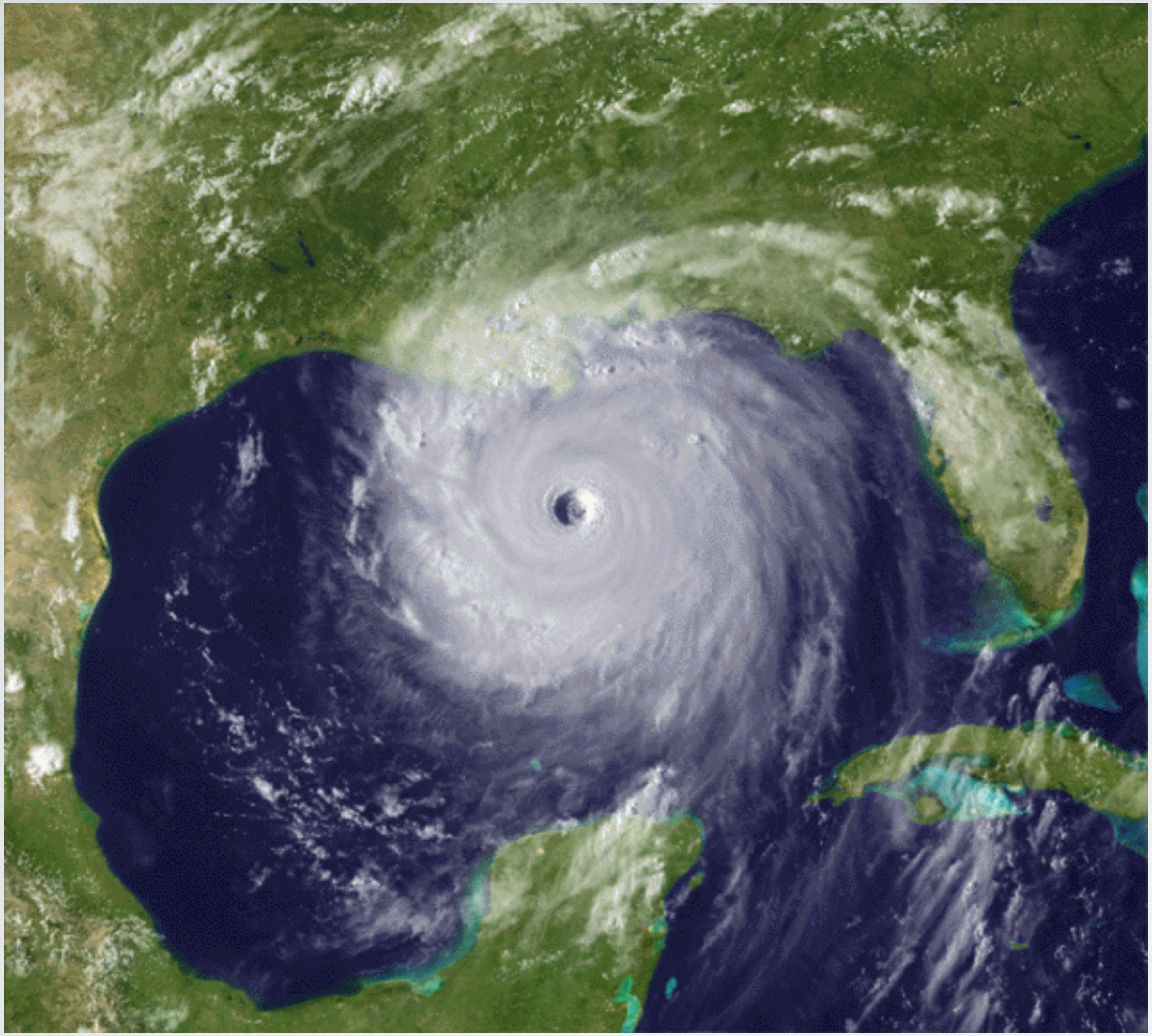
North Atlantic hurricane activity: past, present and future



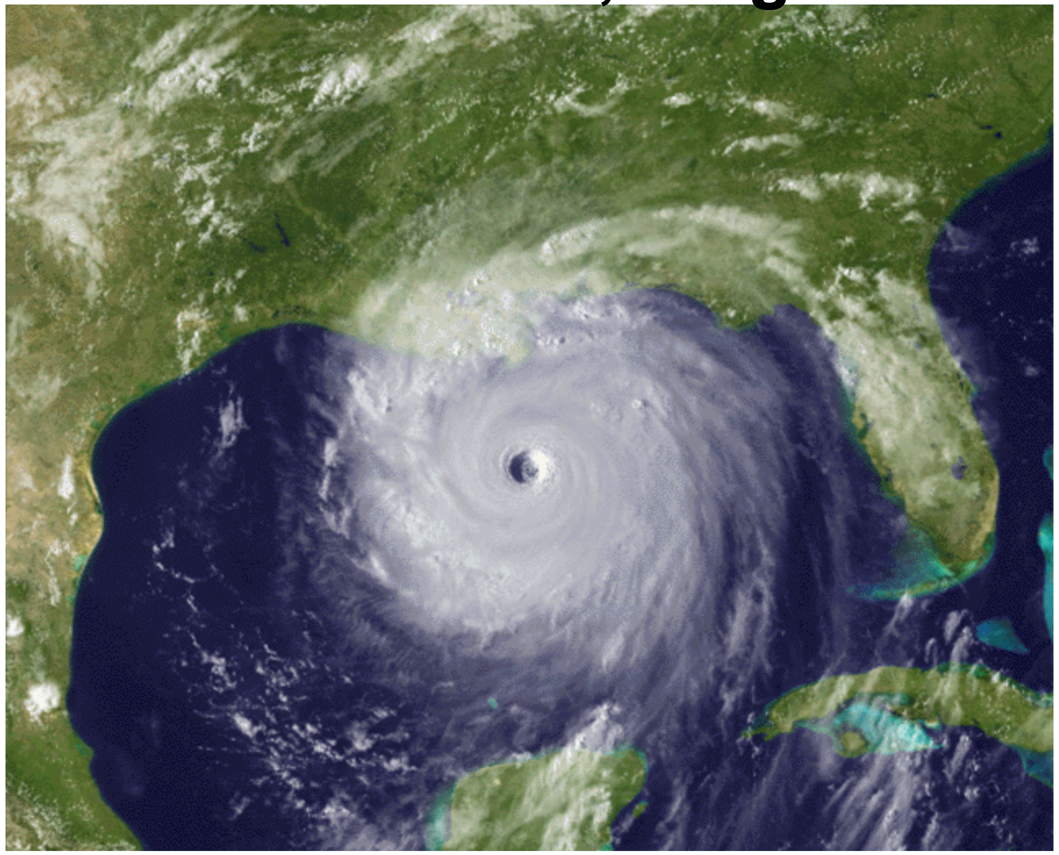
Rym Msadek, NOAA/GFDL, Princeton USA

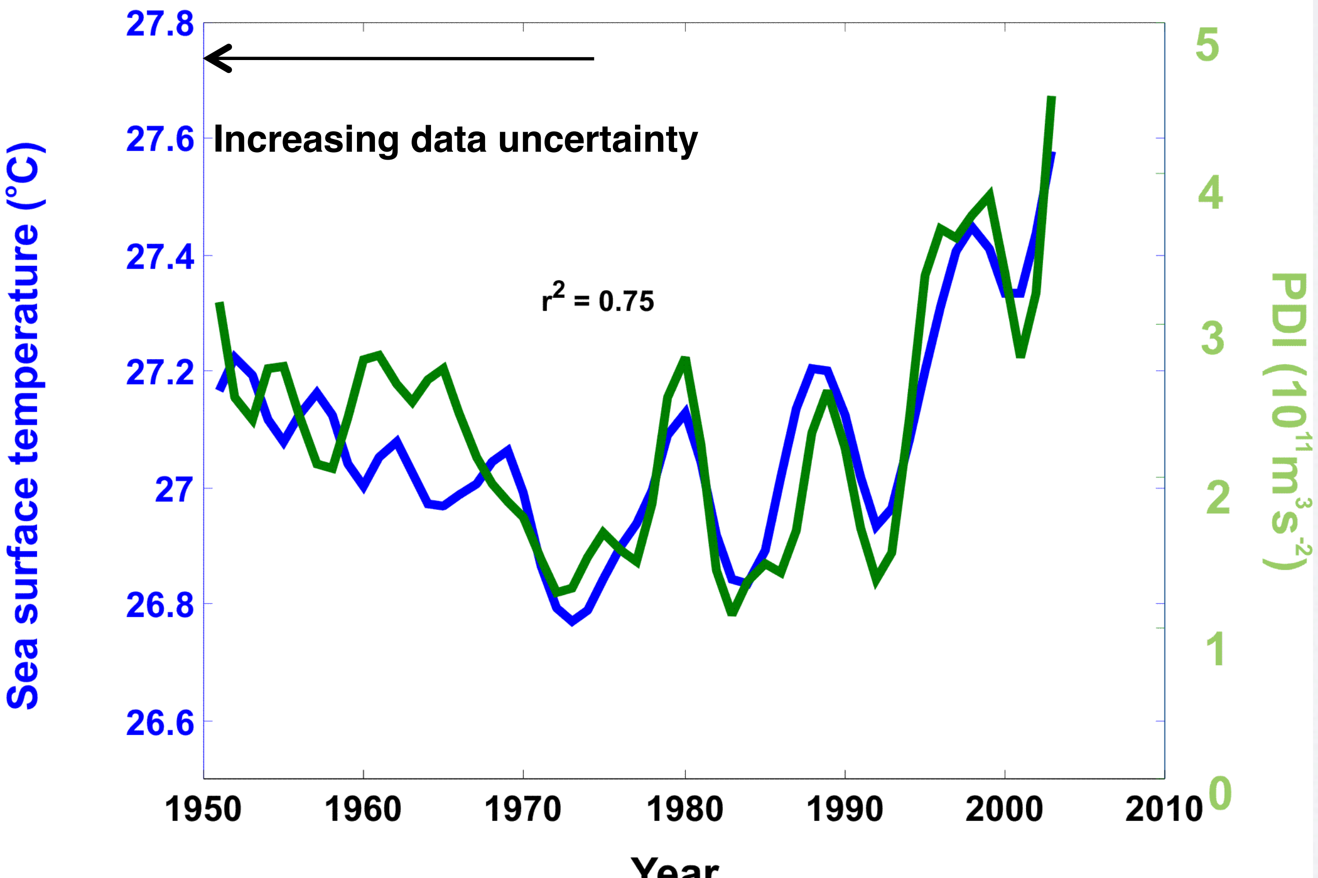
Co-authors: Gabriel A. Vecchi, Thomas R. Knutson

NTU International Science Conference on Climate Change: Multidecadal and Beyond
National Taiwan University, September 17-21, 2012

Motivation

Hurricane Katrina, Aug. 2005





Emanuel (2007)

Human and economic cost of hurricane Katrina (2005) or TC Nargis (2008), growing population in coastal regions
=> detection/attribution of observed changes:need to know how TC activity will response to human-induced climate change and distinguish forced changes from natural variability

-Projections of future hurricane activity
will the projected increase in global temperature lead to more frequent and/or more intense tropical storms and hurricanes?

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

Outline

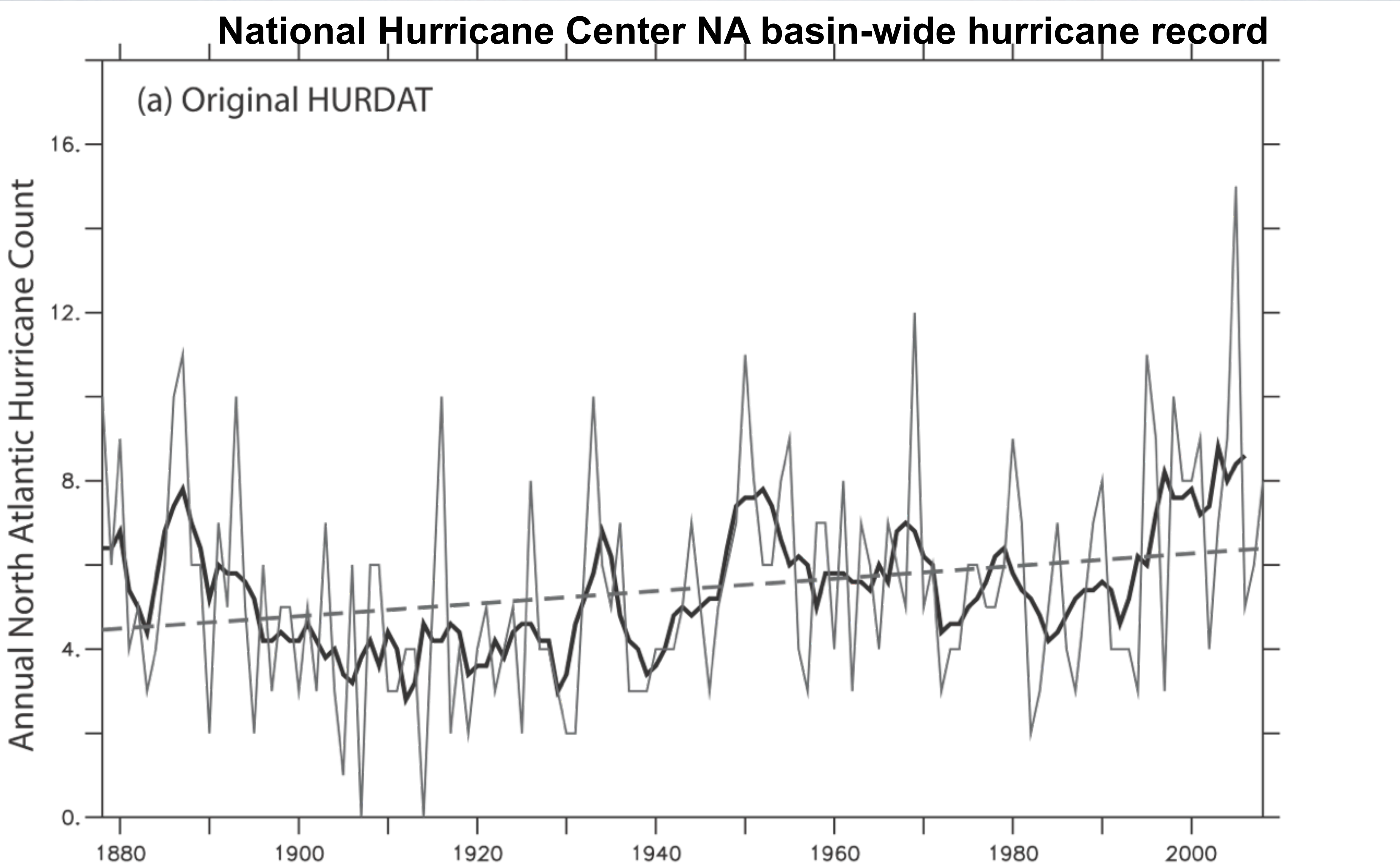
1) Atlantic hurricanes in observations: Is there a detectable anthropogenic influence on hurricane activity?
=> DETECTION and ATTRIBUTION

2) Atlantic hurricanes in models: What are the projected changes of future (21st century) hurricane activity?
=> CENTENNIAL PROJECTIONS

3) What are the main sources of uncertainty in these projections?
=> UNCERTAINTIES

4) Is there any skill in predicting hurricane variability beyond seasonal time scales?
=> DECADAL PREDICTIONS

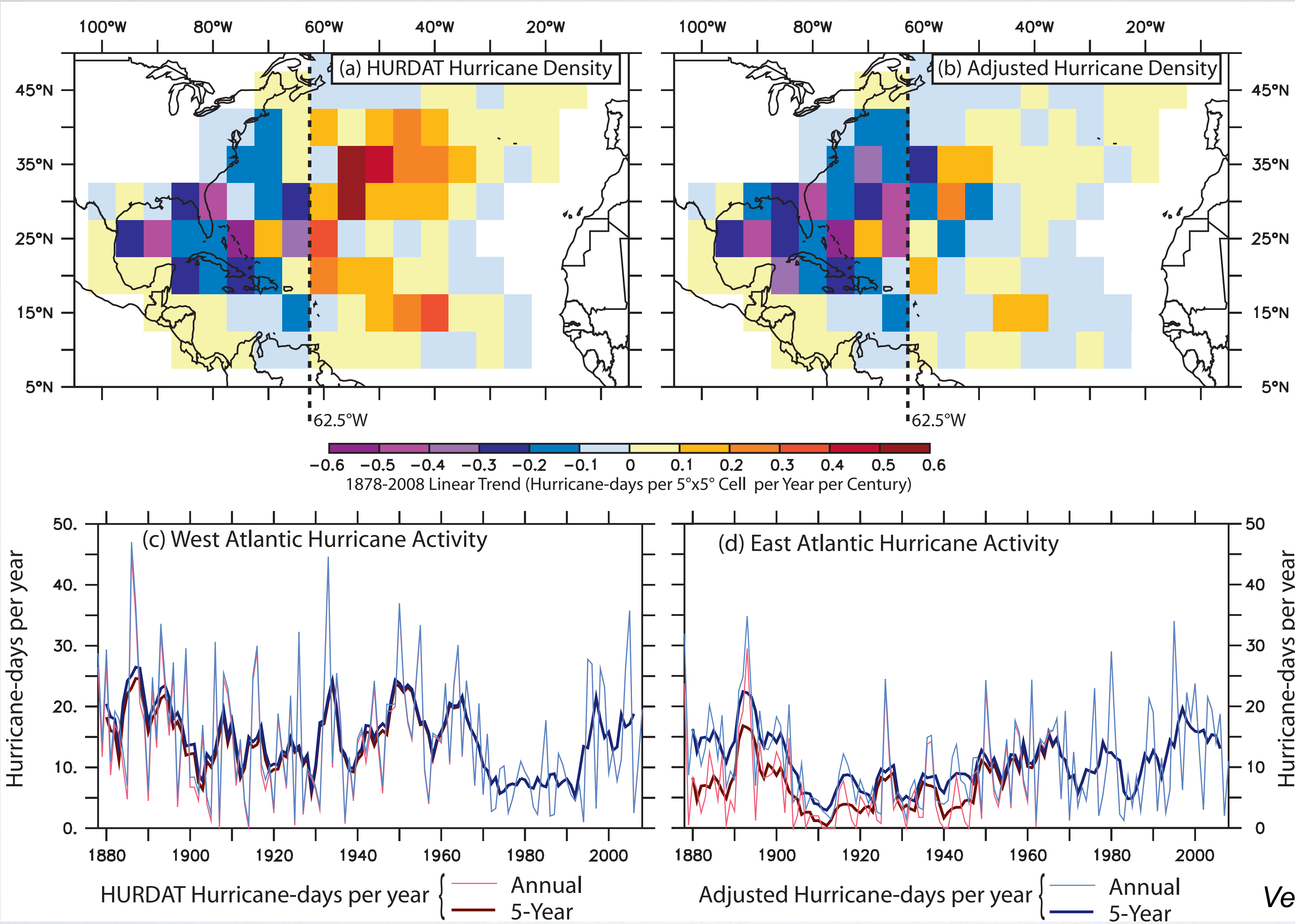
Is there any evidence of hurricane activity change in the observed record?



Vecchi and Knutson (2008, 2011)
Landsea et al. (2010)

The tropical storm counts record shows a secular increase. But imperfect sampling in the pre-satellite era. Can the trend reflect the increased observational capabilities?

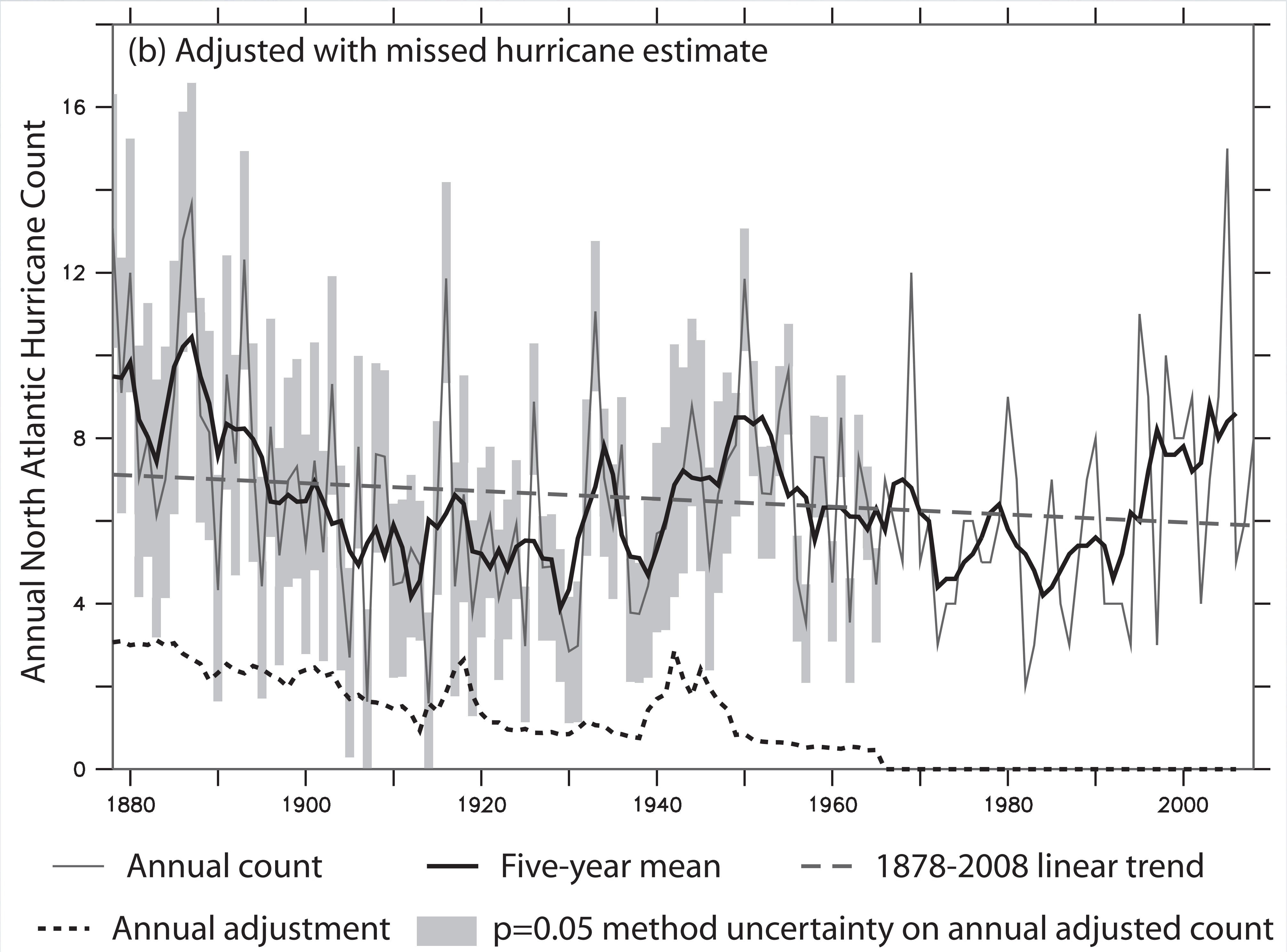
Is there any evidence of hurricane activity change in the observed record?



Vecchi and Knutson (2011)

Only storms far from landfalling regions have increased.
Ship tracks have changed in density and location over time => Long term changes in hurricane activity spatially heterogeneous and data are biased

Is there any evidence of hurricane activity change in the observed record?



Atlantic tropical storm and hurricane counts so not show significant increasing trends after adjustment for estimated missing storms

Vecchi and Knutson (2008, 2011)
Landsea et al. (2010)

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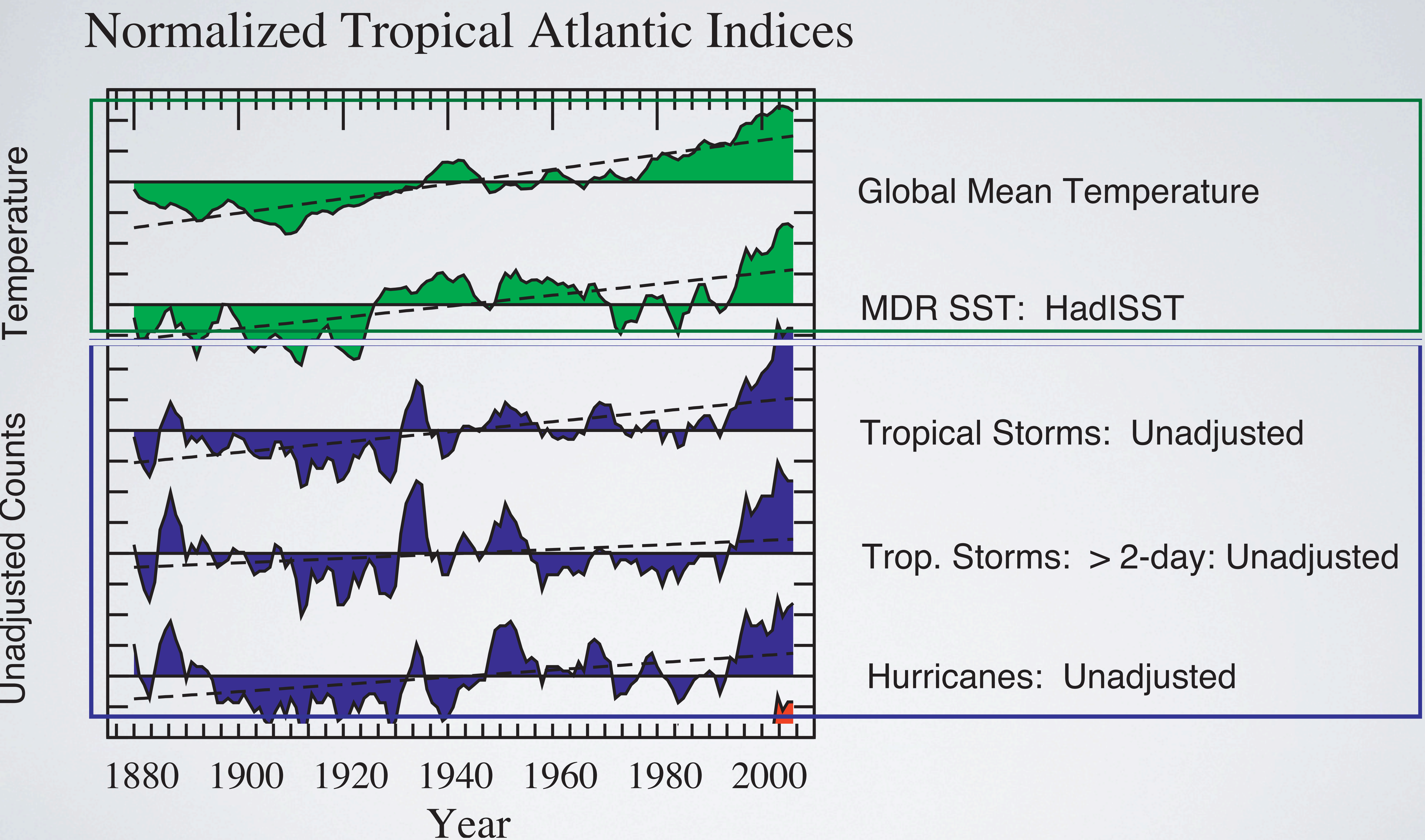

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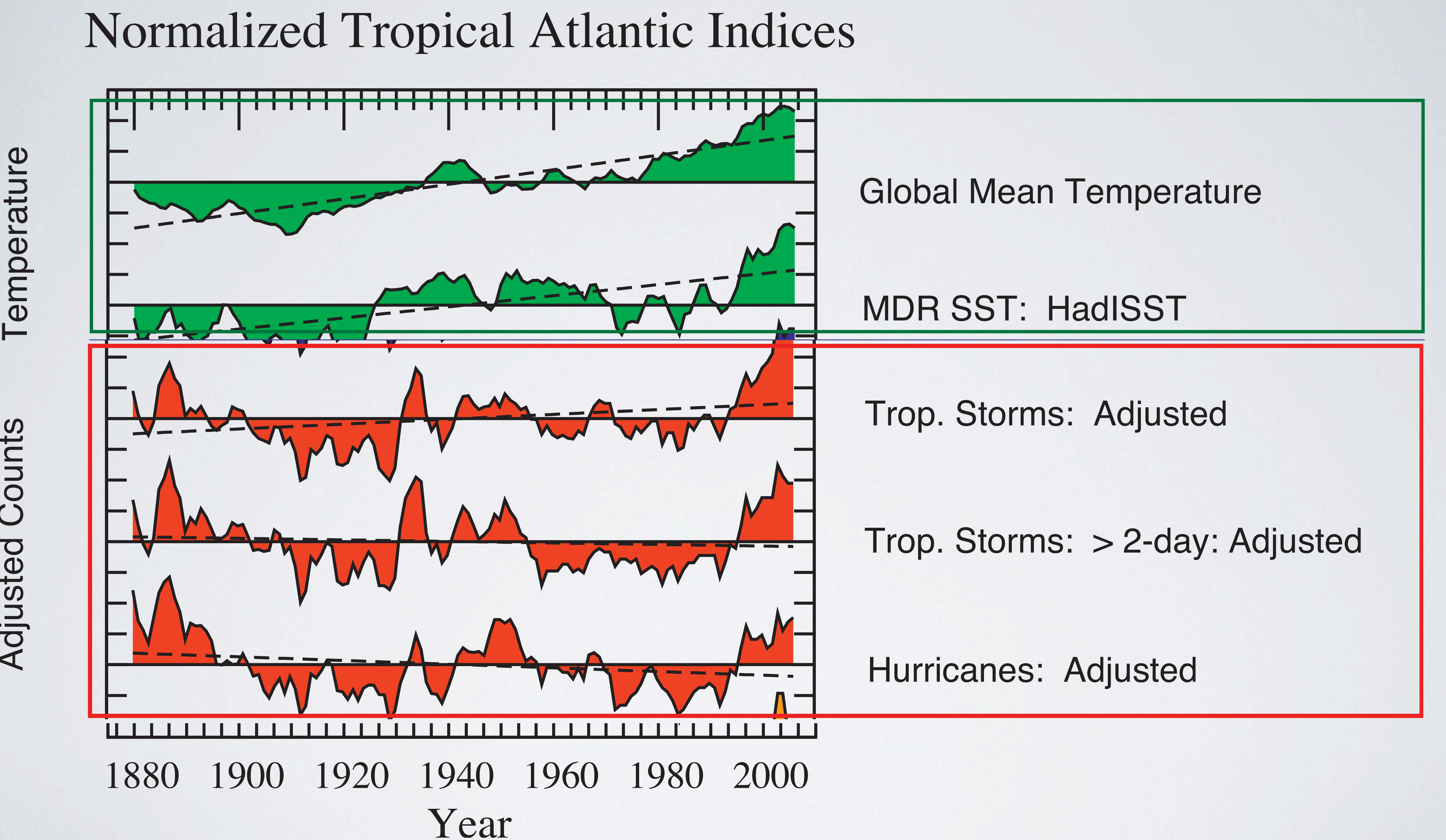

Premature to conclude any changes based on present record
Use of paleo data could clarify the picture

Vecchi and Knutson (2008, 2011)
Landsea et al. (2009)

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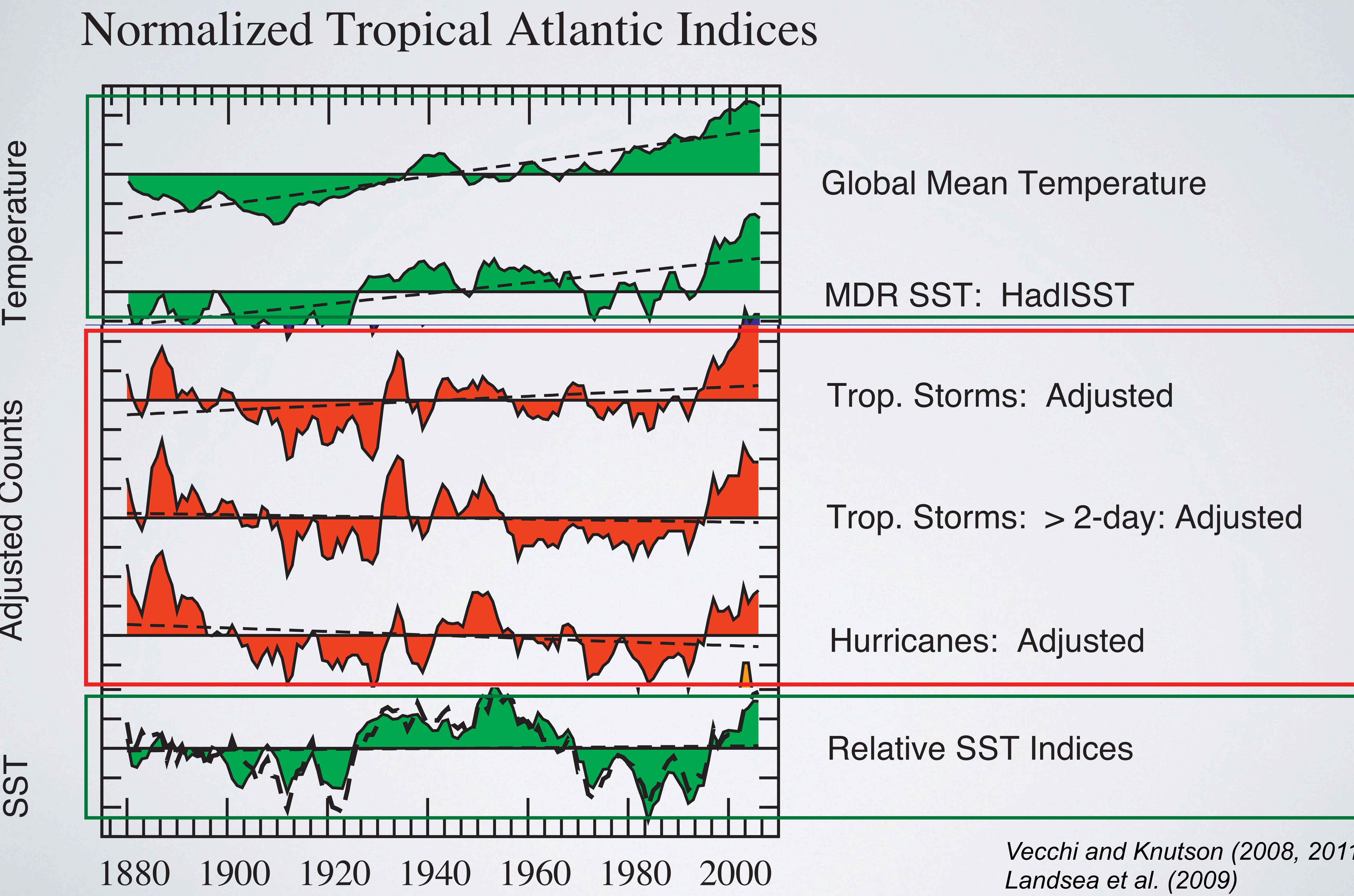
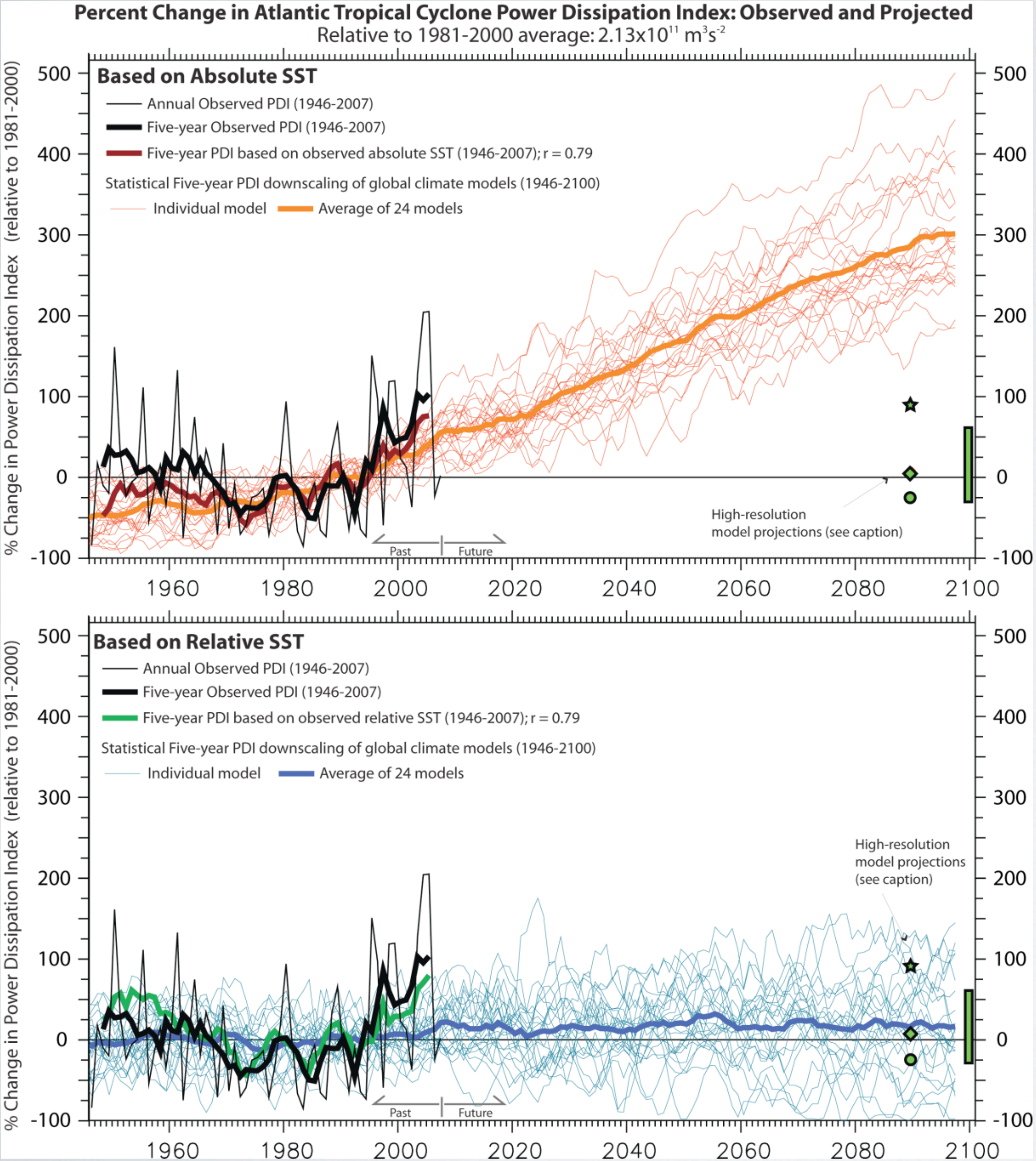


Vecchi and Knutson (2008, 2011)
Landsea et al. (2009)

Hurricane frequency projections for two SST indices



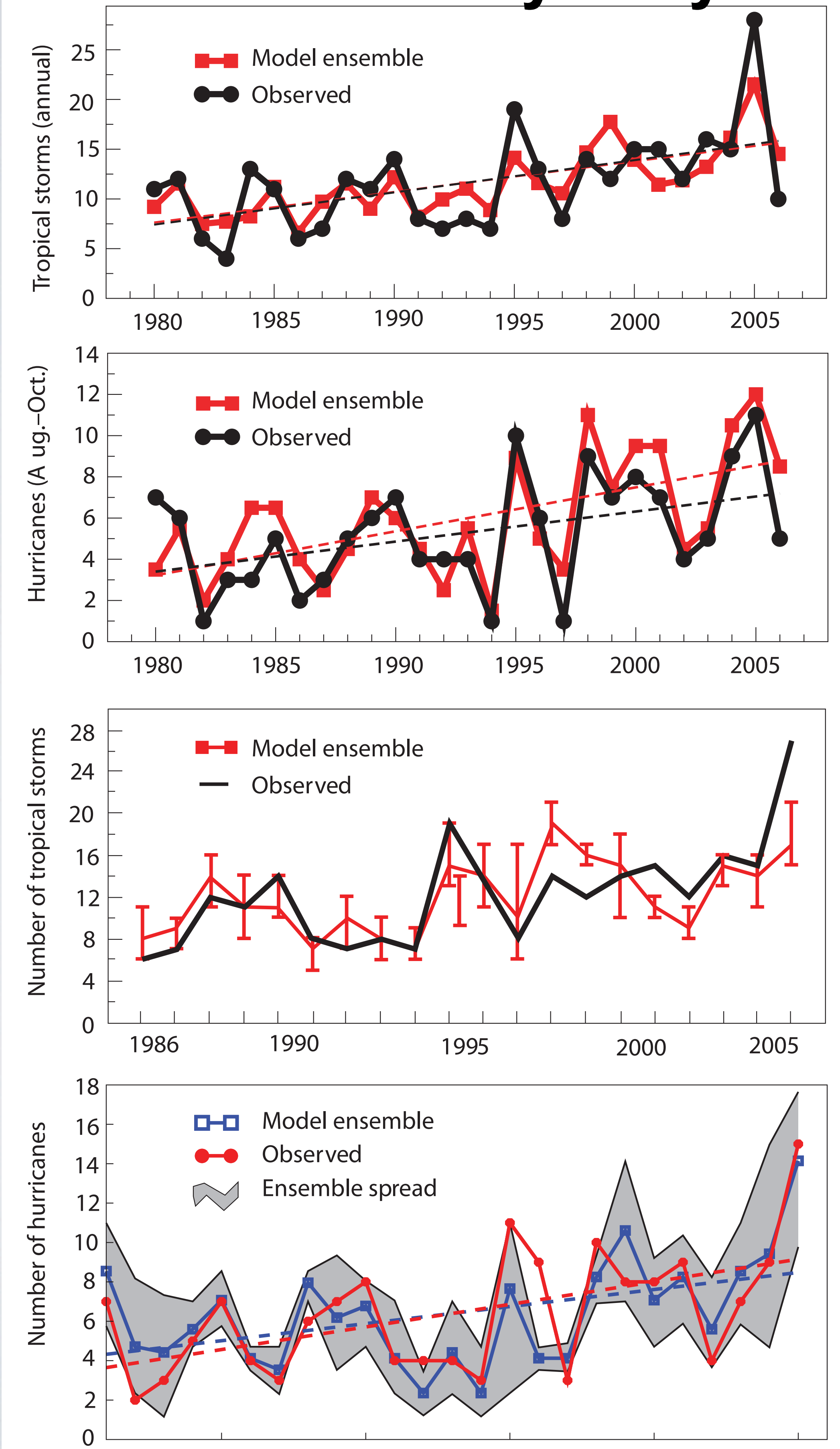
Atlantic hurricane activity (PDI) is correlated with local Atlantic SST (top) and with Atlantic SST relative to tropical mean SST (bottom).

However, these two SST measures behave very differently in greenhouse warming scenarios. Local Atlantic SST warms strongly, but Atlantic SST relative to tropical mean SST does not.

Since PI is largely controlled by departure of local SST change from tropical-mean SST change it is better to use this measure for hurricane projections

Vecchi and Sodden (2007), Vecchi et al. (2008), Swanson (2008)

Significant improvement in simulating past variability of Atlantic hurricane activity in dynamical models



Statistical-dynamical downscaling model
Uses NCEP reanalysis
(Emanuel et al. 2008)

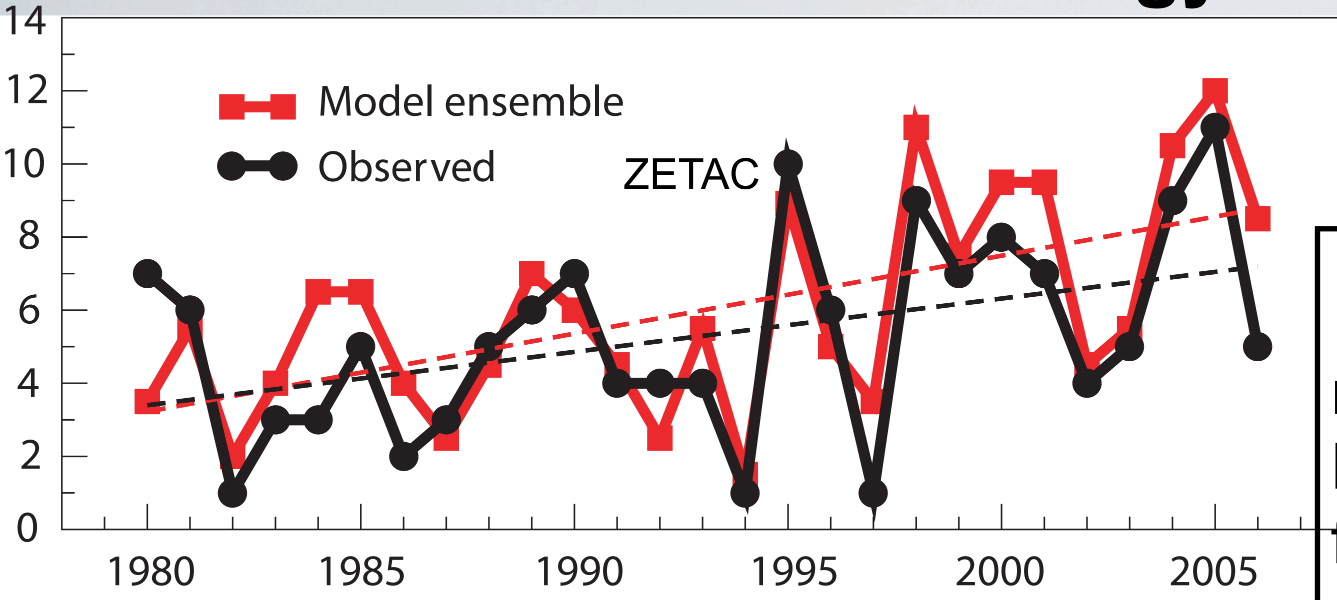
18km regional downscaling model
Uses NCEP reanalysis
(Knutson et al. 2008)

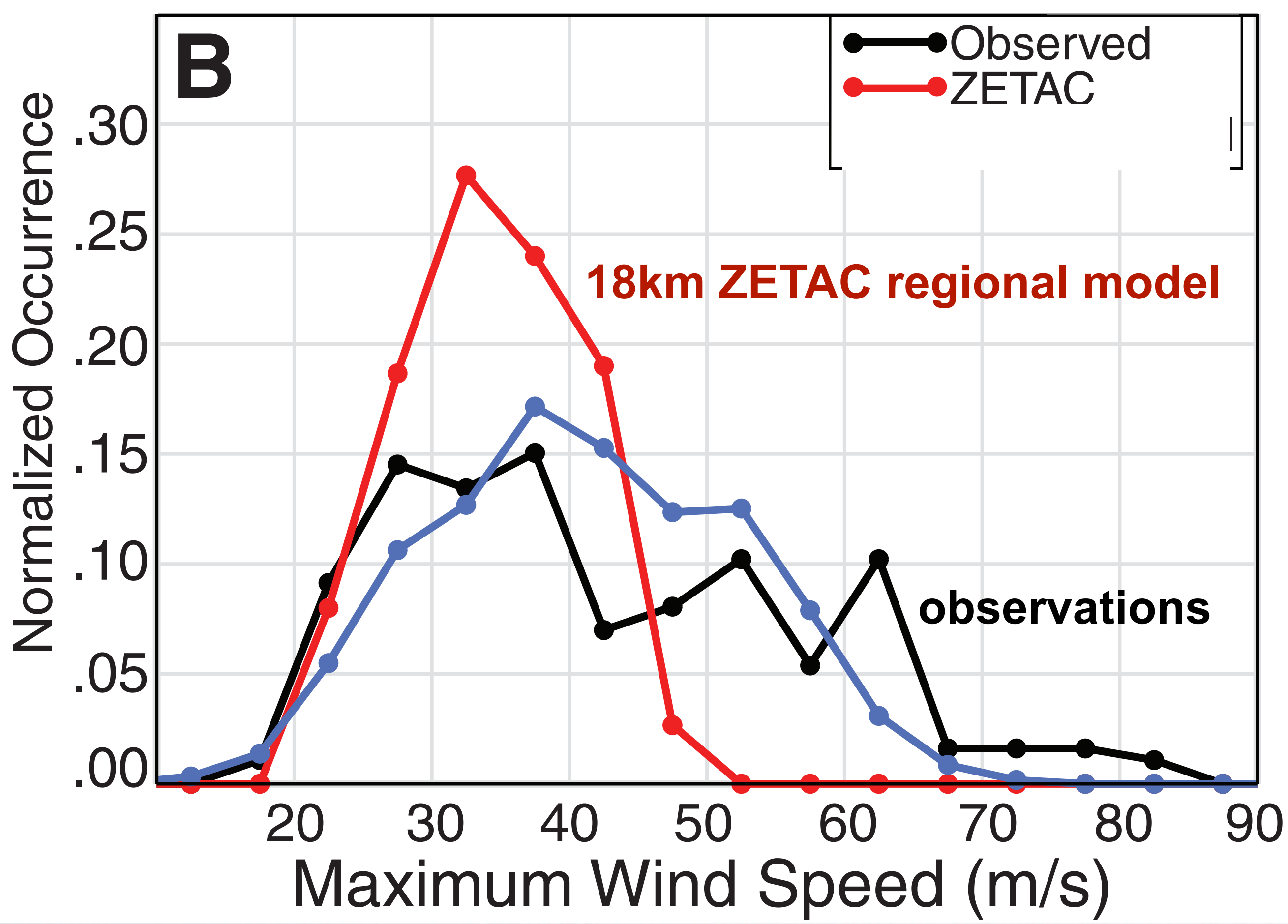
100km SST-forced AGCM
(LaRow et al. 2008)

50km SST-forced AGCM
Uses observed SST, sea-ice, and radiative forcing
(Zhao et al. 2009)

Knutson et al. (2010)

Projections of future hurricane activity: control climatology of intensities





ZETAC model *(Zhao et al. 2009)*

1/6 degree (18 km) grid, 45 vertical levels
non hydrostatic, resolved convection
Lin Microphysics, Mellor-Yamada BL formulation,
Atl domain (105W-10E; 10S-45N)
Boundary forcing: Observed SST + NCEP 4X daily reanalyses
Large scale (wave 0-2) interior spectral nudging of all variables toward NCEP with a timescale of 36 hrs,
interactive land model,
time step 30s
CPU requirements: about 300 CPU hr/day or 750,000 CPU hrs for 27 three-month seasons.
Typically Aug 1-Oct 31 simulations (+ 3-day spin-up) *Zhao et al. (2009, 2010), Bender et al. (2010)*

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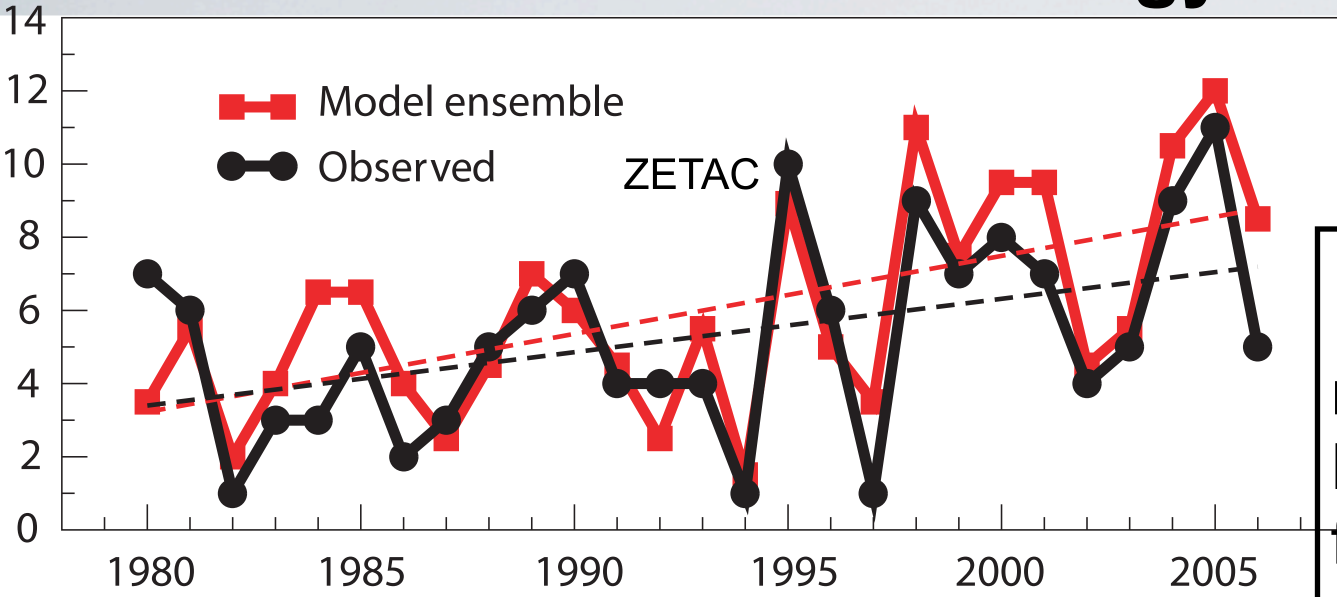

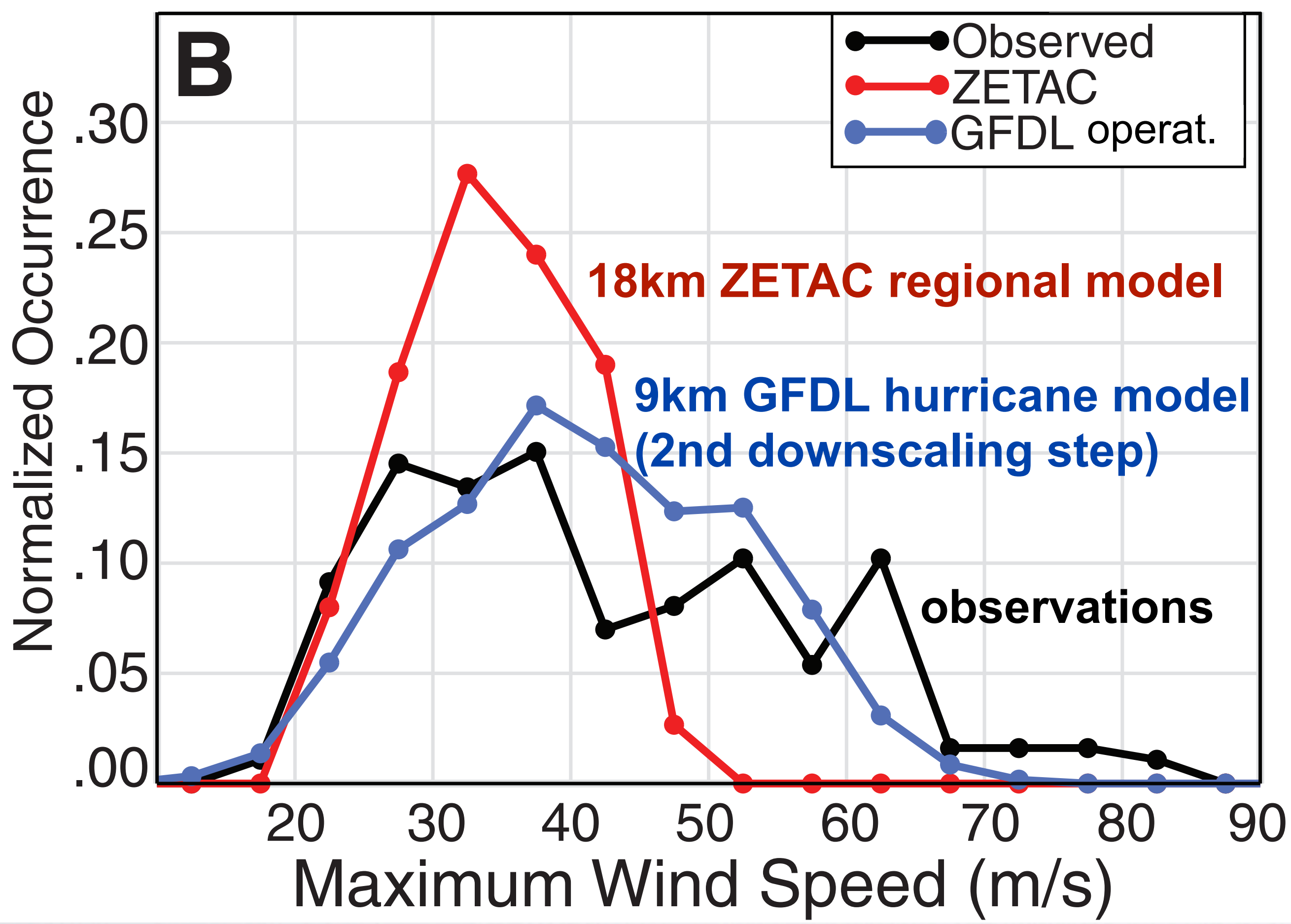

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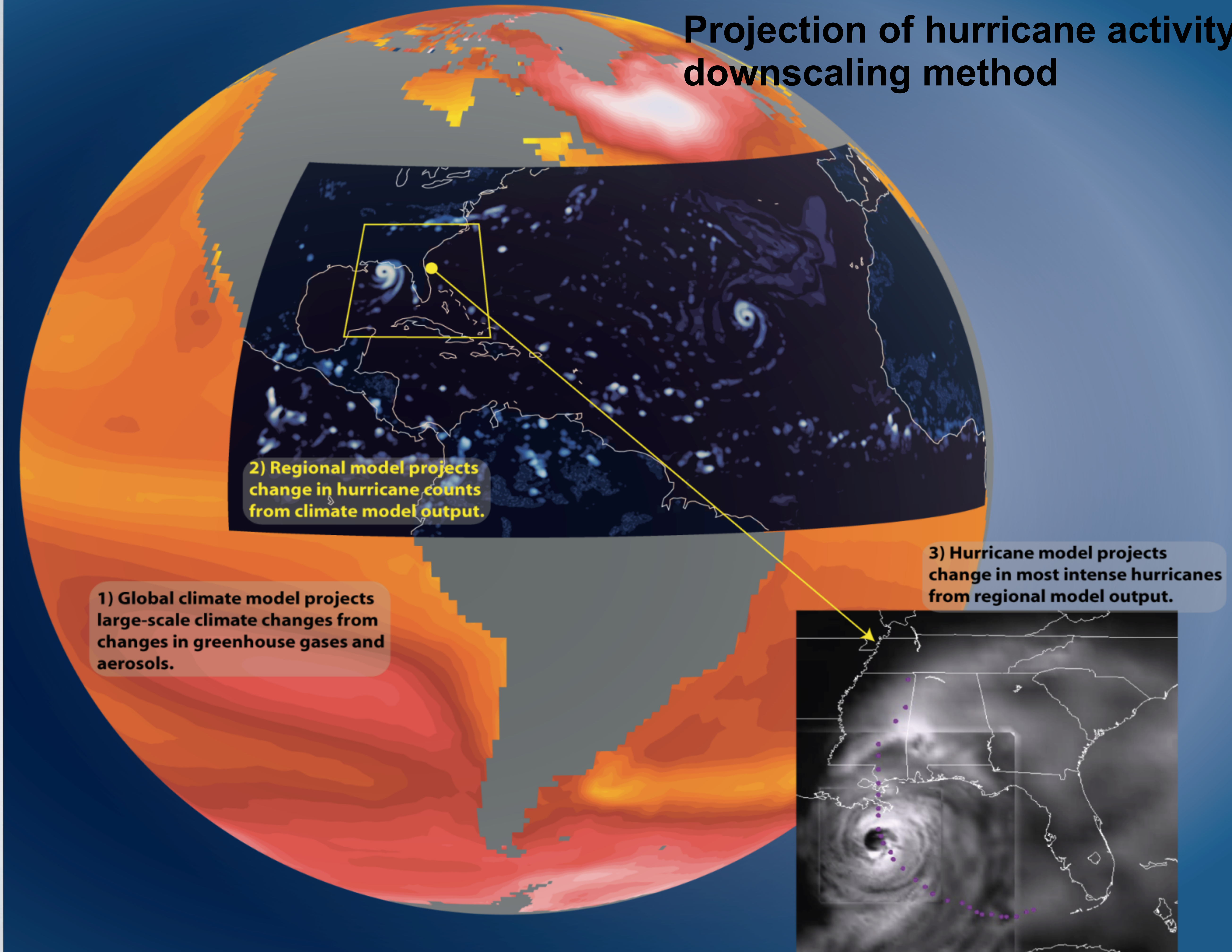
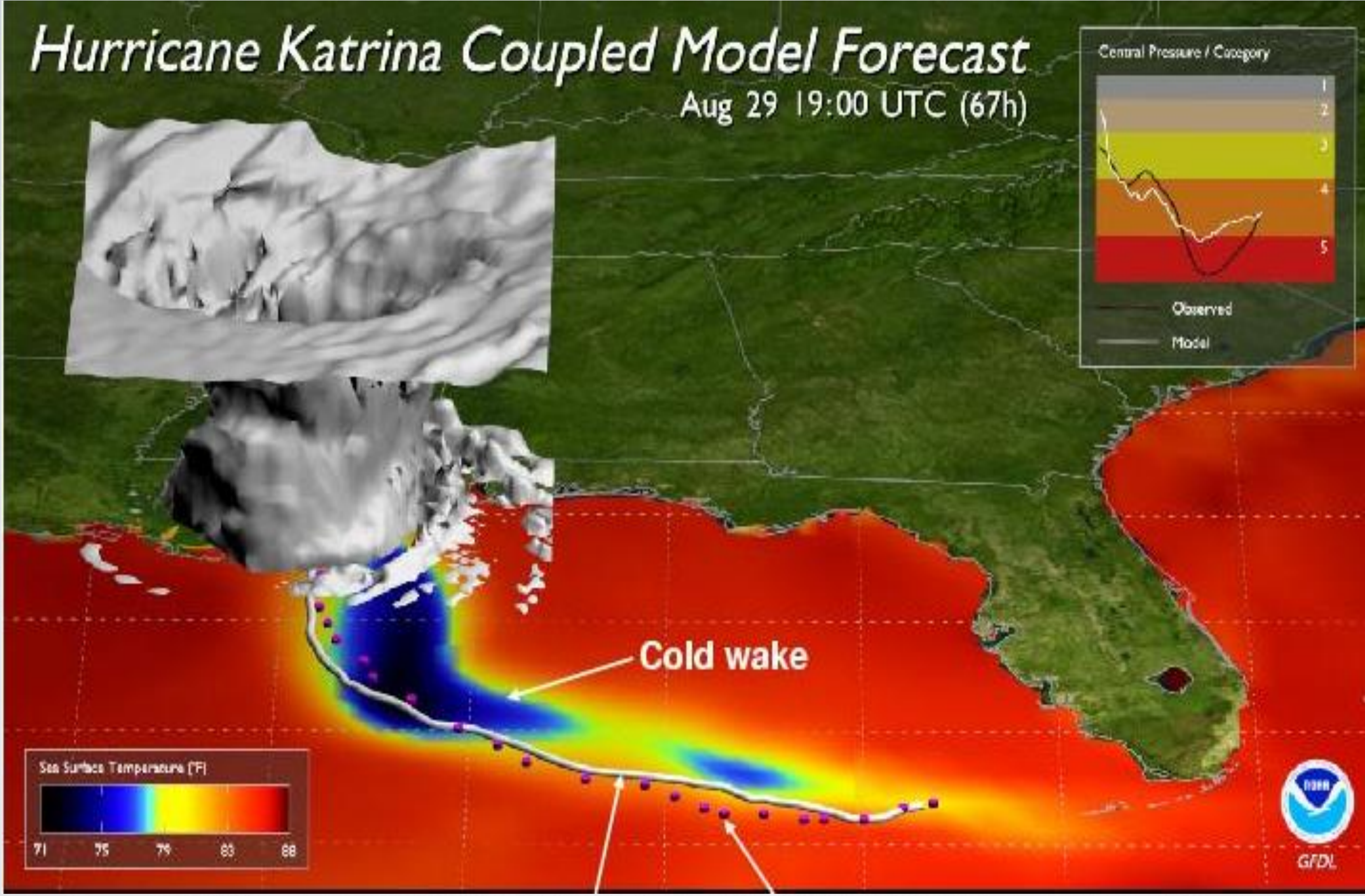
Since the 18-km grid ZETAC model fails to simulate wind speeds greater than ~47 m/s, a second downscaling step is necessary. Use GFDL Hurricane Prediction System (operational at NCEP and Navy) to re-simulate all individual storms from ZETAC (control and warm climates). So far only done for the Atlantic

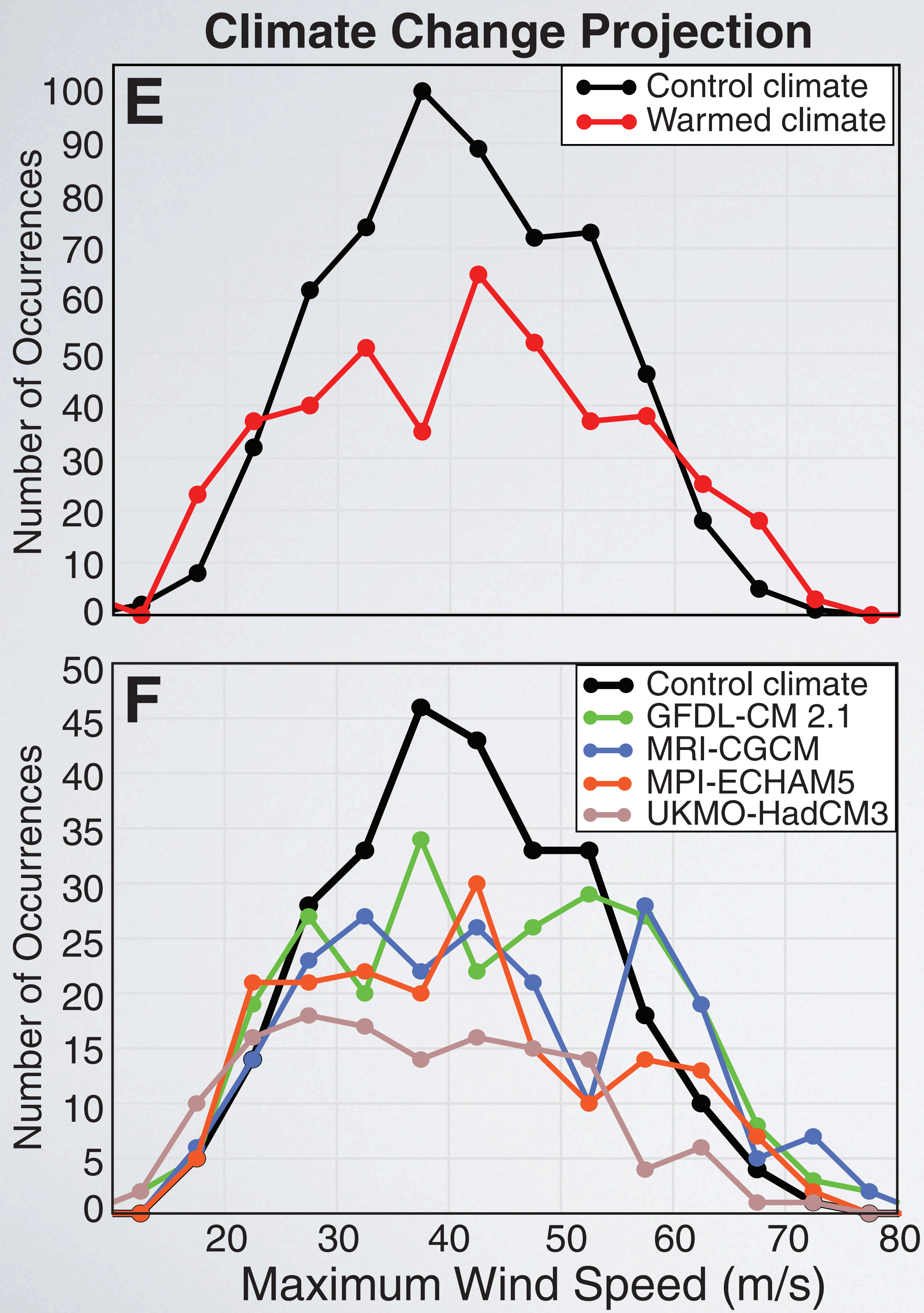
Projection of hurricane activity downscaling method





Nested moveable mesh follows motion of tropical cyclone with grid spacing 9km. => Each TC from ZETAC downscaled in the hurricane models. 1) identify time max intensity in ZETAC then back up 3 days from that to begin 5-day hurricane model integration

Projections of future hurricane activity: CMIP3 results



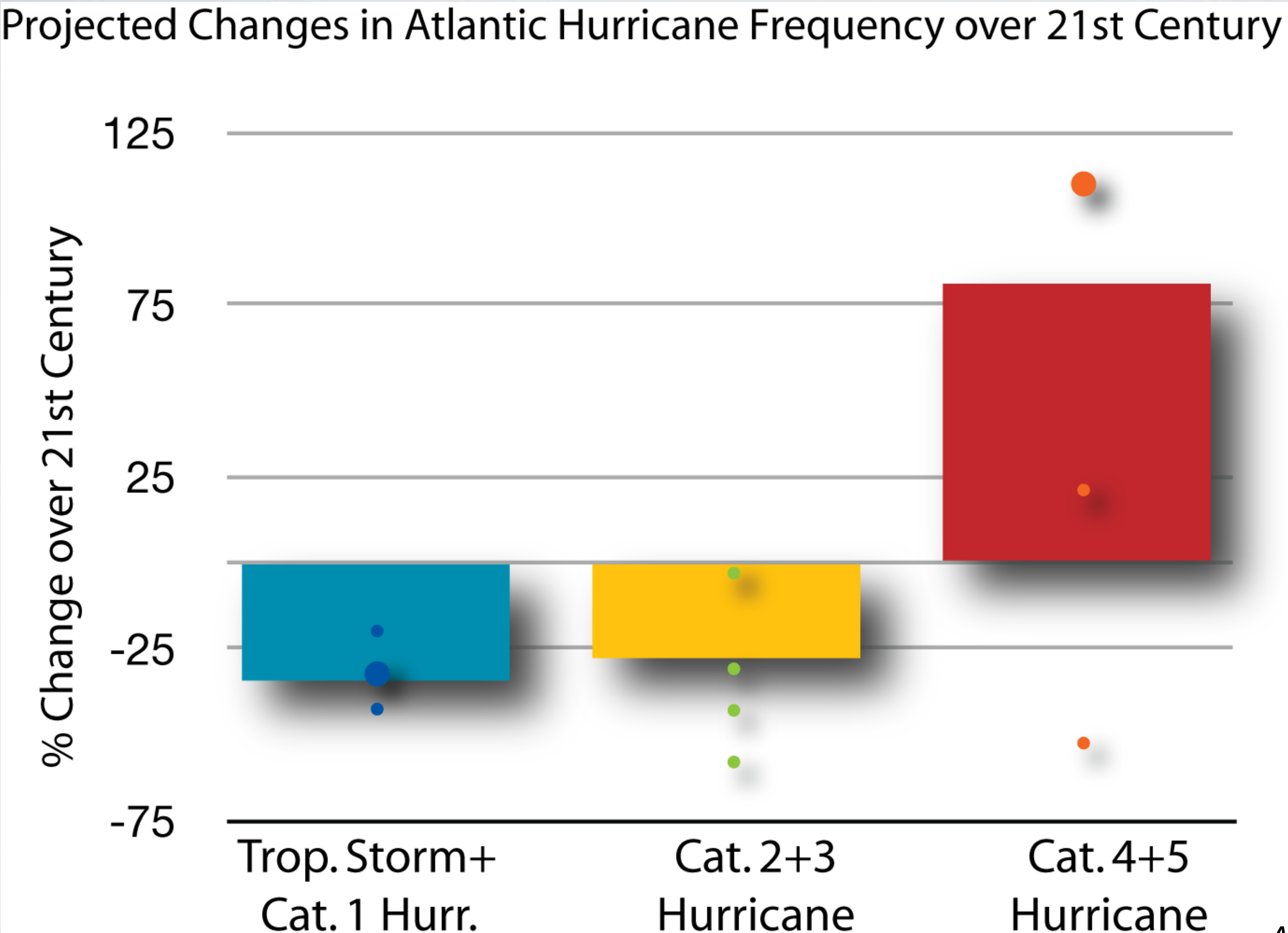
Overall decrease of the number of tropical storms and hurricanes in a warmer climate

Found for the ensemble mean and the individual climate models

However, the rarer most intense simulated hurricanes occur up to 3 times as often in the warmer climate and increase for 3 of 4 individual models

Bender et al. (2010)

Projections of future hurricane activity: CMIP3 results



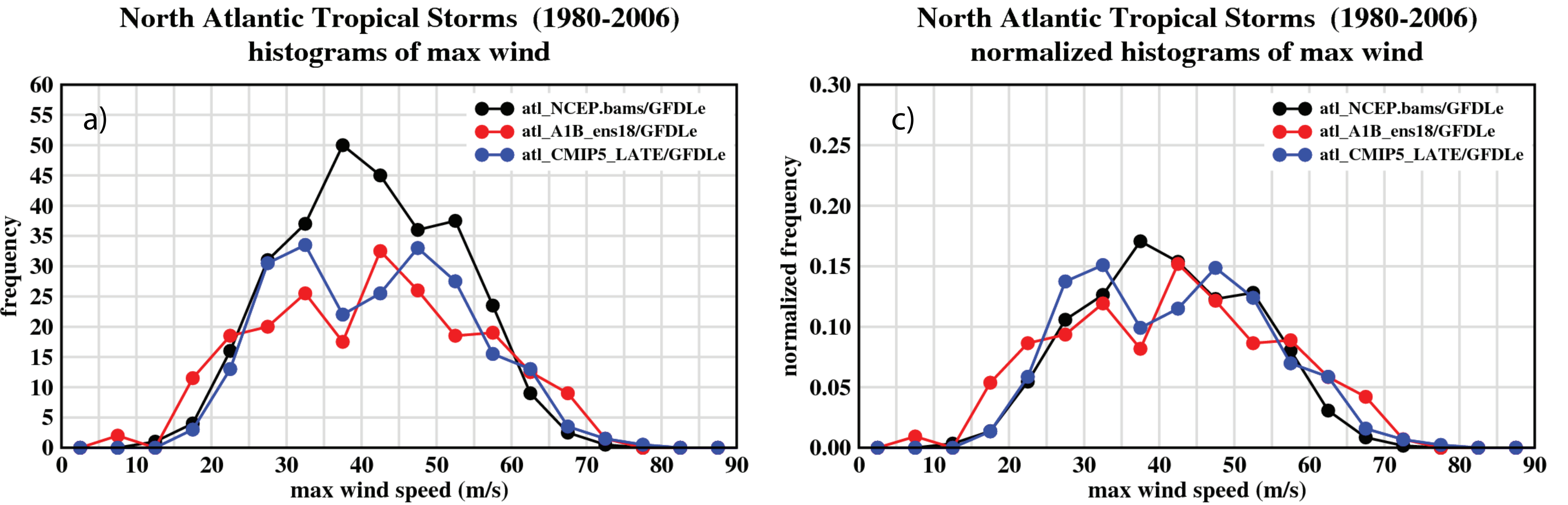
Cat 4+5 frequency: 81% increase, or 10% per decade

Estimated net impact of these changes on damage potential: +28%

Adapted from Bender et al. (2010)

Colored bars show changes for the18 model CMIP3 ensemble (27 seasons); dots show range of changes across 4 individual CMIP models (13 seasons).

Projections of future hurricane activity: adding CMIP5 results



CMIP5 vs CMIP3 robust results in response to anthropogenic warming

-Fewer Atl tropical storms (-27% in CMIP3, -23% in CMIP5), fewer hurricanes (-17% in CMIP3;-19% in CMIP5)

-Increased frequency of most intense hurricanes (cat 4-5), +39% in CMIP5 (not statistically significant), +86% in CMIP3 (in 3/10 ind. models)

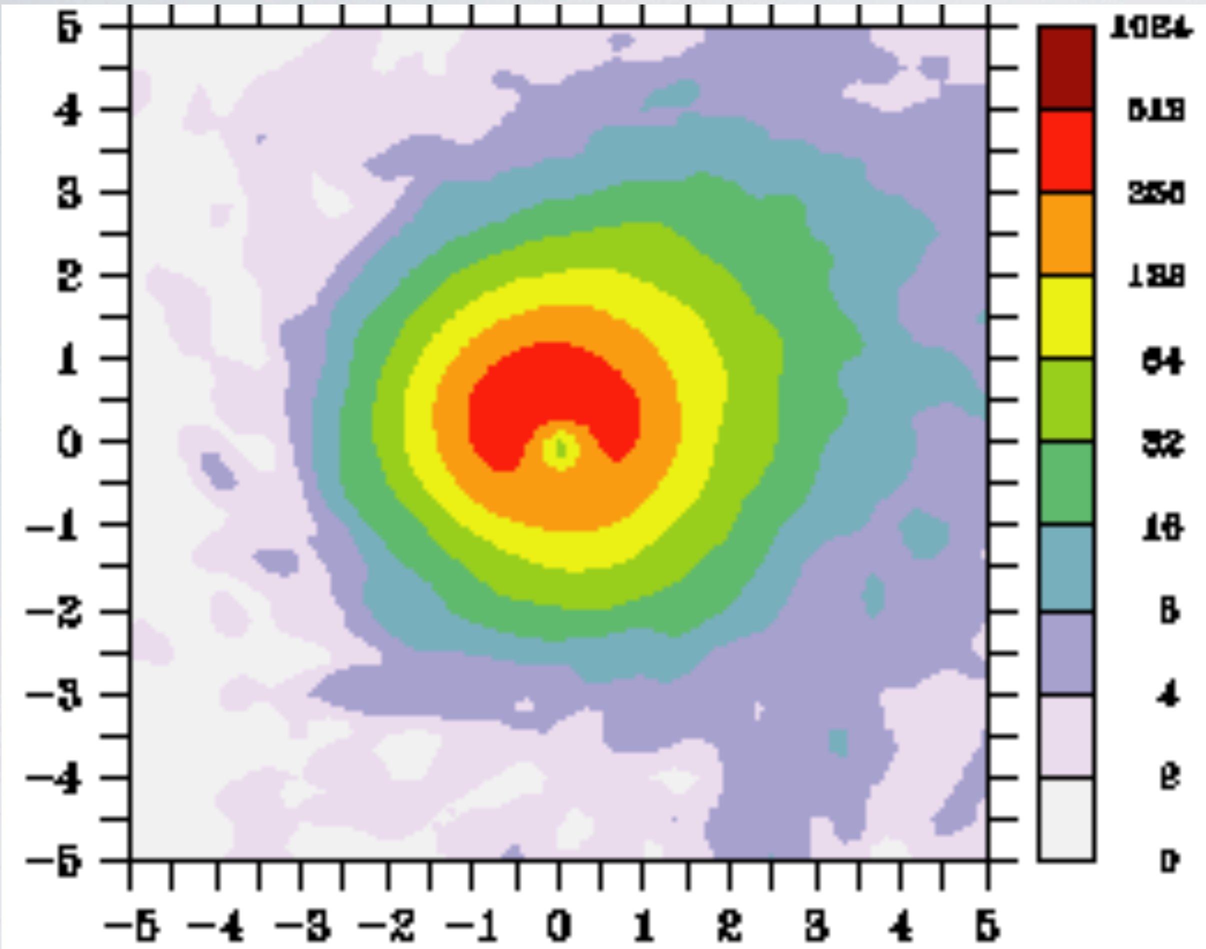
-Projected change of mean intensity positive in both CMIP3 and CMIP5 (not shown)
-No landfall information

Knutson et al. (2012, submitted)

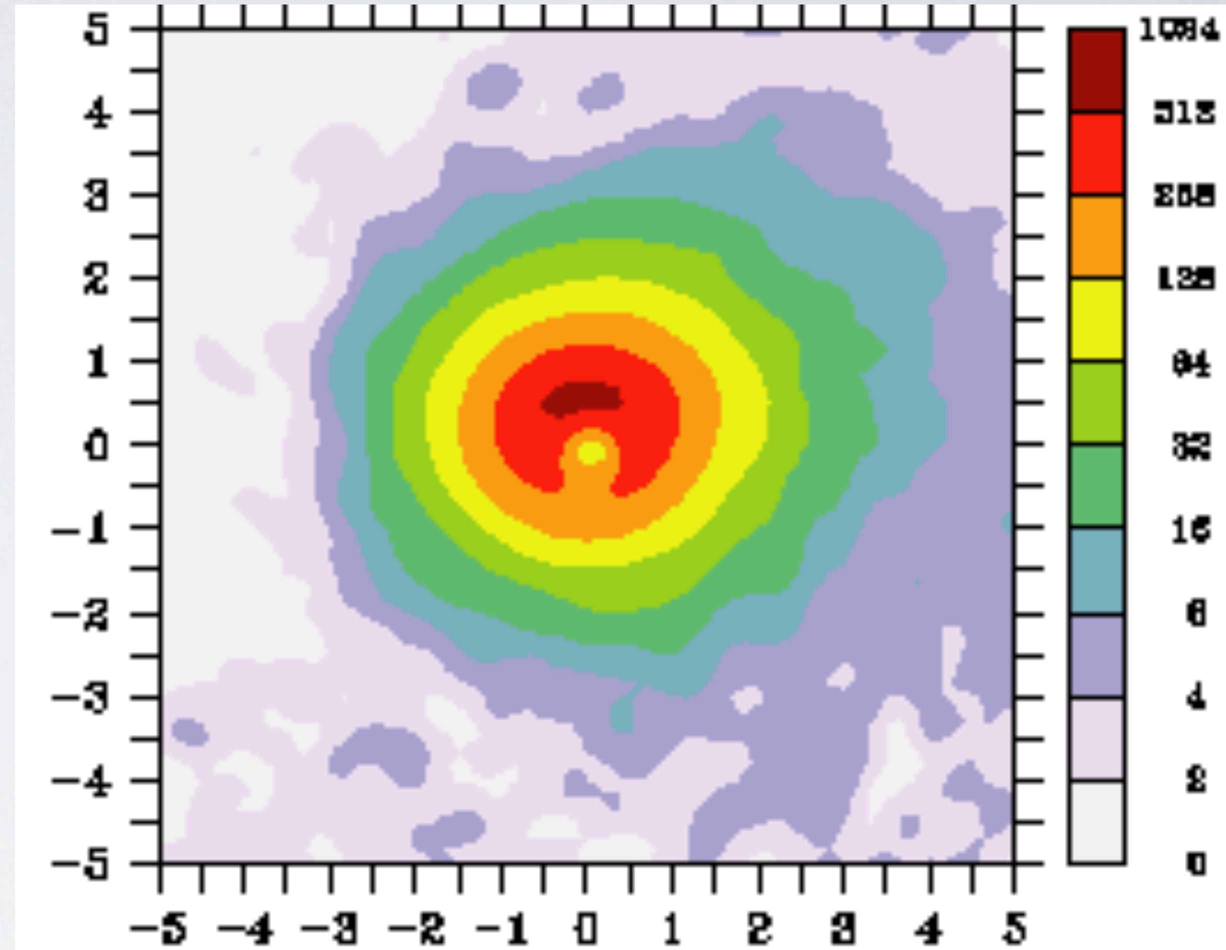
Projections of future hurricane activity: increased rainfall associated with hurricanes

Rainfall rates (ASO, mm/day)

Control climate



Warmer climate



Knutson et al. (2008, Nature Geo., 2012 sub.)

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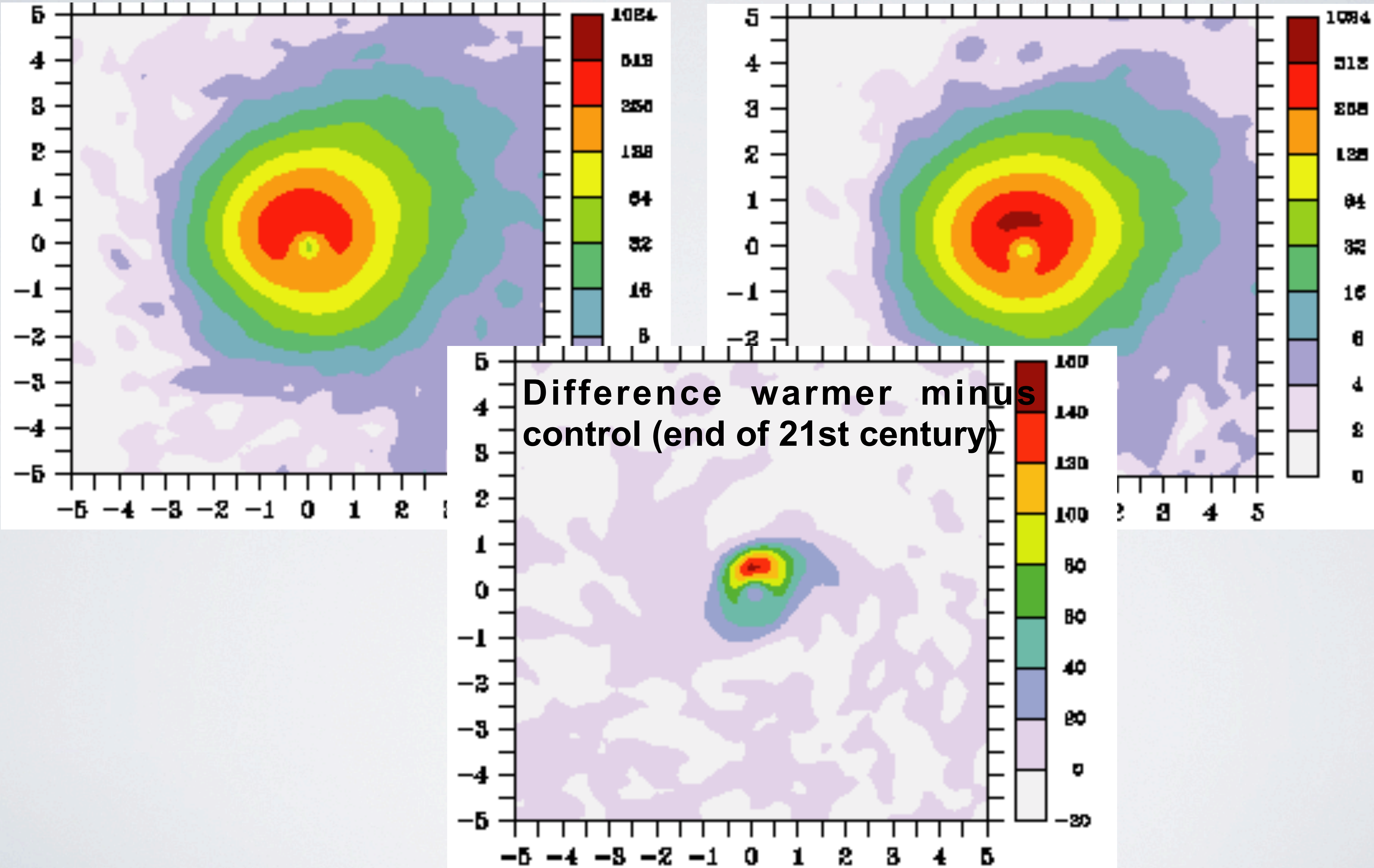
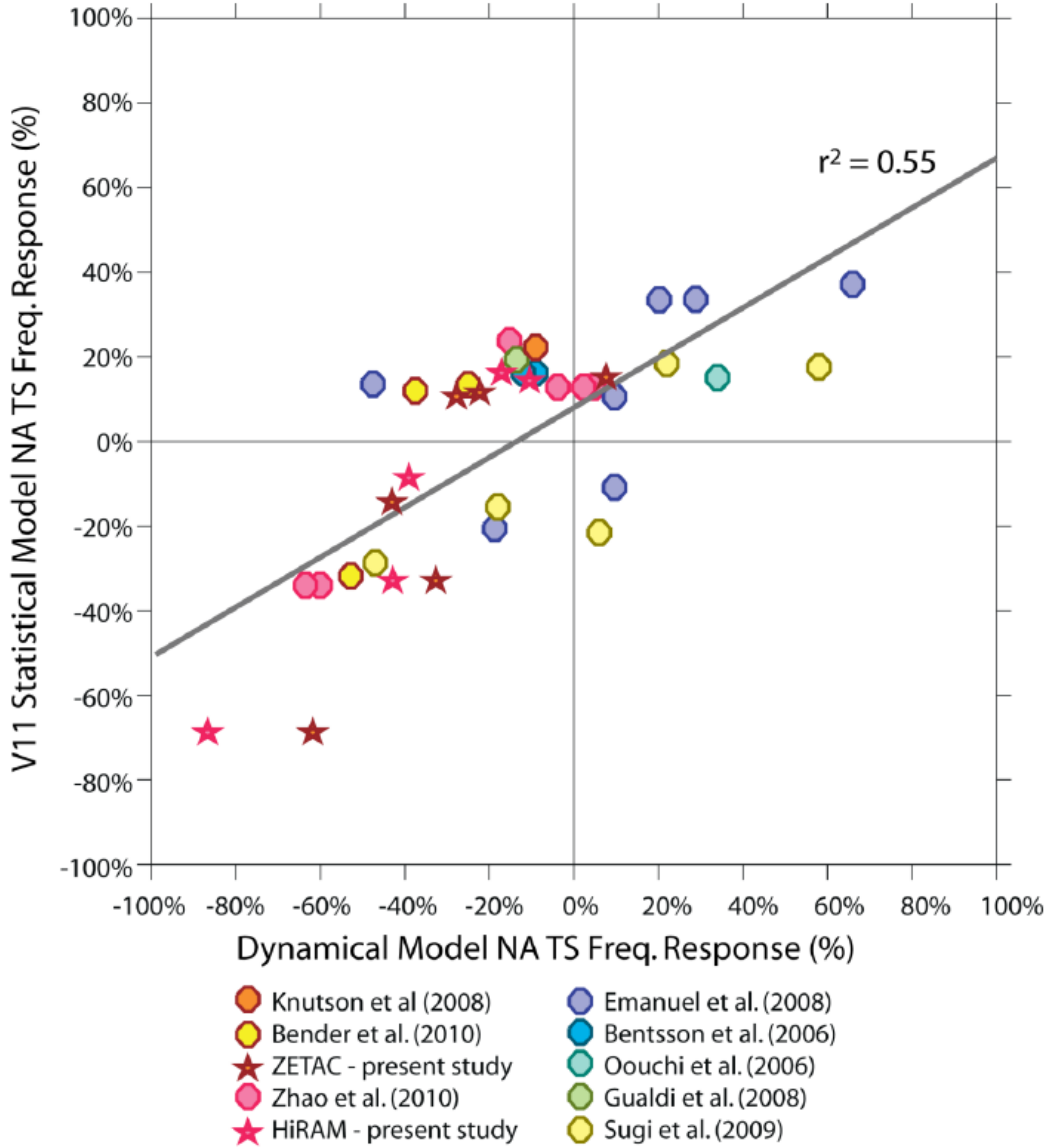


Increase in storm-related rainfall rate within 100km of of the storm centre

Knutson et al. (2008, Nature Geo., 2012 sub.)

How consistent are these projections among models?



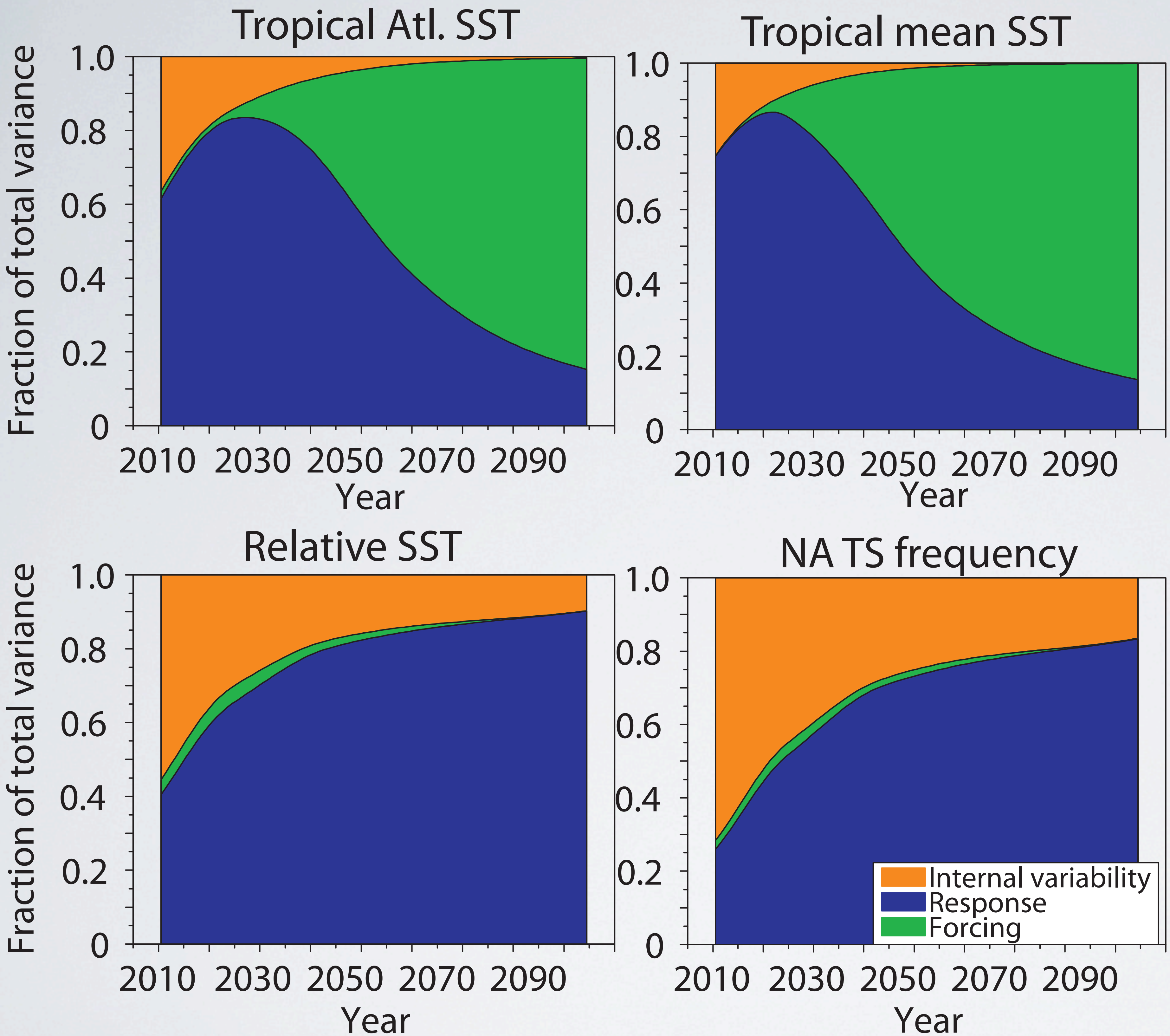
Relative SST describes the dynamical model projections fairly well in the Atlantic.

The projected range is wide (-70% to +40%)

SSTs not well constrained in climate models...

Villarini and Vecchi (2012), Knutson et al. (2012)

Assessing the uncertainty of these projections



Even though Atlantic SST is a predictor, partitioning for NA Tropical Storms distinct.

Short term: Variability

Medium term: Response & Variability

Long term: Response

Sources of uncertainty

Variability: Chaotic variations independent of radiative forcing changes

Response: How climate will respond to changing GHGs

Forcing: How GHGs will change in the future

Villarini and Vecchi (2012) after Hawkins and Sutton (2009)

Decadal predictions: a initial/boundary value problem

Decadal climate variations arise from

-Internal variability of the climate system (e.g. slow changes in the ocean)

-Response of the climate system to external forcing changes (greenhouse gases, aerosols, etc.)

Observing systems

Assimilation systems

Models

Changing radiative forcing

Weather and seasonal predictions (initial value problem)

Centennial projections (boundary value problem)

Decadal predictions

Unified system for predictions and projections from seasonal to decadal to centennial time scales

GFDL decadal prediction system/Experimental design

Most climate projections focused solely on the response to radiative forcing changes.
Key question: Can we produce better predictions if we use information describing the initial state of the climate? Part of CMIP5 and IPCC AR5

Model:
Currently use of CM2.1 model (2ºatm, 1ºocean, Delworth et al. 2006)

Initial conditions:
Ensemble Coupled Data Assimilation (ECDA) reanalysis (Zhang et al. 2007)
. Atmosphere NCEP reanalysis (T,u,v,ps)
.Ocean XBT,CTD, satellites, Argo
.Radiative forcing GHG, solar, aerosols,volcanoes

Initialized runs
10 members ensemble, starting every year from 1960-2012, run for 10yrs (total of more than 5000 model years). Use observed estimates of radiative forcings 1960-2005, RCP4.5 thereafter

Uninitialized runs:
10 members ensemble, from 1861-2040. Use observed estimates of radiative forcings 1960-2005, RCP4.5 thereafter

Model outputs available at
http://nomads.gfdl.noaa.gov:8080/DataPortal/cmip5.jsp

Rosati et al. (2012), Yang et al. (2012)

Statistical model for hurricane predictions

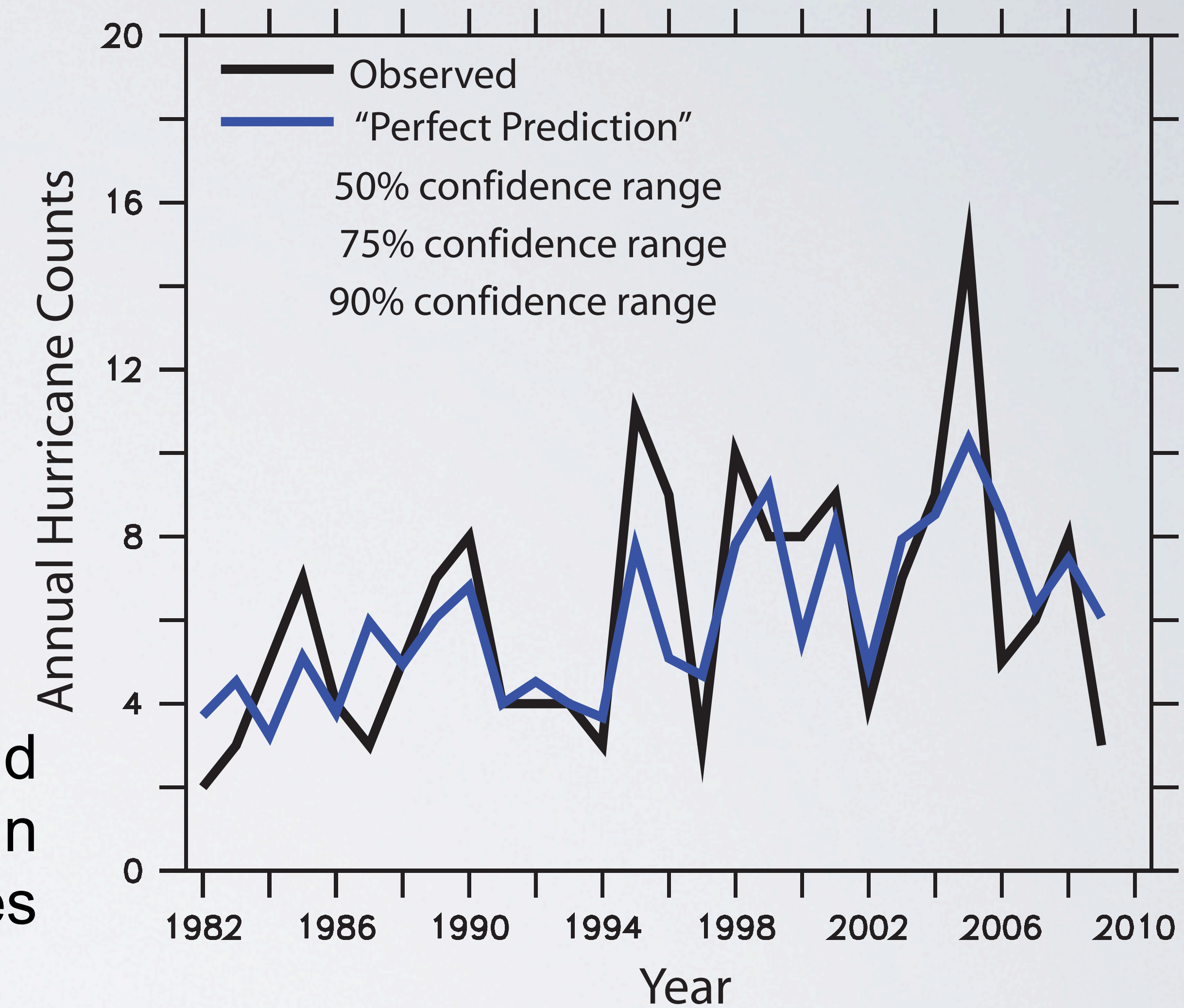
Statistical model trained on a suite of of HIRAM-C180 experiments exploring different possible climates

Use two covariates as predictors:
-Tropical Atlantic SST MDR (positive)
-Tropical mean SST (negative)
Poisson regression model trained on HIRAM-C180 gives the rate of occurrence:

$$\lambda = e^{a + bSST_{MDR} - cSST_{TROP}}$$

$$\lambda = e^{1.707 + 1.388 SST_{MDR} - 1.521 SST_{TROP}}$$

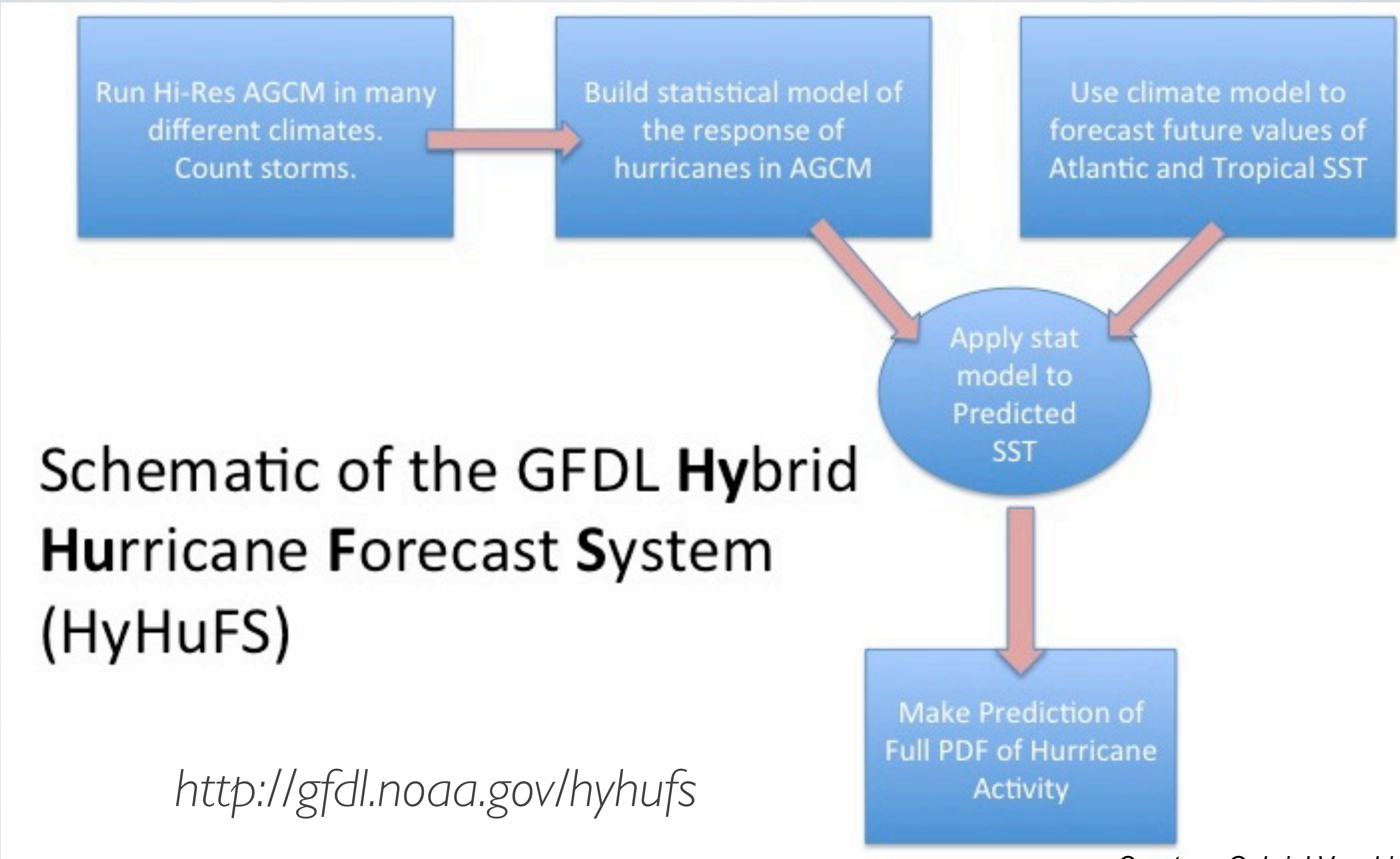
Fitted model able to reproduce observations and high-resolution dynamical mode. Provides an inexpensive understanding on what control hurricanes



Vecchi et al. (2011)

Statistical model for hurricane predictions

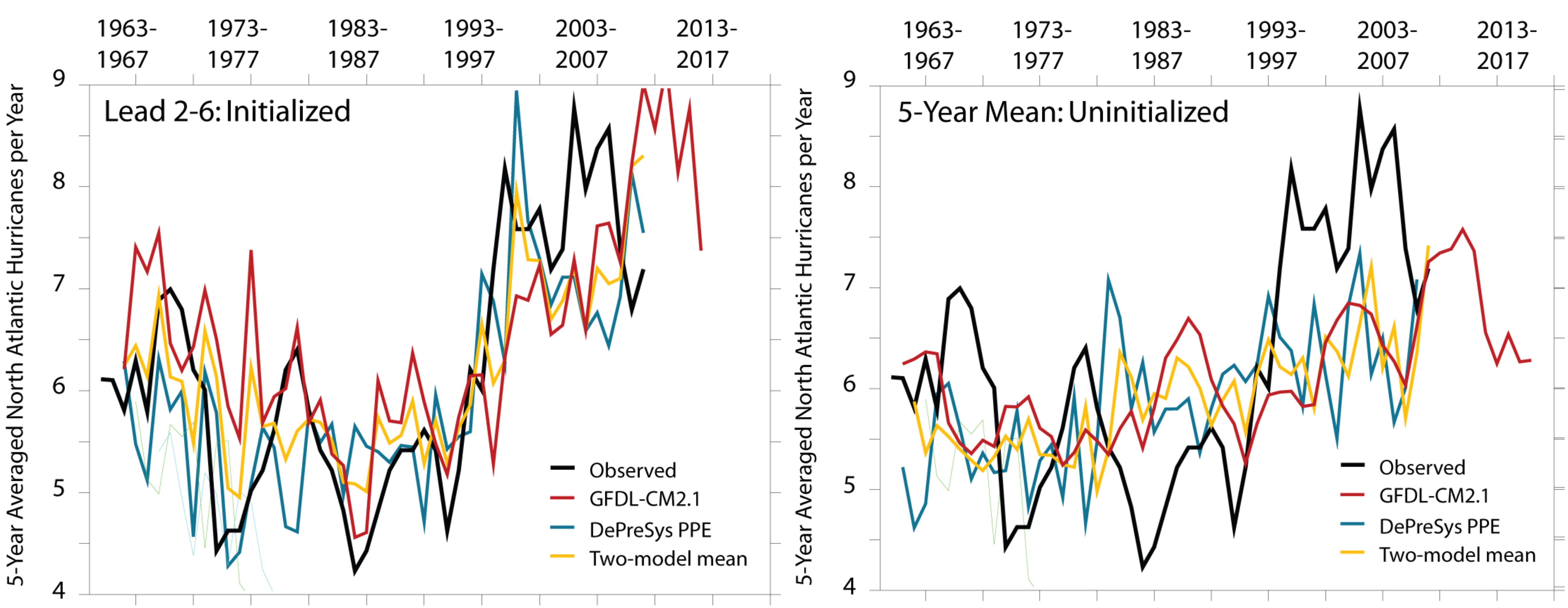
$$\lambda = e^{a + bSST_{MDR} - cSST_{TROP}}$$



Courtesy Gabriel Vecchi

Results: retrospective multi-year predictions of hurricane frequency in two CMIP5 models

5-yr predictions



Retrospective predictions encouraging: qualitatively better predictions than uninitialized

Vecchi, Msadek and coauthors (2012, submitted)

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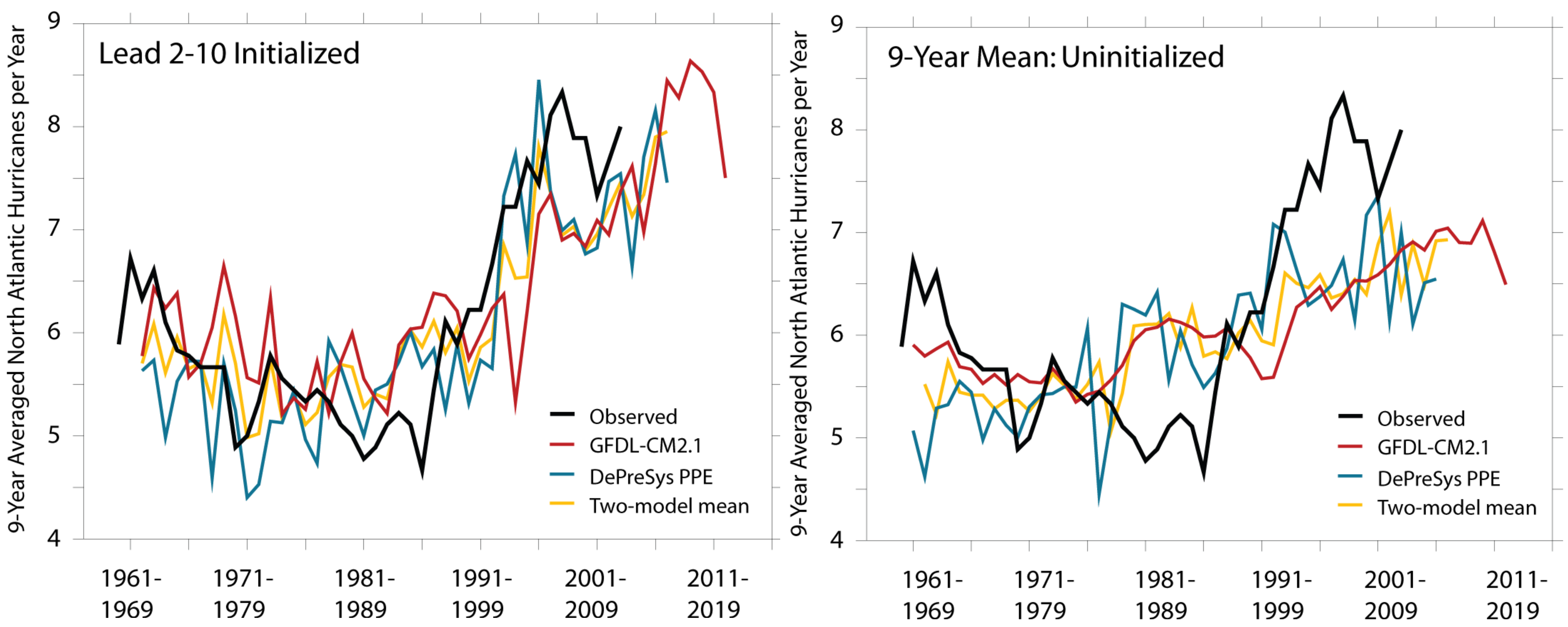
9-yr predictions



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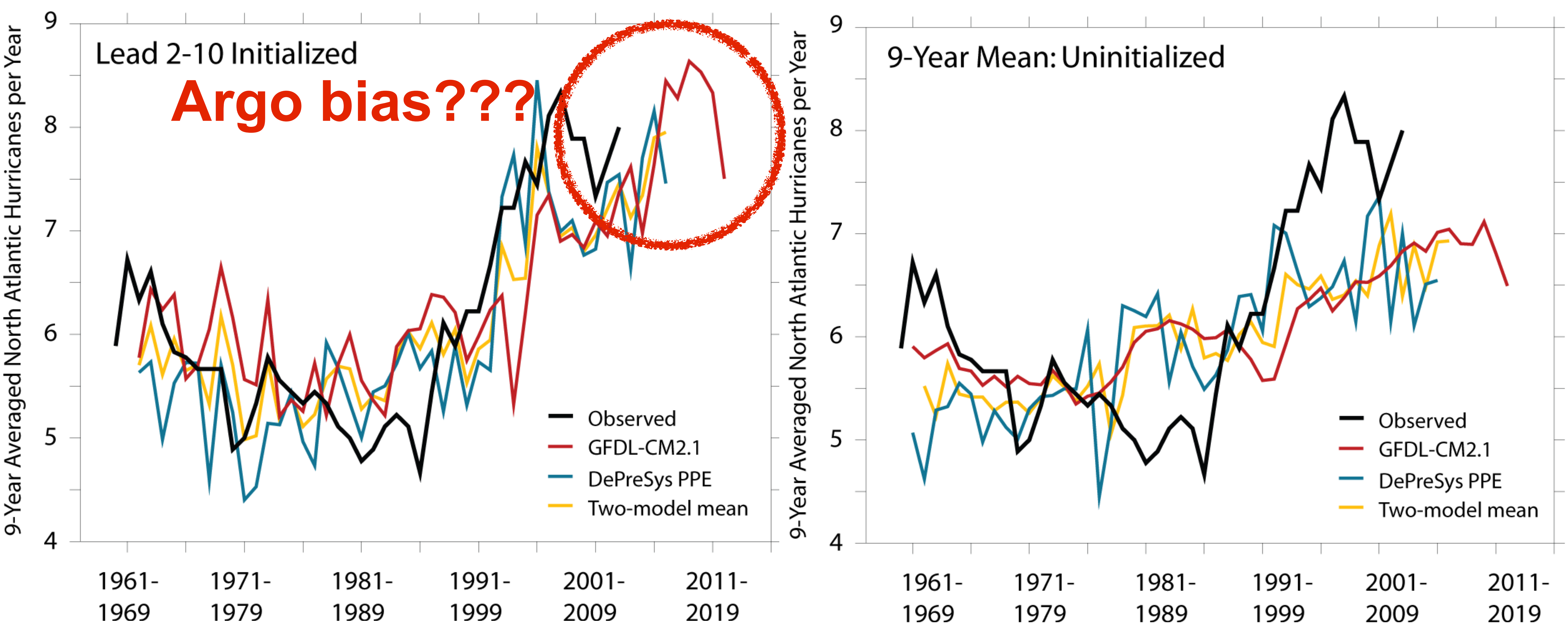
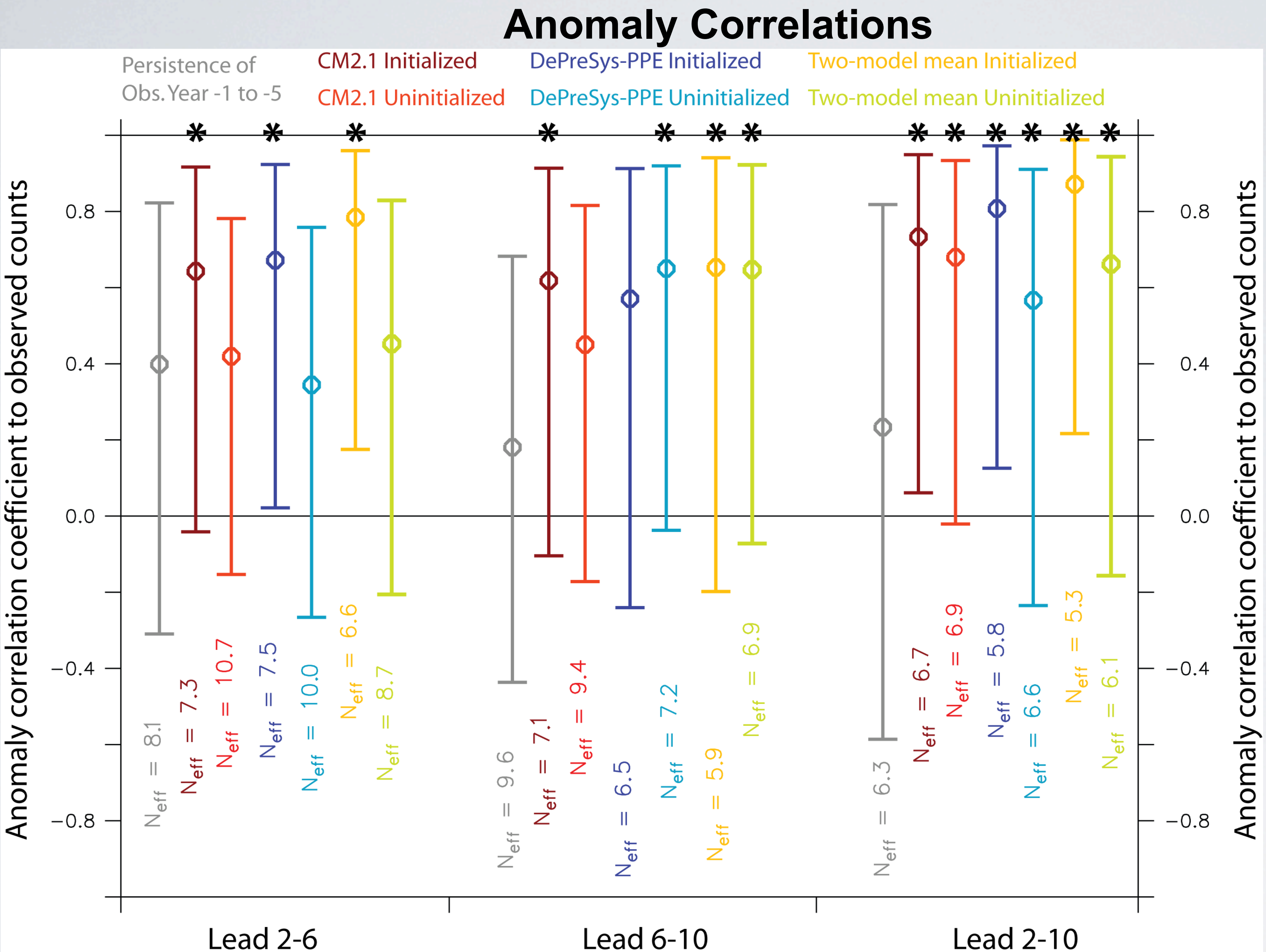


Retrospective predictions encouraging: qualitatively better predictions than uninitialized

Spurious increase after 2003: change in observational sampling induced changes in lead-dependent climatology

Vecchi, Msadek and coauthors (2012, submitted)

Results: retrospective multi-year predictions of hurricane frequency in two CMIP5 models



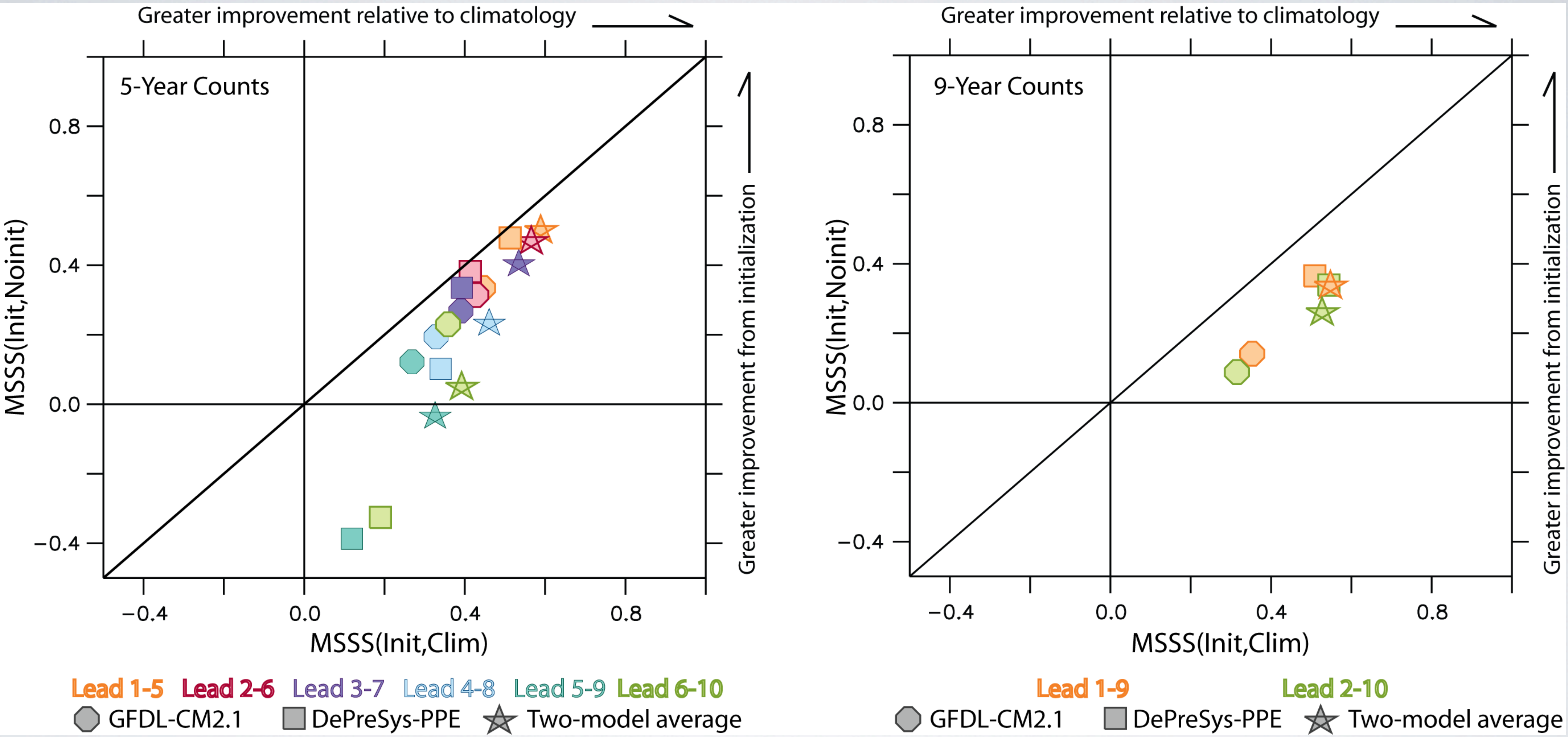
90% uncertainty level

Retrospective predictions encouraging, but small sample size limits confidence
=> Very few effective degrees of freedom
Highest skill for the two-model average
Results consistent with *Smith et al. (2010)***...except the confidence interval**

Vecchi, Msadek and coauthors (2012, submitted)

Results: retrospective multi-year predictions of hurricane frequency in two CMIP5 models

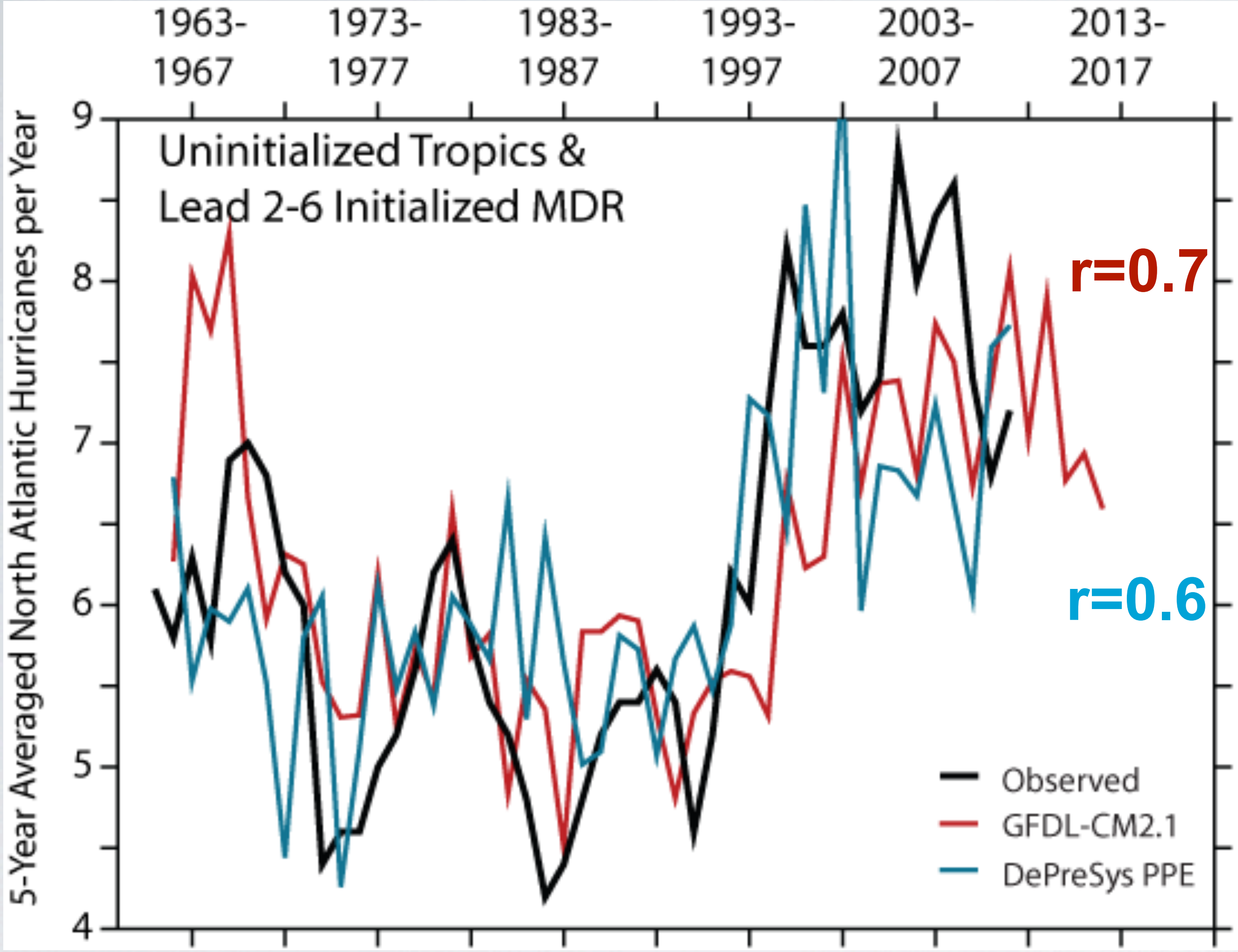
Mean Squared Skill Score (MSSS)



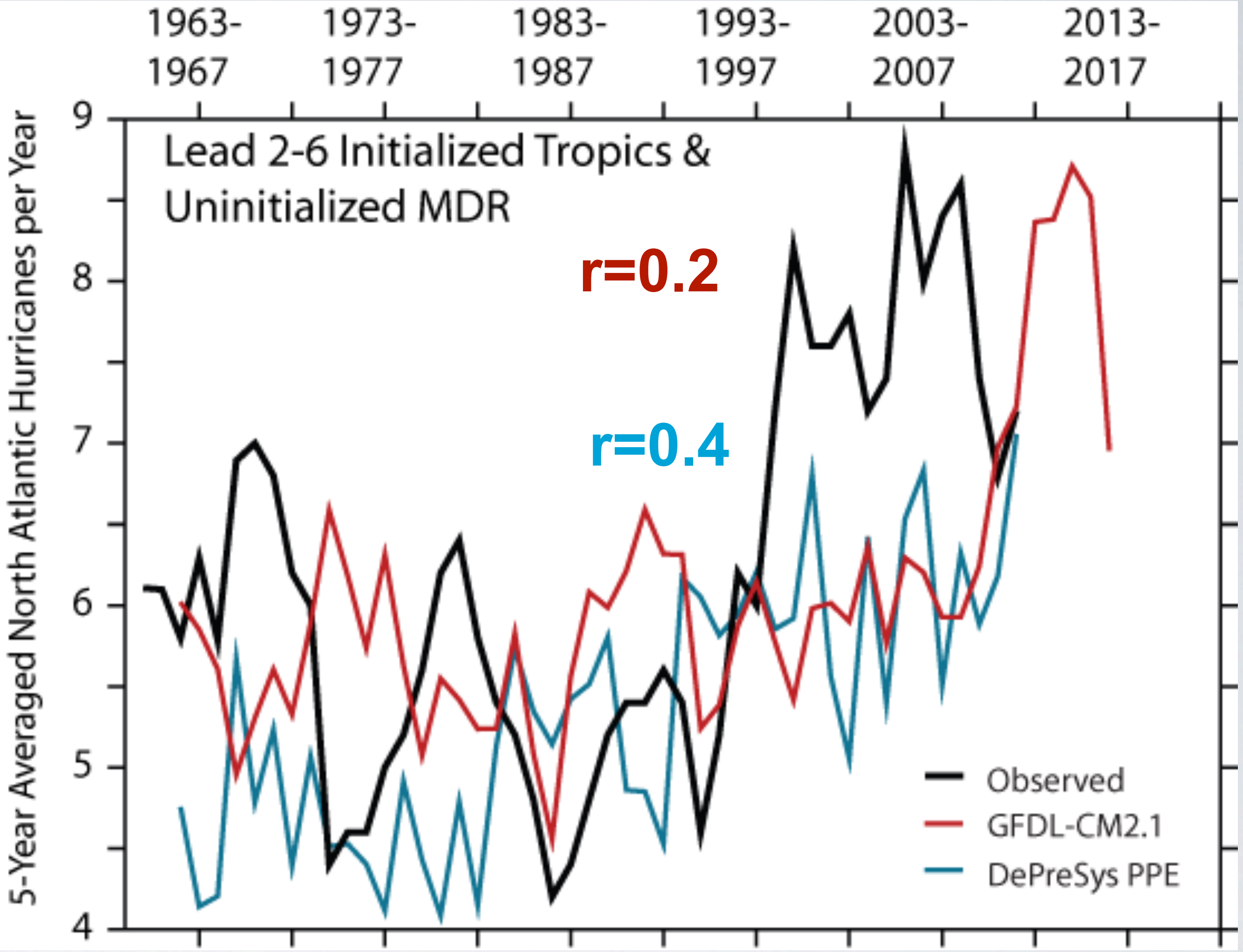
Reduction of the conditional bias that is large in the uninitialized predictions

Vecchi, Msadek and coauthors (2012, submitted)

Where does the skill come from?



Impact of SST Atl. MDR



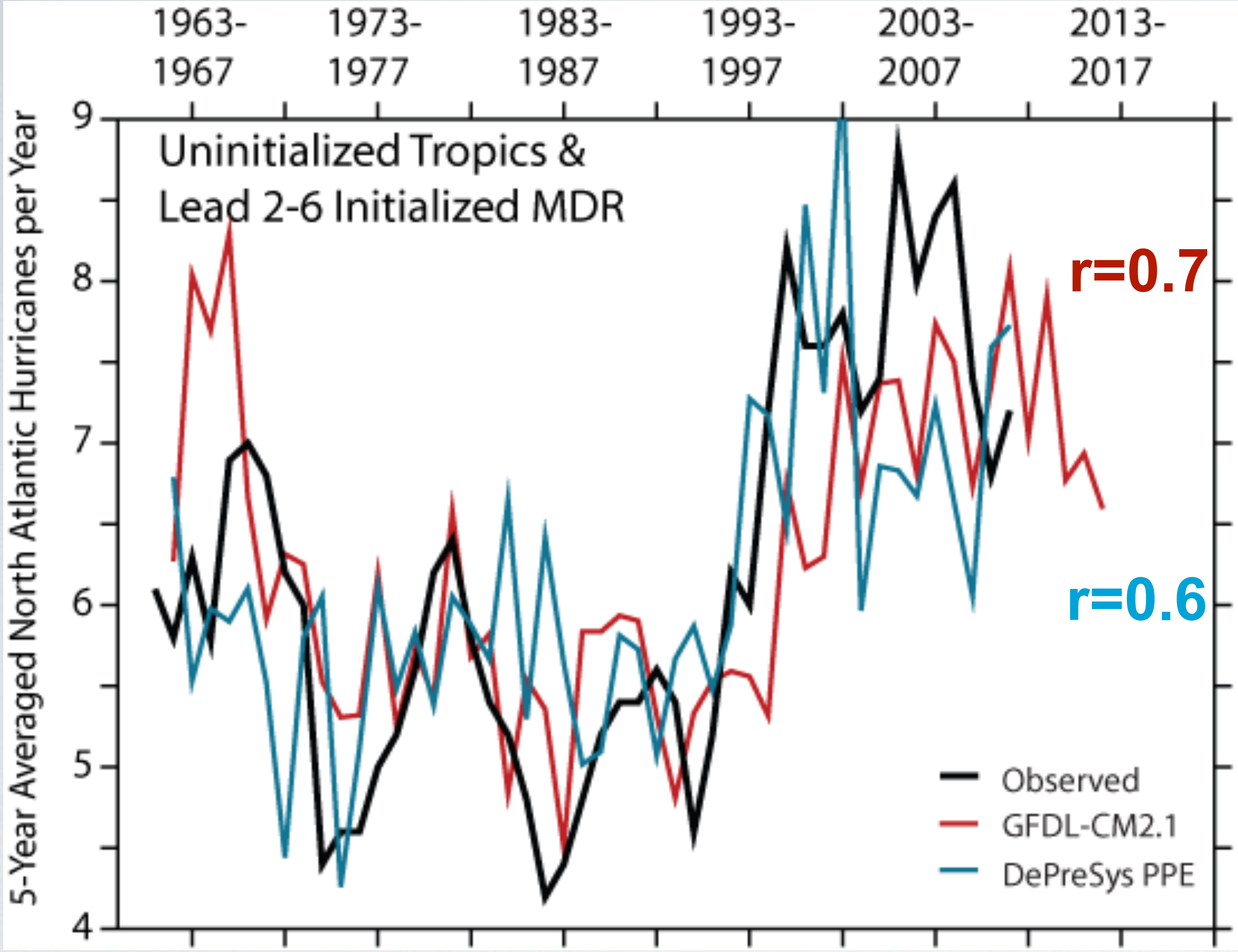
Impact of SST tropical mean

Nominal improvement results from better representation of Atlantic MDR when initializing the coupled models

Vecchi, Msadek and coauthors (2012, submitted)

Where does the skill come from?

Argo?



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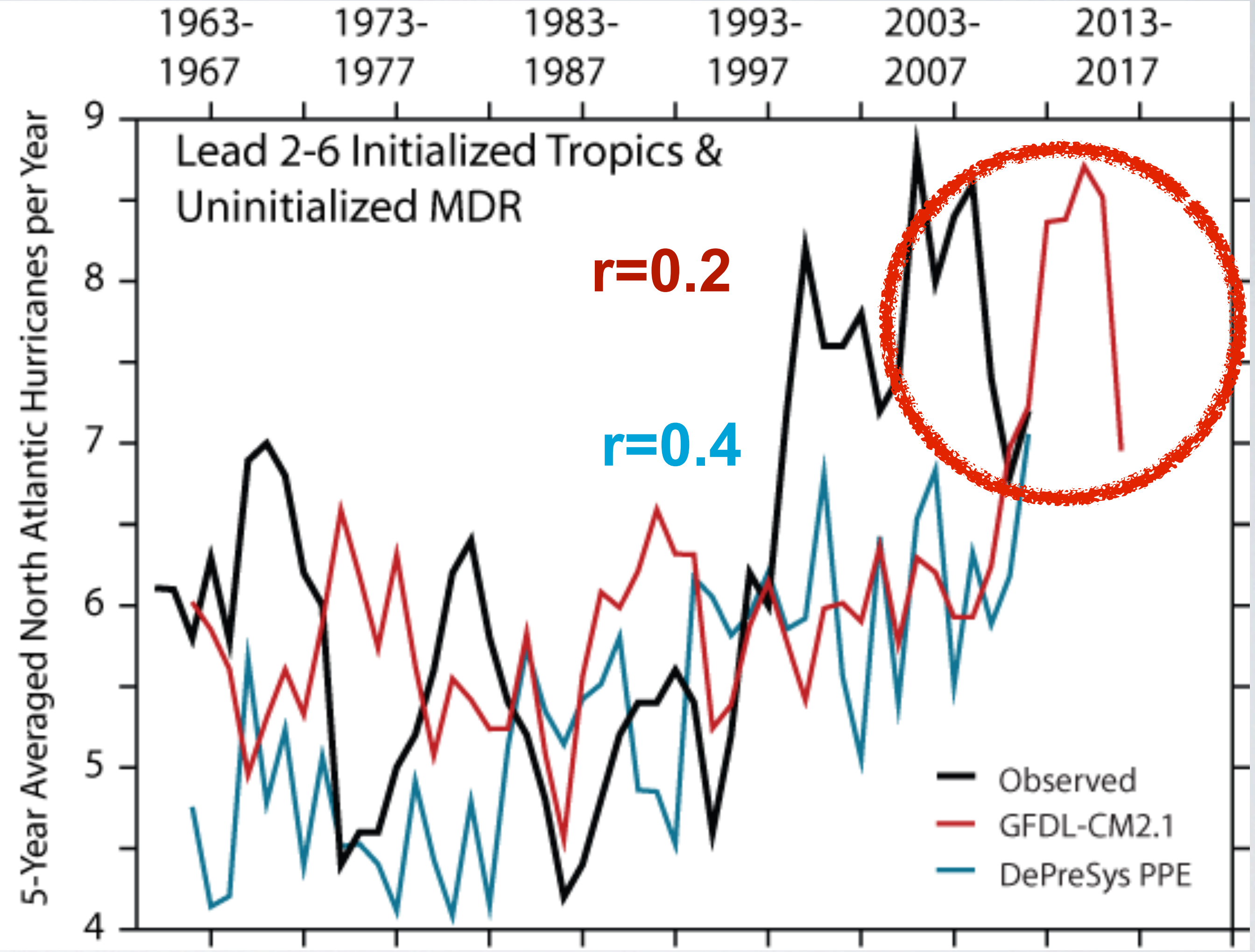

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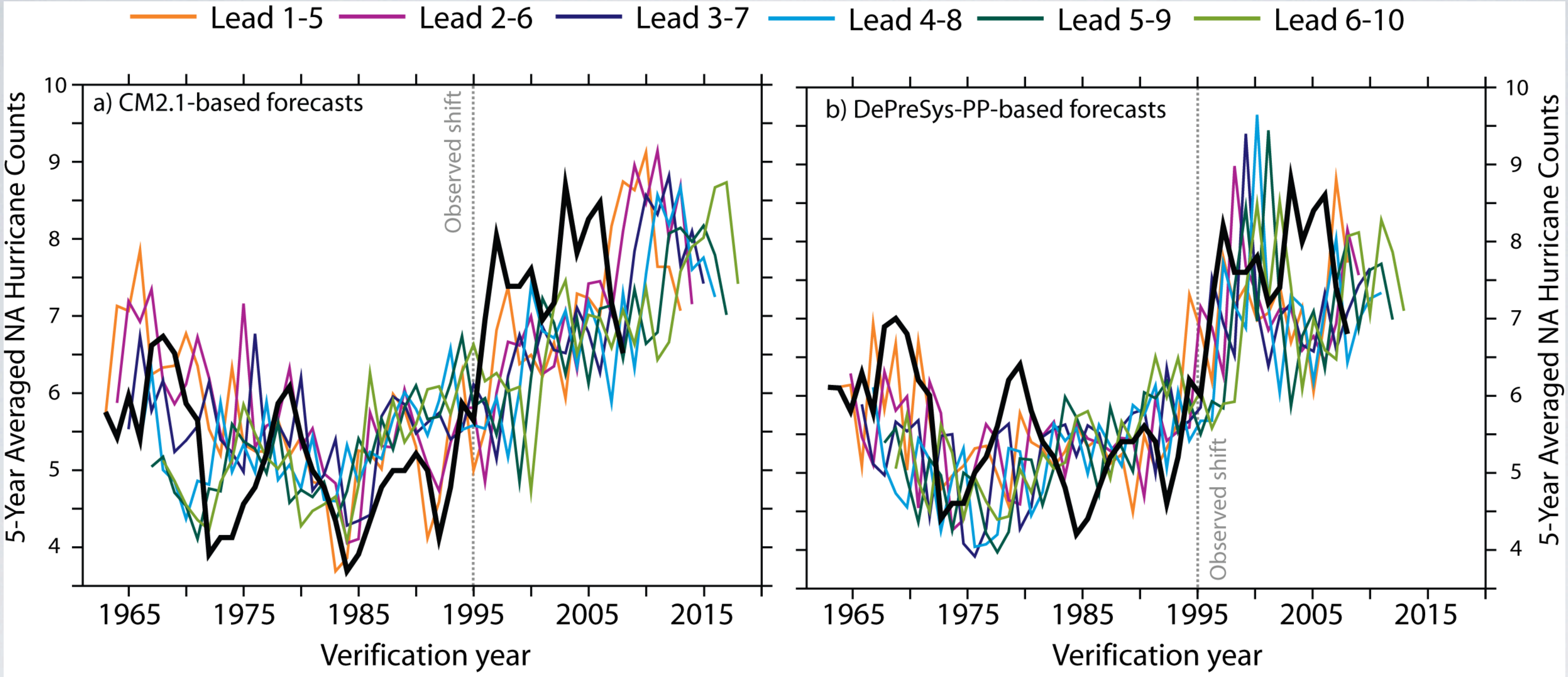

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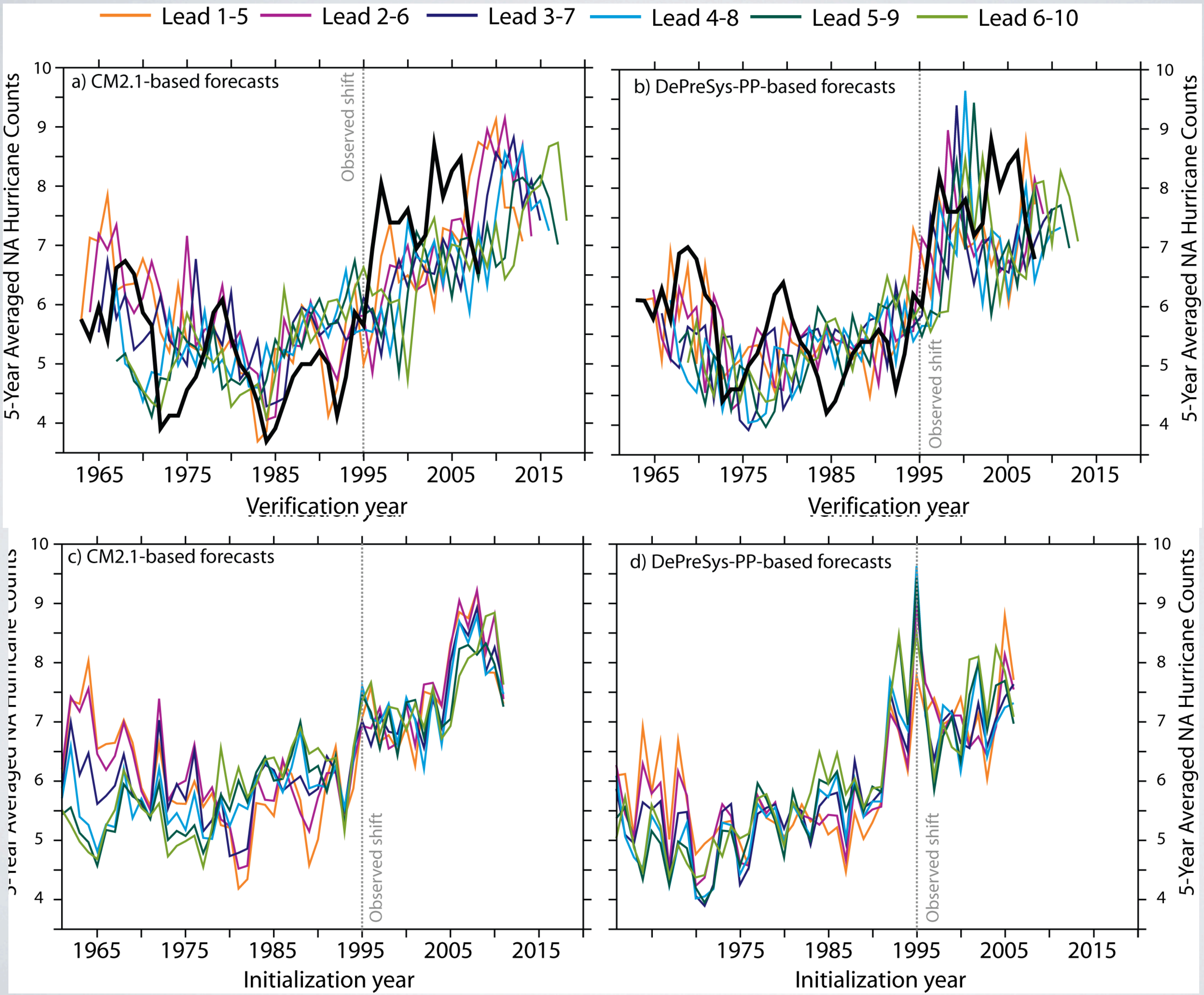
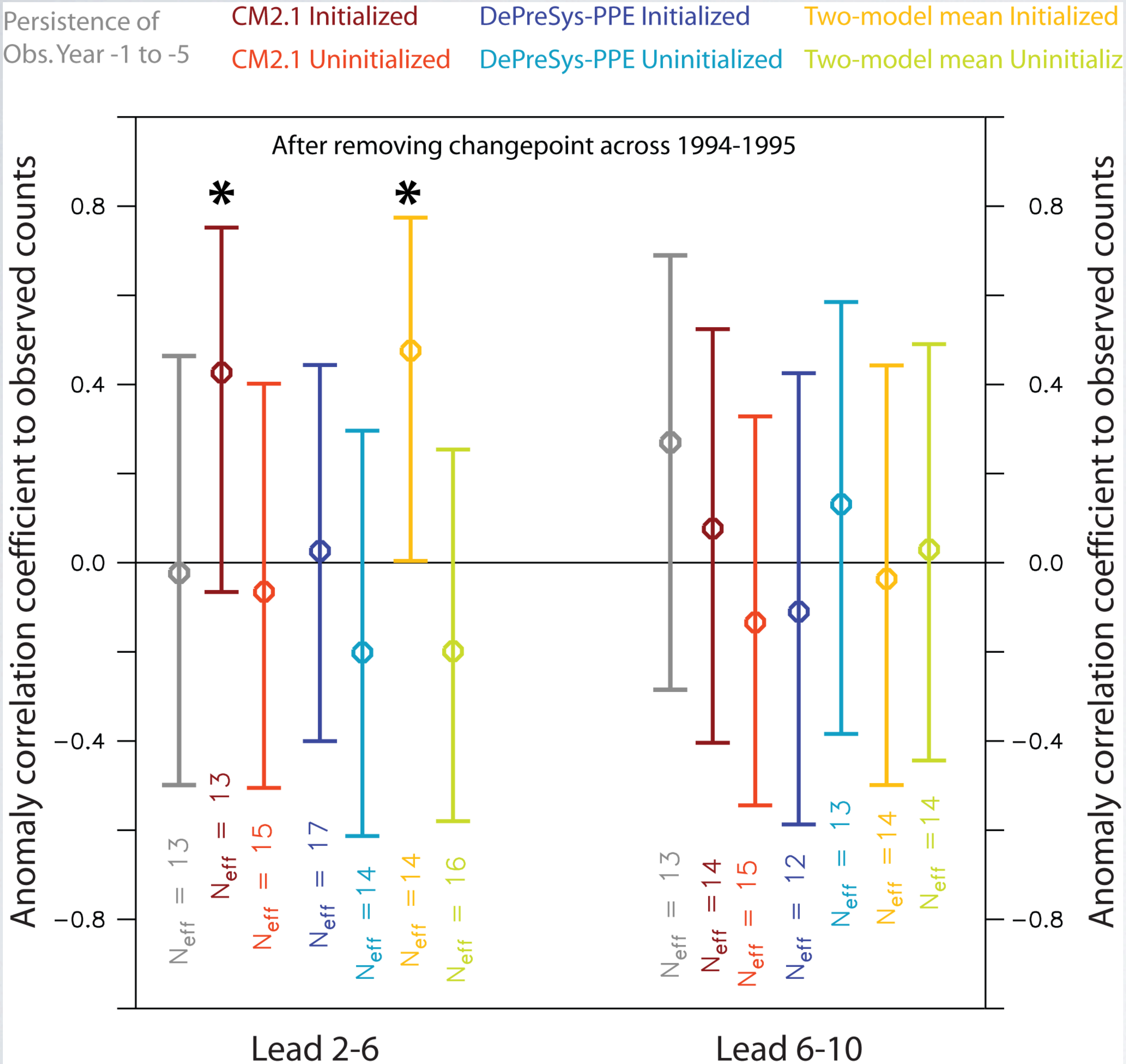


Where does the skill come from?

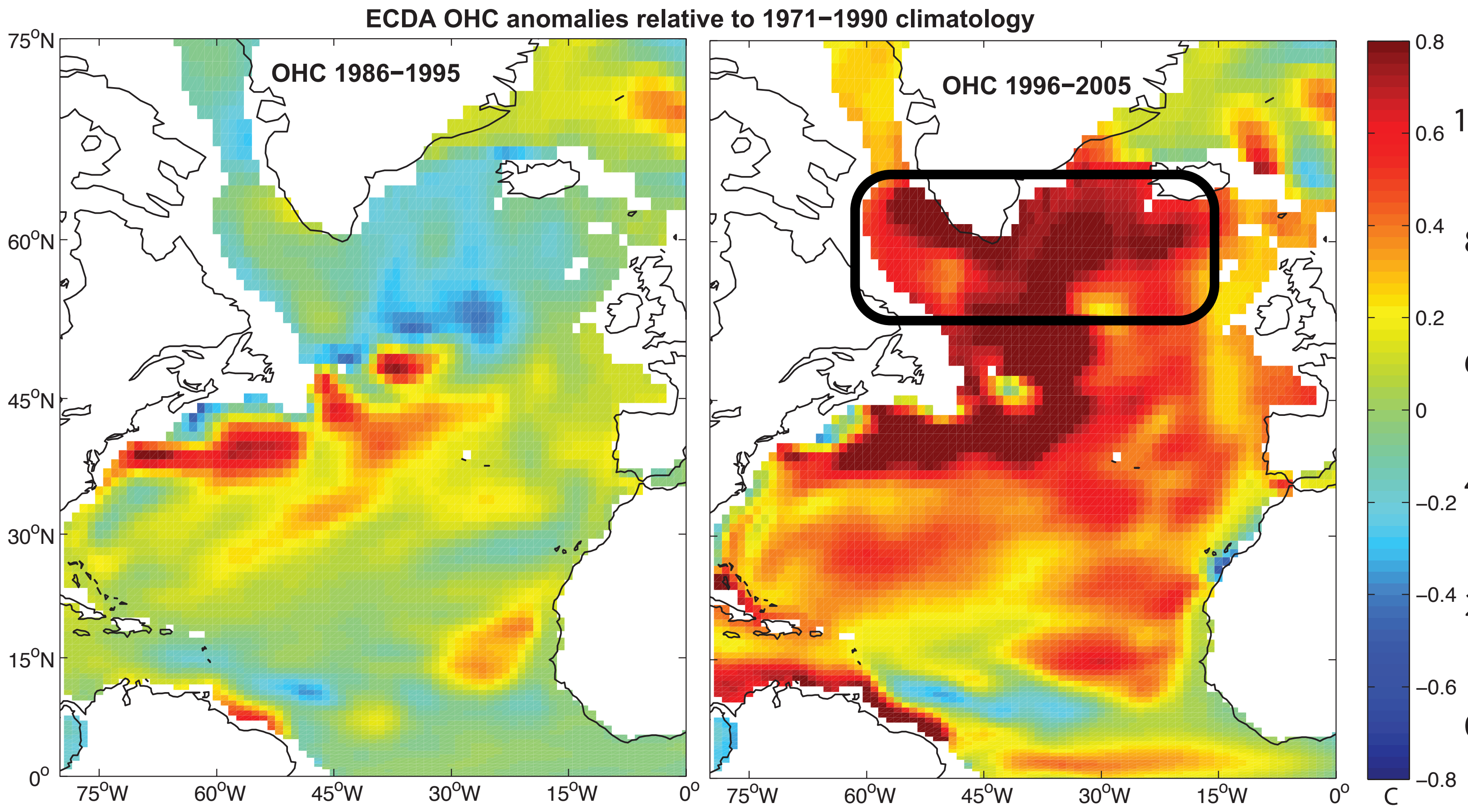
Anomaly correlations with the mid 90's shift "removed"



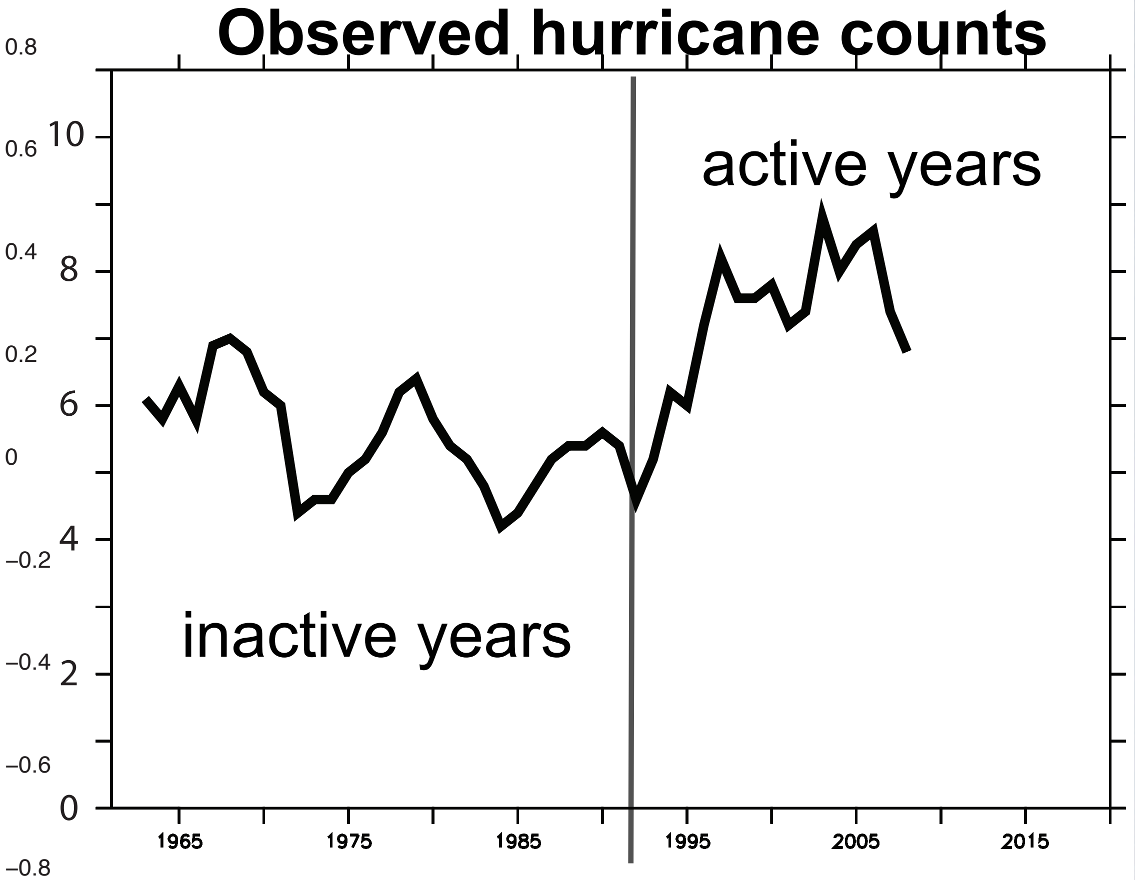
The correlations drop substantially => decadal signal dominated by the trend that arises from mid 90s change point
=>Implications for future "real" predictions: won't be as good as retrospective predictions unless a change point of similar character happens AND we can predict it

Vecchi, Msadek and coauthors (2012, submitted)

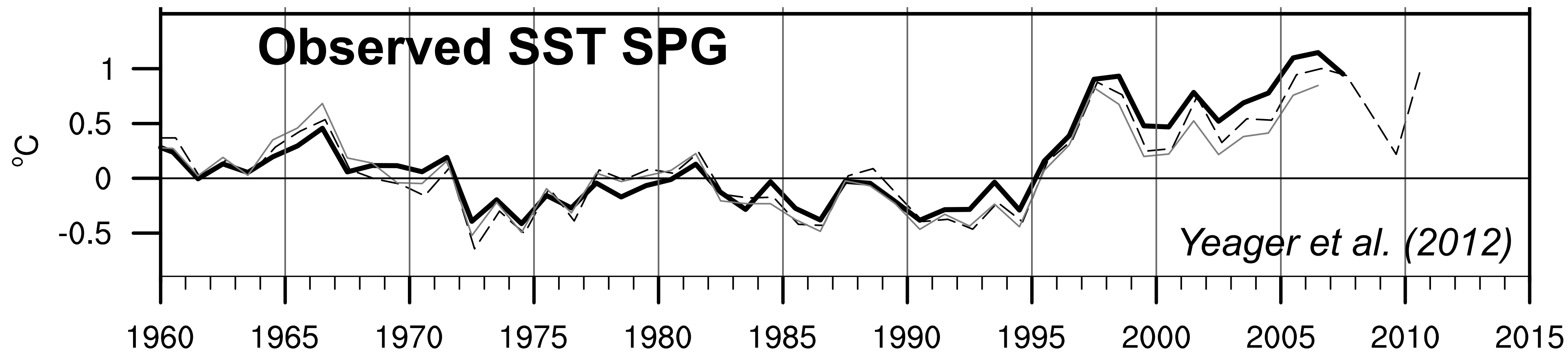
Is the change in mid 90s in hurricane frequency related to the SPG climate shift? Remote influence on hurricanes suggested by *Smith et al (2010)*



Msadek, Rosati, Delworth and coauthors (2012, in prep)



tipping point

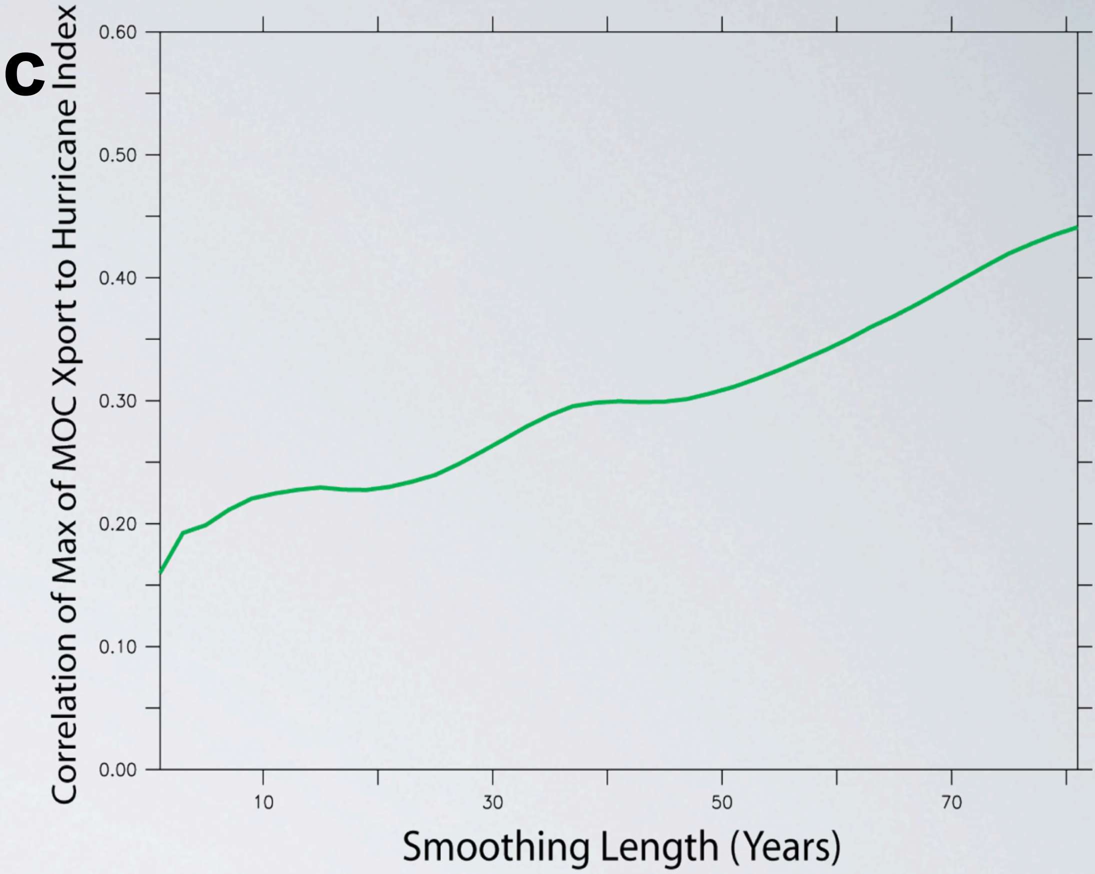


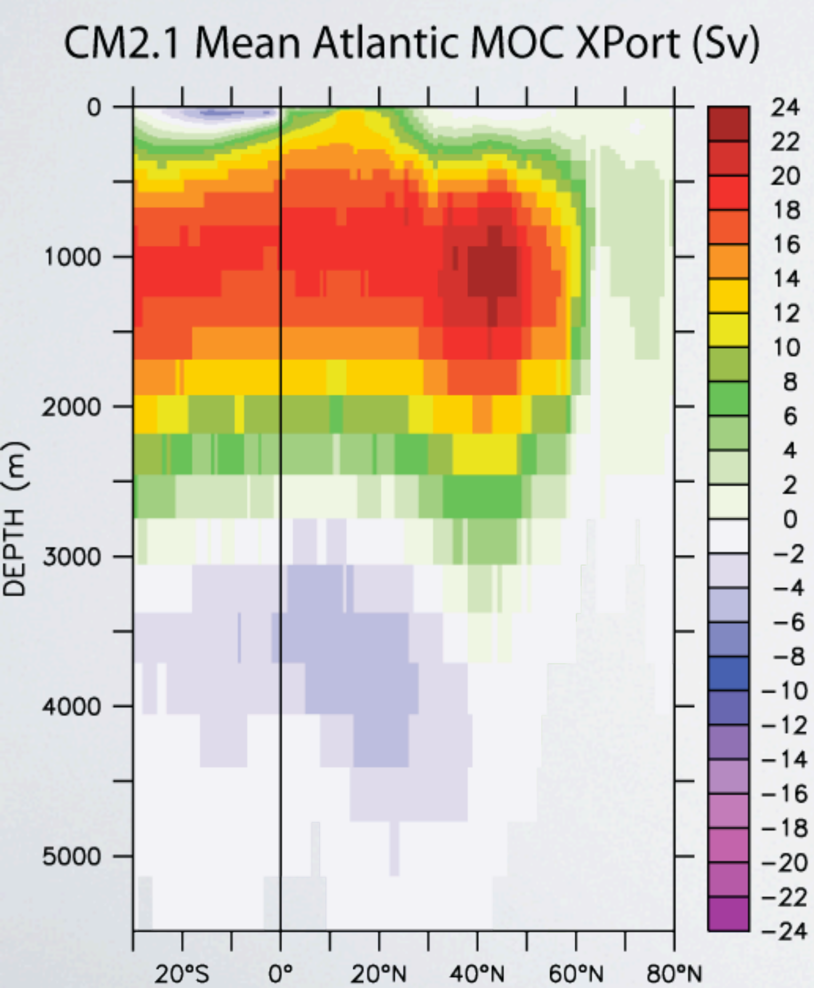
Abrupt warming of the North Atlantic subpolar gyre observed in 1995 linked to MOC response to persistent NAO forcing, predictable in several CMIP5 experiments.
If hurricanes shift linked to that it could affect their predictability

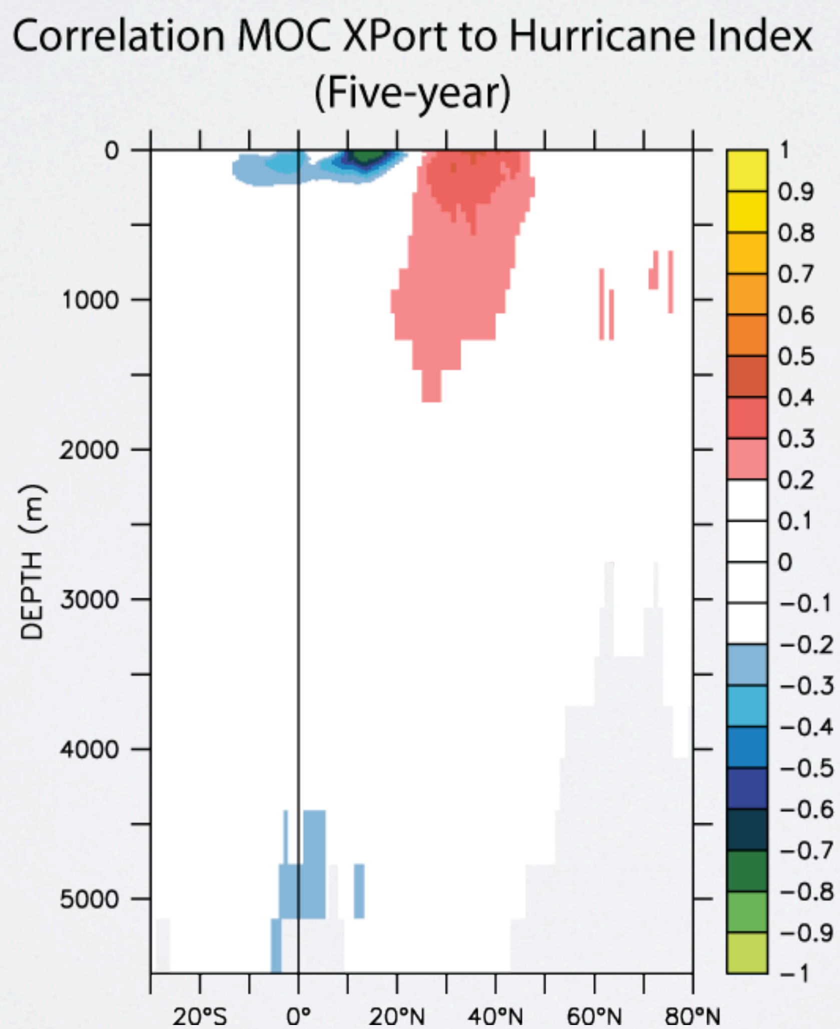
Linking hurricane changes to North Atlantic

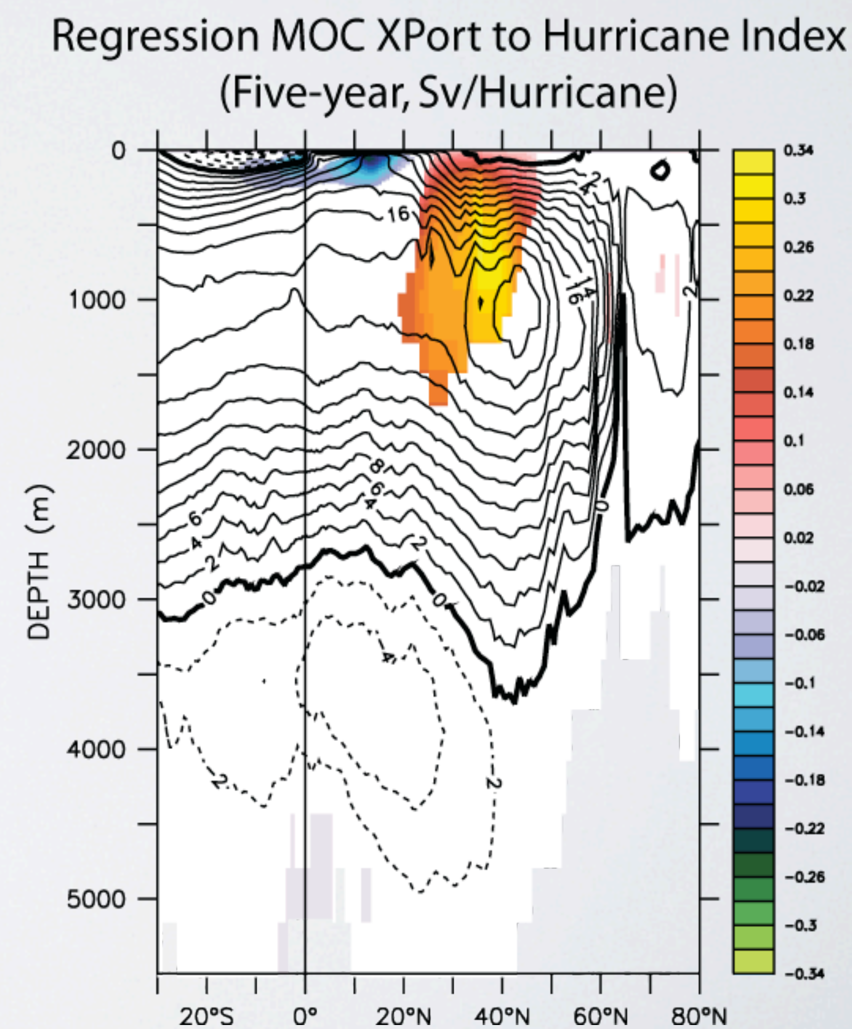
Hurricane index correlated with MOC max at lowest frequencies (centennial).

At decadal timescales perhaps related to shifts in MOC max and shallow changes.



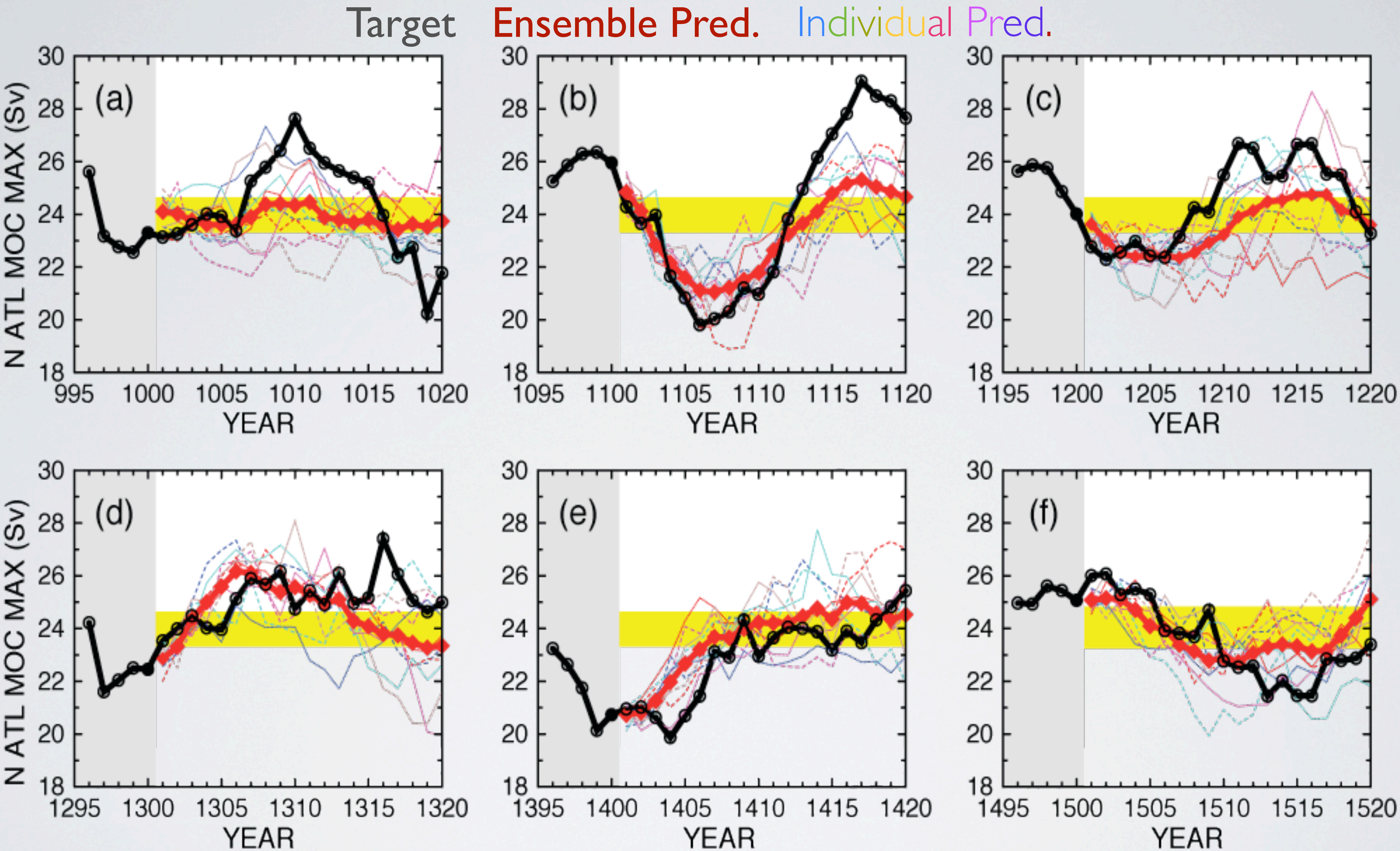






Msadek and Vecchi (2012, in prep.)

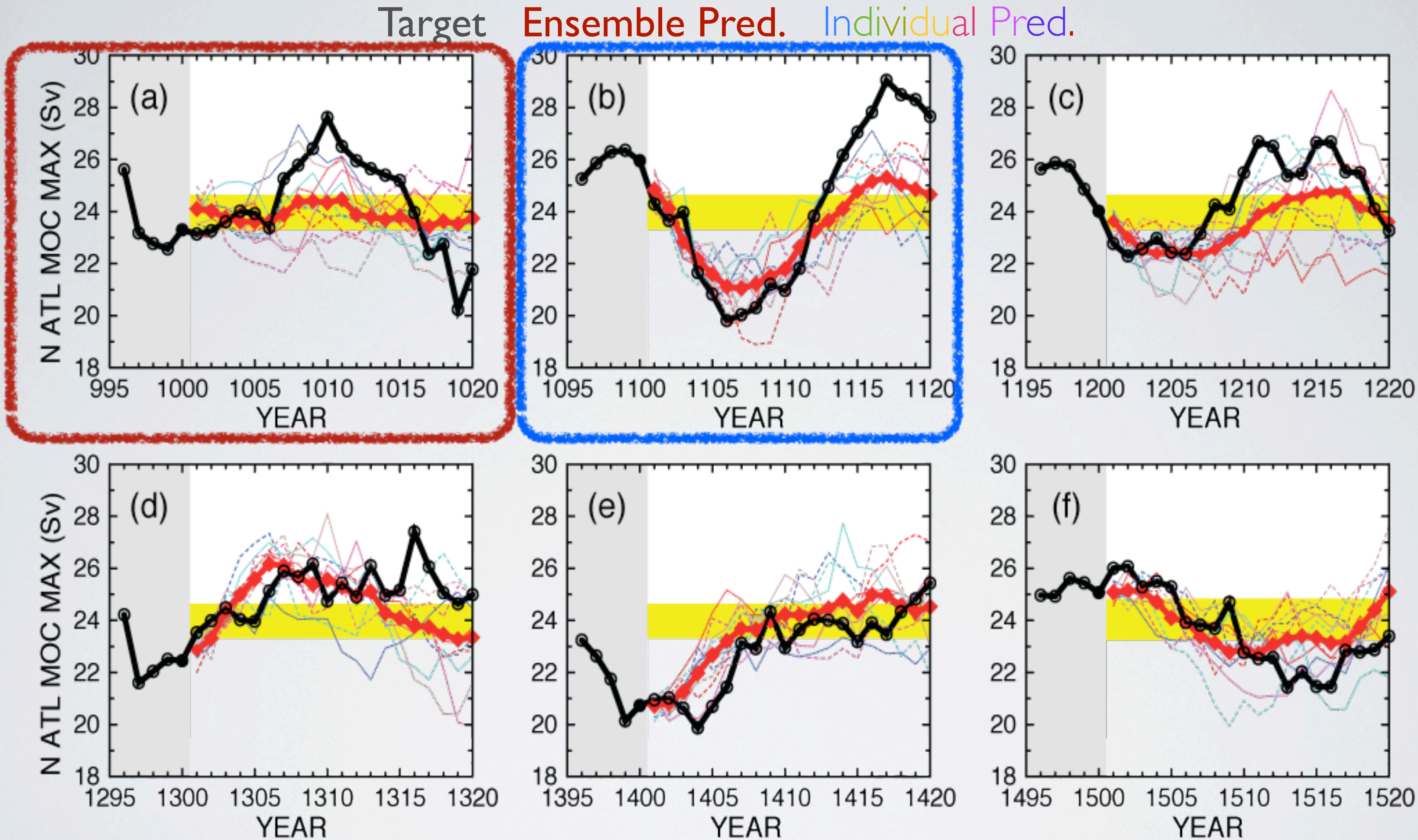
MOC shows some predictability on decadal time scales



Marked dependence in initial conditions

Msadek, Dixon, Delworth and Hurlin (2010)

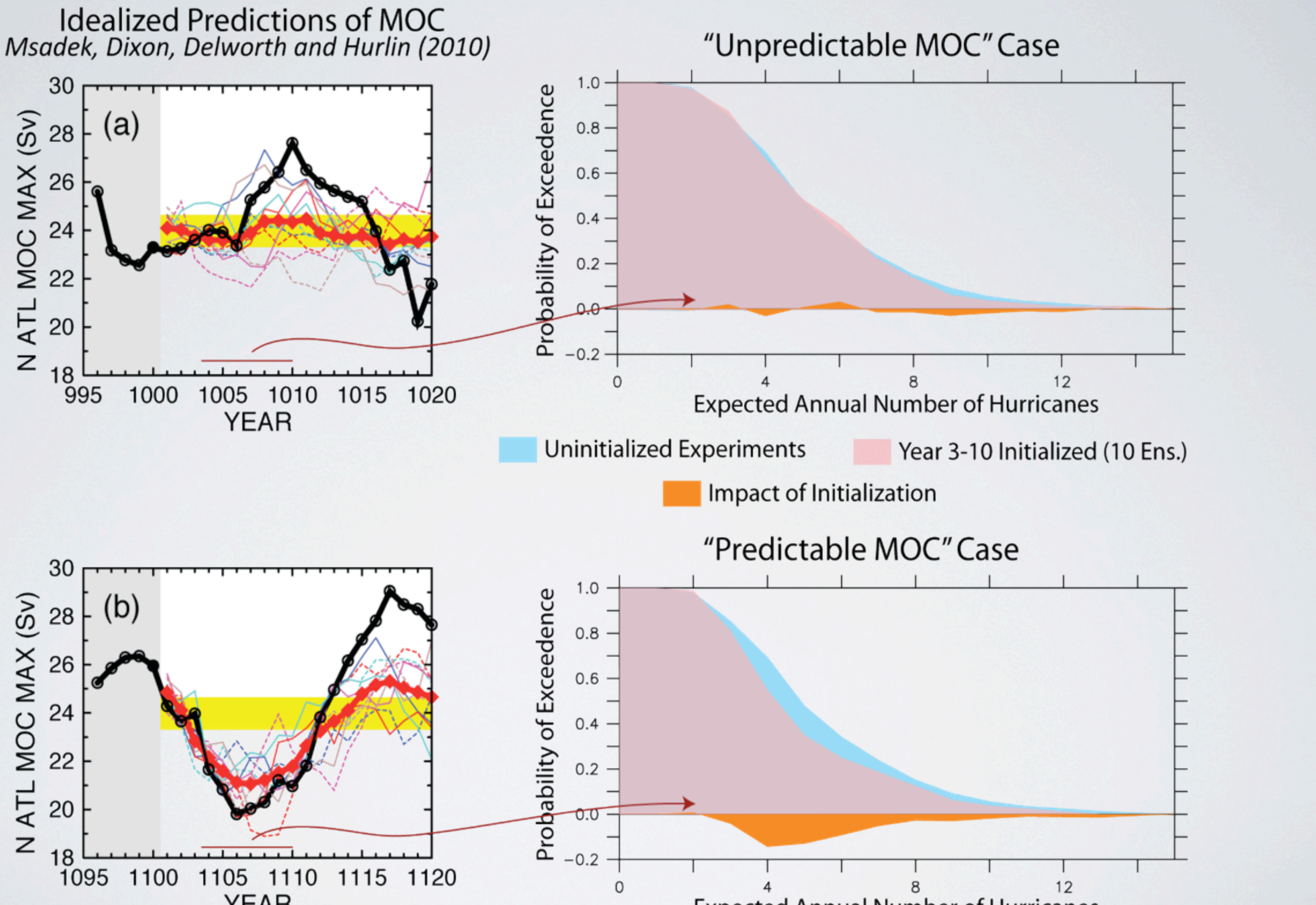
MOC shows some predictability on decadal time scales



Marked dependence in initial conditions

Msadek, Dixon, Delworth and Hurlin (2010)

Hurricane index has some predictability when MOC does



Reduced probability of actives years

Msadek and Vecchi (2012, in prep.)

Conclusions

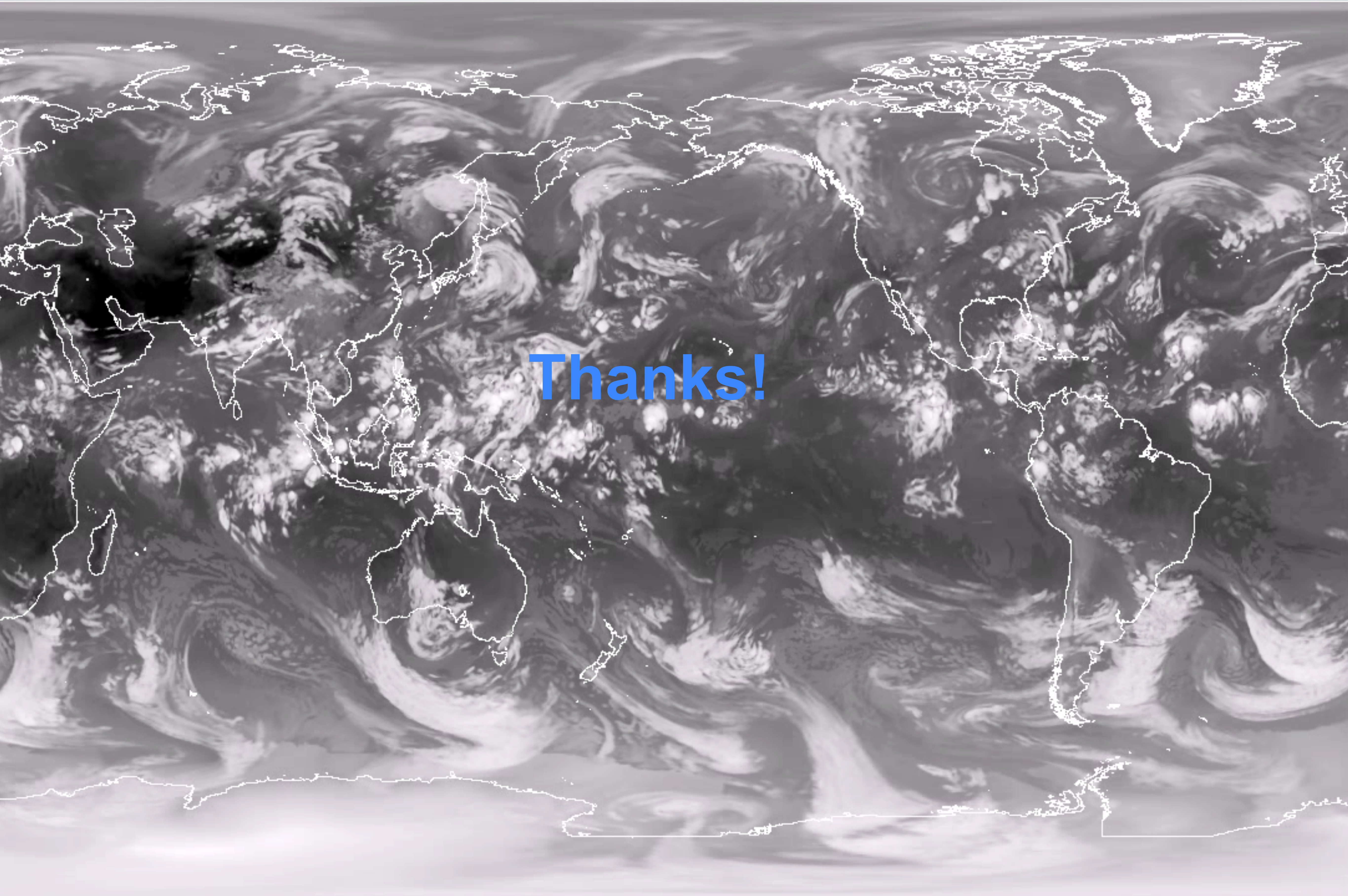
-It is premature to conclude that human activity--and particularly greenhouse warming--has already had a detectable impact on tropical cyclone activity.

-Projected GFDL model hurricane response to global warming: likely fewer tropical storms and hurricanes but increase in the frequency of most intense hurricanes. Also higher rainfall rate => strong societal impact
This change may not be detectable for many decades due to high noise levels
No information about landfalling storms yet

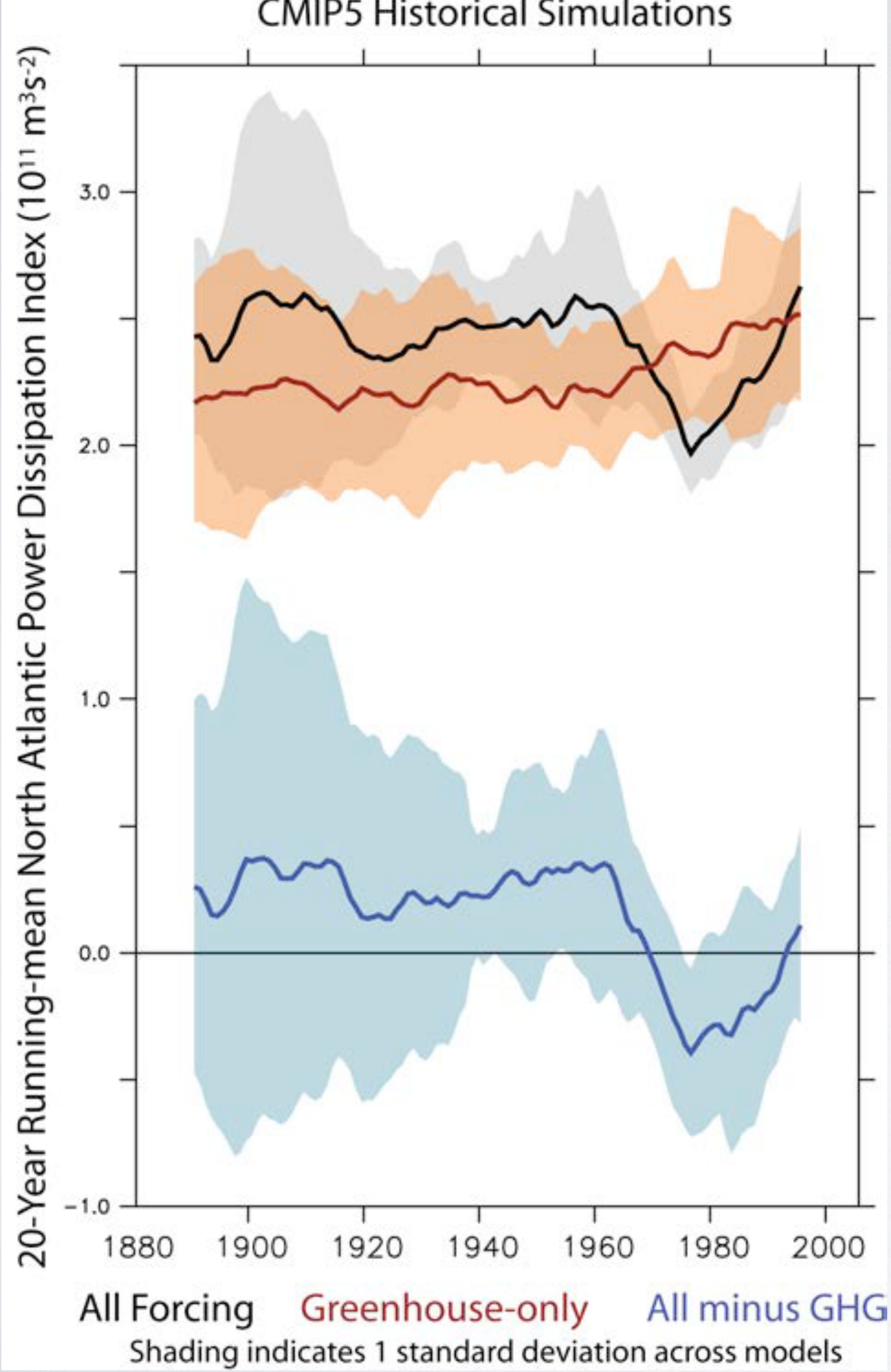
-Confidence relies in the models' ability to successfully reproduce past variability but remaining caveats include model limitations (clouds, aerosols, intense hurricane simulations) and dependence on climate change conditions for downscaling
Internal variability and response to forcing (e.g aerosols) are also large sources of uncertainty.

-The relative warming of each basin wrt tropical mean will determine future response of TCs. Improving the quality of regional SST projections in coupled GCMs is key to reduce uncertainty of hurricane projections. Challenging because it involves cloud feedbacks and climate response to aerosols

-Initialized multi-year predictions are encouraging but the short record limits our confidence. The mid 90's shift is the source of observed and simulated trend over 20th century; predicting it and understanding its origin are key for future predictions.
Changes in observational system make predictions challenging


Thanks!

Extra slides

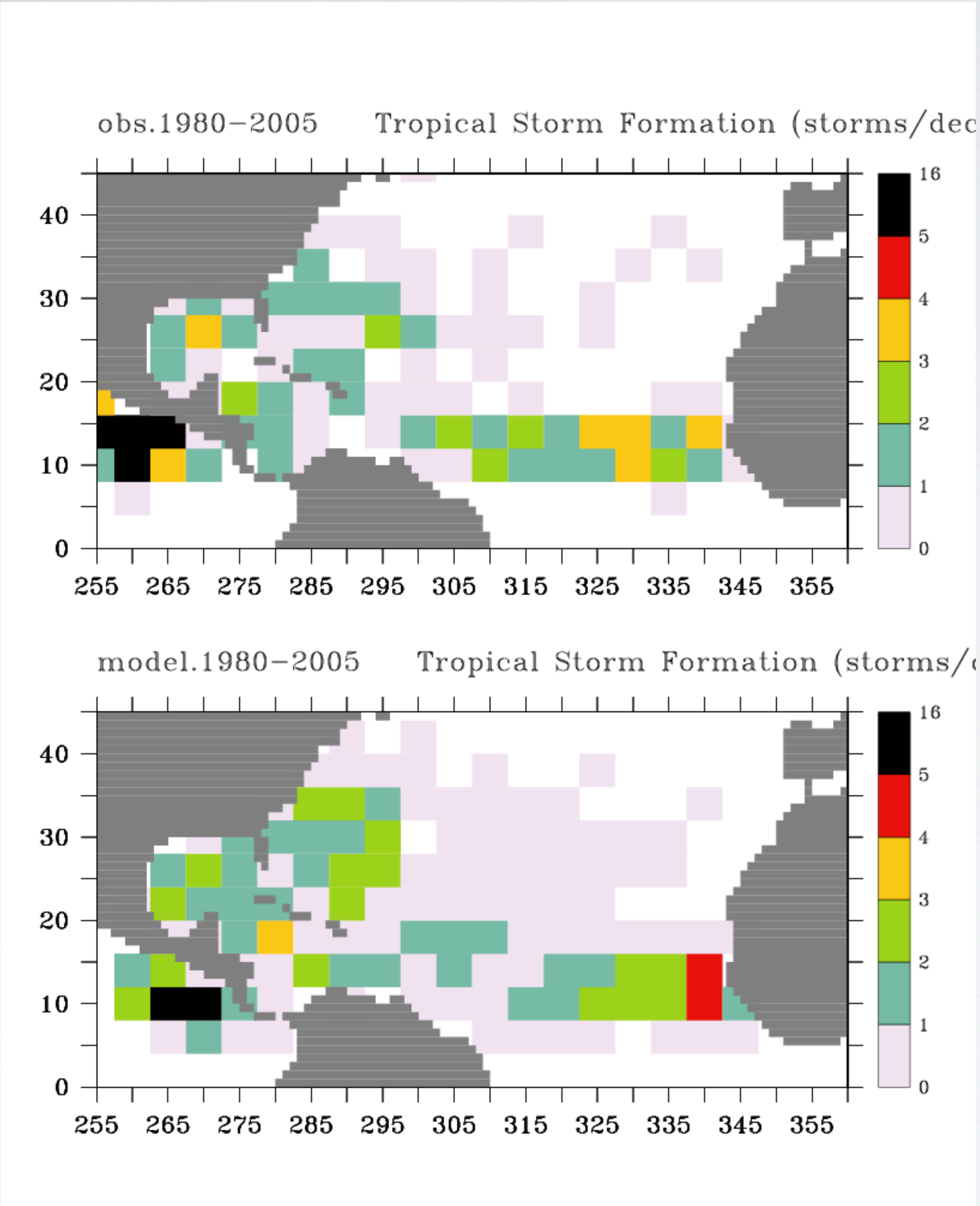


CMIP5 historical experiments only explain a fraction (~25%) of the recently observed multidecadal variation in PDI, indicating a strong role for internal variability

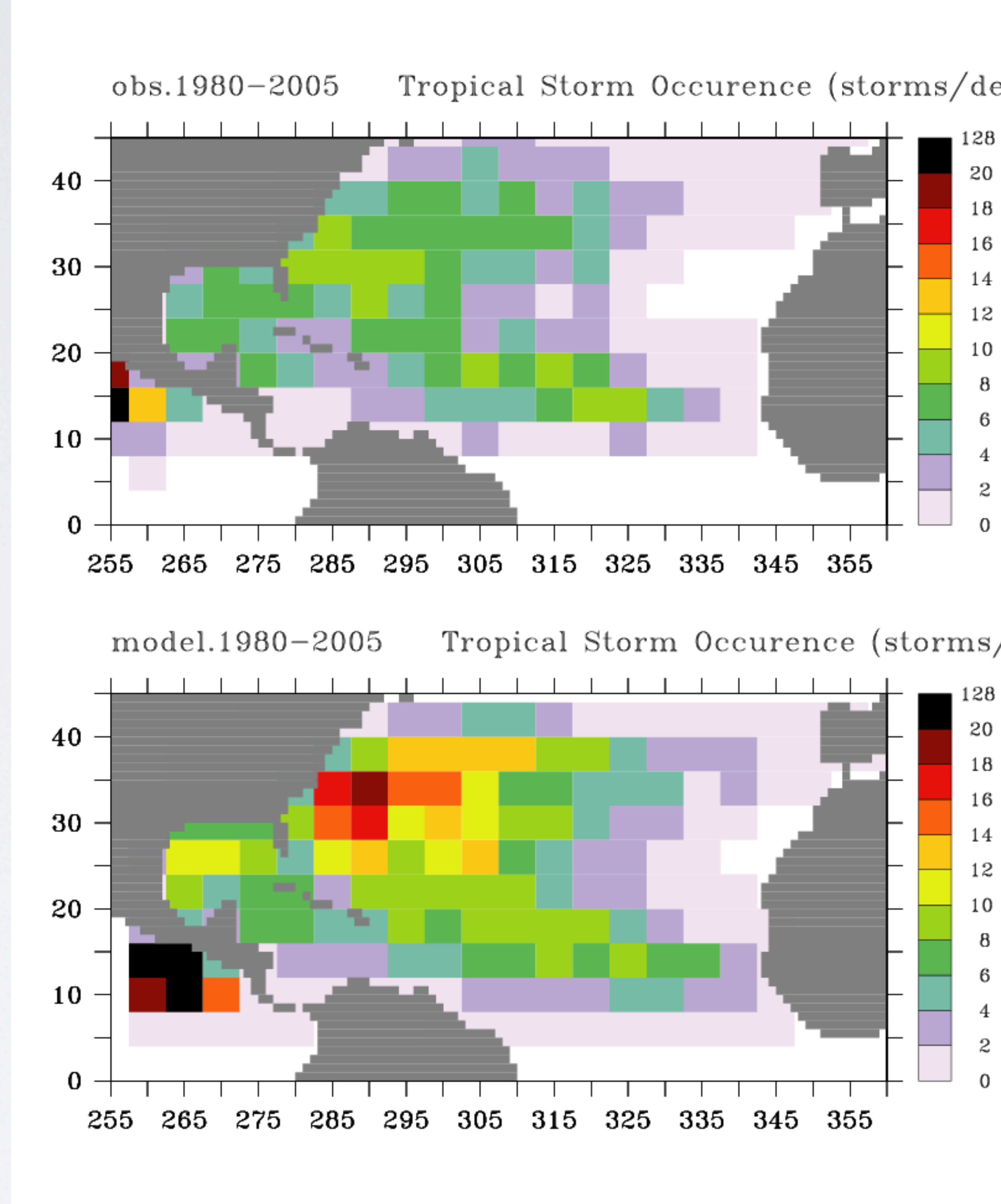
Source: Villarini and Vecchi, 2012 (submitted)

Zetac Regional Model Downscaling: geographical distribution of storms

Tropical Storm Formation

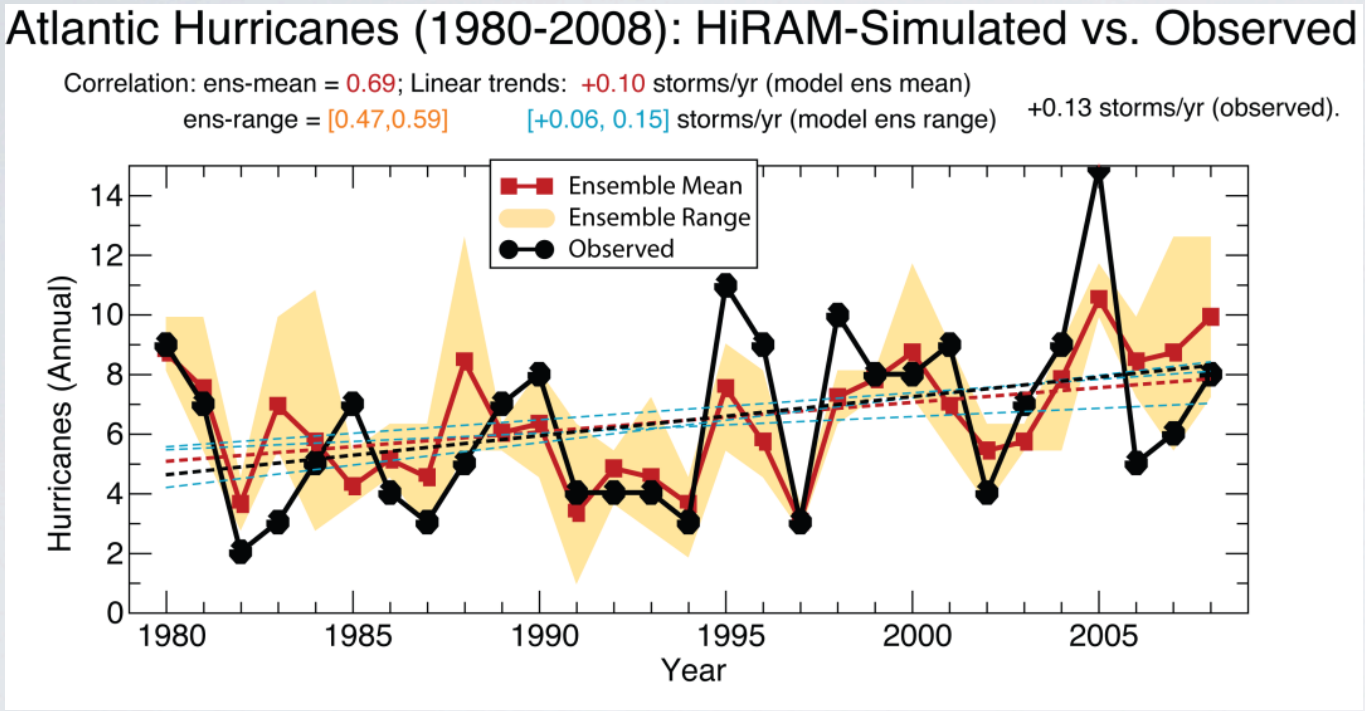


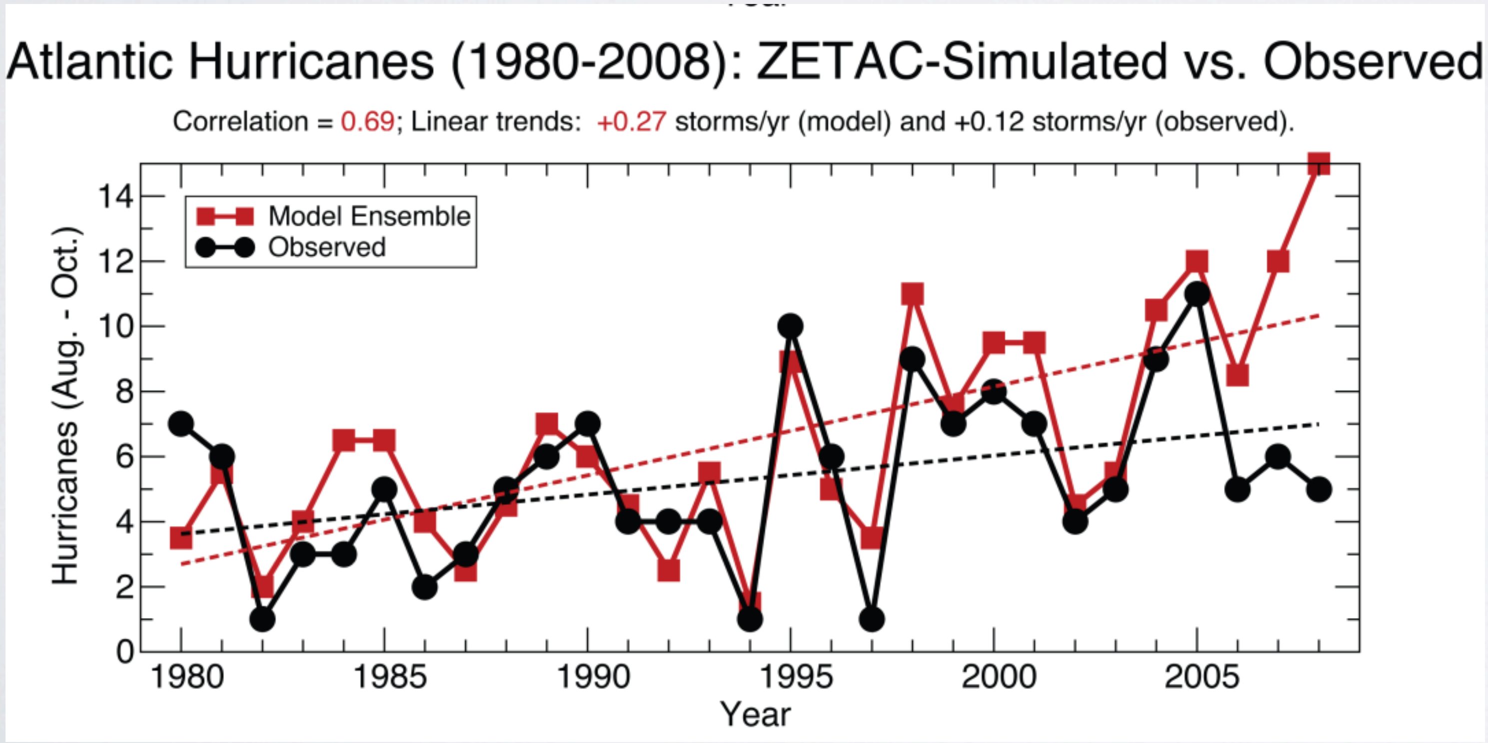
Tropical Storm Occurrence



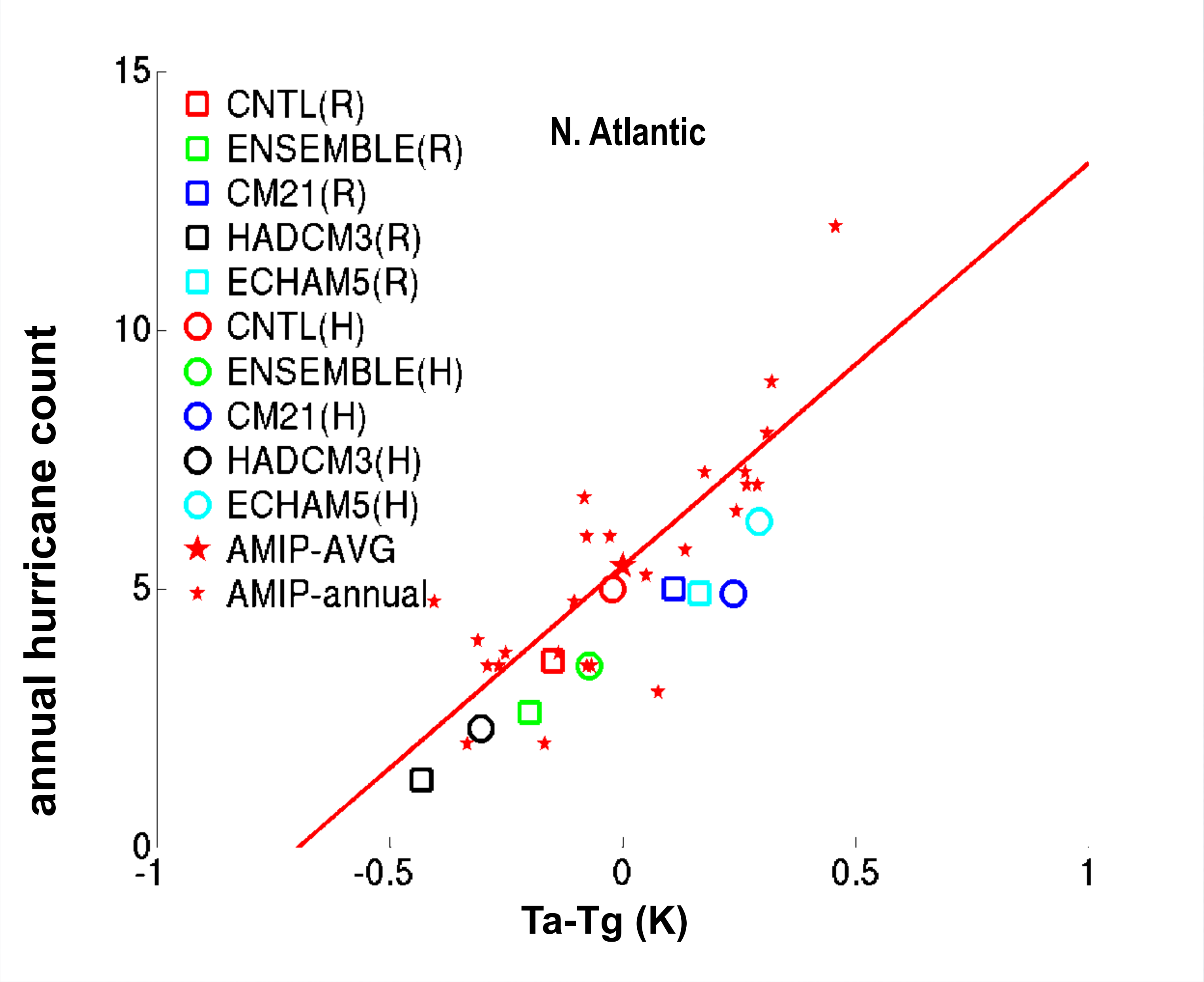
Source: Knutson et al., *Bull. Amer. Meteor. Soc*, 2007.

Two GFDL models reproduce the interannual variability of Atlantic hurricane counts; trend in NCEP reanalysis forced ZETAC model is too large

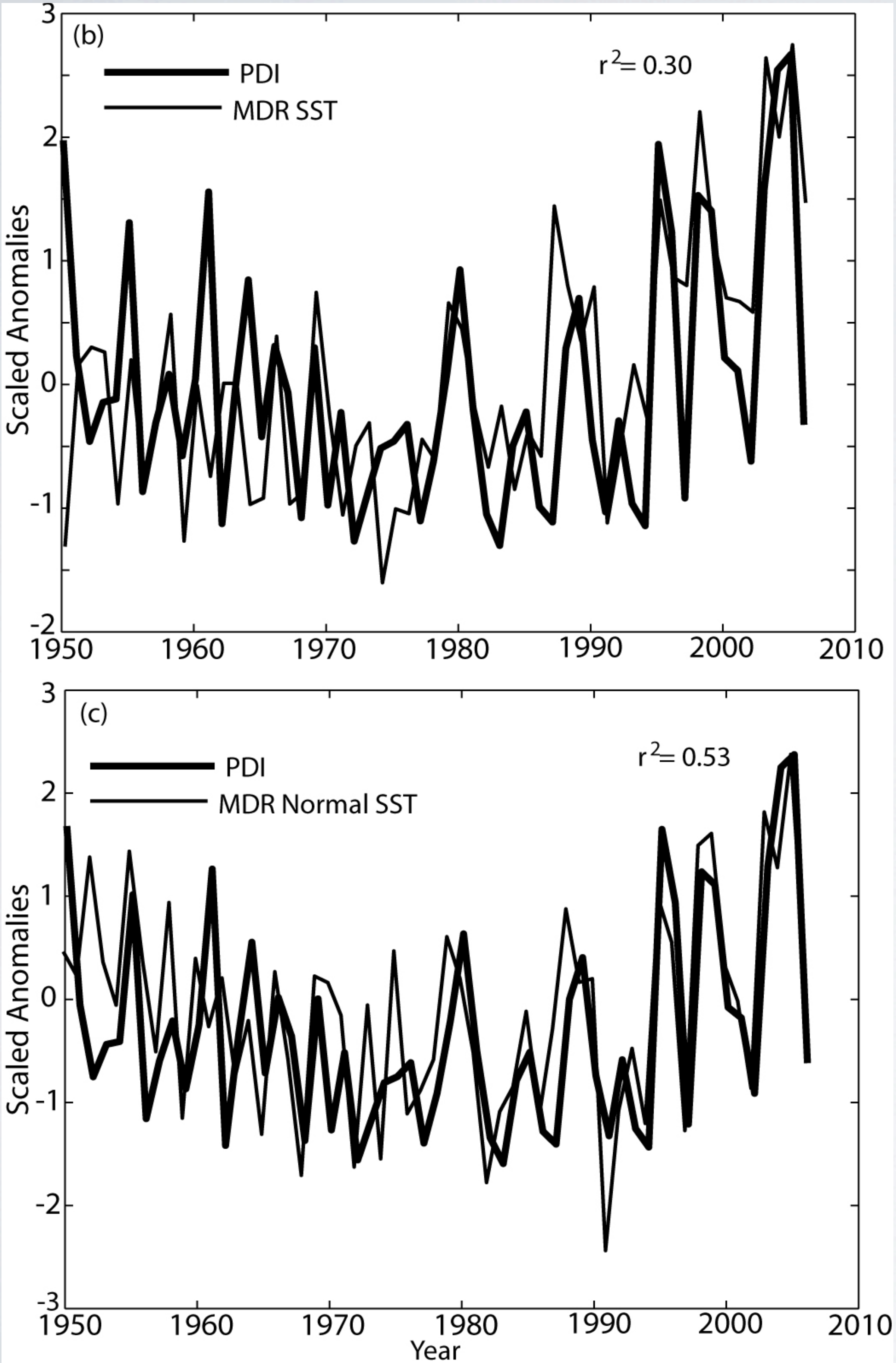




The HIRAM 50-km grid model simulated hurricane count changes (interannual and A1B scenario) are consistent with expectation based on tropical Atlantic SST minus global tropical mean SST (Ta -Tg).



Source: Zhao, Held, Lin, and Vecchi (J. Climate, 2009)

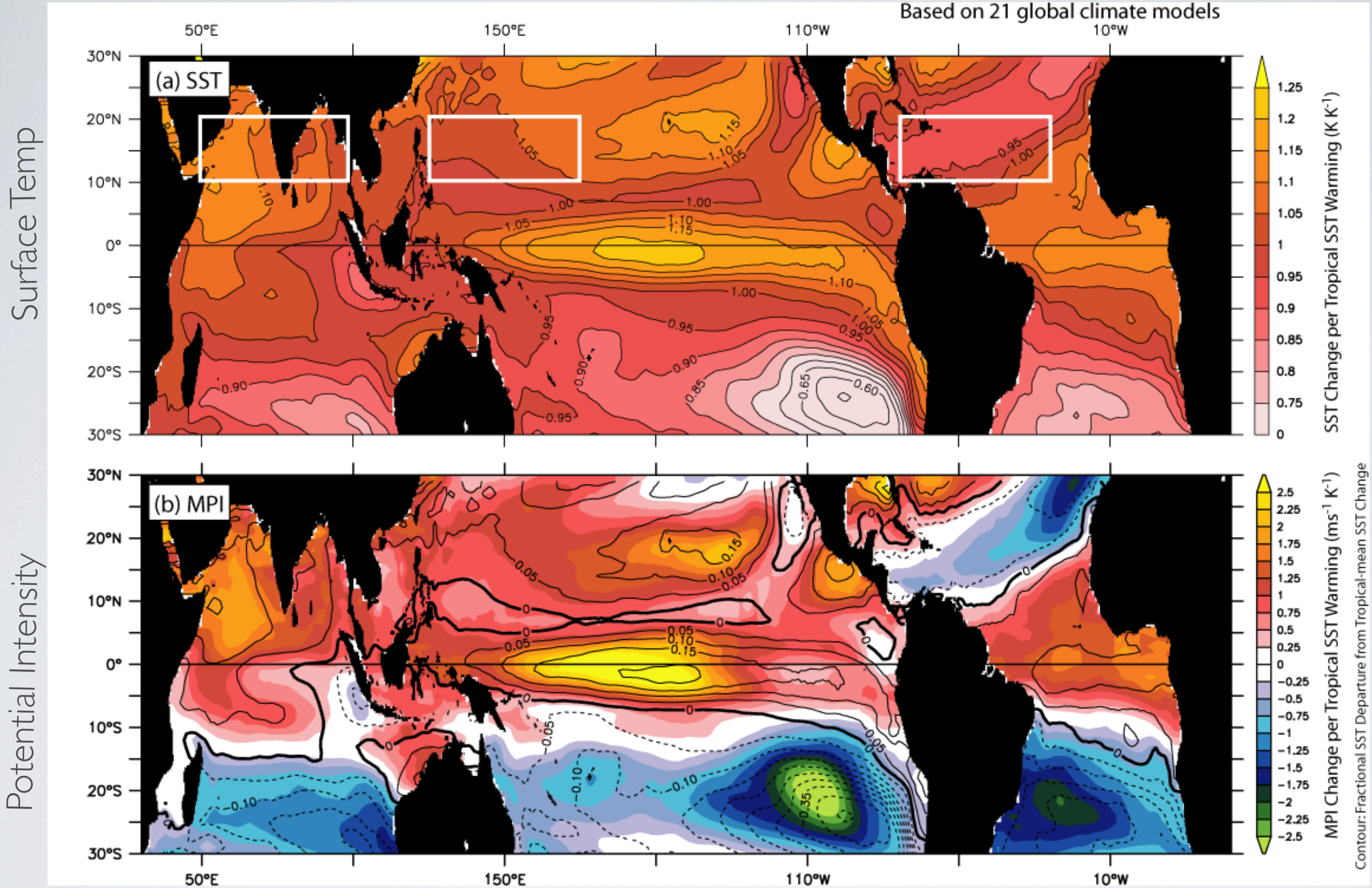


Atlantic hurricane activity (PDI) is correlated with local Atlantic SST (top) and with Atlantic SST relative to tropical mean SST (bottom).

These two SST measures behave very differently in greenhouse warming scenarios. Local Atlantic SST warms strongly, but Atlantic SST relative to tropical mean SST does not.

Source: Swanson, *G-cubed*, 2008

GCM Projections of 21st Century Changes in Large-Scale Environment



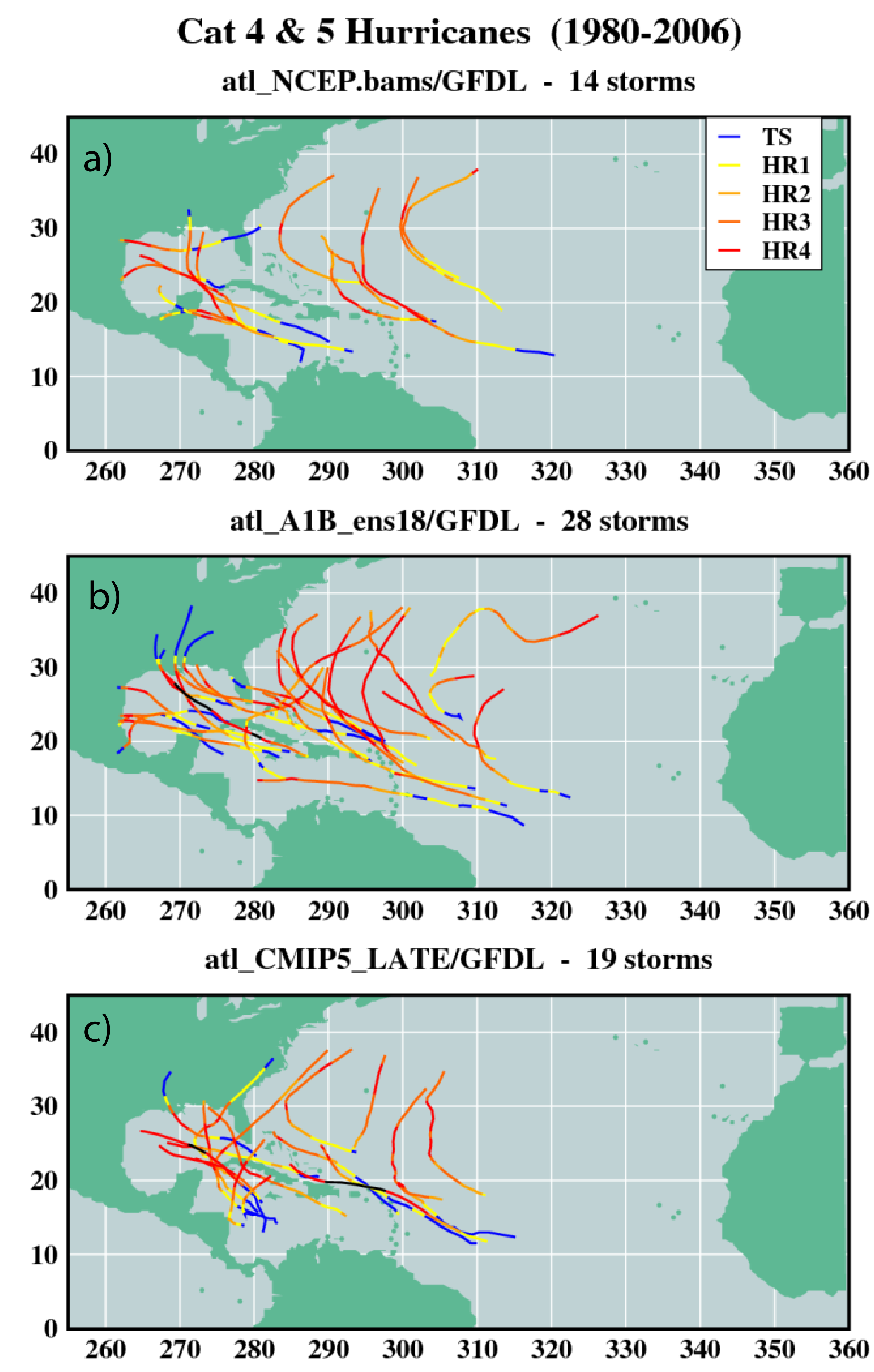
Model projections SST change show tropics warming. However, projections of PI change - a theoretical upper-bound on hurricane intensity - show areas of both increase and decrease, since PI is largely controlled by departure of local SST change from tropical-mean SST change.

These mixed changes in PI suggest that model projections of future hurricane activity will depend on details of SST change.

The sensitivity of PI to relative SST suggest that internal variabiity more efficient at modifying cyclones than uniform warming.

Source: Vecchi and Soden (2007, Nature)

Late 21st century projections of Atlantic Intense Hurricanes



shift toward Gulf of Mexico in CMIP5 but caution needed to assess any regional changes

Comparison of track maps for cat 4-5 storms

Knutson et al. 2012