Atlantic Hurricane Attribution, Predictions & Projections

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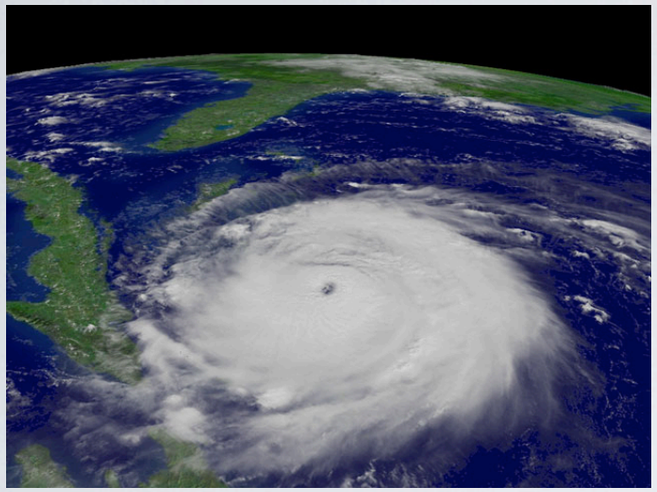
1-NOAA-GFDL; 2-NOAA-NCEP;
3-Princeton U.; 4-U. Miami;
5-U. Wisc.-Milw.; 6-Old Dominion U.

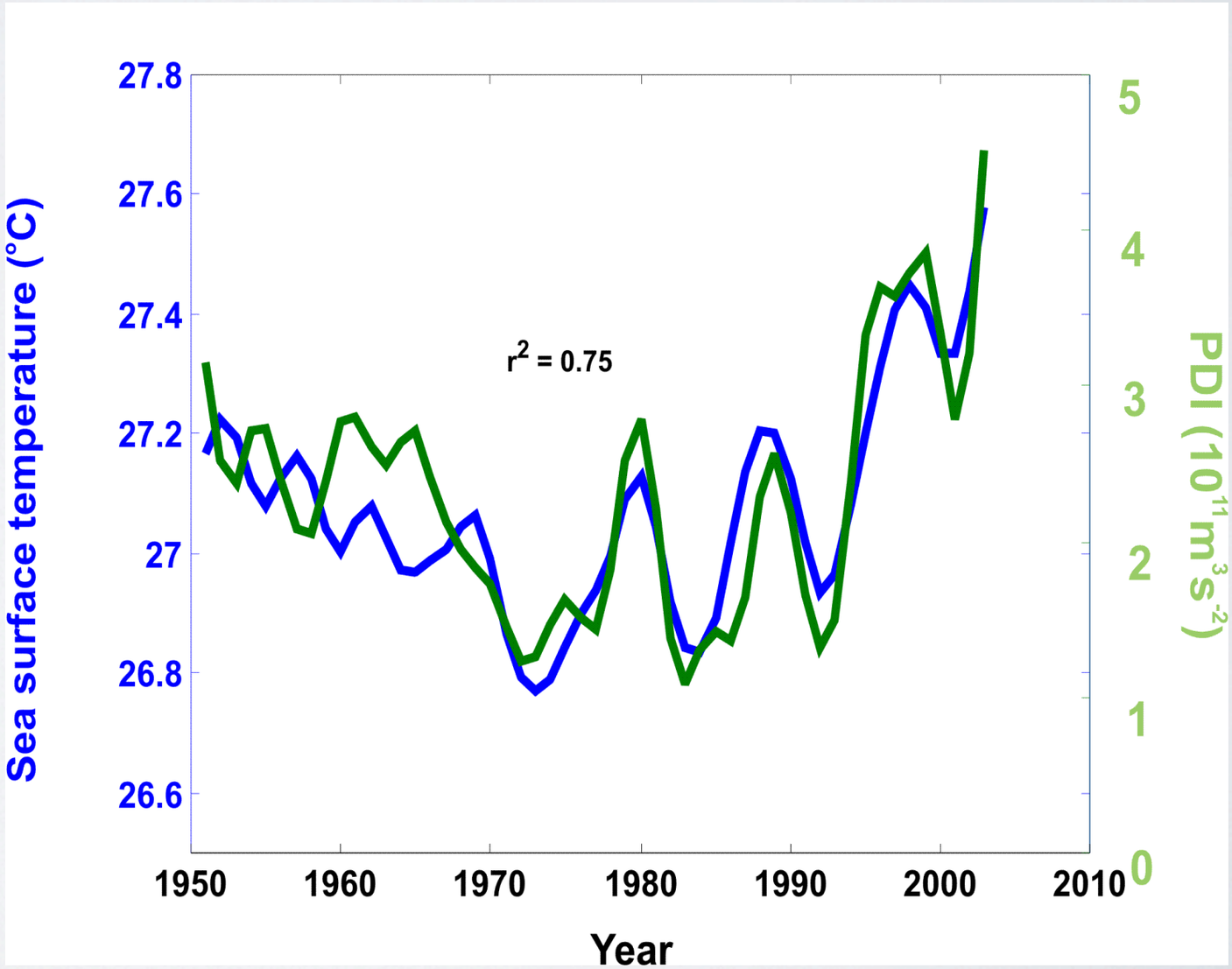
Image: NASA.

North Atlantic tropical cyclones



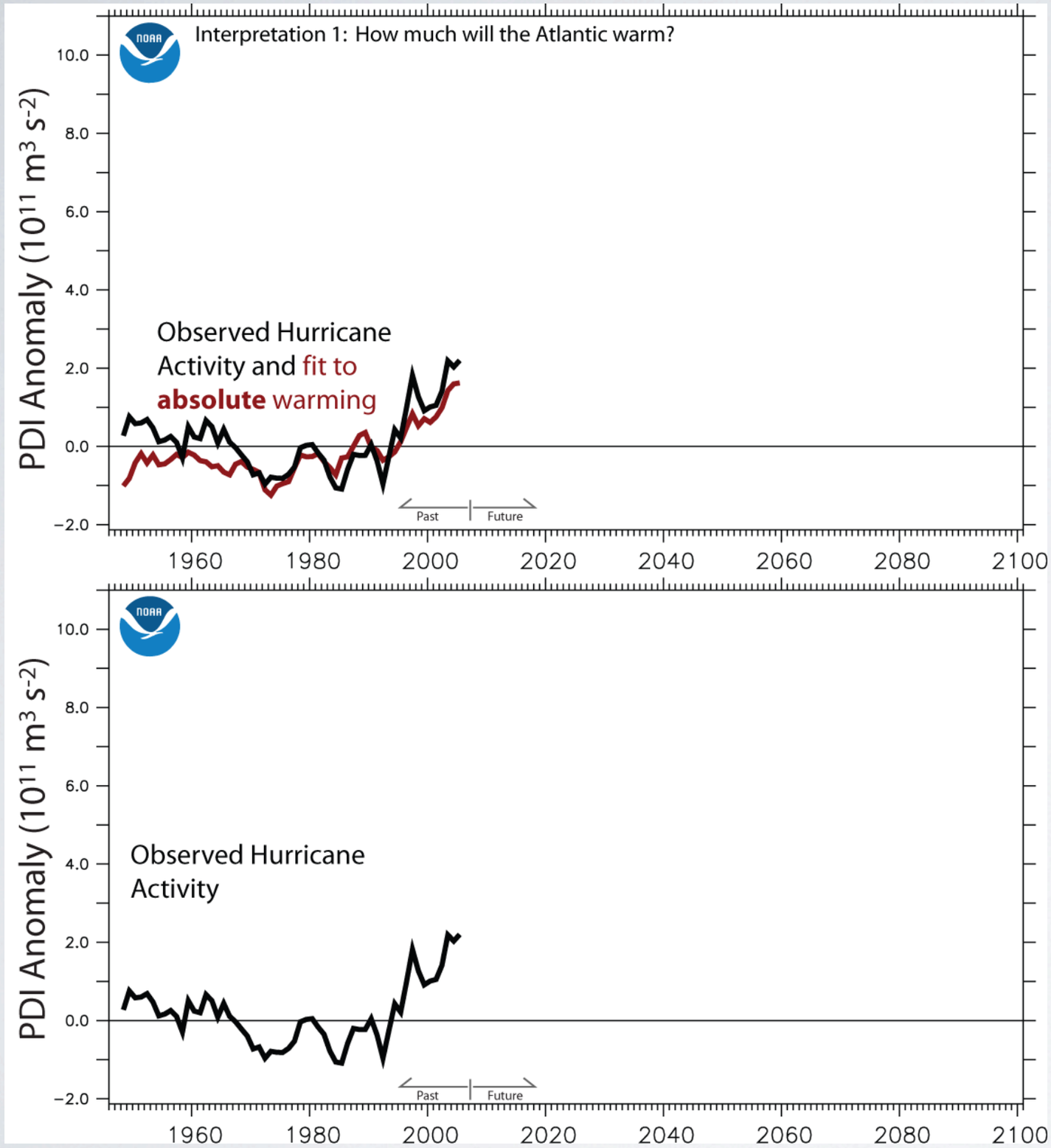
- Recent increase in activity
  - Including extreme 2004-2005 seasons
- Why? Implications for future?

$$PDI = \sum_{storms} \sum_{duration} u^3$$



Emanuel (2005 Nature; 2007, J. Clim.)

One Temperature Predictor of Atlantic Hurricane Activity

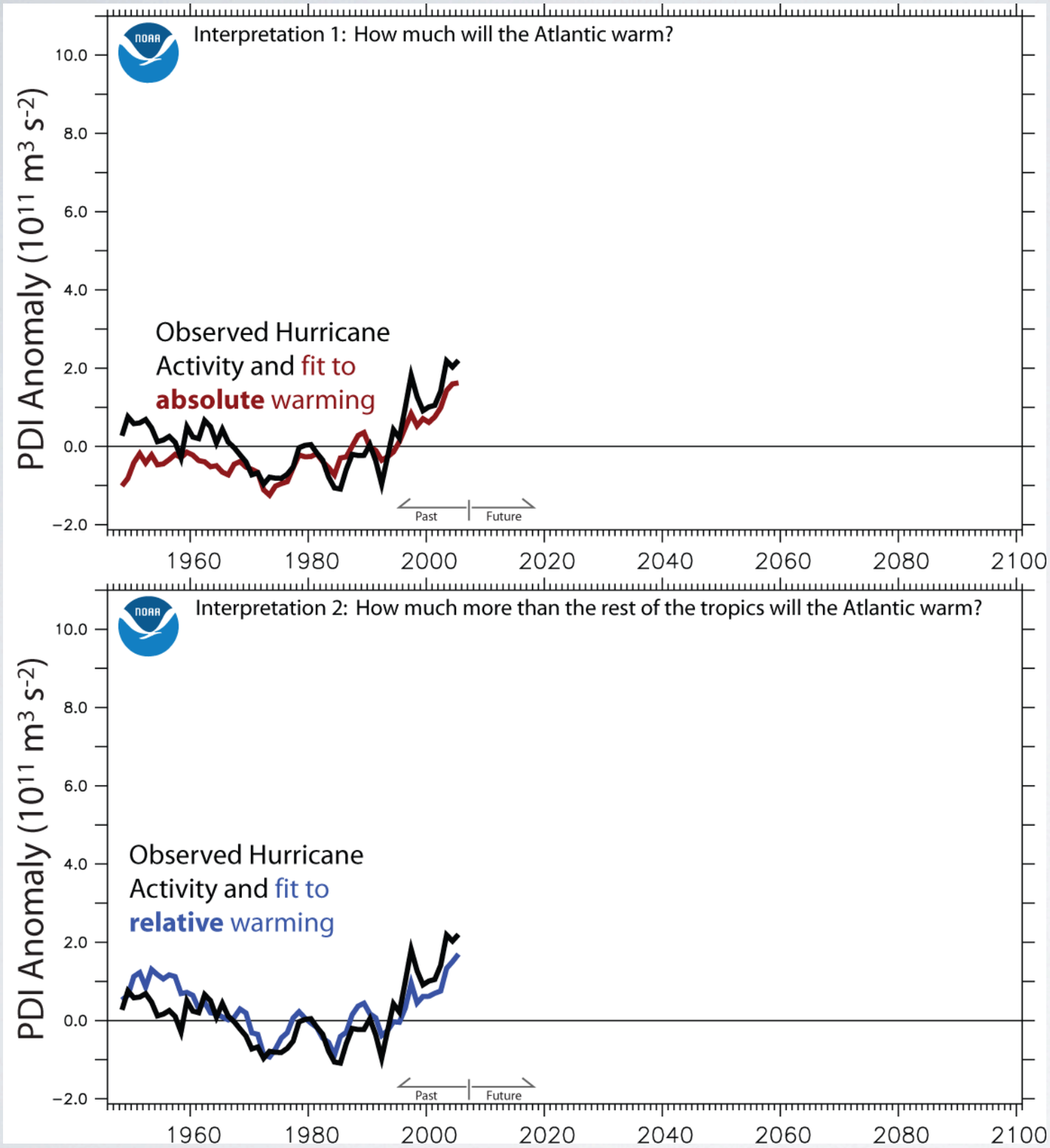


Observed Activity

Absolute Atlantic Temperature

Vecchi, Swanson and Soden (2008, Science)

Two Temperature Predictors of Atlantic Hurricane Activity

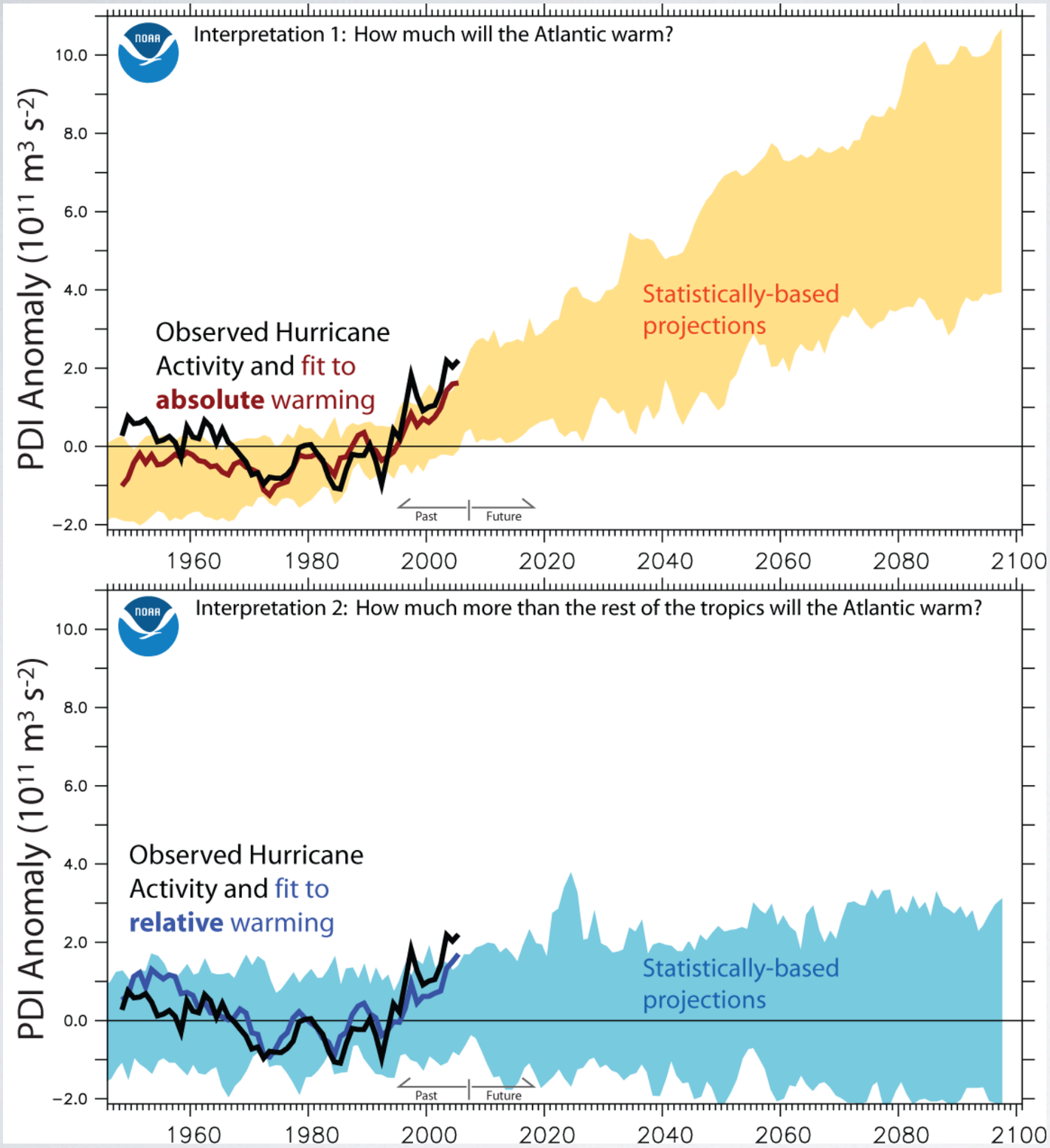


Observed Activity
Absolute Atlantic Temperature

Observed Activity
Relative Atlantic Temperature

Vecchi, Swanson and Soden (2008, Science)

Two Statistical Projections of Atlantic Hurricane Activity



Observed Activity
Absolute Atlantic Temperature

Observed Activity
Relative Atlantic Temperature

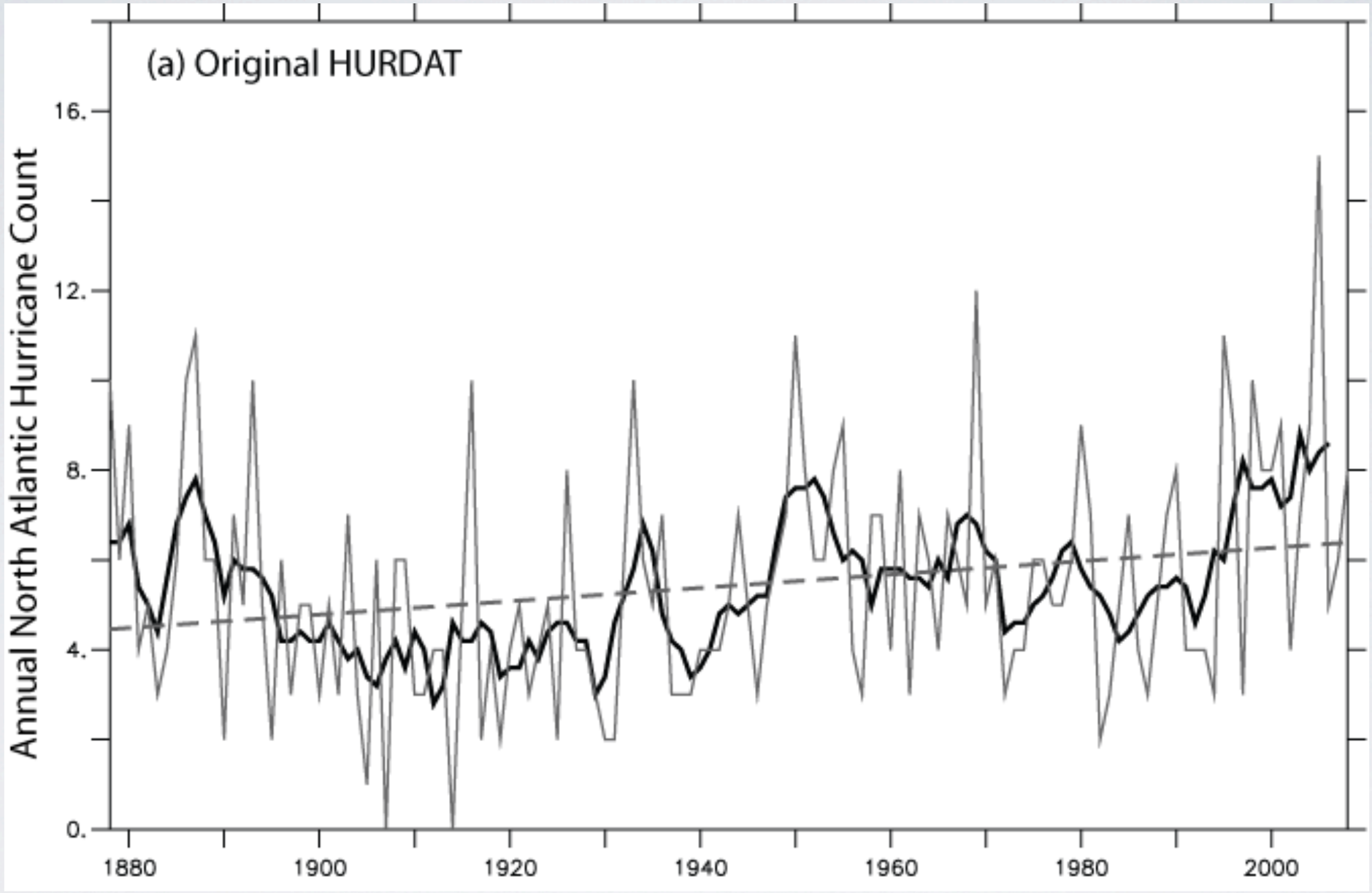
Vecchi, Swanson and Soden (2008, Science)

Outline

- Historical Atlantic Tropical Storm & Hurricane Record
- Downscaling Techniques
- Response of Hurricanes to Radiative Forcing
- Summary
- Experimental long-lead predictions

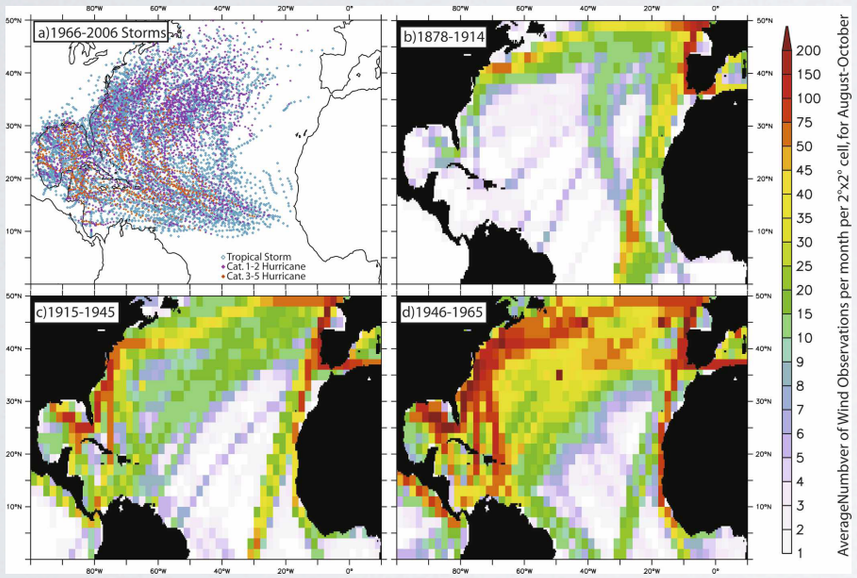
Recorded NA Hurricanes Show Clear Increase

But was there really an increase?

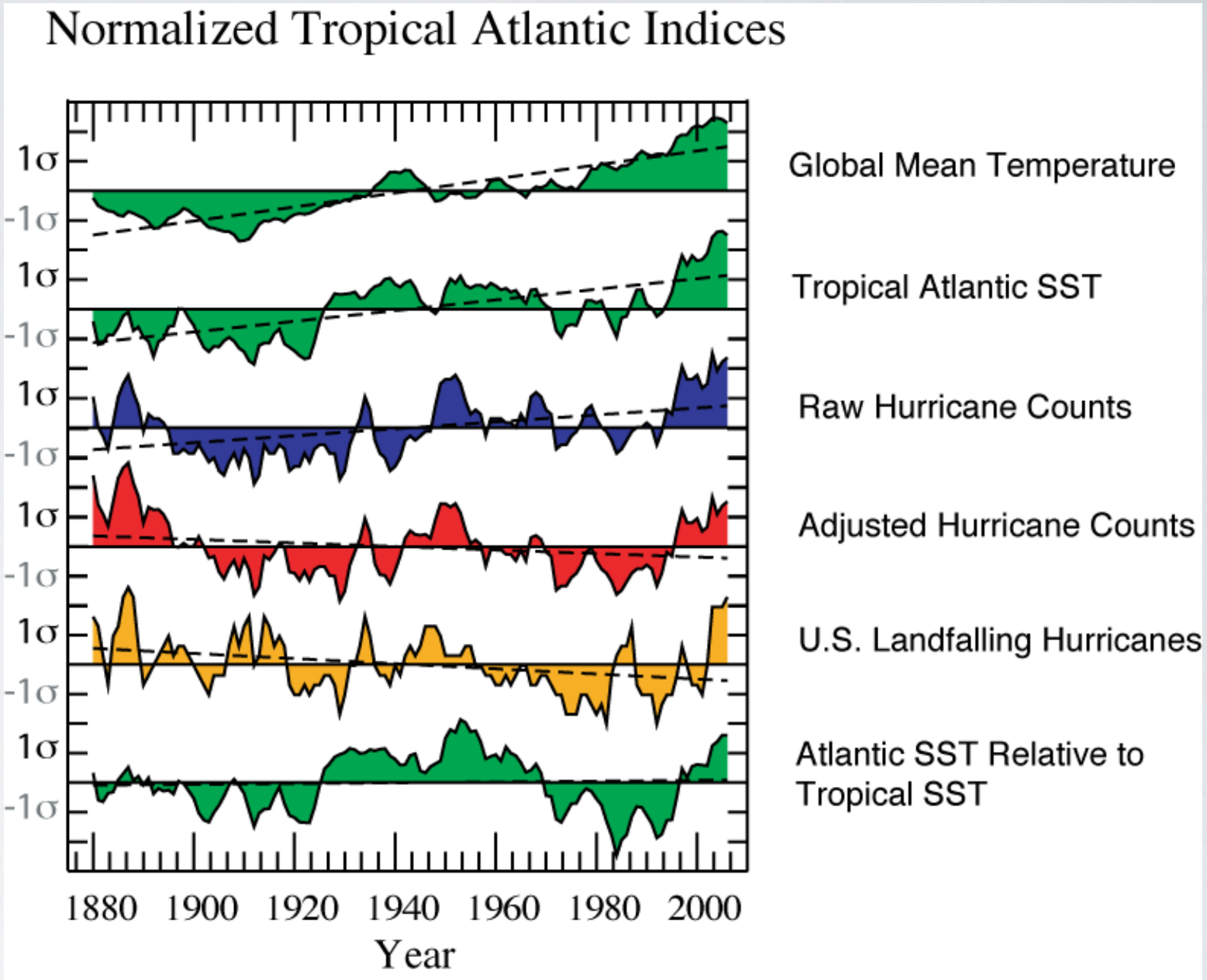


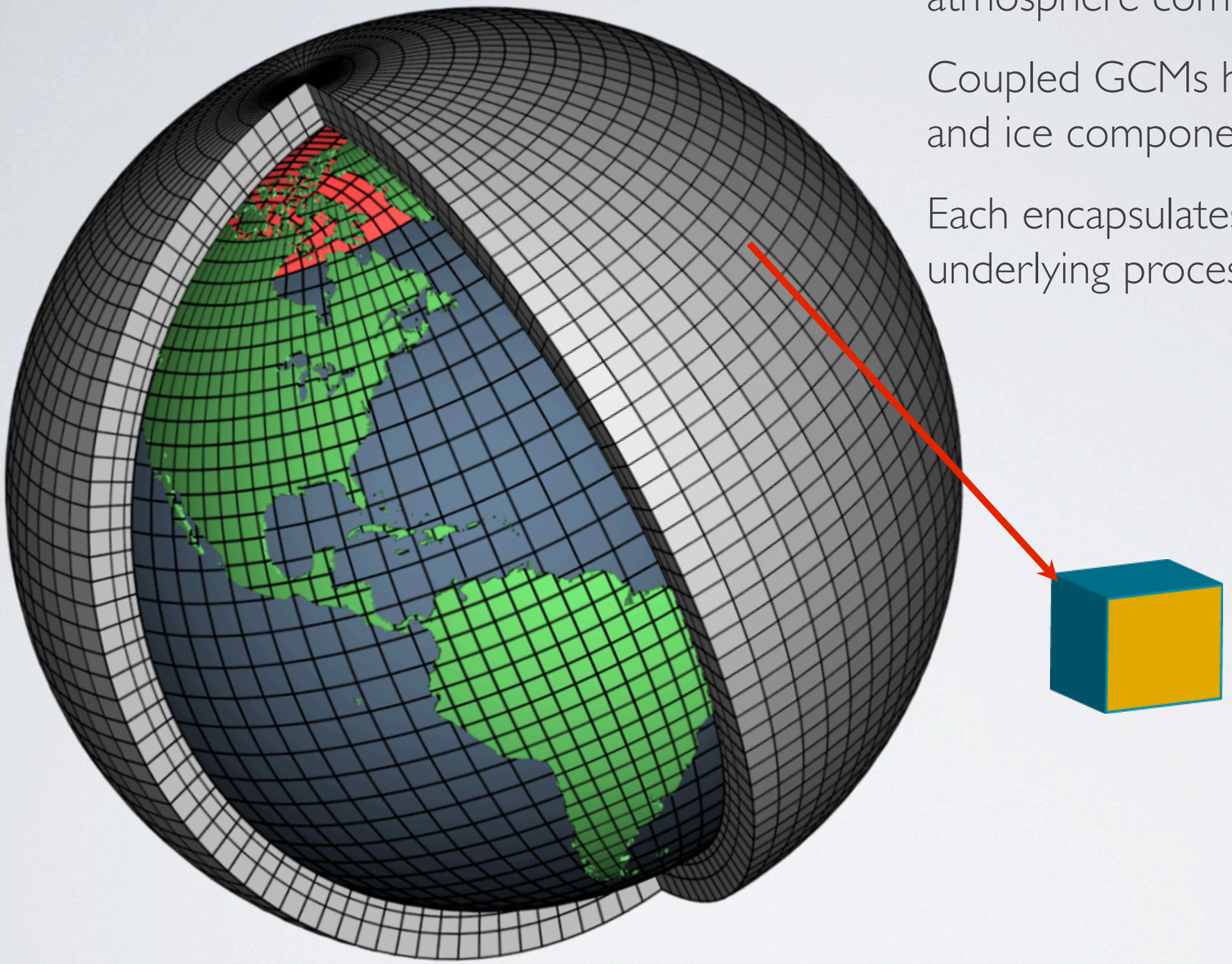
Vecchi and Knutson (2010)

Adjustments to storm counts based on ship/storm track locations and density



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





Atmospheric GCMs have land and atmosphere components.

Coupled GCMs have land, ocean, atmosphere and ice components.

Each encapsulates our best understanding of underlying processes controlling its evolution.

In each grid cell:

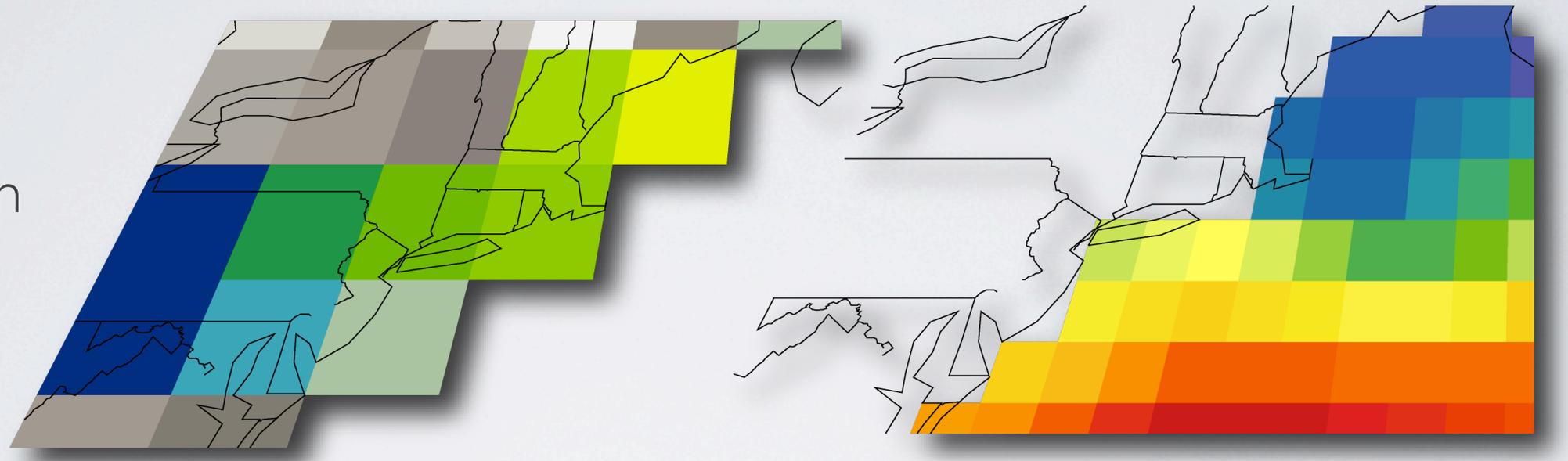
- ⋆conserve momentum ($F=m \cdot a$)
- ⋆account for changes in mass and composition
- ⋆conserve energy (radiation, latent, etc...)

AGCM: "Force" with sun, atmospheric composition (e.g., CO_2, O_3, aerosols)

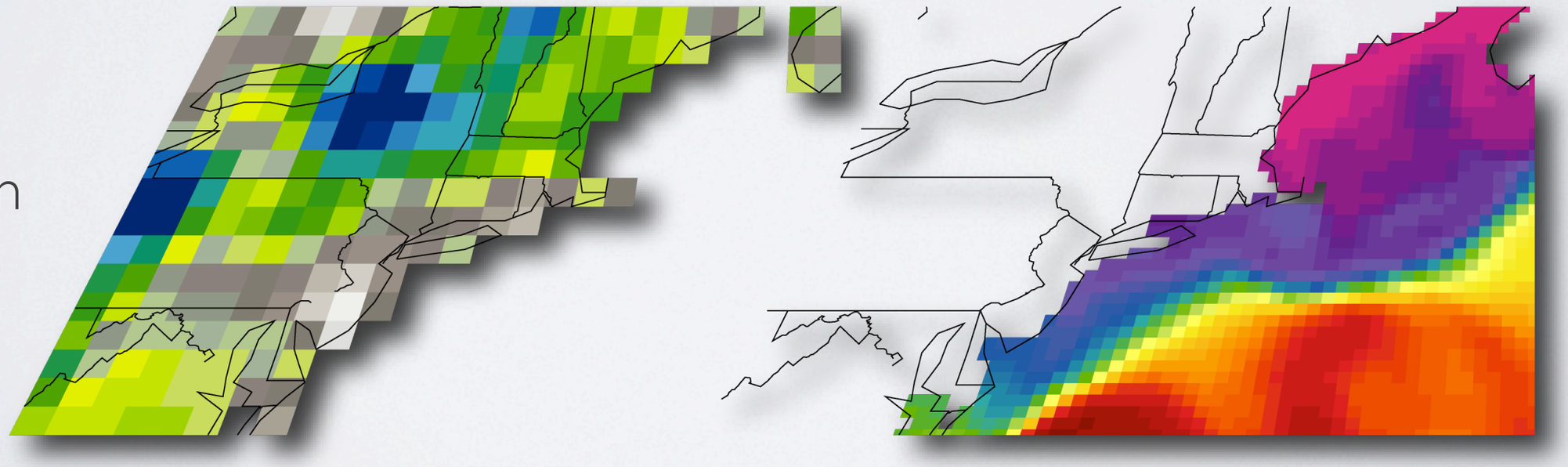
CGCM: "Force" with sun, atmospheric composition (e.g., CO_2, O_3, aerosols)

Resolution (computer power) limits ability to represent processes and phenomena

Medium resolution (CM2.1)



High resolution (CM2.5)



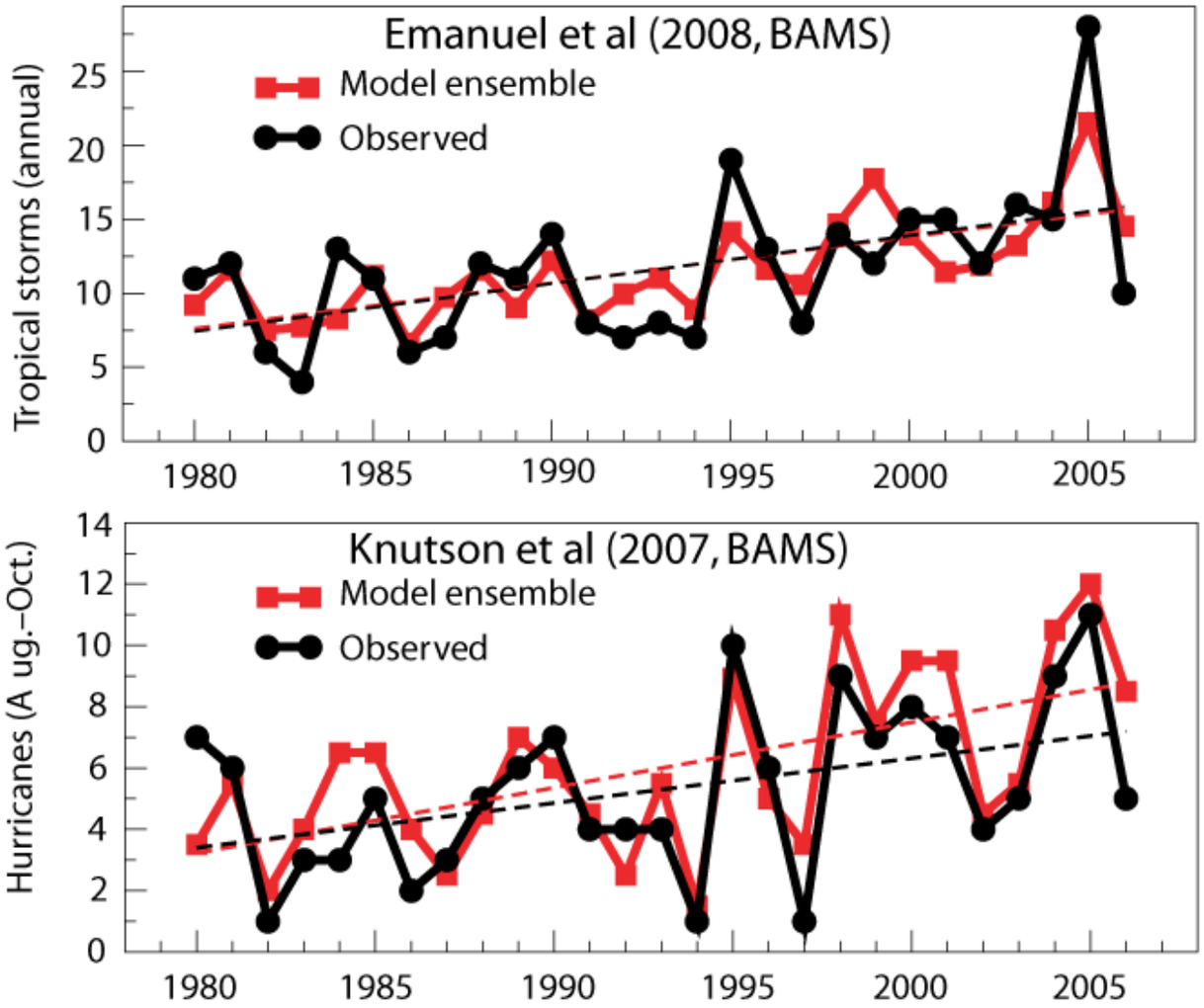
Precipitation

Ocean temp.

NOAA-GFDL C180
Atmosphere Model

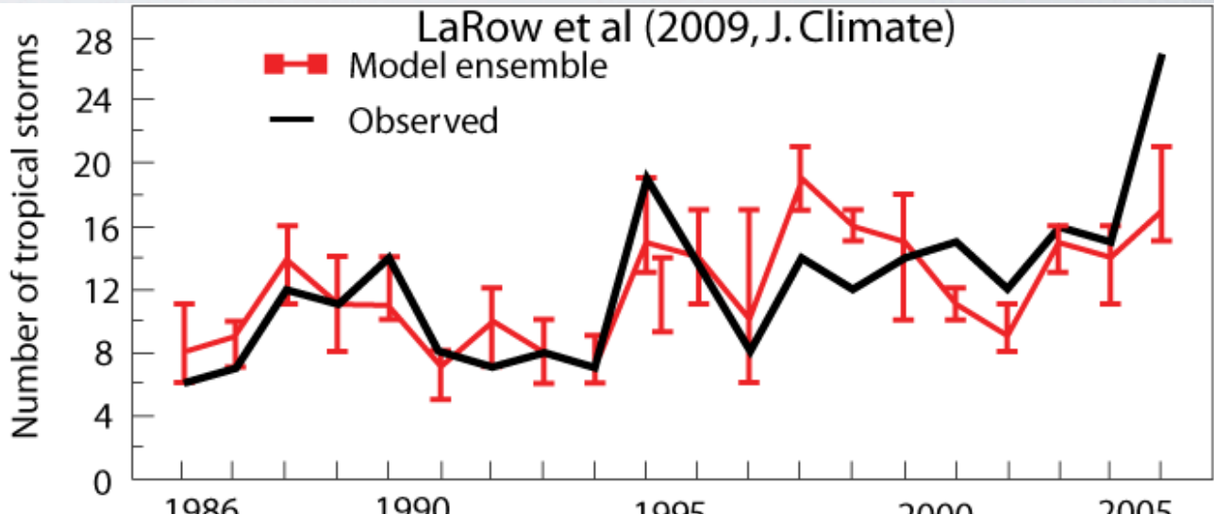
Dynamical Models Exhibit Skill in Seasonal Basin-wide Hurricane Frequency

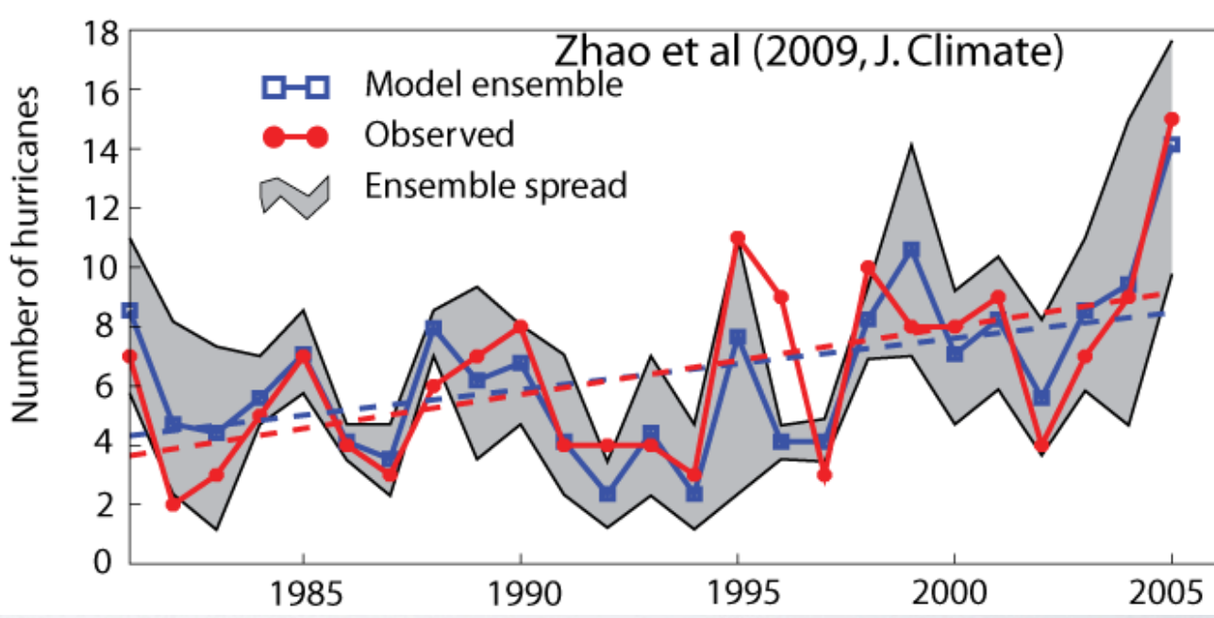
Statistical-dynamical hybrid model



18-km regional model

100km SST-forced AGCM





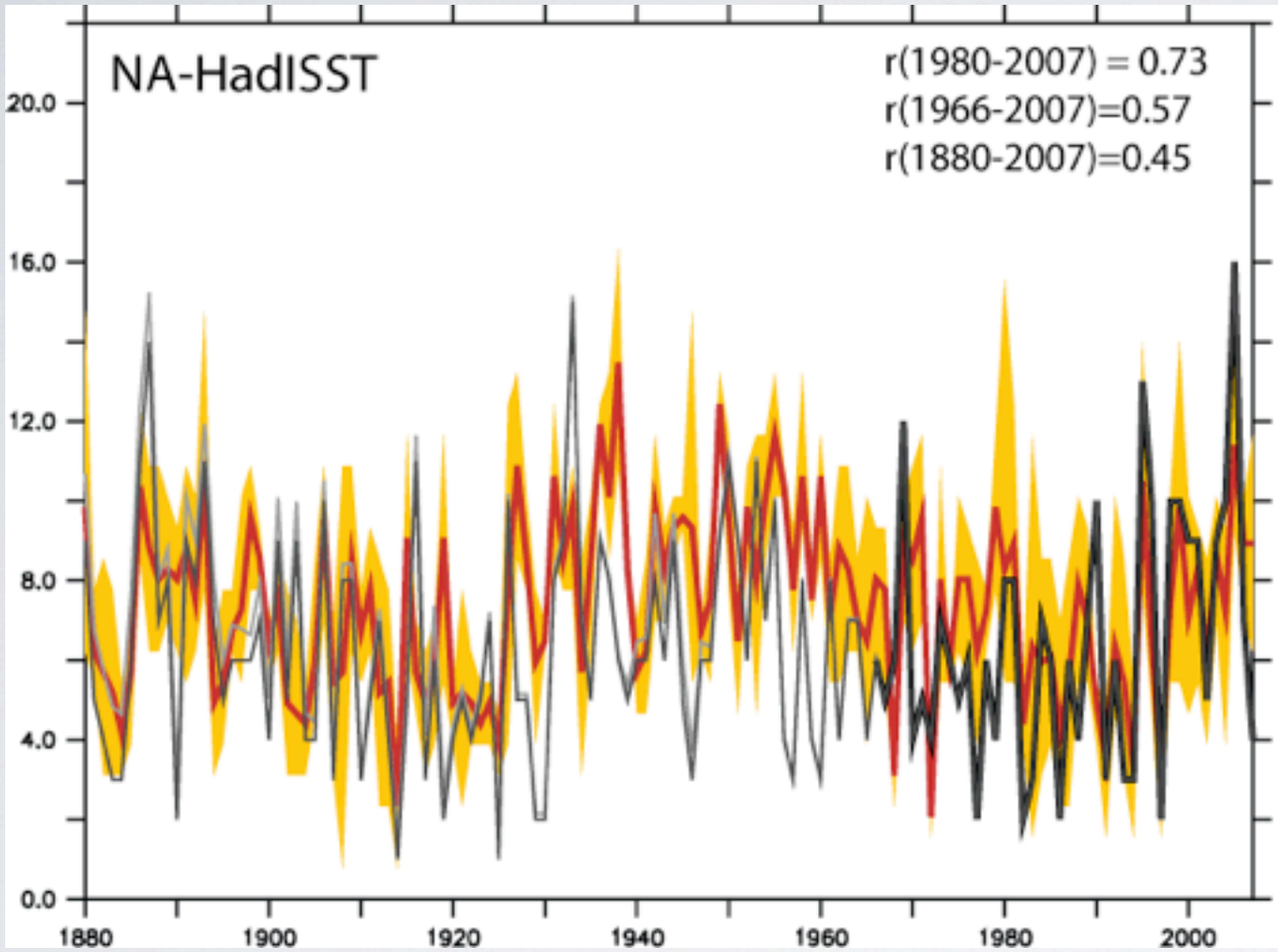
50km SST-forced AGCM

Figure adapted from Knutson et al (2010, Nat. Geosci.)

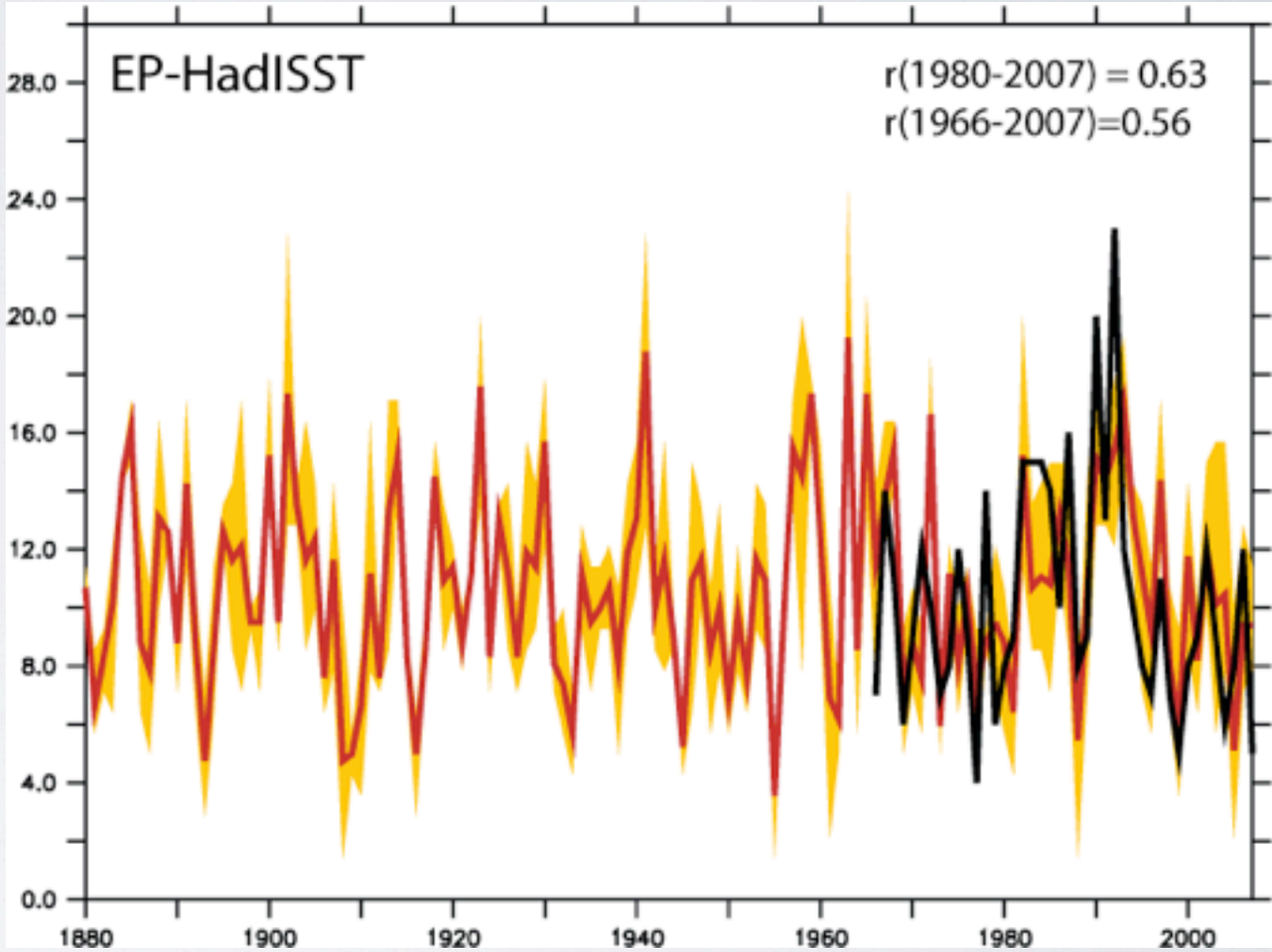
Skill in Century-Scale SST-Forced AGCM Hindcasts

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

North Atlantic TC



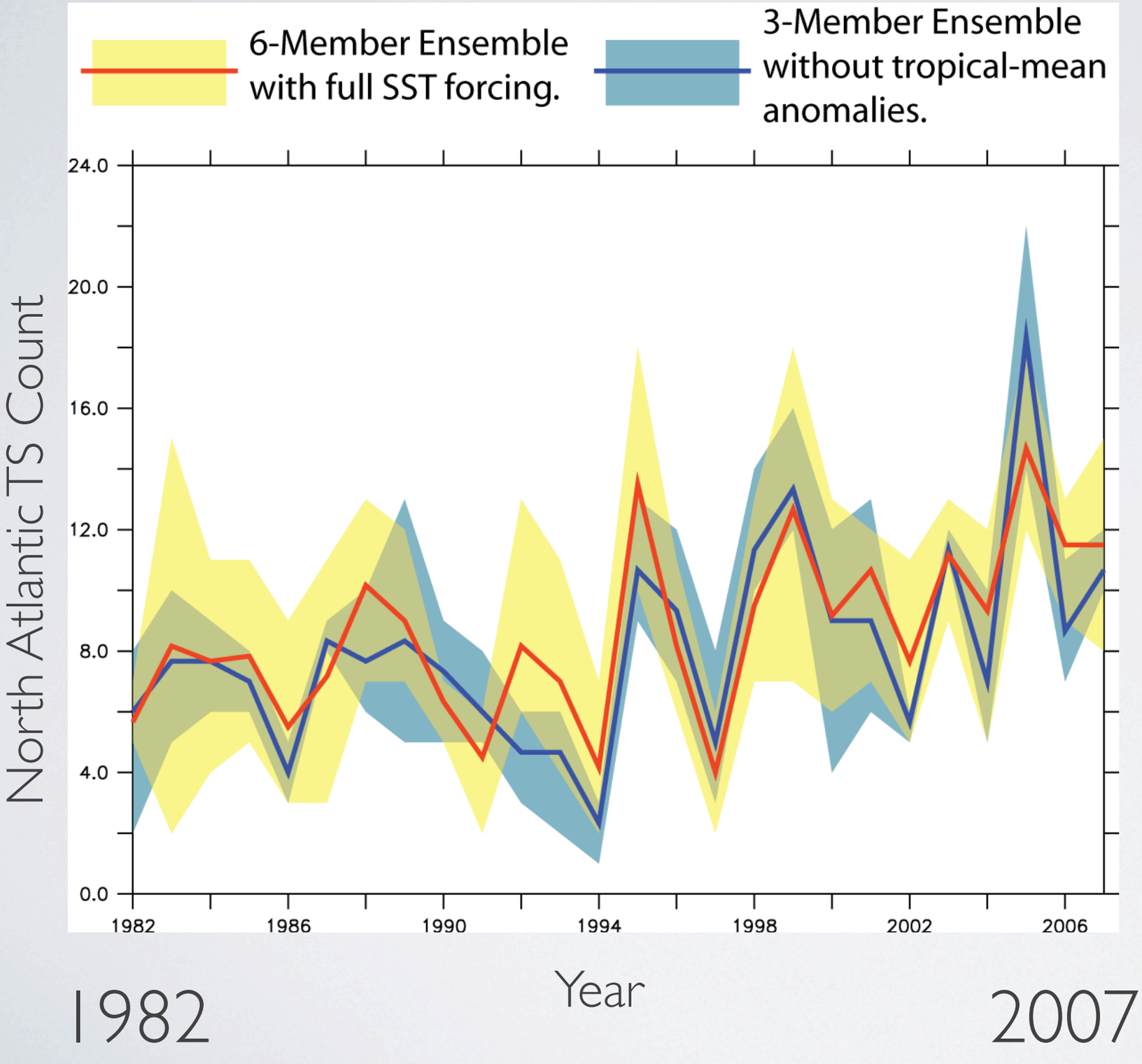
East Pacific TC



Observed **Model Mean** **Model Range**

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

NA TS Increase not Driven by Uniform Component of Recent Warming



With tropical-mean warming

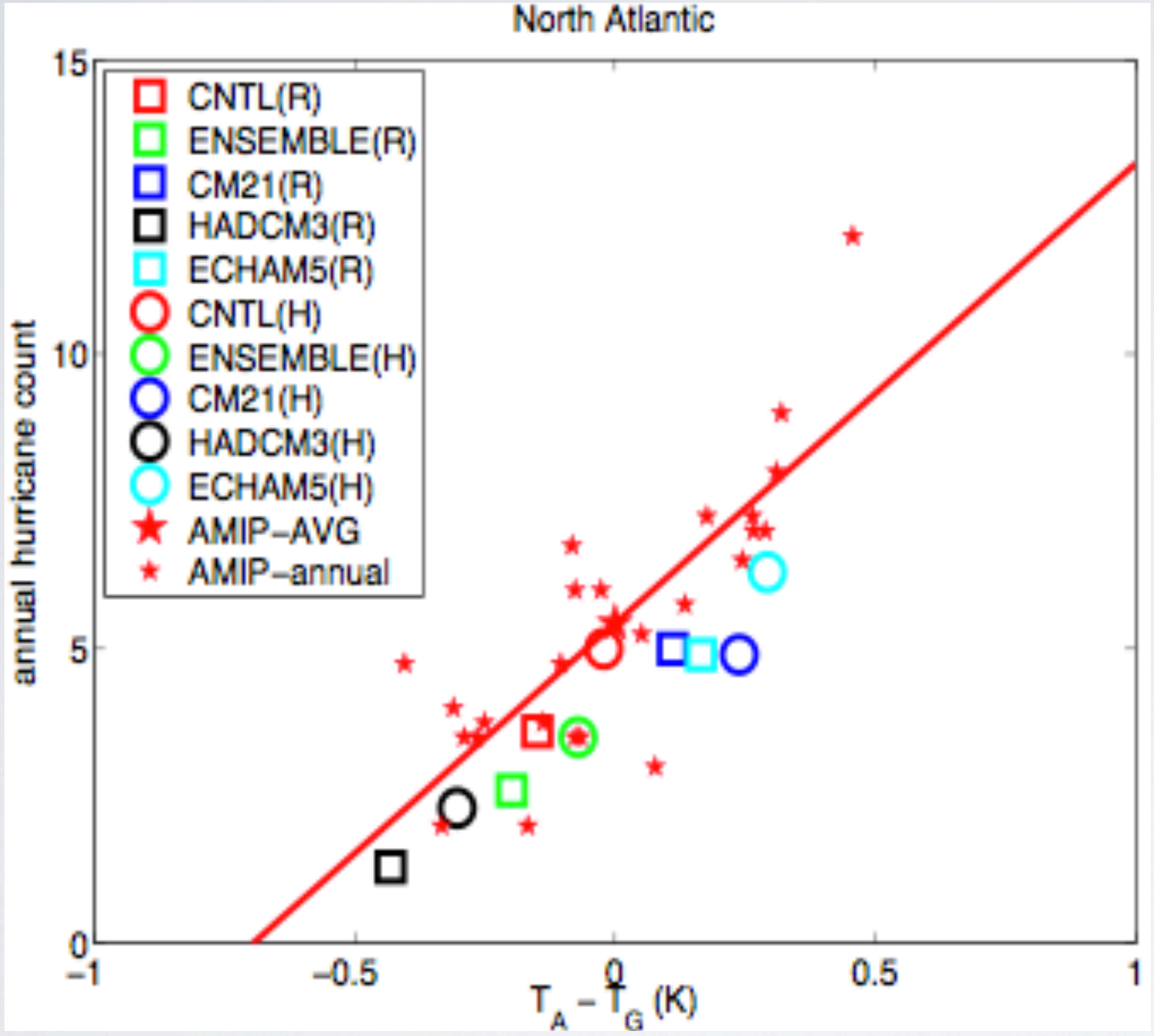
Without tropical-mean warming

Vecchi, Delworth, Zhao and Held (2012, in prep.)

1982

2007

HiRAM C180 (and observations + controls to large-scale) Suggest **Relative SSTA** as a Predictor



Relative SSTA = Atlantic SSTA minus Tropical SSTA

Zhao *et al.* (2009, J. Climate), Zhao *et al.* (2010, MWR, Sub.)

&

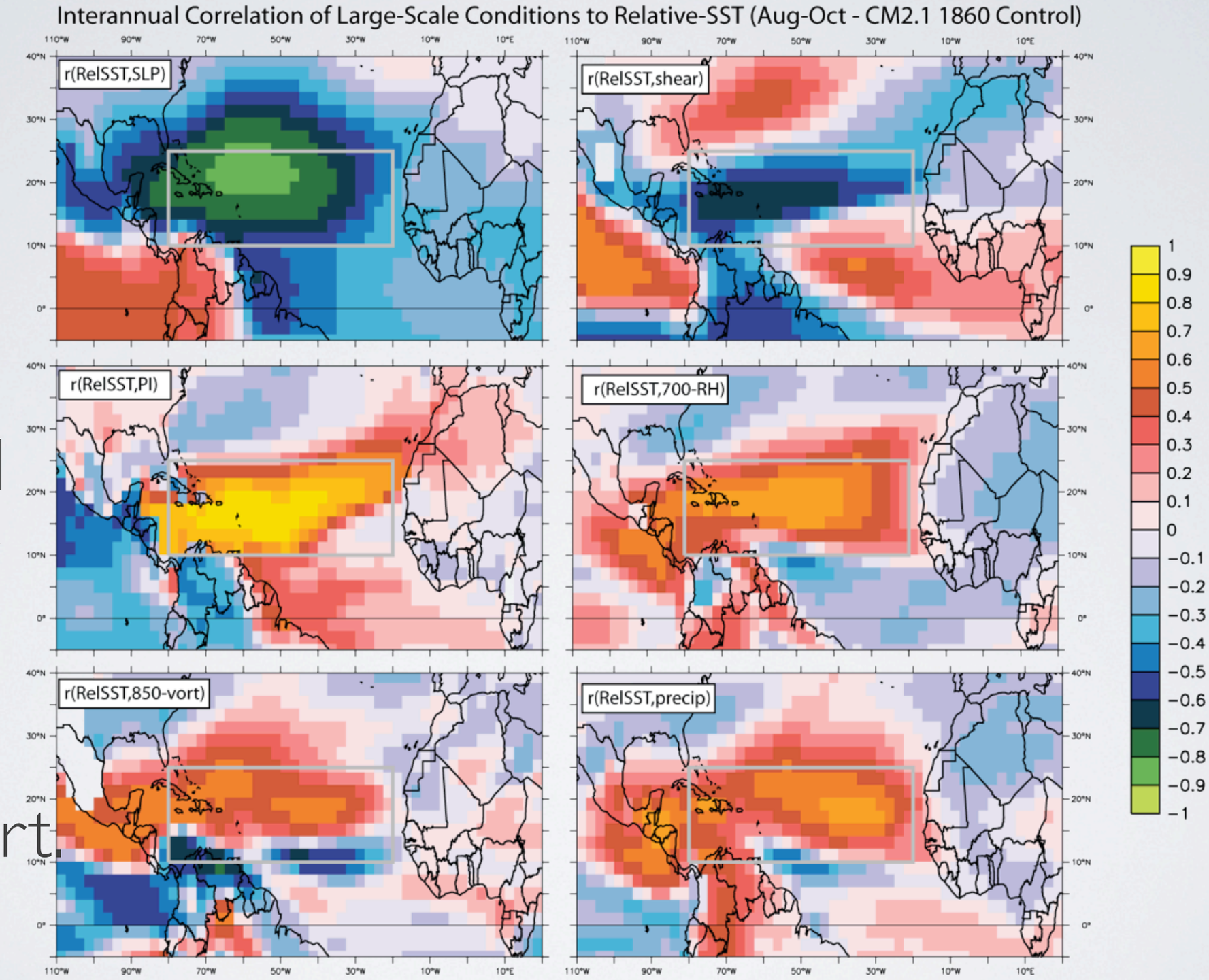
Latif et al (2007, GRL), Vecchi and Soden (2007, Nature), Knutson et al (2008, Nature Geosci.), Swanson (2008, G3), Vecchi et al (2008, Science), Villarini et al (2010, MWR)....

In CGCMs Hurricane-Relevant Large-Scale Conditions Co-vary Constructively With Relative-SST (Atlantic minus Tropical)

SLP

Potential Intensity

850hPa vort.



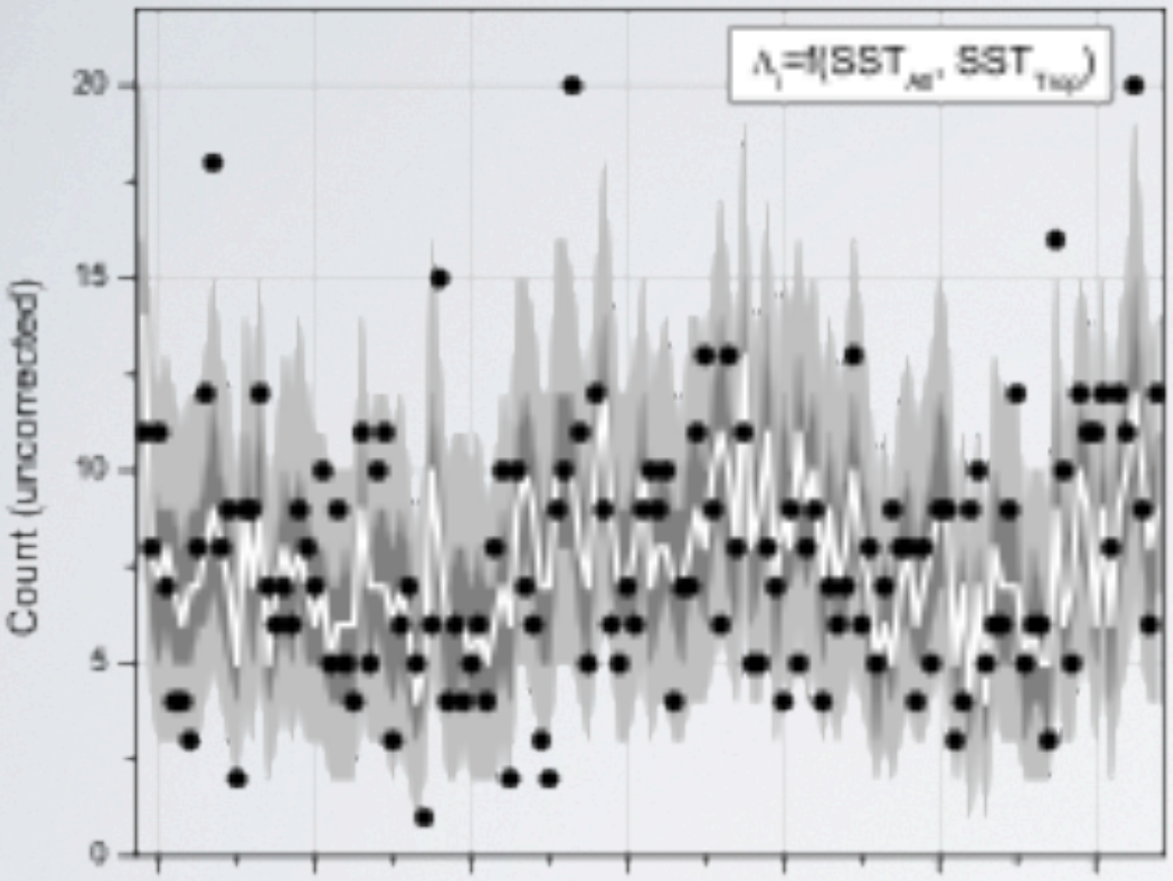
Shear

700hPa RH

Precip

Vecchi et al. (2012, in prep.)

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



Villarini, Vecchi and Smith (2010, J. Clim.)

Knutson et al. (2008) Swanson (2008), Vecchi et al. (2008), Zhao et al. (2009, 2010), Villarini et al. (2010, 2011.a,,.c), Villarini and Vecchi (2011)

Atlantic SST acts to increase frequency.

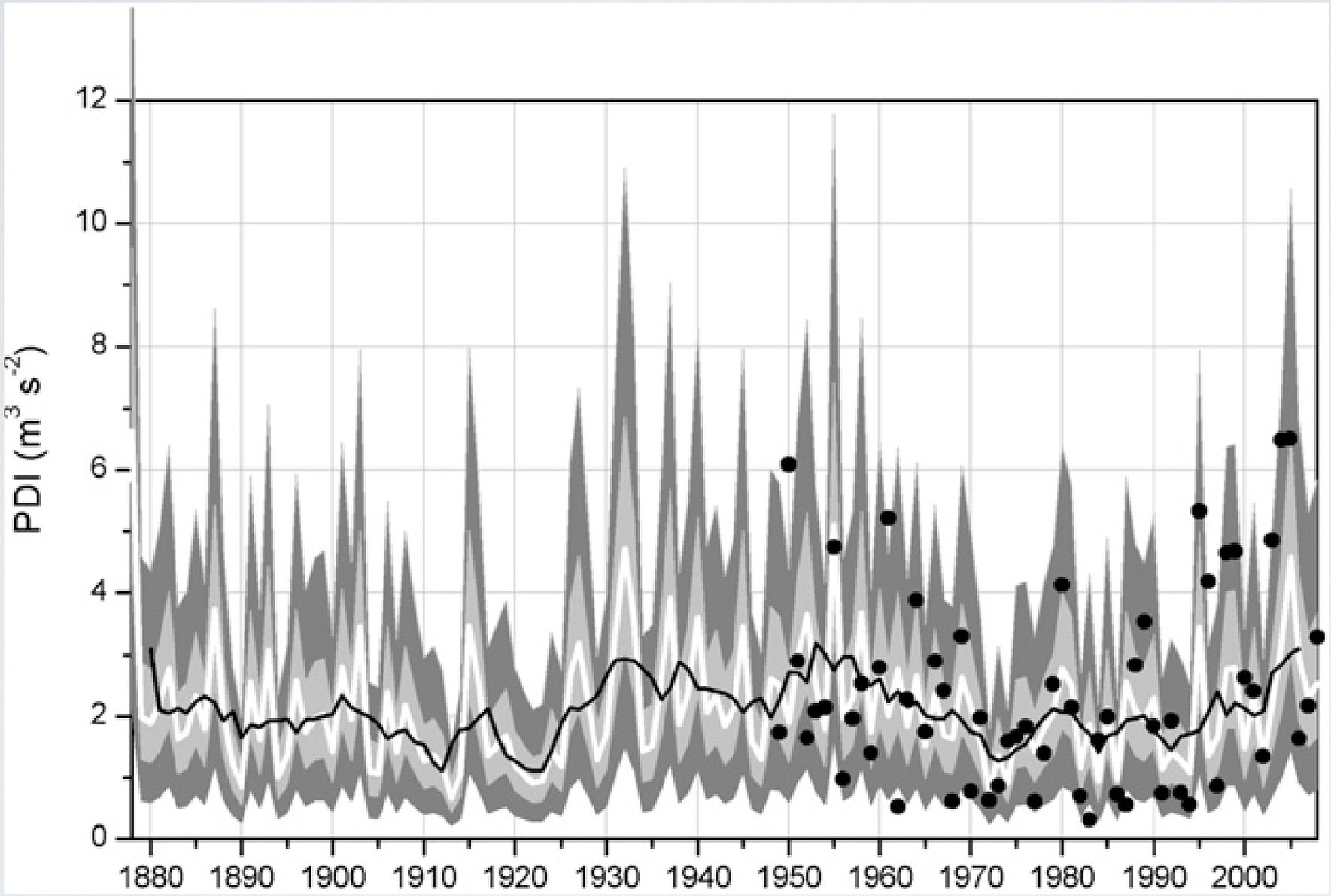
Tropical-mean SST acts to reduce frequency.

$$Rate = e^{a+bSST_{ATL}-cSST_{TRO}}$$

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)

Statistical modeling of PDI (sum of wind speed cubed) since WWII retains SST_{mdr} as positive and SST_{trop} as negative predictors. Enables estimate of pre-WWII PDI and predictions of PDI.



Villarini and Vecchi (2012, J. Climate)

No trend in reconstruction of annual & five year PDI from SST indices. Dots are observed.

Response of NA TS Frequency to Radiative Forcing

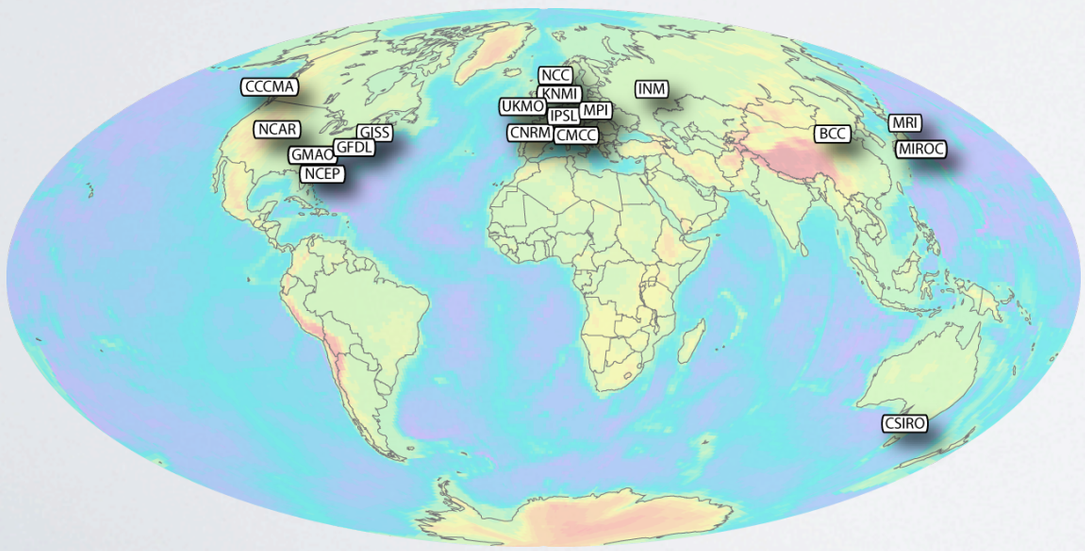
Coupled Model Inter-comparison Projects (CMIP3 & CMIP5)

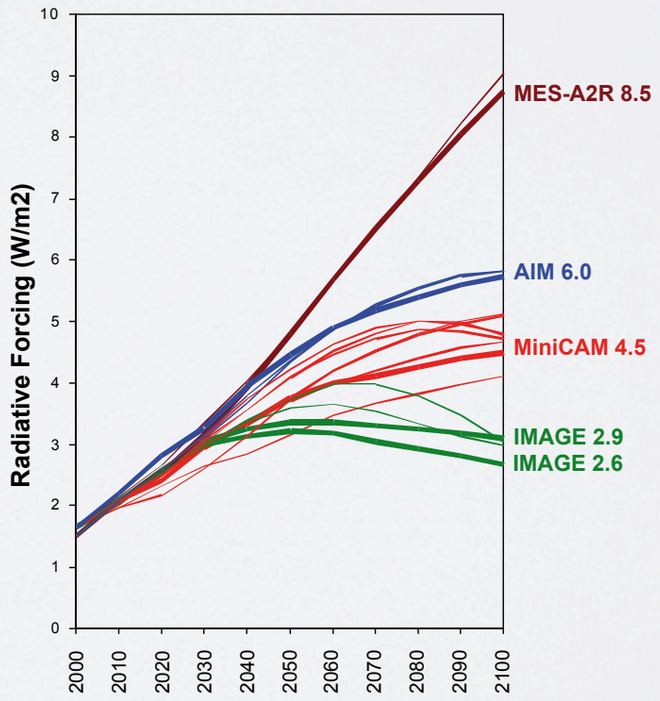
Taylor et al. (2012)

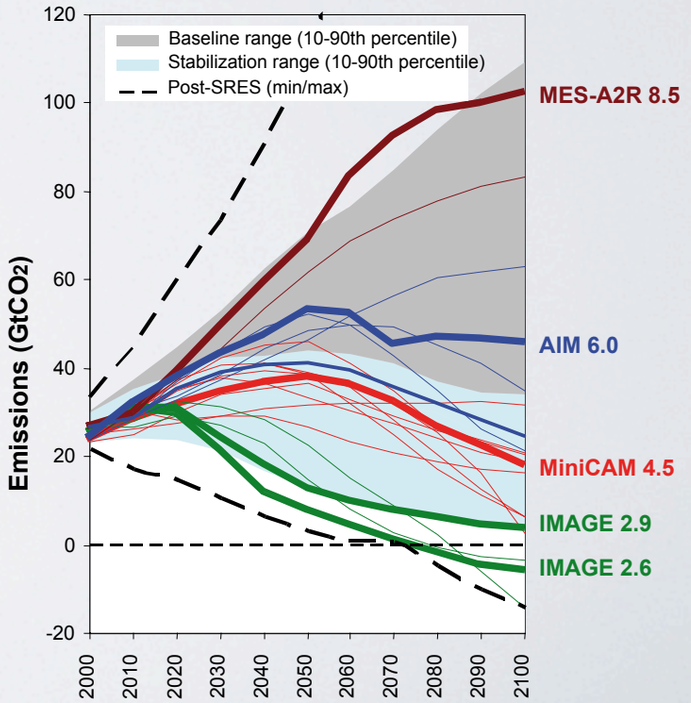
- Coordinated GCM experiments to address key issues in climate science:

  Paleoclimate, response to CO_2, aerosols, volcanoes, high-resolution, decadal predictability, earth-system modeling, geoengineering…

- Around 20 centers worldwide (including GFDL)
- CMIP3 (assessed in IPCC-AR4) finalized mid-2000s, data still quite useful
- CMIP5 (to be assessed in IPCC-AR5) entering the "analysis" phase: centers have made data publicly available





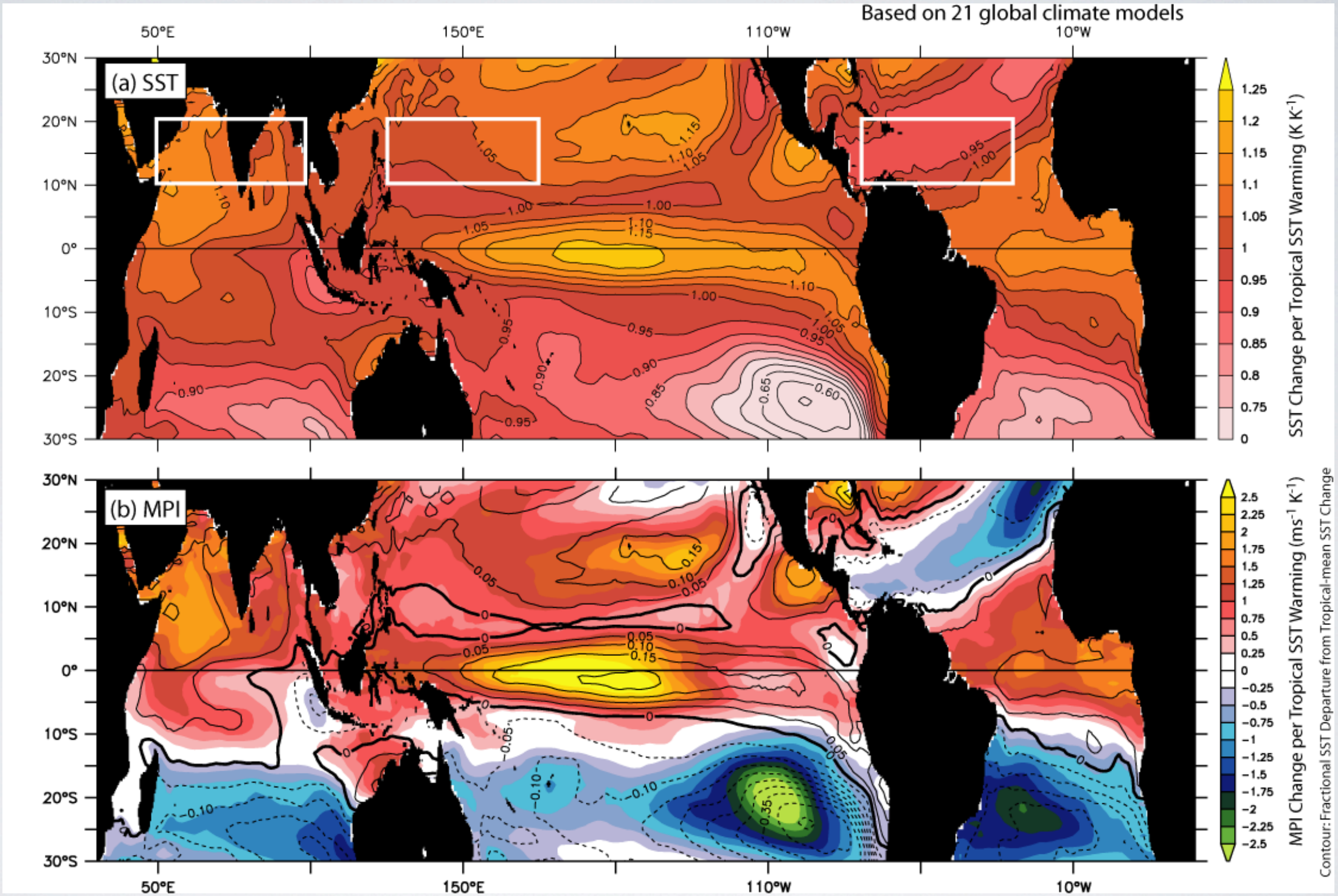


GCM Projections of 21st Century Changes:

Potential change intensity follows SST minus tropical-mean SST

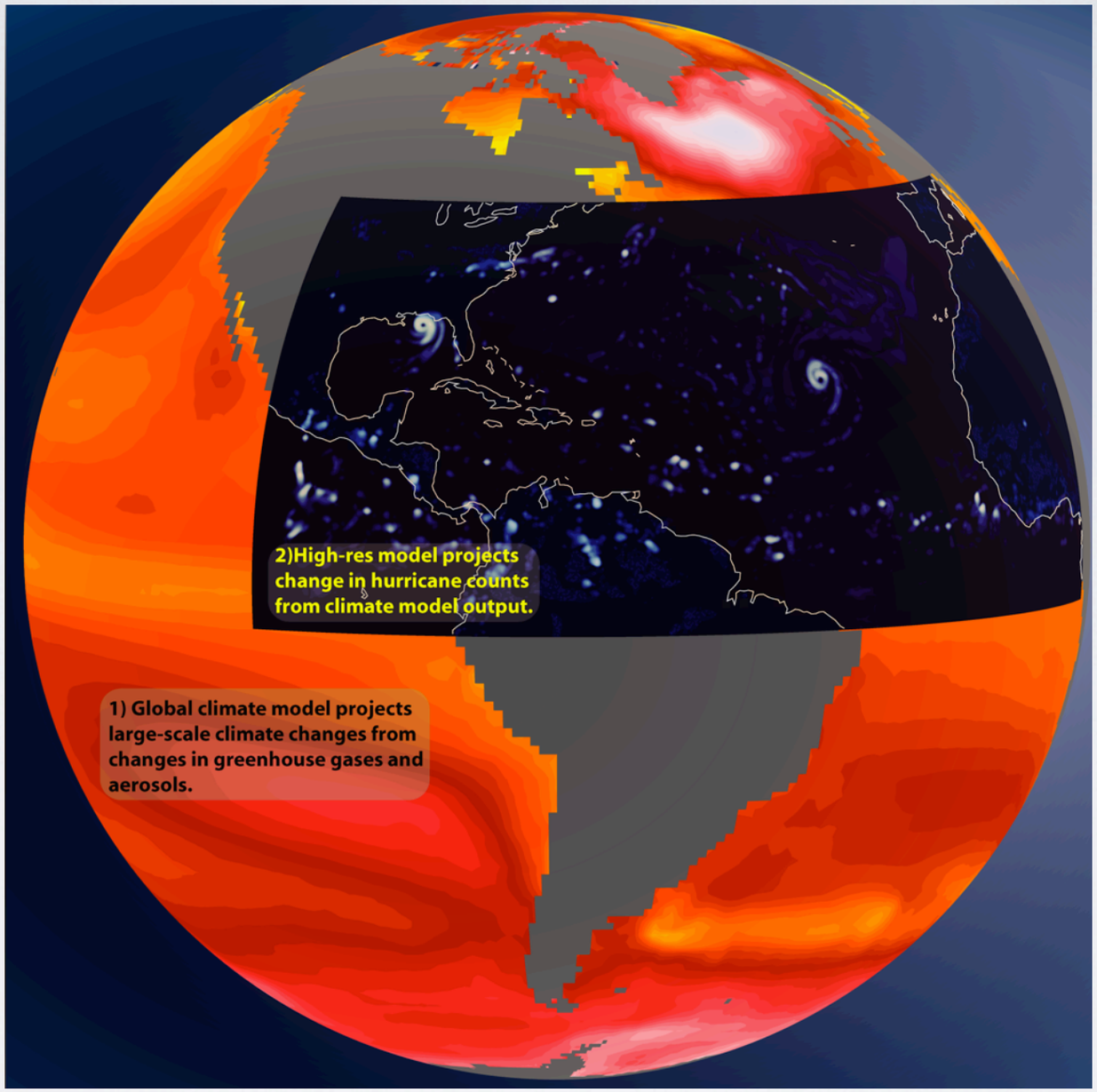
Surface Temp.

Potential Intensity



Vecchi and Soden (2007, Nature)

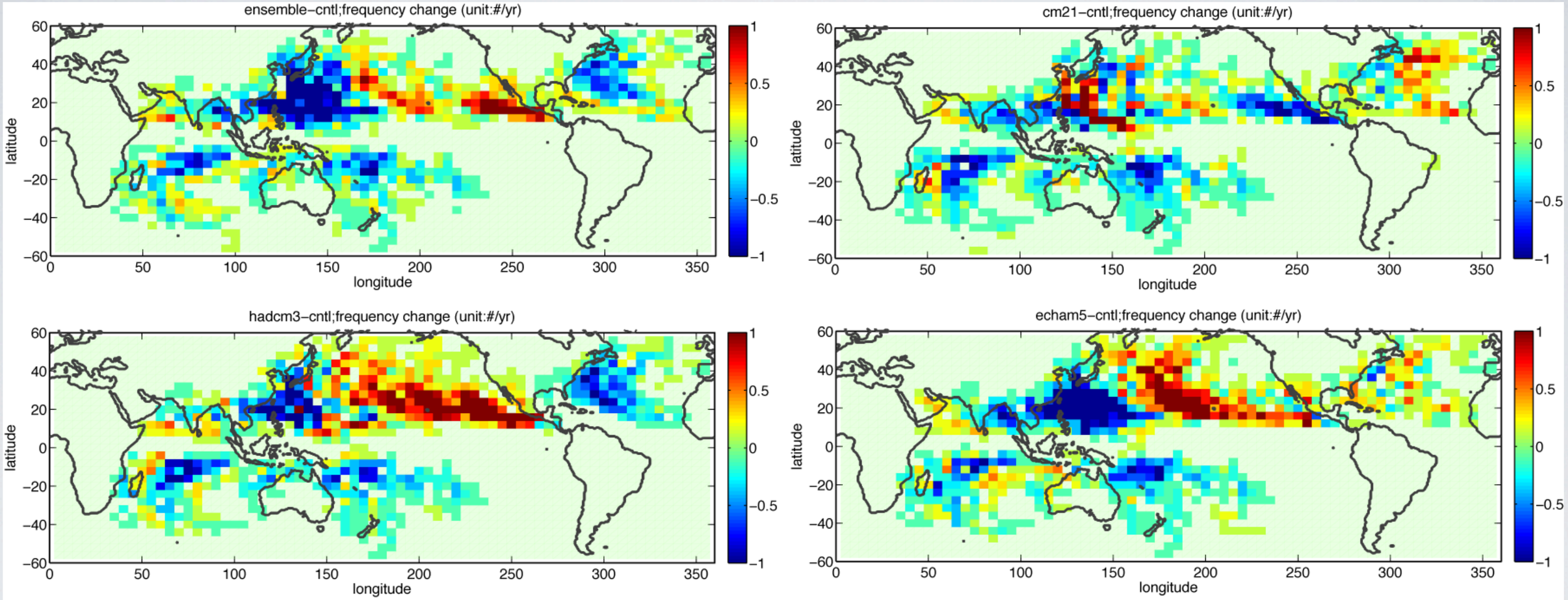
"Downscale" Climate Model Projections With High-Resolution or Statistical Models



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)

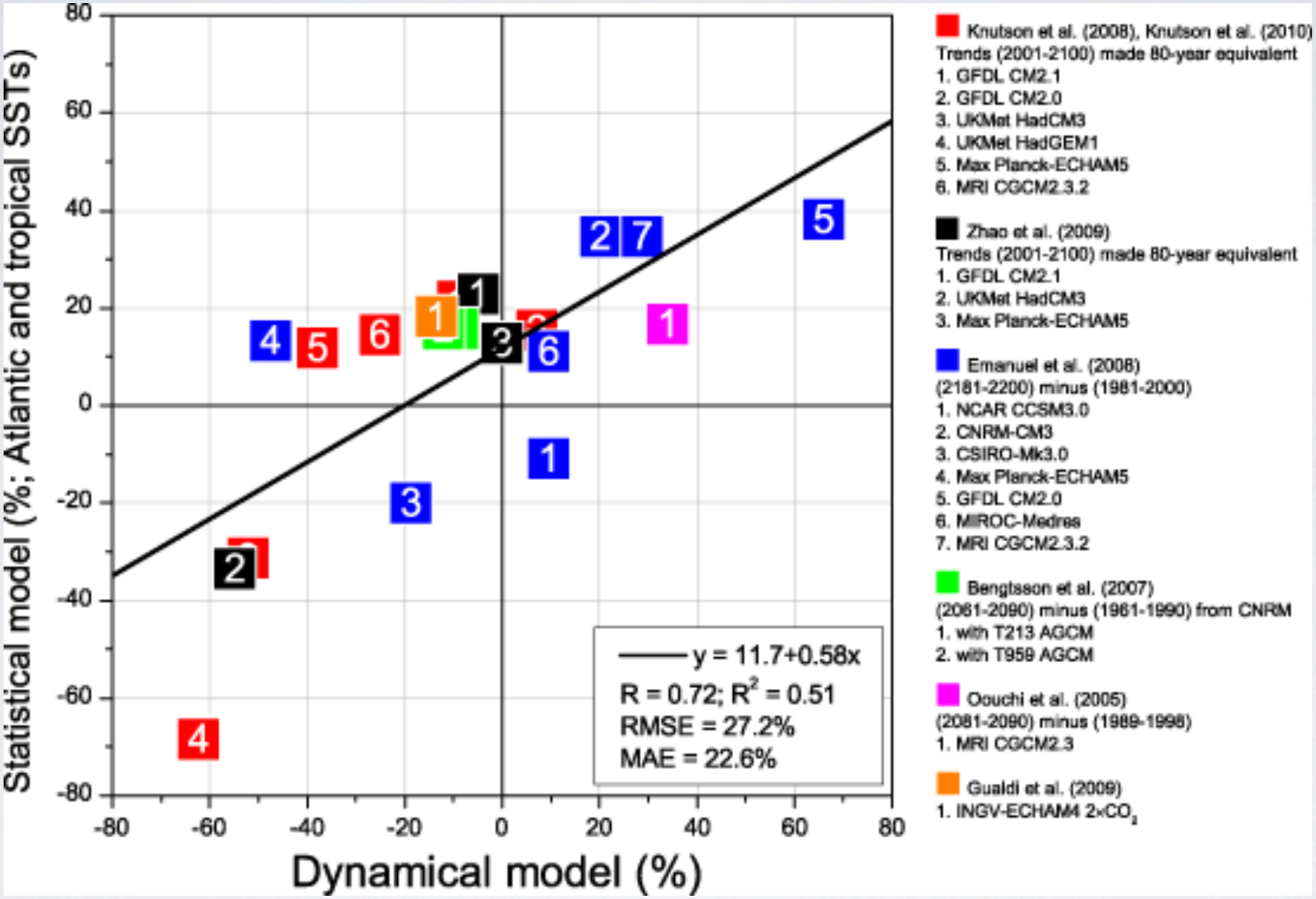
Regional increase/decrease much larger than global-mean.

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

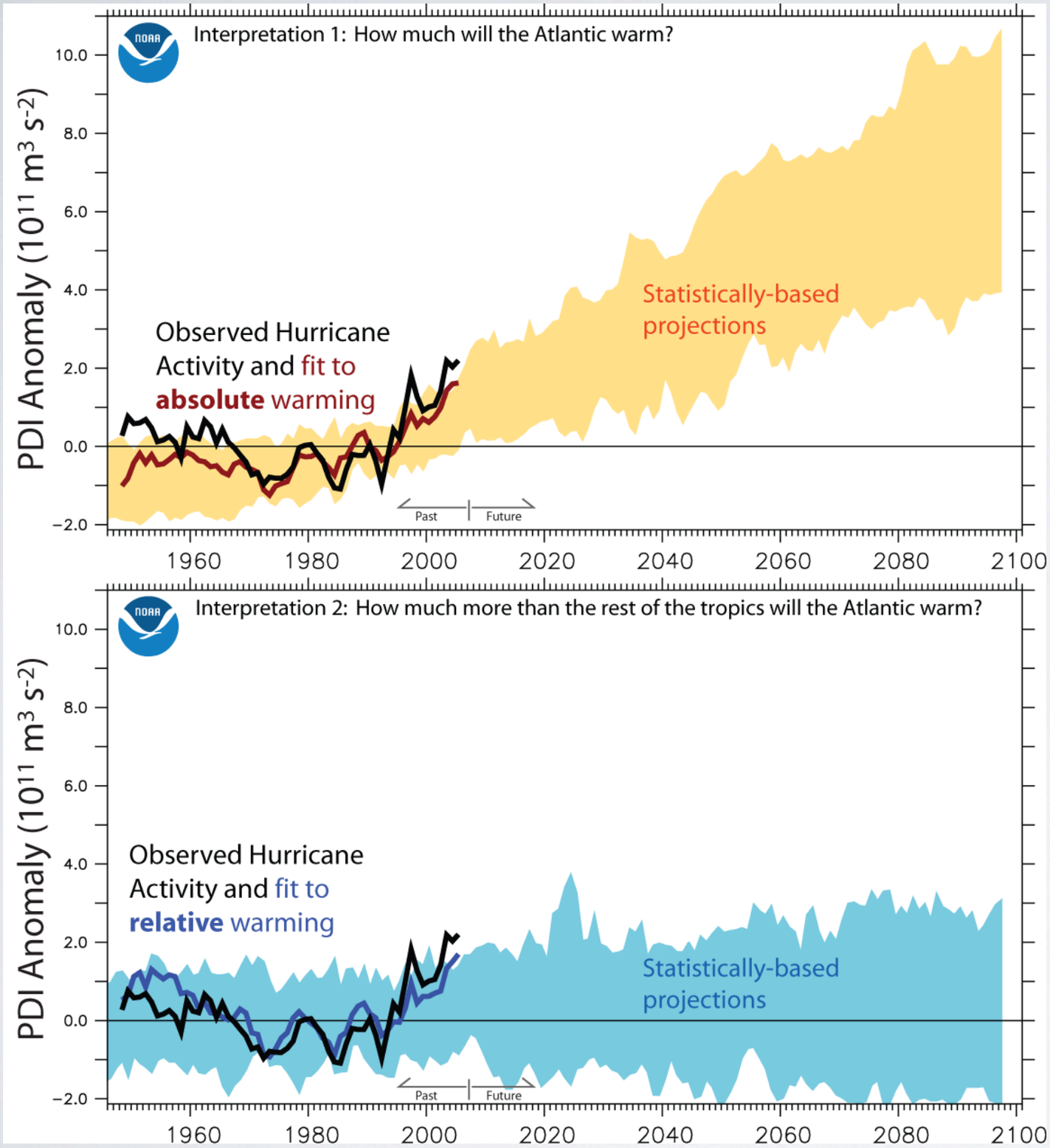
Dynamical models exhibit consistent relationship to MDR and tropical SSTs - all consistent with observations



Villarini et al (2011, J. Clim)

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

Two Statistical Projections of Atlantic Hurricane Activity

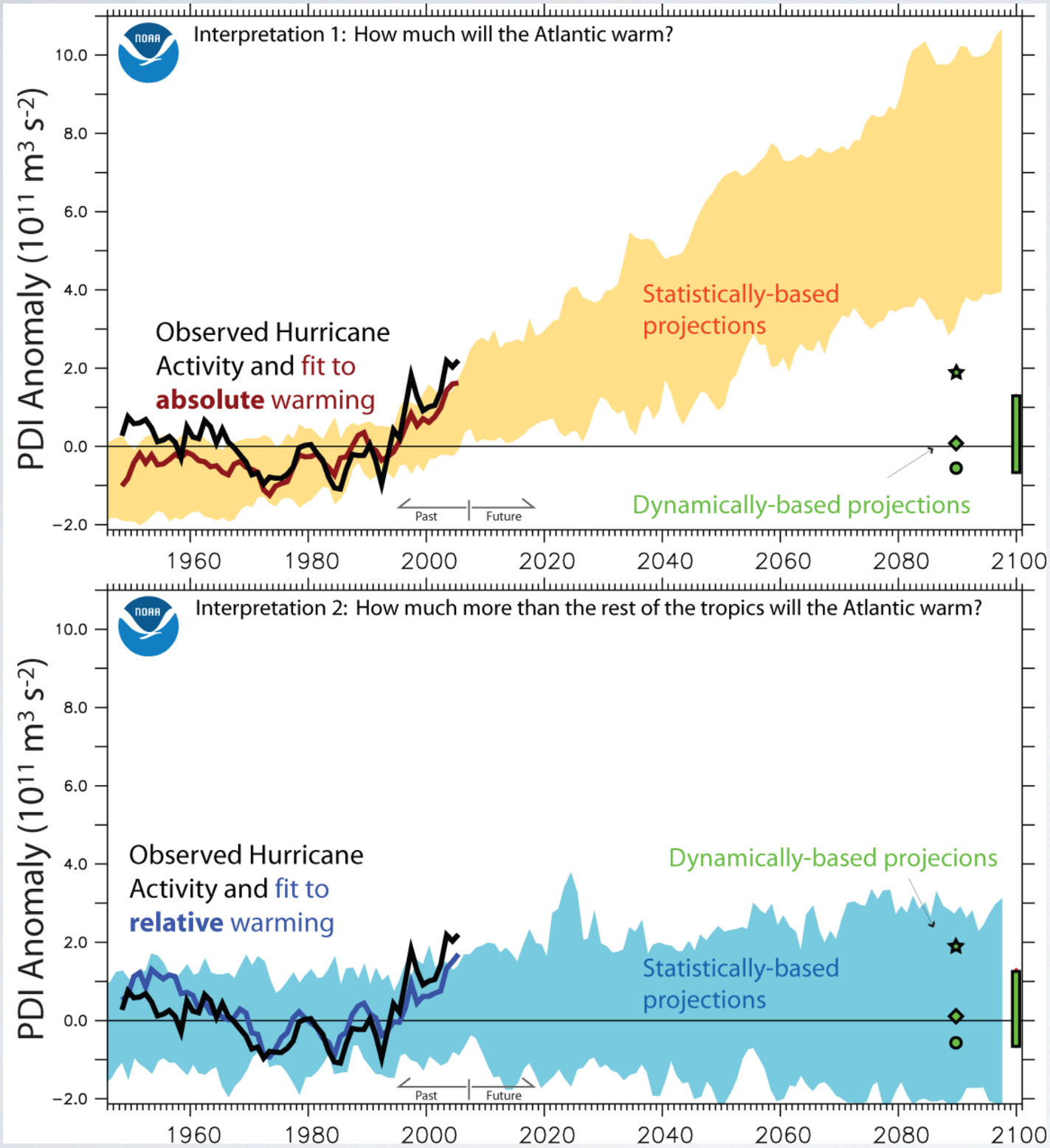


Observed Activity
Absolute Atlantic Temperature

Observed Activity
Relative Atlantic Temperature

Vecchi, Swanson and Soden (2008, Science)

…Add Dynamical Projections of Atlantic Hurricane Activity



Observed Activity

Absolute Atlantic Temperature

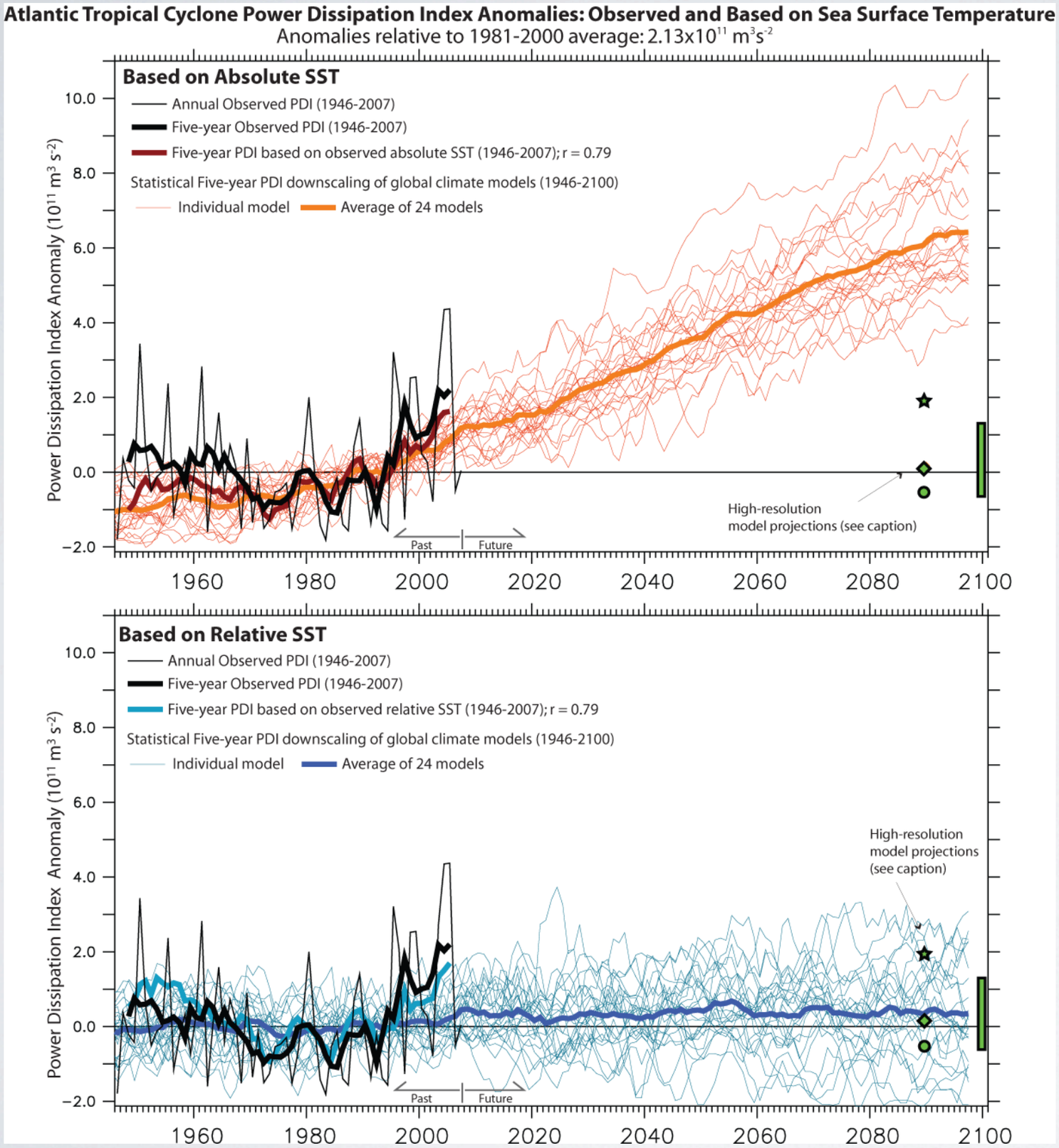
Dynamical Model Projections

Observed Activity

Relative Atlantic Temperature

Vecchi, Swanson and Soden (2008, Science)

…Add Dynamical Projections of Atlantic Hurricane Activity



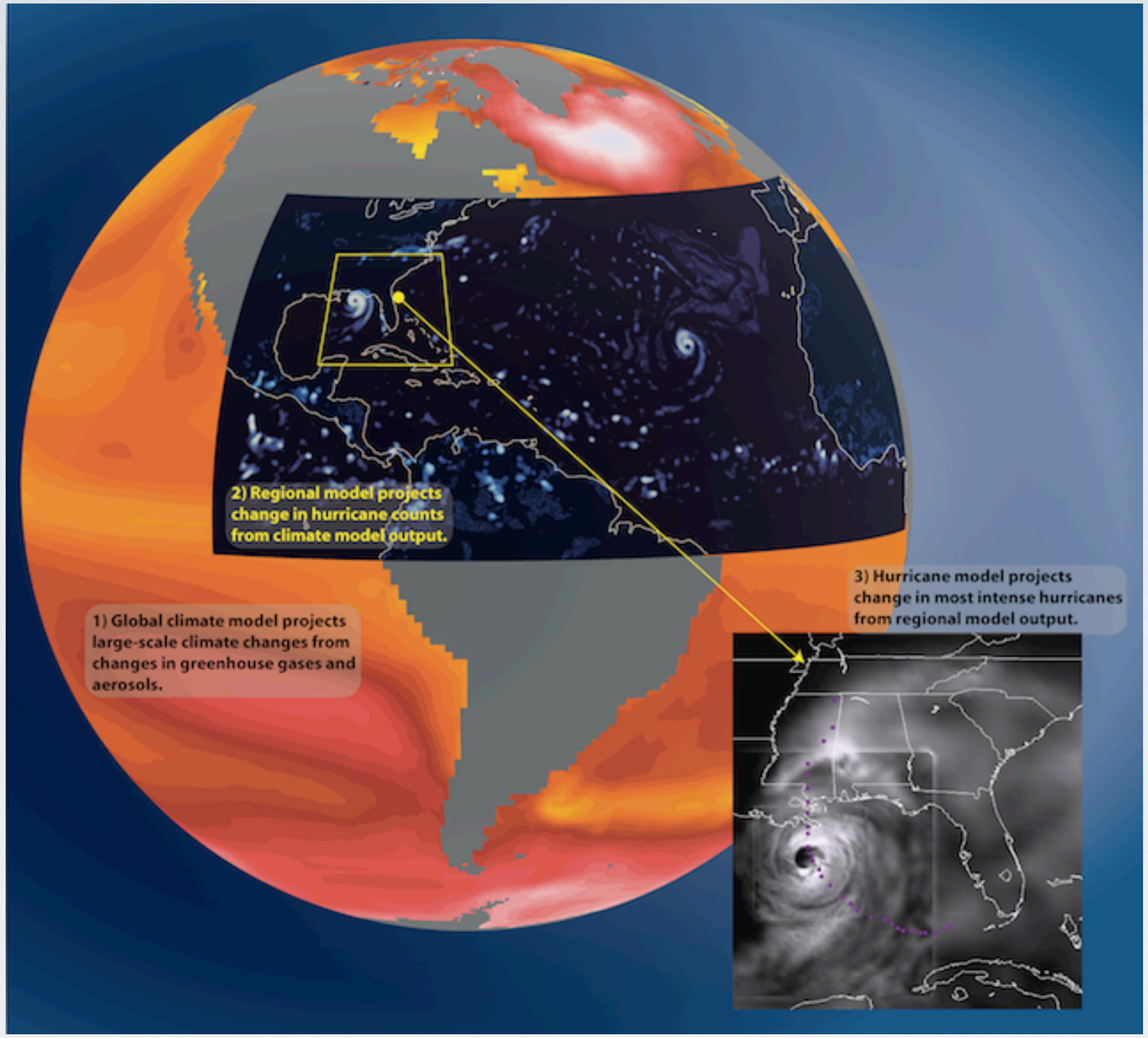
Observed Activity
Absolute Atlantic Temperature

Dynamical Model Projections

Observed Activity
Relative Atlantic Temperature

Vecchi, Swanson and Soden (2008, Science)

Strongest cyclones projected with double downscaling

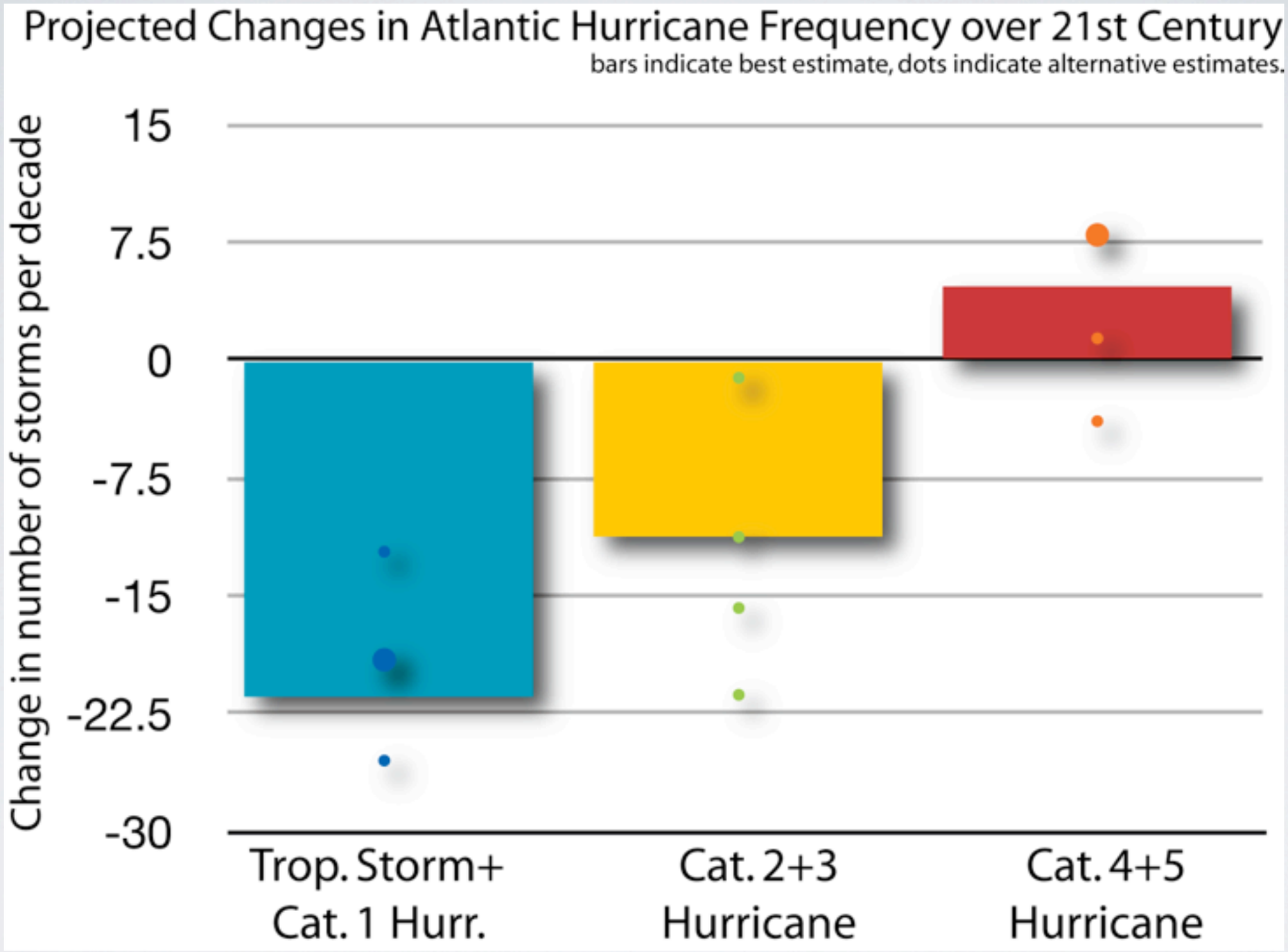


Adapted from
Bender et al (2010, Science)

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)

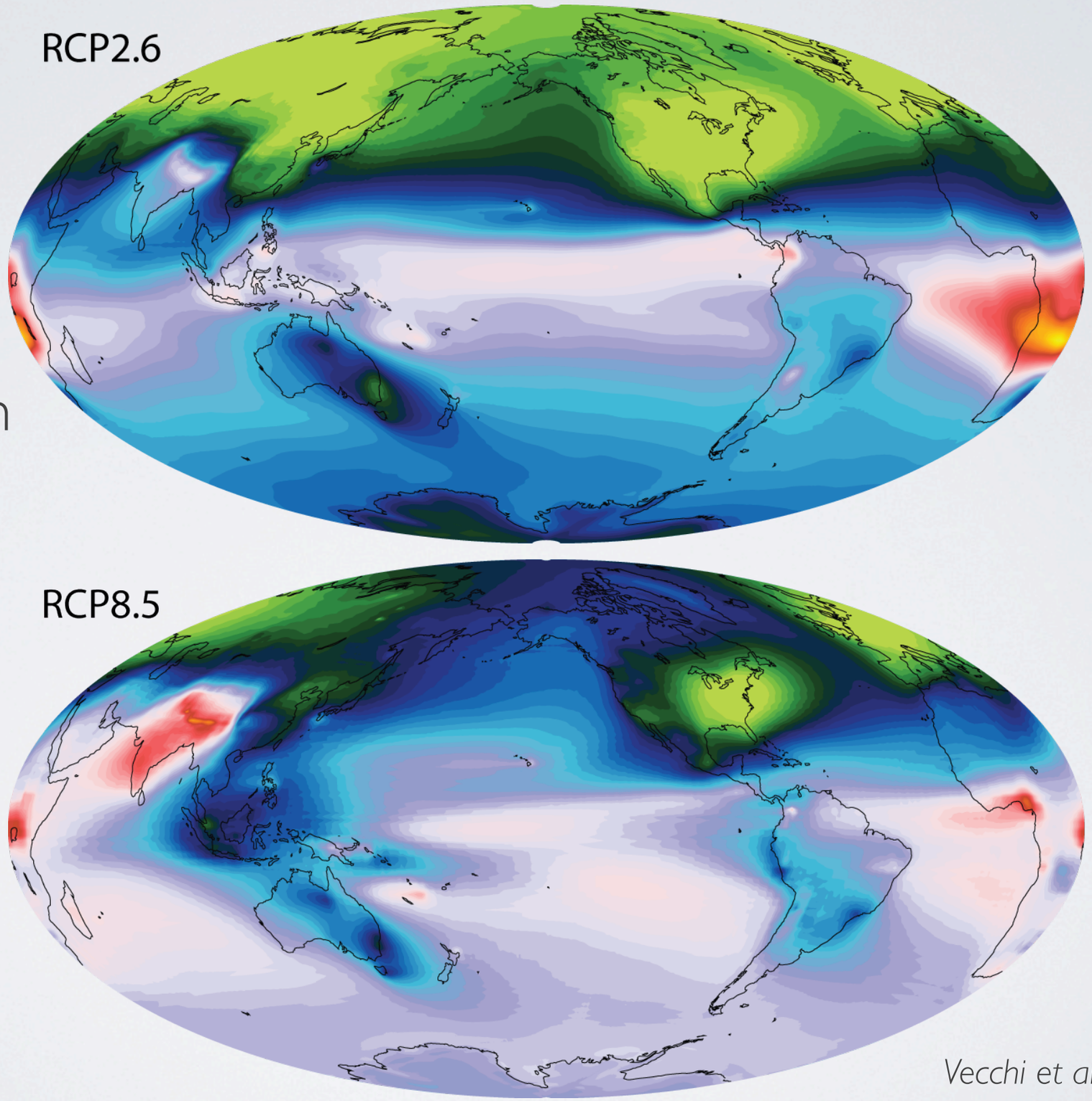
Hurricanes and CMIP5

New coupled model inter-comparison, includes large aerosol reductions in future projections.

New 21st Century Scenarios include big aerosol forcing, many new models have more ways to respond to aerosols

2100 CO_2
~1.2x1990

Projected pollution controls: reduced aerosols



2100 CO_2
~4x1990

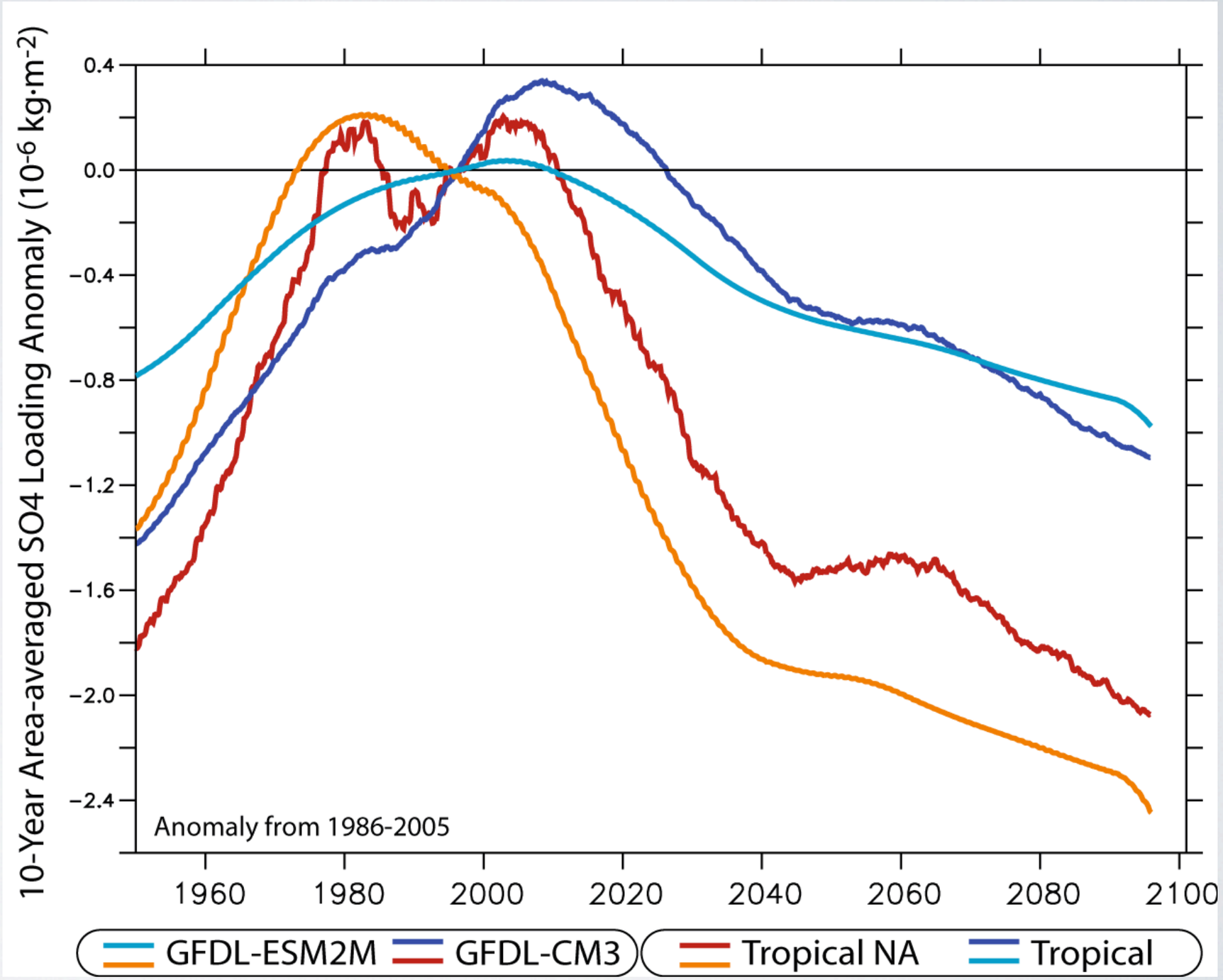
Vecchi et al. (2012, in prep.)

New 21st Century Scenarios include big aerosol forcing, many new models have more ways to respond to aerosols

Projected increase in wealth =>

pollution controls =>

reduced aerosols



Vecchi et al. (2012, in prep.)

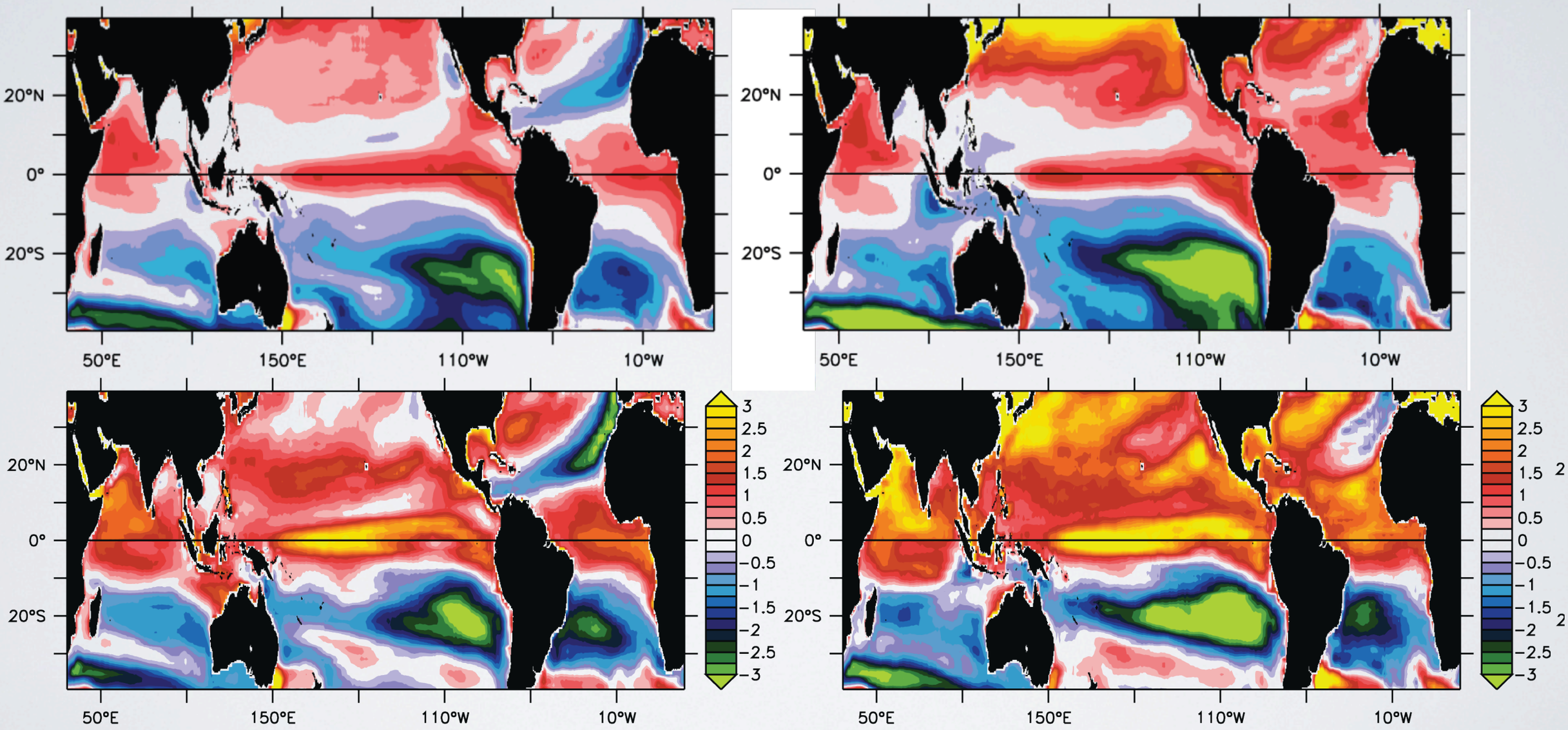
In CMIP5, some factors impacting hurricanes (shear and potential intensity) show impact of non-GHG forcing.

Jun-Nov averages: left at CO2 doubling right 2051-2070

Upper: Sea surface temperature

Response to CO_2 increase

RCP2.6: Small CO_2 increase & large aerosol decrease



Lower: Potential Intensity: theoretical upper bound on storm strength

Vecchi et al. (2012, in prep.)

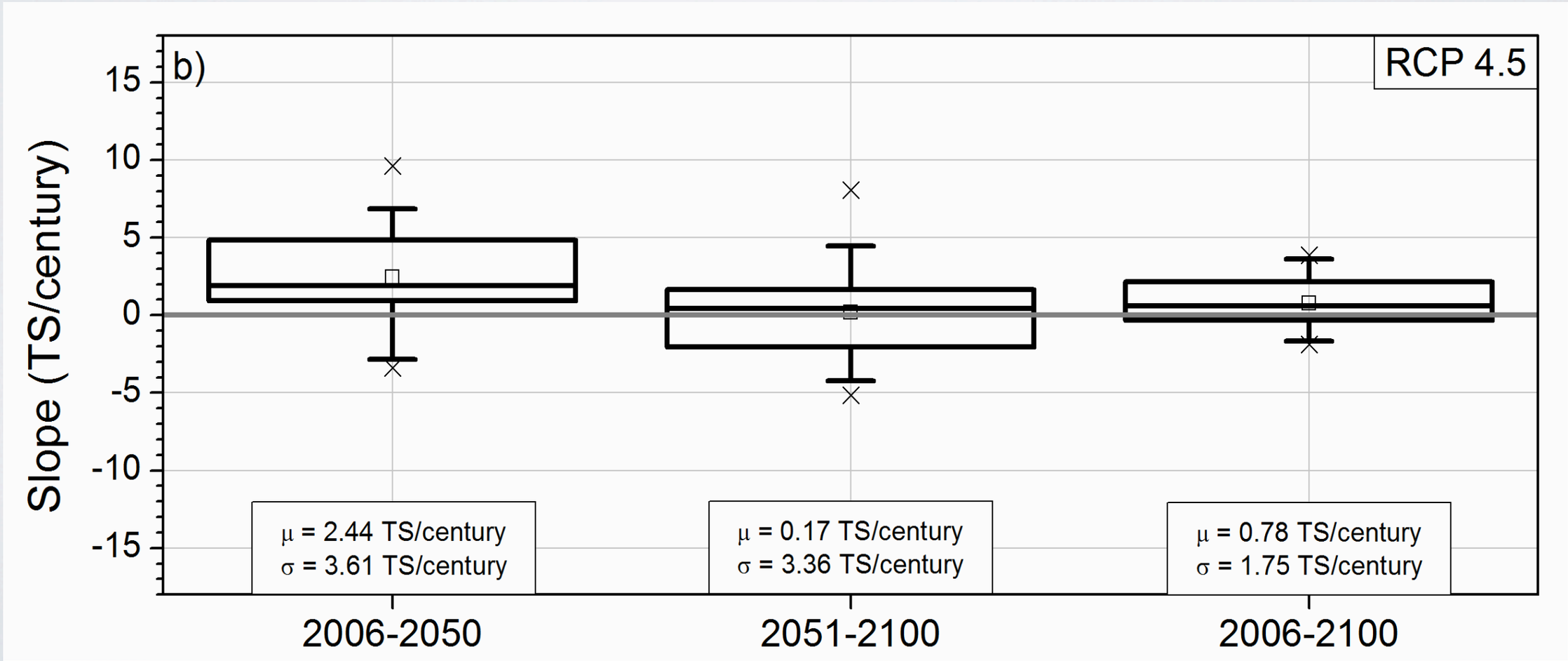
Use homogenized data and HiRAM storm counts to build statistical models for exploration, prediction and projections

Consistent with high-res dynamical models, understanding on controls to hurricanes & "cheap".

$$Rate = e^{a+bSST_{ATL}-cSST_{TRO}}$$

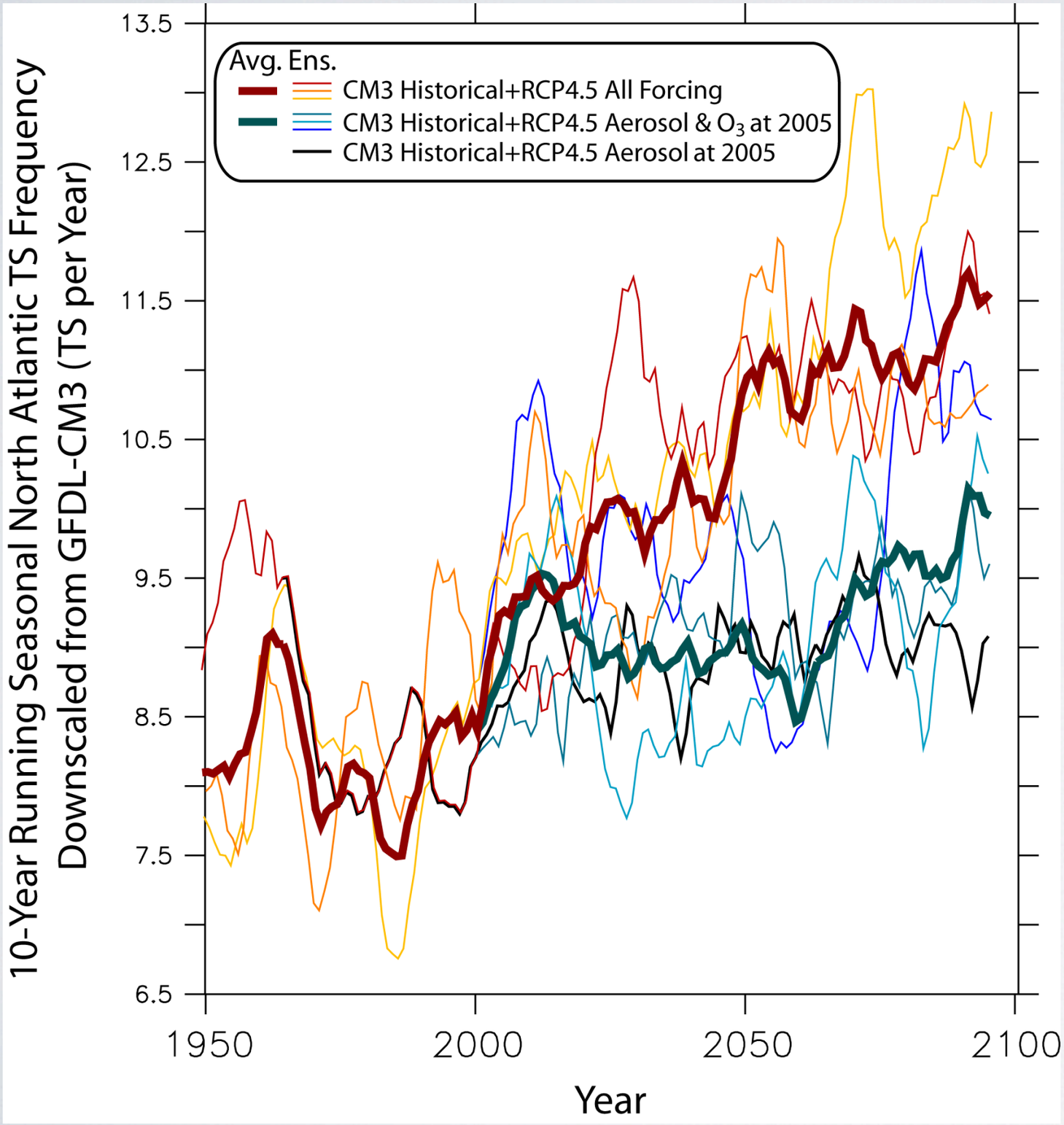
Statistical NA TS Projections from 17 CMIP5 CGCMs

Villarini and Vecchi (2012)



Knutson et al. (2008) Swanson (2008), Vecchi et al. (2008), Zhao et al. (2009, 2010), Villarini et al. (2010, 2011.a.,.c), Villarini and Vecchi (2011, 2012)

GFDL-CM3 indicates aerosols key for NA TS projections



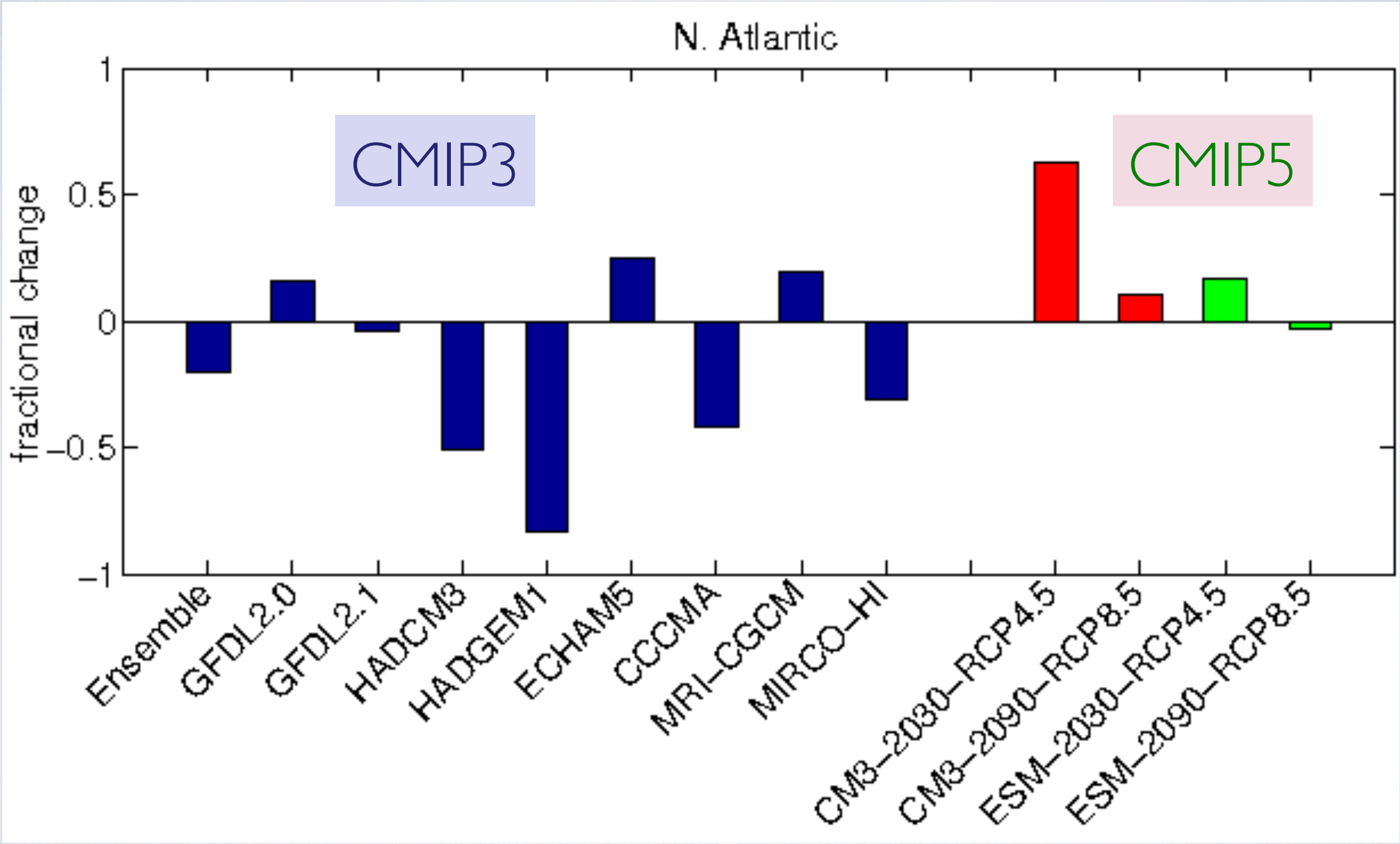
All Forcing

No future aerosol or O_3

No future aerosol

Villarini and Vecchi (2012)

C180-HiRAM NA Hurricane Projections including CMIP5

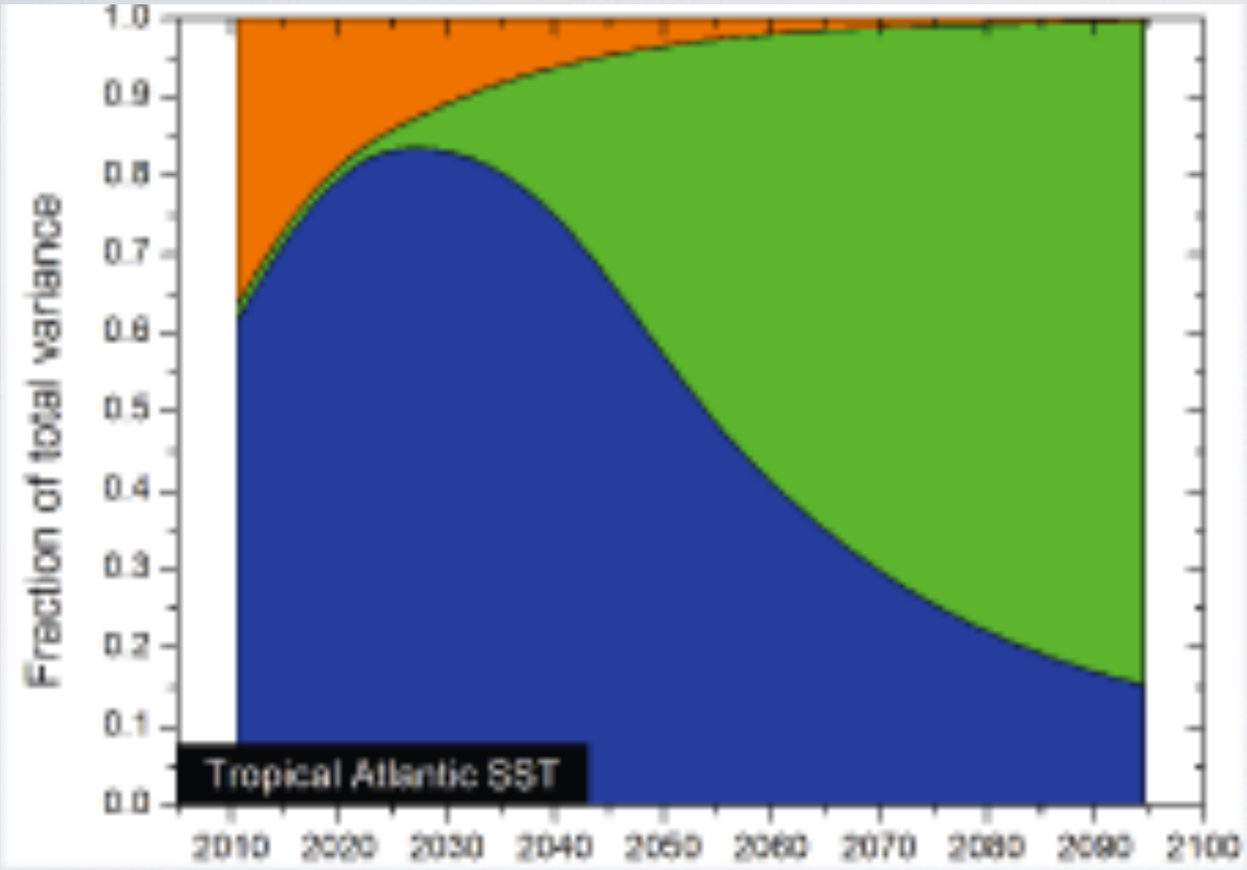


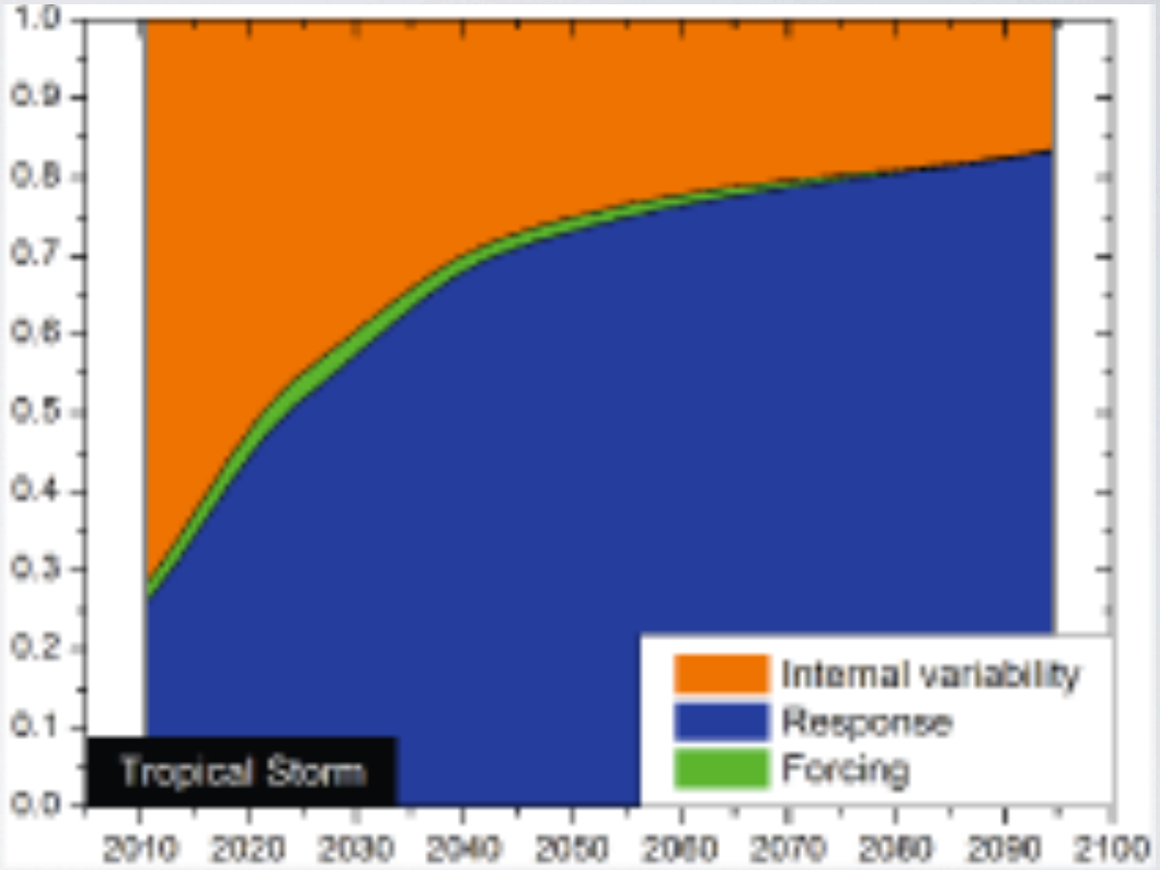
Adapted from Zhao et al. (2009, J. Clim.) and Held et al. (2012, in prep)

Key uncertainty sources to projections of decadal TS activity

Tropical Atlantic SSTA

NA TS Frequency





Villarini et al. (2011), Villarini and Vecchi (2012, submitted)

Sources of uncertainty (after Hawkins and Sutton, 2009)

- Variability: independent of radiative forcing changes
- Response: "how will climate respond to changing GHGs & Aerosols?"
- Forcing: "how will GHGs & Aerosols change in the future?"

Summary

- Premature to attribute the observed increase in NA TC activity to radiative forcing, particularly greenhouse gases

- "Relative SST" a parsimonious description of SST (tied to stability and atmospheric changes):
  - 1982-2007 TC increase in NA due to pattern of SST change - what drove pattern?
    Not robustly associate with CO_2 response of CMIP3/CMIP5 models
    Consistent with internal variability in some CMIP3/CMIP5 models
    Indications that aerosol (soot, dust, etc.) reductions contributed

- NA Hurr. Response to CO_2: likely fewer, probably stronger, probably wetter
  NA Hurr. Response to aerosol reduction: probably more & stronger (how many/much?)

- Internal variability and systematic model differences dominant source of uncertainty in tropical storms even at century scales. On long timescales forcing uncertainty dominates for SST.

- Hybrid hurricane forecast system exhibits skill from November of previous year, preliminary multi-year forecasts results encouraging.

- ***If sensitivity in high-res GCM correct, may need to predict decadal SST patterns better than we know past changes.***

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Initialized seasonal and multi-year hurricane forecasts

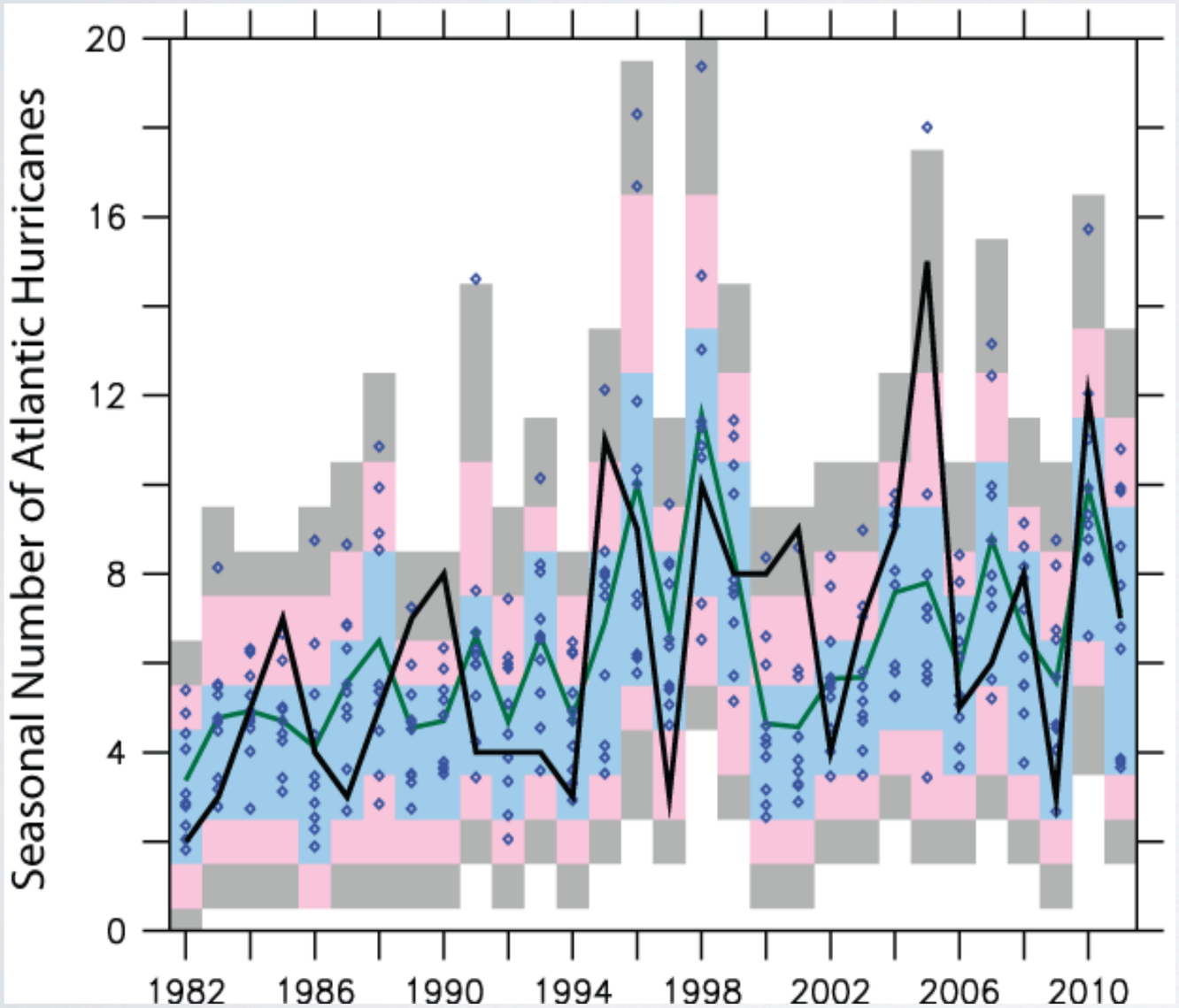
- Experimental long-lead seasonal forecasts
- Experimental multi-year to decadal forecasts

Experimental Extended (one year lead) Atlantic Hurricane Forecasts

http://www.gfdl.noaa.gov/hyhufs

GFDL "HyHuFS ": Experimental forecast for next season

- Hybrid (statistical-dynamical) Hurricane Forecast System (as early as October)
- Retrospective performance (1982-2009, with 2010-2011 based on actual forecasts)



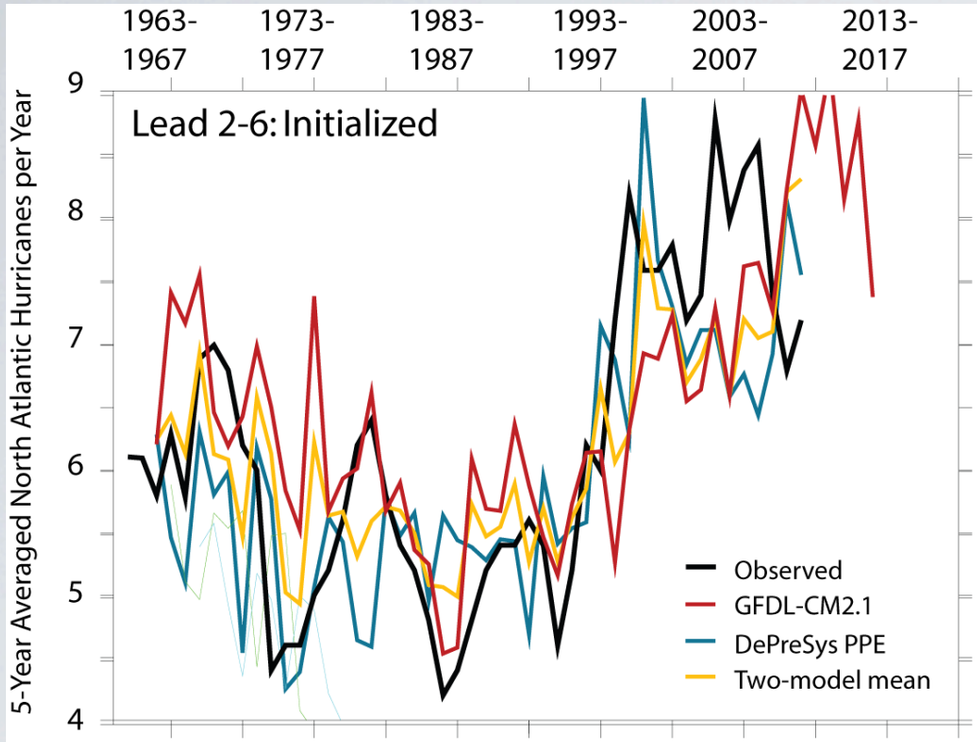
March forecasts:
r = 0.6

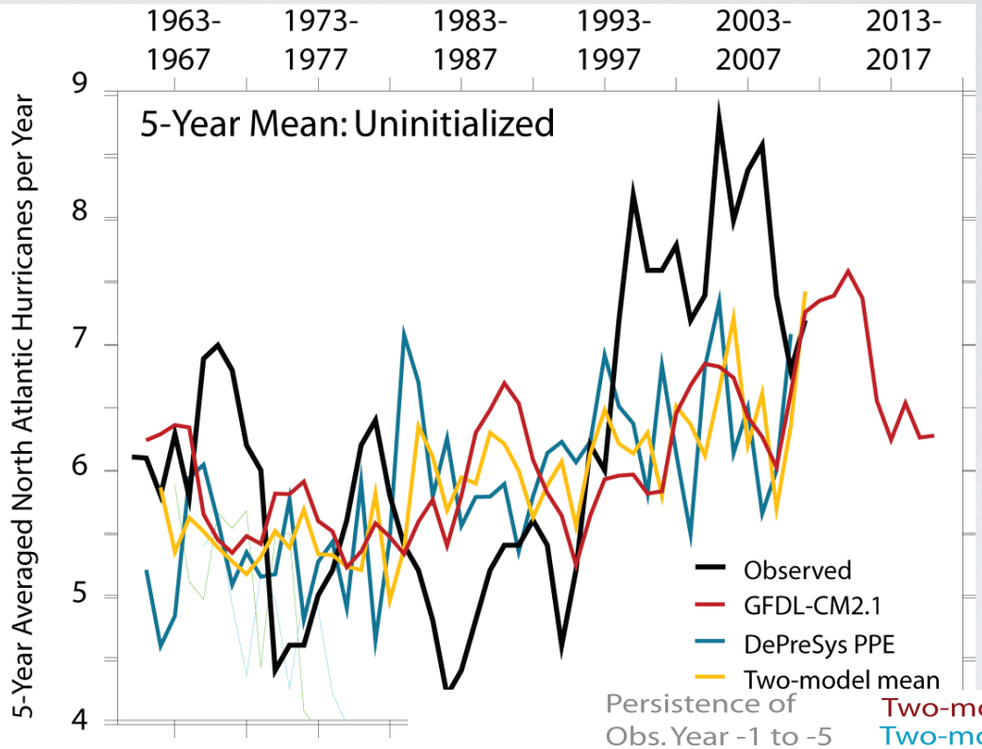
EXPERIMENTAL:
NOT OFFICIAL
FORECAST

Source: Vecchi et al. 2011 Monthly Weather Review.

Experimental decadal predictions

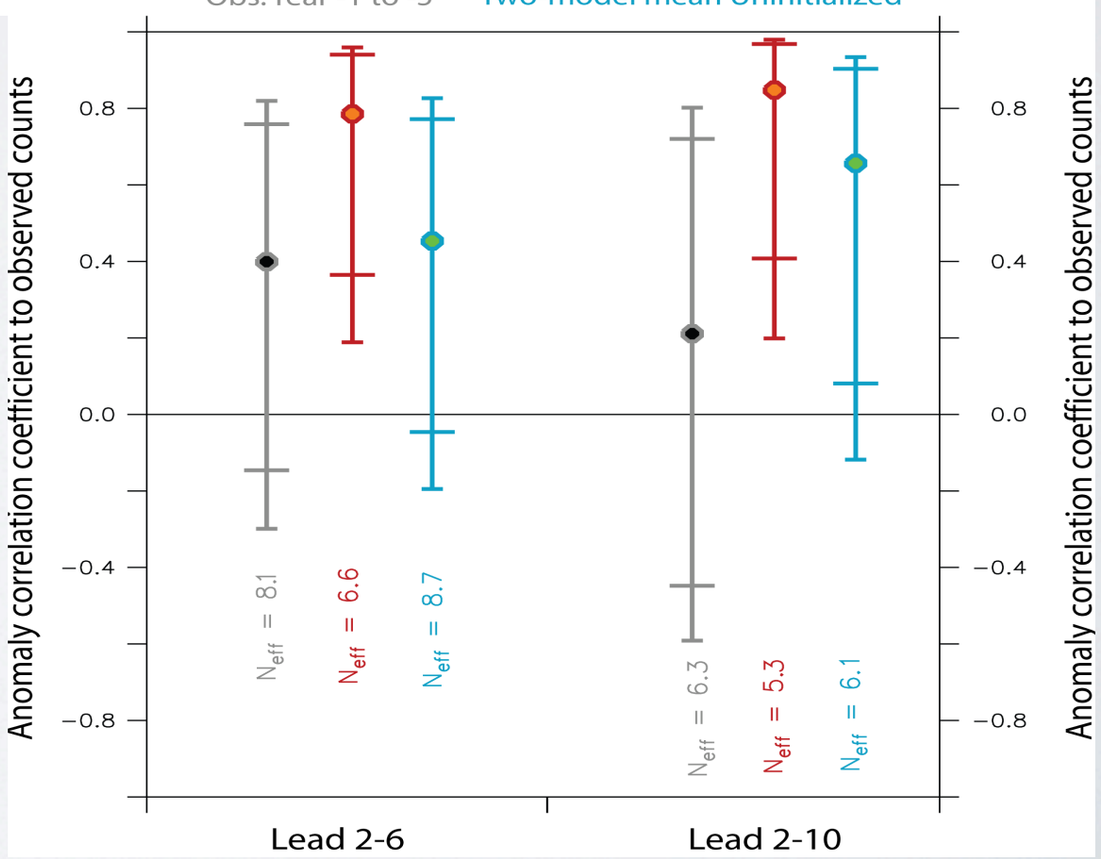
Hybrid system: statistical hurricanes, dynamical decadal climate forecasts





EXPERIMENTAL: NOT OFFICIAL FORECAST

- Retrospective predictions encouraging.
- However, small sample size limits confidence
- Skill arises more from recognizing 1994-1995 shift than actually predicting it.
- This is for basinwide North Atlantic Hurricane frequency only.



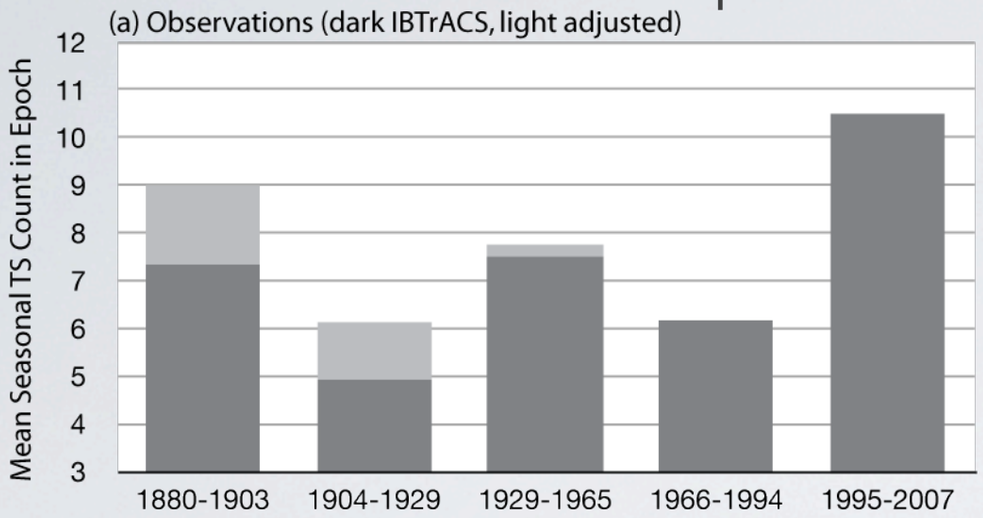
Vecchi et al. (2012 in prep.), see also Smith et al. (2010, Science)

Sensitivity to SST Uncertainty

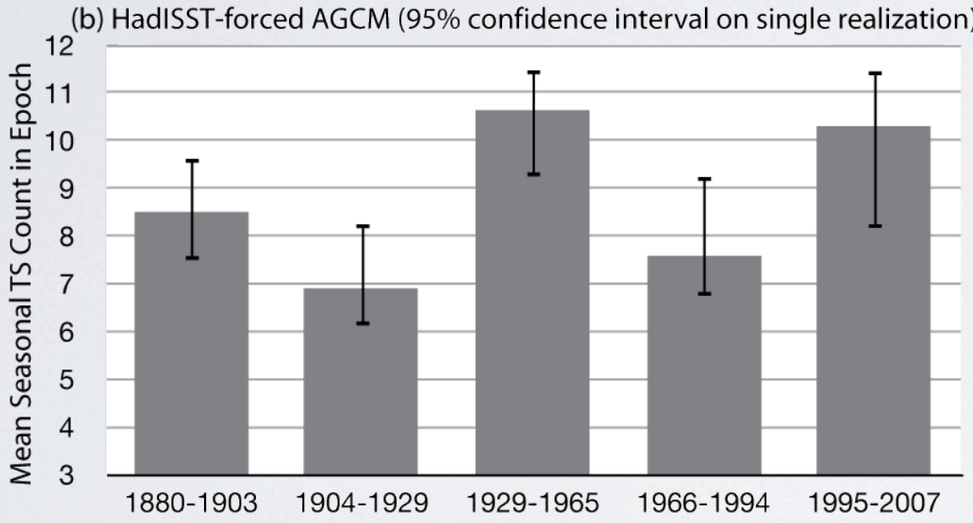
If AGCM sensitivity (and relative-SST statistical models) correct:

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

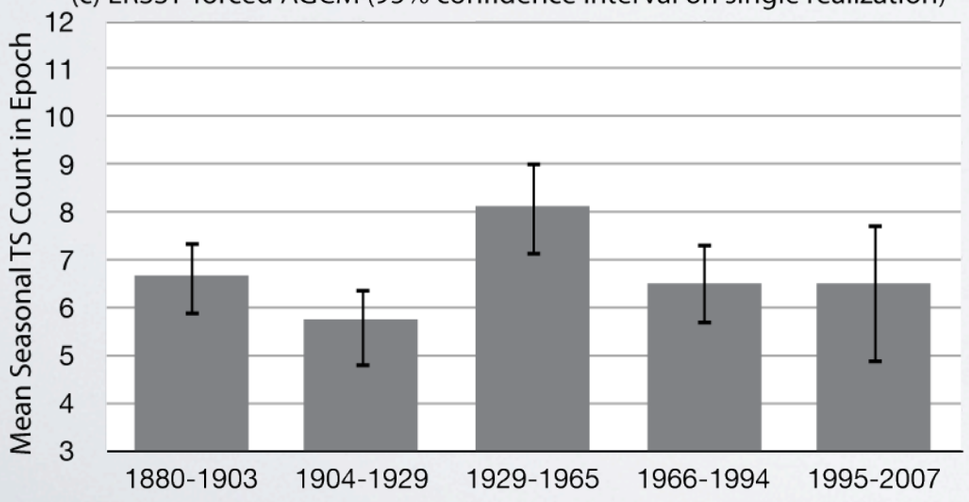
Ability of AGCM to Recover Multi-decadal TS Variability Depends on SST Forcing



Observed



HadISST-Forced AGCM



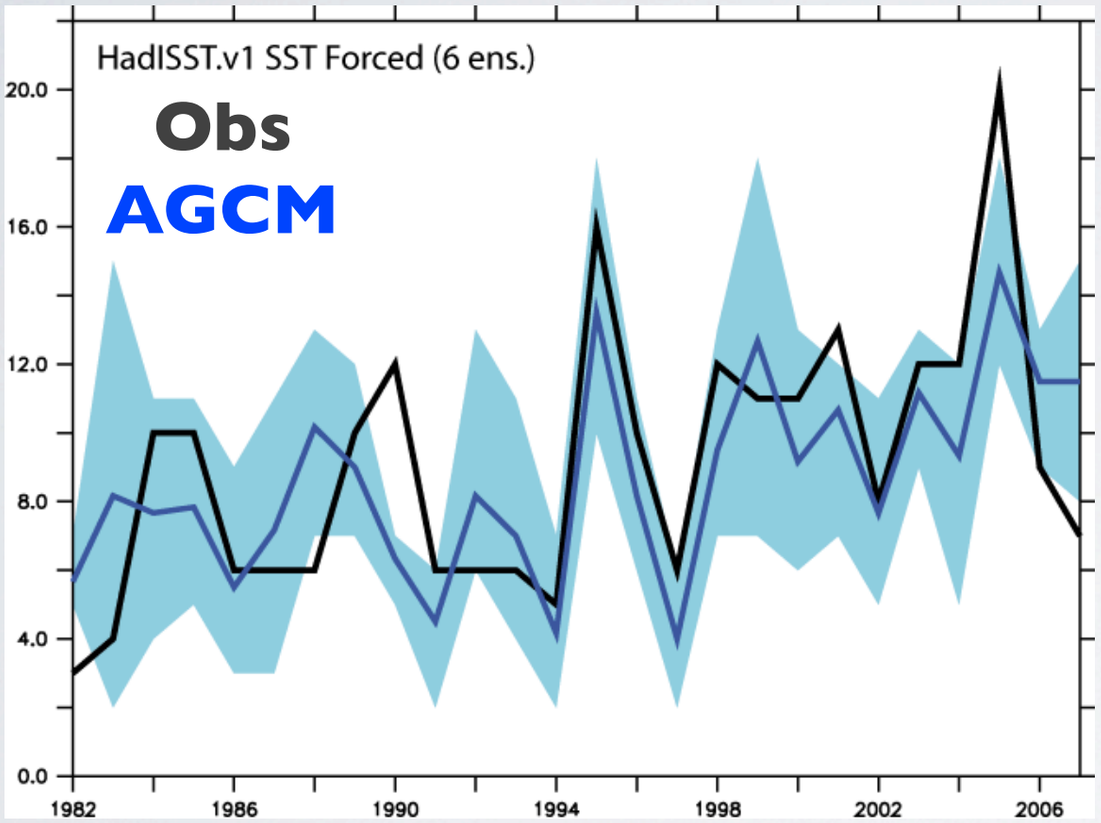
ERSST-Forced AGCM

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

Model Response Exhibits Sensitivity To Forcing Used

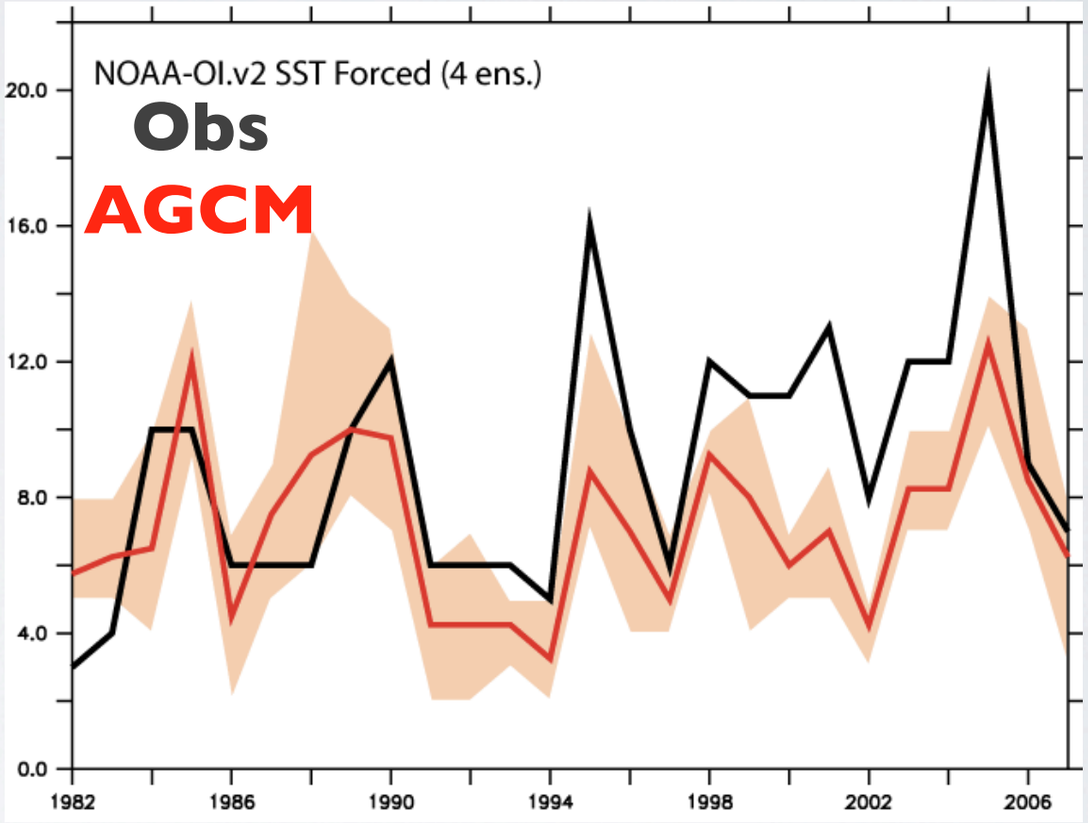
Tropical Storm Frequency Response to Same
AGCM but different estimates of observed SST

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?