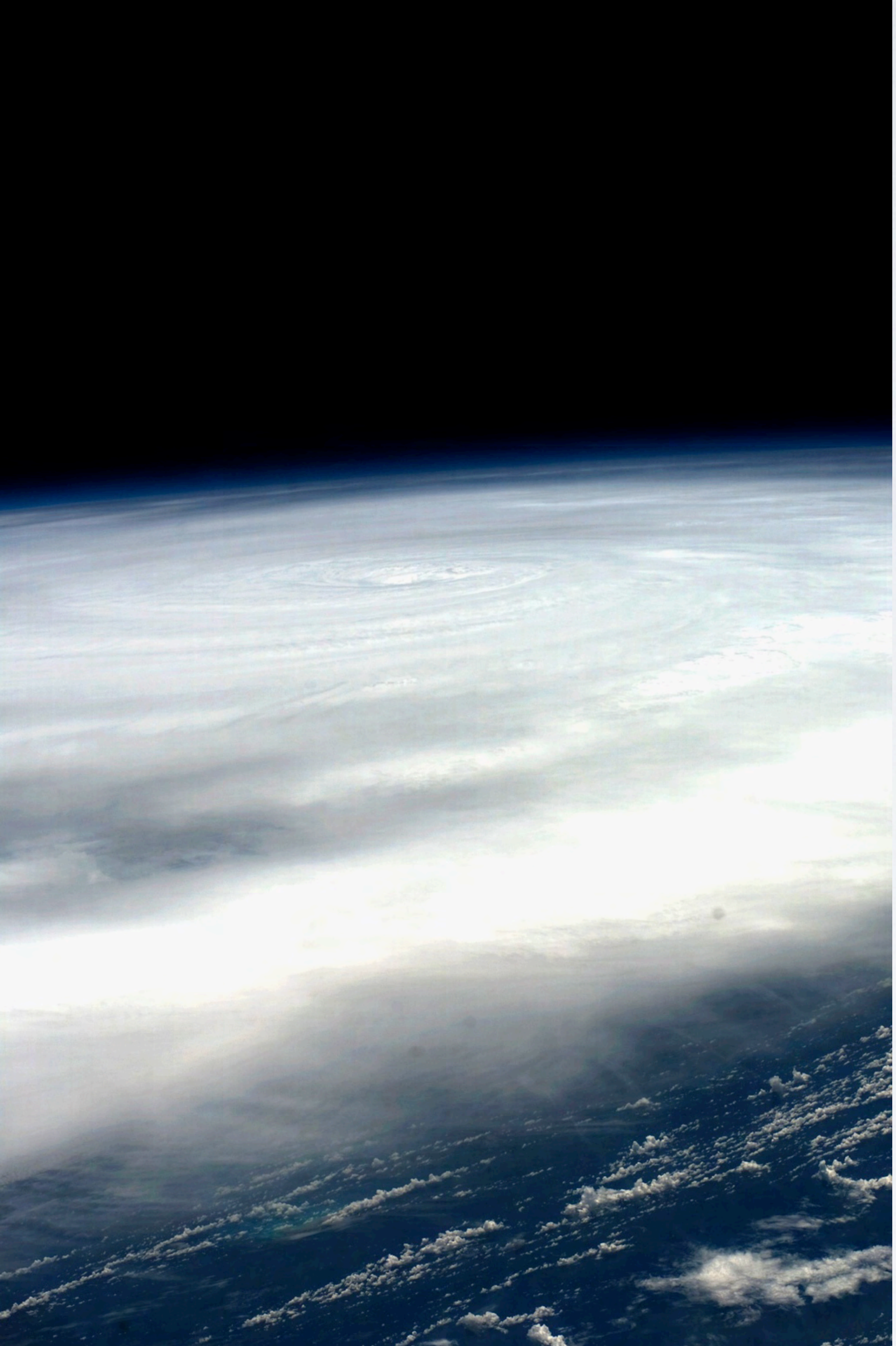


Deriving Hurricane Frequency Information from Global Climate Models

Gabriel Vecchi
NOAA/GFDL
Princeton, NJ

Gabriel.A.Vecchi@noaa.gov

Image: NASA.

Outline

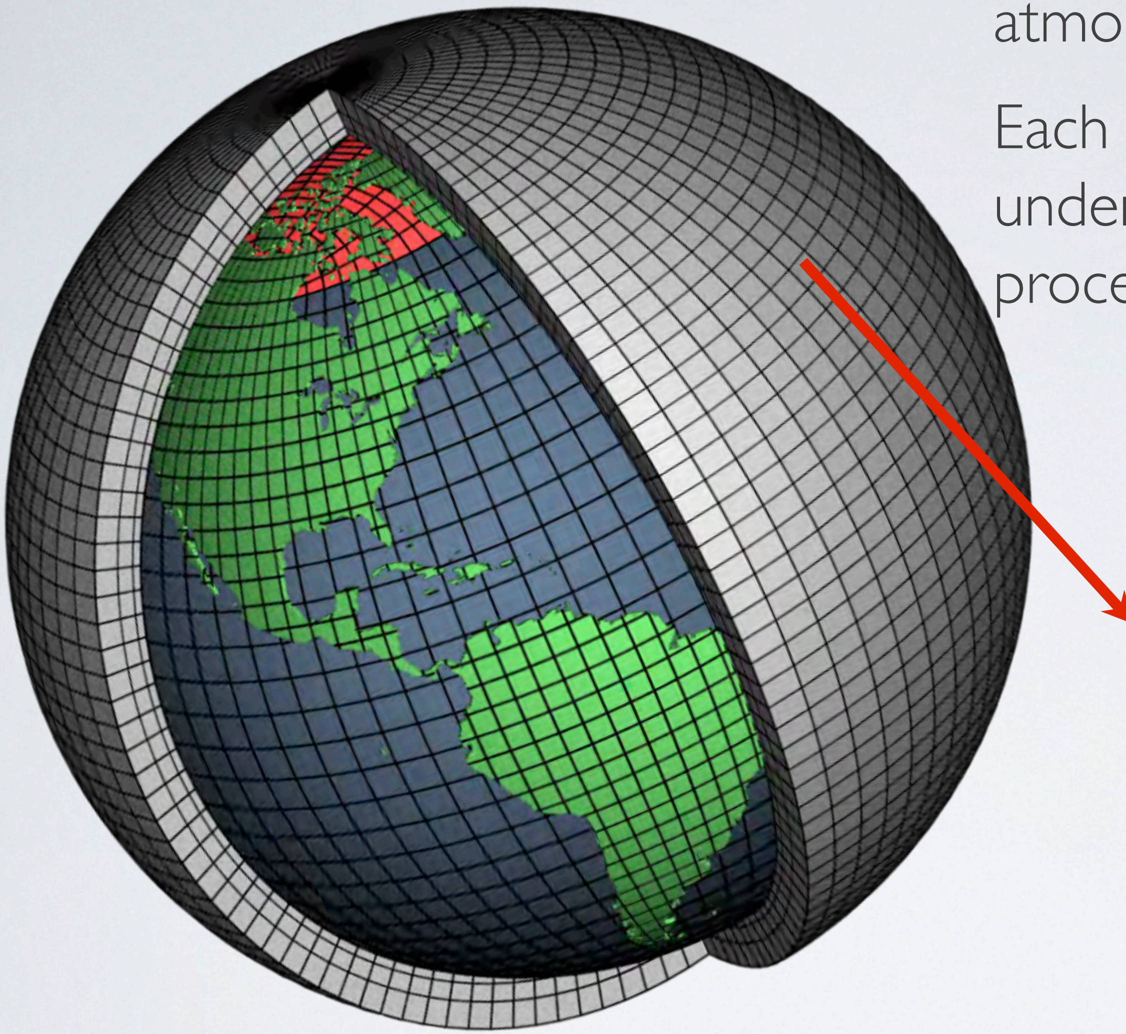
- What are “global climate models” (GCMs)?
- How can we extract hurricane frequency information from them?
  - Statistical Downscaling
  - Dynamical Downscaling
- Applications of Downscaling to 21st Century Projections

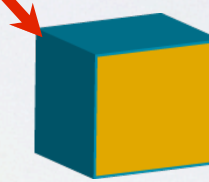
What are Global Climate Models?

- Mathematical representations of the processes controlling the evolution and interaction of the ocean, atmosphere, land and sea ice (equations of motion, thermodynamics, radiative transfer, etc.).
- Equations are discretized (broken up into “grid-cells”) to be run on some of the world’s most powerful computers.
- Equations derived from “first principles” (resolved) at grid-scale (limited by computer power), processes at smaller scales must be “parameterized”.
- Initial and (perhaps time-evolving) boundary conditions are specified, subsequent state of climate system emerges from integrated impact of processes.

Models have land, ocean, atmosphere and ice components.

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





In each grid cell:

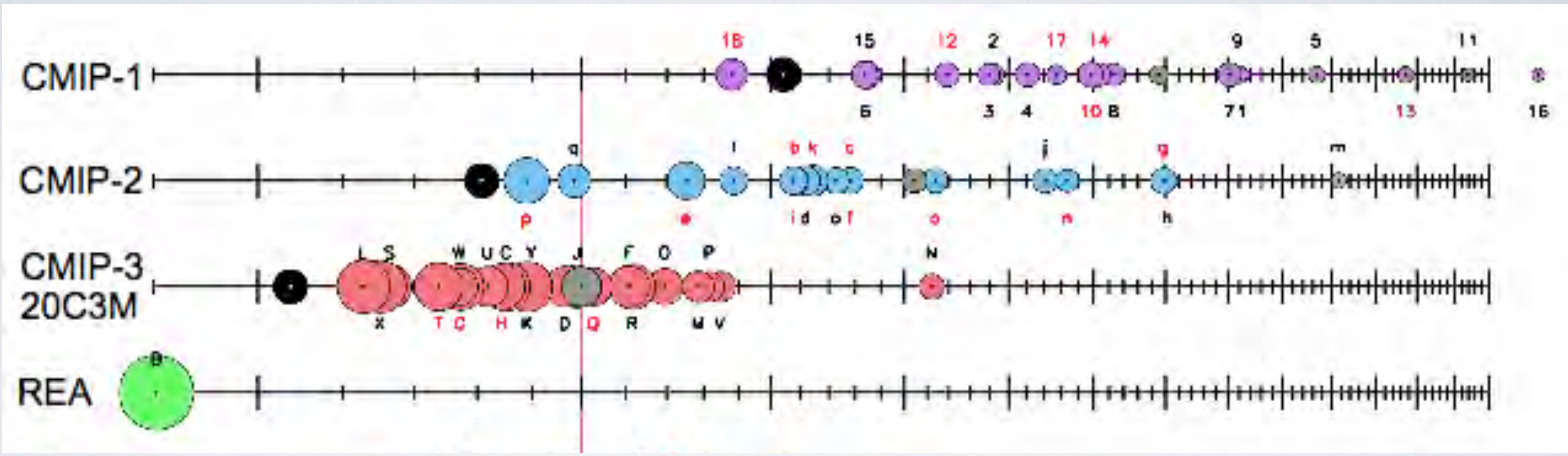
- ⋆conserve momentum (F=m ·a)
- ⋆account for changes in mass and composition
- ⋆conserve energy (radiation, latent, etc...)

“Force” with solar radiation, structure of continents and atmospheric composition (opacity)

Climate Model Fidelity to Climatology Has Steadily Improved

Skill at reproducing 20th Century

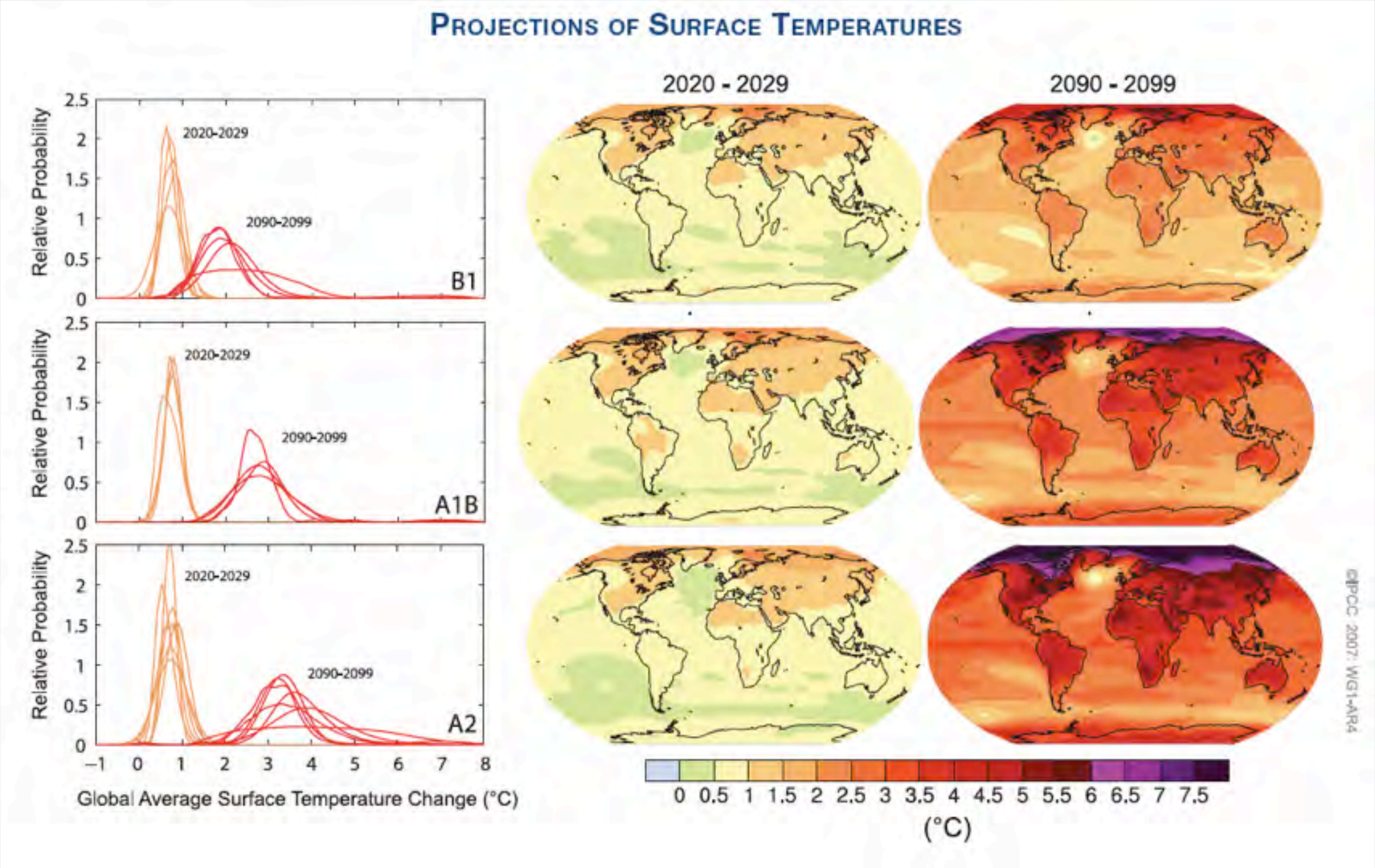
Newer models



Reichler and Kim (2008, BAMS)

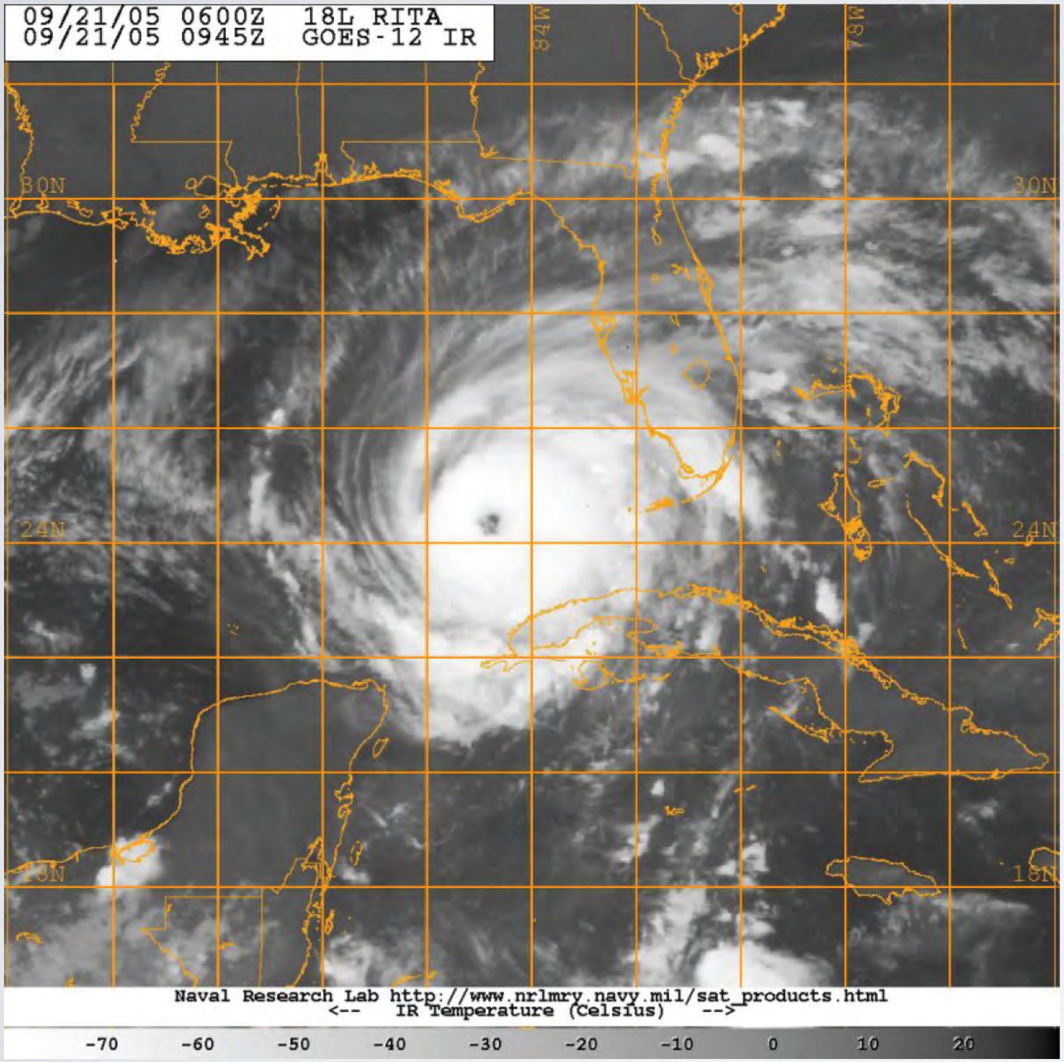
- Skill increasing with time
- Multi-model average better than any individual model
- Ability to reproduce climatology not necessarily projection skill

GCMs provide information about future state of climate given scenarios about future atmospheric composition (e.g., greenhouse gases)



IPCC-AR(2007)

Computing Power Limits Ability of "IPCC-AR4 Class" Global Climate Models to Represent Hurricanes...



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

Nonetheless, tropical storms are affected by ***large-scale*** conditions that today's climate models ***can*** represent.

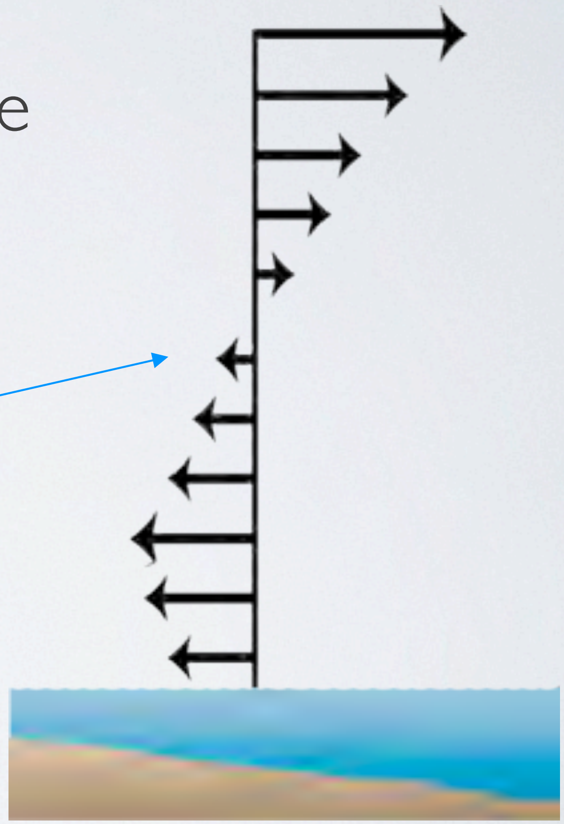
Factors that favor storm development and intensification:

- Warm ocean surface
- Cool upper atmosphere
- Low vertical wind shear
- Moist middle atmosphere
- etc.

} Help define potential intensity

cf. Emanuel, Holland

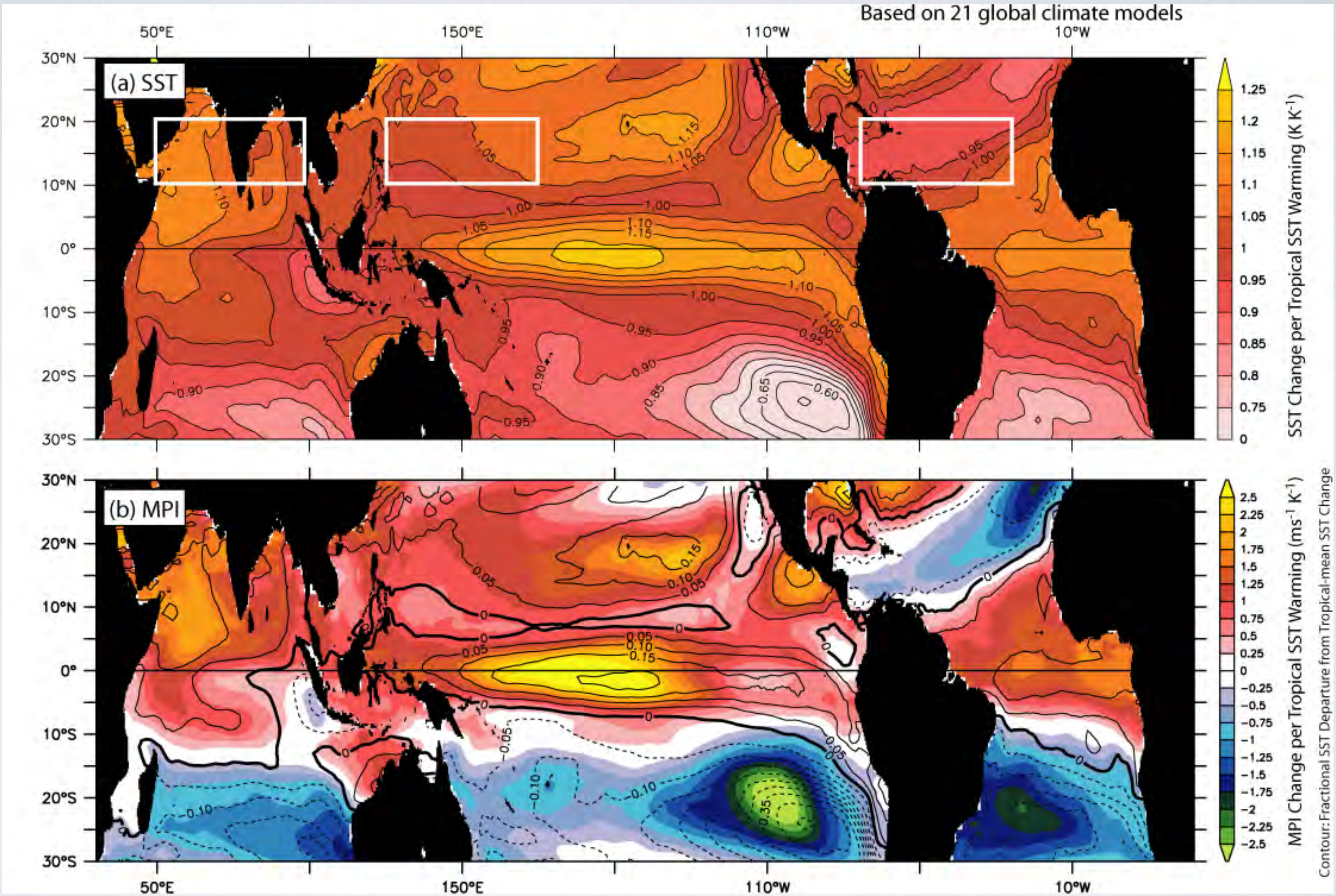
Vertical wind shear



GCM Projections of 21st Century Changes

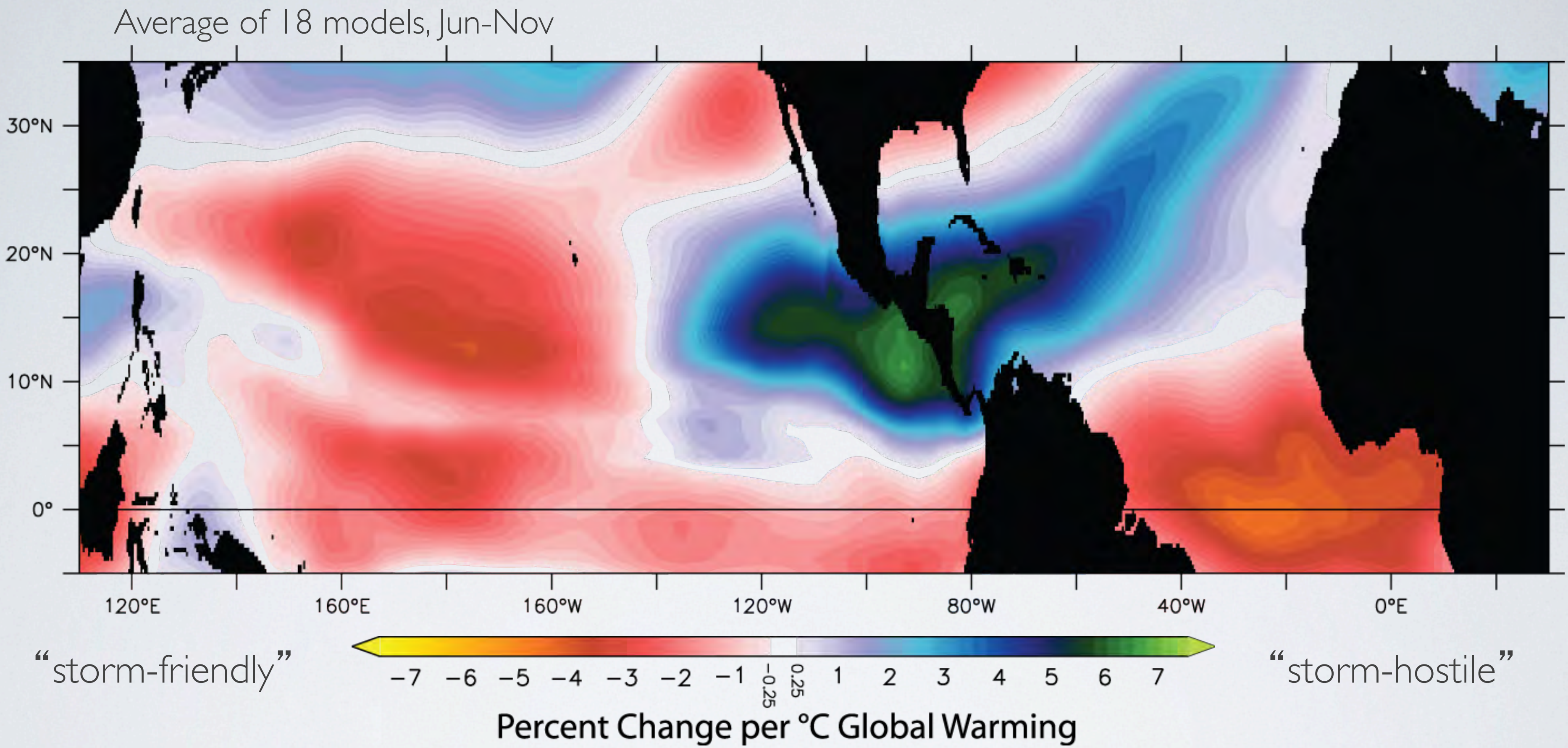
Surface Temp.

Potential Intensity



Vecchi and Soden (2007, Nature)

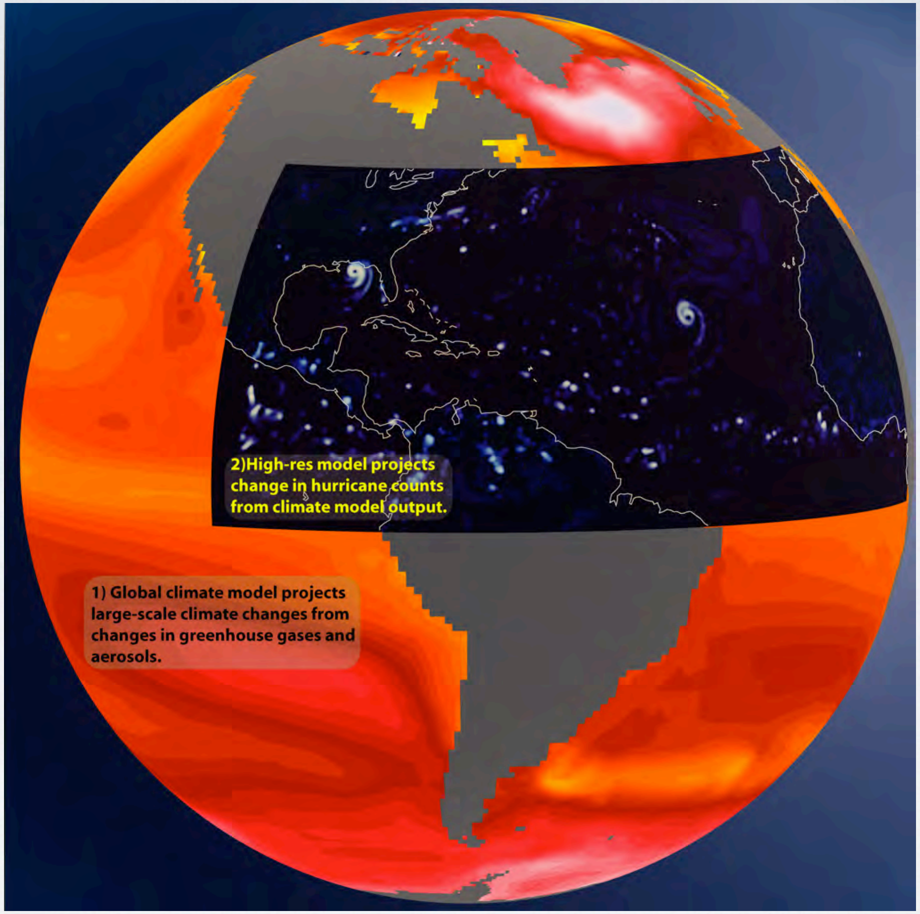
Projected 21st Century Changes in Vertical Wind Shear



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

Vecchi and Soden (2007, GRL)

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



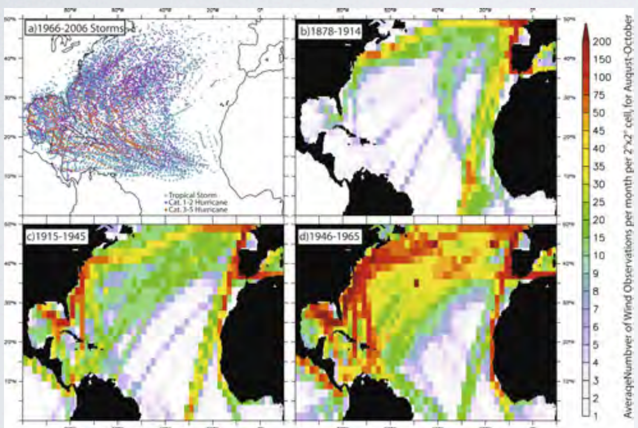
Global Climate Models -> High-resolution Model

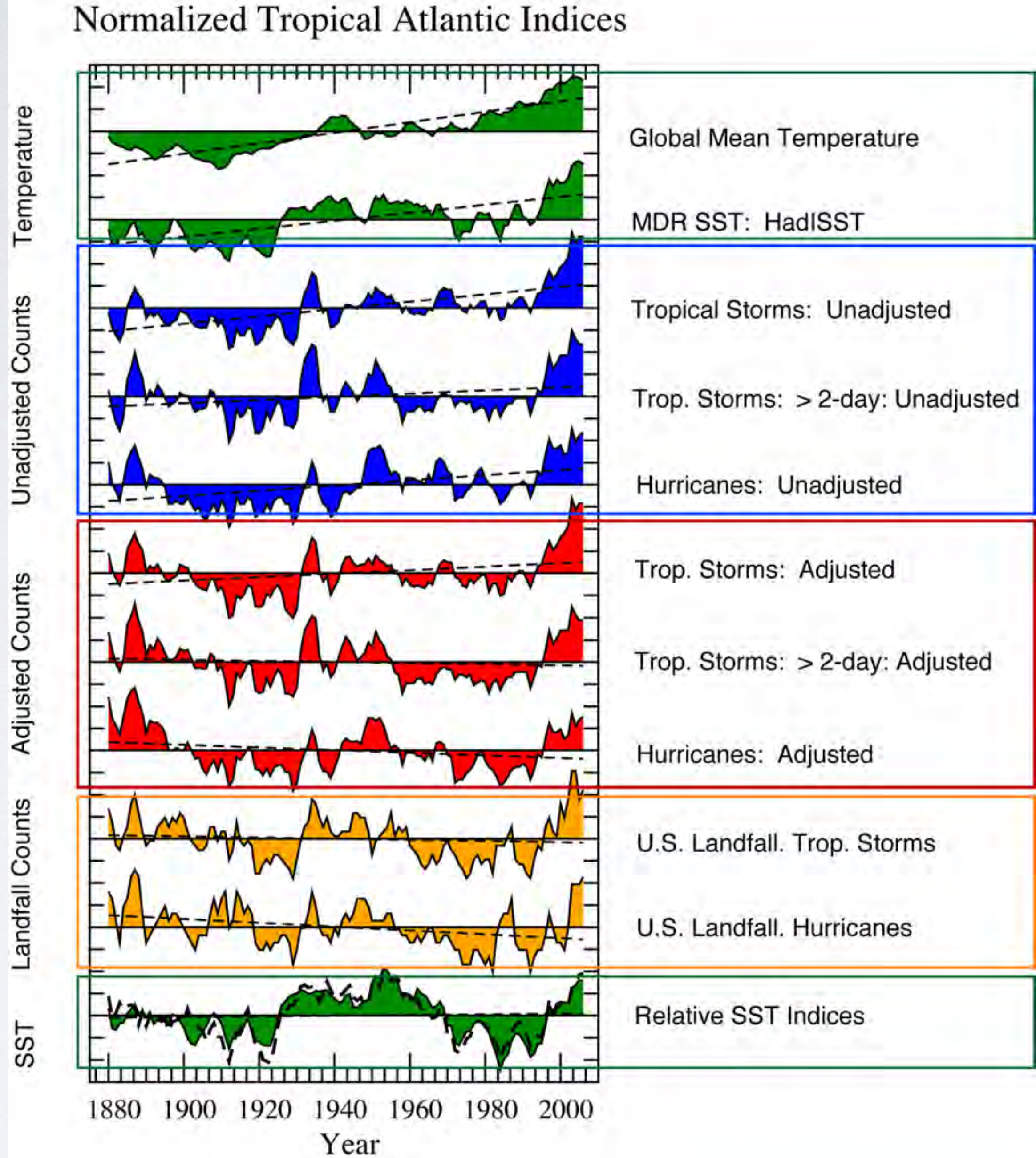
Large-scale TS Frequency

Statistical Downscaling

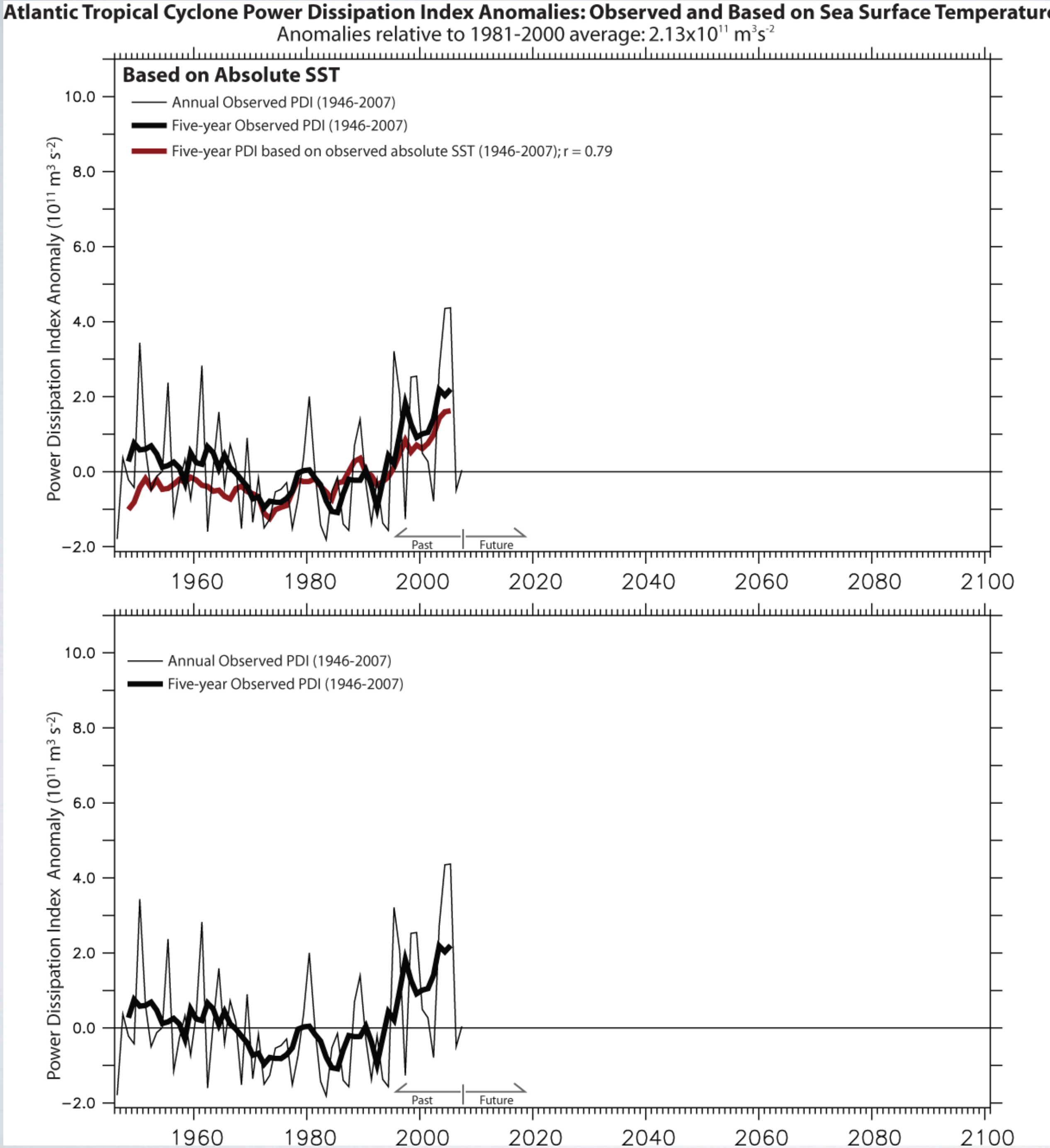
- Build a statistical model of tropical cyclone activity based on climate covariates
- Apply statistical model to the covariates emerging from climate models

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





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

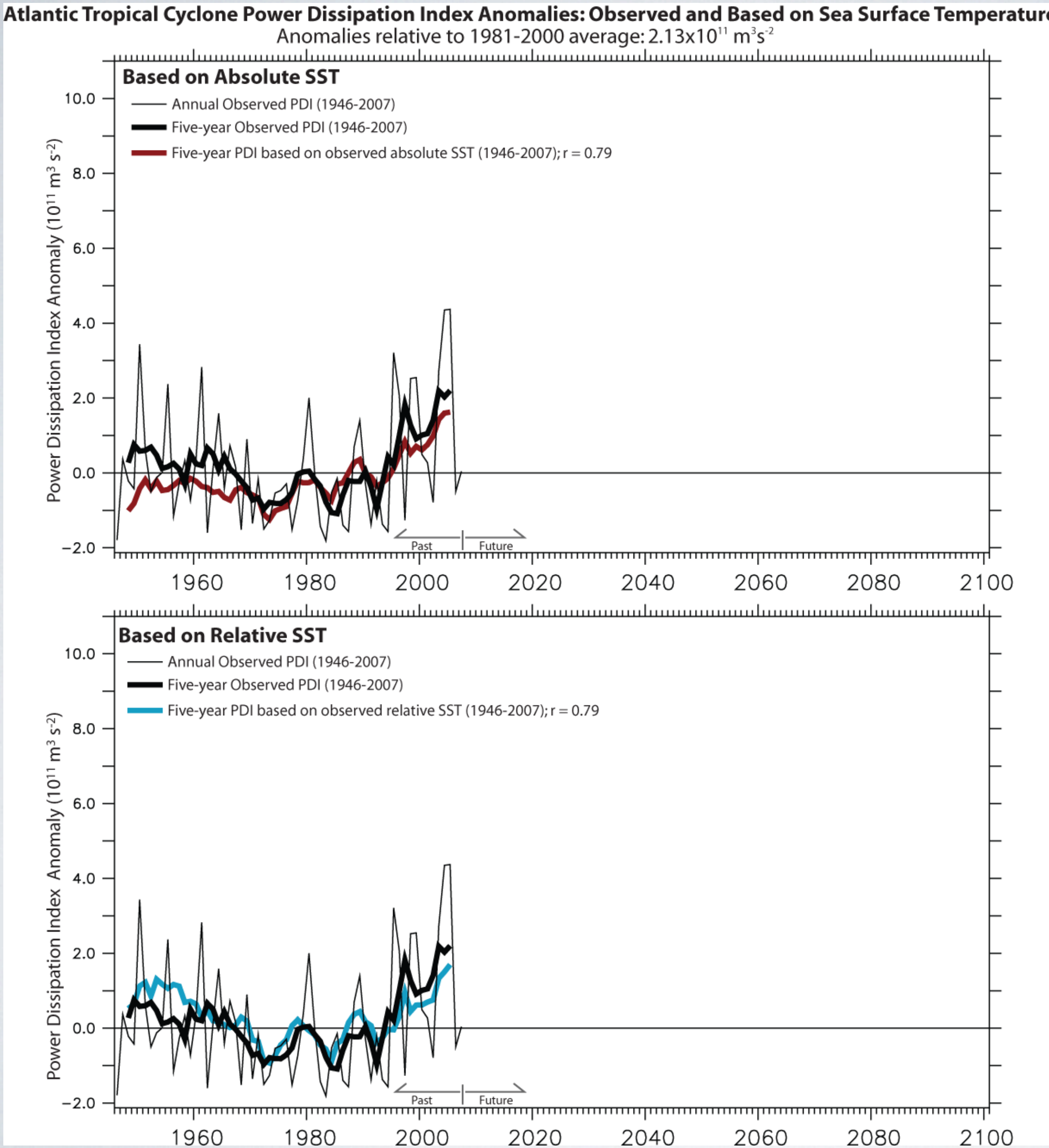


Observed PDI

PDI Regressed on:
Absolute SST

If causal, can attribute.

Vecchi, Swanson and Soden (2008, Science)



Observed PDI

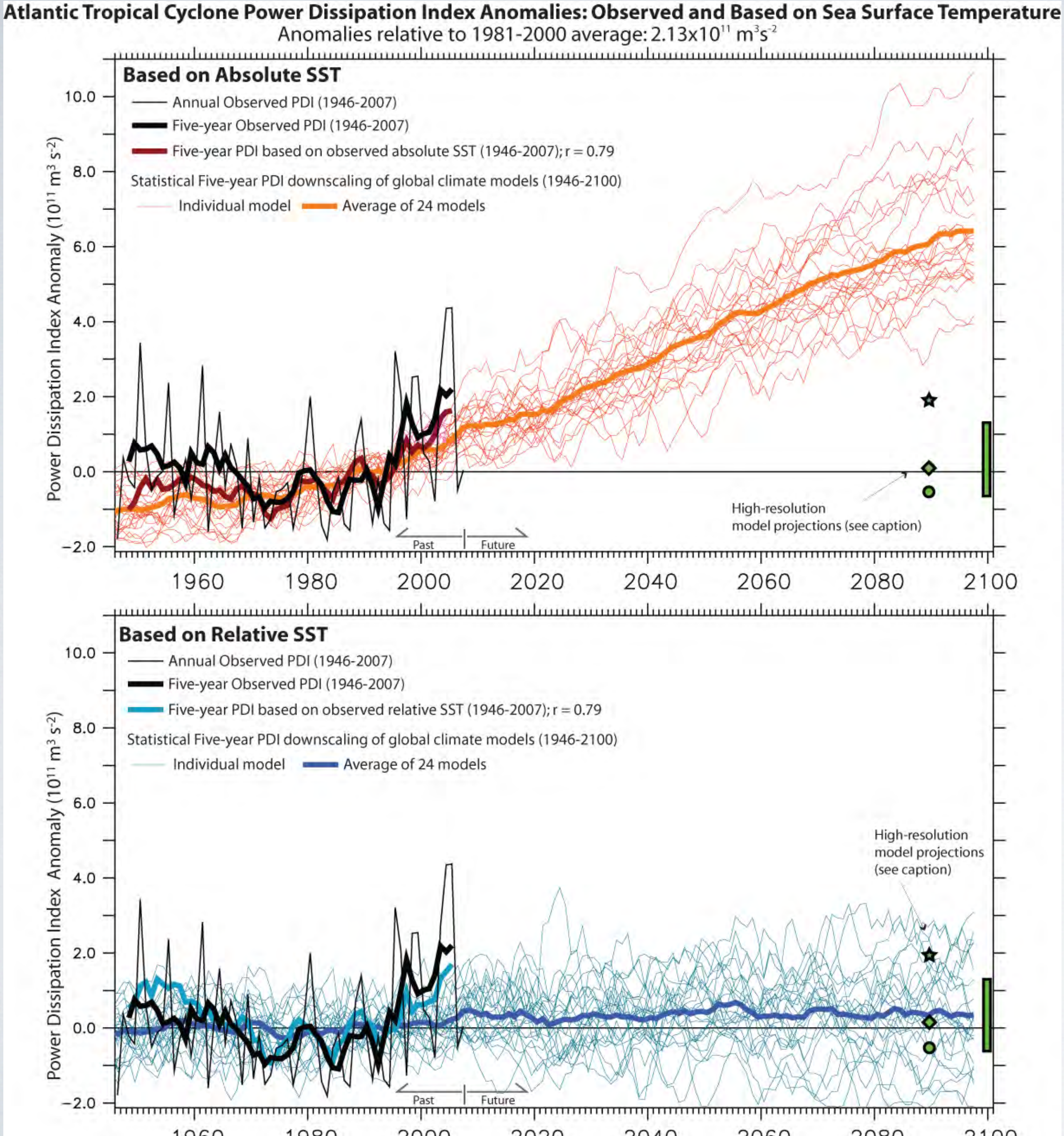
PDI Regressed on:
Absolute SST

If causal, can attribute.

PDI Regressed on:
Relative SST

If causal, **cannot** attribute.

Vecchi, Swanson and Soden (2008, Science)



Observed PDI

PDI Regressed on:
Absolute SST
Model Abs. SST

High-resolution model activity change

Emanuel et al (08),Knutson et al (08)
Oouchi et al (06),Bengtsson et al (07)

PDI Regressed on:
Relative SST
Model Rel. SST

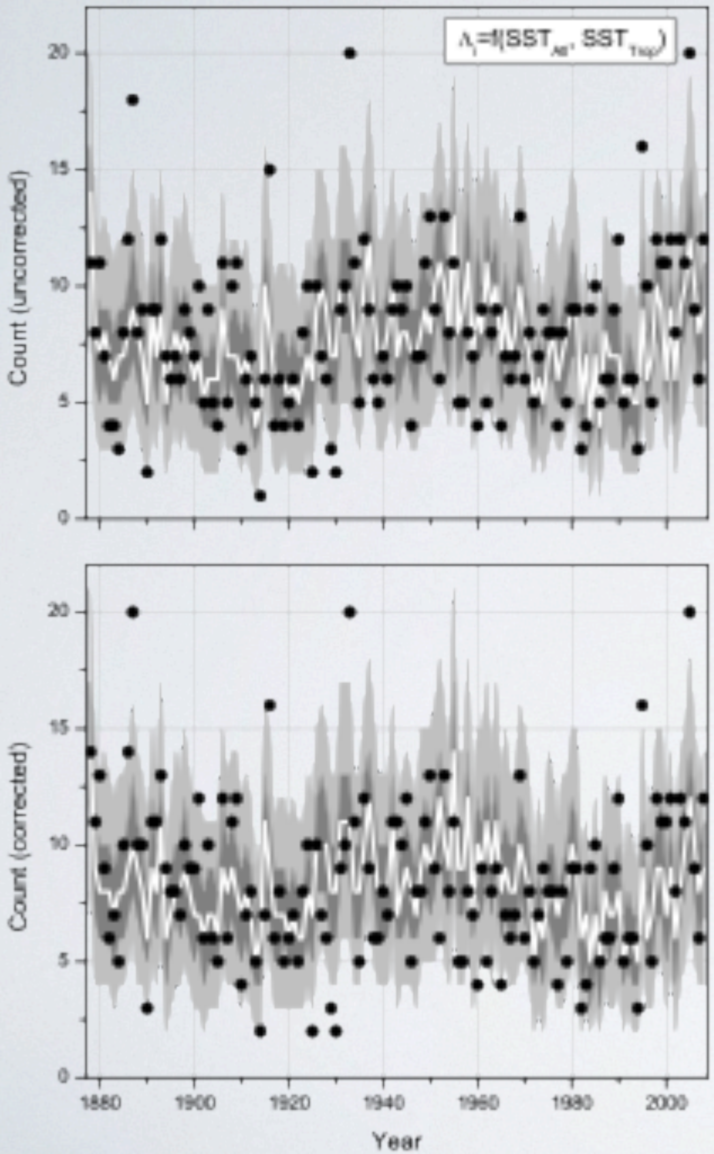
Vecchi, Swanson and Soden (2008, Science)

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.

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.

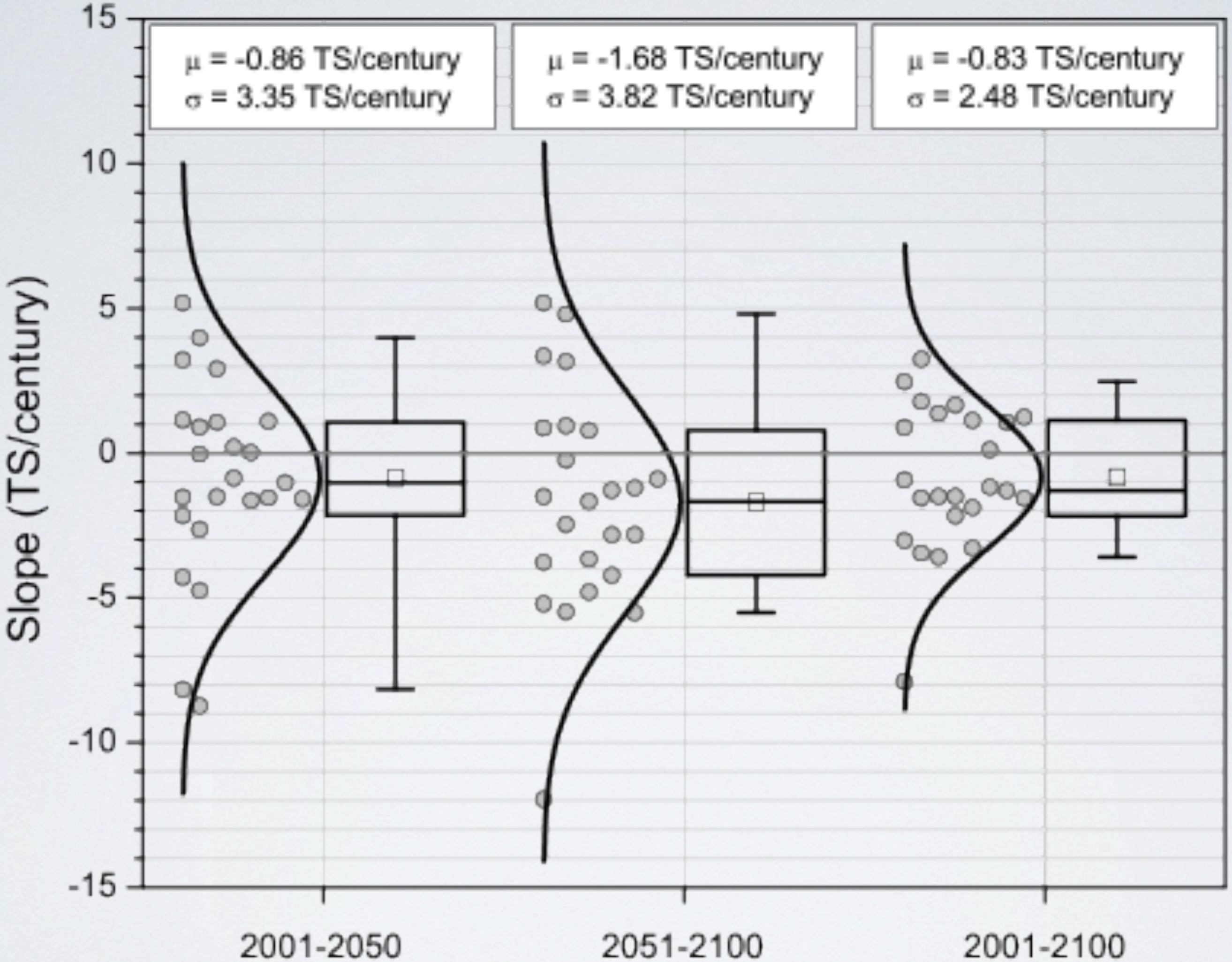
Small impact from uniform warming.

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)

Statistical Projections of 21st Century NA TS Trends



Villarini et al (2011, in press)

Dynamical Downscaling (High-Resolution Models)

Regional and global atmospheric models at higher resolution than can be afforded for GCMs, in which tropical cyclones (or regional feature of interest) emerge from underlying dynamics

GFDL regional model simulation.

Knutson et al (2007, BAMS)

Models ranging in 100km to 18km resolution.

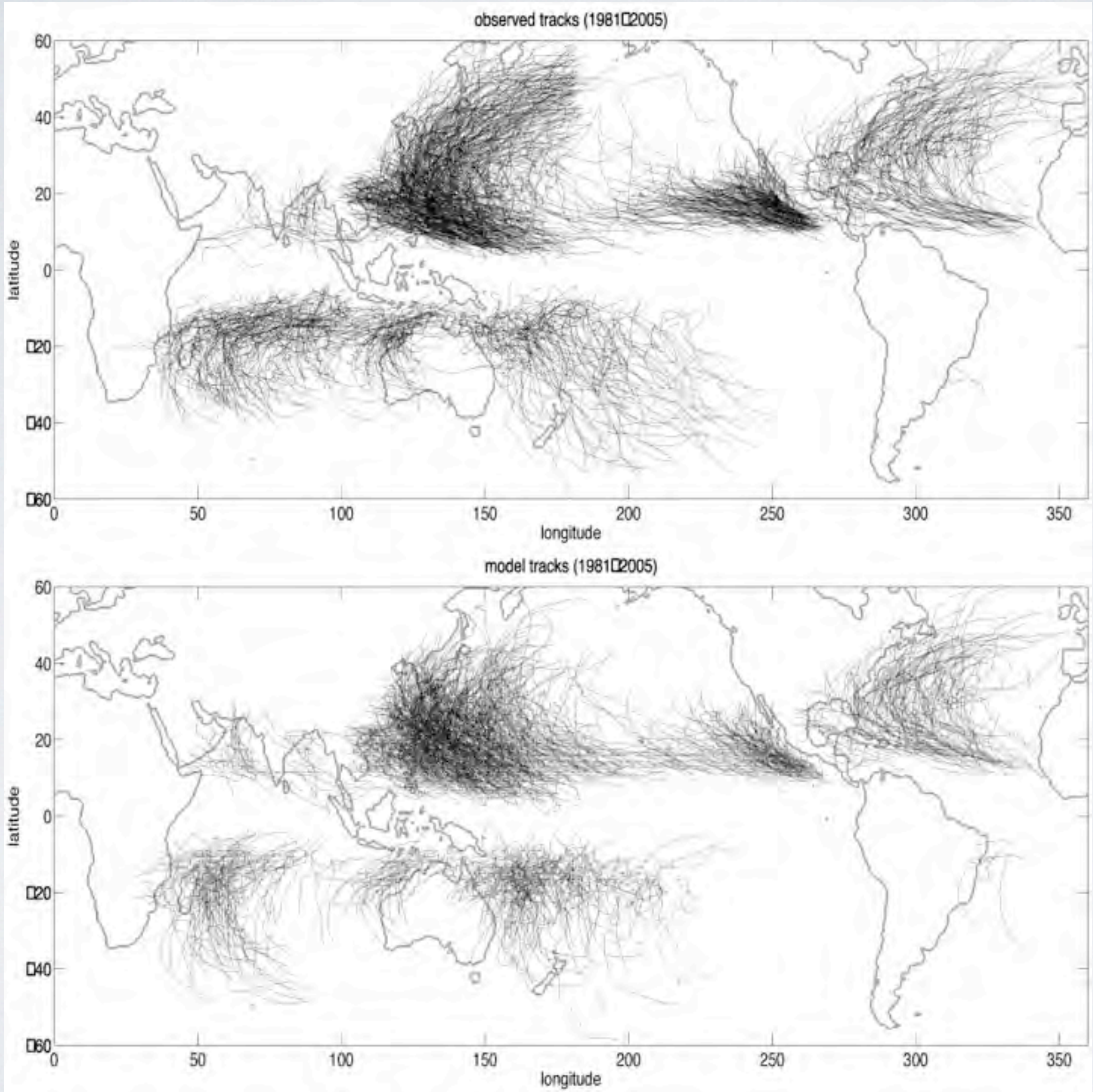
GFDL global model simulation.

Zhao et al. (2009, J. Climate)

Models can recover many aspects of observed hurricane tracks

Observed

C180 Model

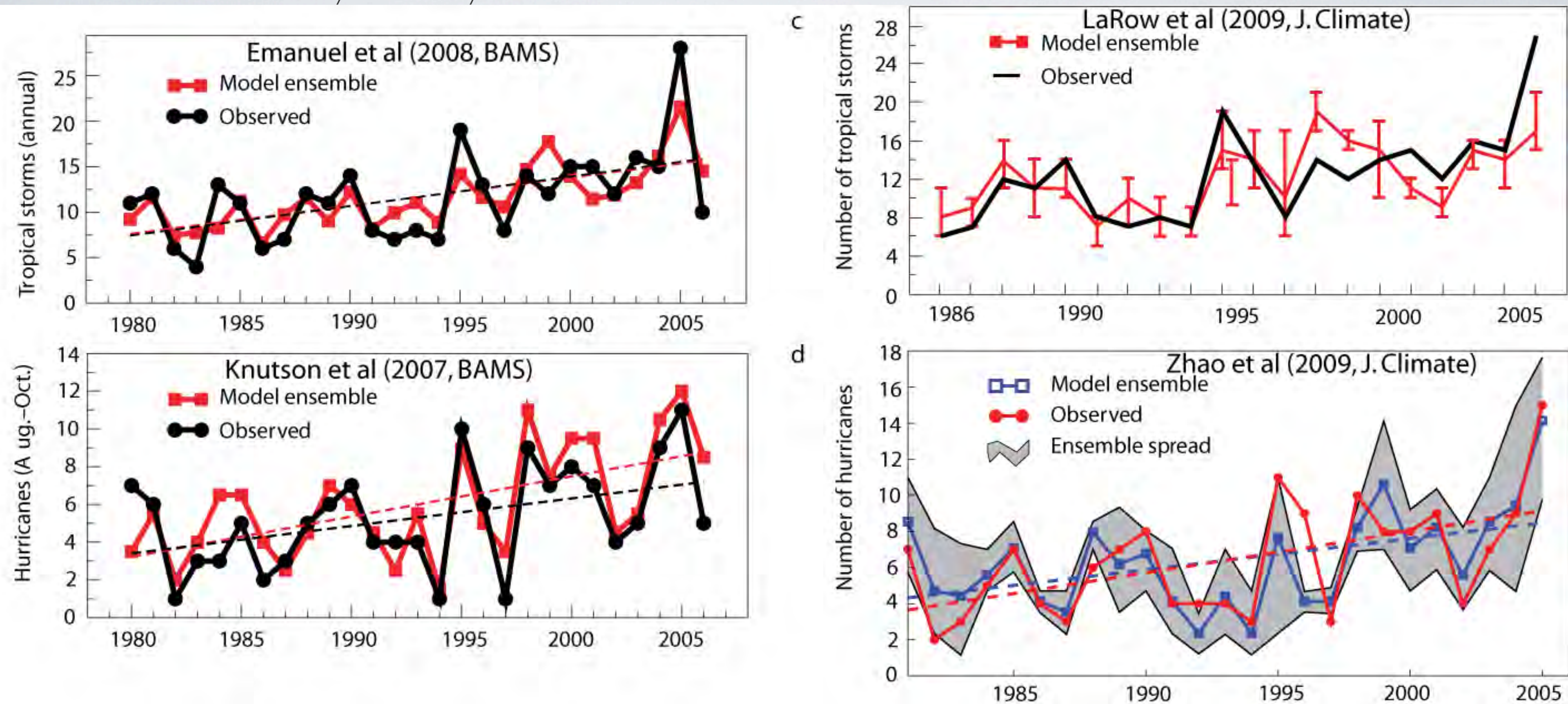


Zhao et al (2009, J. Climate)

Dynamical Models Exhibit Skill in Seasonal Basin-wide Hurricane Frequency

Statistical-dynamical hybrid model

100km SST-forced AGCM



18-km regional model

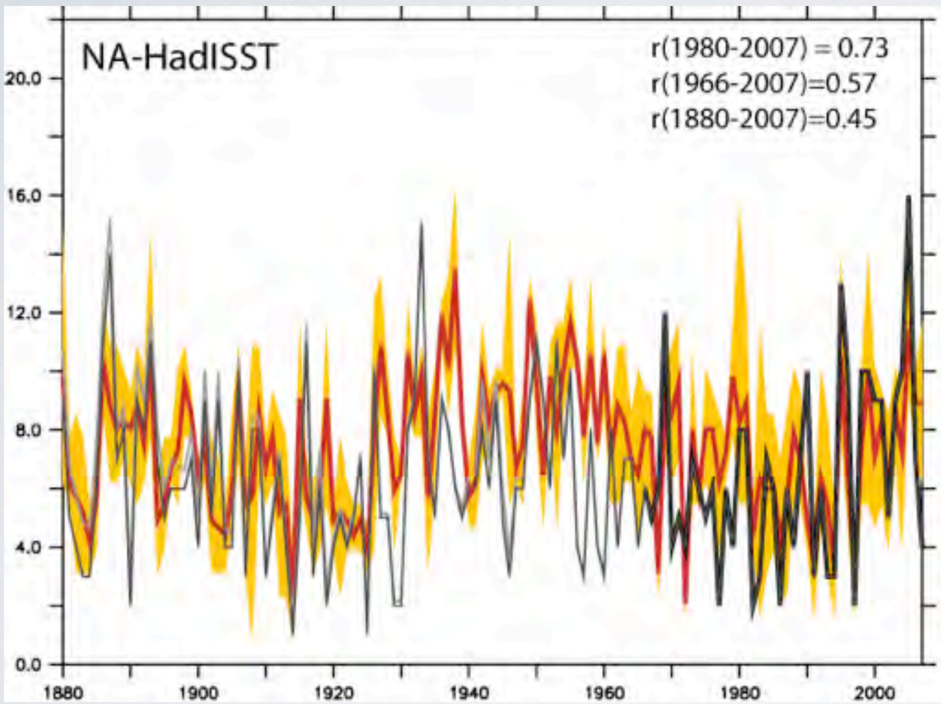
50km SST-forced AGCM

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

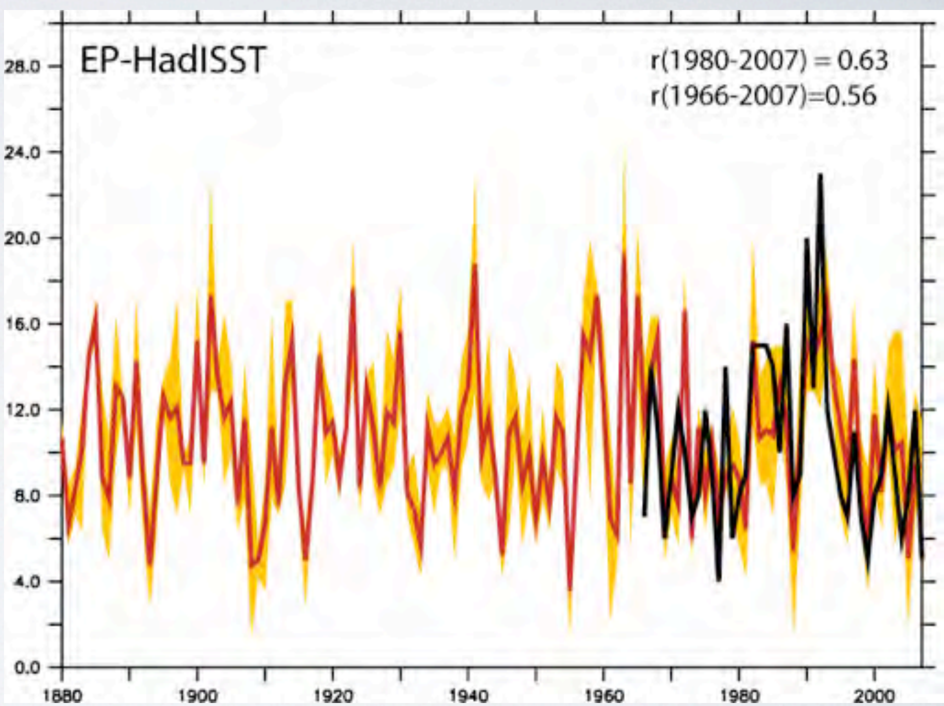
Model Recovers Century-Scale TS Changes

Using 100km version of Zhao et al (2009, J. Clim.) High-Res Model

North Atlantic TSs

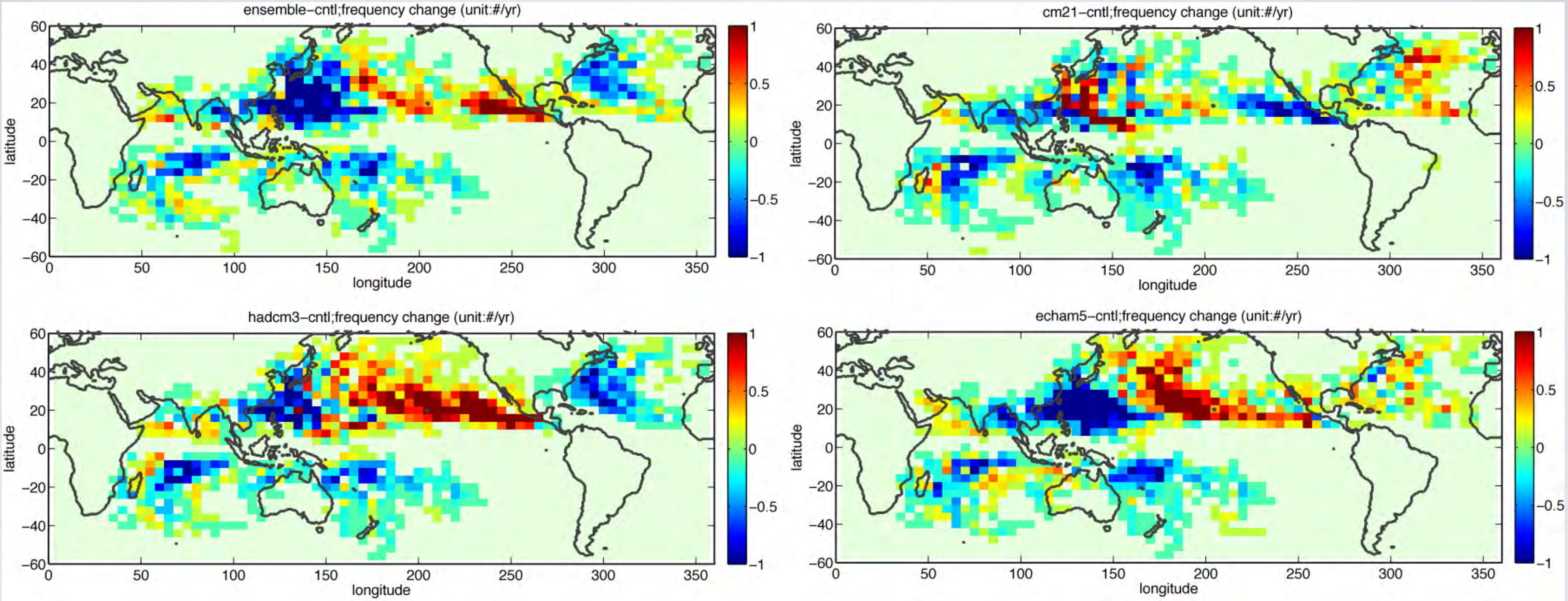


East Pacific TSs



Vecchi et al (2011, in prep.)

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)

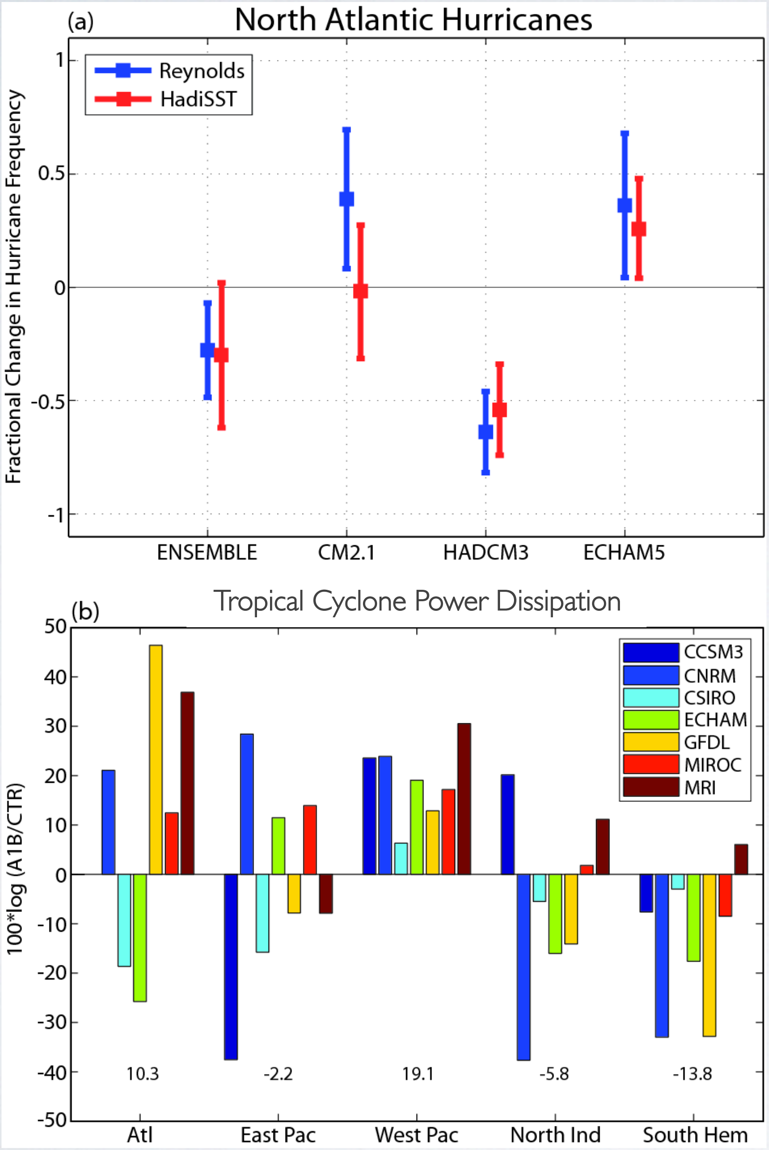
Regional increase/decrease much larger than global-mean.

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

Future TC Projections: Dependence on Climate Model



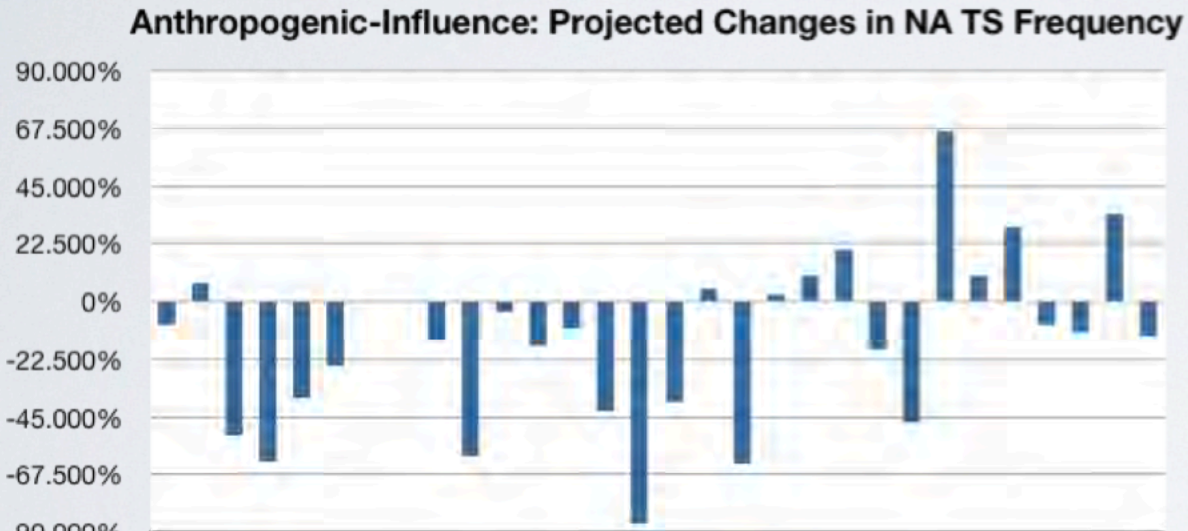
Zhao et al (2009, J. Climate)

Projections of late 21st century tropical cyclone metrics (hurricane count, power dissipation) depend strongly on the particular climate model used to provide the large-scale climate change projections for the downscaling model.

Emanuel et al (2008, BAMS)

Divergence of 21st Century projections of TS Frequency

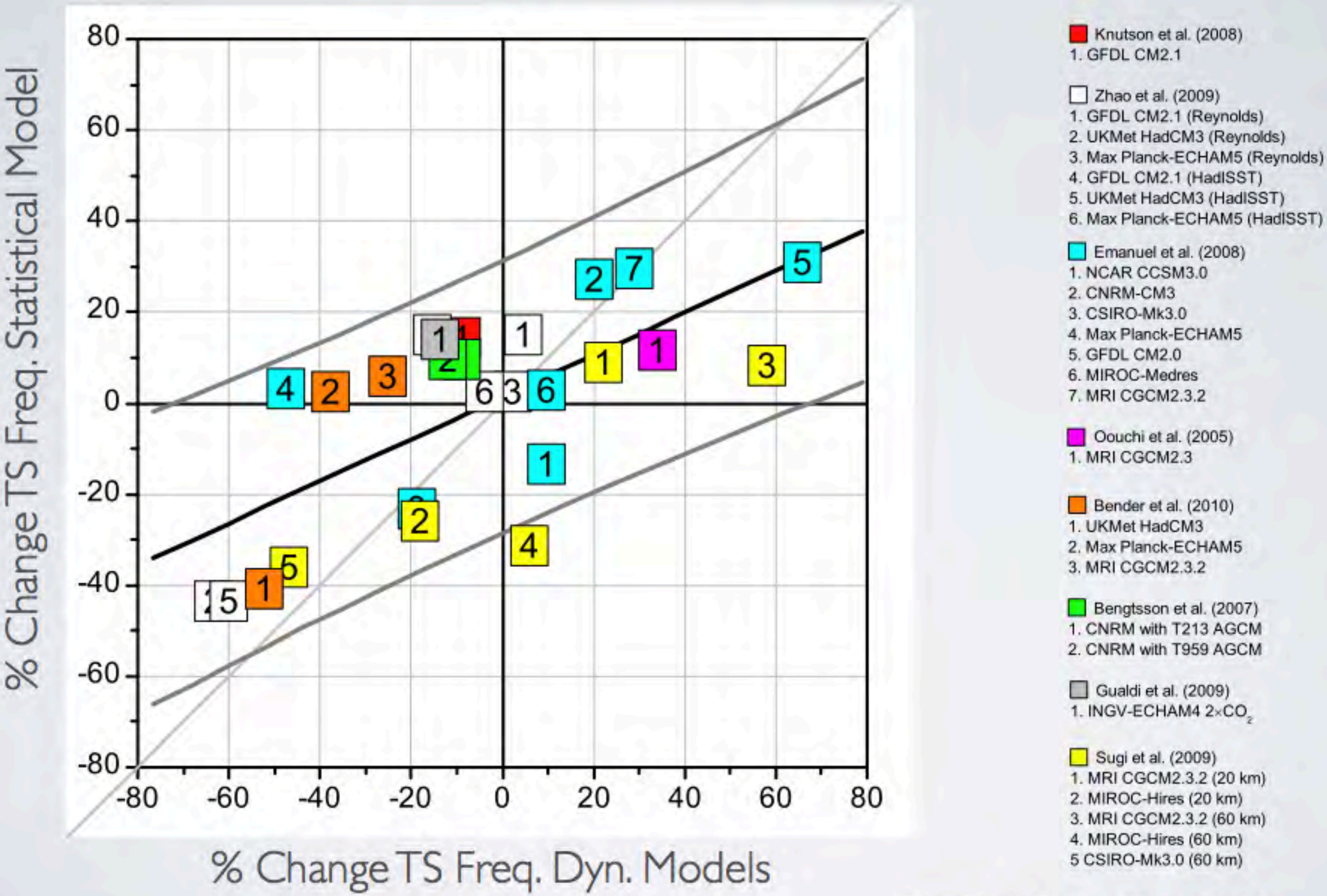
- Even sign of NA TS frequency response to GHG unclear: Not big help in decadal predictability
- Various studies downscale different coupled models, and over different periods



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

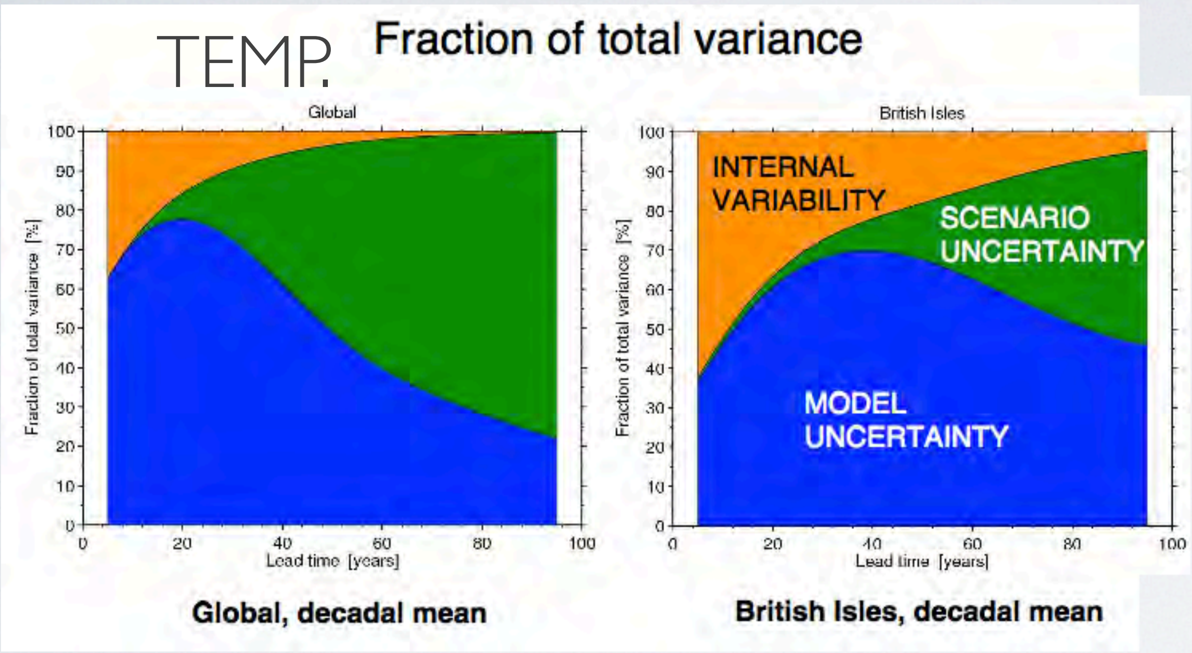
Is there any consistency in the various projections?

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



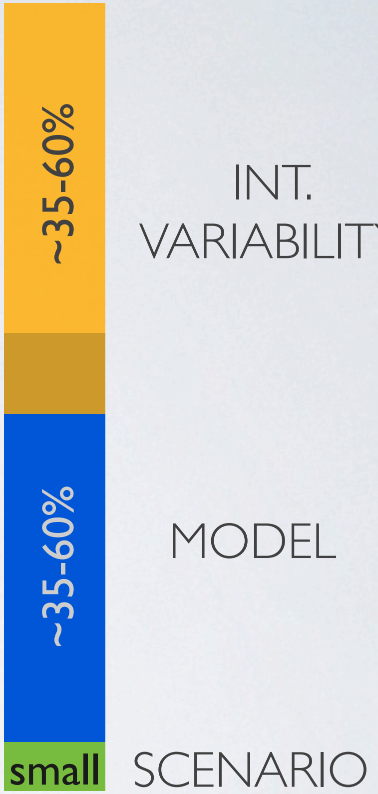
Villarini et al (2011, J. Clim. in press)

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



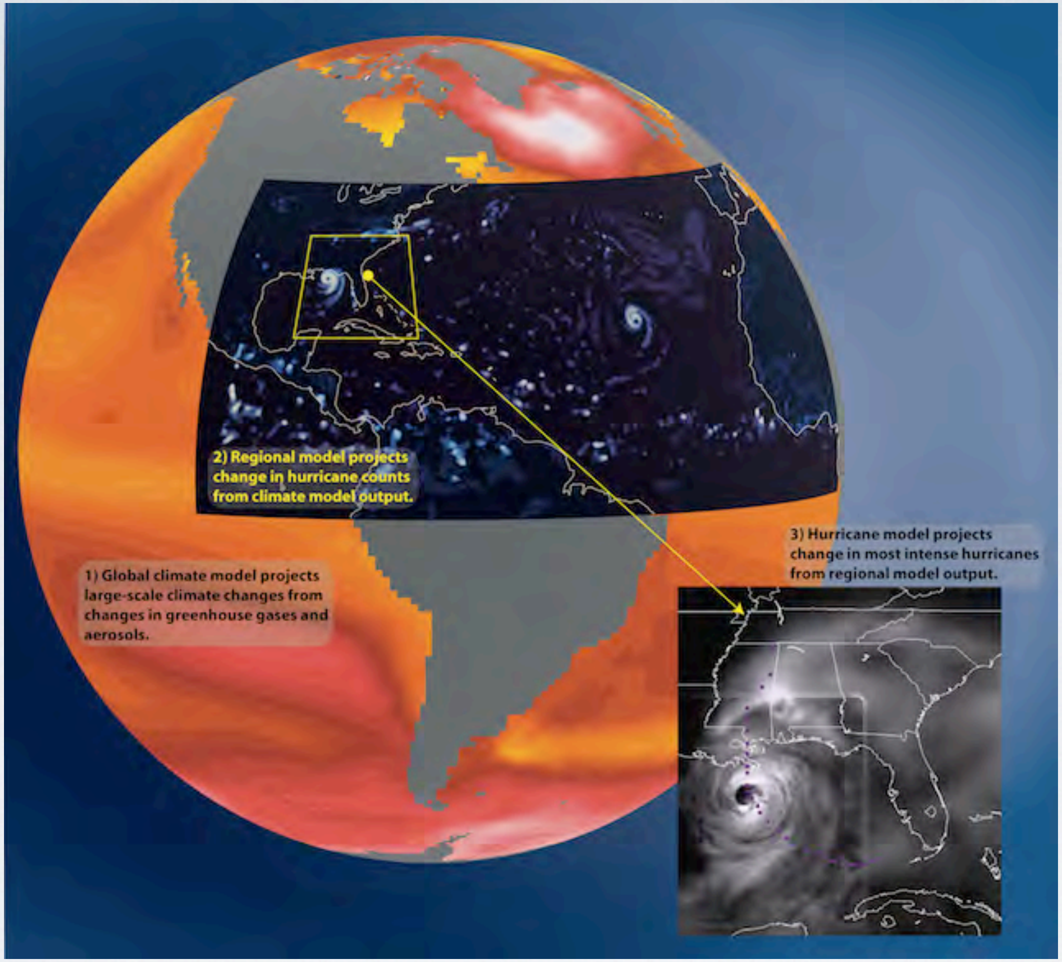
Hawkins and Sutton (2009)

TS count trends



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

Strongest cyclones projected with double downscaling

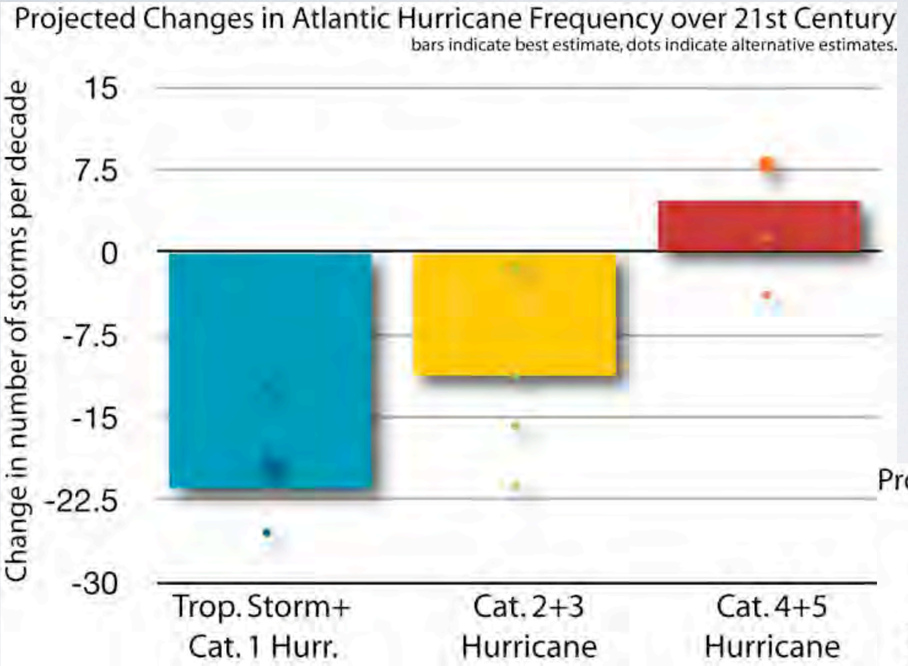


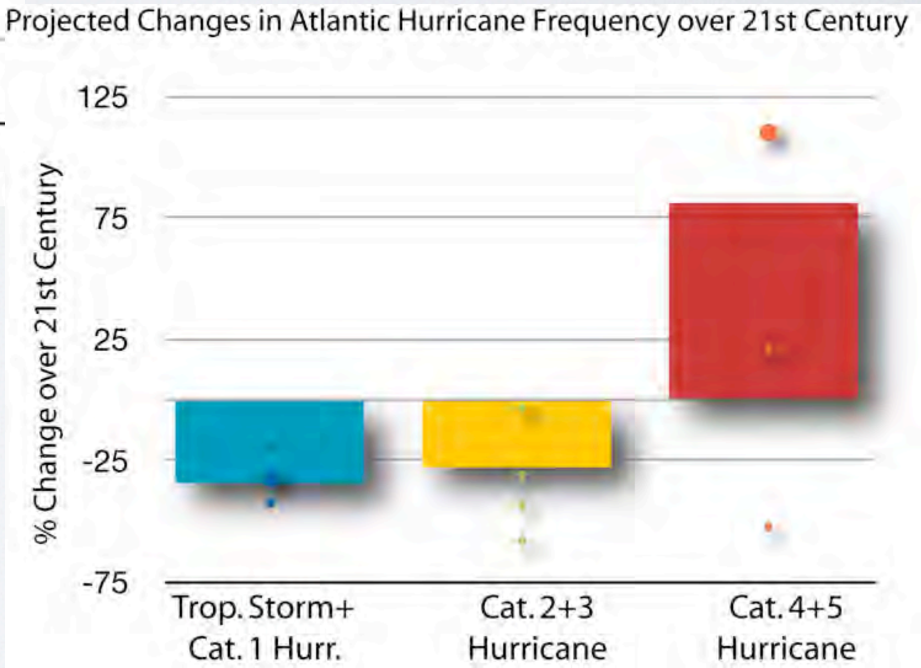
Adapted from Bender et al (2010, Science)

Global Climate Models -> Regional Model -> Hurricane model

Large-scale TS Frequency Intensity

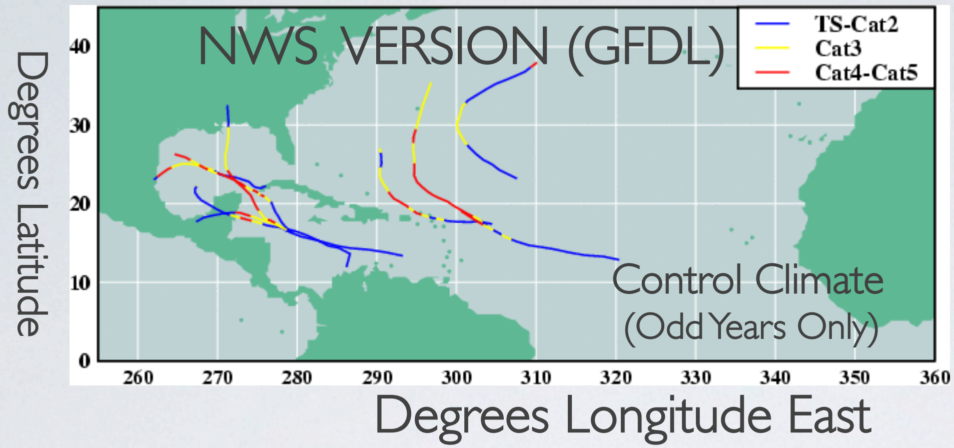
Overall frequency decrease, but strongest storms may become more frequent



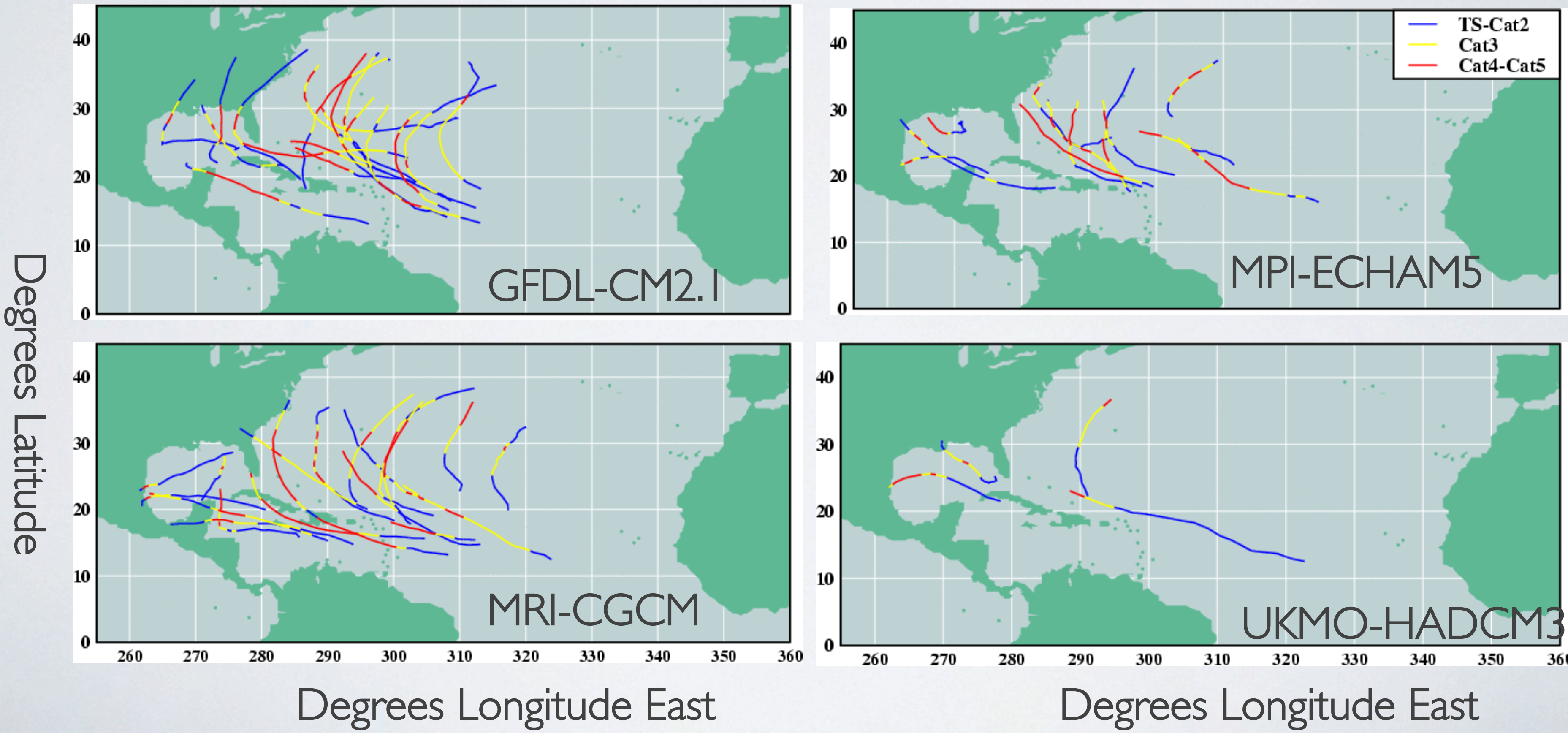


Adapted from Bender et al (2010, Science)

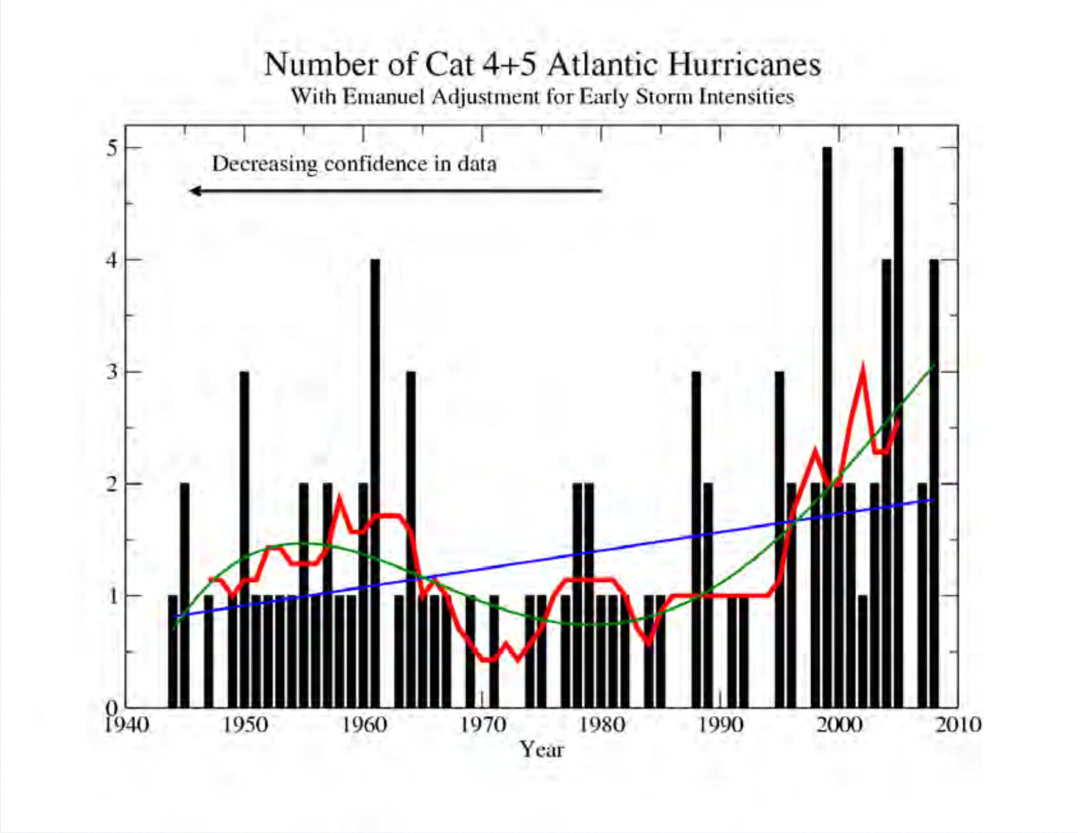
Tracks of Storms that Reached Category 4 or 5 Intensity



Late 21st Century Warmed Climate Projection based on 4 Individual CMIP3 Climate Models

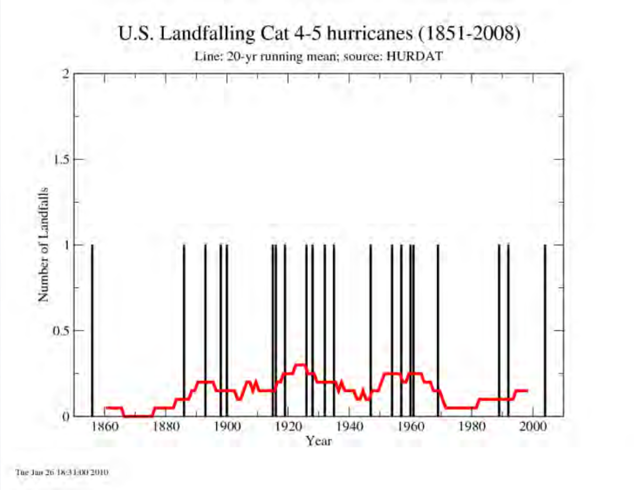


Emergence Time Scale: If the observed Cat 4+5 data since 1944 represents the noise (e.g. through bootstrap resampling), how long would it take for a trend of ~10% per decade in Cat 4+5 frequency to emerge from noise? Answer: ~60 yr (by then 95% of cases are positive)



Instead, assume residuals from a 4th order polynomial: 55 yr

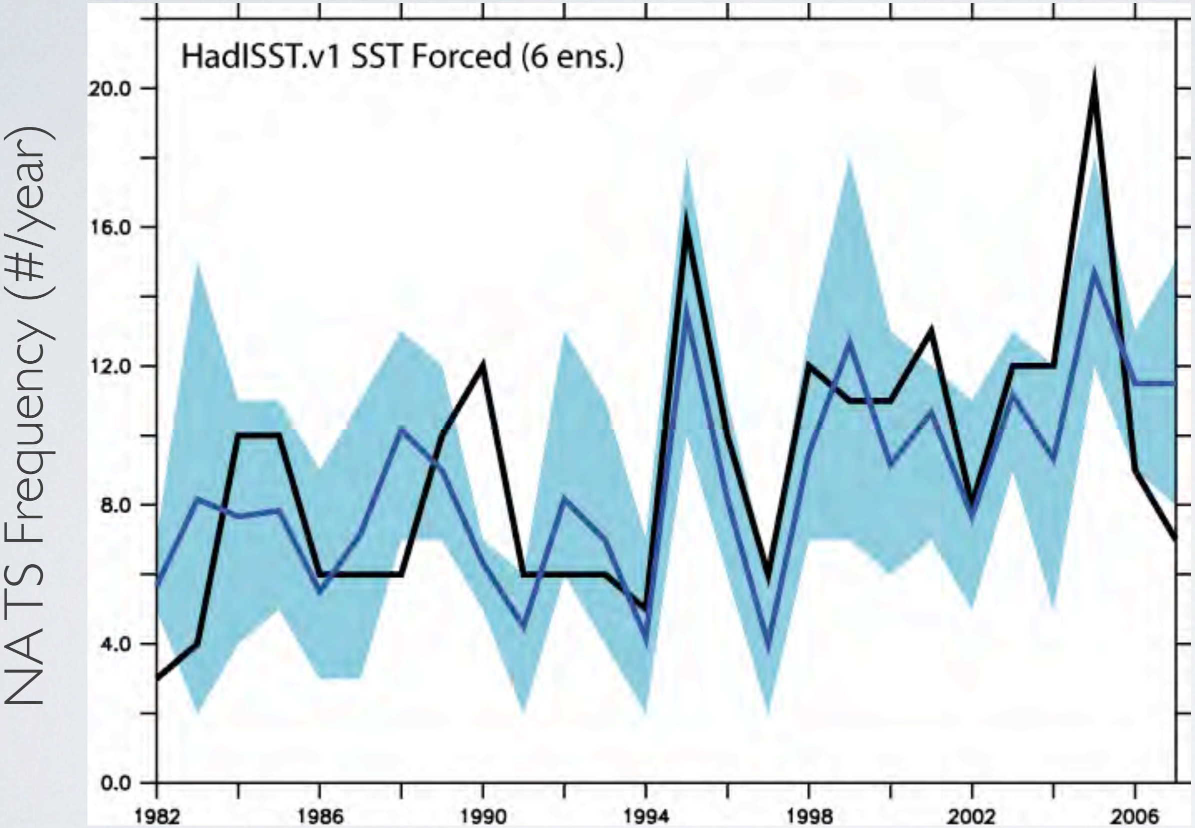
Instead, resample chunks of length 3-7 yr: 65-70 yr



Source: Bender et al., *Science*, 2010.

Attribution of Recent TS Frequency Increase in North Atlantic

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



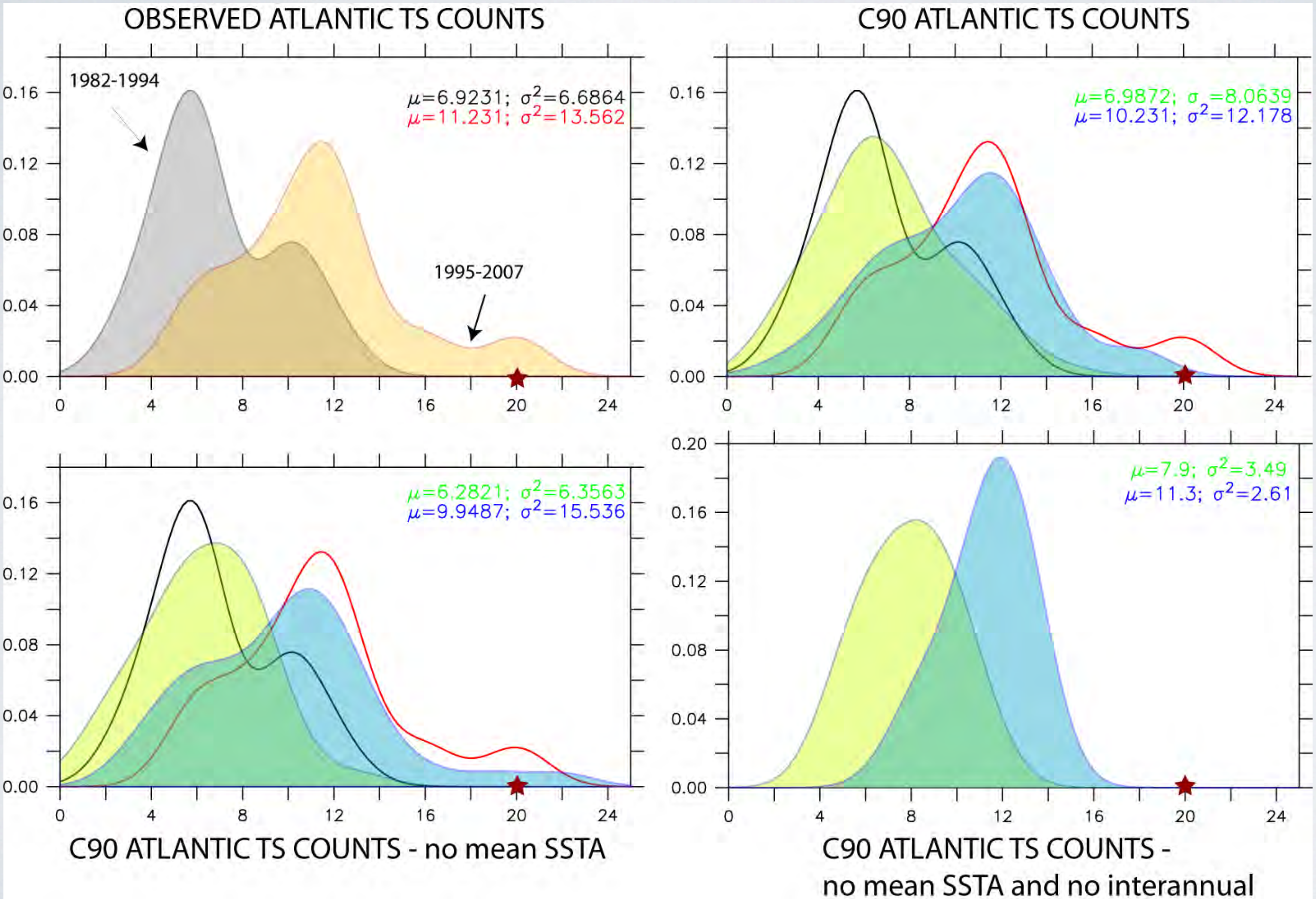
What aspect of SST drove increase?

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

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

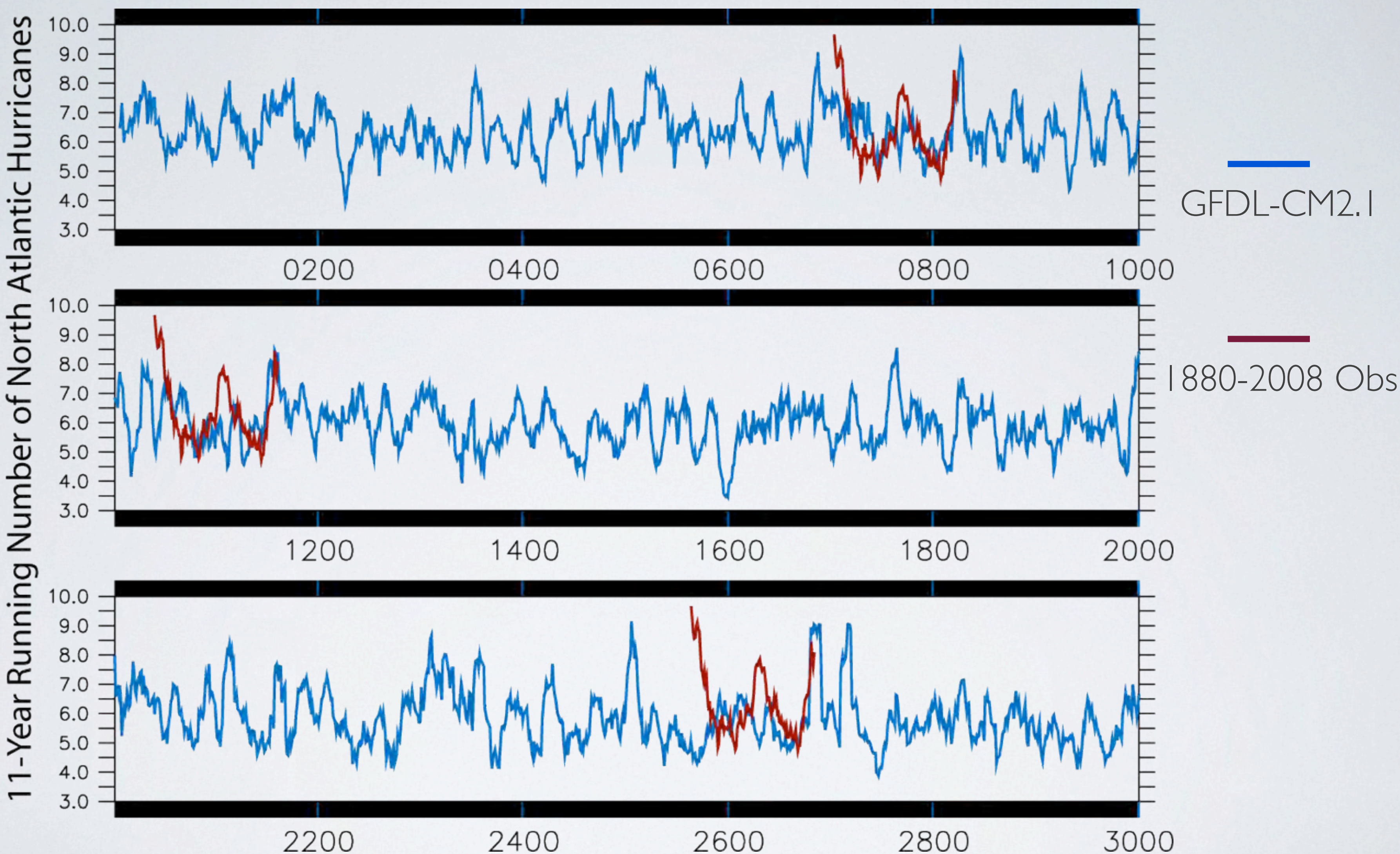
* lasting two days or more

★ 2005 Observed



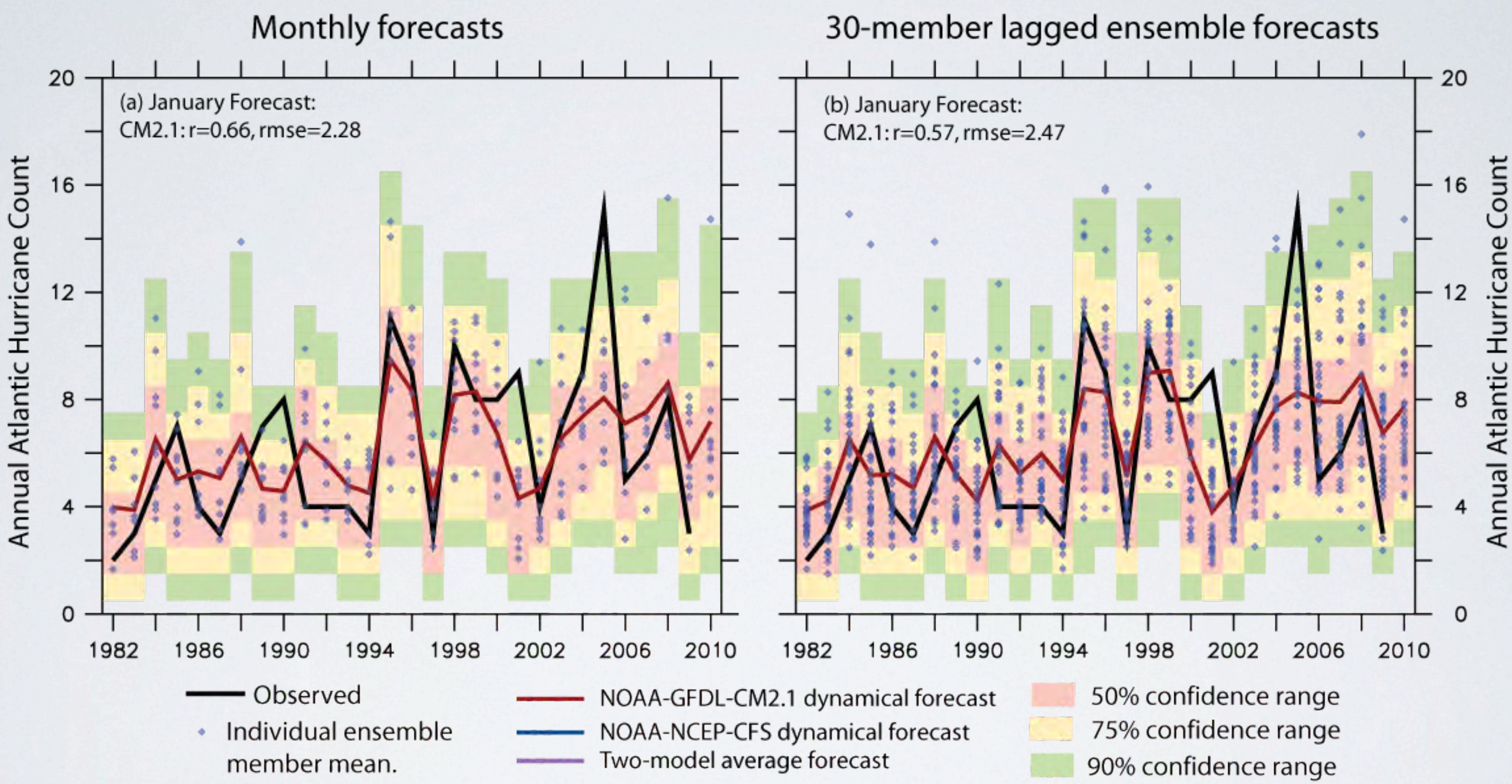
Vecchi, Delworth, Held and Zhao (2011, in prep.)

Statistical hurricane counts in GFDL CM2.1Preindustrial-Control Run



Even in absence of radiative forcing changes, large changes

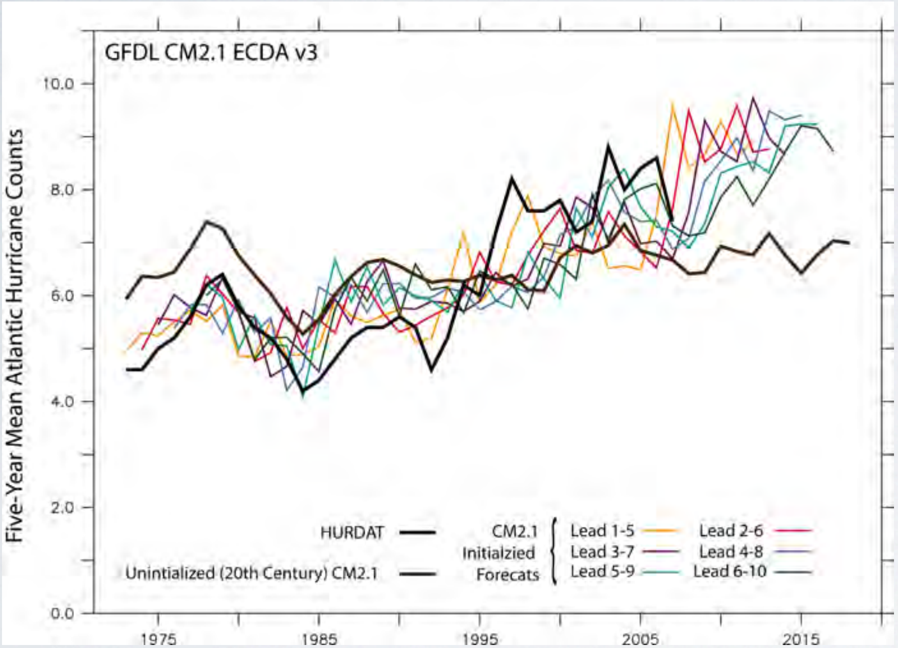
Statistical-Dynamical Hurricane Frequency Retrospective Forecasts Initialized January Exhibit Skill



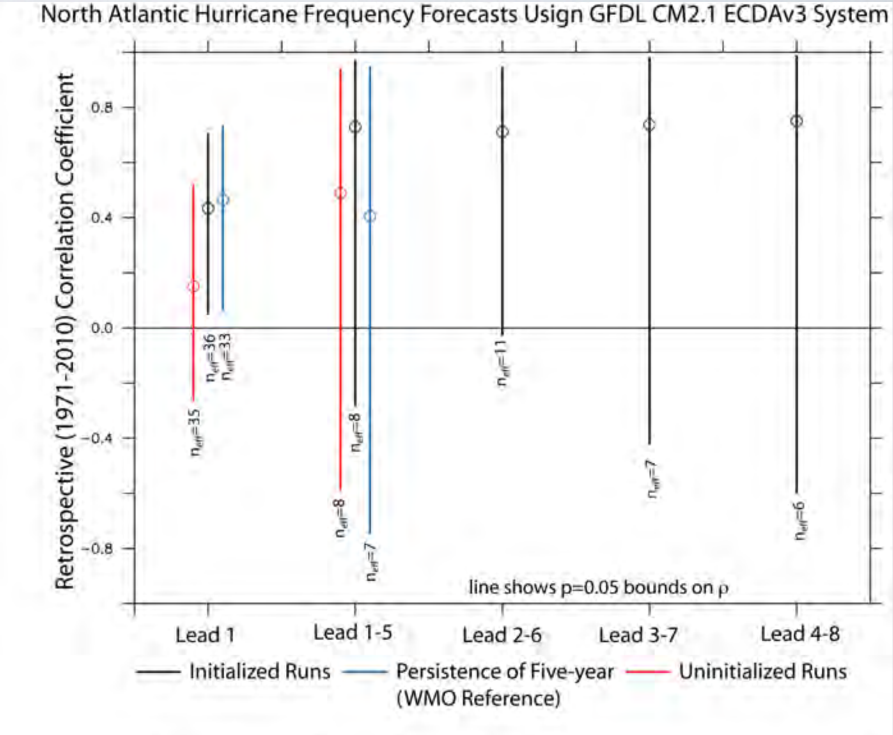
Vecchi *et al.* (2011, MWR in press)

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)

Conclusions:

i) It is premature to conclude that human activity--and particularly greenhouse warming--has already had a detectable impact on Atlantic hurricane activity.

ii) Atlantic tropical storm and hurricane counts--after adjustment for estimated missing storms--do not show significant increasing trends since the late 1800s.

iii) GFDL model late 21st century (ensemble) projections suggest a decrease in the number of hurricanes in the Atlantic (-24% to -32%), but nearly a doubling in the frequency of very intense (Cat 4-5) hurricanes by 2100. However, based on present understanding, we would not expect the increase in Cat 4-5's to be detectable for a number of decades.

iv) Substantial dependence on which global model supplies climate change conditions for downscaling. But no indications of a large Atlantic PDI sensitivity (e.g. 300% by 2100) as obtained from statistical extrapolation.

v) Remaining caveats include model limitations (e.g., clouds; indirect aerosols; intense hurricane simulation) and observed data concerns.

vi) GCMs moving towards resolutions that enable directly resolving TCs in the models