

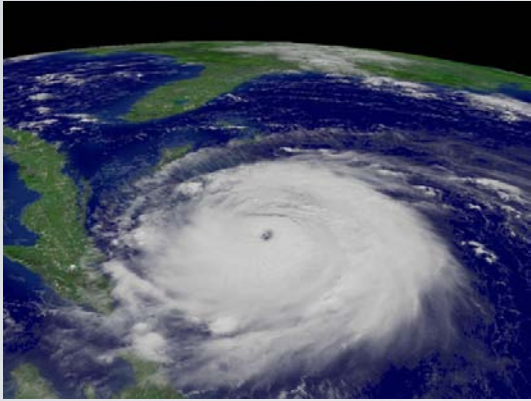


HURRICANE ATTRIBUTION, PREDICTIONS & PROJECTIONS

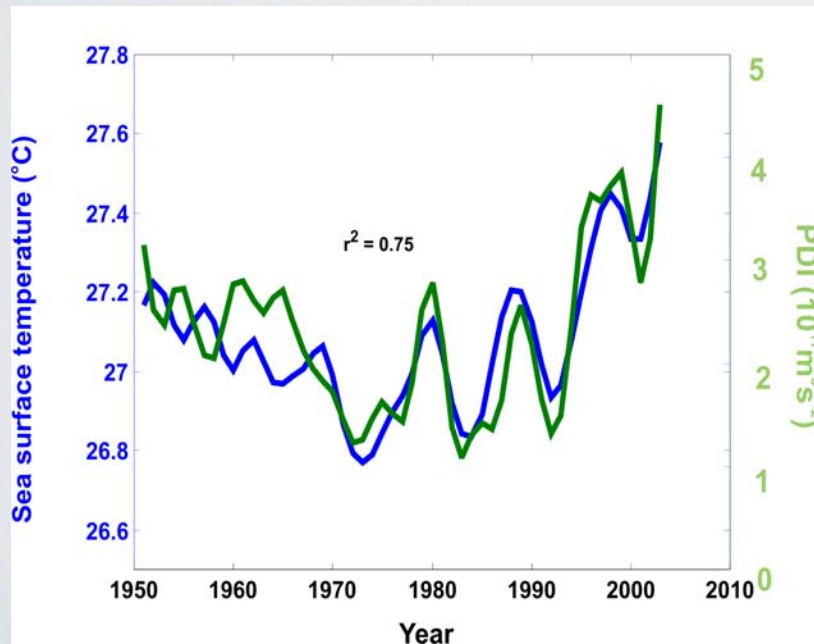
Gabriel Vecchi
NOAA/GFDL
Princeton, NJ

Image: NASA.

NORTH ATLANTIC TROPICAL CYCLONES



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



Emanuel (2007, J. Clim.)

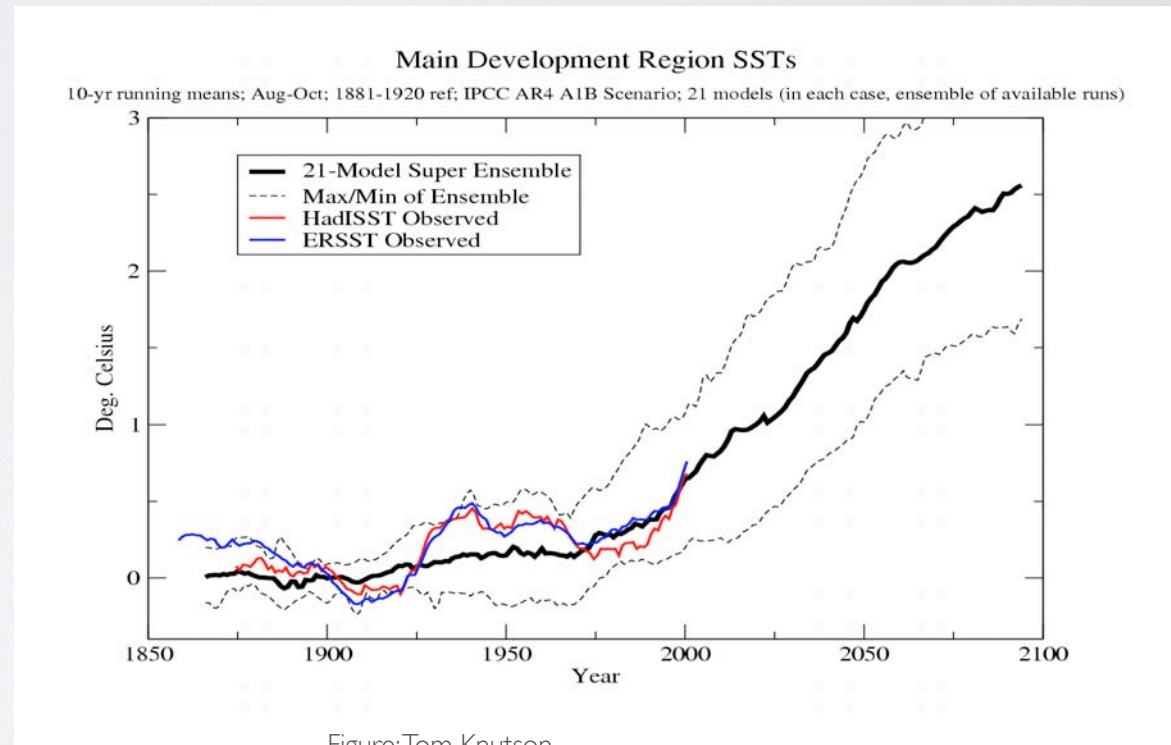
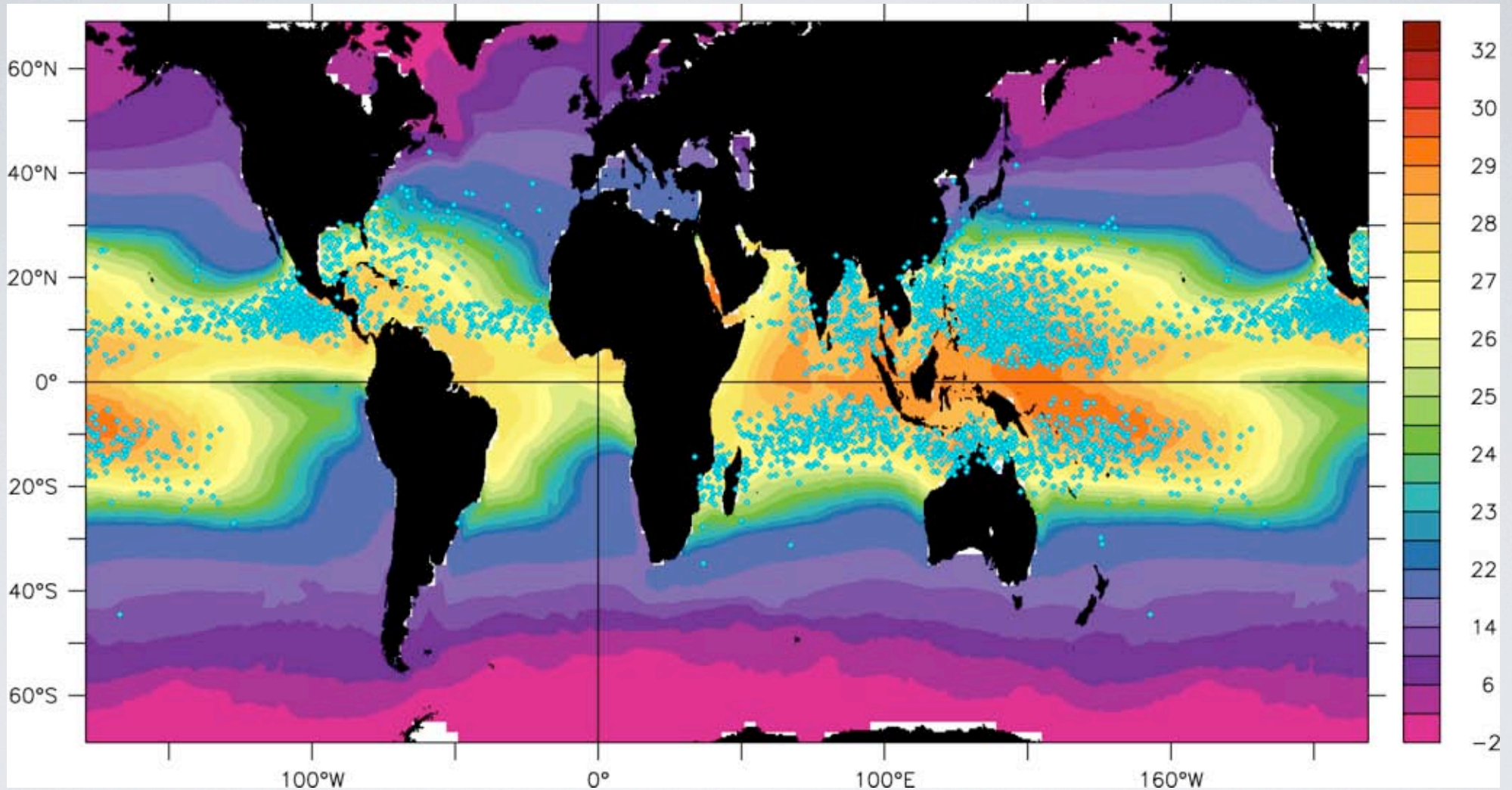


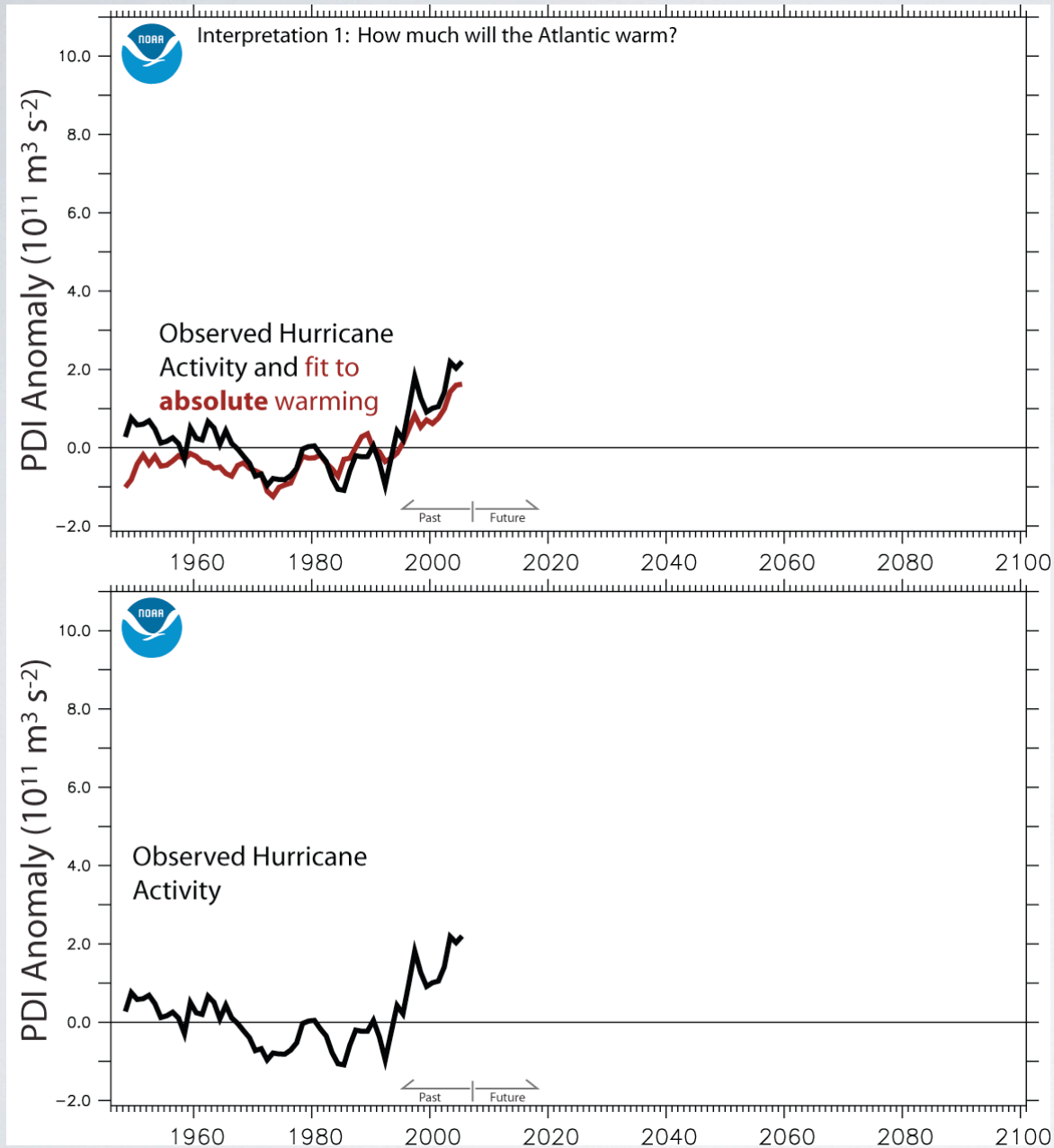
Figure: Tom Knutson

HISTORICALLY, TROPICAL CYCLONES FORM OVER WARM WATER



But warm water not enough, e.g. cyclones “like” an environment without strong wind shear to disrupt them, a moist mid-troposphere and a cool upper atmosphere.

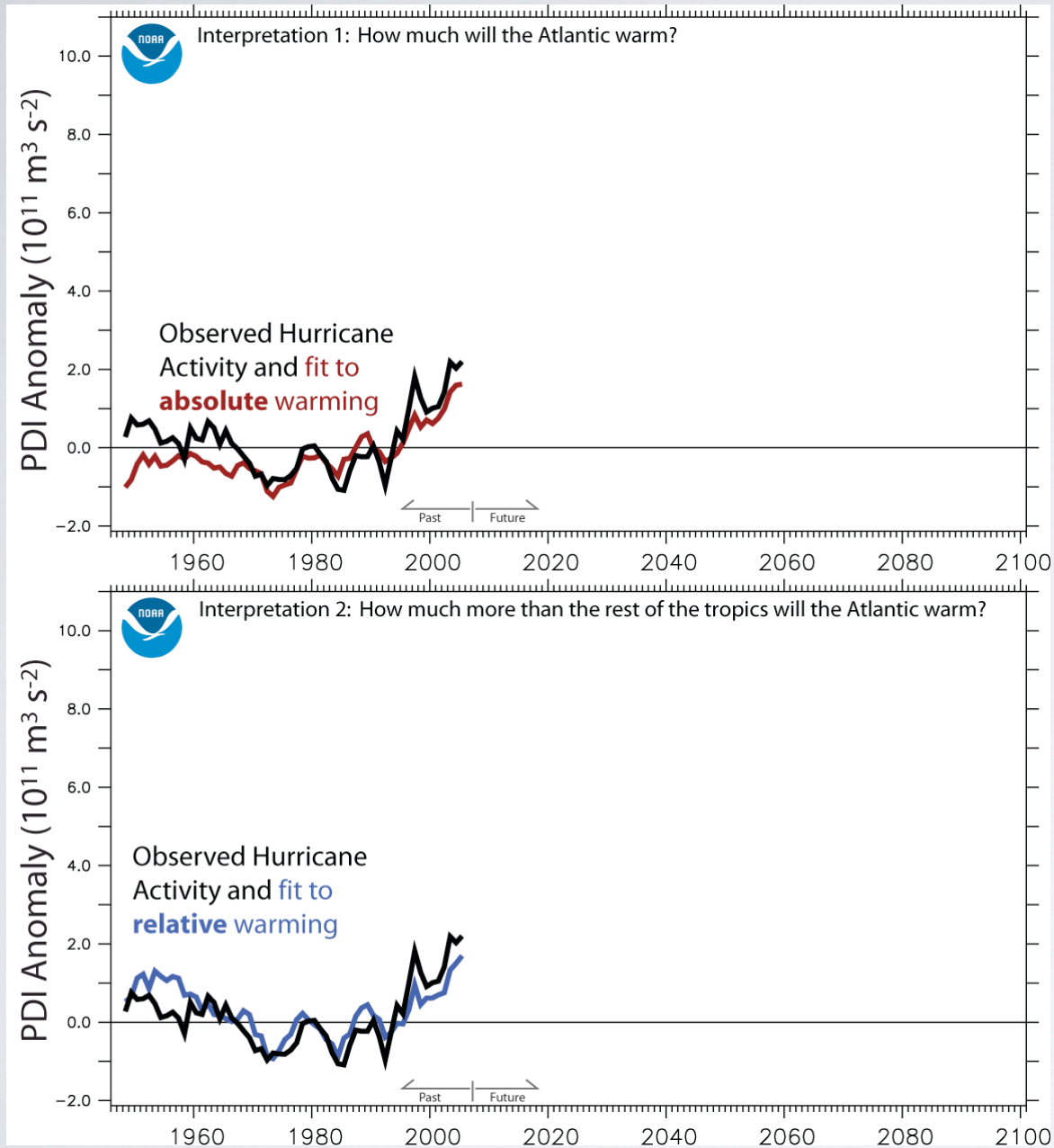
ONE TEMPERATURE PREDICTOR OF ATLANTIC HURRICANE ACTIVITY



Observed Activity
Absolute Atlantic
Temperature

Vecchi, Swanson and Soden
(2008, Science)

TWO TEMPERATURE PREDICTORS OF ATLANTIC HURRICANE ACTIVITY

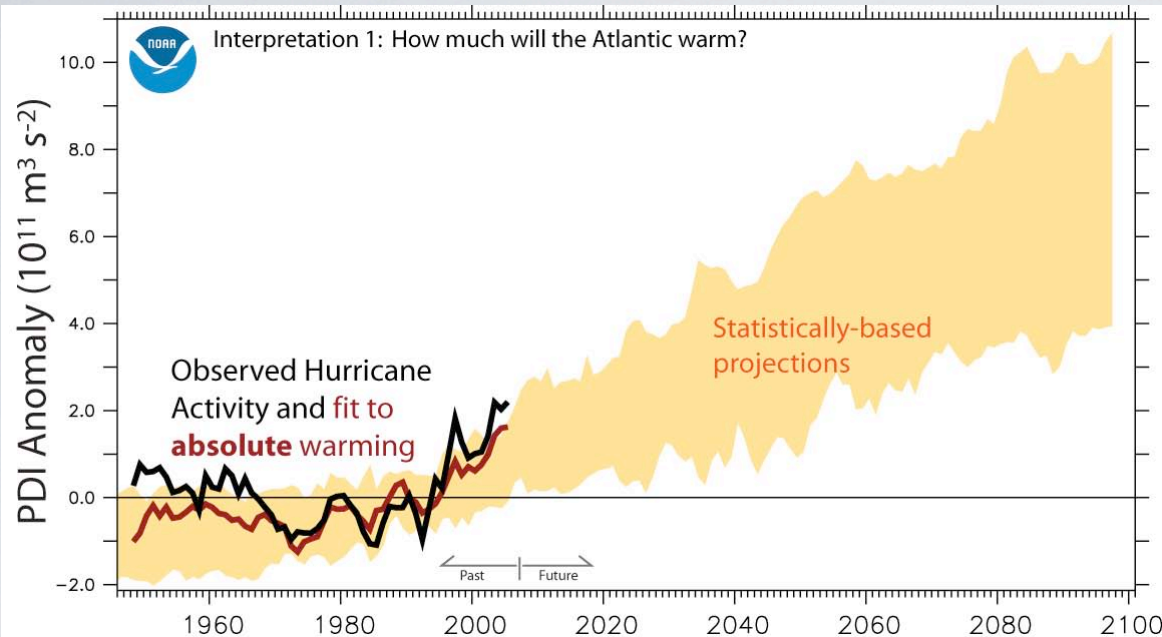


Observed Activity
Absolute Atlantic
Temperature

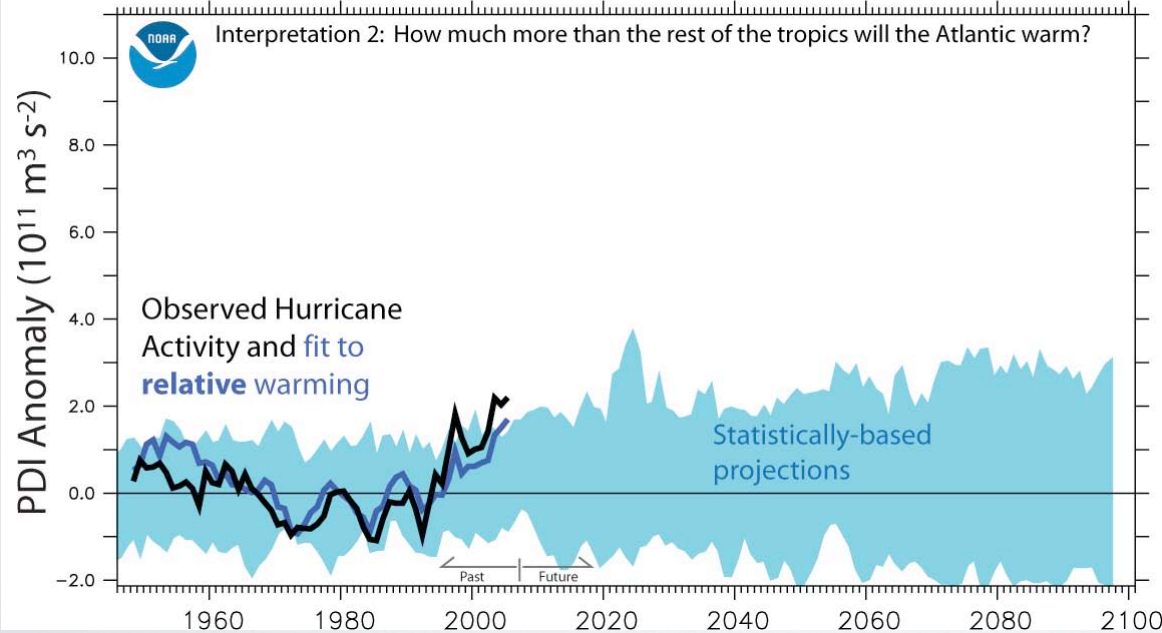
Observed Activity
Relative Atlantic
Temperature

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

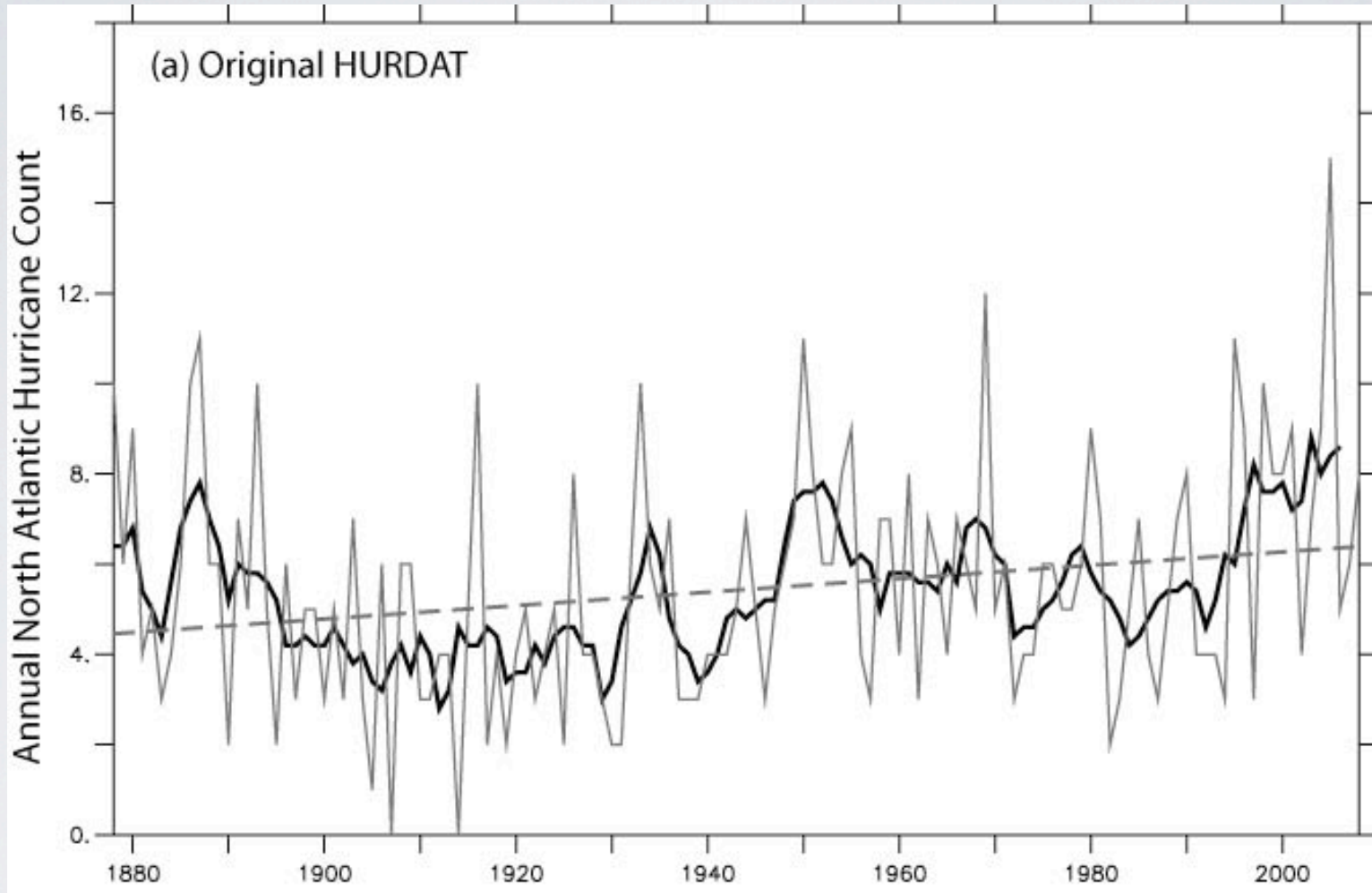
- Tools:
 - Observational records
 - Global climate models
 - High-resolution dynamical models
 - Statistical models
- Attribution of recent increase in Atlantic activity
- Predictions of seasonal activity
- Century-scale projections

OUTLINE

- Tools:
 - **Observational records**
 - Global climate models
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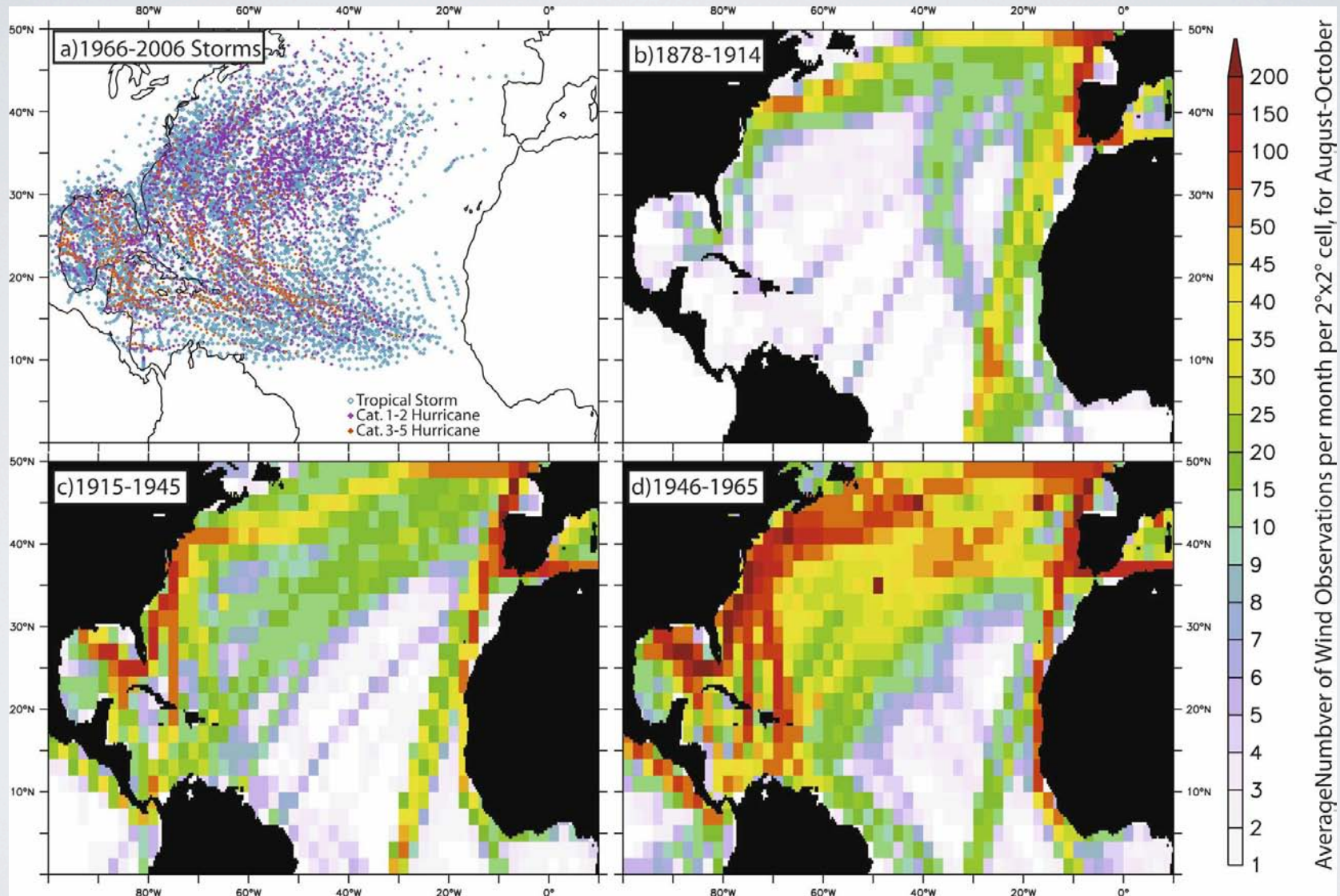
RECORDED NA HURRICANES SHOW CLEAR INCREASE

But was there really an increase?



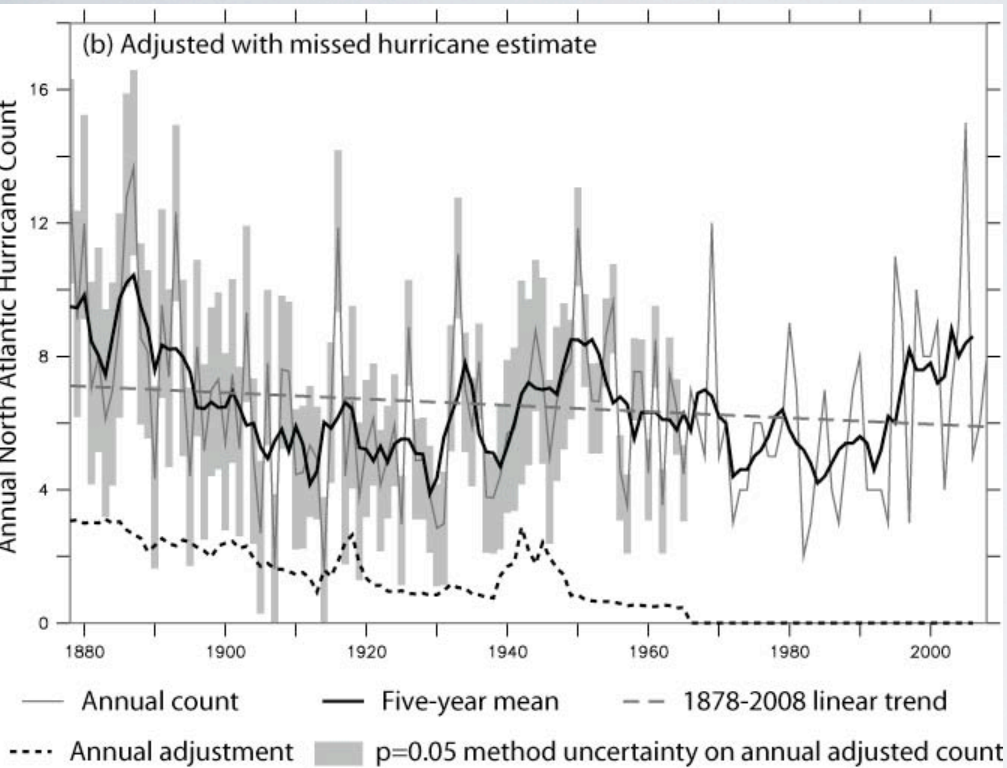
Vecchi and Knutson (2011, J. Climate, in press)

ABILITY TO OBSERVE CYCLONES HAS ALSO CHANGED WITH TIME: E.G., SHIP TRACK DENSITY



OBSERVED NA HURRICANE FREQUENCY CHANGES

NA Basinwide Hurricane Record



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

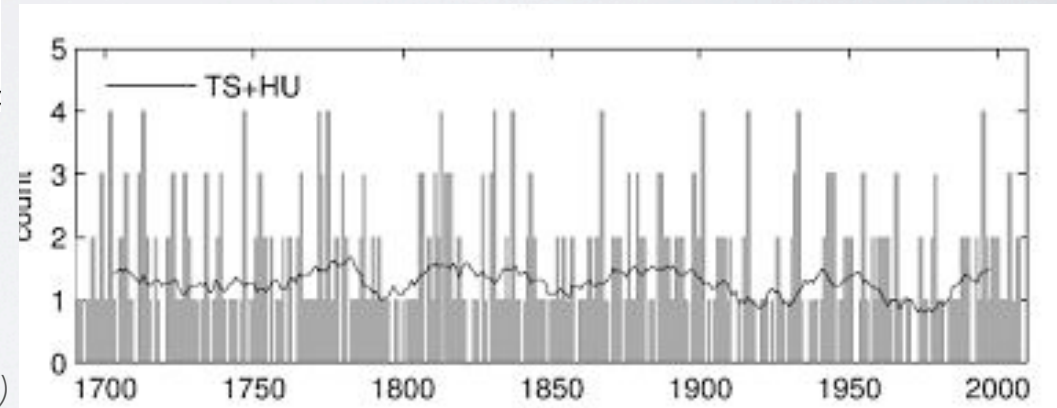
Chenoweth and Divine (2008)

Record Uncertain

Many timescales

Centennial Trend Unclear

Document-based reconstruction of Antilles TS and HU

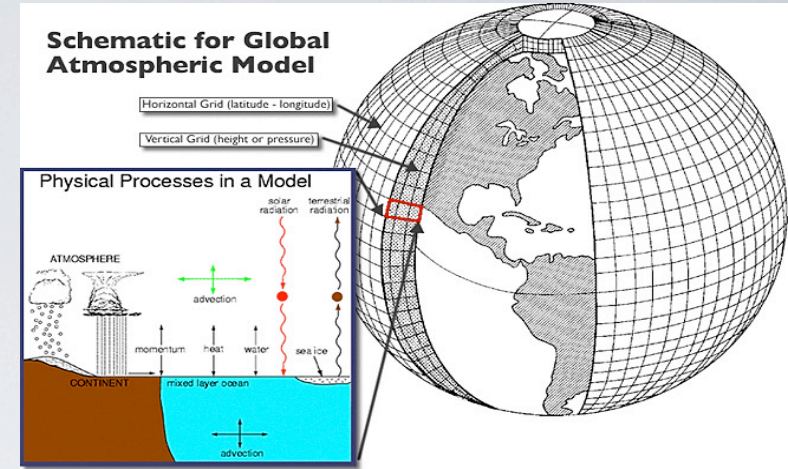
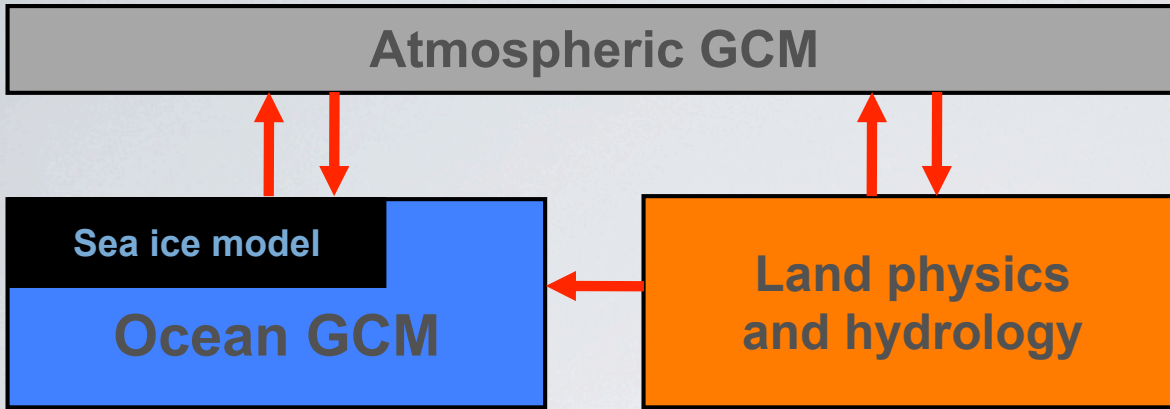


Various efforts to homogenize instrumental TC record (e.g., Landsea 2007, Chang and Guo 2007, Mann et al 2007, Vecchi and Knutson 2008, Landsea et al 2010, Vecchi and Knutson 2010).

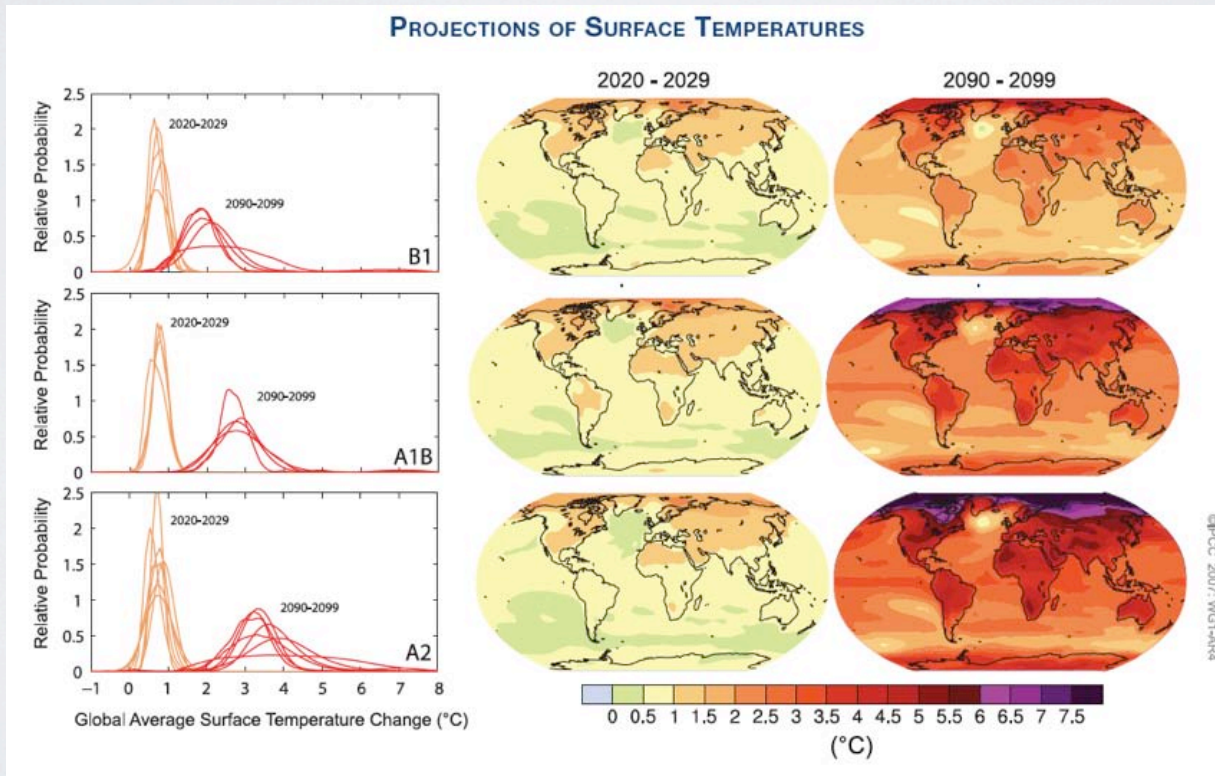
Data Archeology and Paleo-proxy Indicators Complement Instrumental Records (e.g., Chenoweth and Divine 2008, Mann et al 2009)

OUTLINE

- Tools:
 - Observational records
 - **Global climate models**
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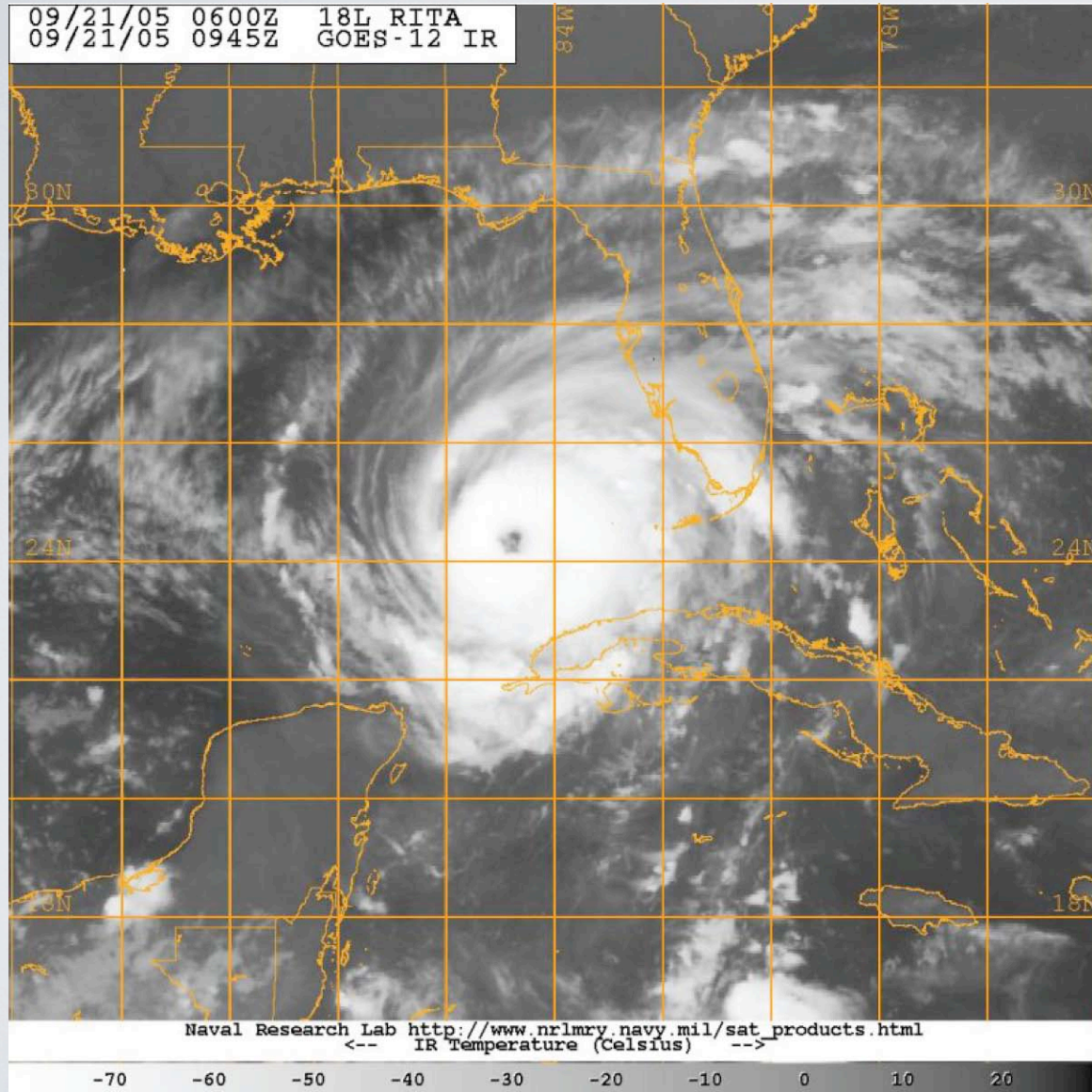


CAN GLOBAL CLIMATE MODELS GIVE GUIDANCE ABOUT CHANGES IN ATLANTIC STORM ACTIVITY?



IPCC-AR(2007)

NOT DIRECTLY: CURRENT COMPUTING POWER LIMITS ABILITY OF GLOBAL CLIMATE MODELS TO REPRESENT HURRICANES...

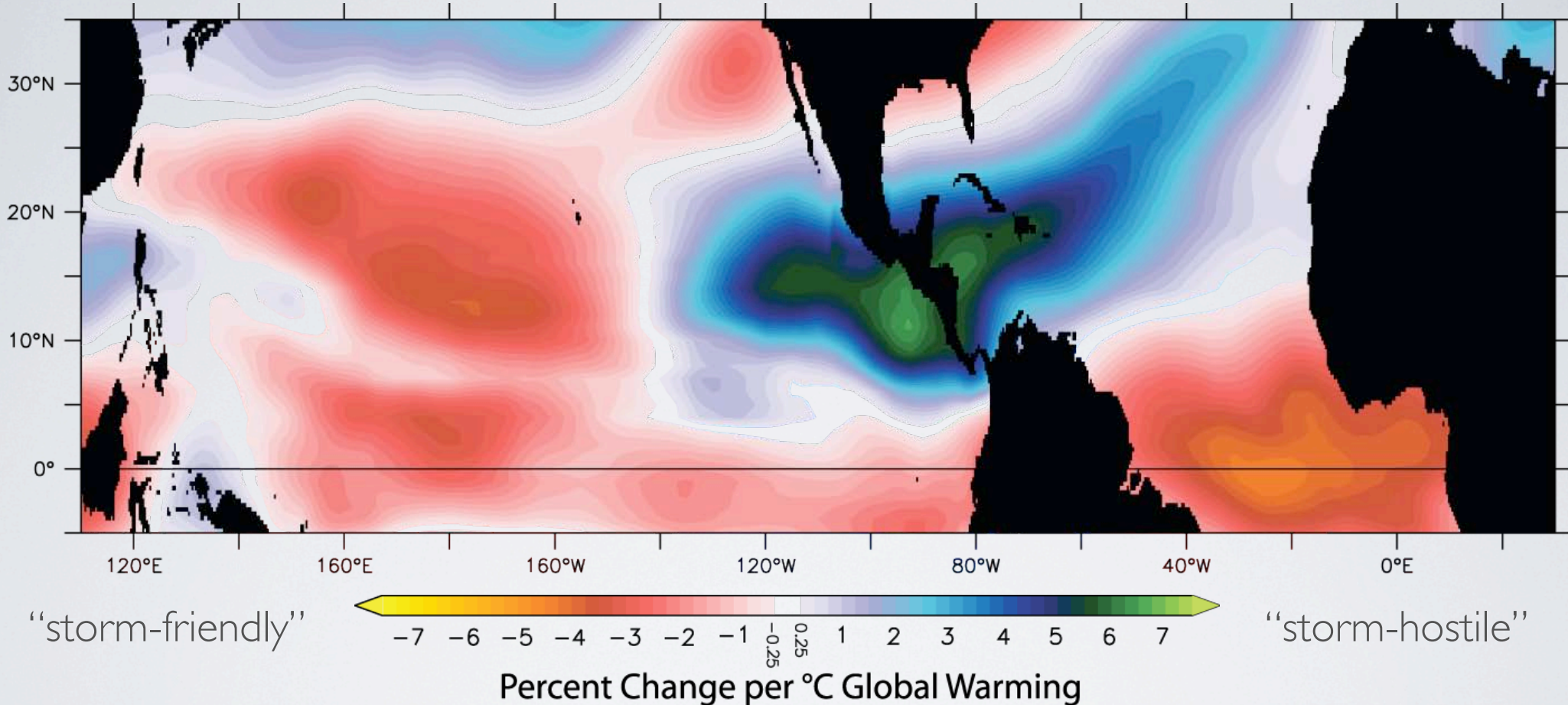


But GCMs can give large-scale conditions that influence hurricane activity (e.g., shear, potential intensity (PI), SST, etc)

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

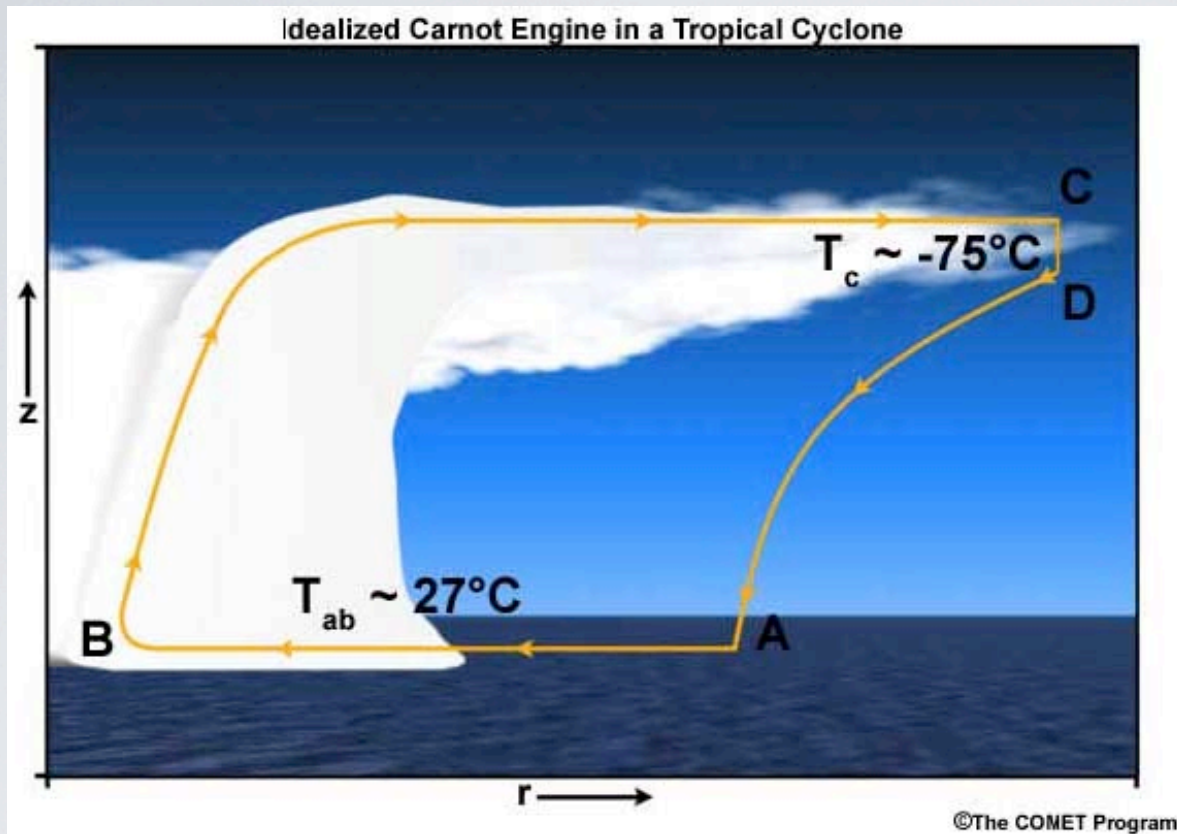
PROJECTED 21ST CENTURY CHANGES IN VERTICAL WIND SHEAR

Average of 18 models, Jun-Nov



Over swath of tropical Atlantic and East Pacific, increased wind-shear, related to a reduction in the Pacific Walker circulation.

THEORY OF MAXIMUM POTENTIAL INTENSITY



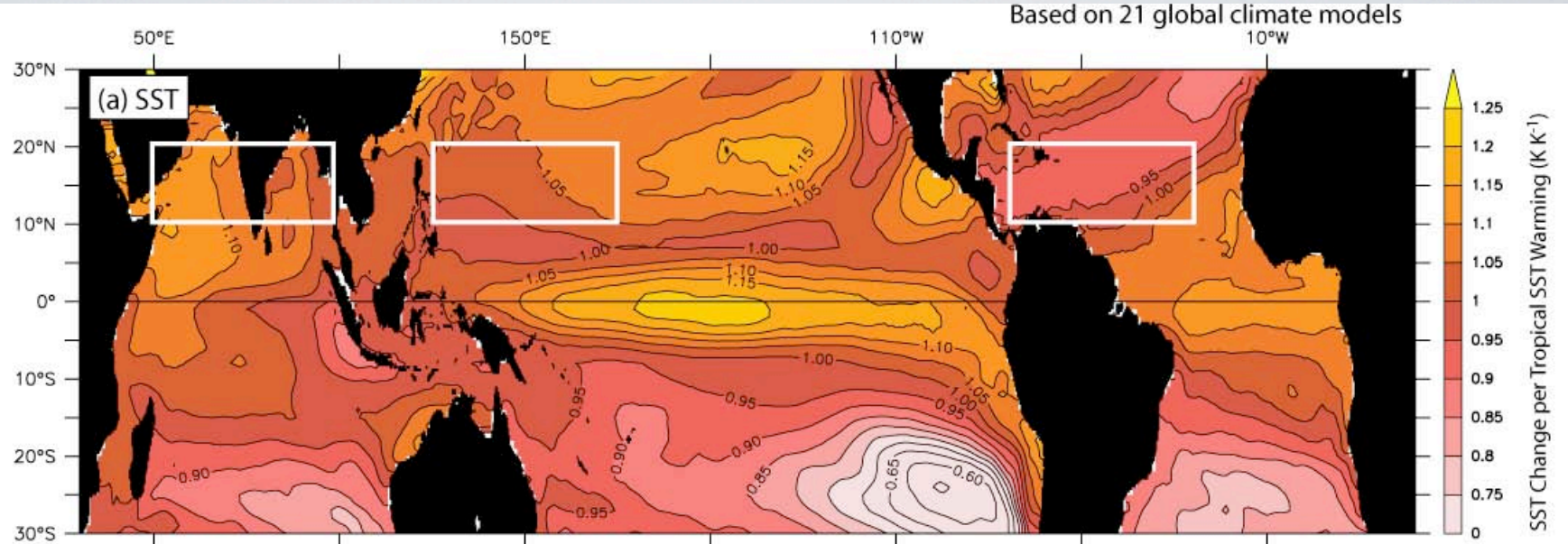
cf. Bister and Emanuel (1998)

Potential Intensity = “Fuel” * “Efficiency”

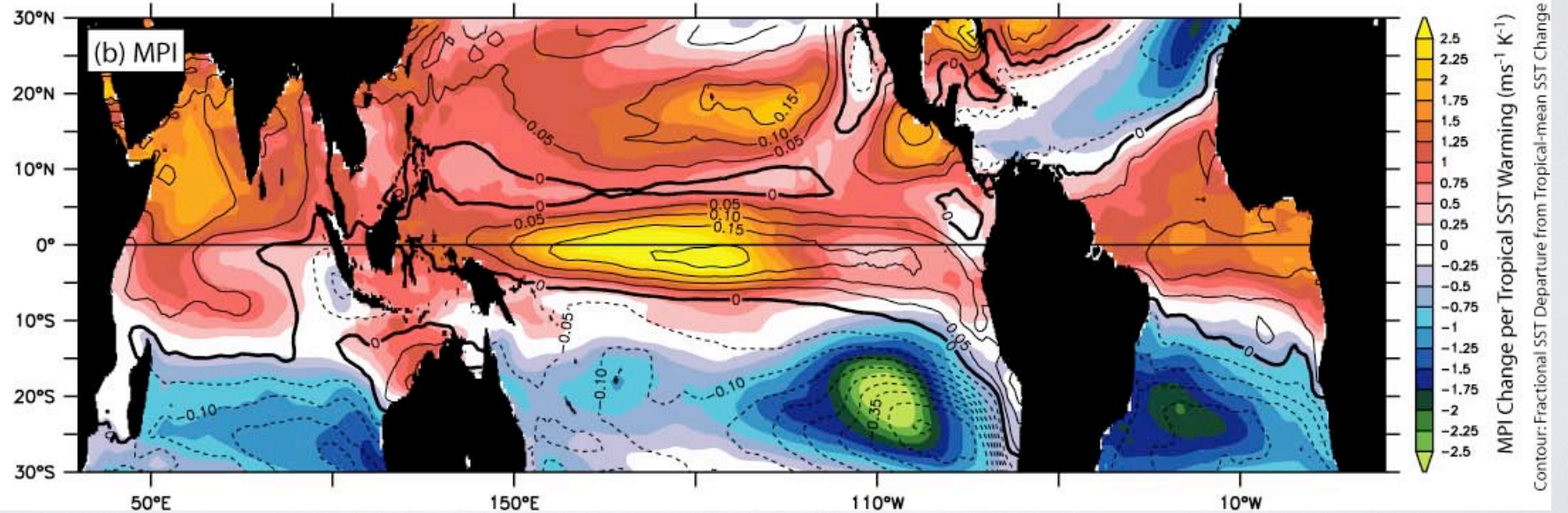
Roughly speaking, “Fuel” increases as ocean warms and “Efficiency” increases as ocean warms, decreases as upper atmosphere warms

POTENTIAL INTENSITY TRACKS SST RELATIVE TO TROPICAL-MEAN, NOT LOCAL SST

SST Projection



PI Projection



Vecchi and Soden (2007, Nature)

OUTLINE

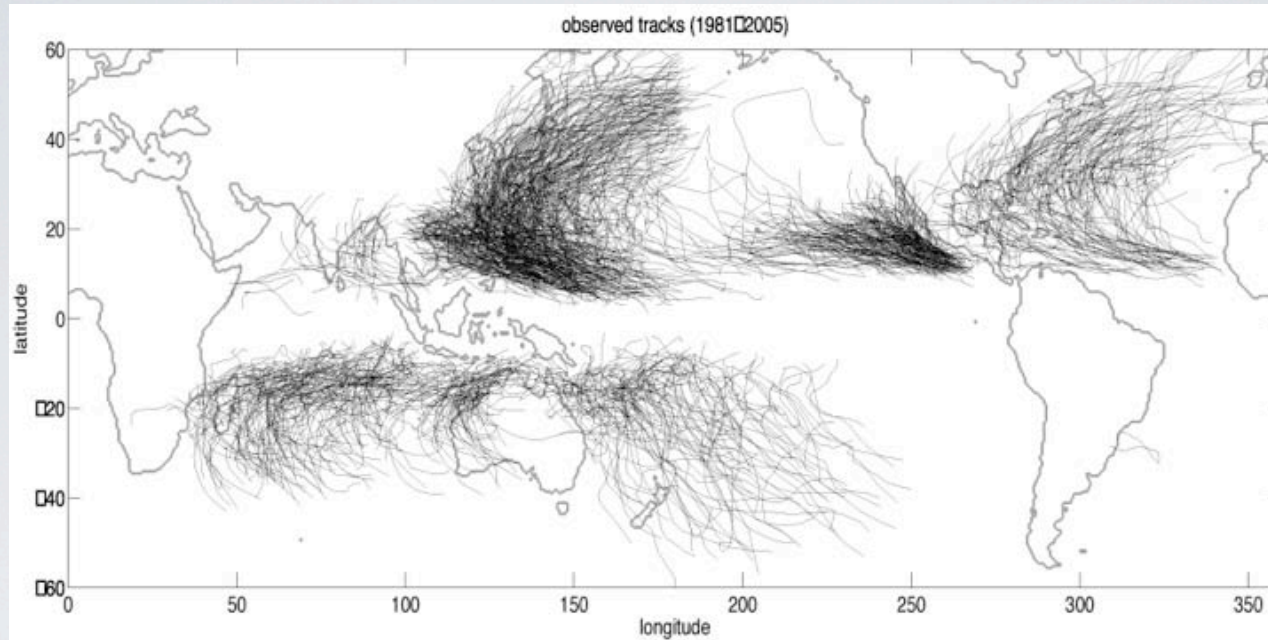
- Tools:
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**NOAA-GFDL C180
Atmosphere Model**

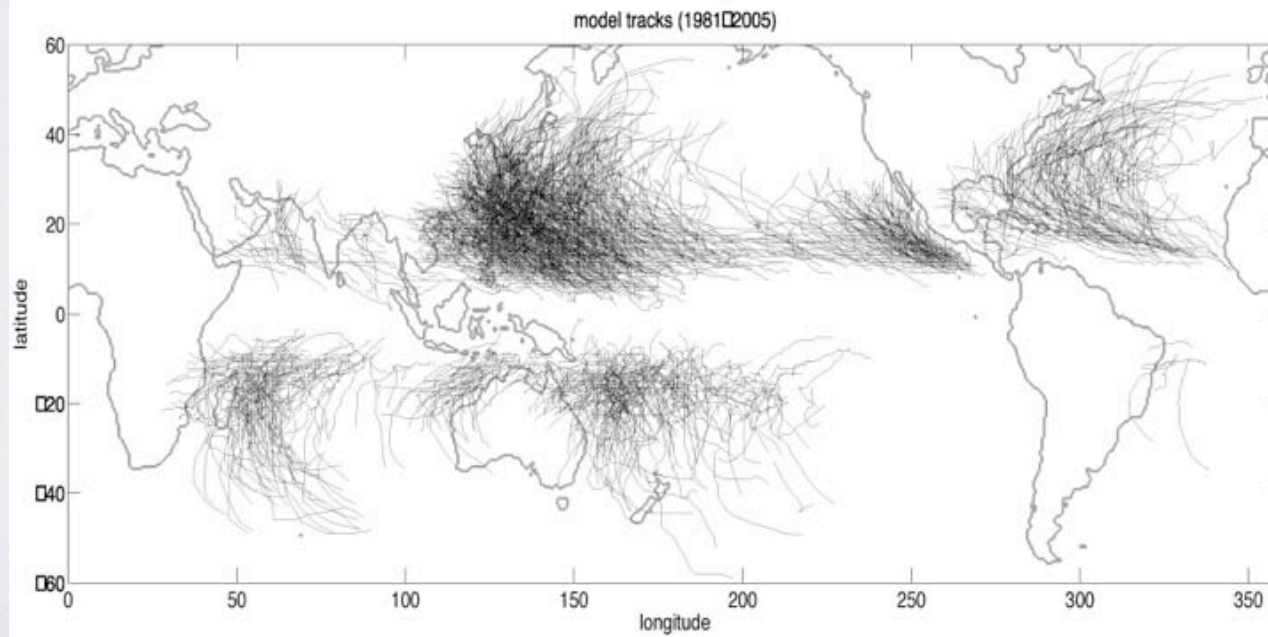


MODEL RECOVERS MANY ASPECTS OF OBSERVED HURRICANE TRACKS

Observed



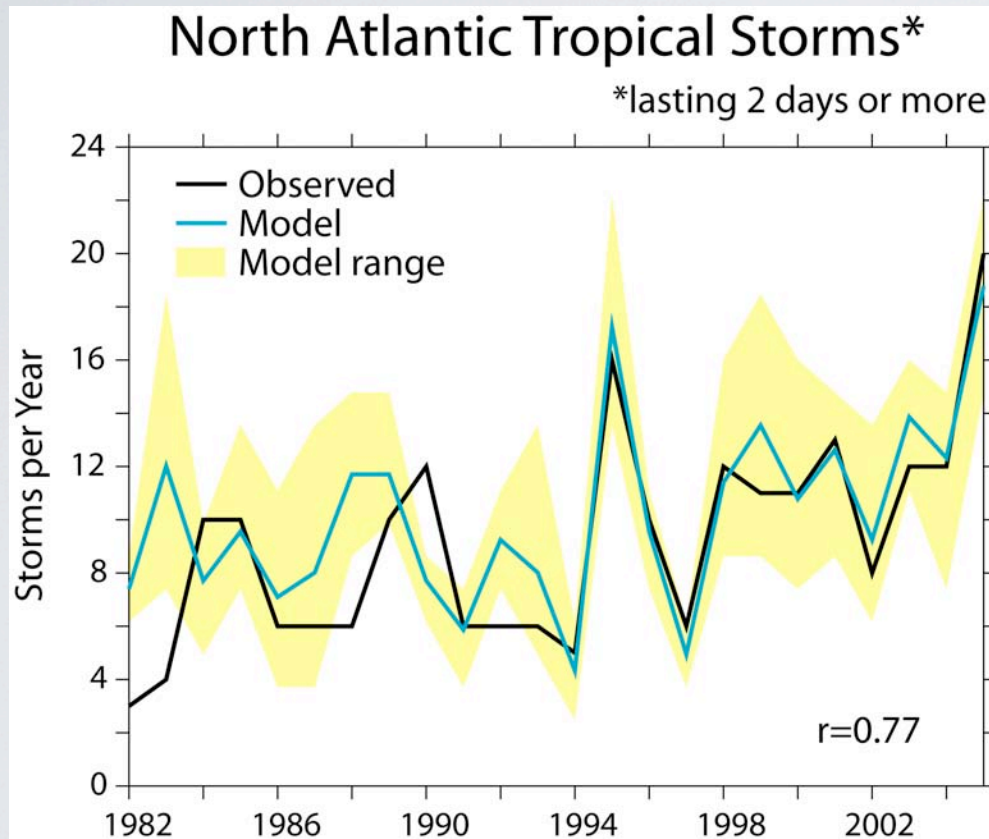
CI80 Model



*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)



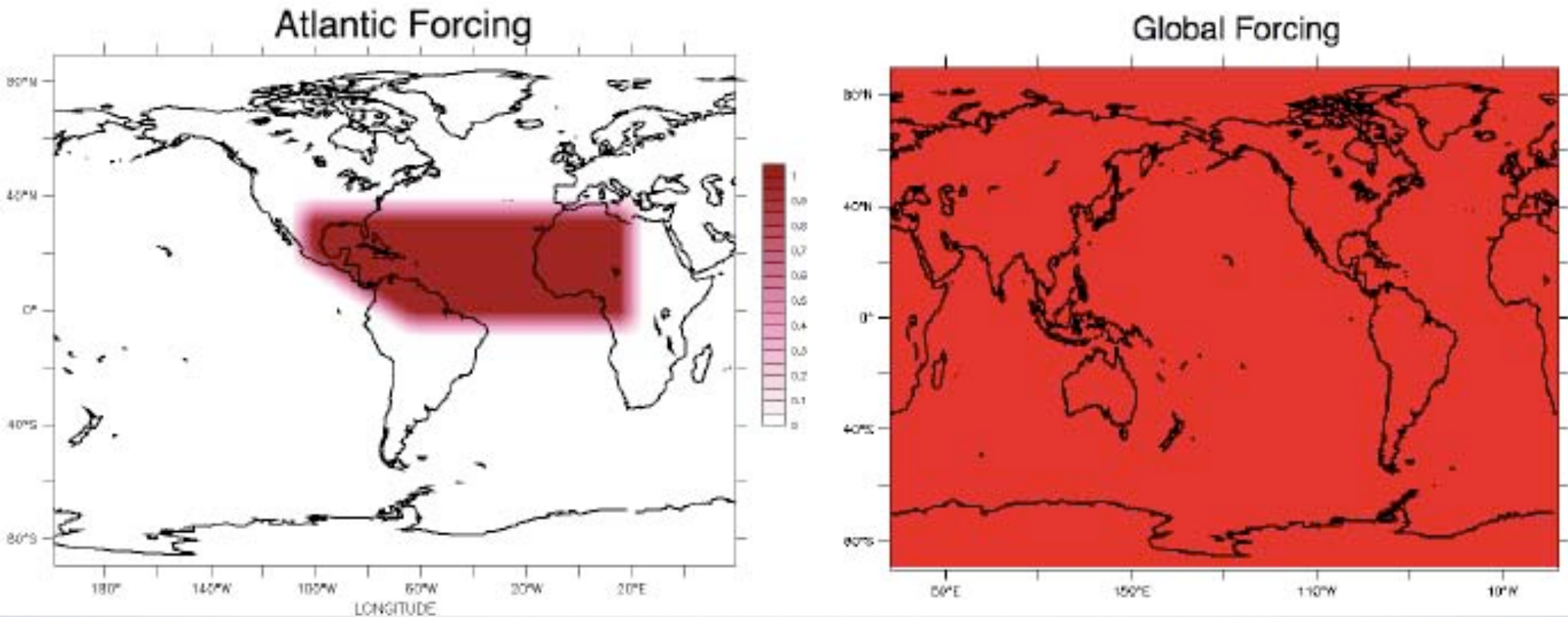
Adapted from AM2 with:

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

IDEALIZED FORCING EXPERIMENTS

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

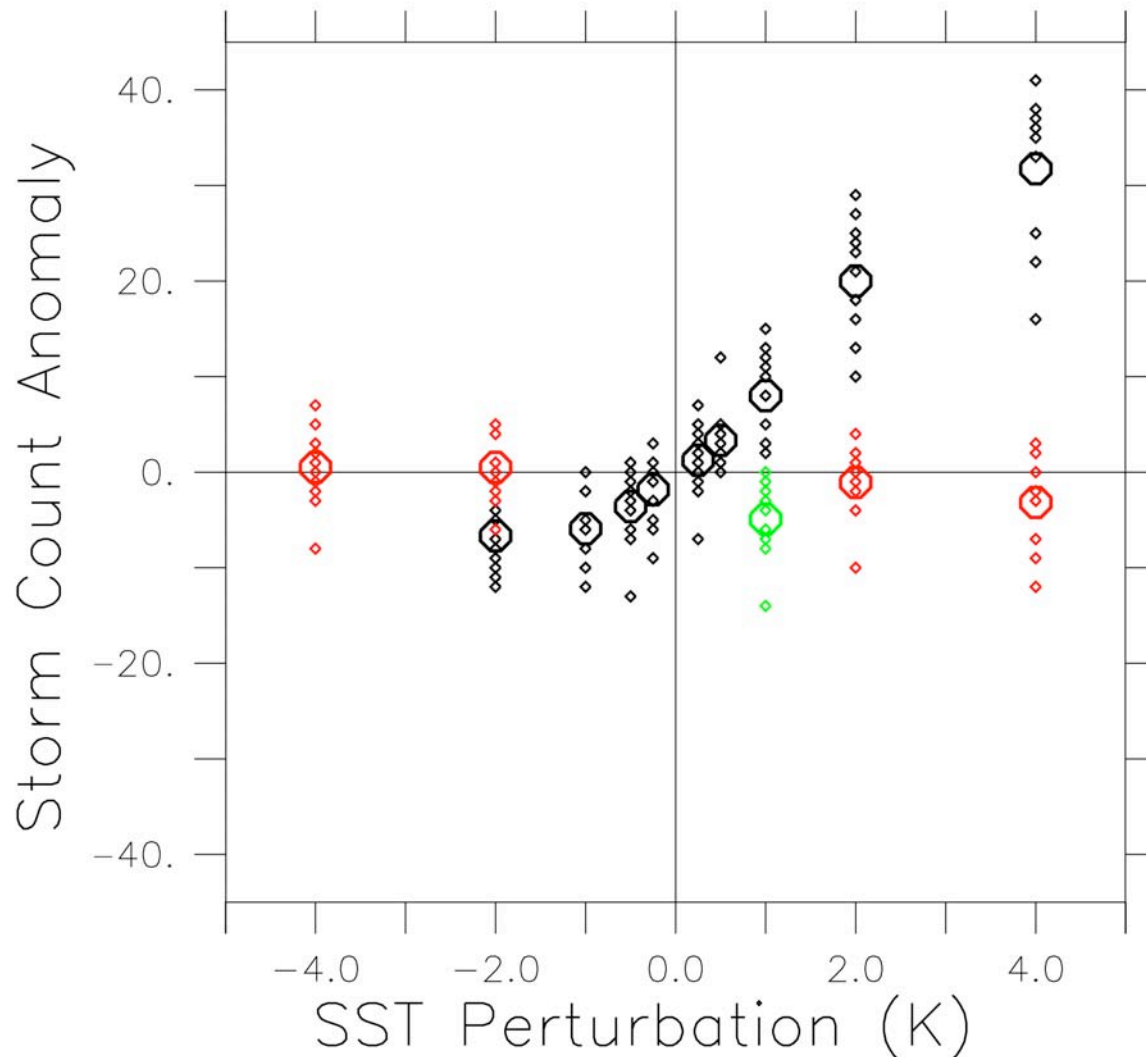
- Similar Atlantic Response to Atlantic and Uniform F'cing
- Little Pacific Response to Atlantic compared to Uniform



NORTH ATLANTIC RESPONSE TO IDEALIZED SST

Change in Annual NA Storms from Idealized SST:

NATL, GLO, EQU



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)

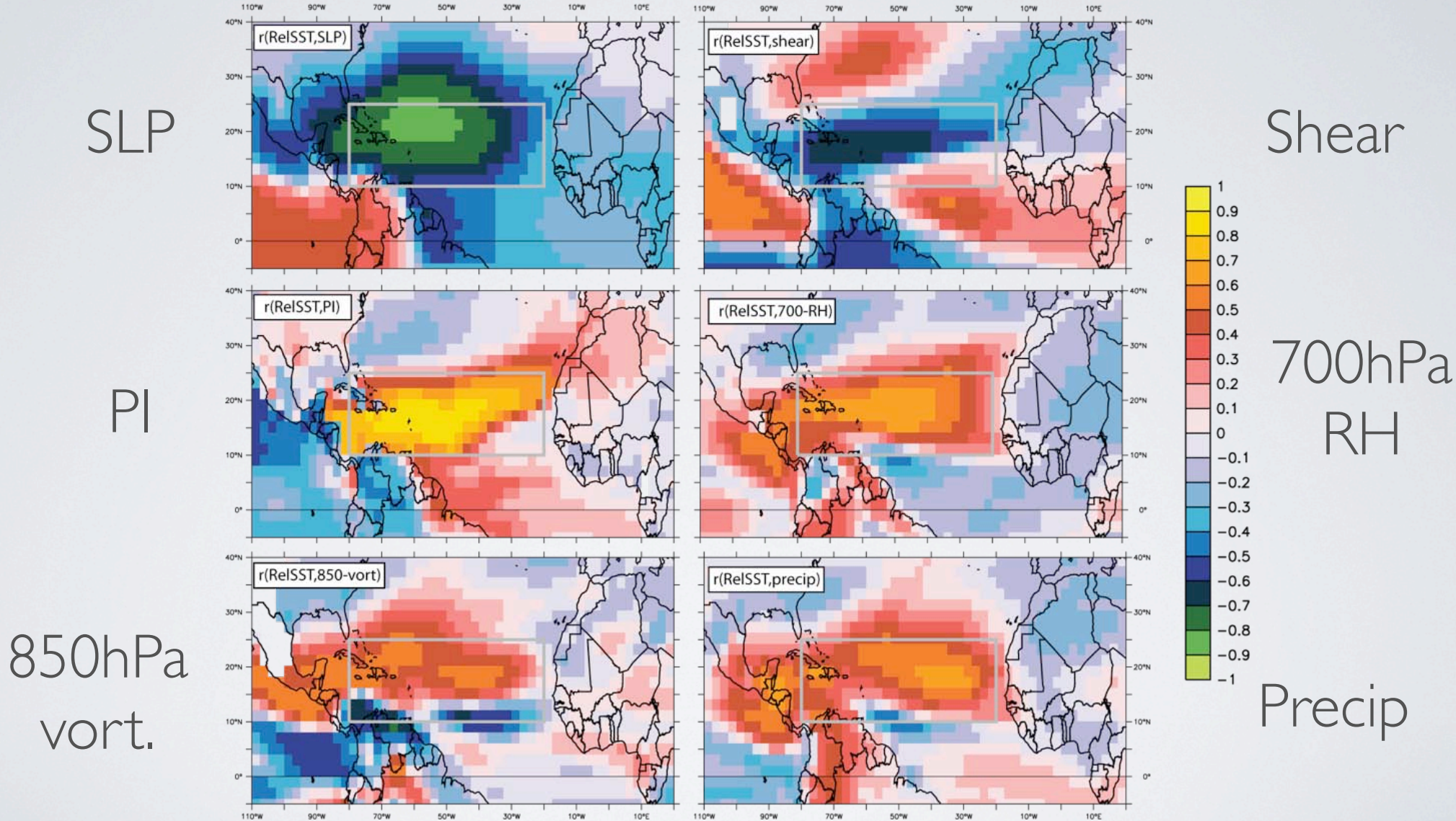
- Build statistical models of TS frequency:
 - >2 day duration basin-wide with and without adjustment
 - Landfalling
- Explore range of models, sensitivity to:
 - Possible covariates:
(NAO, SOI, **Atlantic SST, Tropical SST**)
 - Model structure (Poisson vs. Negative Binomial).
 - Penalizing criterion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

TROPICAL SST AS PREDICTOR OF CYCLONE ACTIVITY?

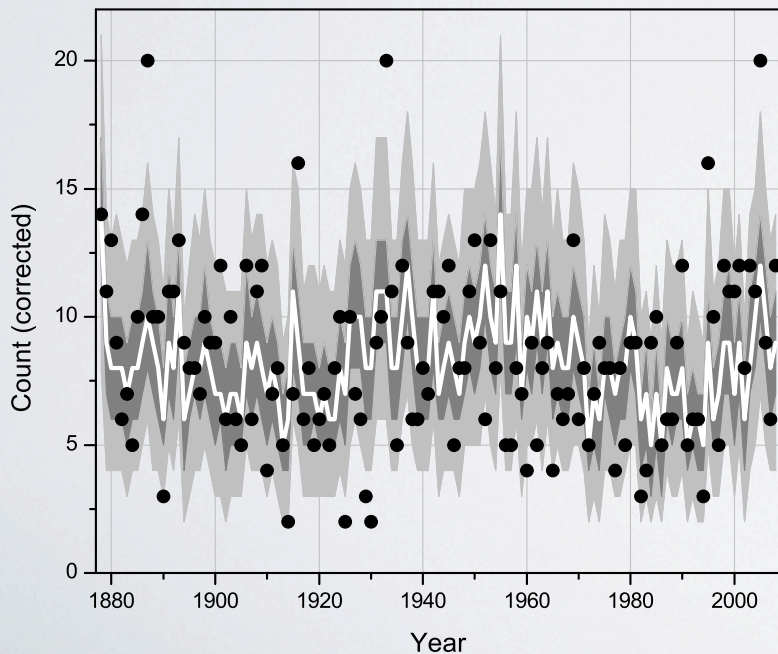
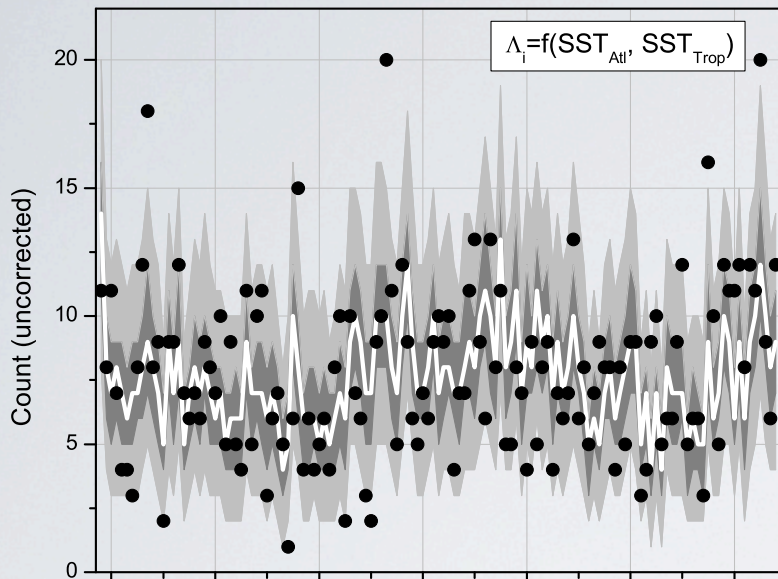
- Remote SST changes impact Atlantic wind shear:
 - During El Niño (e.g., Gray 1975)
 - Warming-induced weakening of Walker circulation increases shear (Vecchi and Soden 2007)
 - Warming of Indo-West Pacific increases shear (Latif et al 2007, GRL)
- Remote warming acts to increase thermodynamic stability:
 - 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)
- High-resolution studies indicate warming relative to tropical-mean relevant quantity:
 - Knutson et al (2008), Zhao et al (2010), Vecchi et al (2011, in prep)

HURRICANE-RELEVANT LARGE-SCALE CONDITIONS CO-VARY CONSTRUCTIVELY WITH RELATIVE-SST

Interannual Correlation of Large-Scale Conditions to Relative-SST (Aug-Oct - CM2.1 1860 Control)



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)	2.11 (0.03)
	2.03 (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)	-1.22 (0.22)
	-0.91 (0.20)	-1.05 (0.19)

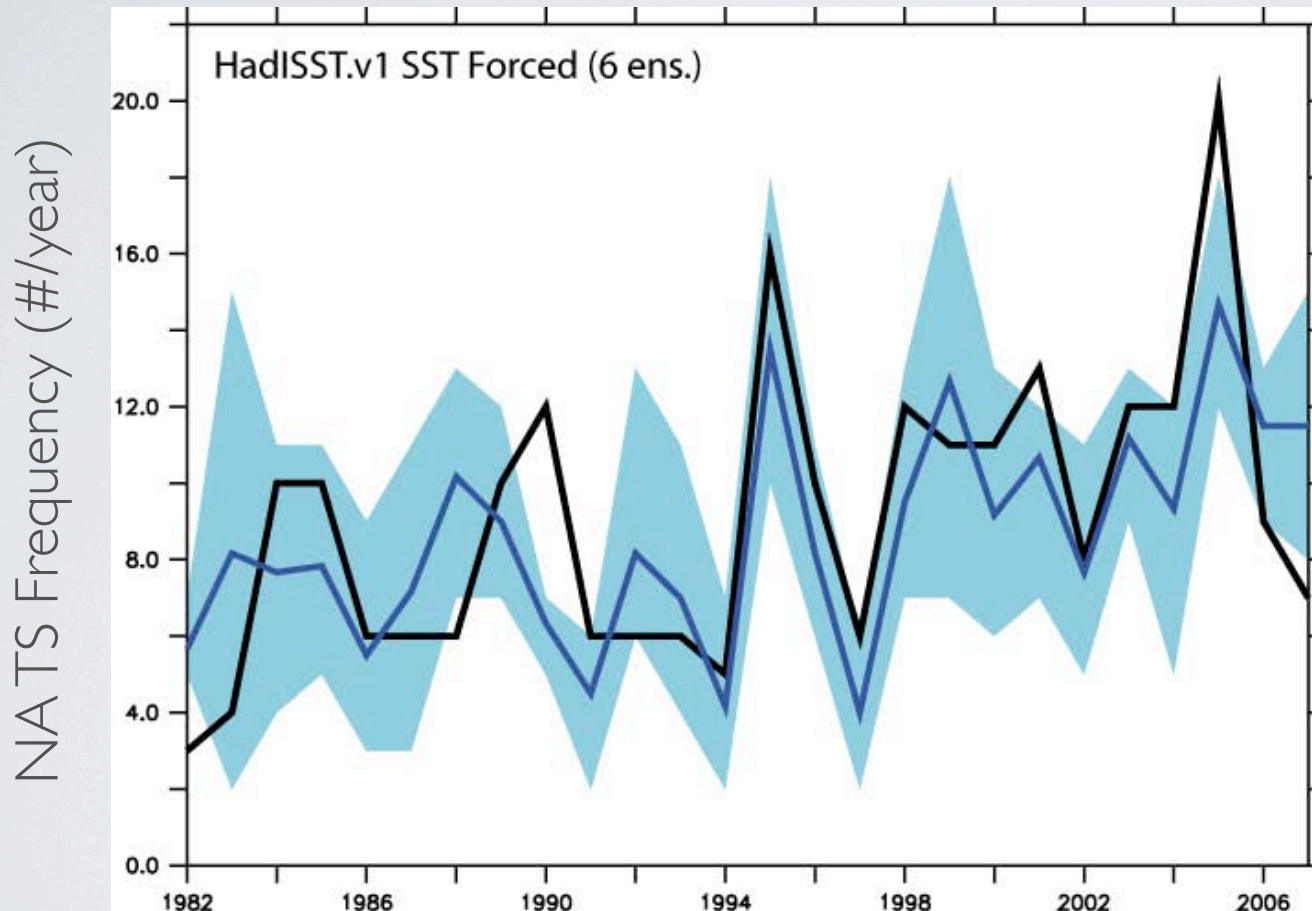
Villarini, Vecchi and Smith (2010, MWR)

OUTLINE

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

ATTRIBUTION OF RECENT TS FREQUENCY INCREASE IN NORTH ATLANTIC

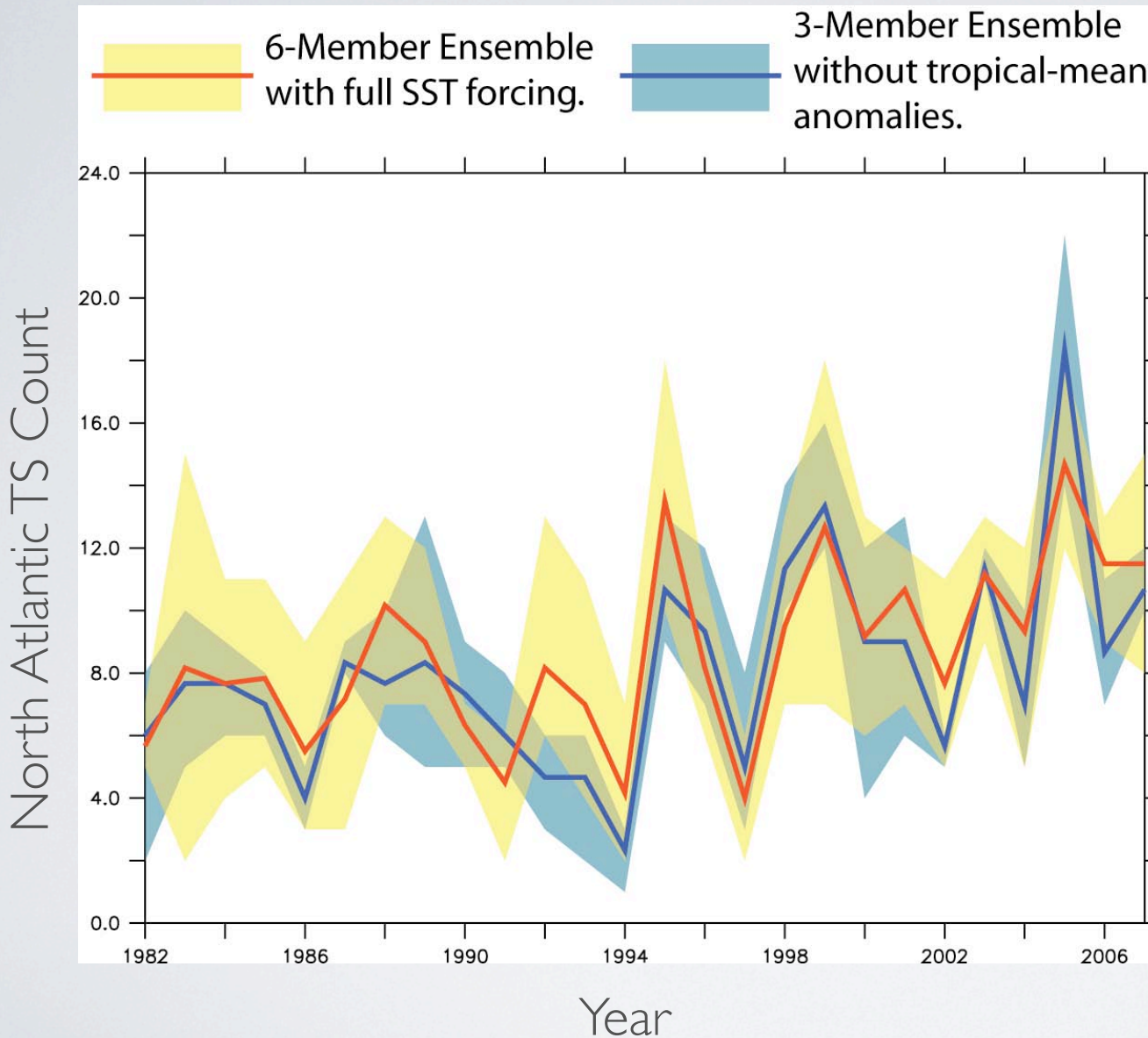
100km GFDL-HiRAM AGCM recovers recent NA TS Trend when
forced with HadISST.v1 SST



What aspect of SST
drove increase?

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

NA TS INCREASE NOT DRIVEN BY UNIFORM COMPONENT OF RECENT SST WARMING



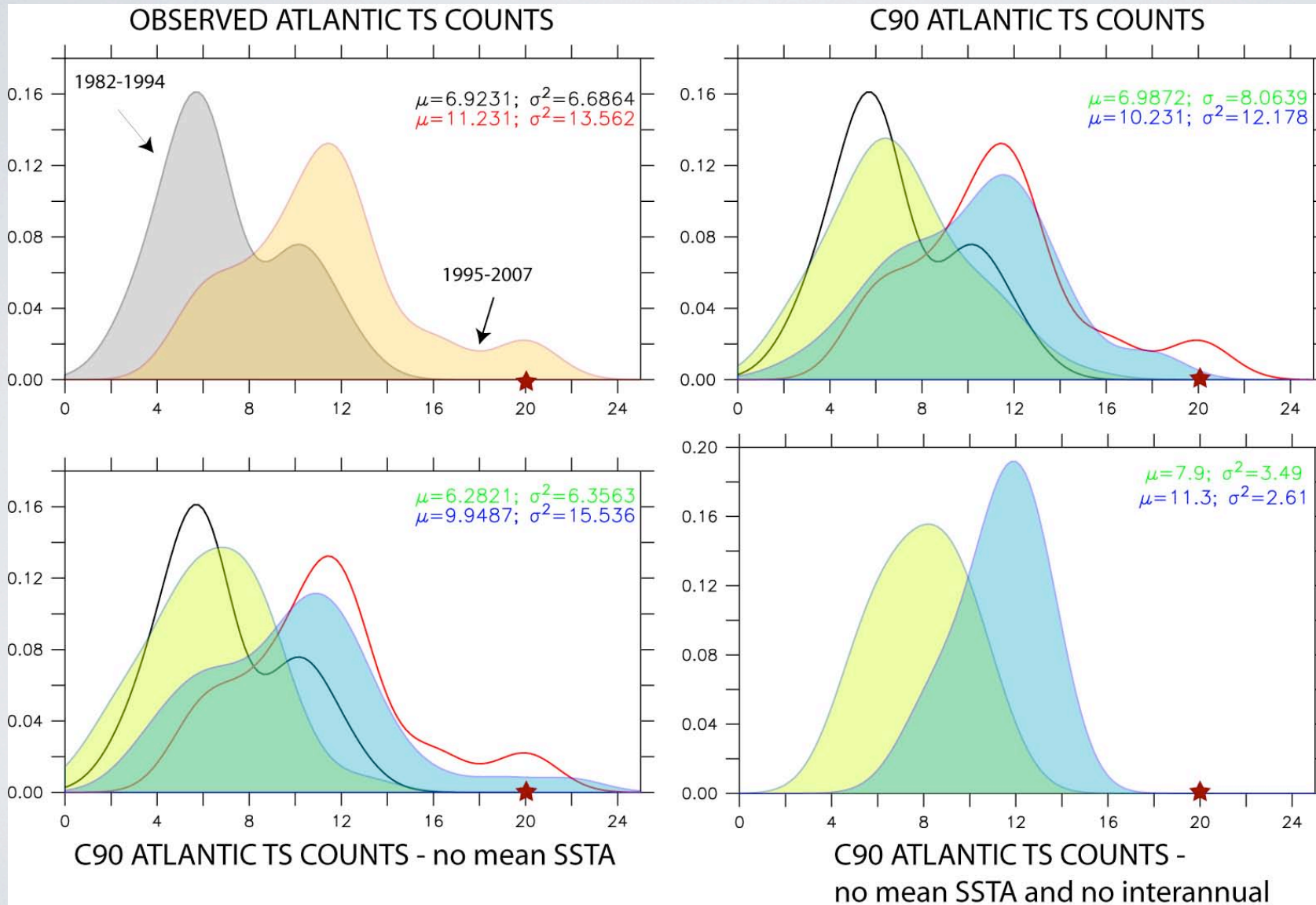
100km AGCM
1982-2007 North Atlantic tropical storm count not sensitive to removing tropical-mean SSTA forcing.

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

1982-94 AND 1995-2007 PDFS OF NATS COUNT*

* lasting two days or more

★ 2005 Observed

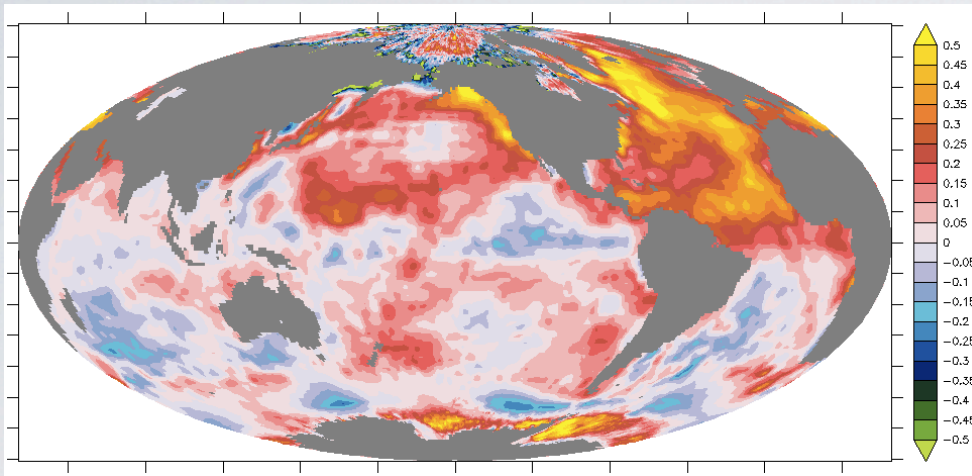


Vecchi, Delworth, Held and Zhao (2011, in prep.)

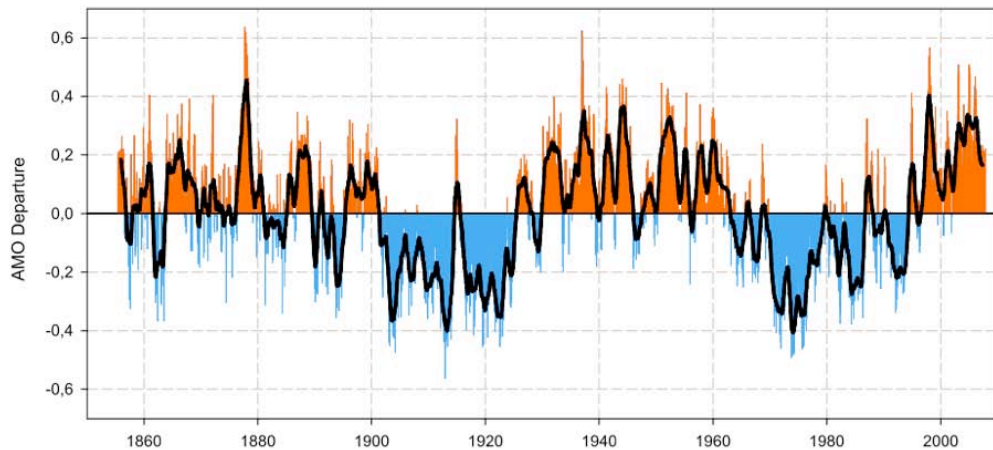
SHIFT IN MEAN TS COUNTS ATTRIBUTABLE TO “AMO” SST CHANGE ACROSS 1994-1995

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

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



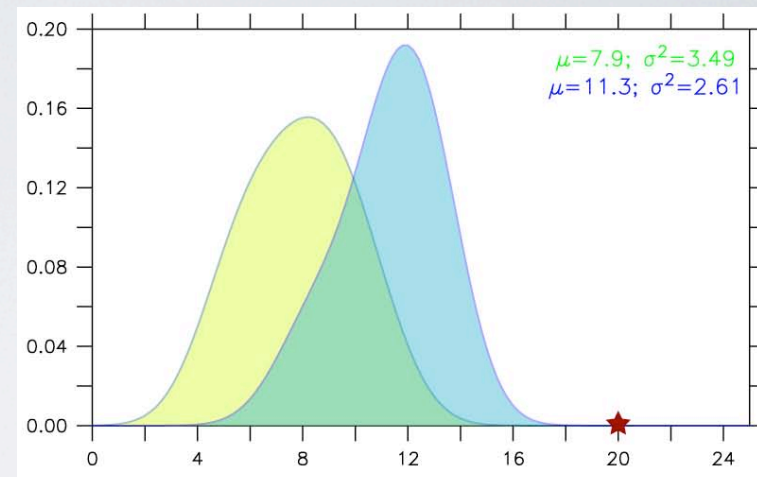
Monthly values for the AMO index, 1856–2008



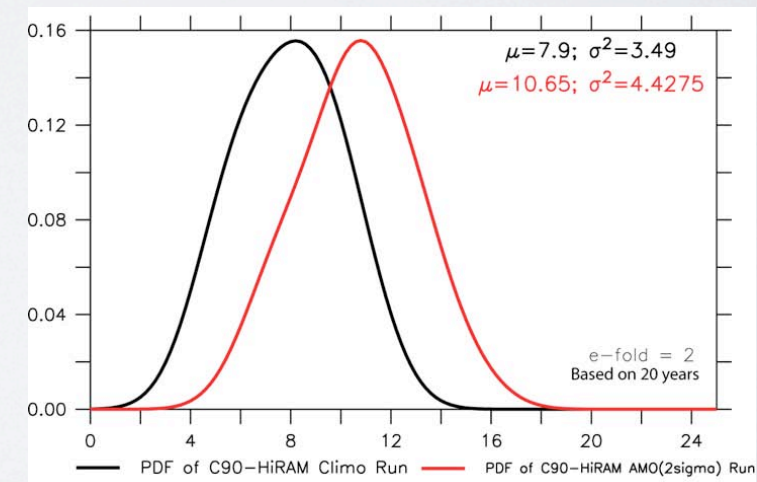
AMO Index: Regression of SST onto NA SST

Knight et al (2005)

Response to decadal shift



Response to “AMO” forcing

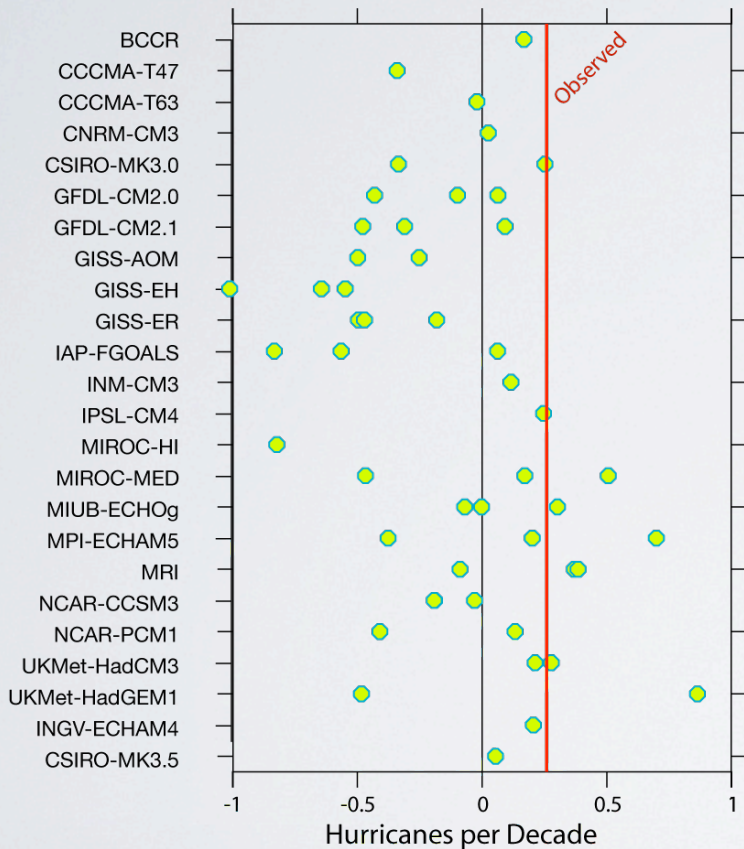


Vecchi, Delworth, Held and Zhao (2011, in prep.)

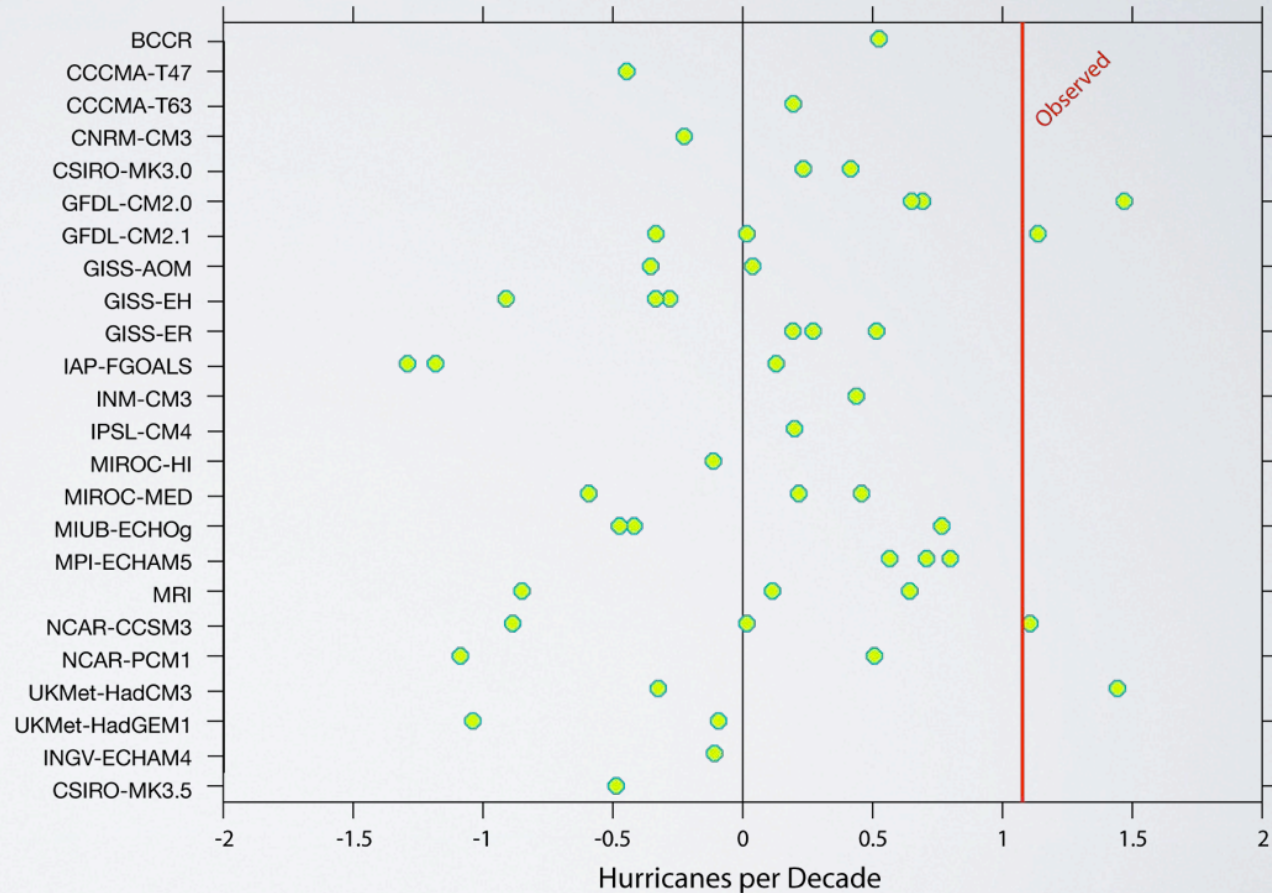
RECENT INCREASE NOT ROBUSTLY "FORCED" IN CMIP3 MODELS

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

1960-2000 Trend in Hurricane Freq. Index from 20C3M CMIP3 Models



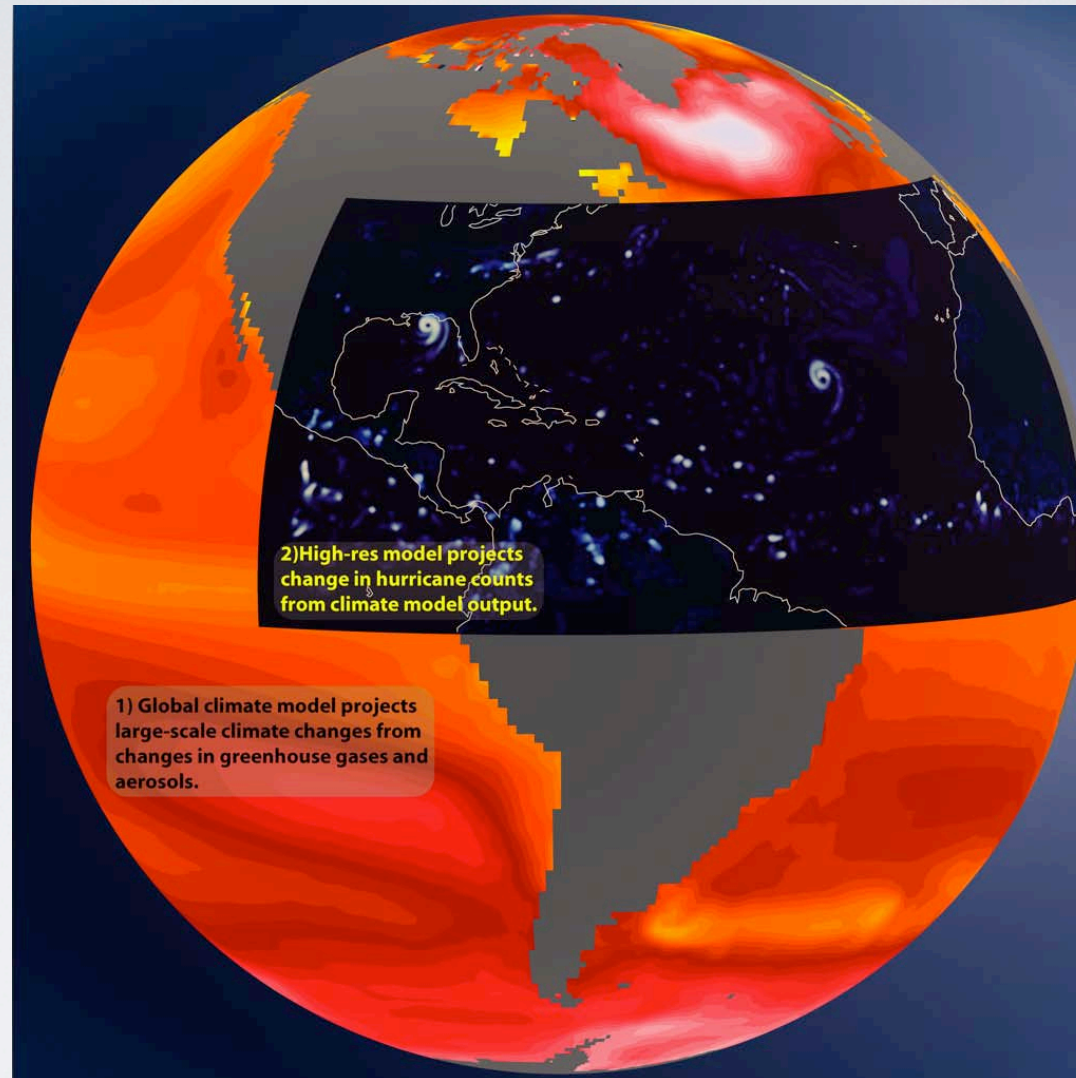
1976-2000 Trend in Hurricane Freq. Index from 20C3M CMIP3 Models



OUTLINE

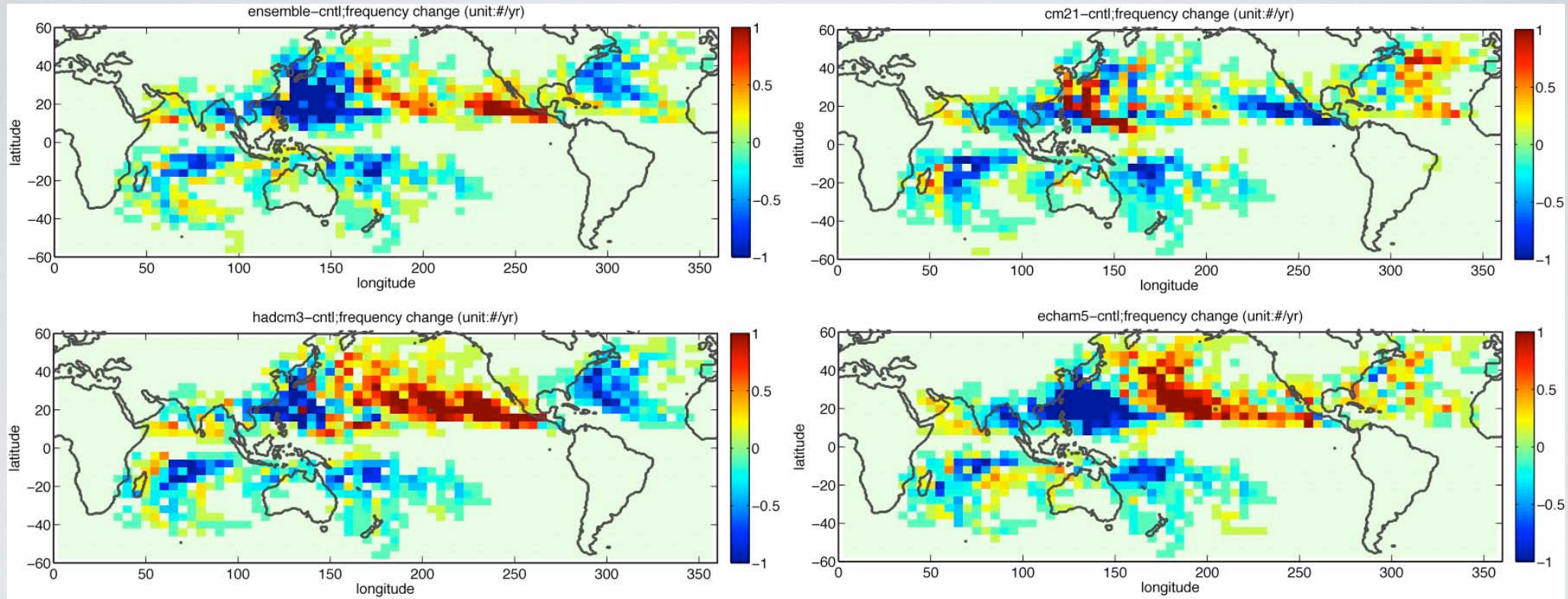
- Tools:
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FOR TC ACTIVITY, “DOWNSCALE” CLIMATE MODEL PROJECTIONS WITH HIGH-RESOLUTION (OR STATISTICAL) MODELS



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.

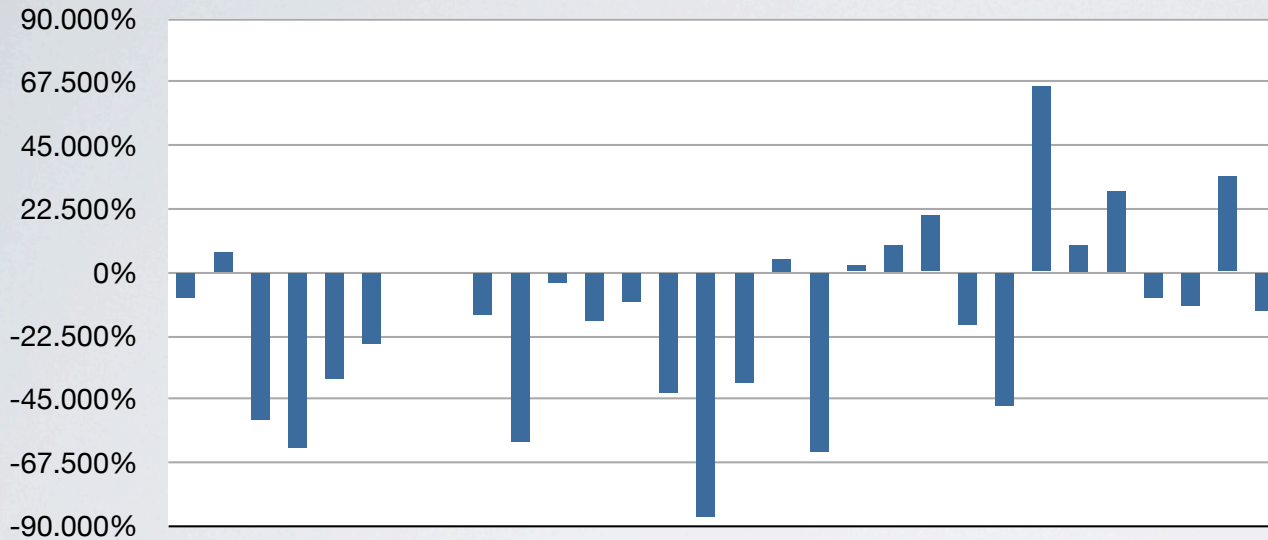
Sensitivity of response seen in many studies

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

Anthropogenic-Influence: Projected 21s Century Changes in NA TS Frequency

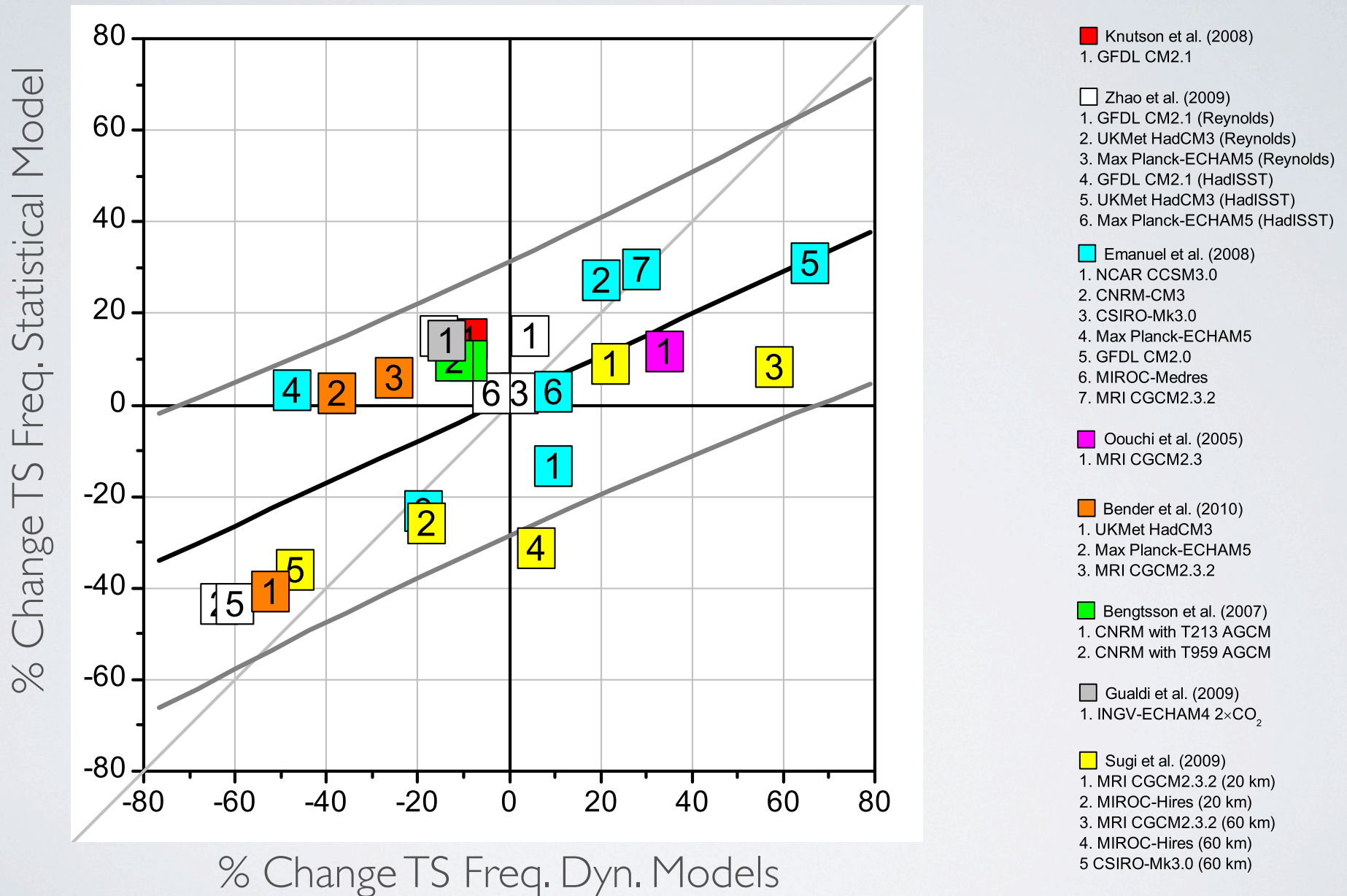


Oouchi et al (2005)
Bengtsson et al (2007)
Emanuel et al (2008)
Knutson et al (2008)
Zhao et al (2009)
Gualdi et al (2009)

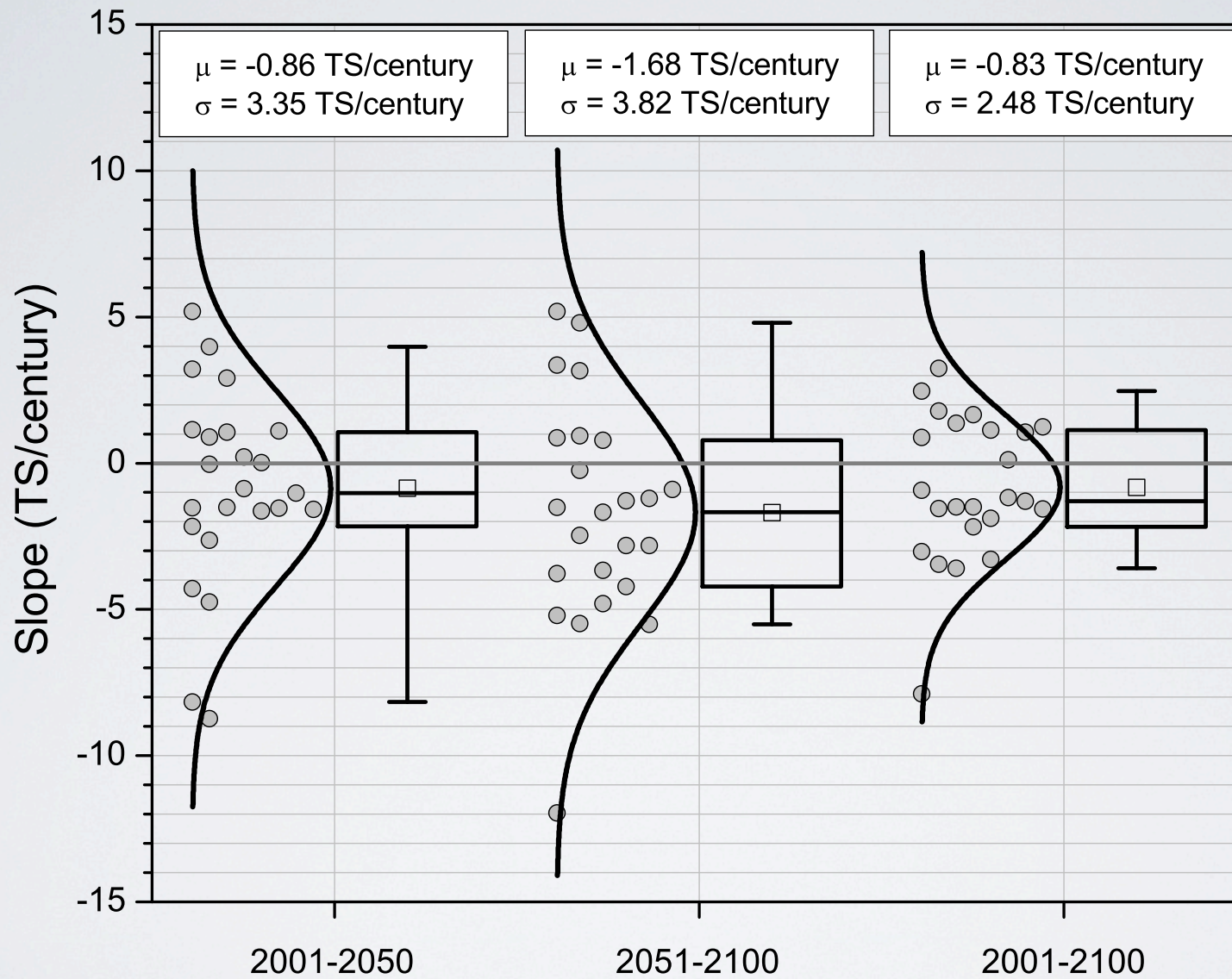
- Even sign of NA TS frequency response to GHG unclear:
Not big help in decadal predictability (yet?)
- Various studies downscale different coupled models, and over different periods

Is there any consistency in the various projections?

DYNAMICAL MODELS EXHIBIT CONSISTENT RELATIONSHIP TO LARGE-SCALE THROUGH STATISTICAL MODEL - ALL CONSISTENT WITH OBSERVATIONS



Statistical Projections of 21st Century NA TS Trends

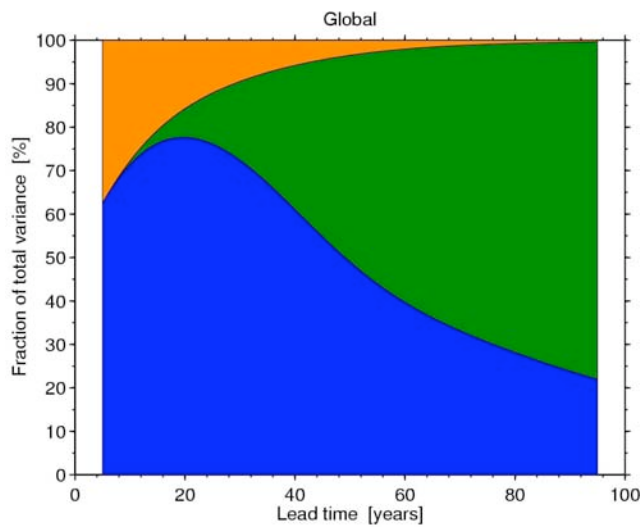


Villarini et al (2011, in press)

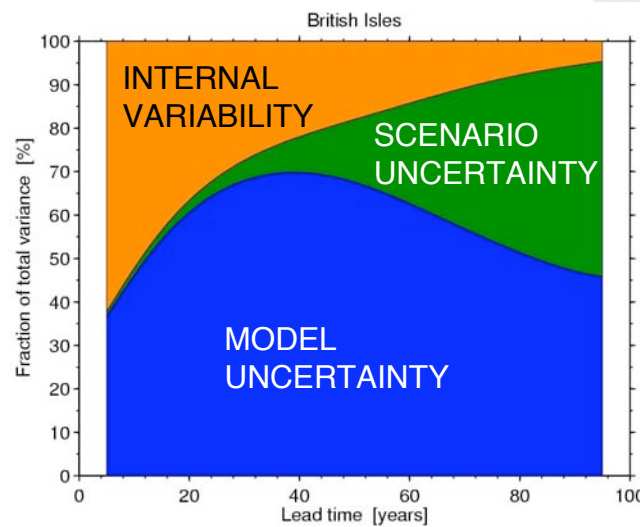
NA TS PROJECTIONS: INTERNAL VARIABILITY A PRIMARY SOURCE OF UNCERTAINTY EVEN IN 100-YEAR TRENDS

TS COUNTS

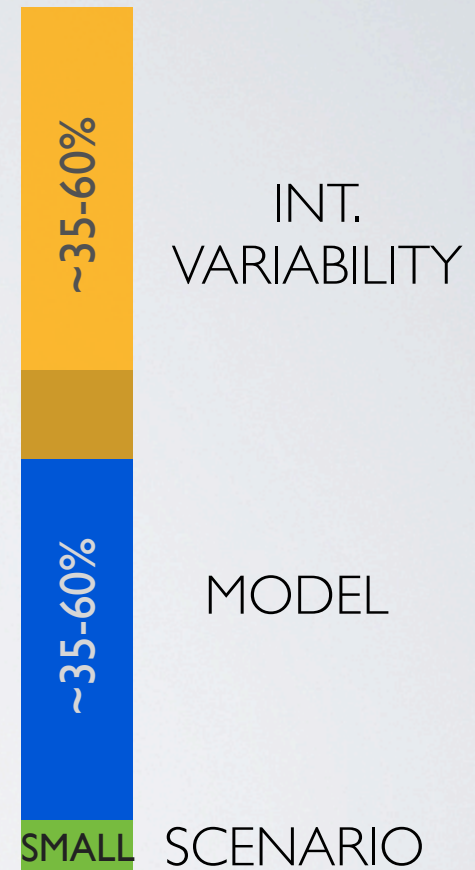
TEMP. Fraction of total variance



Global, decadal mean



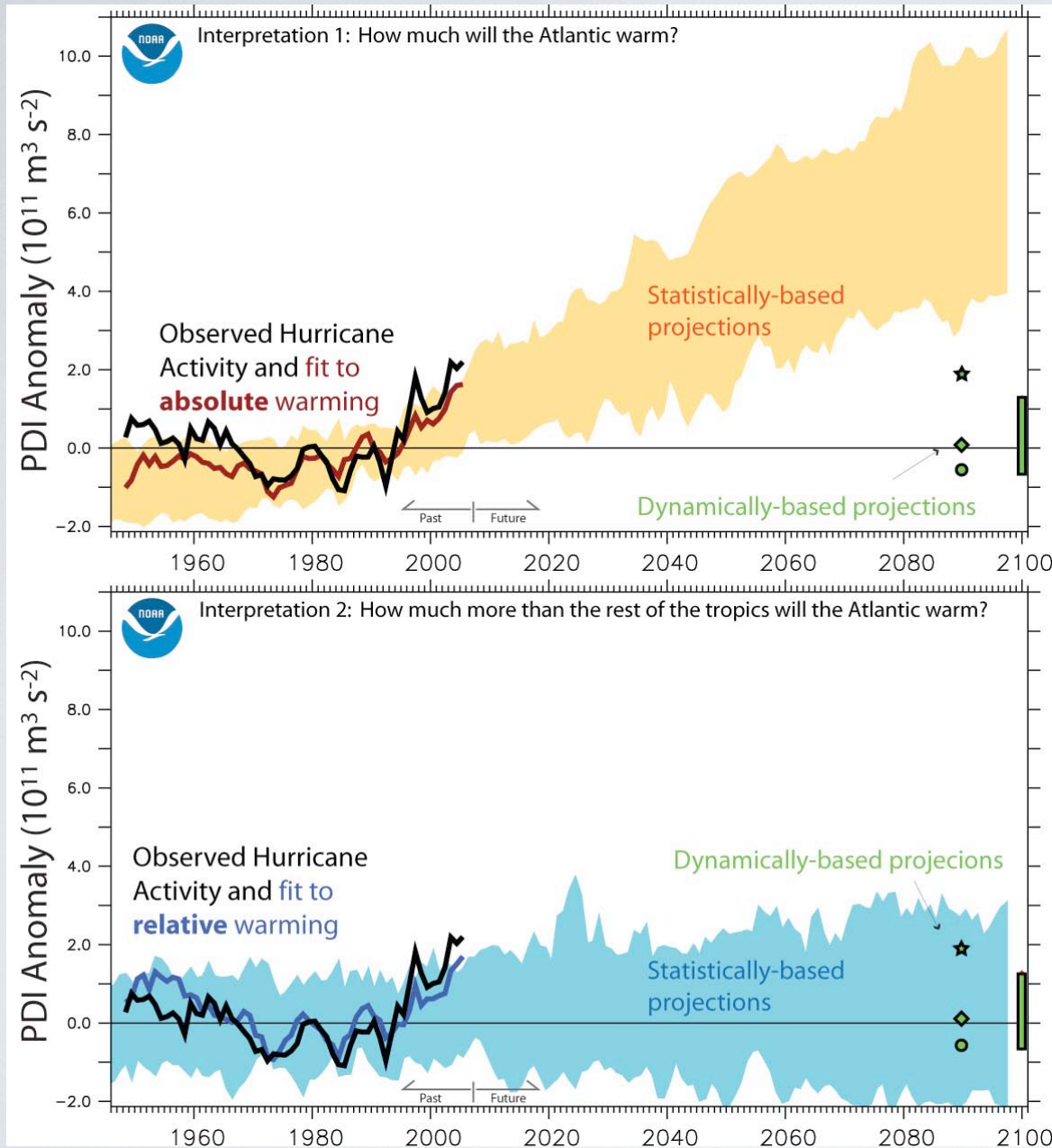
British Isles, decadal mean



Hawkins and Sutton (2009)

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

...ADD DYNAMICAL PROJECTIONS OF ATLANTIC HURRICANE ACTIVITY



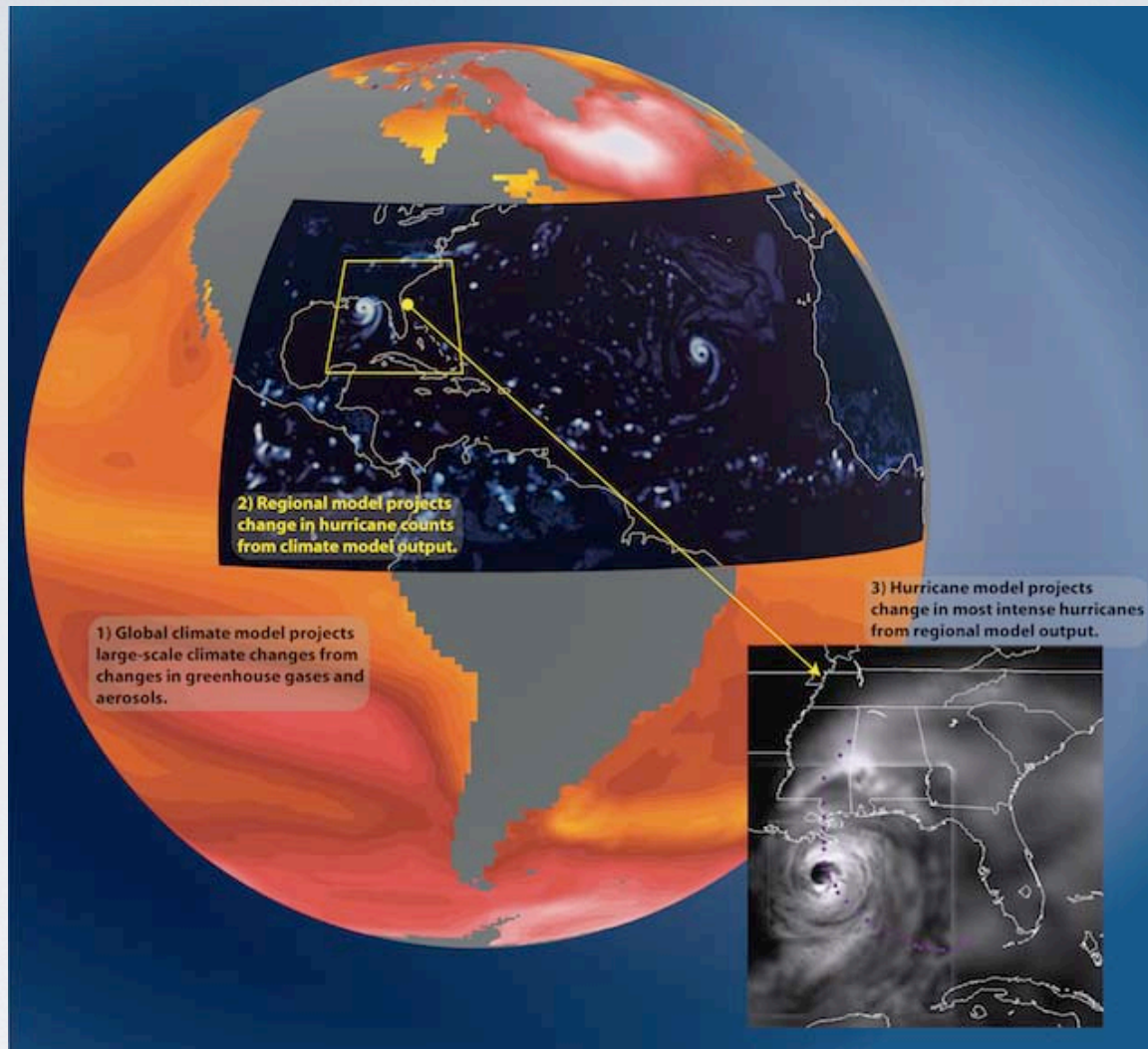
Observed Activity
Absolute Atlantic
Temperature

Dynamical Model
Projections

Observed Activity
Relative Atlantic
Temperature

Vecchi, Swanson and Soden
(2008, Science)

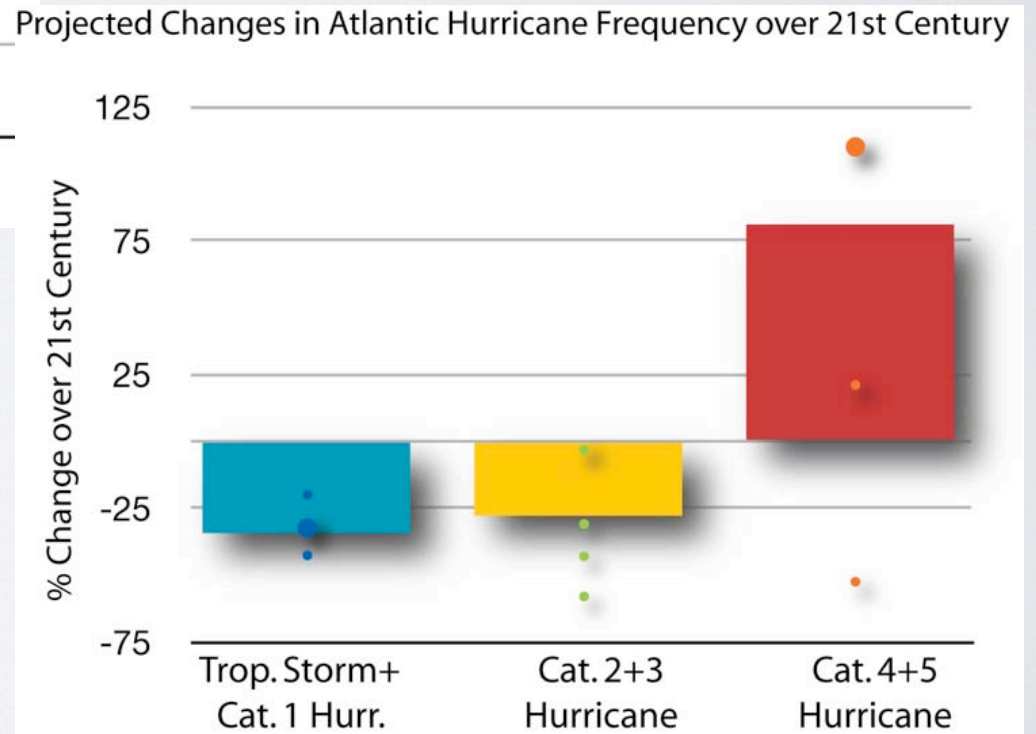
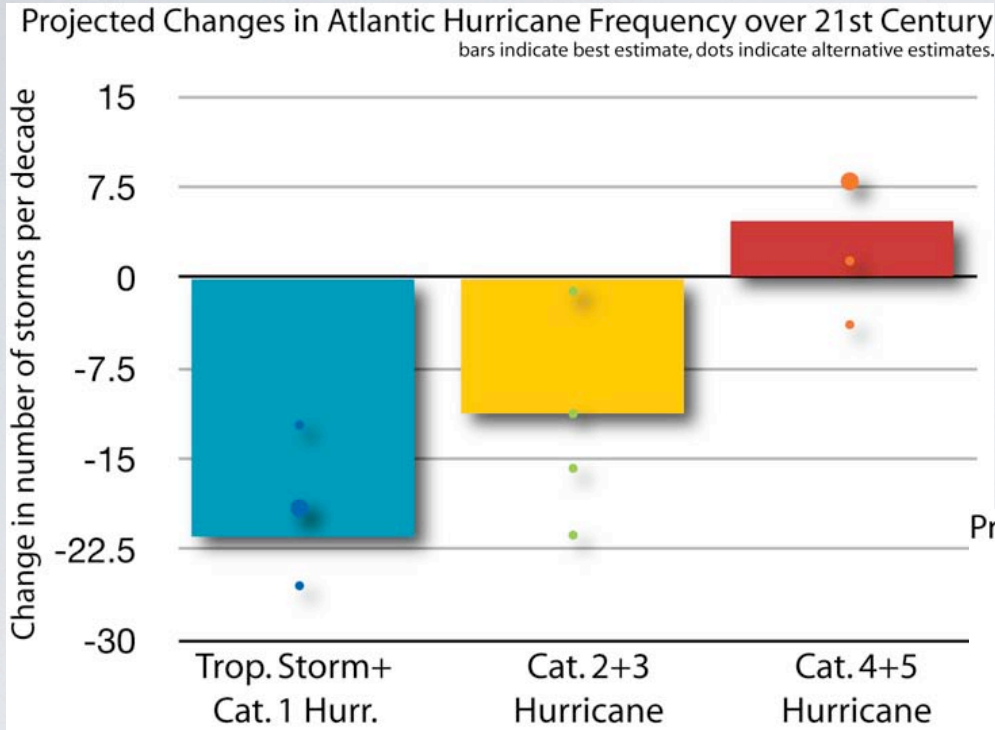
STRONGEST CYCLONES PROJECTED WITH DOUBLE DOWNSCALING



*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

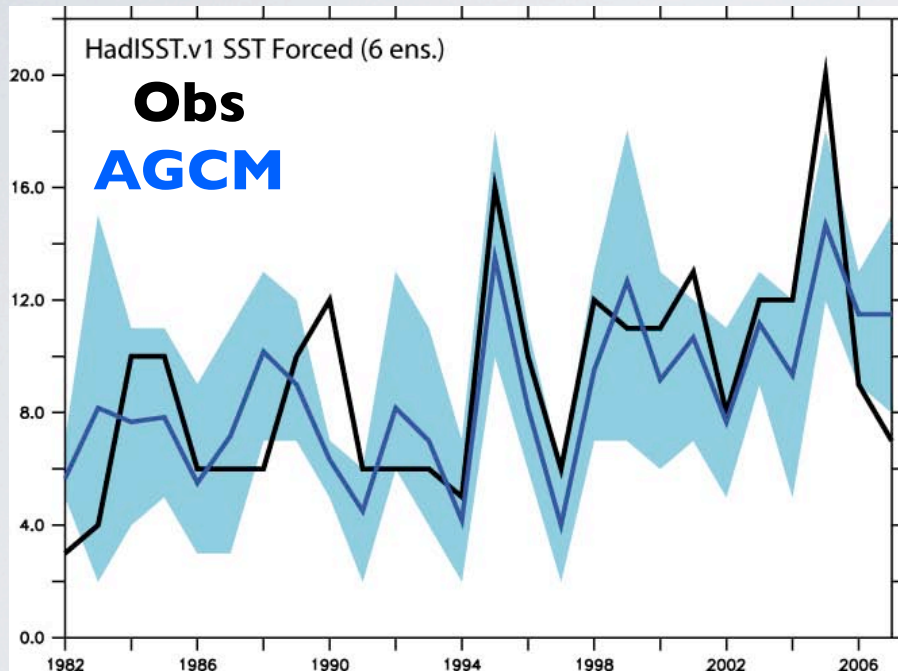
If AGCM sensitivity (and relative-SST statistical models) correct:

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

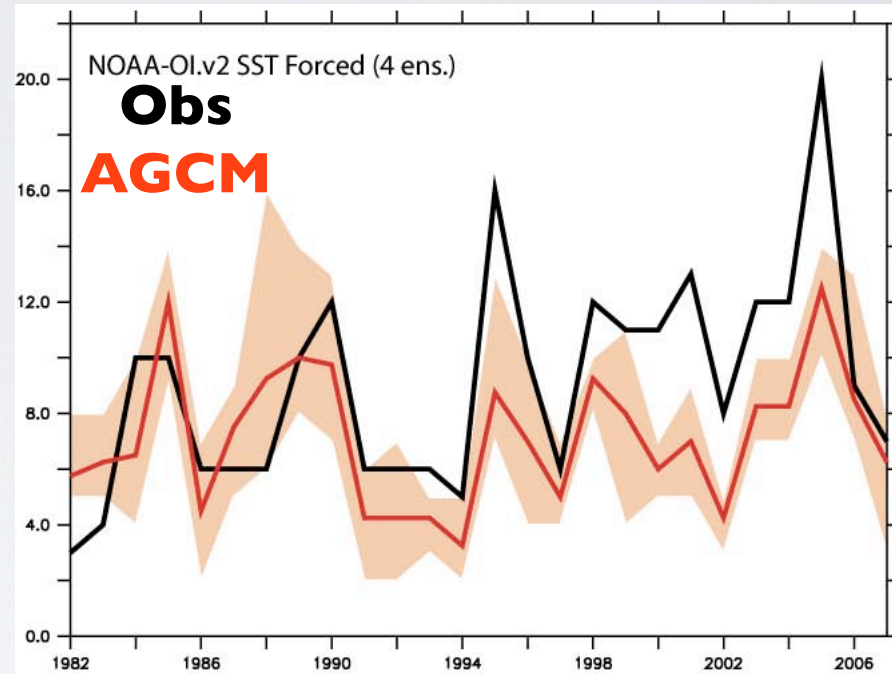
Tropical Storm Frequency Response to Same AGCM but different estimates of observed SST

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 CO₂) 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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