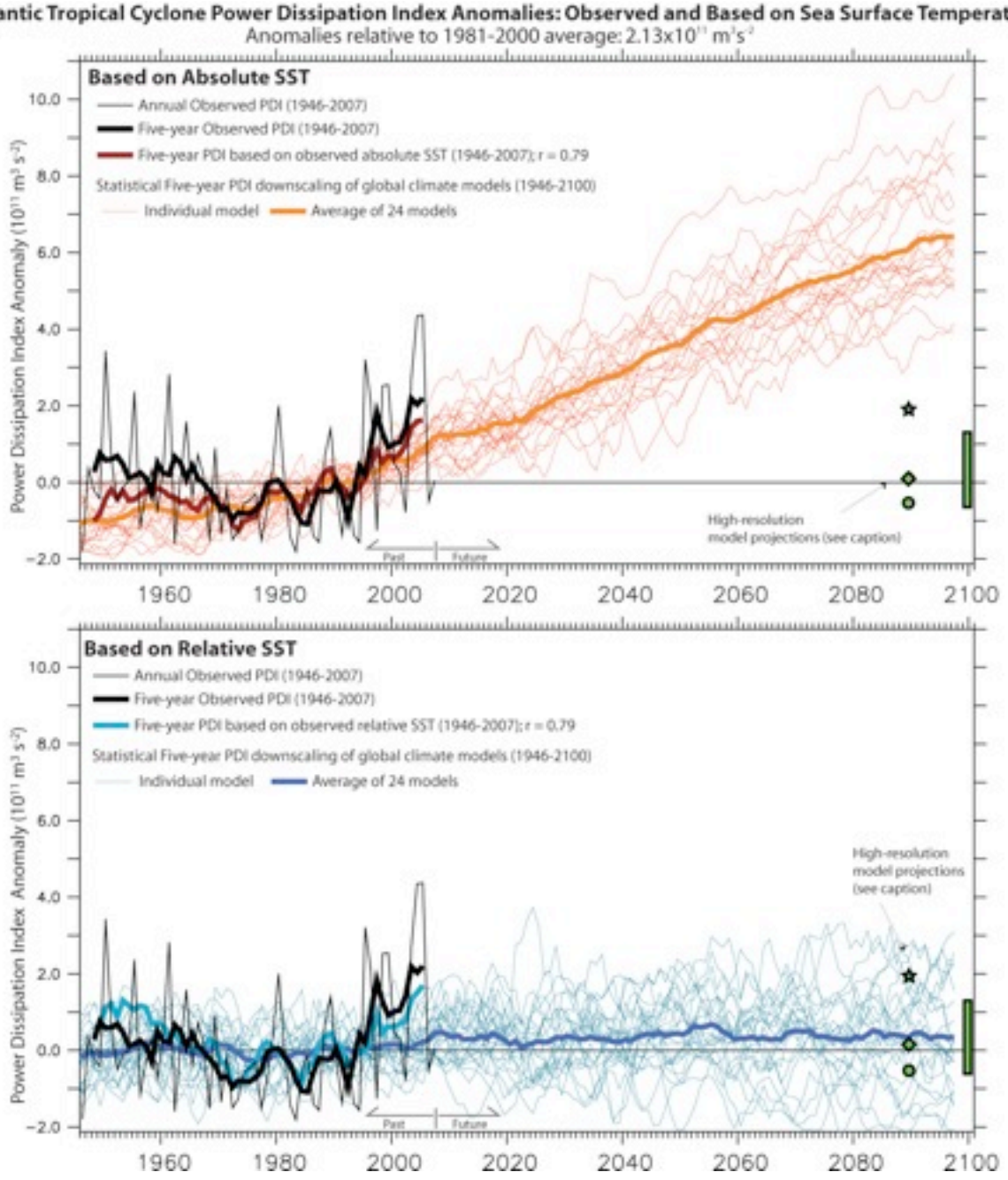
If causal, can attribute to GHG.

see also Swanson (2008)

Relative MDR SST

If causal, cannot attribute.

Vecchi, Swanson and Soden (2008, Science)



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)

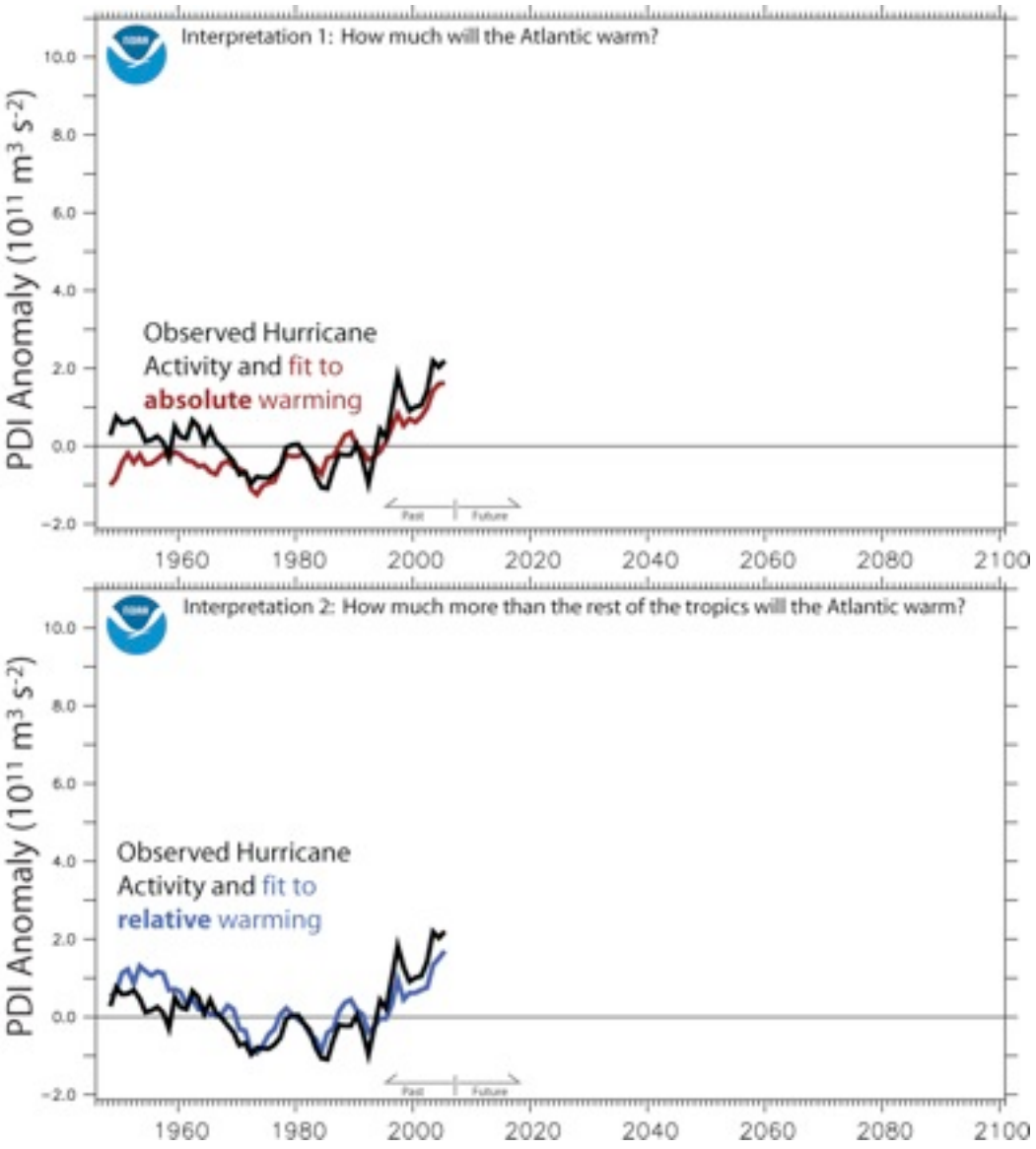
Relative SST

Model Rel. SST

Vecchi, Swanson and Soden (2008, Science)

Gabriel Vecchi, NOAA/GFDL, Princeton, NJ

Two Temperature Predictors of Atlantic Hurricane Activity



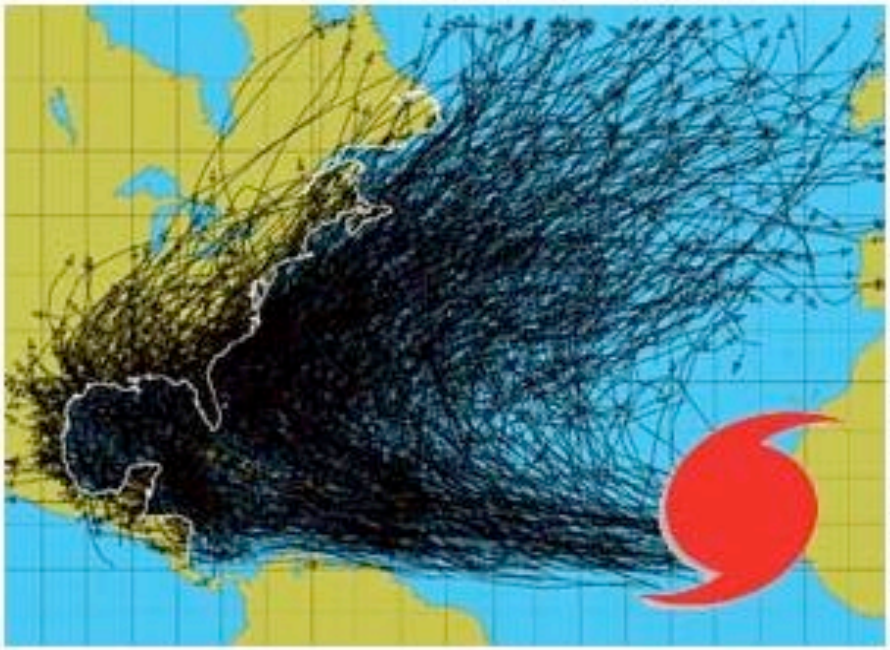
Observed Activity
Absolute Atlantic Temperature

Observed Activity
Relative Atlantic Temperature

Vecchi, Swanson and Soden (2008, Science)

Gabriel Vecchi, NOAA/GFDL, Princeton, NJ

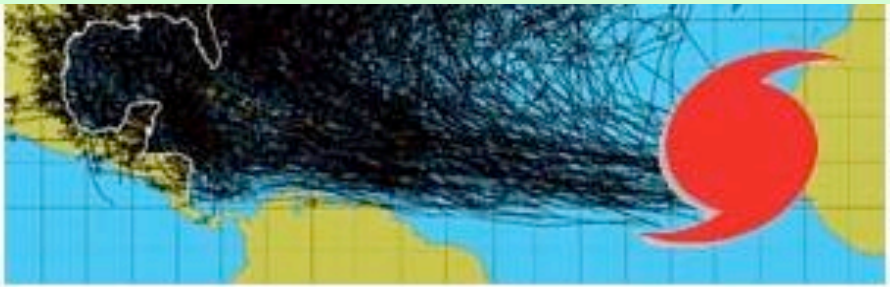
NOAA ATTRIBUTES RECENT INCREASE IN HURRICANE ACTIVITY TO NATURALLY OCCURRING MULTI-DECADAL CLIMATE VARIABILITY*



Nov. 29, 2005 — The nation is now wrapping up the 11th year of a new era of heightened Atlantic hurricane activity. This era has been unfolding in the Atlantic since 1995, and is expected to continue for the next decade or perhaps longer. NOAA attributes this increased activity to natural occurring cycles in tropical climate patterns near the equator. These cycles, called "the tropical multi-decadal signal," typically last several decades (20 to 30 years or even longer). As a result, the North Atlantic experiences alternating decades long (20 to 30 year periods or even longer) of above normal or below normal hurricane seasons. NOAA research shows that the tropical multi-decadal signal is causing the increased Atlantic hurricane activity since 1995, and is not related to greenhouse warming. **(Click NOAA**

Research by NOAA scientists [..] and [..], currently in press with the *Journal of Climate*, describes the tropical multi-decadal signal and shows that it accounts for the entire inter-related set of conditions that controls hurricane activity for decades at a time."

*EDITOR'S NOTE: This consensus in this on-line magazine story represents the views of some NOAA hurricane researchers and forecasters, but does not necessarily represent the views of all NOAA scientists. It was not the intention of this article to discount the presence of a human-induced global warming element or to attempt to claim that such an element is not present. There is a robust, on-going discussion on hurricanes and climate change within NOAA and the scientific community.



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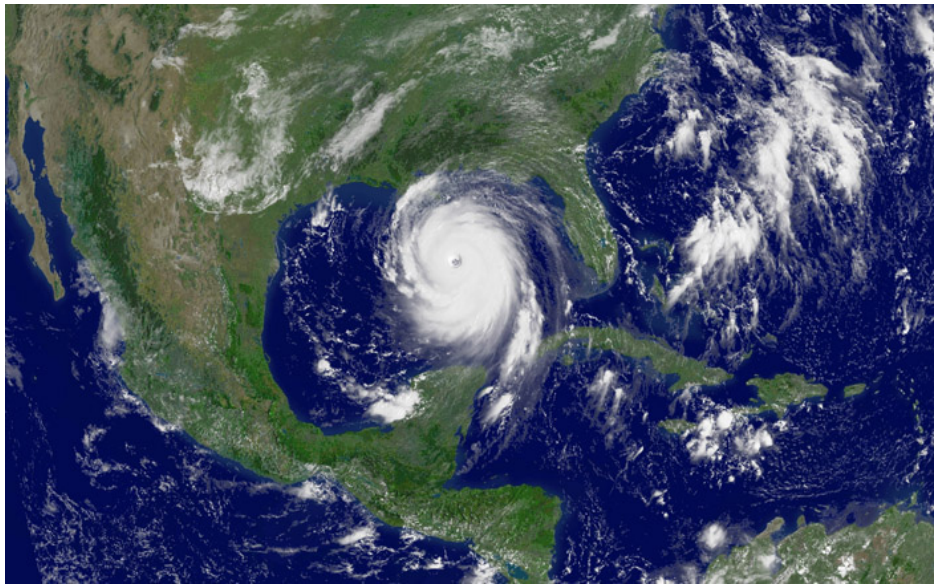


ROSS GELBSPAN

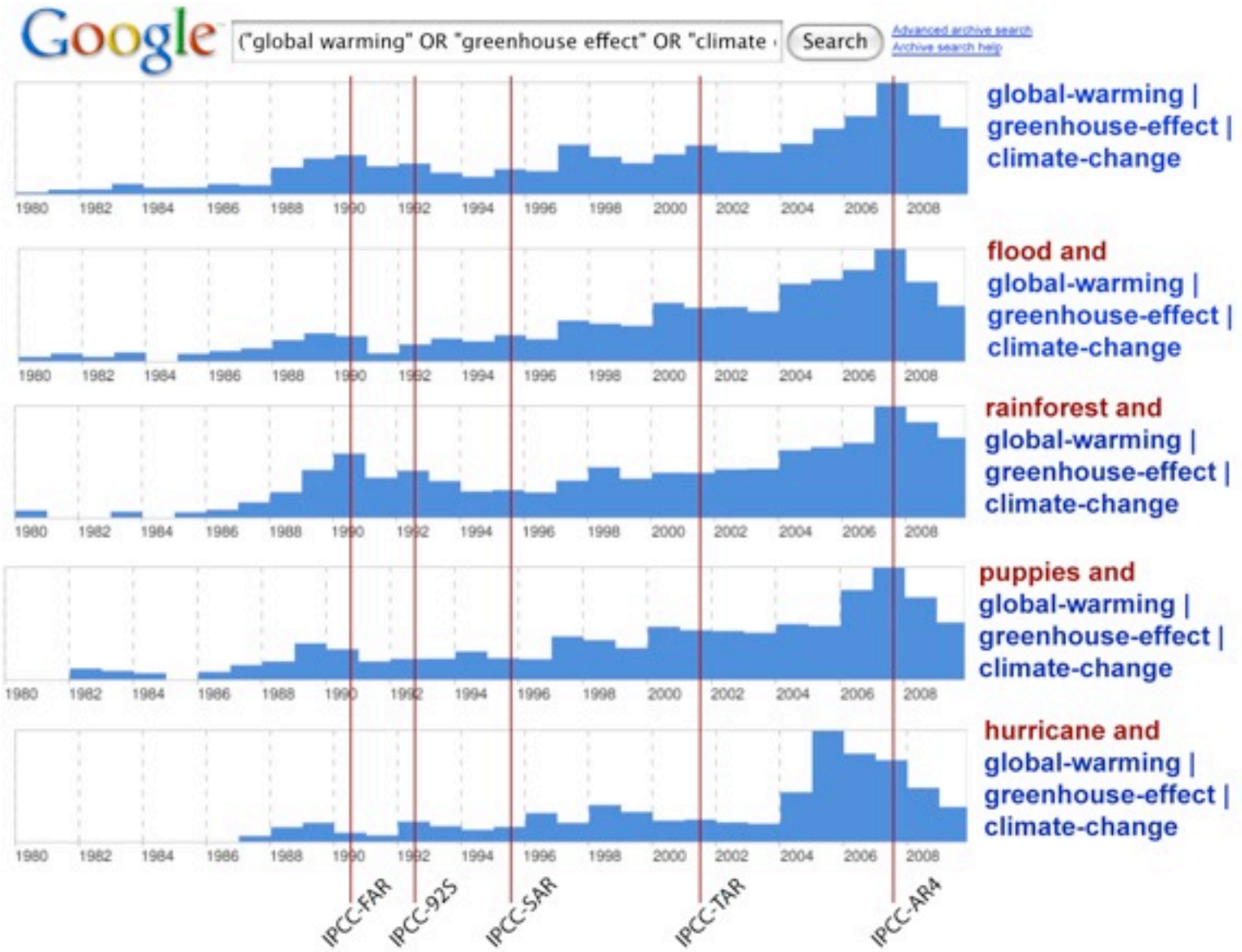
Katrina's real name

The Boston Globe

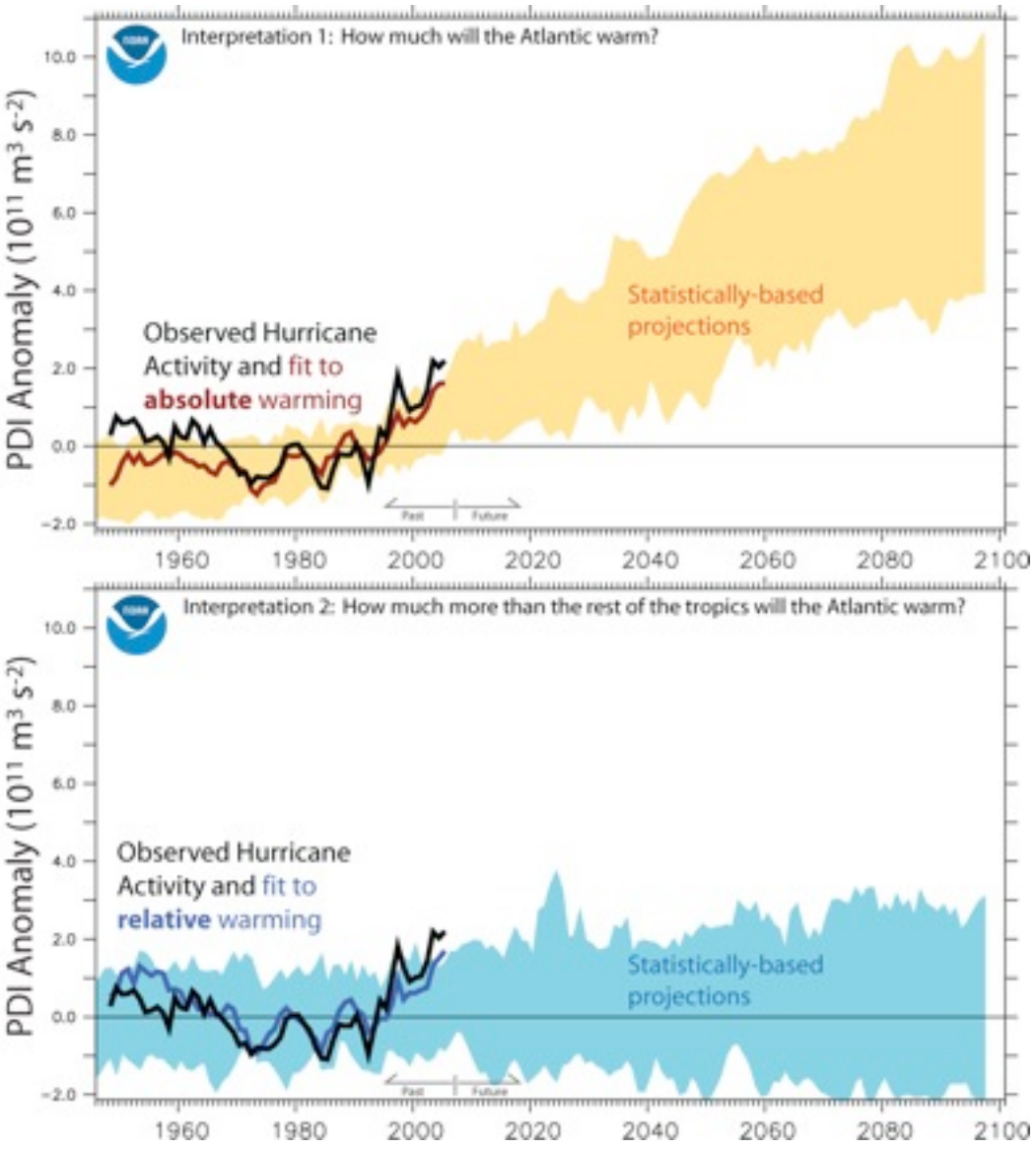
By Ross Gelbspan | August 30, 2005

THE HURRICANE that struck Louisiana yesterday was nicknamed Katrina by the National Weather Service. Its real name is global warming.

News search on global warming and impacts



Two Statistical Projections of Atlantic Hurricane Activity



Observed Activity
Absolute Atlantic Temperature

Observed Activity
Relative Atlantic Temperature

Vecchi, Swanson and Soden (2008, Science)