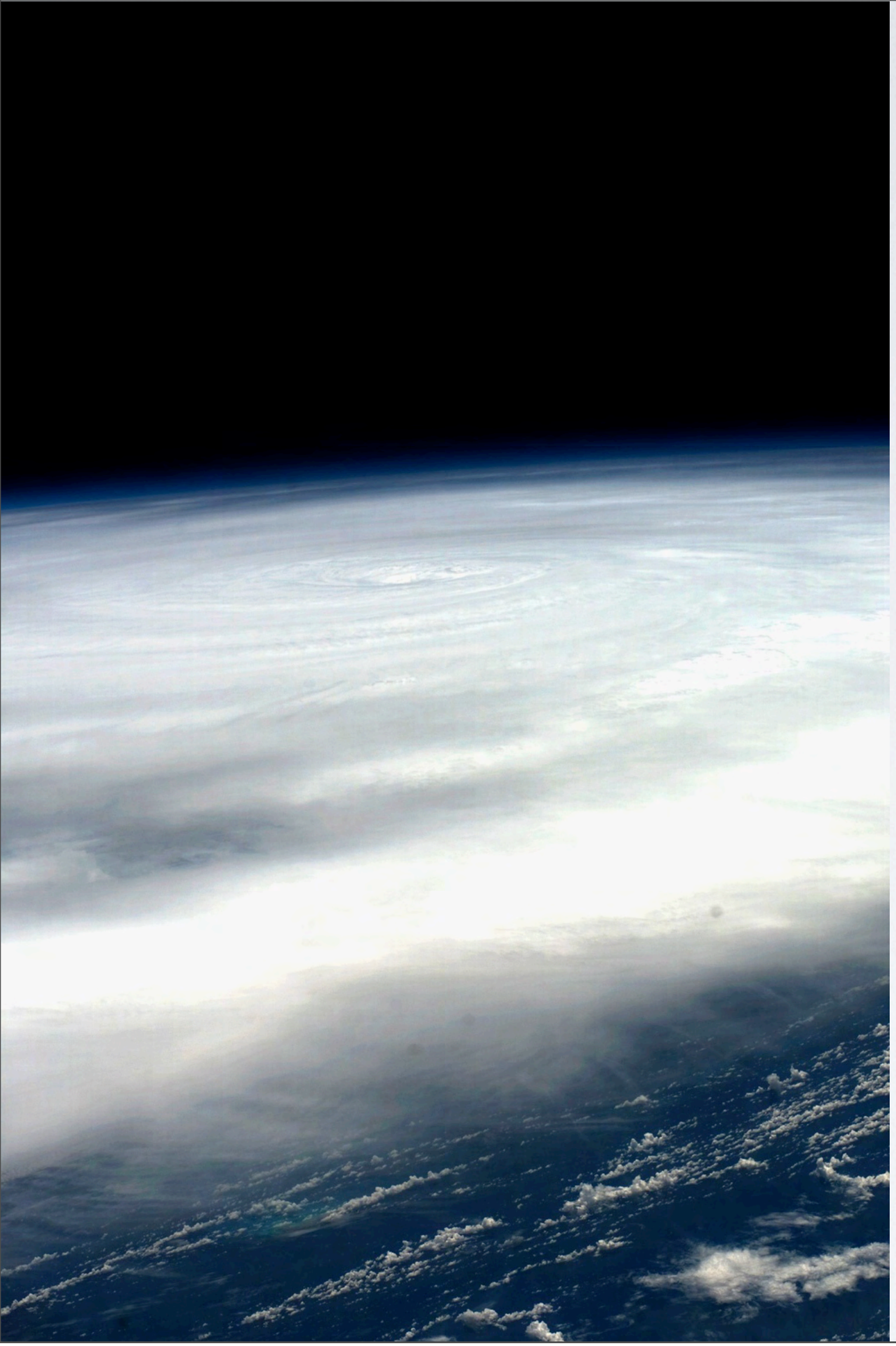
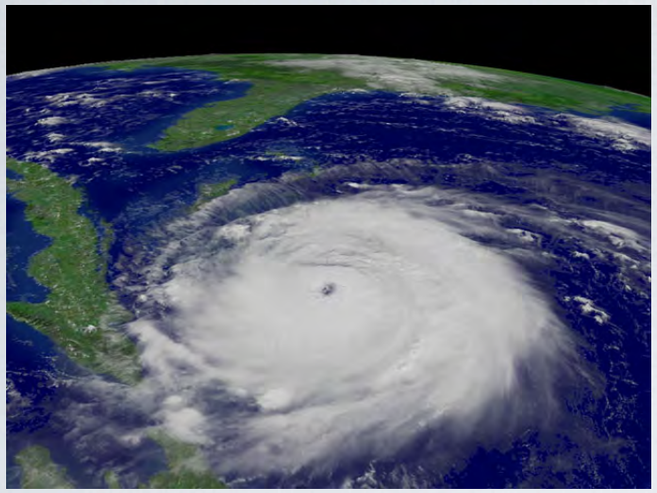


HURRICANE ATTRIBUTION, PREDICTIONS & PROJECTIONS

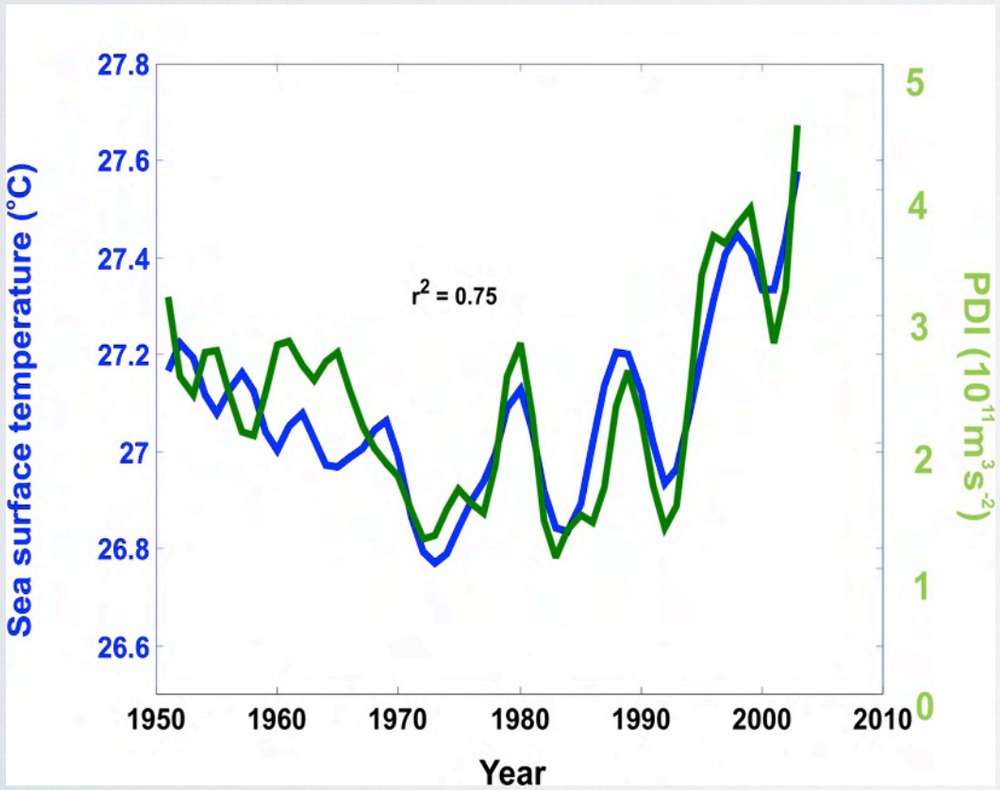
Gabriel Vecchi
NOAA/GFDL
Princeton, NJ

Image: NASA.

North Atlantic tropical cyclones



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



Emanuel (2007, J. Clim.)

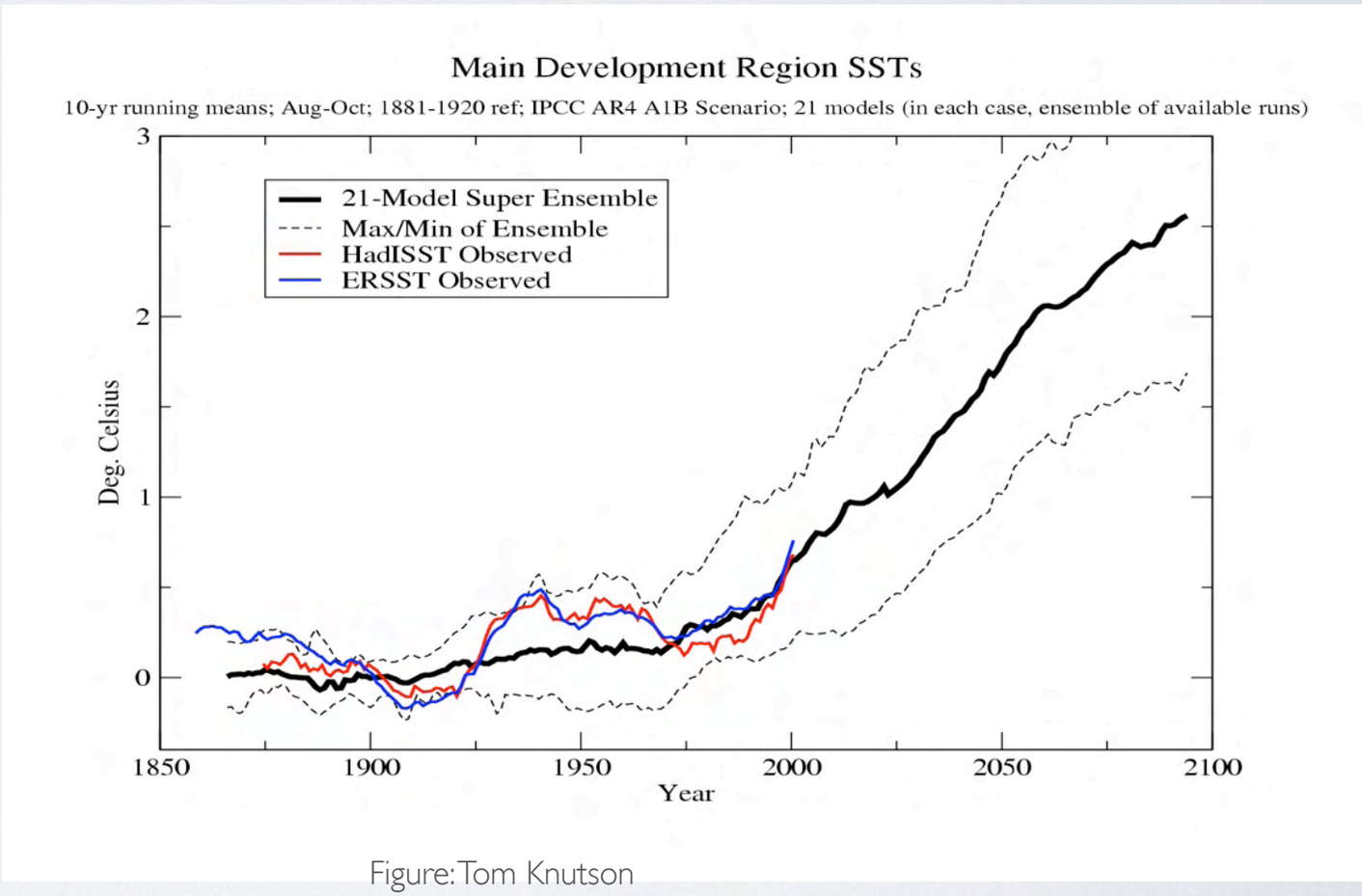
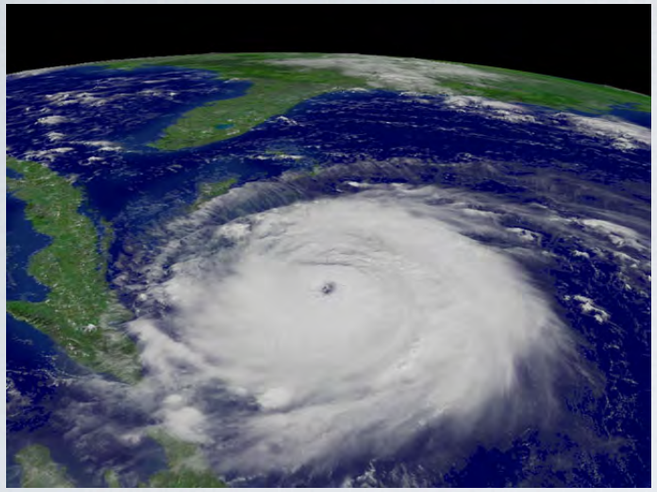
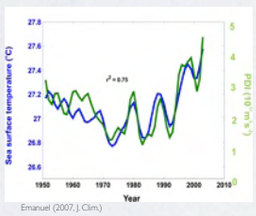


Figure: Tom Knutson

North Atlantic tropical cyclones



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



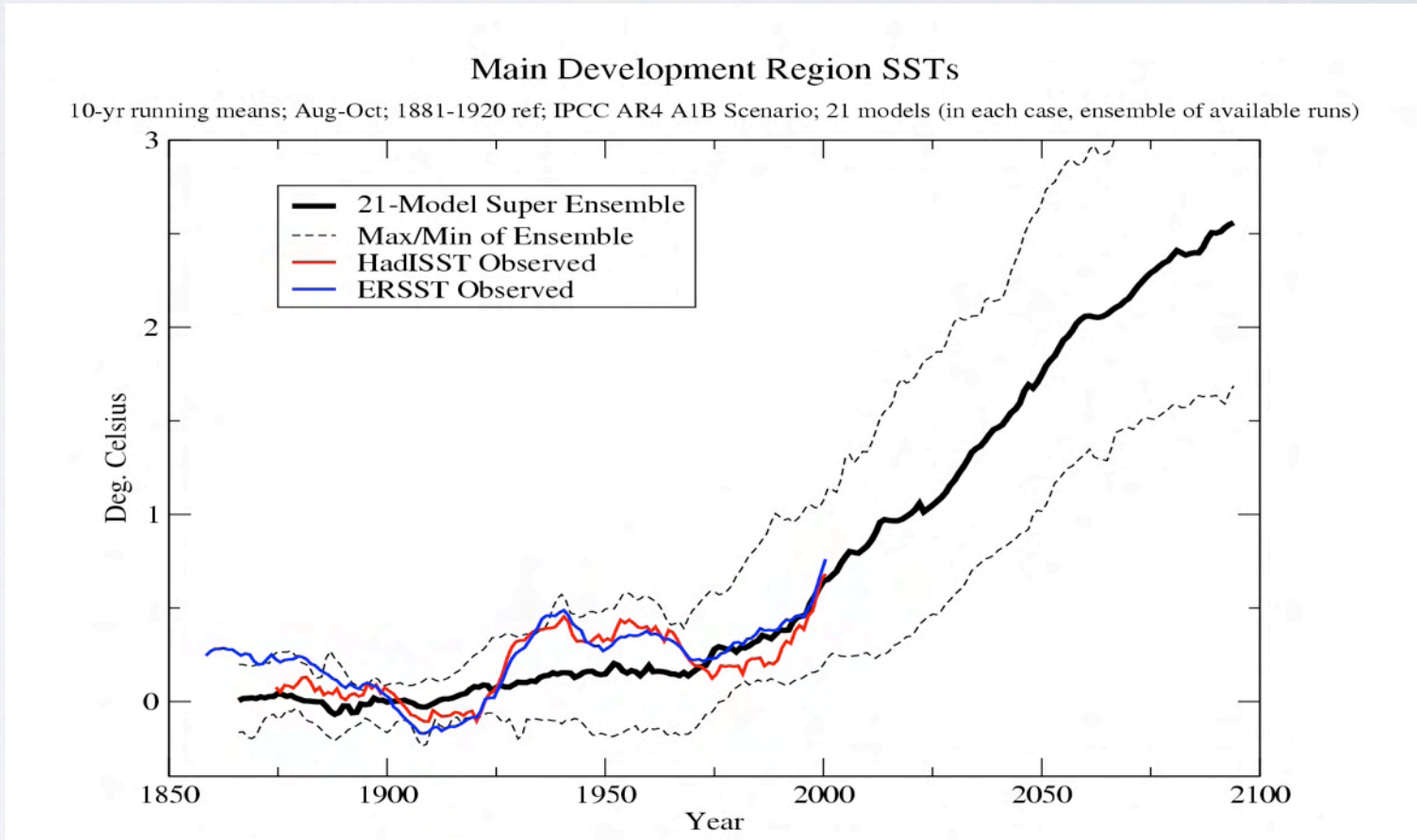
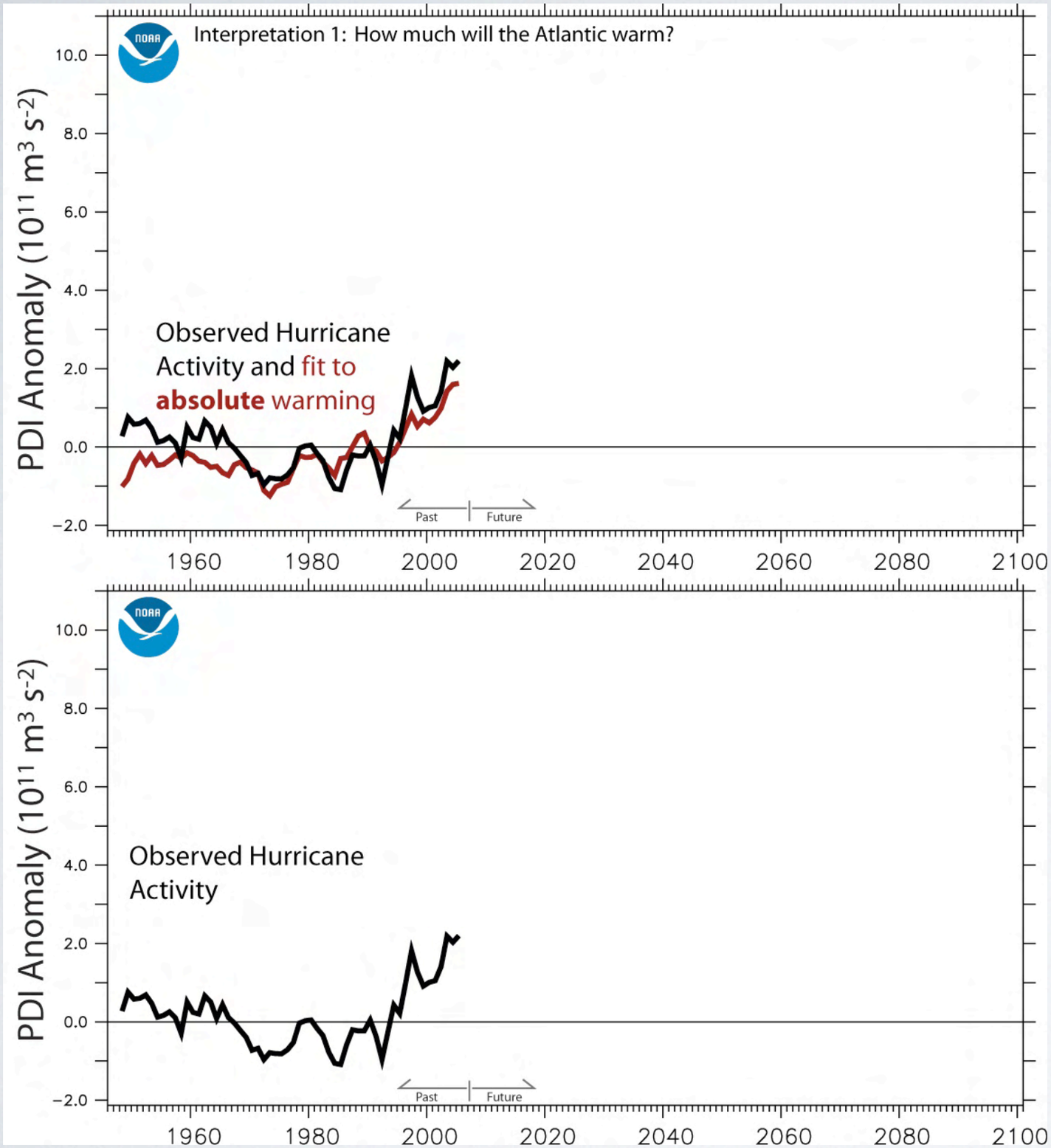


Figure: Tom Knutson

One Temperature Predictor of Atlantic Hurricane Activity

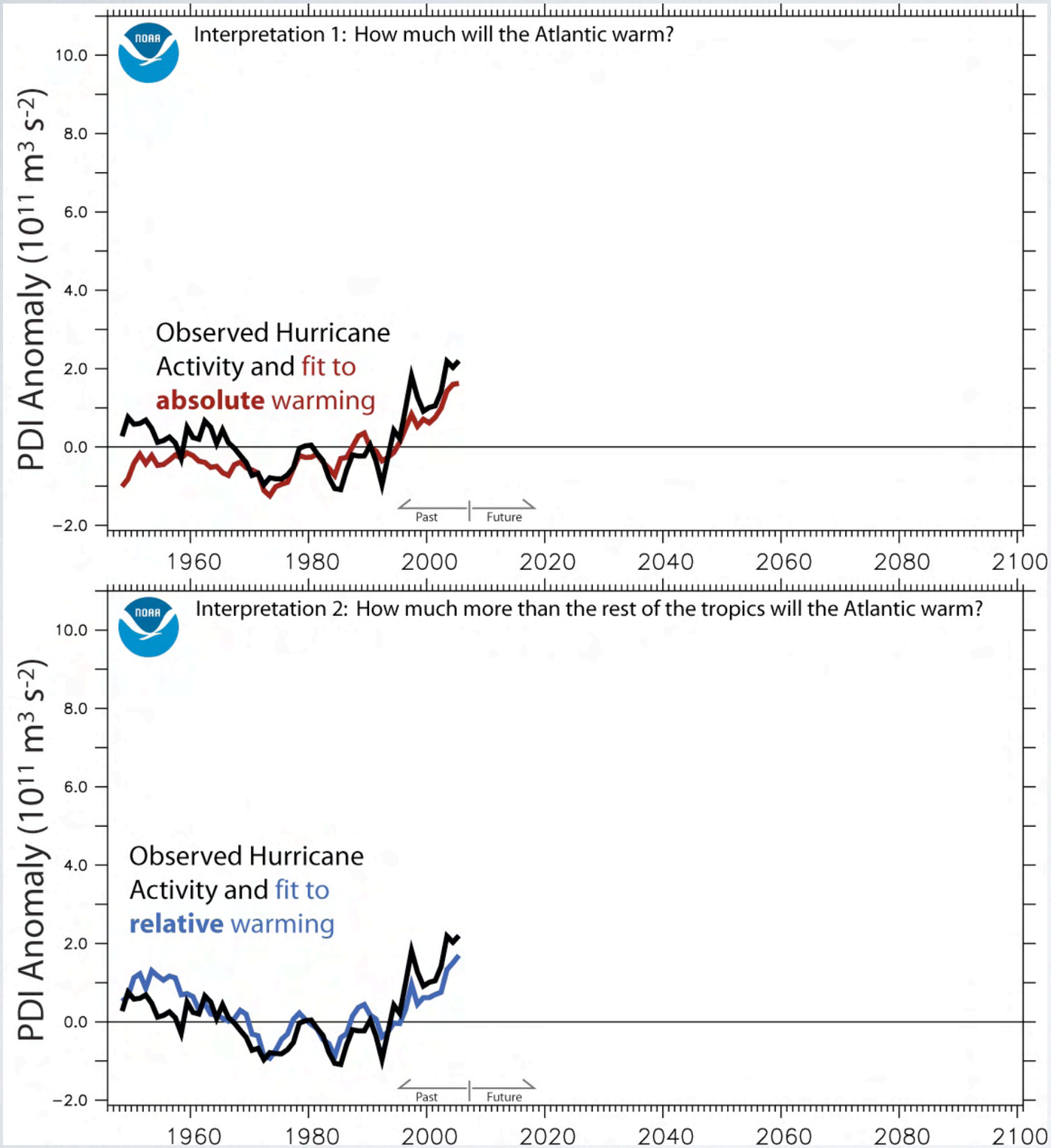


Observed Activity

Absolute Atlantic Temperature

Vecchi, Swanson and Soden (2008, Science)

Two Temperature Predictors of Atlantic Hurricane Activity

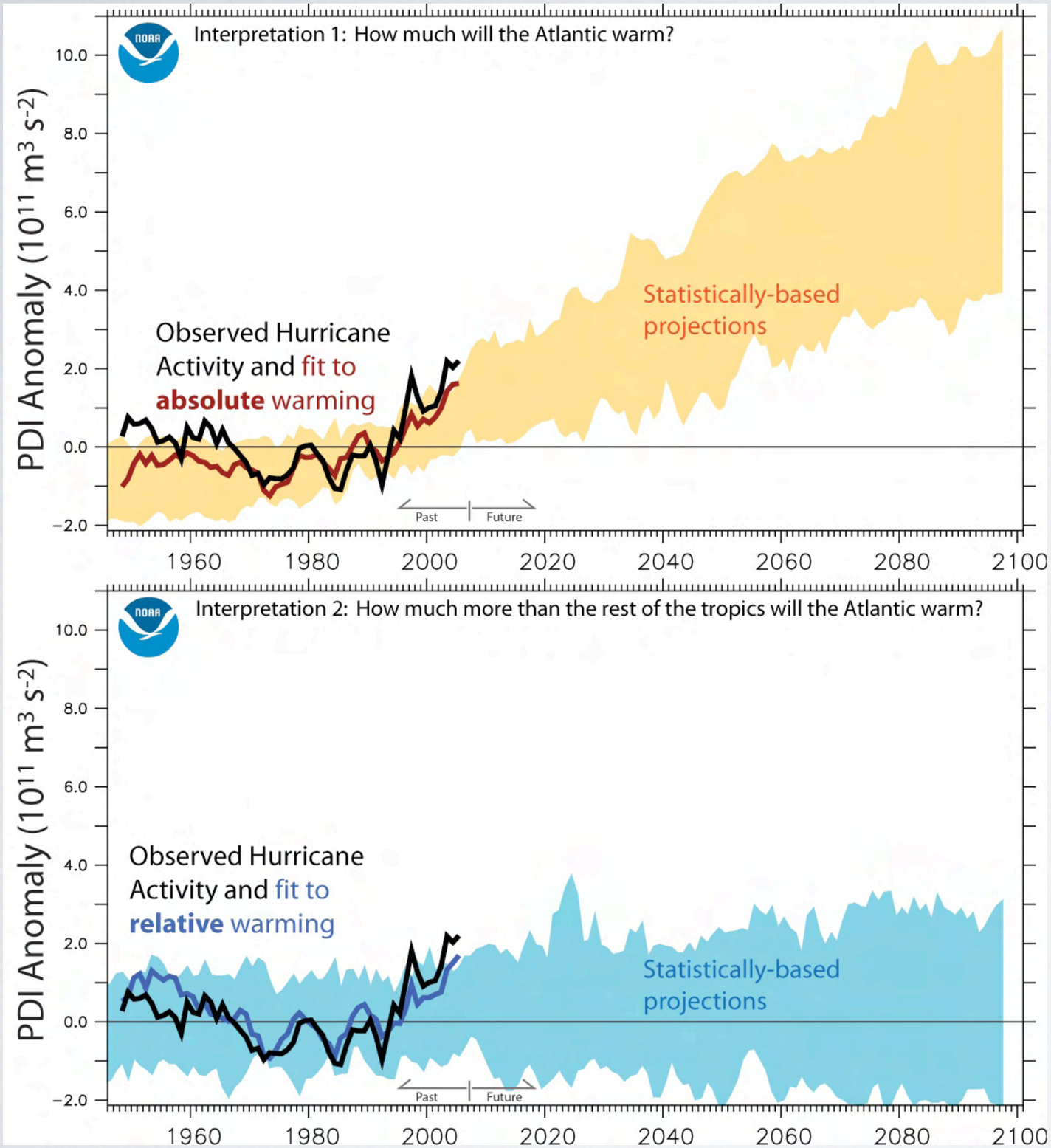


Observed Activity
Absolute Atlantic Temperature

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)

Outline

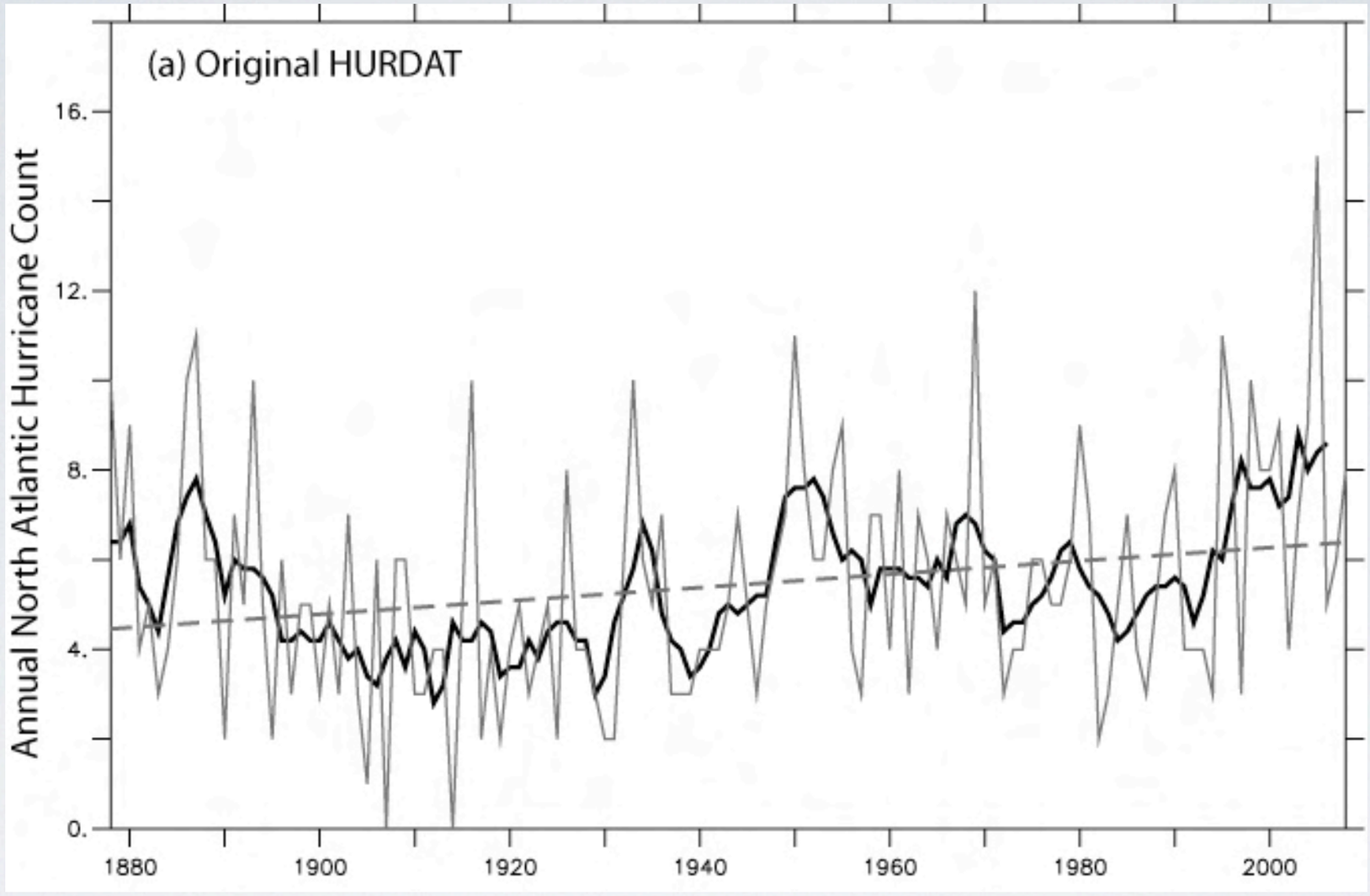
- Tools:
  - Observational records
  - High-resolution dynamical models
  - Statistical models
- Attribution of recent increase in Atlantic activity
- Predictions of seasonal activity
- Century-scale projections

Outline

- Tools:
  - **Observational records**
  - High-resolution dynamical models
  - Statistical models

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

Recorded NA Hurricanes Show Clear Increase

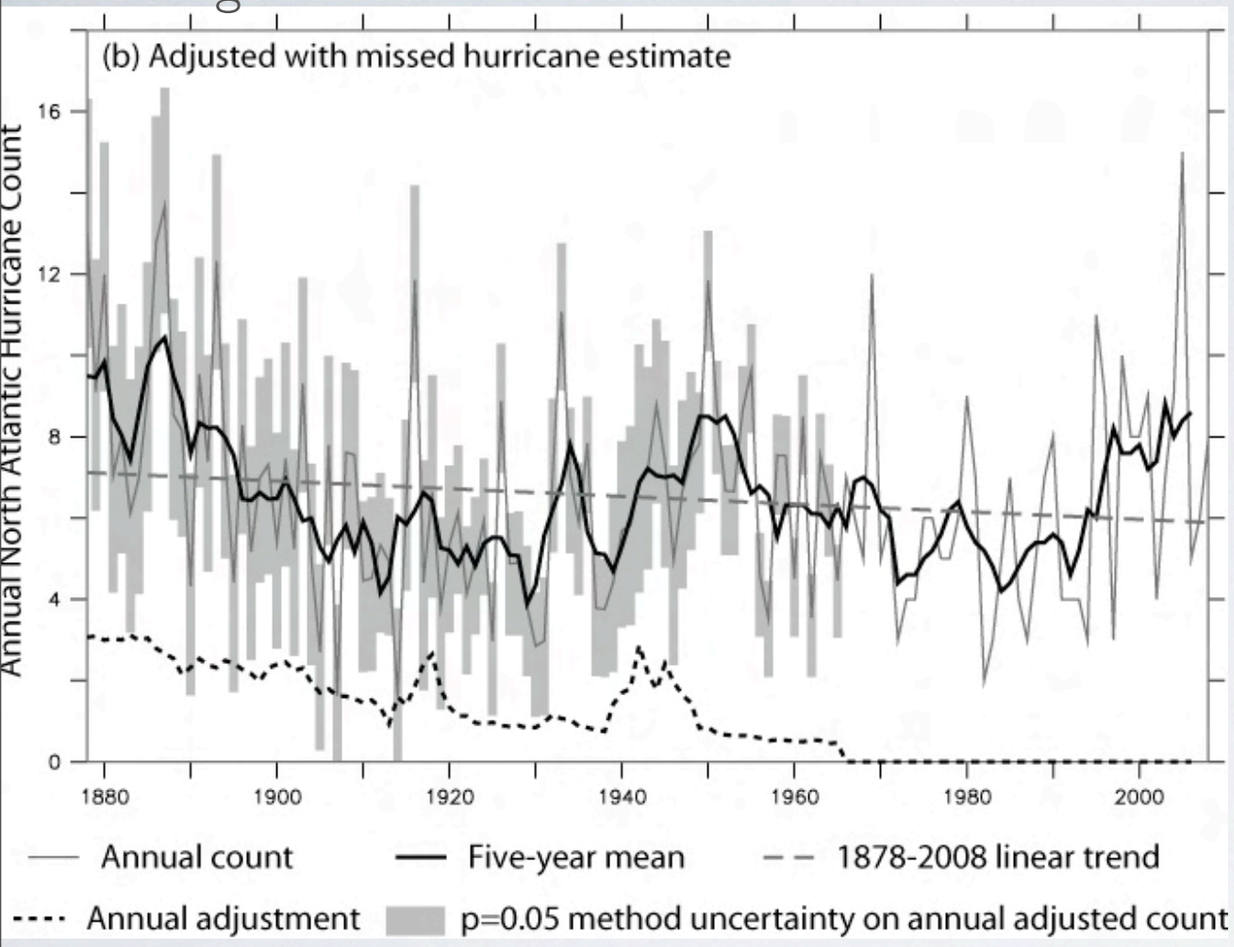


Vecchi and Knutson (2011, J. Climate, in press)

But was there really an increase?

Observed NA Hurricane Frequency Changes

Homogeneized NA Basinwide Hurricane Record



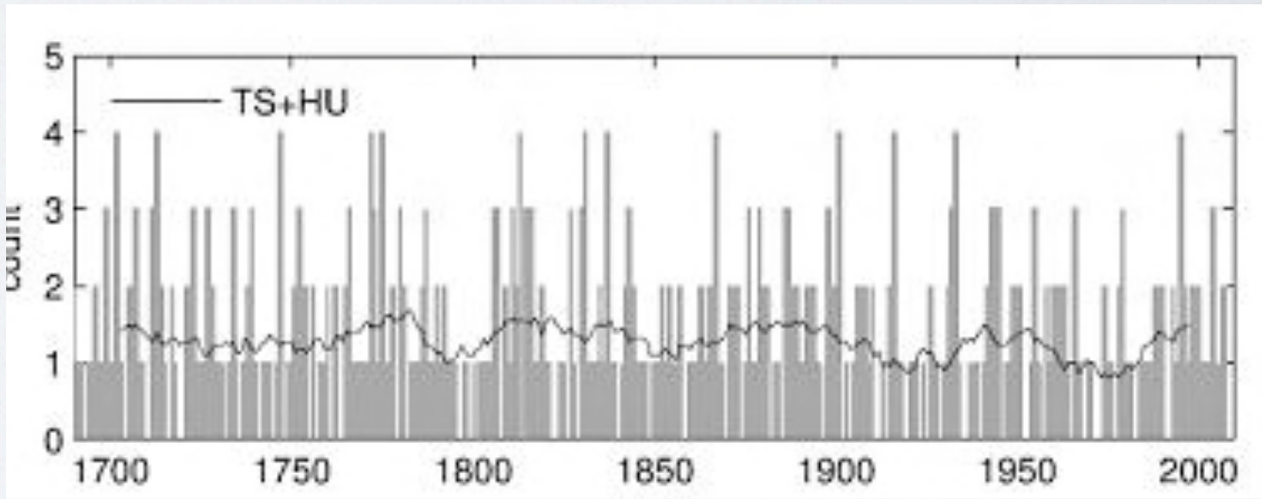
Vecchi and Knutson (2011, J. Climate, in press)

Record Uncertain

Many timescales

Centennial Trend Unclear

Document-based reconstruction of Antilles TS and HU



Chennoweth and Divine (2008)

Various efforts to homogenize instrumental TC record (e.g., Landsea 2007, Chang and Guo 2007, Mann et al 2007, Vecchi and Knutson 2008, Landsea et al 2010, Vecchi and Knutson 2010).

Data Archeology and Paleo-proxy Indicators Complement Instrumental Records (e.g., Chennoweth and Divine 2008, Mann et al 2009)

Outline

- Tools:
  - Observational records
  - **High-resolution dynamical models**
  - Statistical models

- Attribution of recent increase in Atlantic activity
- Predictions of seasonal activity
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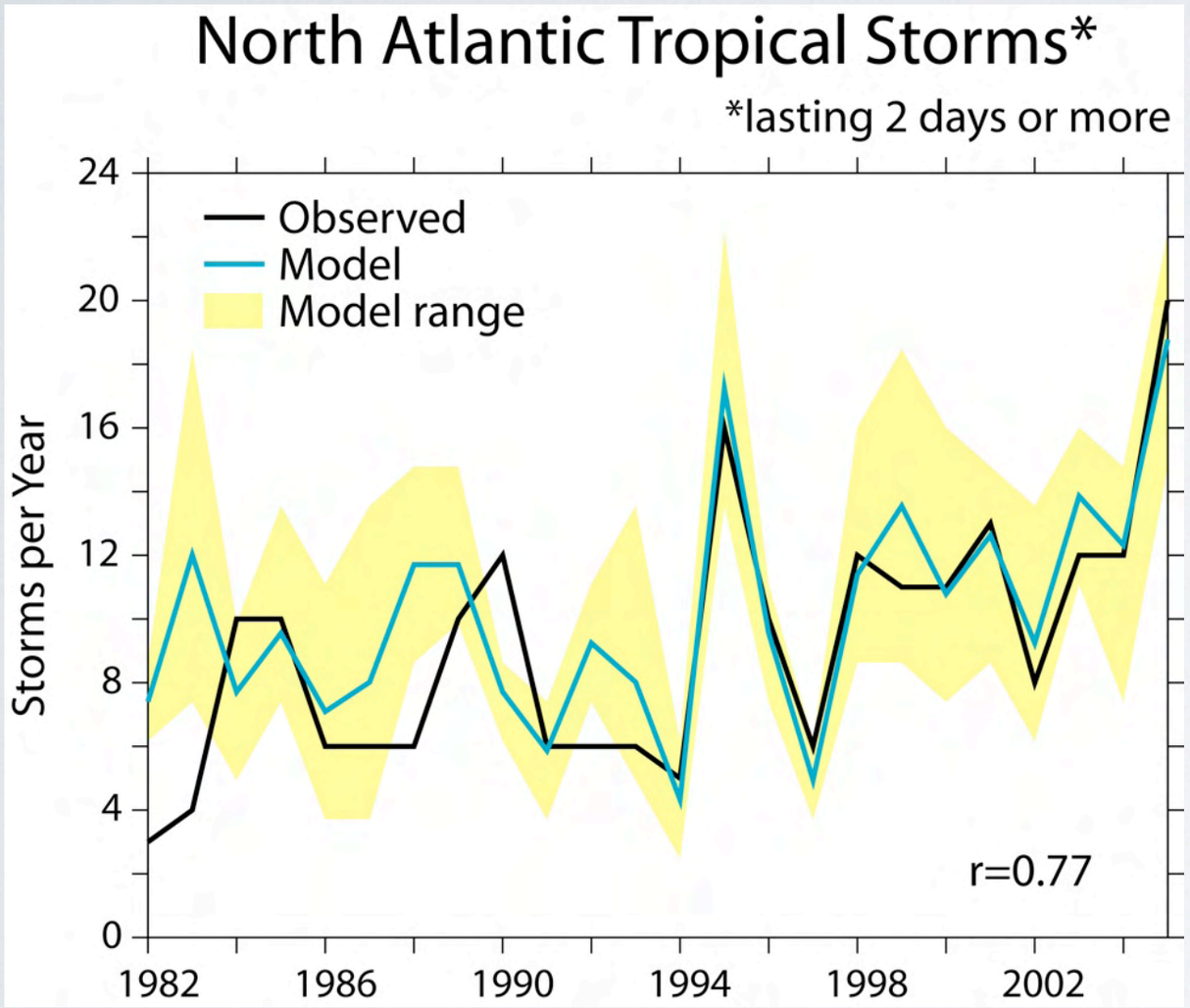
GFDL C-X HiRAM GCMs

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)



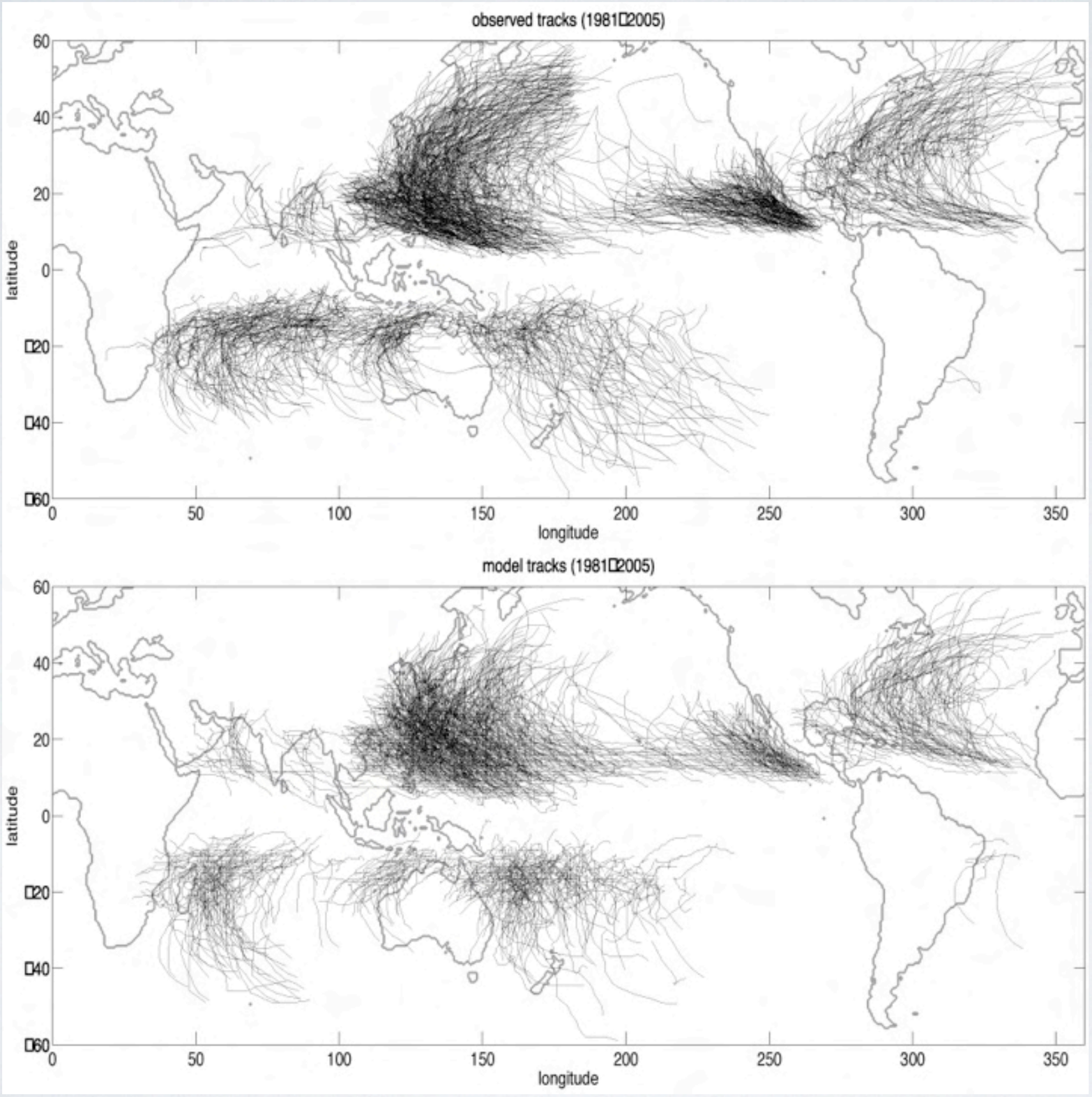
Adapted from AM2 with:

- Deep convection scheme adapted from Bretherton, McCaa and Grenier (MWR, 2004)
- Cubed sphere dynamical core
- Changes to parameterizations of cloud microphysics

MODEL RECOVERS MANY ASPECTS OF OBSERVED HURRICANE TRACKS

Observed

C180 Model

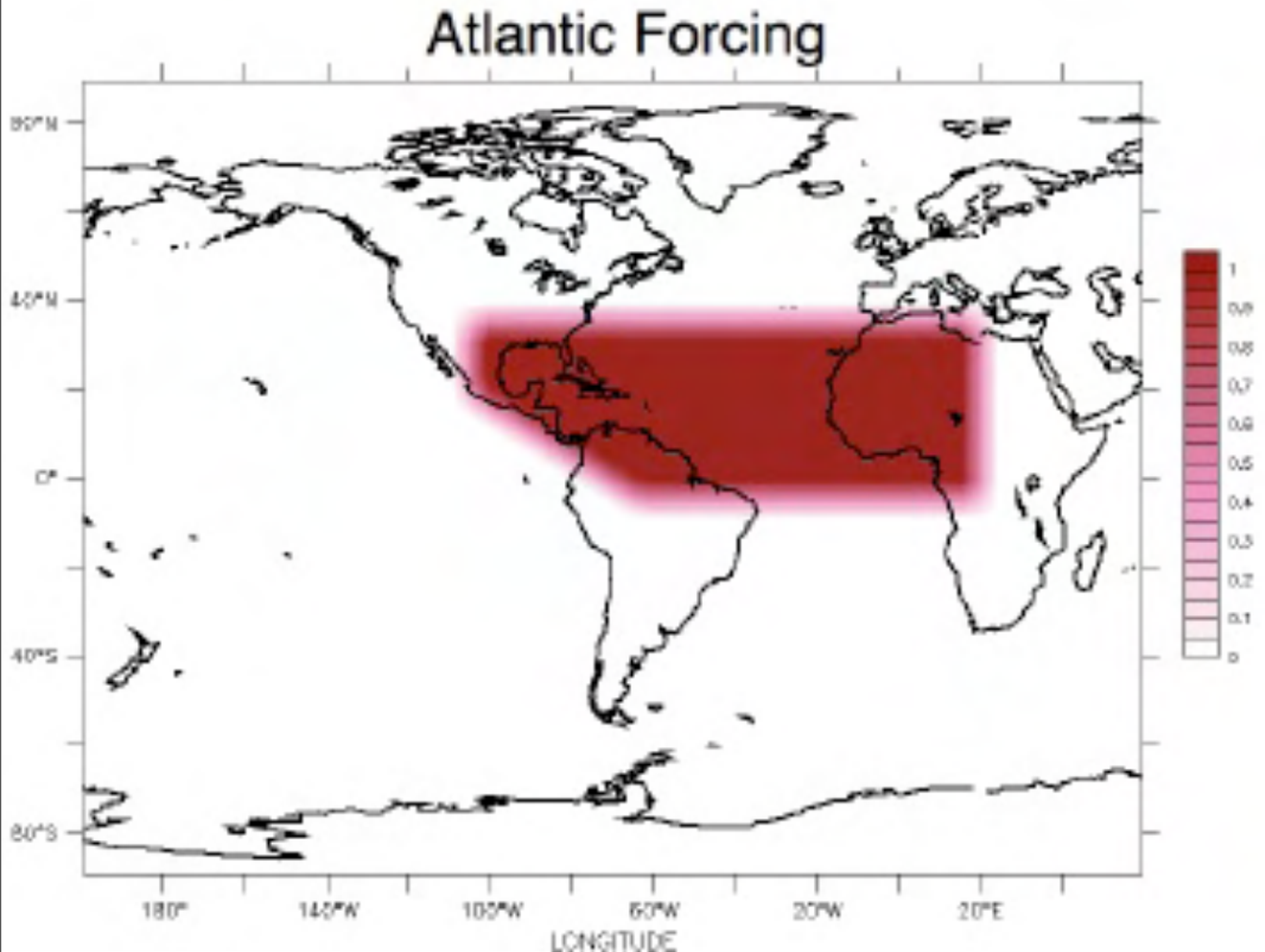


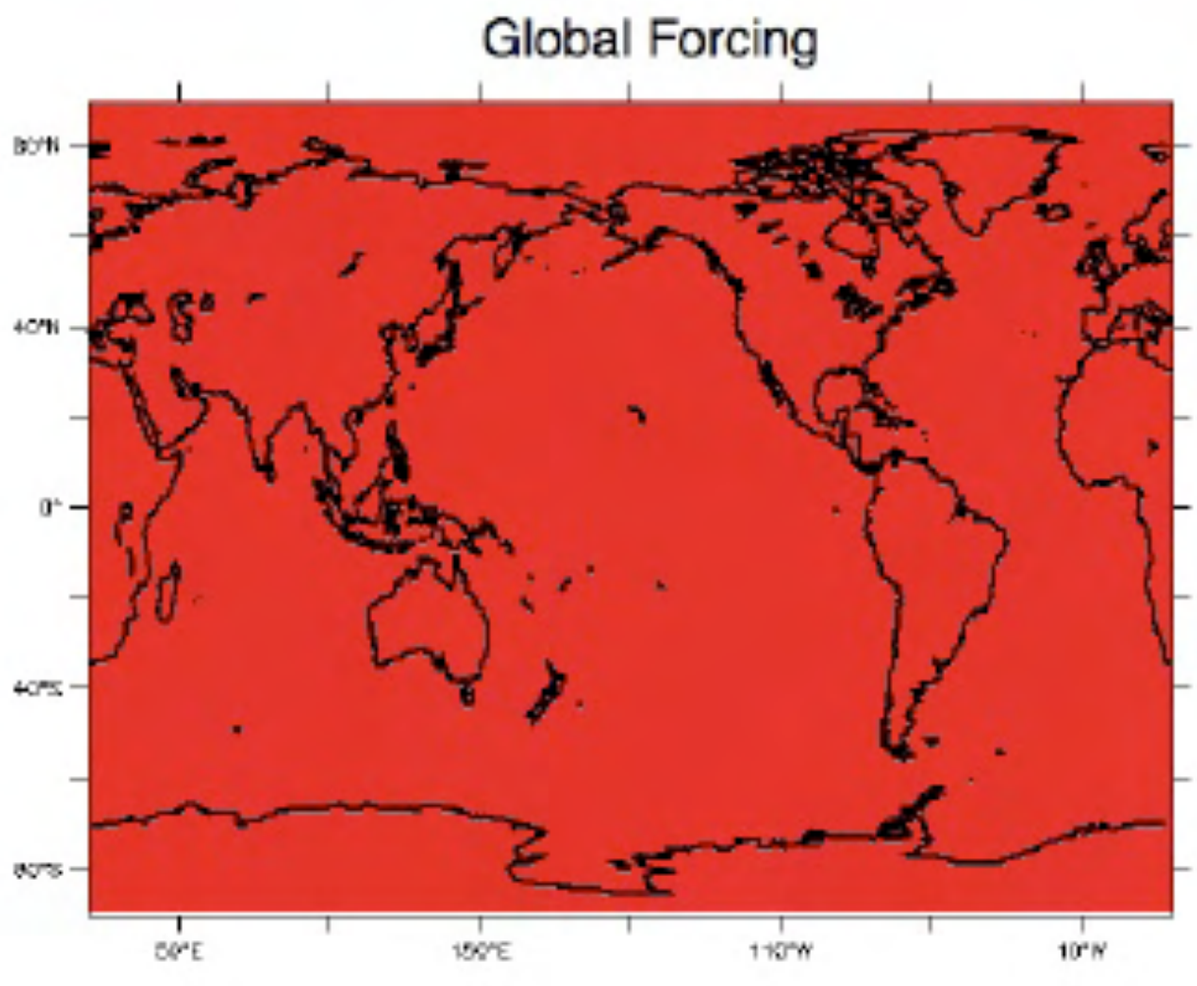
Zhao et al (2009, J. Climate)

Idealized Forcing Experiments

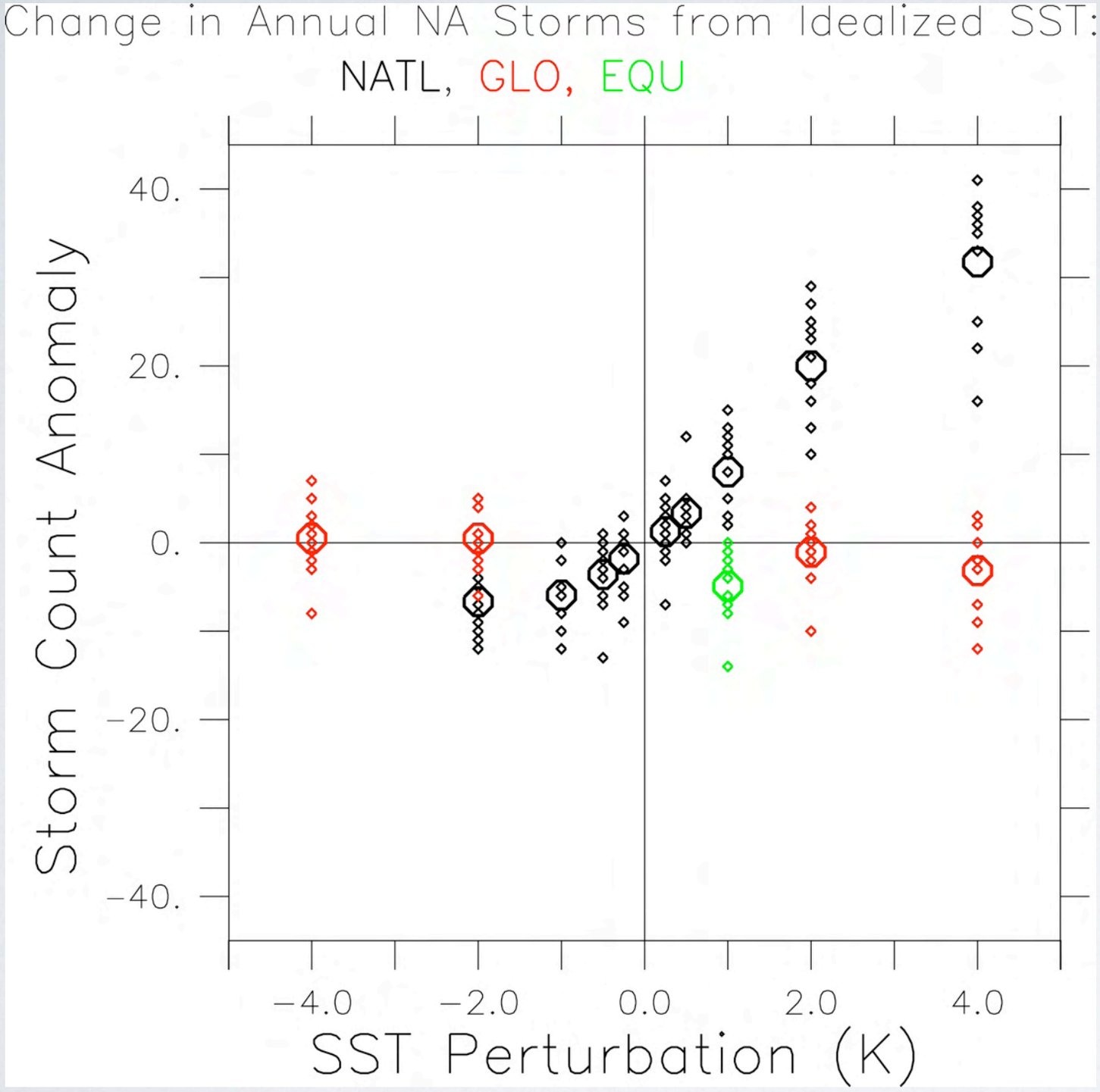
If local SST the dominant control, as opposed to relative SST:

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





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 (2011, in prep.)

STATISTICAL MODELS OF TS FREQUENCY

Villarini, Vecchi and Smith (2010, MWR)

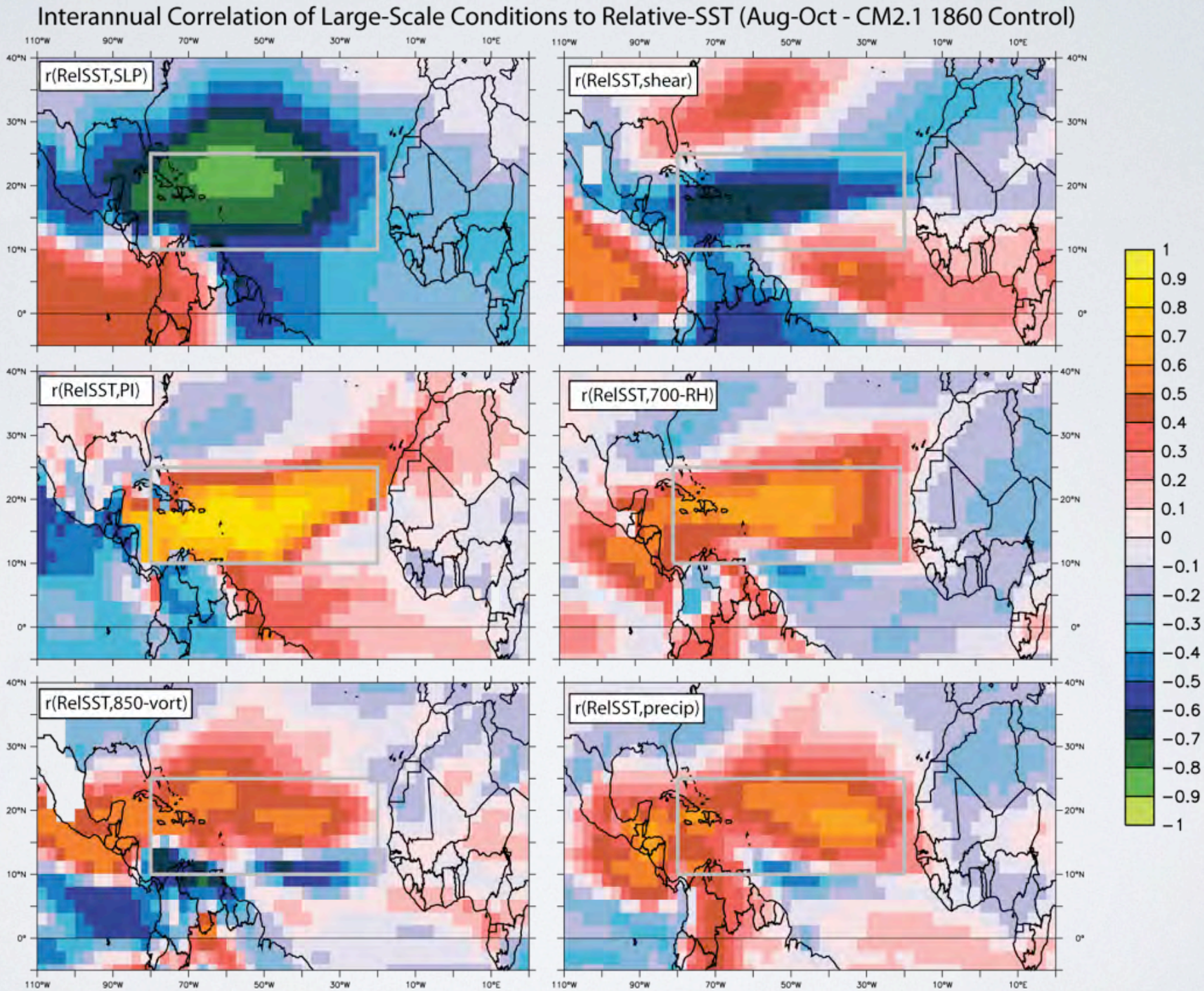
- Build statistical models of TS frequency:
    - >2 day duration basin-wide with and without adjustment
    - Landfalling
- Explore range of models, sensitivity to:
    - Possible covariates:
      (NAO, SOI, **Atlantic SST, Tropical SST**)
    - Model structure (Poisson vs. Negative Binomial).
   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

Hurricane-Relevant Large-Scale Conditions Co-vary Constructively With Relative-SST

SLP

PI

850hPa vort.

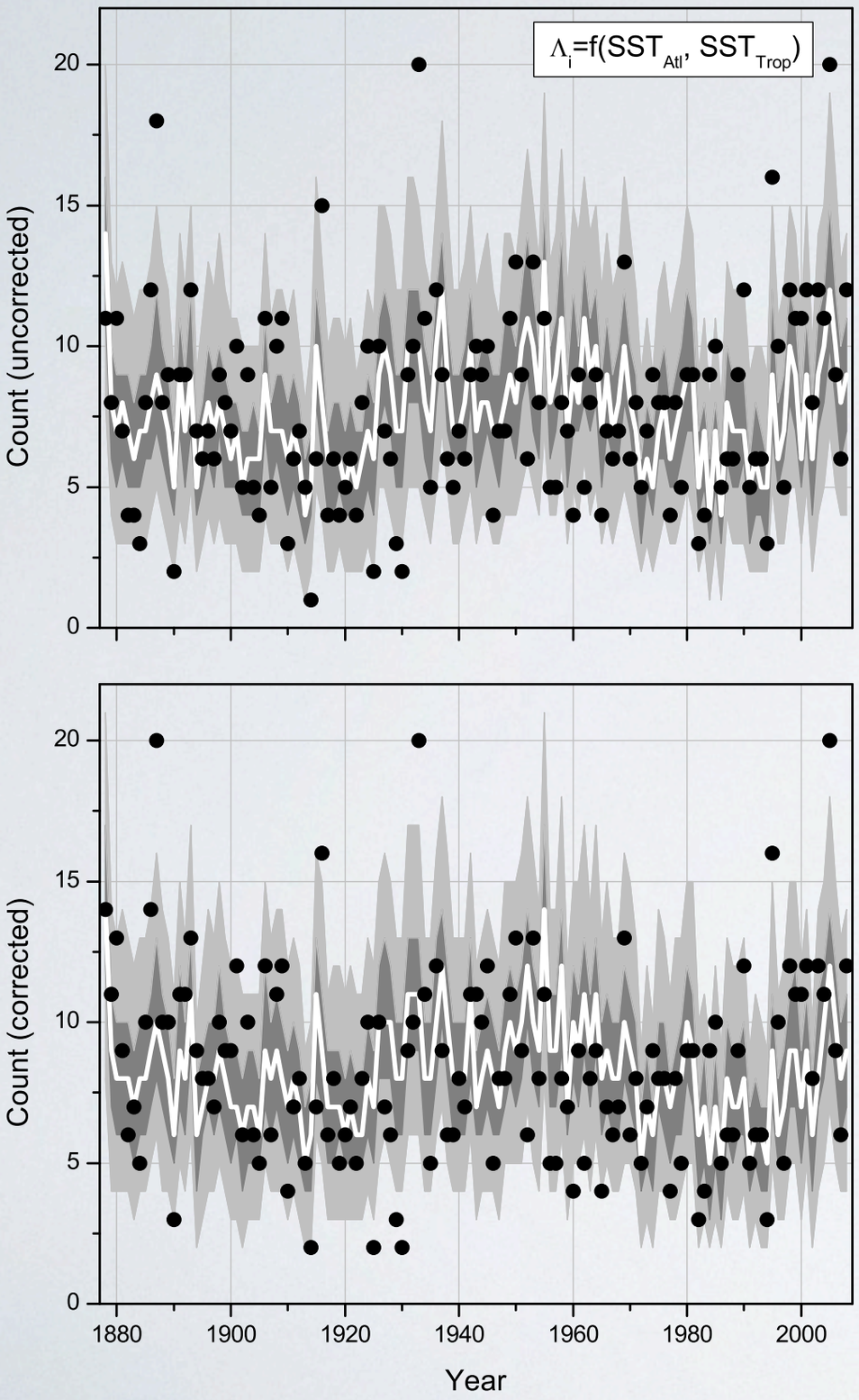


Shear

700hPa RH

Precip

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



Localized Atlantic warming increases frequency.

Remote warming reduces frequency.

Small impact from uniform warming.

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)

Outline

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

- **Attribution of recent increase in Atlantic activity**
- Predictions of seasonal activity
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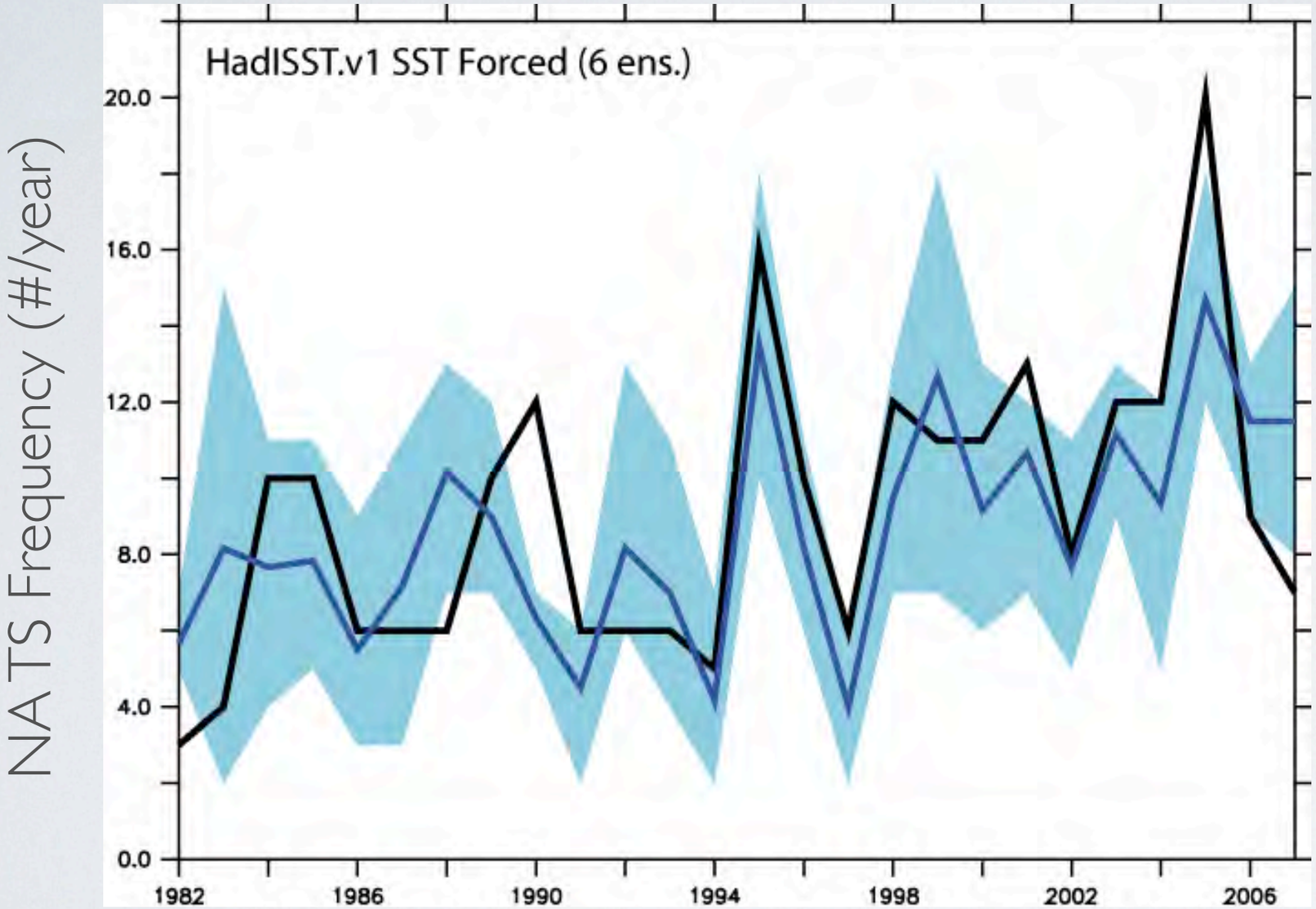
Attribution of Recent TS Frequency Increase in North Atlantic

100km GFDL-HiRAM AGCM recovers recent NA TS Trend when forced with HadISST.v1 SST



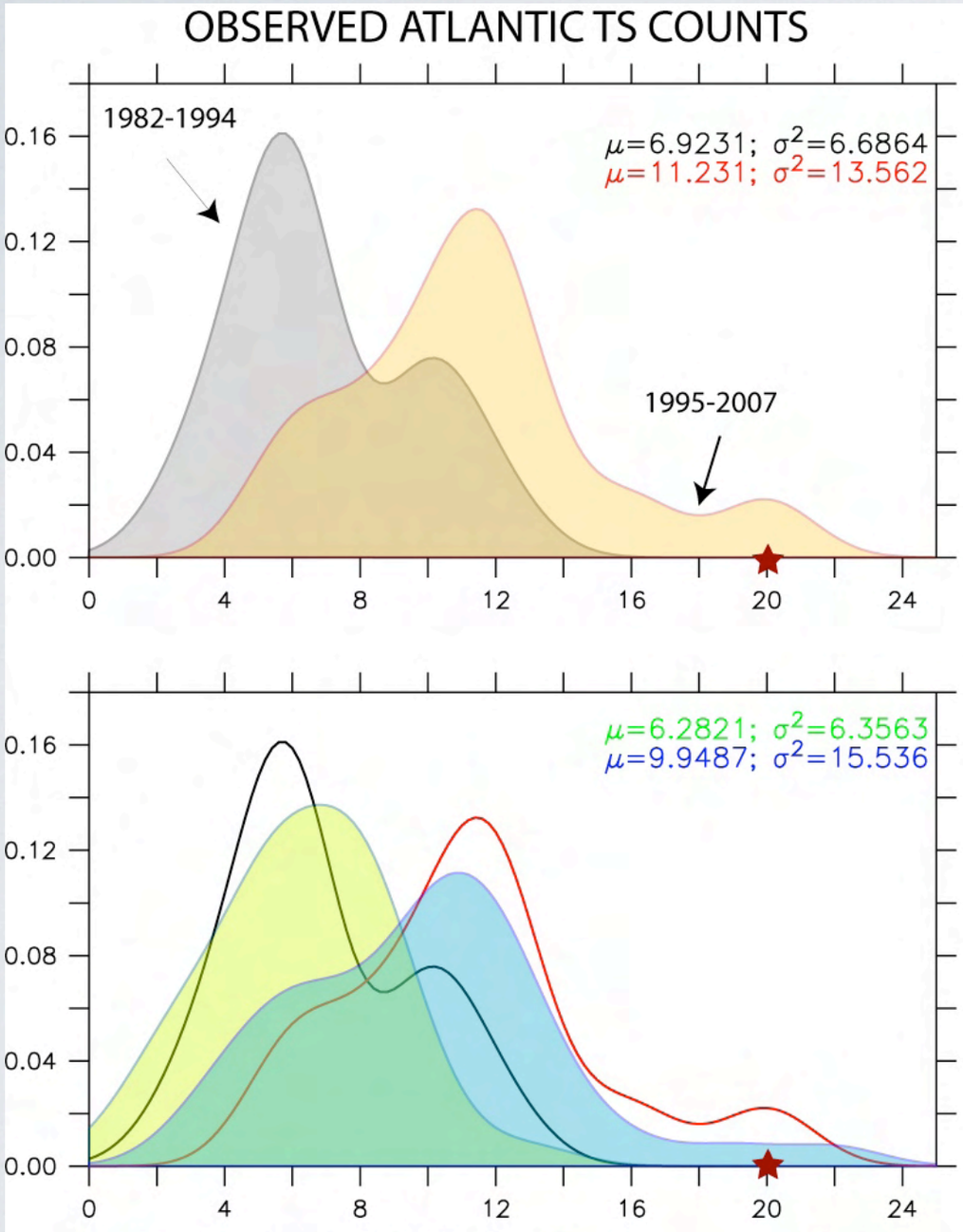
What aspect of SST drove increase?

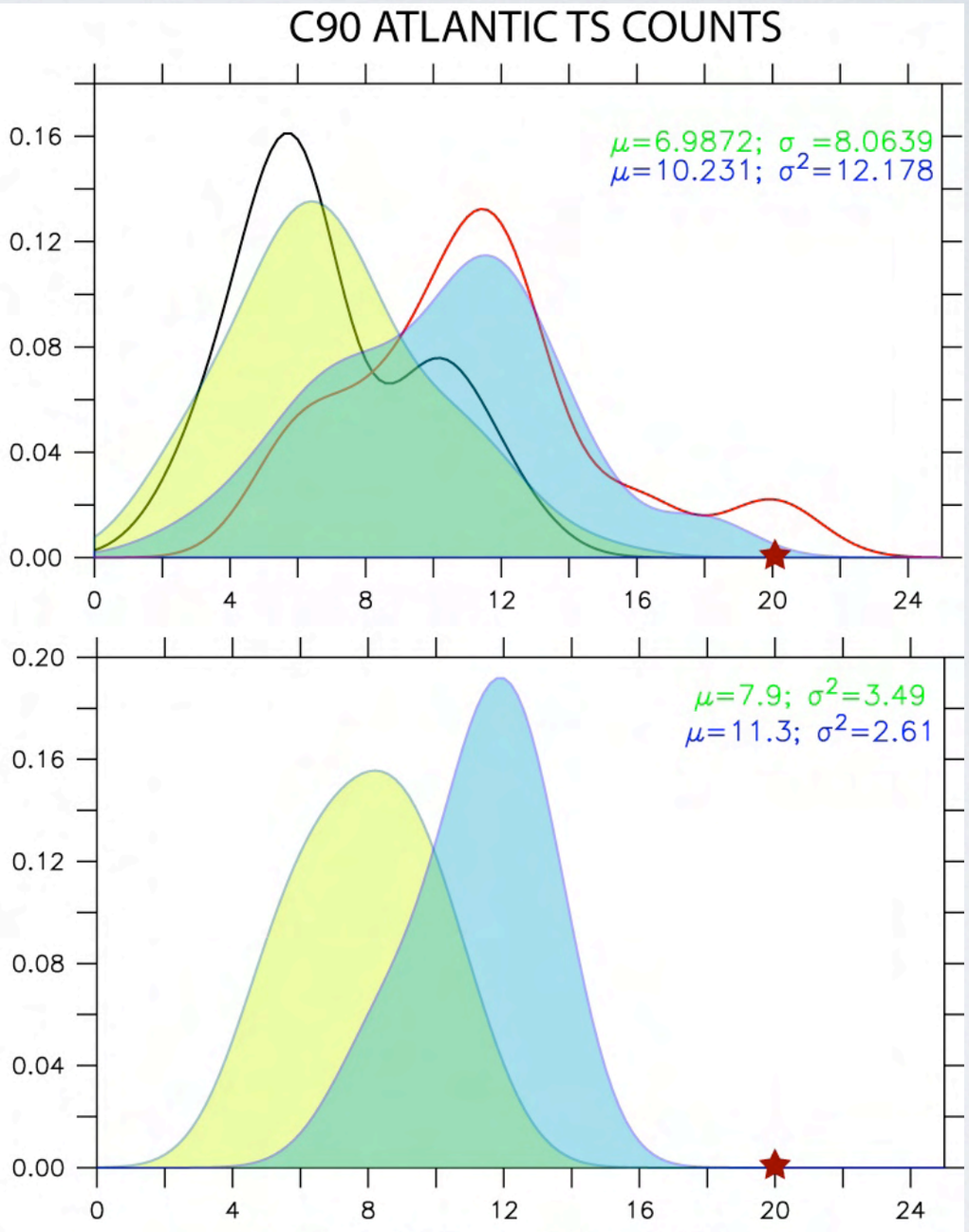
Vecchi, Zhao and Held (2011, in prep.)

1982-94 AND 1995-2007 PDFS OF NA TS COUNT*

* lasting two days or more

★ 2005 Observed



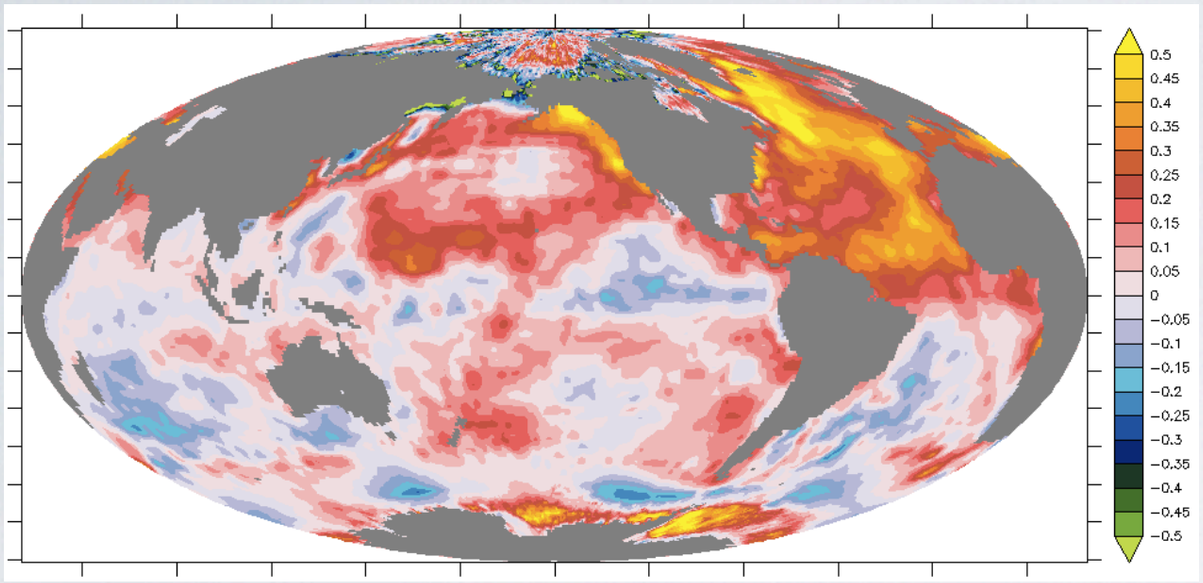


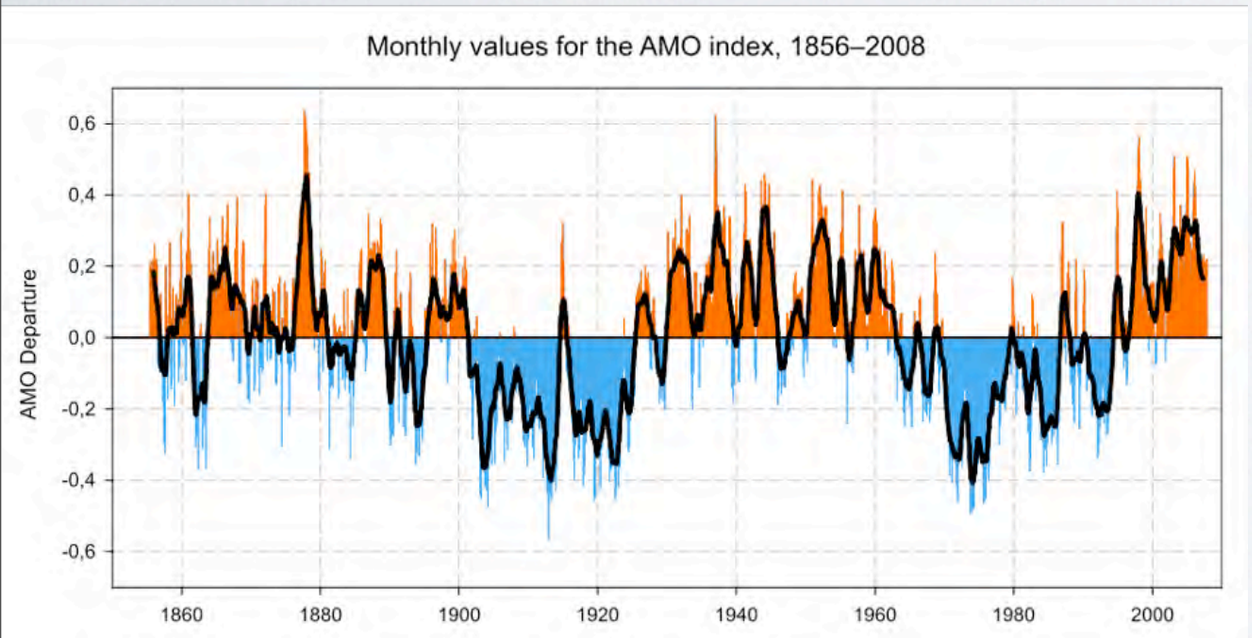
Vecchi, Delworth, Held and Zhao (2011, in prep.)

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

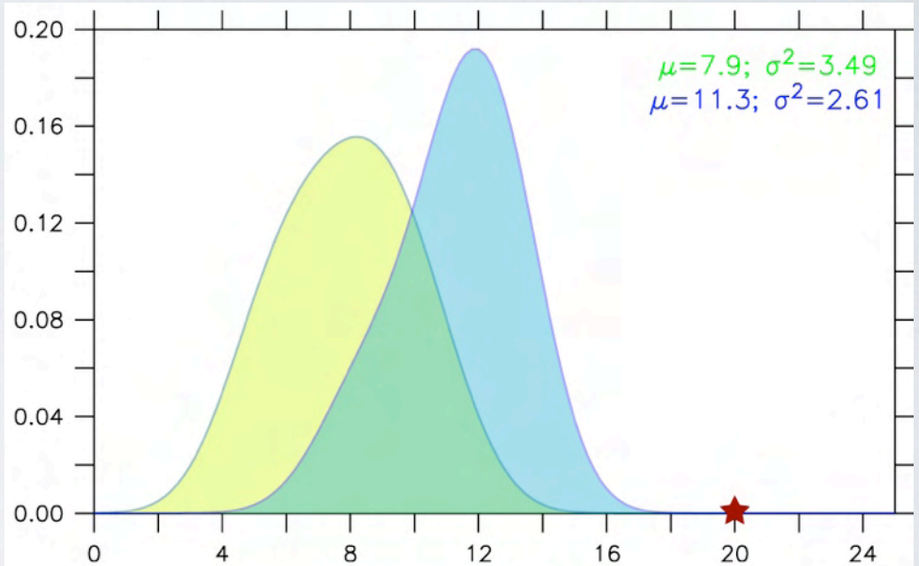




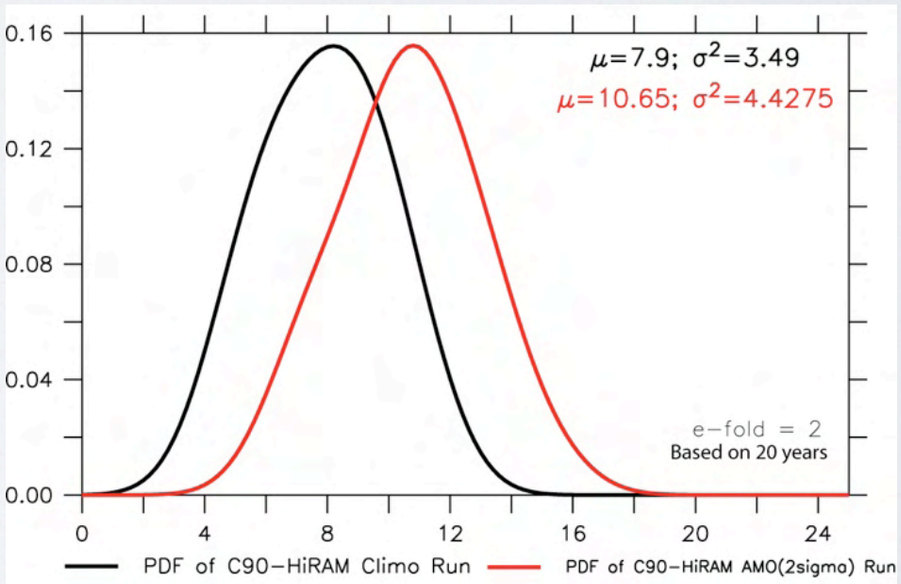
AMO Index: Regression of SST onto NA SST

Knight et al (2005)

Response to decadal shift



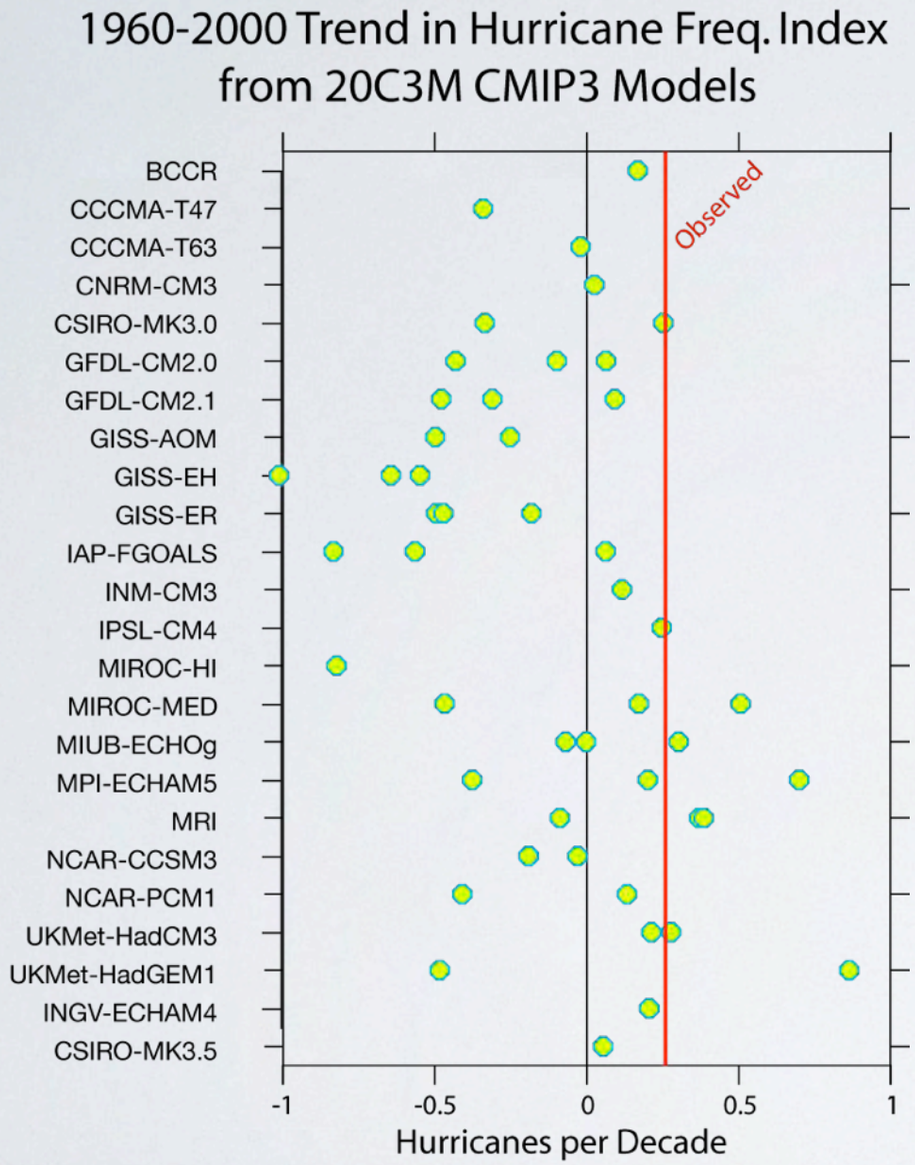
Response to "AMO" forcing

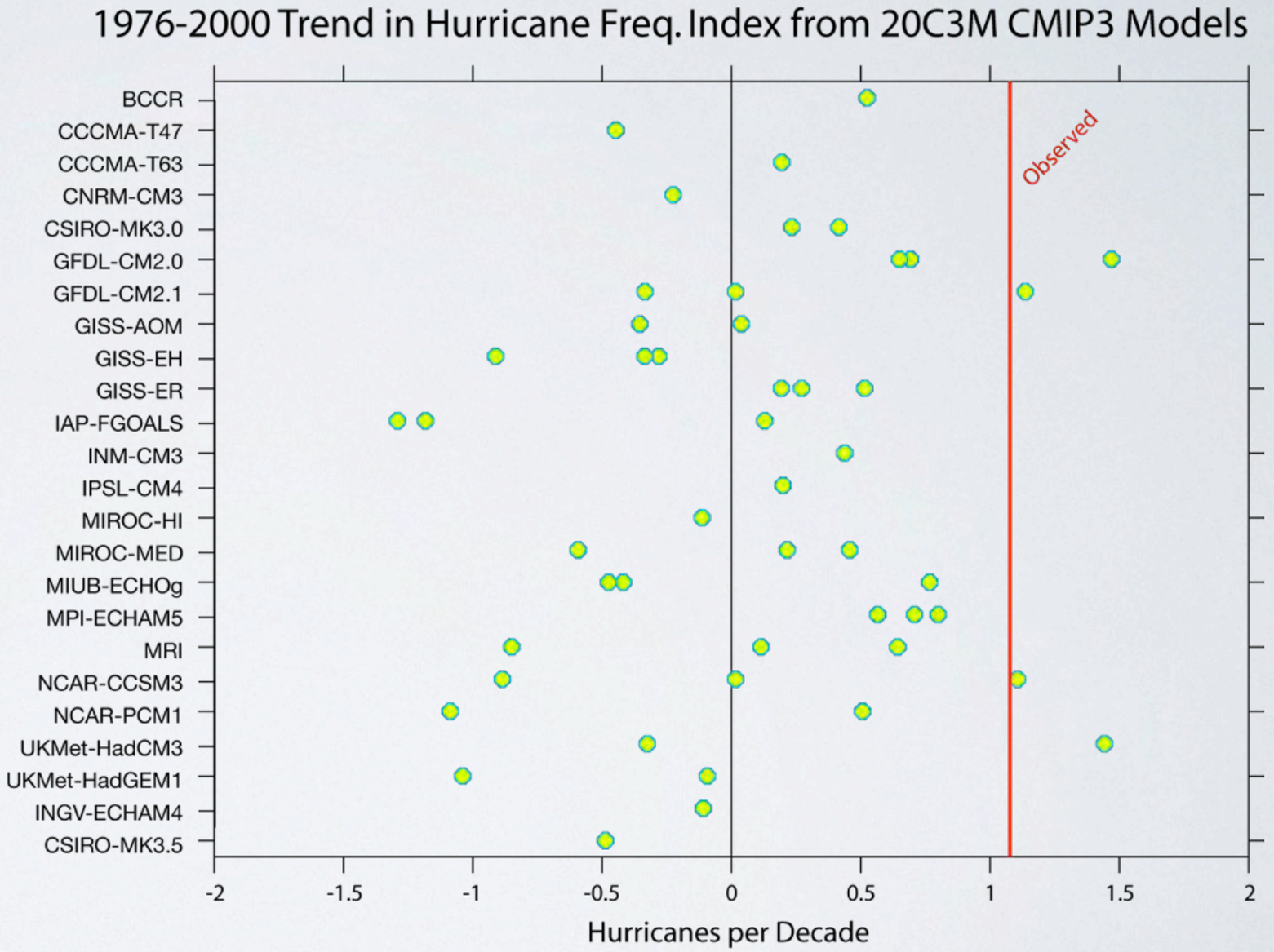


Vecchi, Delworth, Held and Zhao (2011, in prep.)

Recent Increase Not Robustly "Forced" in CMIP3 Models

Recent trends in **statistical hurricane model** applied to CMIP3 20c3m runs





Outline

- Tools:
  - Observational records
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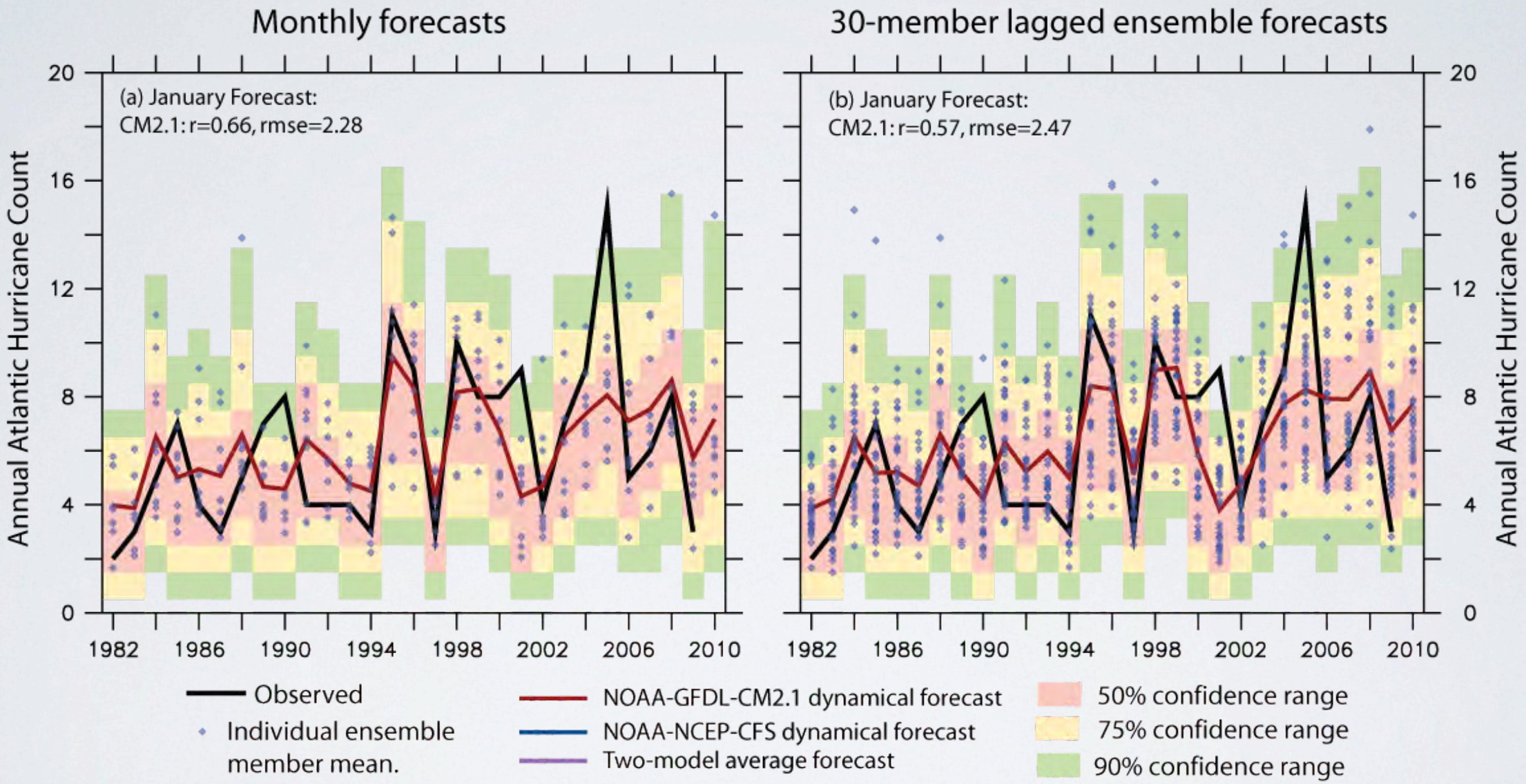
  - Statistical models
- Attribution of recent increase in Atlantic activity
- **Predictions of seasonal activity**
- Century-scale projections

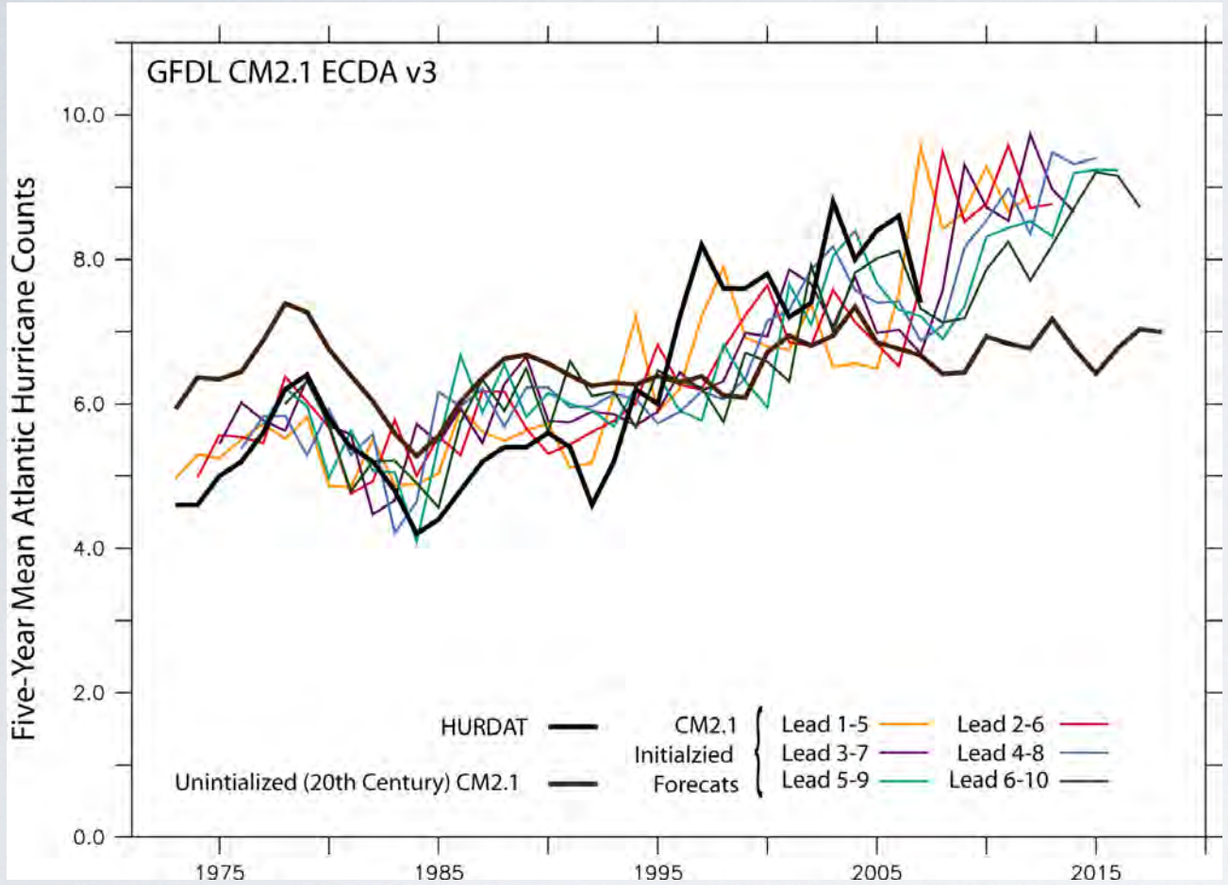
Statistical-Dynamical Hurricane Frequency Retrospective Forecasts Initialized January Exhibit Skill

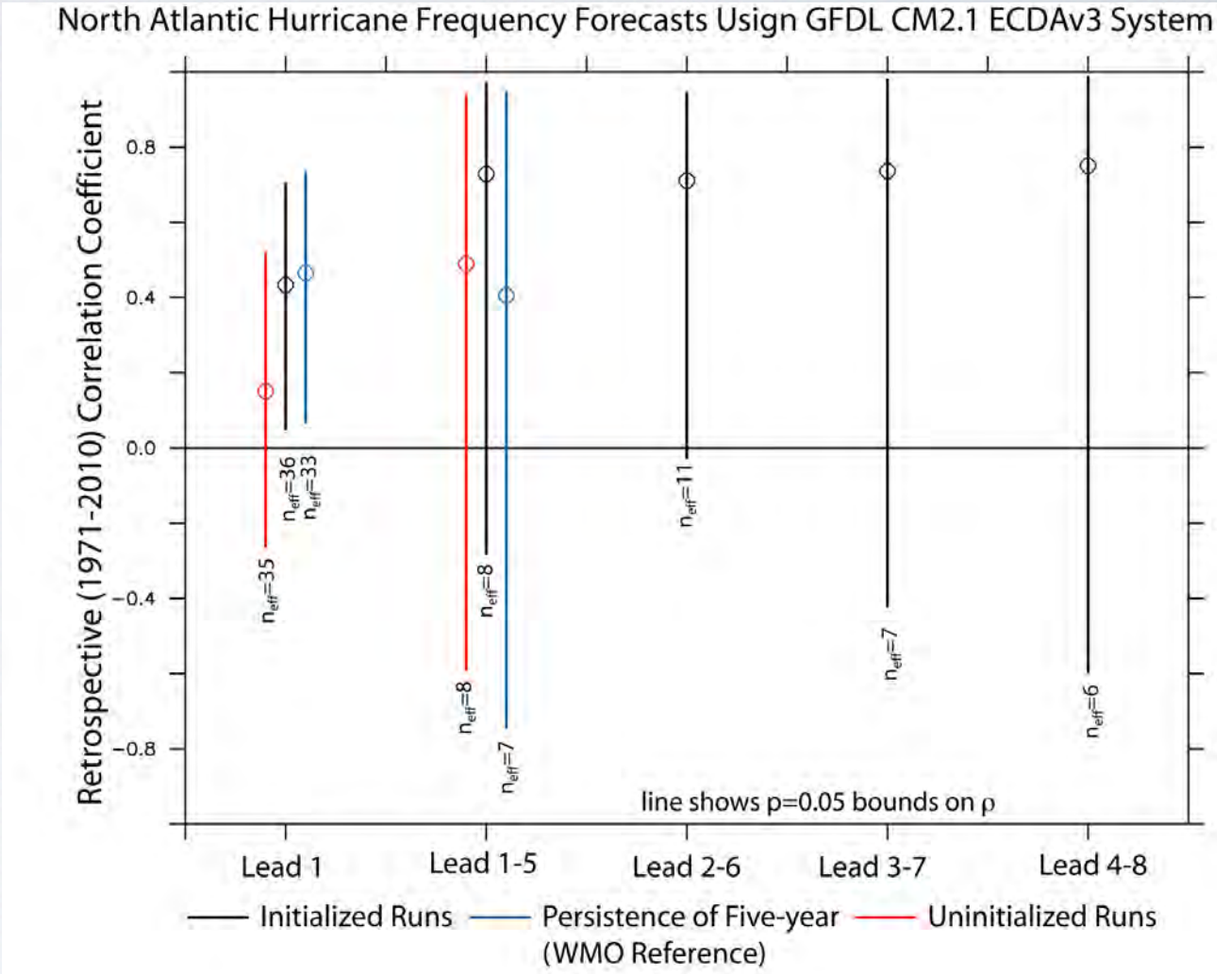


Vecchi *et al.* (2011, MWR in press)

Experimental decadal predictions

Hybrid: statistical hurricanes, GFDL-CM2.1 EnKF decadal forecasts





Vecchi *et al.* (2011 in prep)

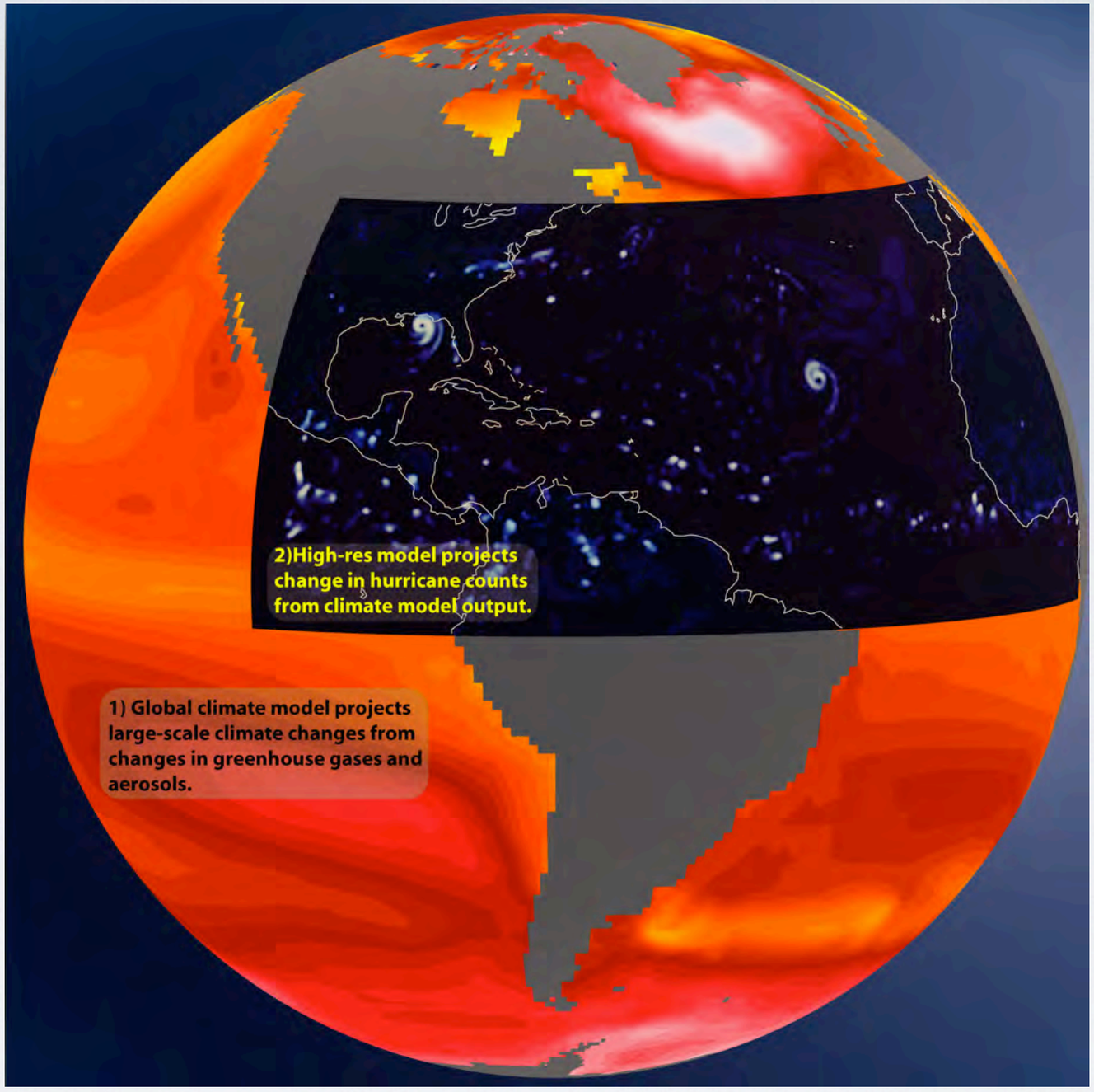
Retrospective predictions of 1971-2010 decadal NA TS frequency show encouragingly high correlation (~0.8).

However, low number of degrees of freedom limit confidence in result (don't have enough realizations to reject no skill)

Outline

- Tools:
  - Observational records
  - High-resolution dynamical models
  - Statistical models
- Attribution of recent increase in Atlantic activity
- Predictions of seasonal activity
- **Century-scale projections**

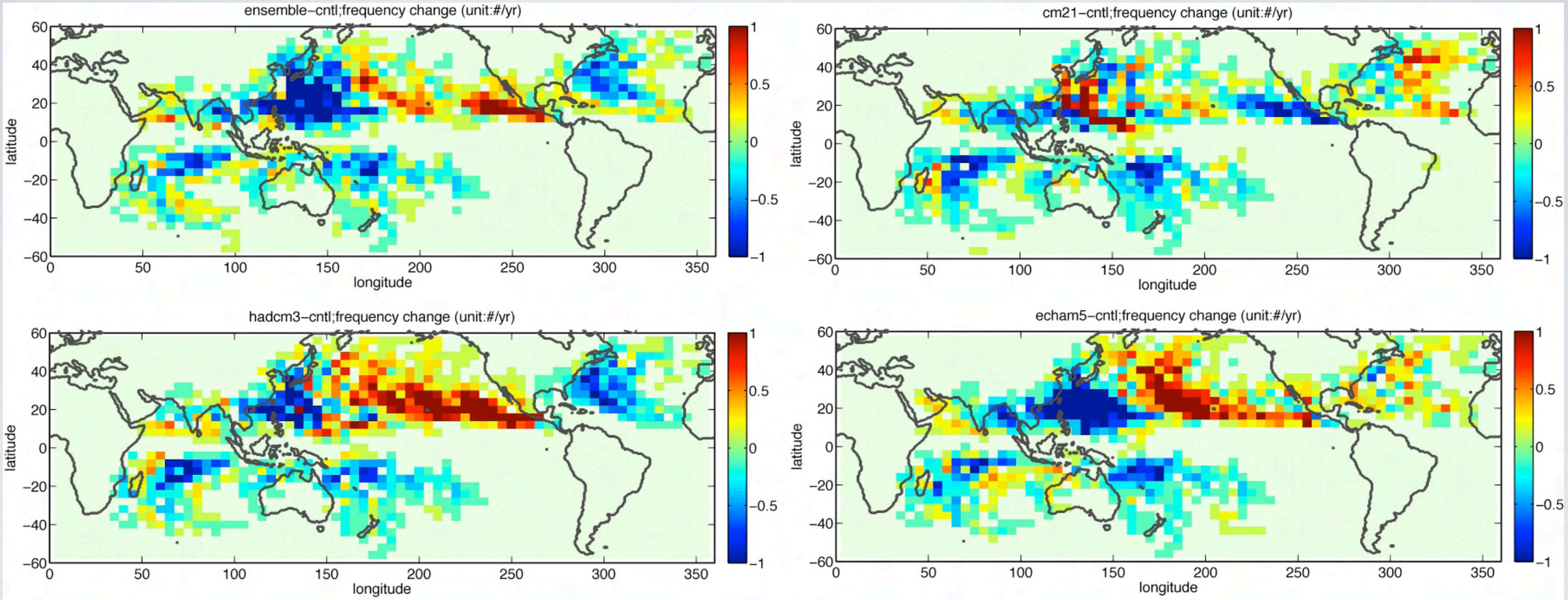
For TC Activity, "Downscale" Climate Model Projections With High-Resolution (or Statistical) Models



Global Climate Models -> High-resolution Model

Large-scale TS Frequency

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.

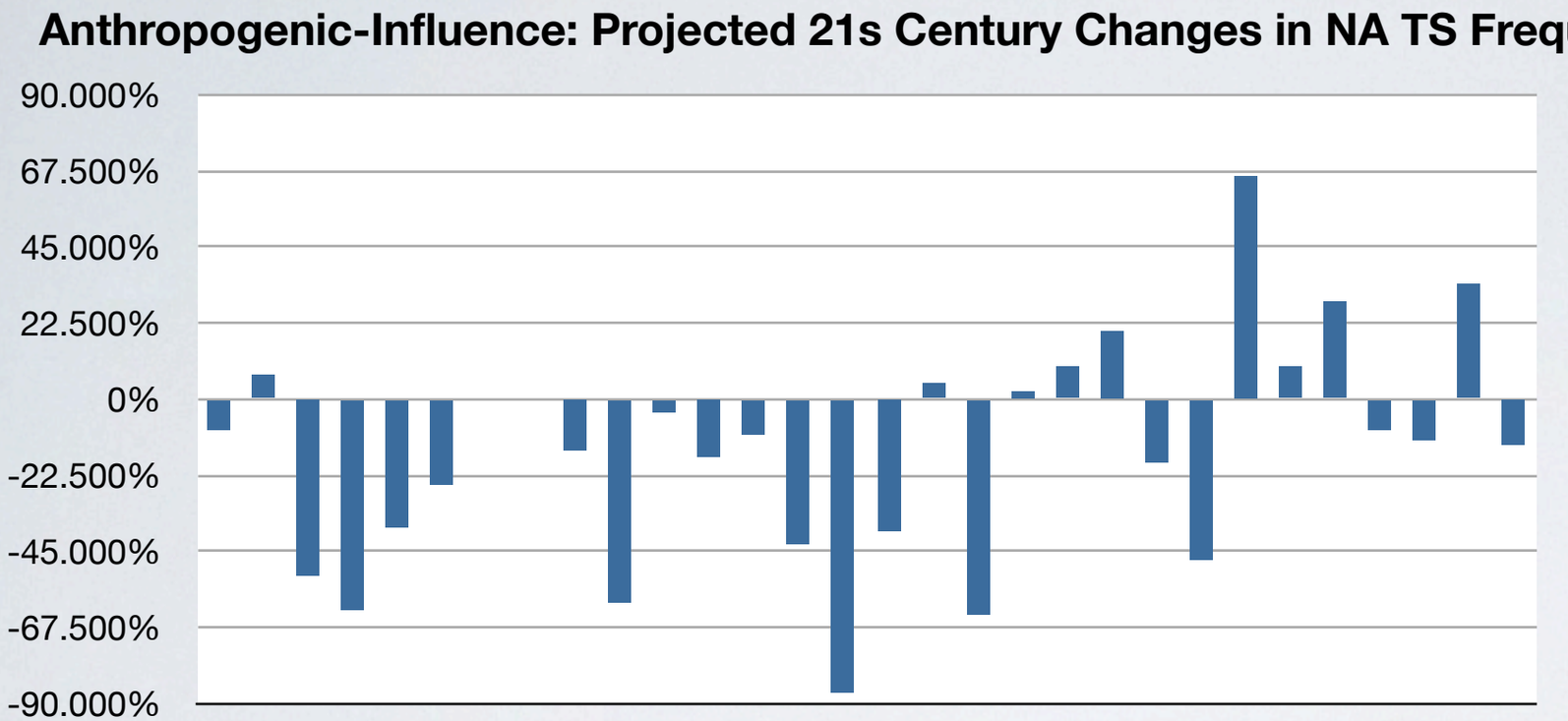
Pattern depends on details of ocean temperature change.

Sensitivity of response seen in many studies

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

Divergence of 21st Century projections of NA TS Frequency

North Atlantic cyclone frequency response high-resolution models applied to 21st Cy. climate projections



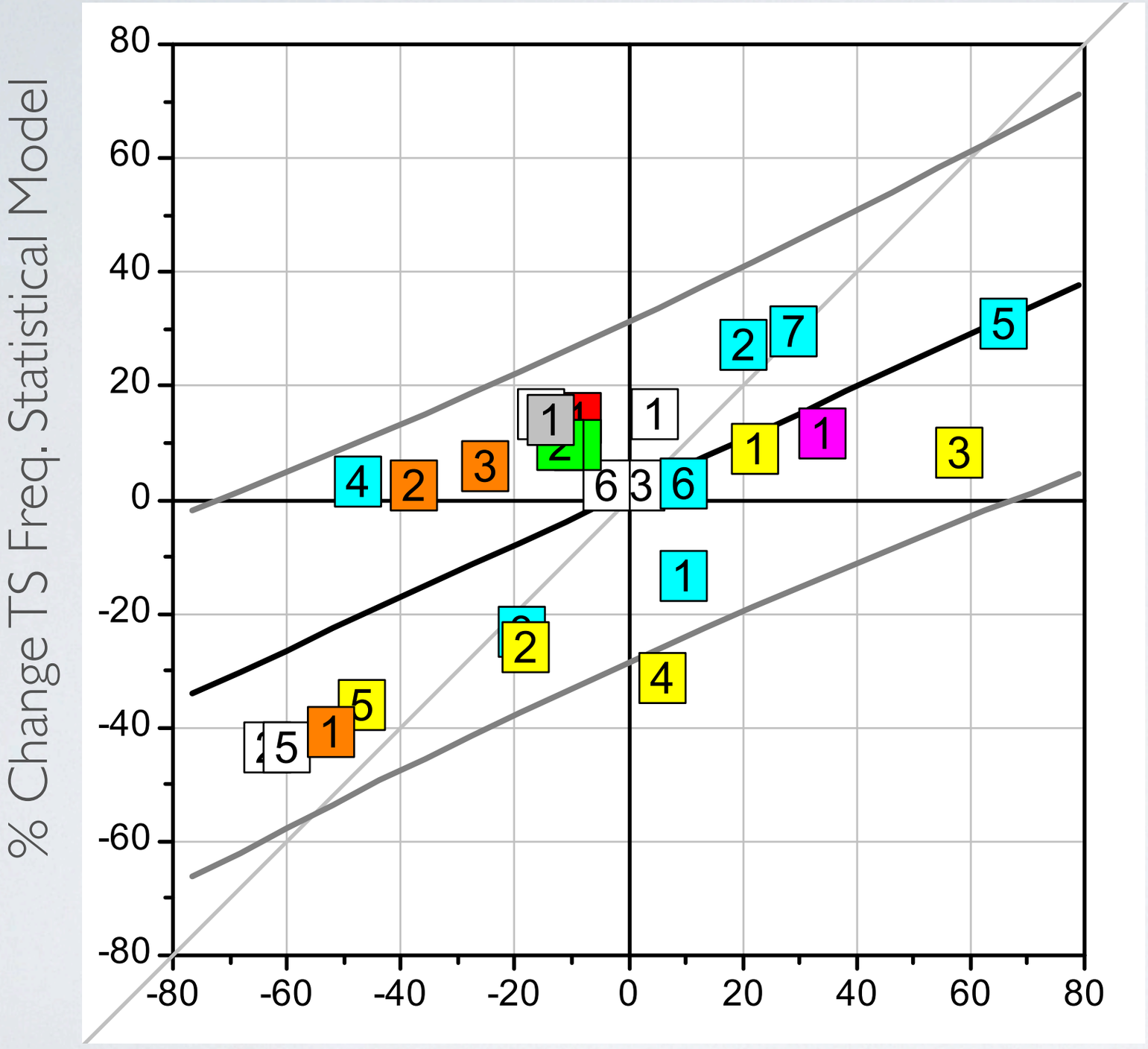
Oouchi et al (2005)
Bengtsson et al (2007)
Emanuel et al (2008)
Knutson et al (2008)
Zhao et al (2009)
Gualdi et al (2009)

- Even sign of NA TS frequency response to GHG unclear:
  Not big help in decadal predictability (yet?)

- Various studies downscale different coupled models, and over different periods

Is there any consistency in the various projections?

Dynamical Models Exhibit Consistent Relationship To Large-Scale Through Statistical Model - All consistent with observations



Knutson et al. (2008)
1. GFDL CM2.1

Zhao et al. (2009)
1. GFDL CM2.1 (Reynolds)
2. UKMet HadCM3 (Reynolds)
3. Max Planck-ECHAM5 (Reynolds)
4. GFDL CM2.1 (HadISST)
5. UKMet HadCM3 (HadISST)
6. Max Planck-ECHAM5 (HadISST)

Emanuel et al. (2008)
1. NCAR CCSM3.0
2. CNRM-CM3
3. CSIRO-Mk3.0
4. Max Planck-ECHAM5
5. GFDL CM2.0
6. MIROC-Medres
7. MRI CGCM2.3.2

Oouchi et al. (2005)
1. MRI CGCM2.3

Bender et al. (2010)
1. UKMet HadCM3
2. Max Planck-ECHAM5
3. MRI CGCM2.3.2

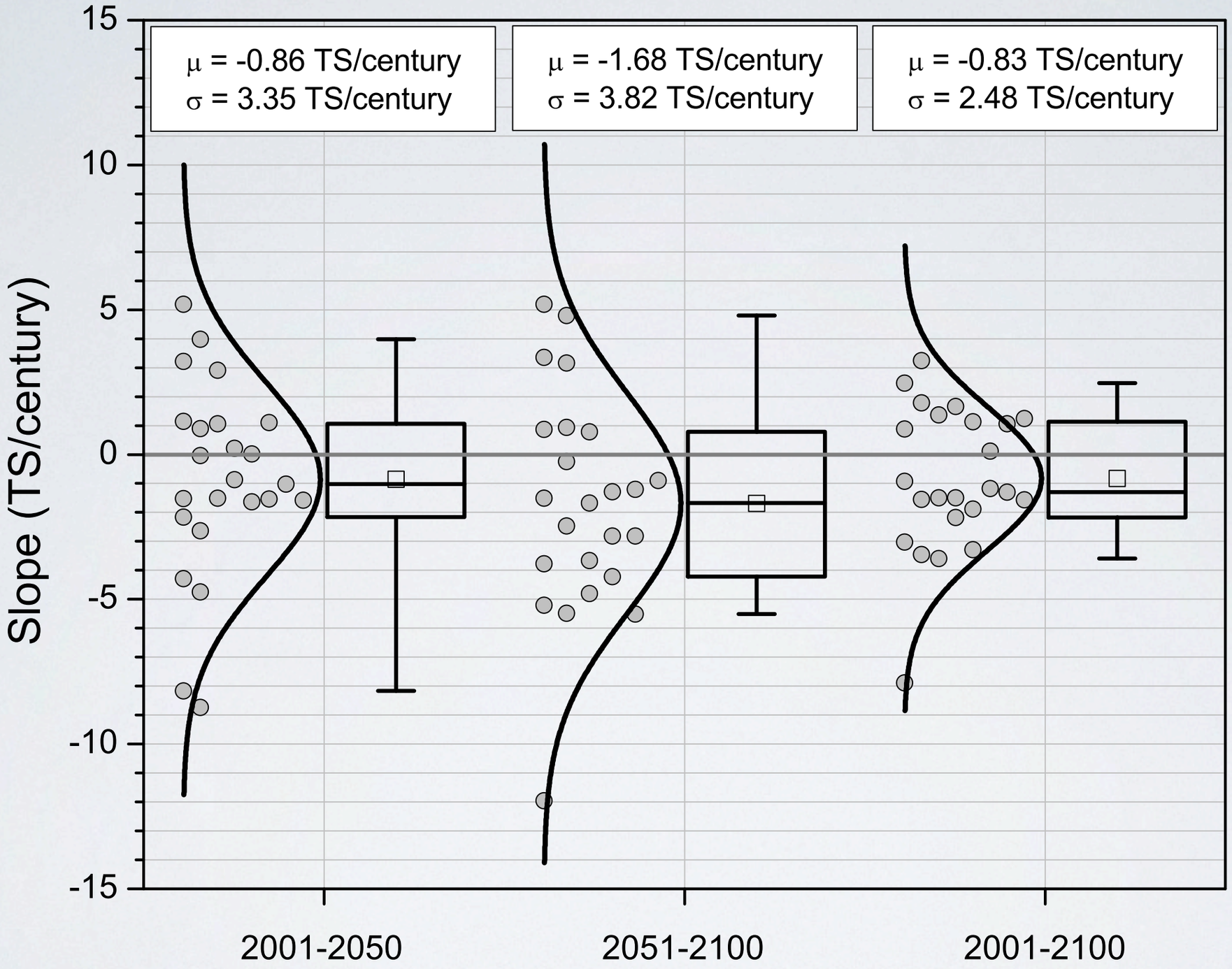
Bengtsson et al. (2007)
1. CNRM with T213 AGCM
2. CNRM with T959 AGCM

Gualdi et al. (2009)
1. INGV-ECHAM4 2×CO_2

Sugi et al. (2009)
1. MRI CGCM2.3.2 (20 km)
2. MIROC-Hires (20 km)
3. MRI CGCM2.3.2 (60 km)
4. MIROC-Hires (60 km)
5 CSIRO-Mk3.0 (60 km)

Villarini et al (2011, J. Clim. in press)

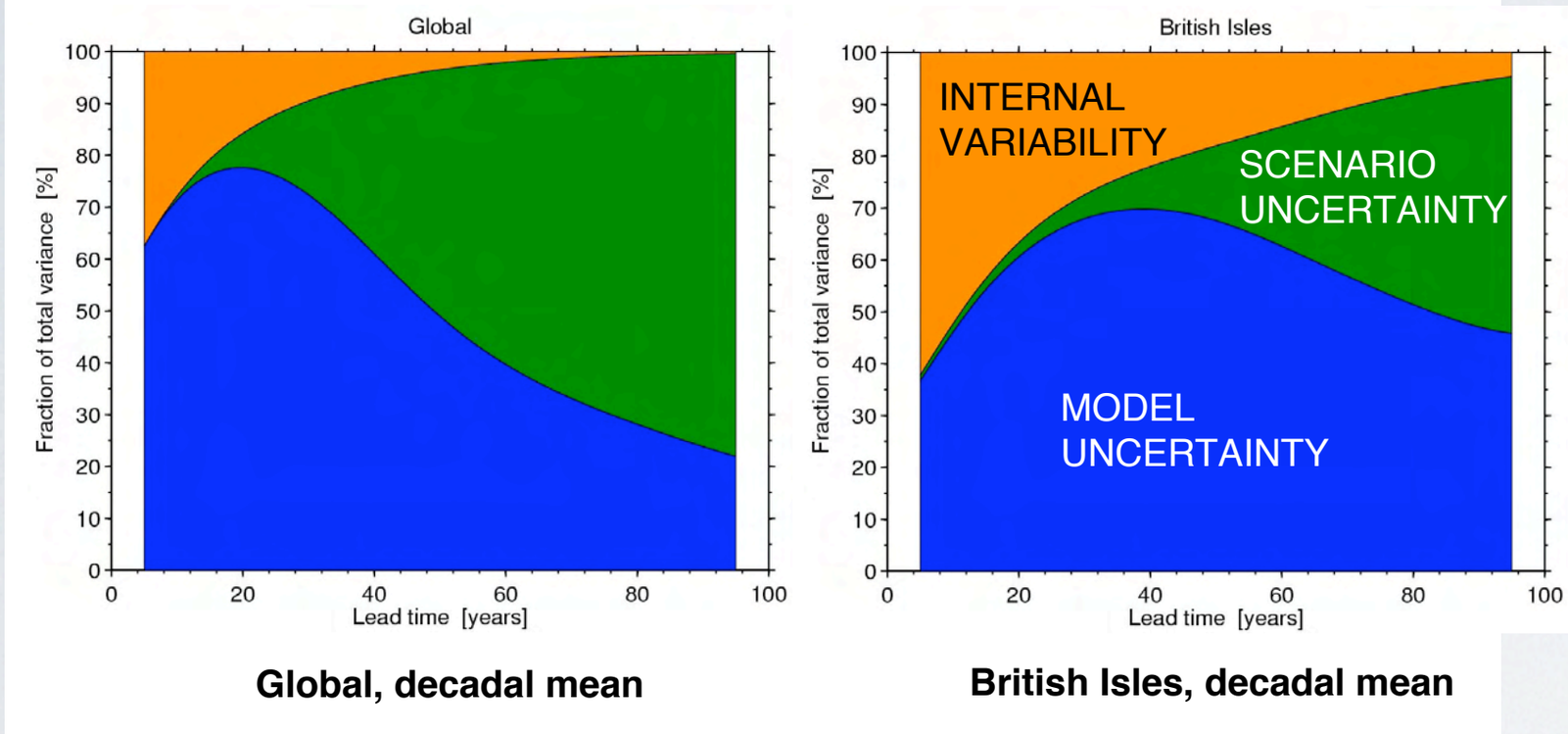
Statistical Projections of 21st Century NA TS Trends



Villarini et al (2011, in press)

NA TS Projections: Internal Variability A Primary Source of Uncertainty Even in 100-year Trends

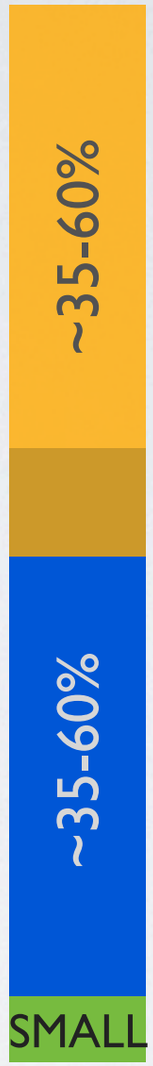
TEMP.



Global, decadal mean **British Isles, decadal mean**

Hawkins and Sutton (2009)

TS COUNTS



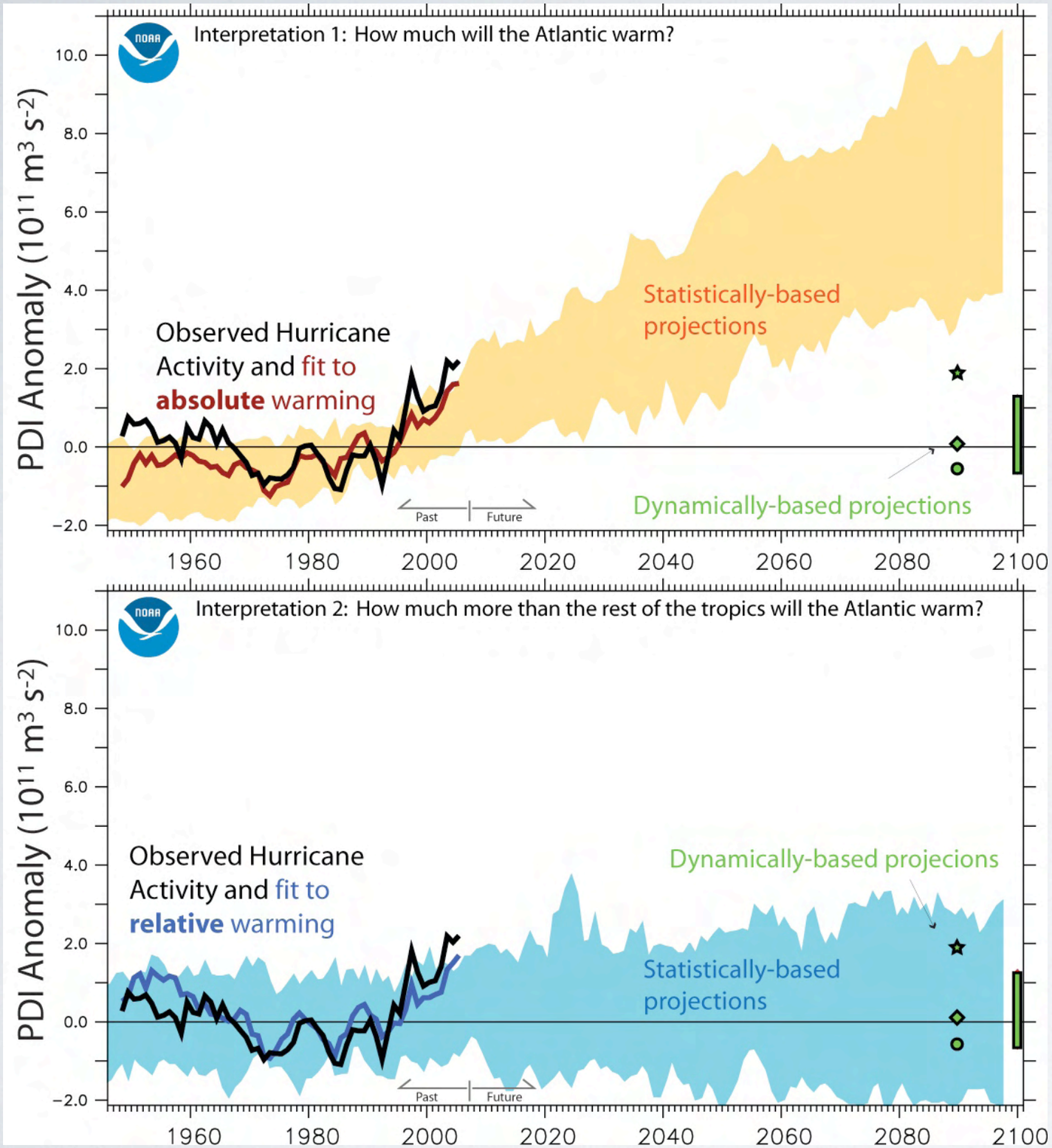
INT. VARIABILITY

MODEL

SCENARIO

Estimate of relative uncertainty sources for 2001-2100 trends in NA TS Counts (adapted from Villarini et al 2011, in press)

…Add Dynamical Projections of Atlantic Hurricane Activity



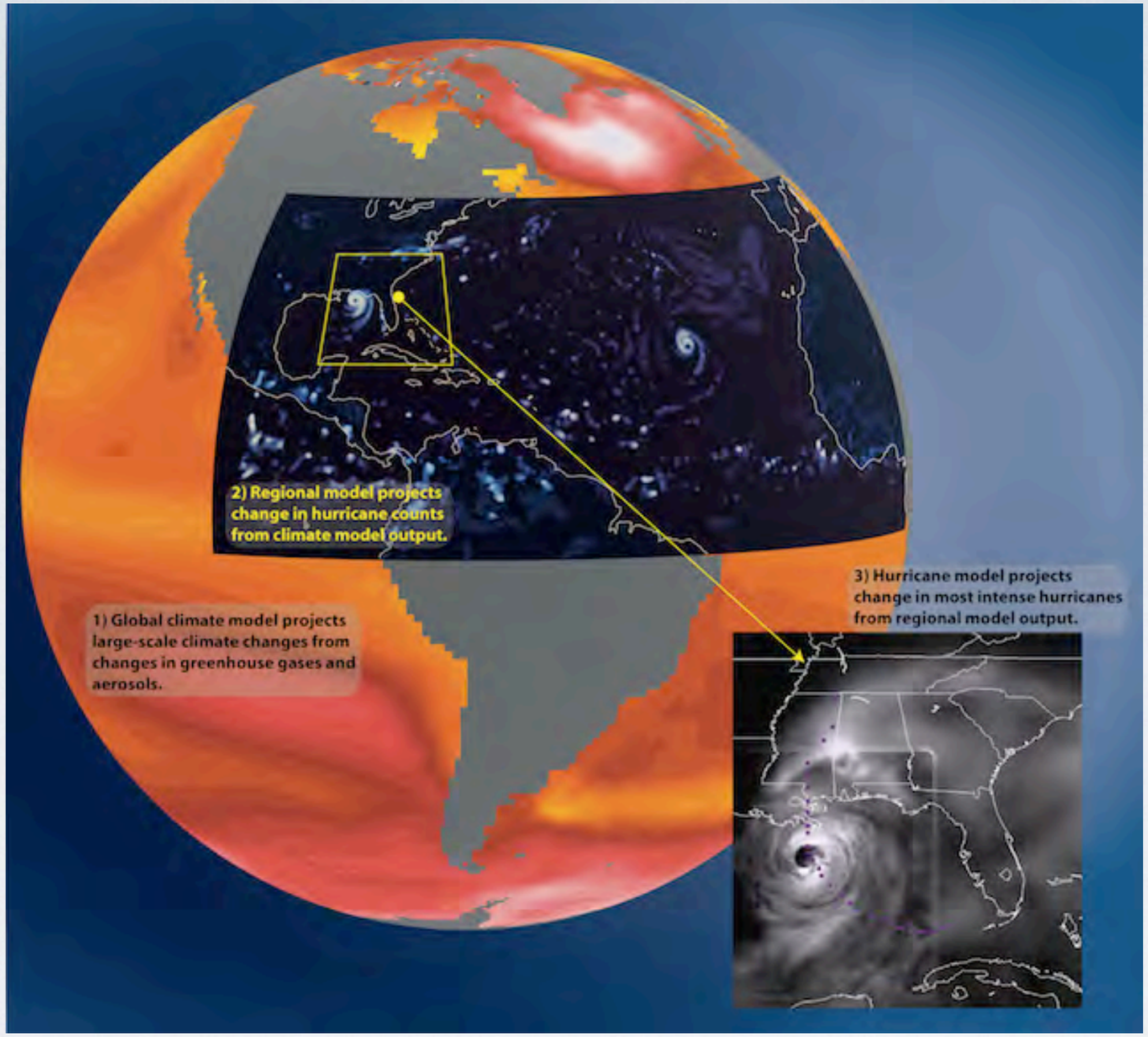
Observed Activity
Absolute Atlantic Temperature

Dynamical Model Projections

Observed Activity
Relative Atlantic Temperature

Vecchi, Swanson and Soden (2008, Science)

STRONGEST CYCLONES PROJECTED WITH DOUBLE DOWNSCALING

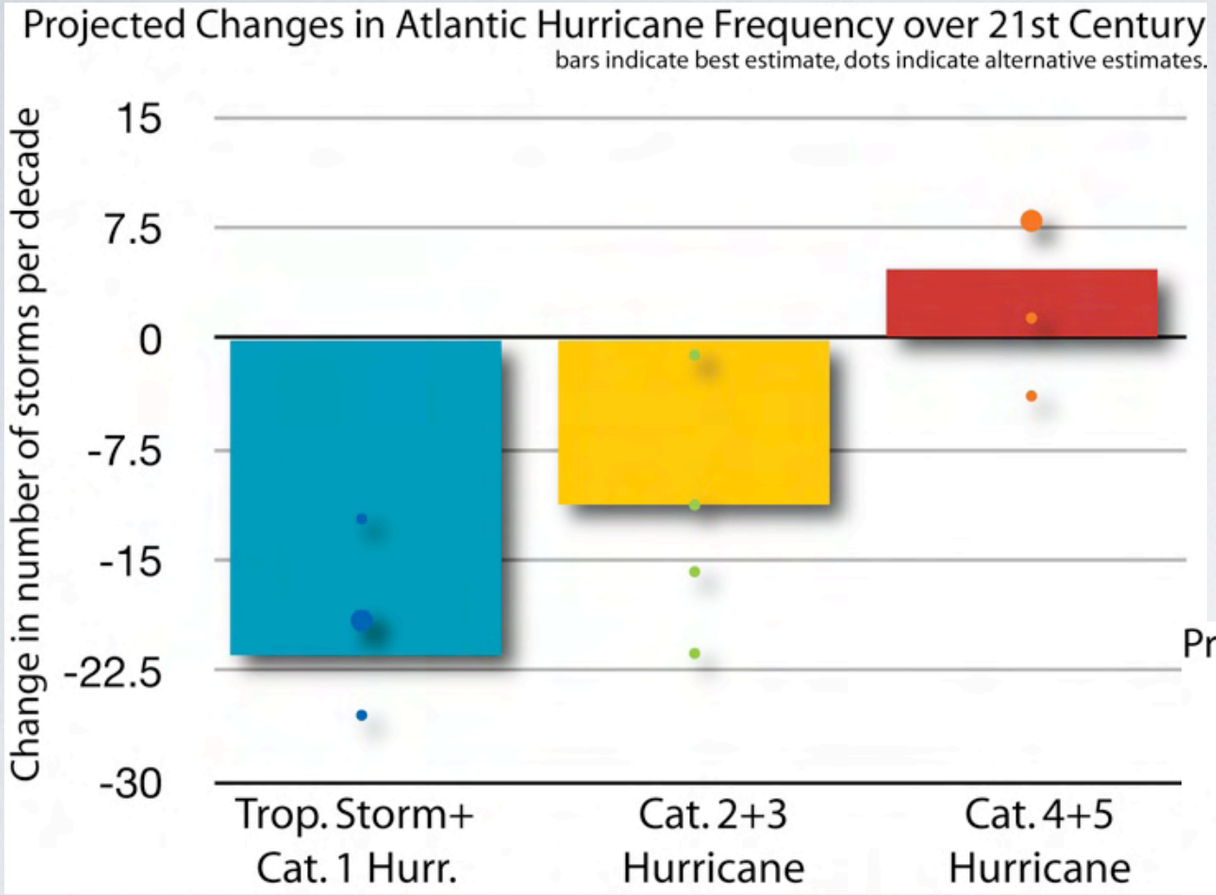


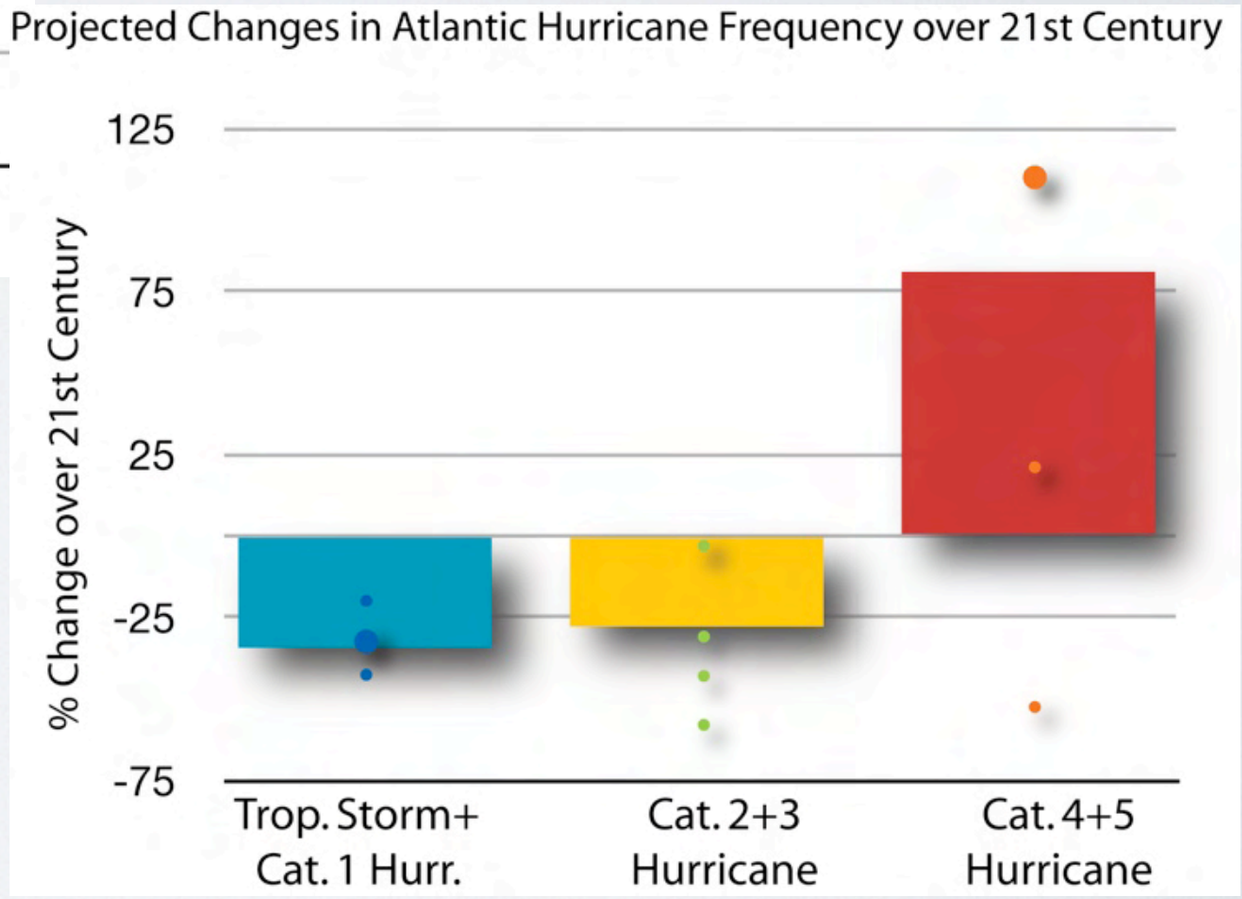
Adapted from
Bender et al (2010, Science)

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)

Sensitivity to SST Uncertainty

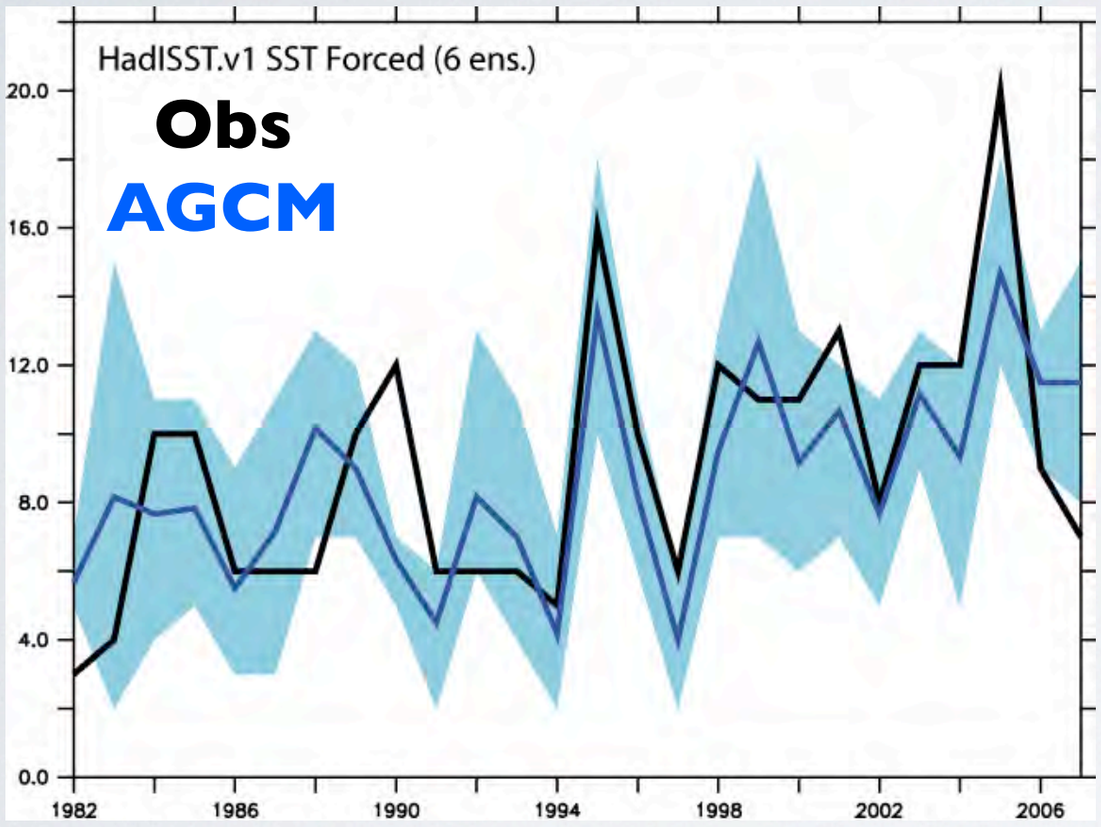
If AGCM sensitivity (and relative-SST statistical models) correct:

We may need to predict decadal SST changes better than we know past changes.
(even over the satellite-SST era;1982-2010)

Model Response Exhibits Sensitivity To Forcing Used

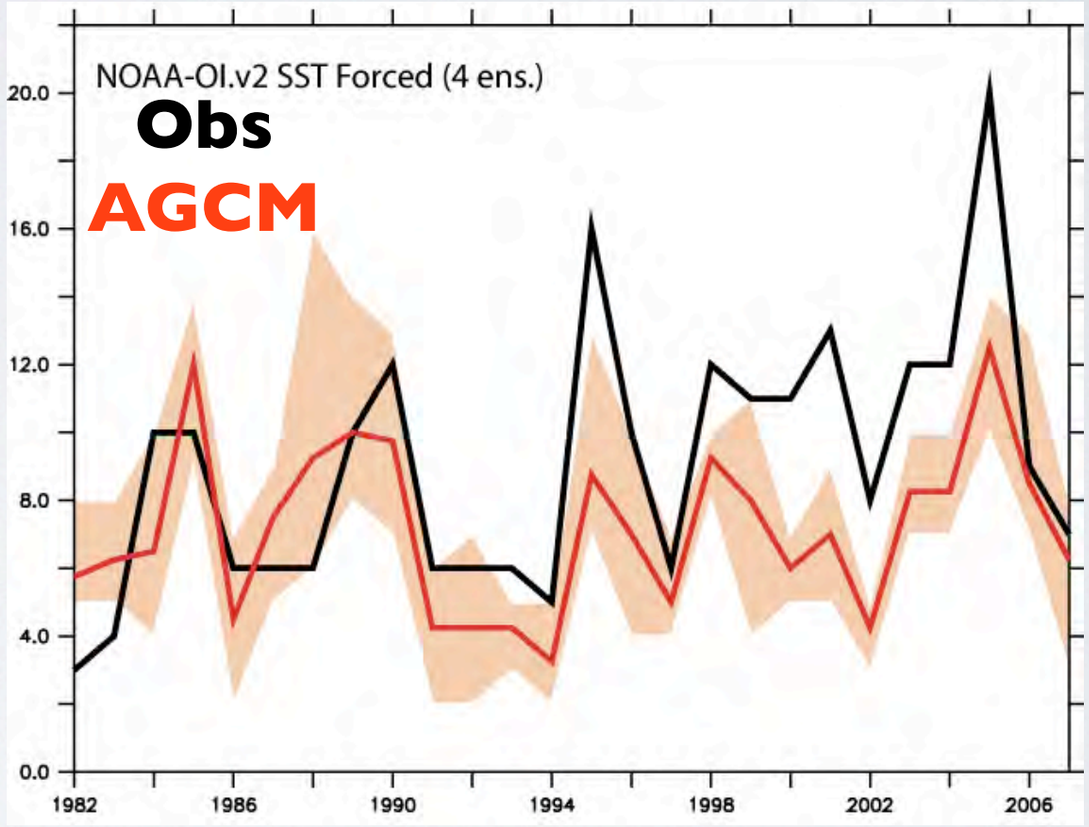
Tropical Storm Frequency Response to Same
AGCM but different estimates of observed SST

HadISST forced



AGCM is 100km version of Zhao et al (2009, J. Clim.)

NOAA-OI.v2 forced



Vecchi, Zhao and Held (2011, in prep.)

How do we evaluate model skill in this context?

SUMMARY

- It is premature to conclude that human activity (particularly CO_2) has already had an impact on Atlantic TS/HU frequency or PDI.
- Atlantic basin-wide activity controlled by SST changes in the Atlantic relative tropics.
- 1982-2007 TC increase in NA due to pattern of SST change
  (what drove pattern? Not robustly associate with forcing in CMIP3 models; consistent with internal variability in CMIP3 models)
- Projected radiative forcing not big source of predictability in frequency.
- Internal variability and systematic model differences dominant source of uncertainty even in 100-year trends.
- Dynamical projections for 21st Century frequency disagree largely due to different large-scale inputs:
  - Atlantic: Little change to frequency (possibly fewer) but increase in intensity.
- ***If sensitivity in high-res GCM correct, may need to predict decadal SST patterns better than we know past changes.***

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