Atlantic Hurricanes and Climate Change

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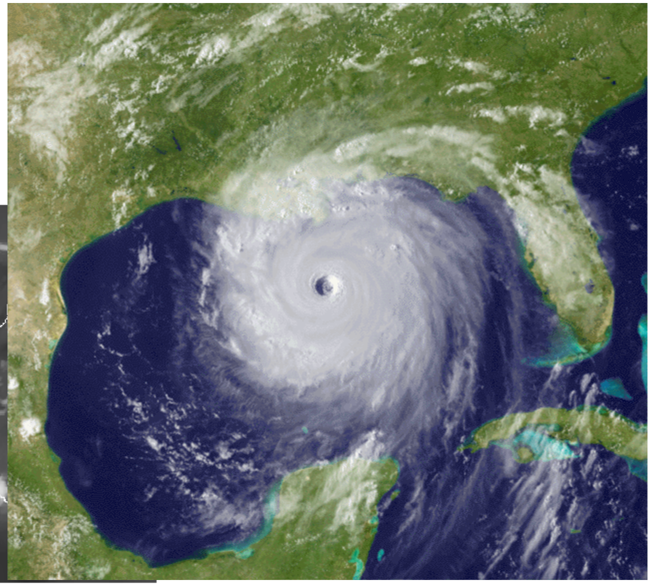
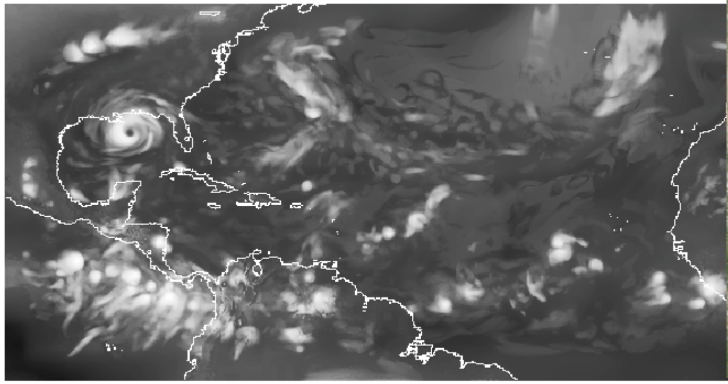
Steve Garner
Ming Zhao
S.-J. Lin

Hurricane Katrina, Aug. 2005





GFDL model simulation of Atlantic hurricane activity

Talk Outline

1. Summary of WMO Expert Team Assessment
2. Analysis of Observations
3. Modeling Studies
4. Remaining Issues…or could we be wrong?

Summary: WMO Expert Team Assessment

Climate Change Detection and Attribution:

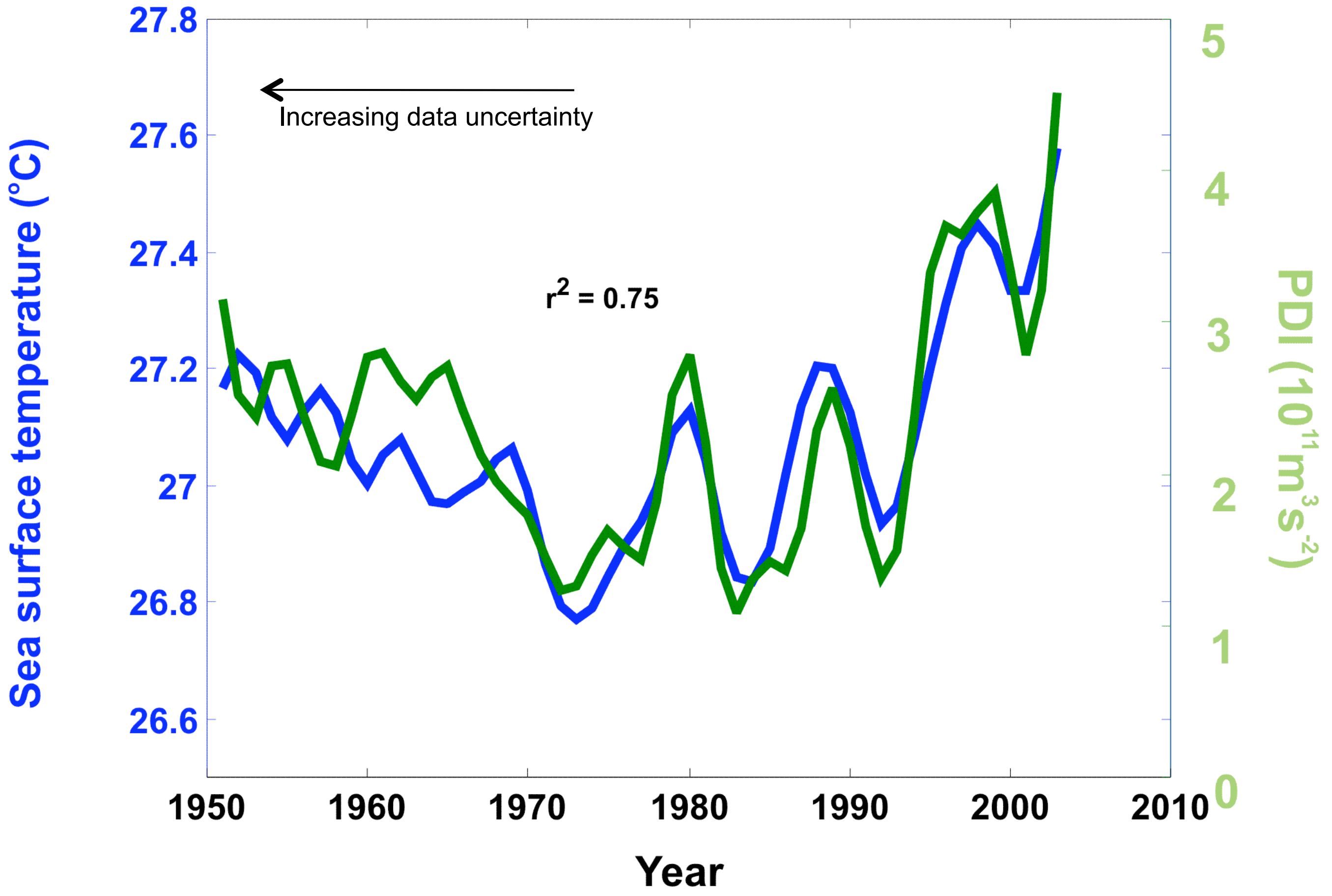
- It remains uncertain whether past changes in tropical cyclone activity exceed natural variability levels.

Projections for late 21st century:

- Likely fewer tropical storms globally (~no change to -34%).
- Likely increase in global average hurricane wind speeds (+2 to11%)
- More frequent very intense storms (> 50% chance these will increase by a substantial percentage in some basins).
- Likely higher hurricane rainfall rates (~ +20% within 100 km of storm.
- Projections for individual basins (e.g., Atlantic) show large variations between modeling studies for all tropical cyclone metrics.

Source: Knutson et al., 2010: Tropical Cyclones and Climate Change. Nature Geoscience, 3, 157-163.

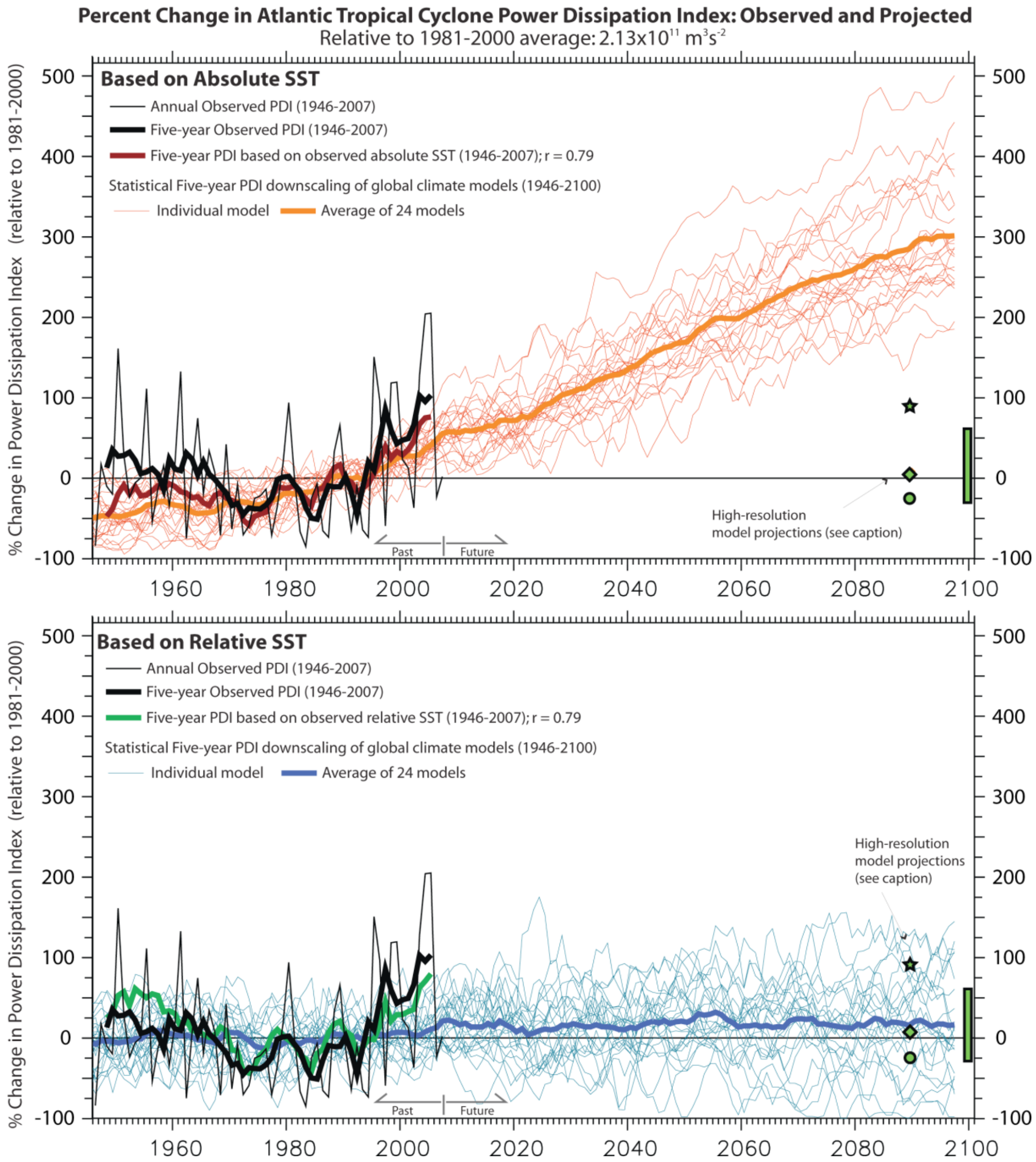
There is some recent evidence that overall Atlantic hurricane activity may have increased since in the 1950s and 60s in association with increasing sea surface temperatures…



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

Source: Kerry Emanuel, J. Climate (2007).

Statistical projections of 21st century Atlantic hurricane activity have a large dependence on the predictor used.



Projection 1: Absolute SST

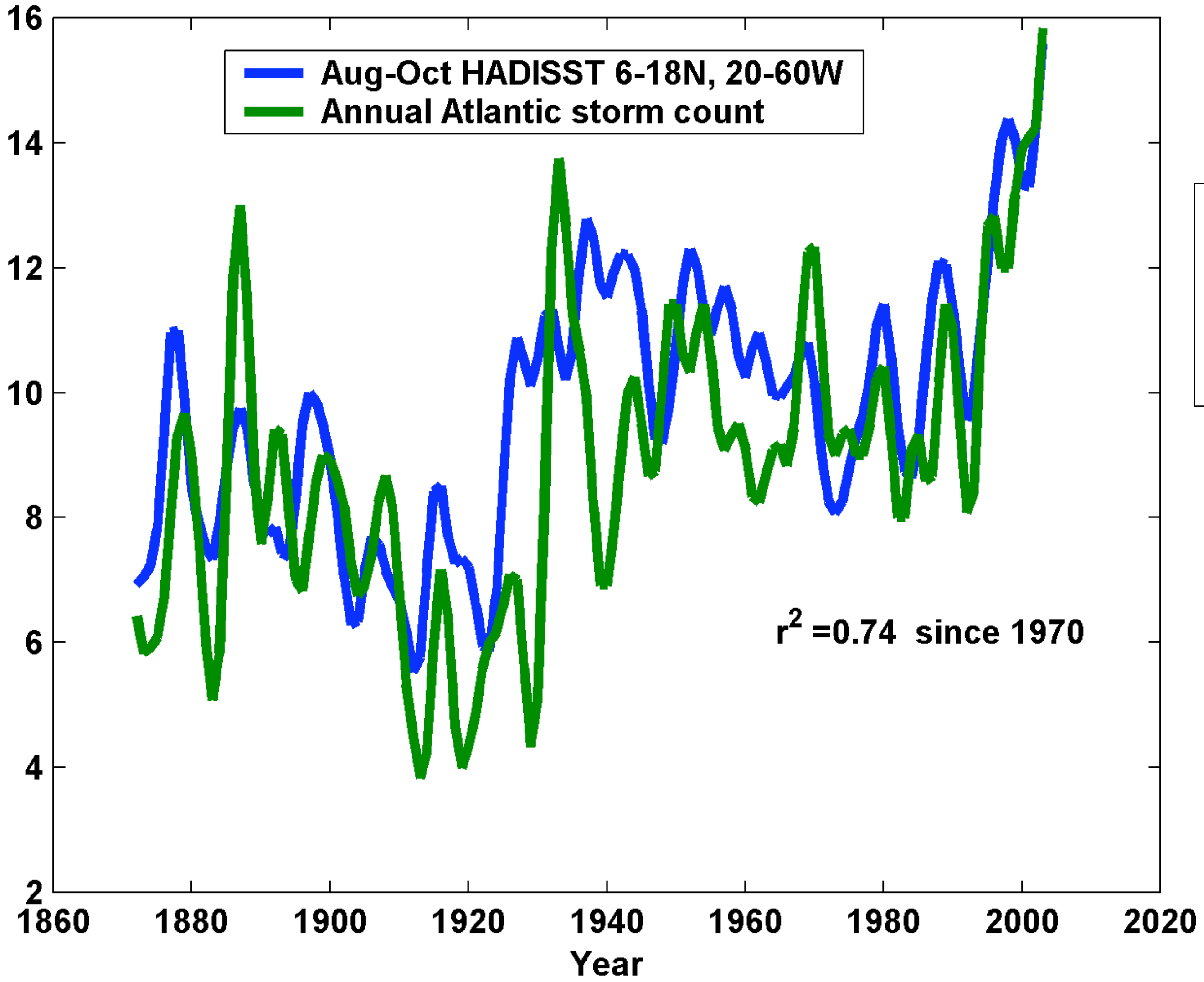
- ~300% projected increase in Power Dissipation
- Indirect attribution: CO_2 → SST → Hurricanes

Projection 2: Relative SST

- Projected change: sign uncertain, +/- 80%
- No Attribution

Source:
Vecchi et al. *Science* (2008)

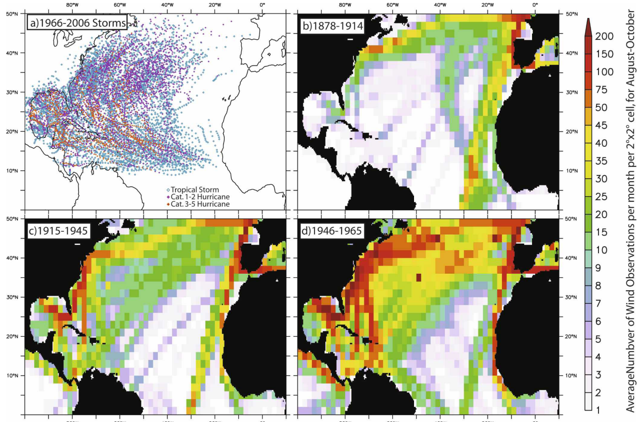
The frequency of tropical storms (low-pass filtered) in the Atlantic basin since 1870 has some correlation with tropical Atlantic SSTs



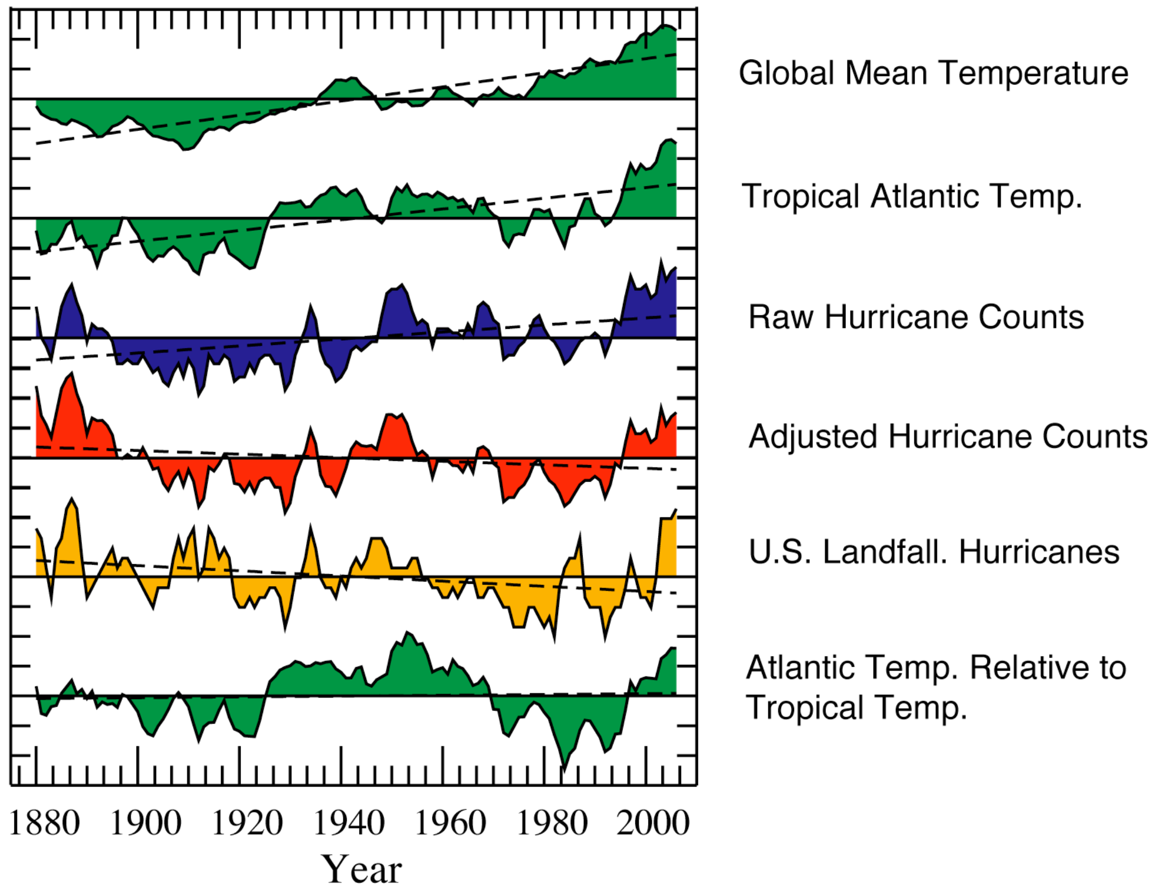
But is the storm record reliable enough for this?

Source: Emanuel (2006); Mann and Emanuel (2006) EOS. See also Holland and Webster (2007) *Phil. Trans. R. Soc. A*

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

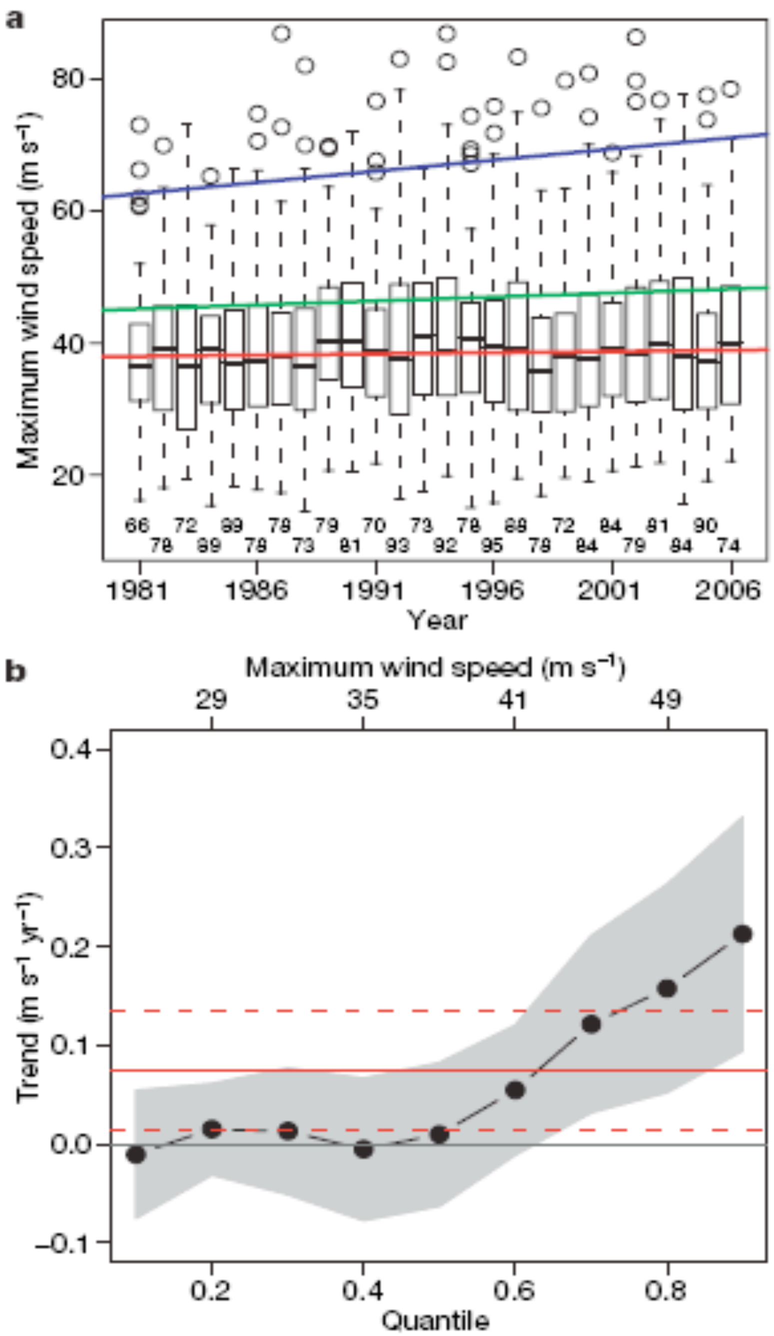


Normalized Tropical Atlantic Indices



Sources:

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



Global Tropical Cyclone Intensity Trends

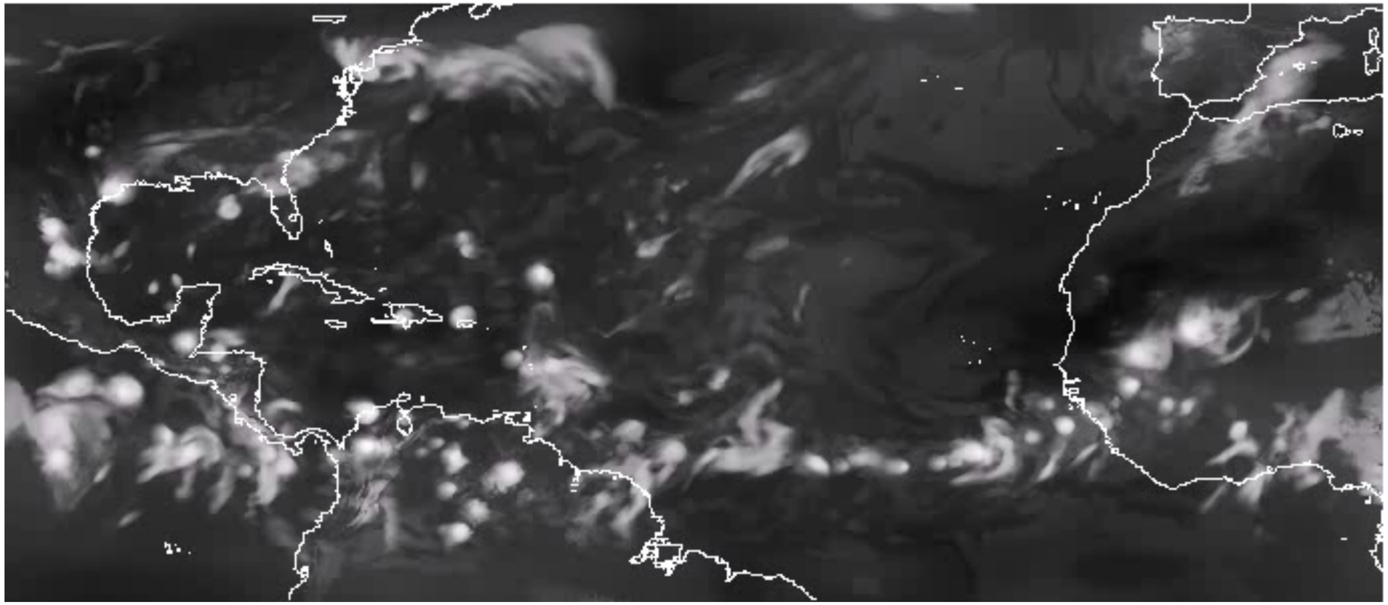
There is some statistical evidence that the strongest hurricanes are getting stronger. This signal is most pronounced in the Atlantic. However, the satellite-based data for the global analysis are only available for 1981-2006. It remains uncertain whether this change exceeds the levels due to natural variability.

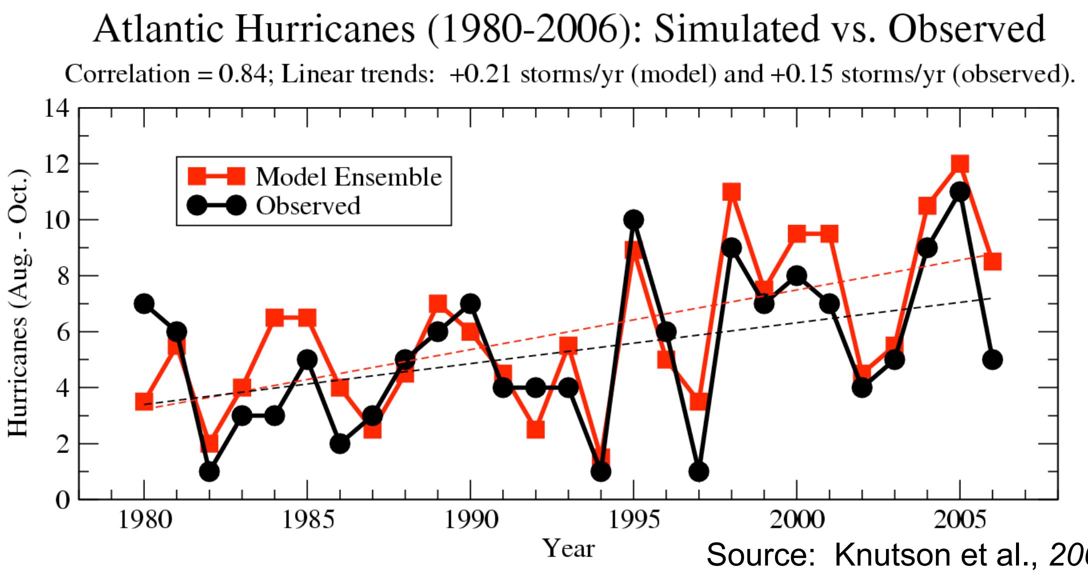
Quantile regression computes linear trends for particular parts of the distribution. The largest increases of intensity are found in the upper quantiles (upper extremes) of the distribution.

Source: Elsner et al., *Nature,* 2008.

Zetac Regional Model reproduces the interannual variability and trend of Atlantic hurricane counts (1980-2006)

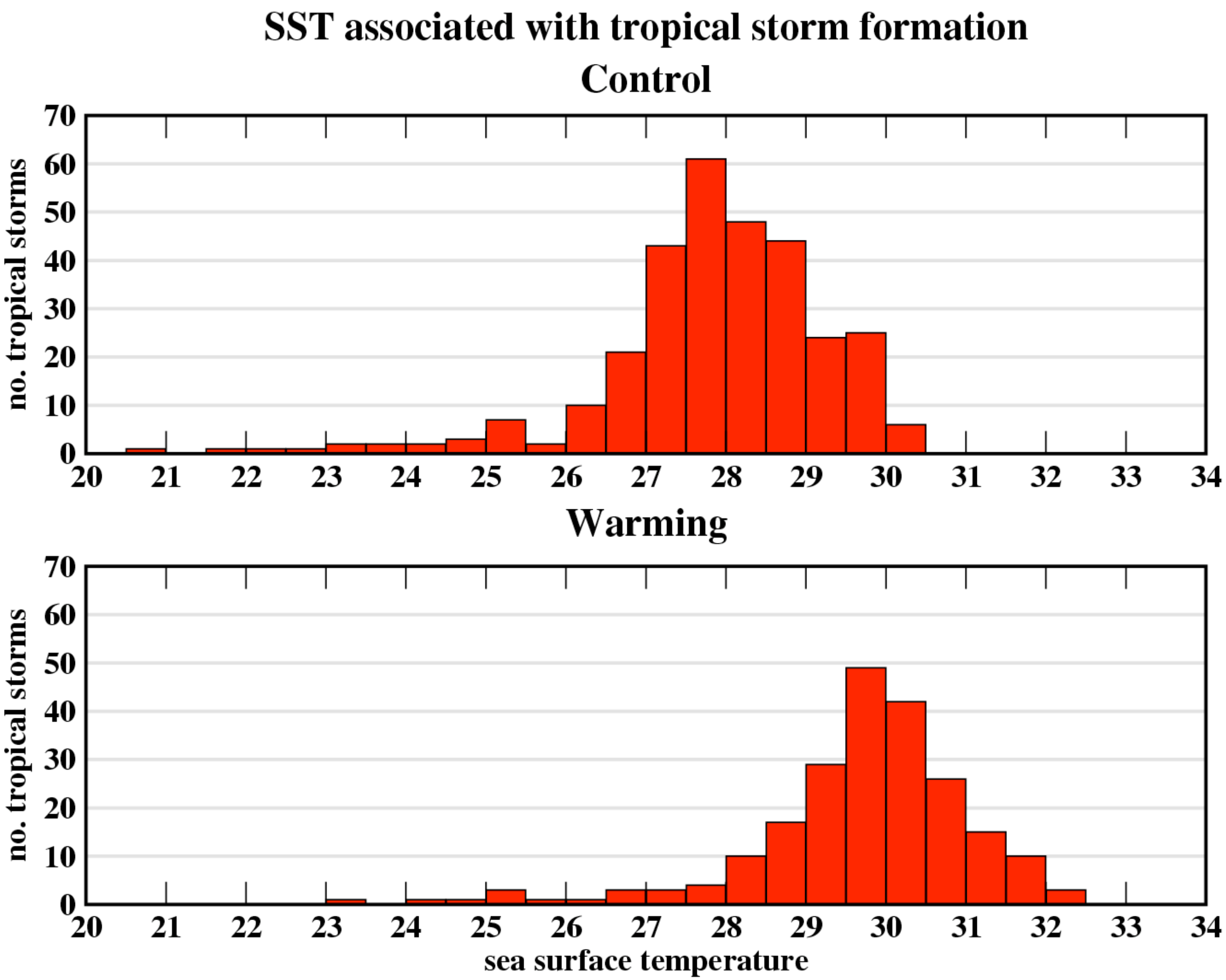
18-km grid model nudged toward large-scale (wave 0-2) NCEP Reanalyses





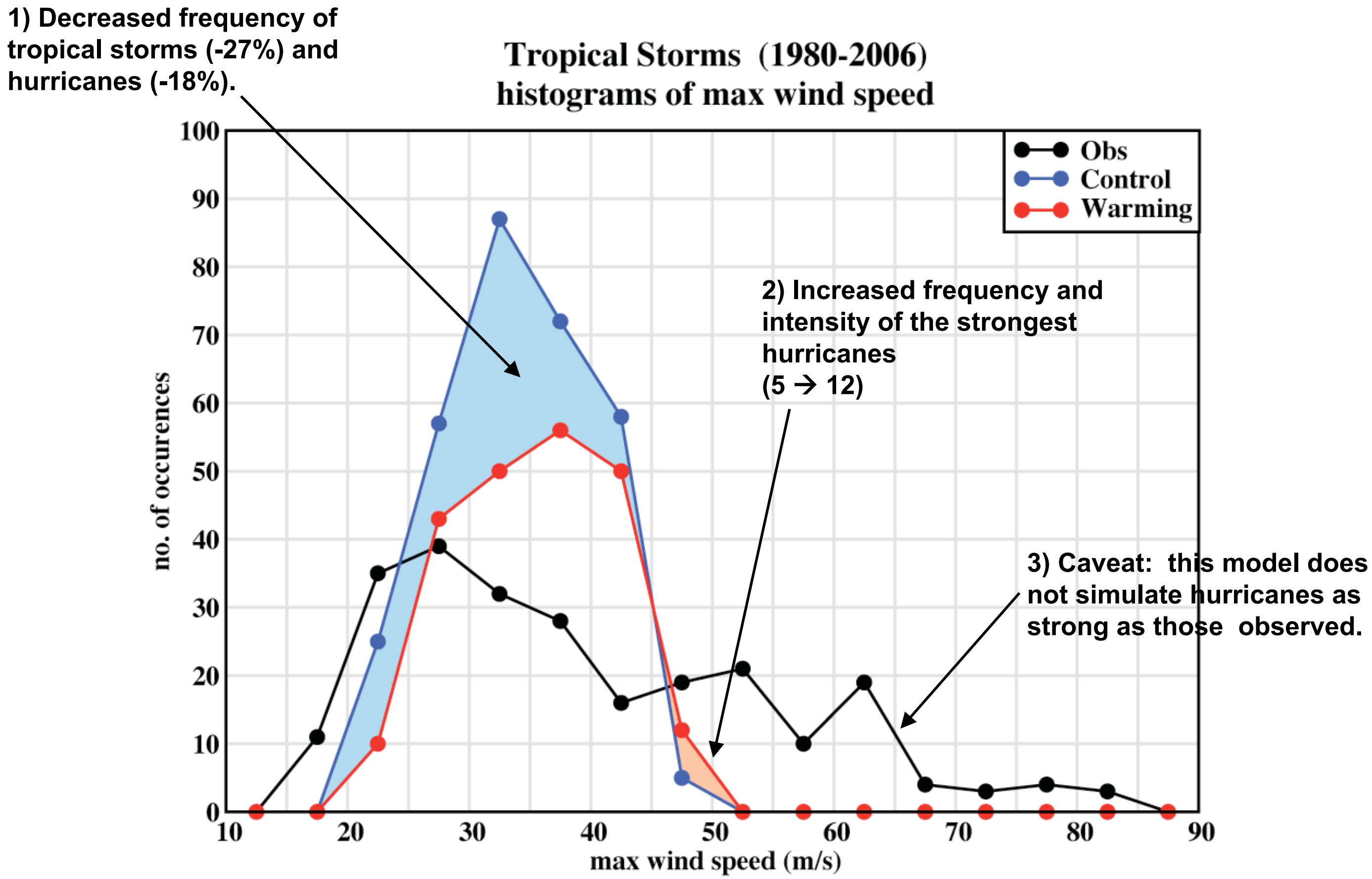
Source: Knutson et al., *2007*, Bull. Amer. Meteor. Soc.

The 26.5^{o}C "threshhold temperature" for tropical storm formation: a *climate dependent* threshhold…



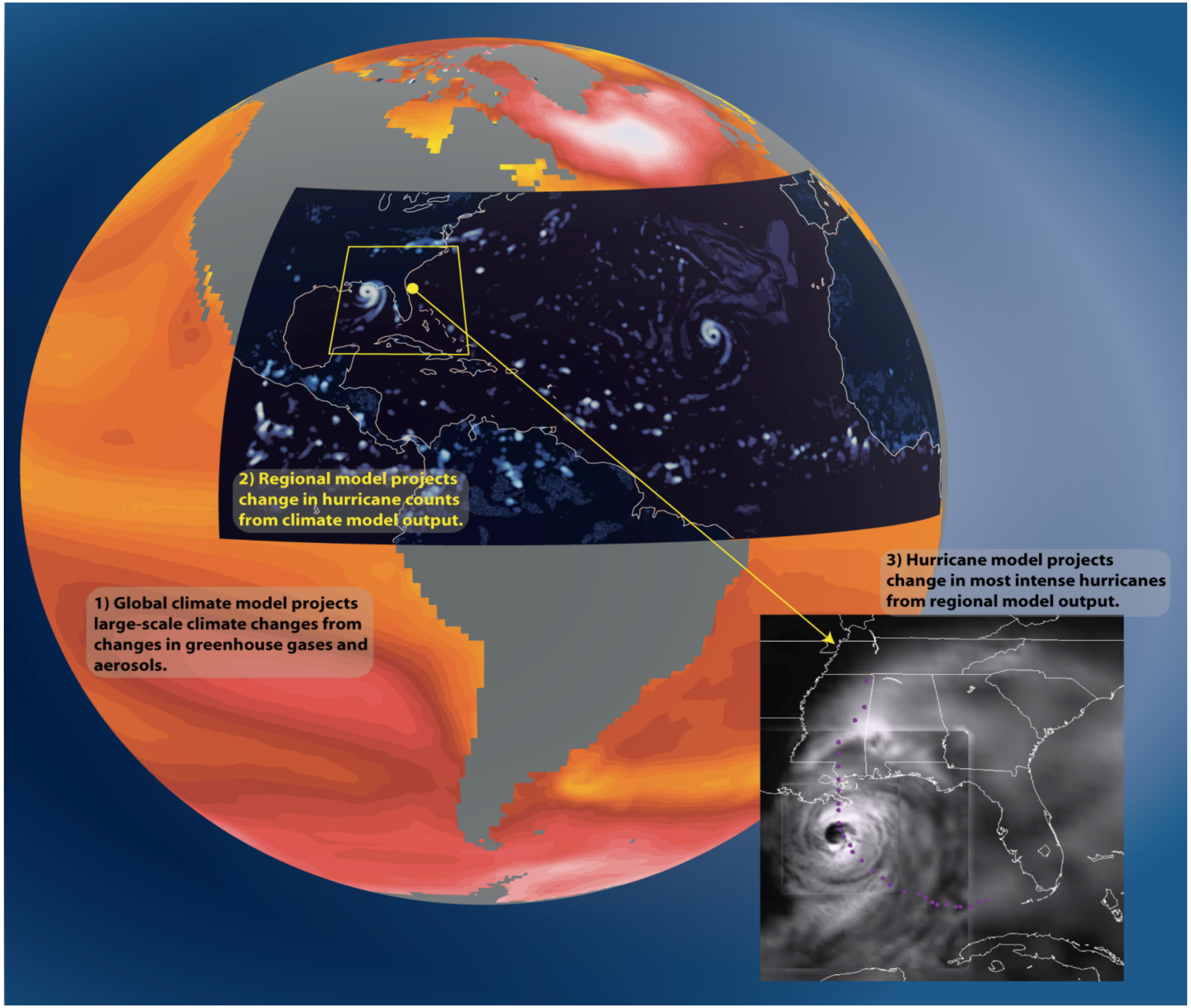
Source: Knutson et al., *2008*, *Nature Geoscience*.

The model provides projections of Atlantic hurricane and tropical storm *<u>frequency</u>* changes for late 21st century, downscaled from a multi-model ensemble climate change (IPCC A1B scenario):



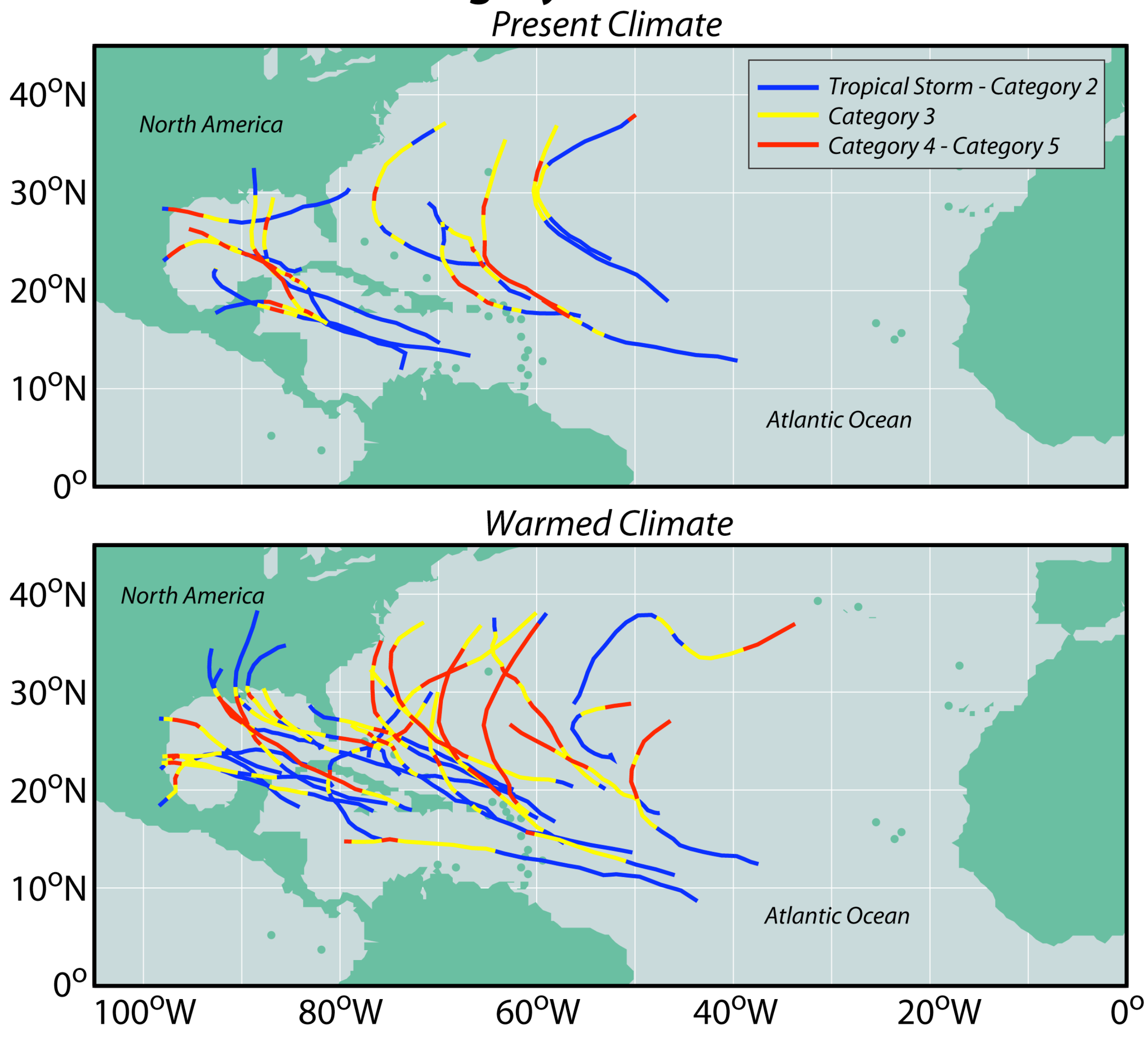
Source: Knutson et al., *2008*, Nature Geoscience.

Modeled Impact of Anthropogenic Warming on the Frequency of Intense Atlantic Hurricanes, Bender et al., *Science,* 2010.

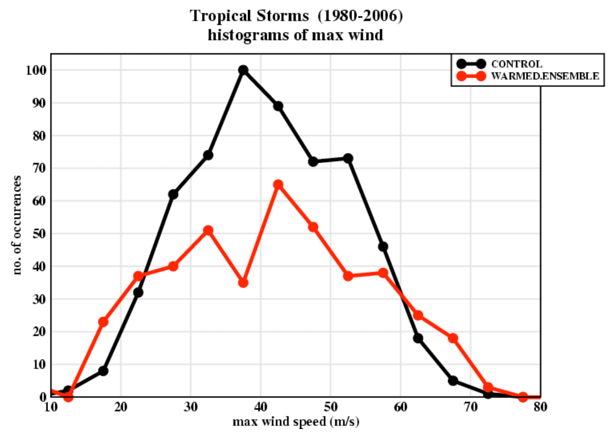


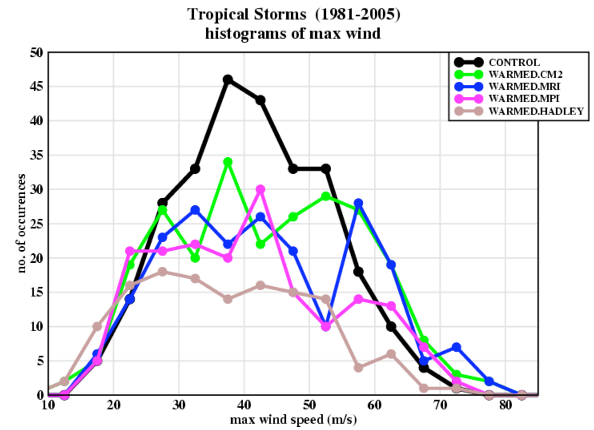
Late 21st Century Climate Warming Projection-- Average of 18 CMIP3 Models

Modeled Category 4 & 5 Hurricane Tracks



The Cat 4-5 increase is not projected for all of the 18 individual models:





(27 Simulated Hurricane Seasons)

Source: Bender et al., Science, 2010

Comparison of Recent Atlantic Hurricane Trends vs 21st Century Projected Trend Rates (in percent per decade)

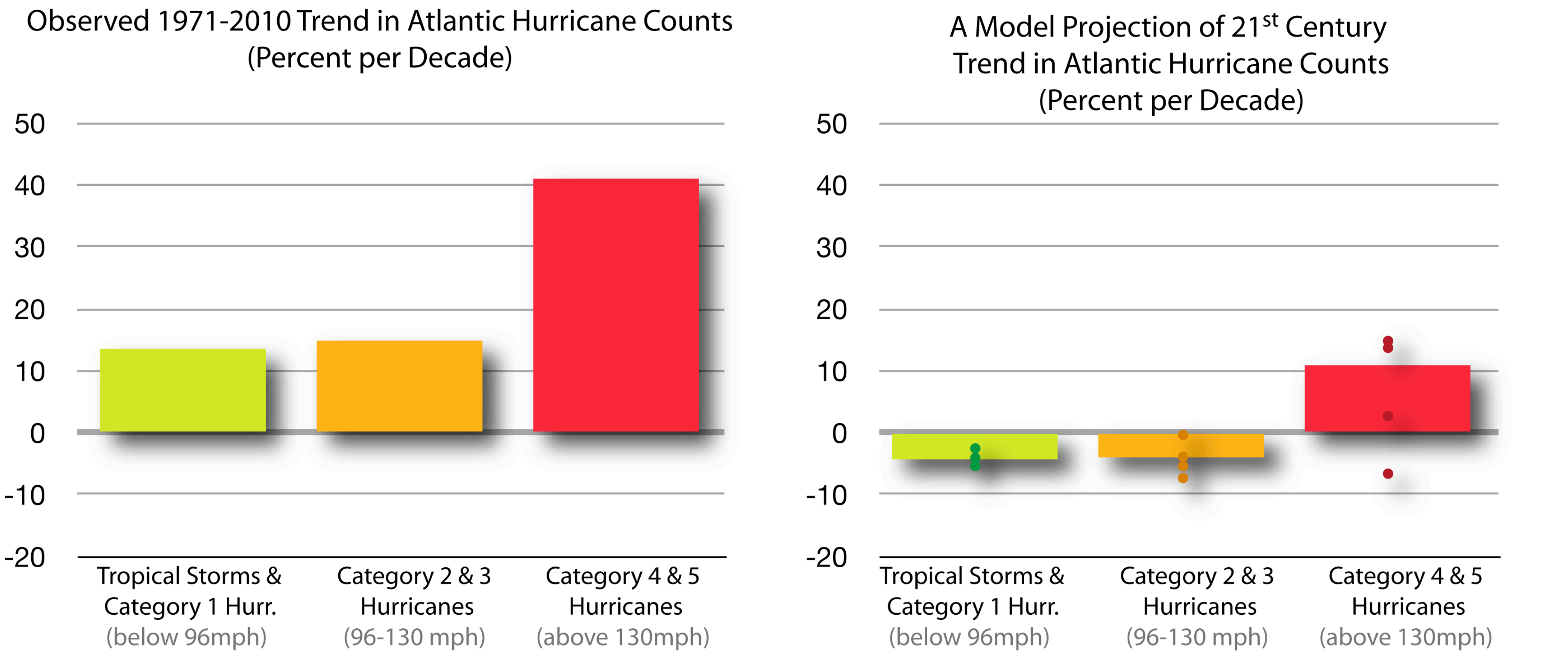
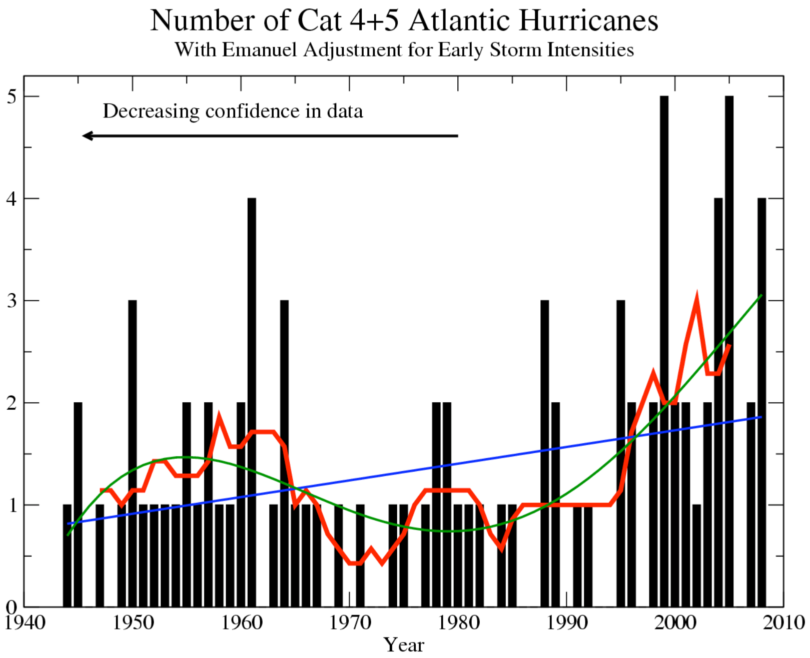
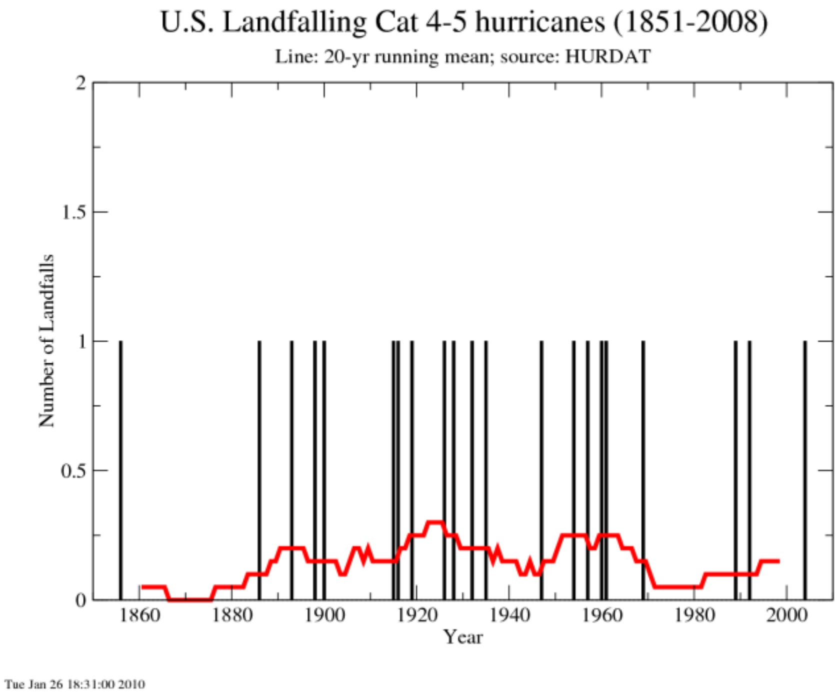


Figure courtesy Gabe Vecchi, GFDL./NOAA

<u>Emergence Time Scale</u>: Assume the observed Cat 4+5 data since 1944 represents the noise (e.g. through bootstrap resampling). Add a 10% per decade trend to samples of this noise and determine the timescale at which 95% of the resulting series have a positive trend.
Estimate: **~60 yr**





Sensitivity tests:
i) assume residuals from a 4^{th} order polynomial: 55 yr;
ii) resample chunks of length 3-7 yr: 65-70 yr

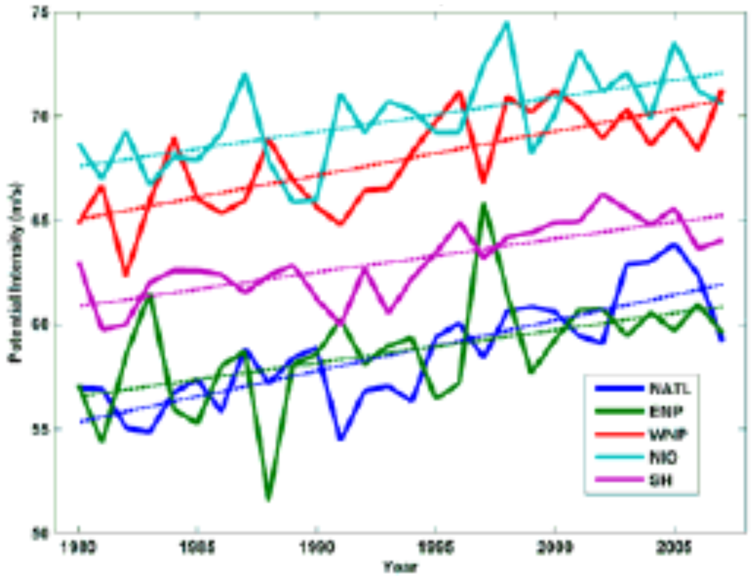
Source: Bender et al., *Science*, 2010.

The role of lower stratospheric / upper tropospheric temperature trends:

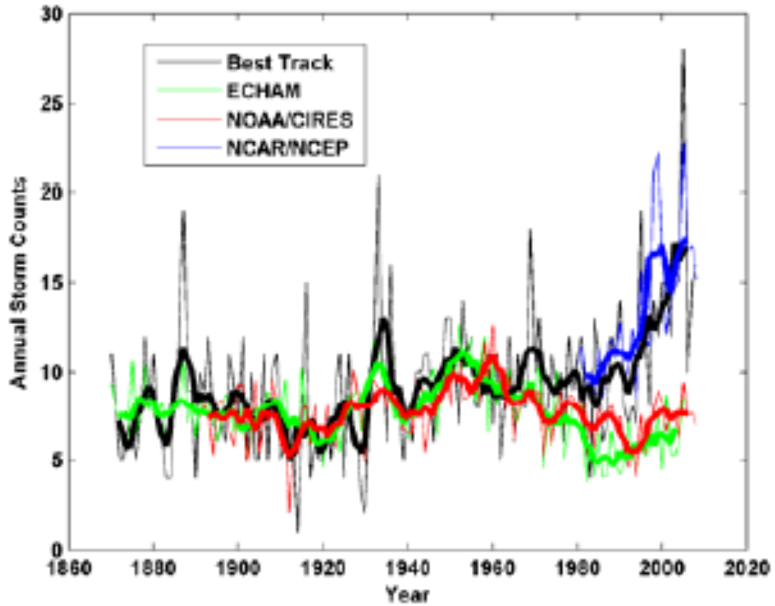
- **NCEP reanalyses show strong cooling trends since 1980 in tropopause transition layer (TTL) temperatures in the tropics – resulting in increasing potential intensity--but are these trends reliable?**

- **Emanuel's statistical/dynamical downscaling framework suggests that the cooling TTL caused increased Atlantic tropical storm frequency since 1980, but current GFDL dynamical models do not show this sensitivity.**

Potential Intensity trends since 1980 from NCEP Reanalysis

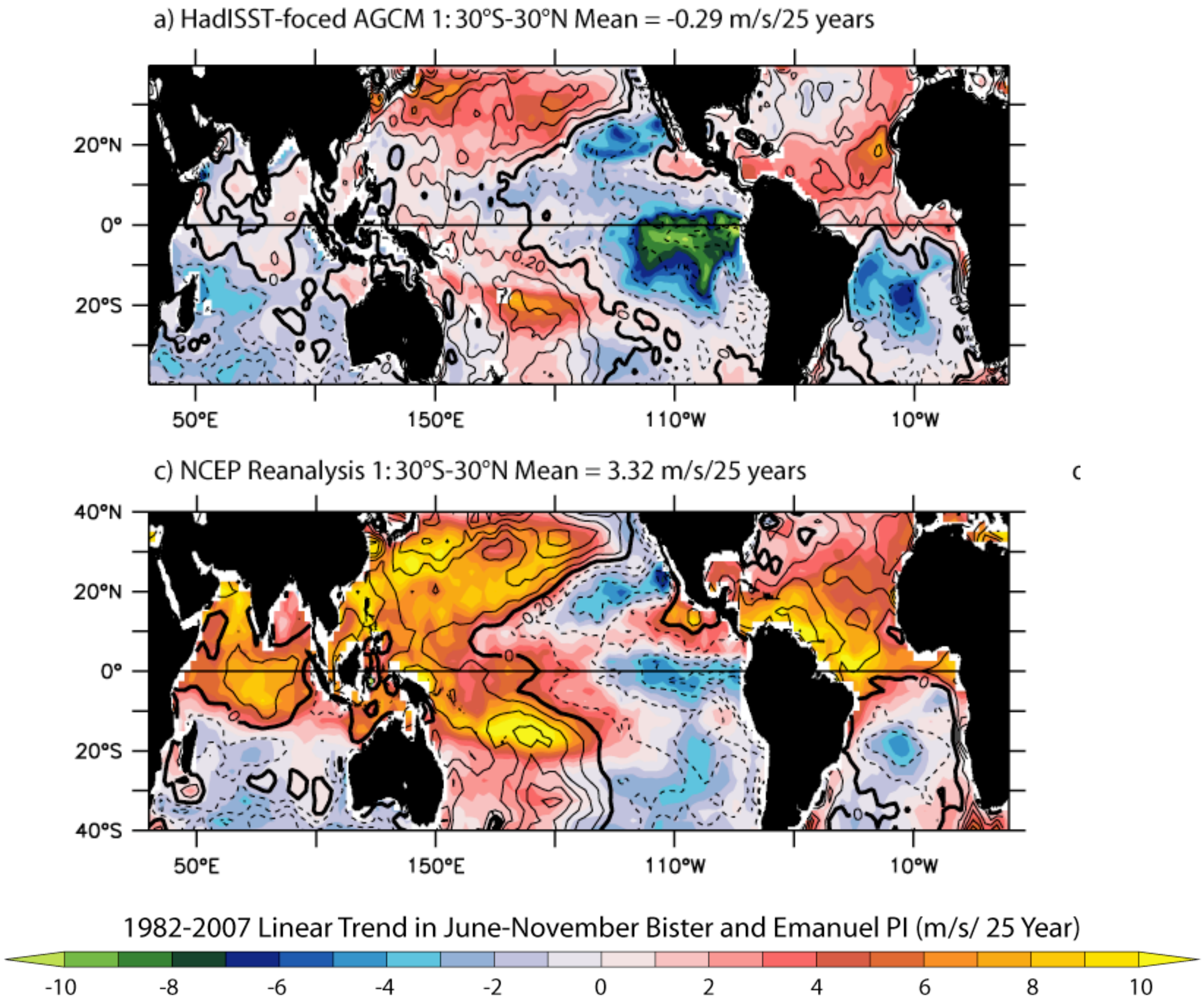


Statistical/Dynamical Downscaling of Atlantic Tropical Storm Frequency (1870-2005)



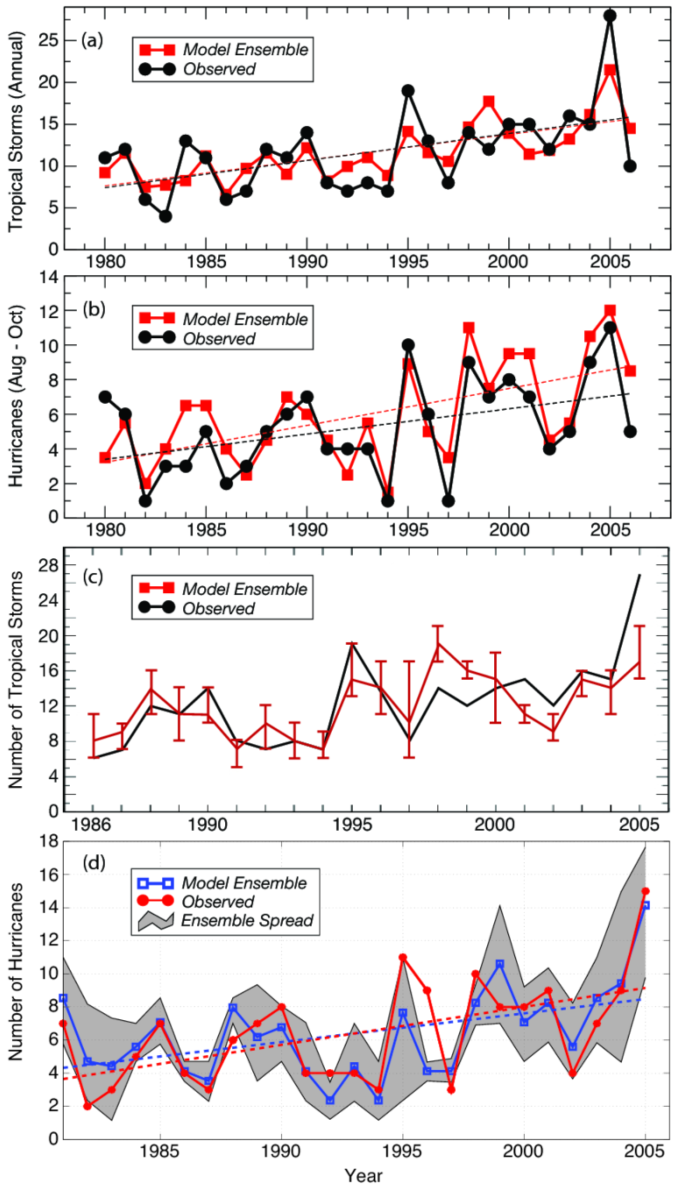
Source: K. Emanuel, AMS Hurricanes and Tropical Meteorology Conference abstract, 2010.

NCEP Reanalysis: large rising trends in Potential Intensity (1982-2007) which are not widely present in a global model forced with observed SSTs.



Source: G. Vecchi, manuscript in preparation, 2011.

Simulating past variability in Atlantic tropical cyclone activity



Progress in simulating past Atlantic hurricane / tropical storm frequency variability using dynamical and statistical/dynamical models.

Left: examples for the Atlantic basin, using high resolution atmospheric models; regional dynamical downscaling models; and statistical/ dynamical techniques.

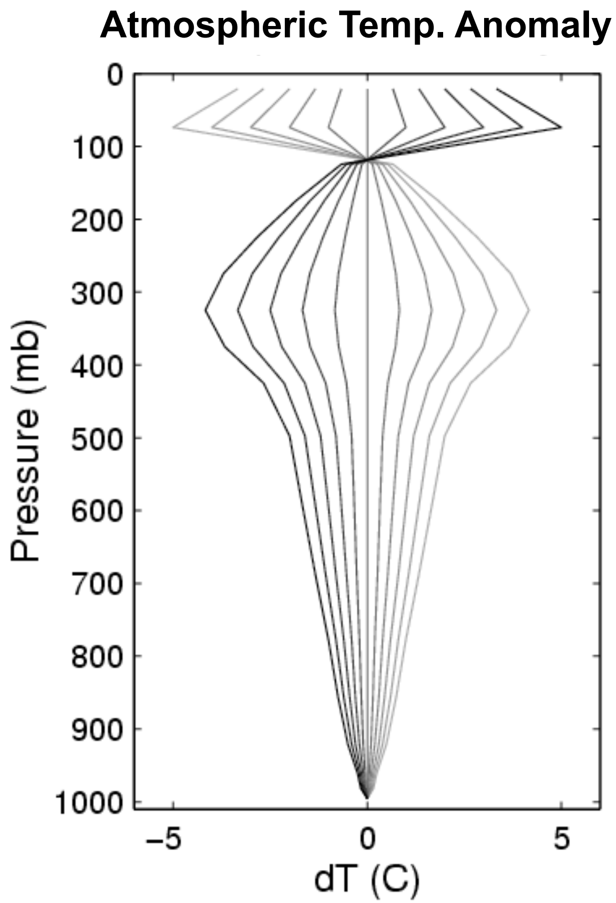
(a) and (b) use NCEP Reanalyses.

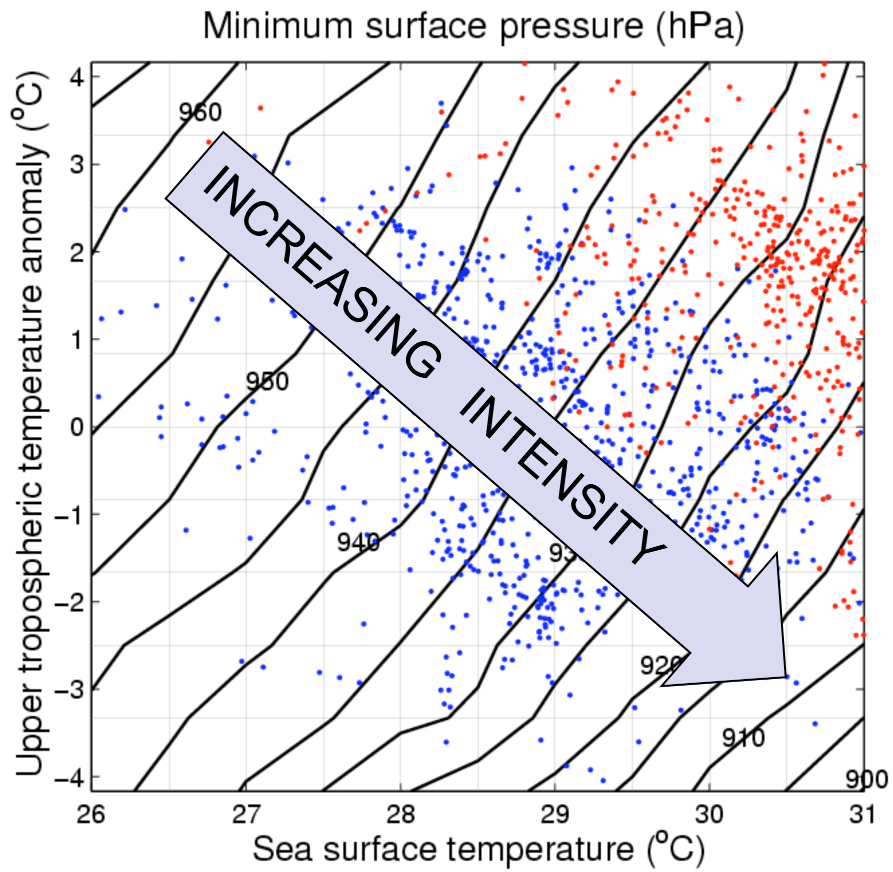
(c) uses SSTs (d) uses SSTs, with greenhouse gases and ozone.

<u>Current questions</u>: Is a strong cooling of tropopause transition layer (TTL) necessary to simulate the Atlantic tropical storm trends over this period? Has the potential intensity increased since 1980 in all TC basins?

Source: Knutson et al., *Nature Geoscience* (2010).

The atmospheric temperature profile has an important influence simulated intensities in the GFDL hurricane model





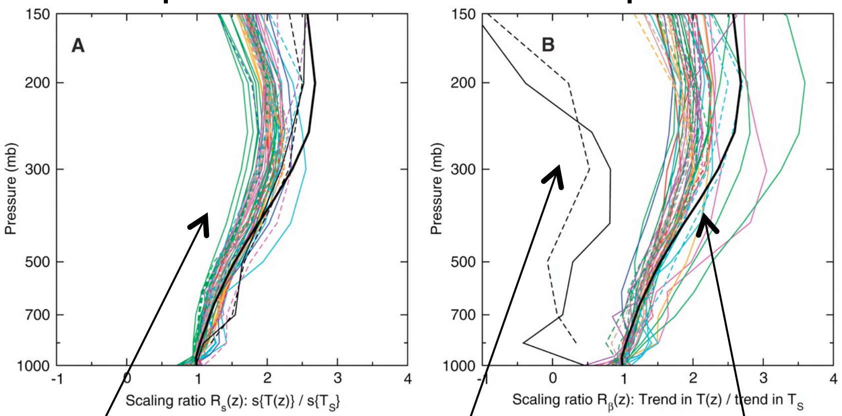
Source: Shen, Tuleya, and Ginis; J. Climate (2000)

How have tropical tropospheric and lower stratospheric temperature changed?

Vertical profile of tropospheric warming:

- **Models and theory predict that the vertical profile of tropical tropospheric warming will amplify with height, while radiosonde-based and some satellite-based observations suggest that the troposphere has warmed uniformly with height. A uniform warming with height would be 'de-stabilizing', and would imply greater future hurricane activity increases than currently projected. Modeling studies and critical reanalysis of observations (e.g., using winds to infer temperature trends) suggest that the observed of 'destabilization' of tropical temperatures from radiosondes and satellites are likely unreliable.**

Interannual Variability vertical profile | **Trend (1979-1999) vertical profile**

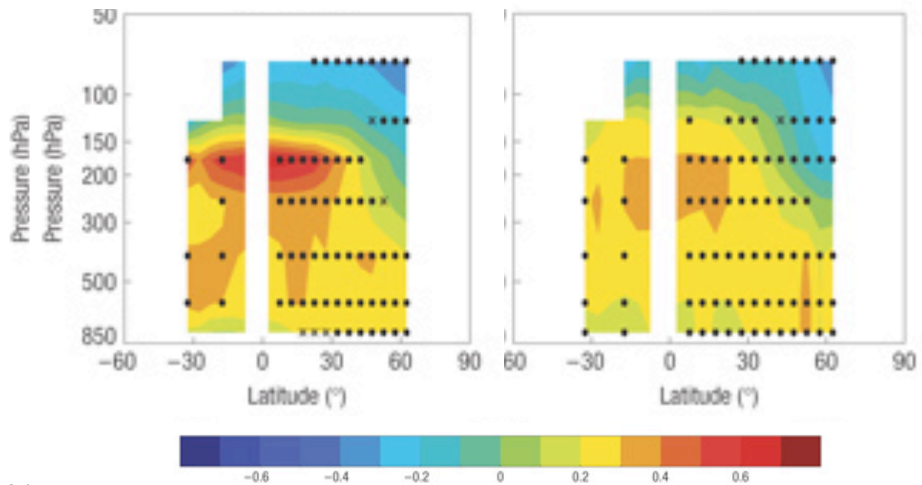


Radiosondes, models and theory

Radiosondes

Models and theory

Trend (1970-2005) derived from Radiosonde winds | **Trend (1970-2005) from climate models**



Sources: Santer et al. *Science* 2005; Allen and Sherwood, *Nature Geoscience*, 2008

Conclusions:

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

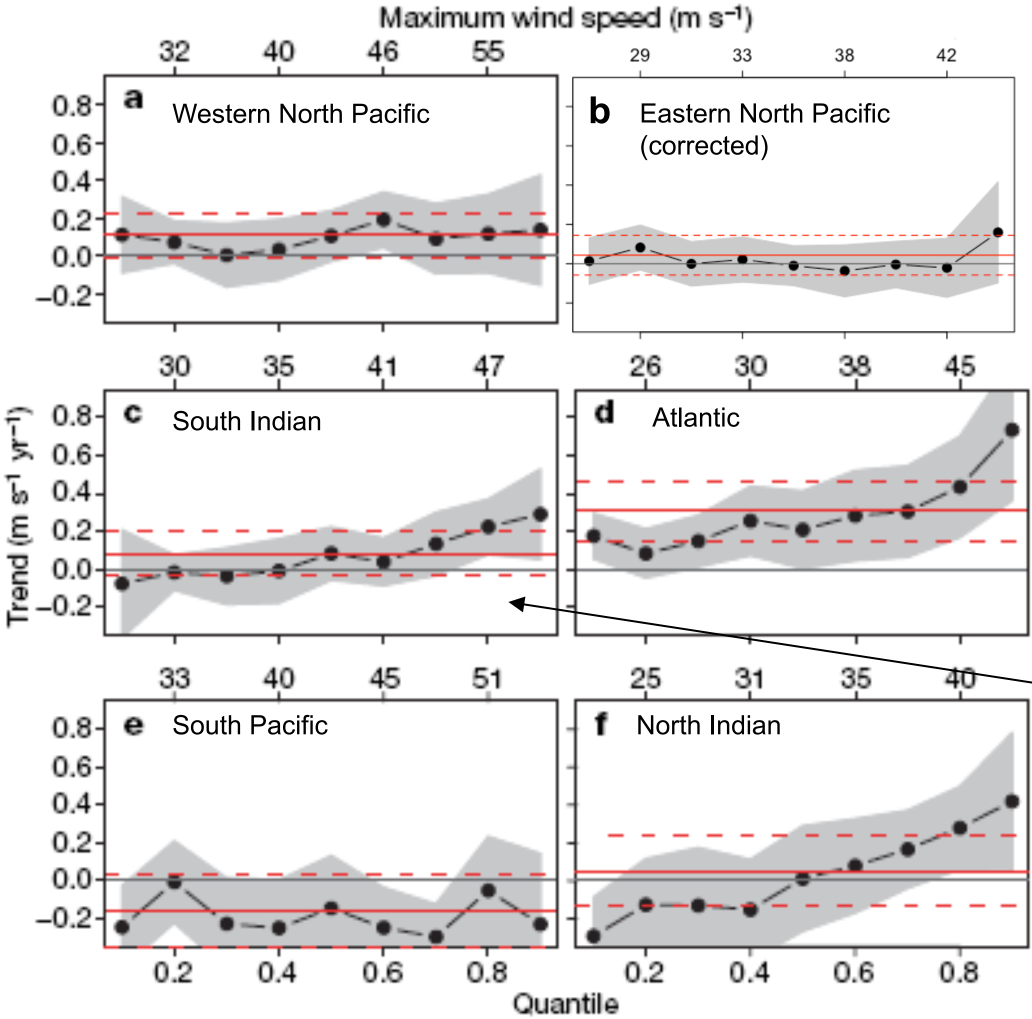
ii) Atlantic tropical storm and hurricane counts--after adjustment for estimated missing storms--do not show significant increasing trends since the late 1800s.

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. Estimated emergence timescale of order six decades.

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

v) Remaining caveats: i) uncertainties in climate model projections (SST patterns, lapse rate changes, cloud feedback, indirect aerosols); ii) intense hurricane simulations; and iii) limitations of past observations.

Tropical Cyclone Intensity Trends in Various Basins



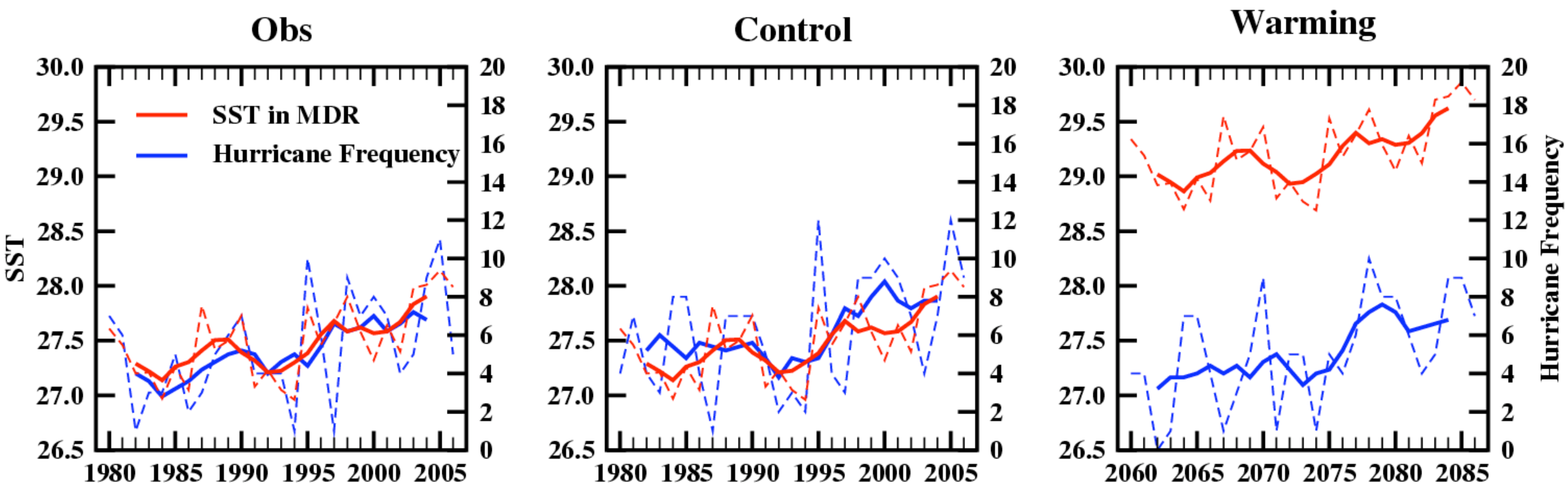
There statistical evidence that the strongest hurricanes are getting stronger is most convincing for the Atlantic (1981-2006).

The North and South Indian Ocean data also suggest increased intensity. Satellite view angle changes over time in those regions necessitated homogeneity adjustments.

The intensity change signal is quite weak for the three Pacific basins.

Source: Elsner et al., *Nature,* 2008.

The control model reproduces the observed close relationship between SST and hurricane frequency (1980-2006), but this statistical relationship does not hold for future human-caused warming in the model.



Hurricane frequency actually *decreases* by 18% in the warm climate case… although the model does not simulate hurricanes as intense as observed.

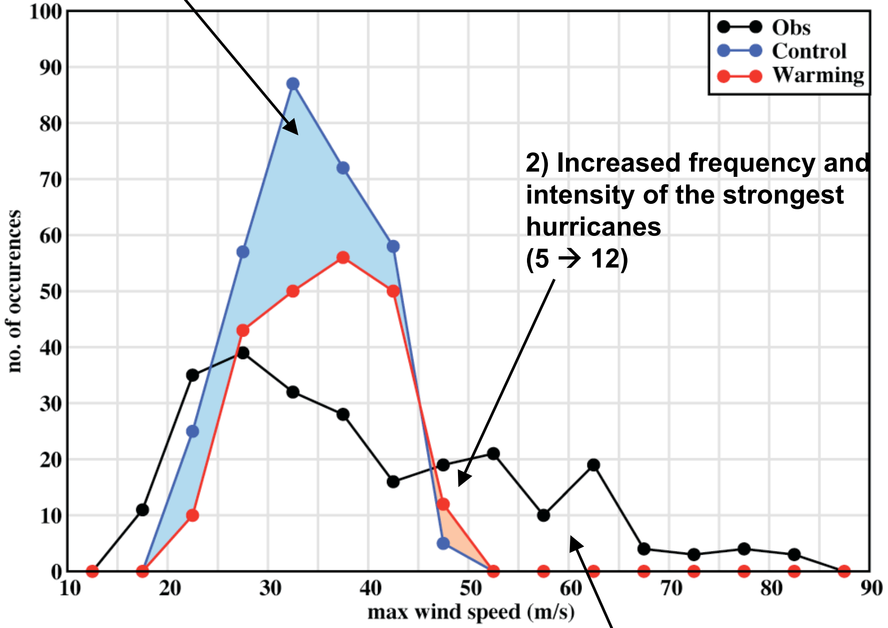
Lesson: Caution using correlations from the present climate to make future climate projections…

Source: Knutson et al., Nature Geoscience (2008).

The model provides projections of Atlantic hurricane and tropical storm *frequency* changes for late 21st century, downscaled from a multi-model ensemble climate change (IPCC A1B scenario):

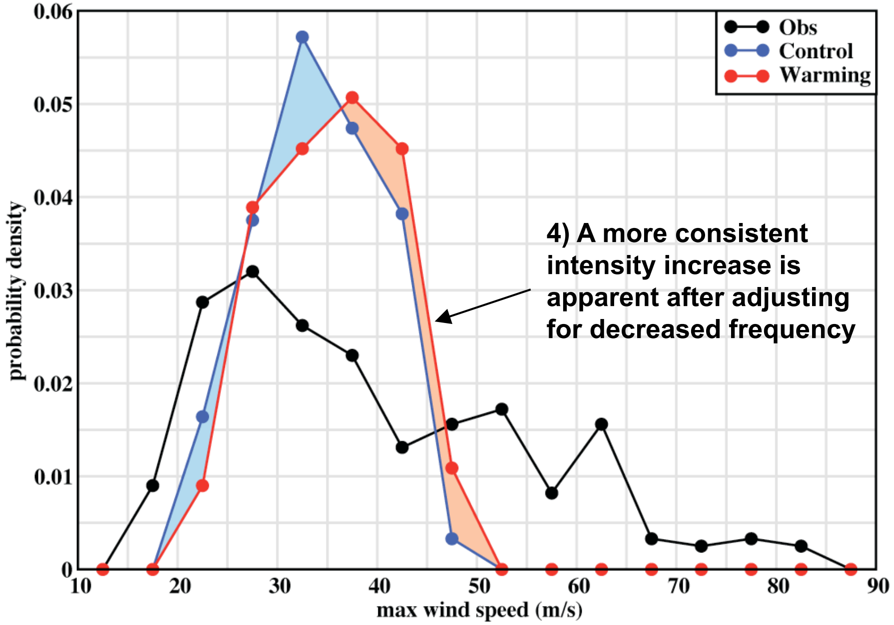
1) Decreased frequency of tropical storms (-27%) and hurricanes (-18%).

Tropical Storms (1980-2006)
histograms of max wind speed



3) Caveat: this model does not simulate hurricanes as strong as those observed.

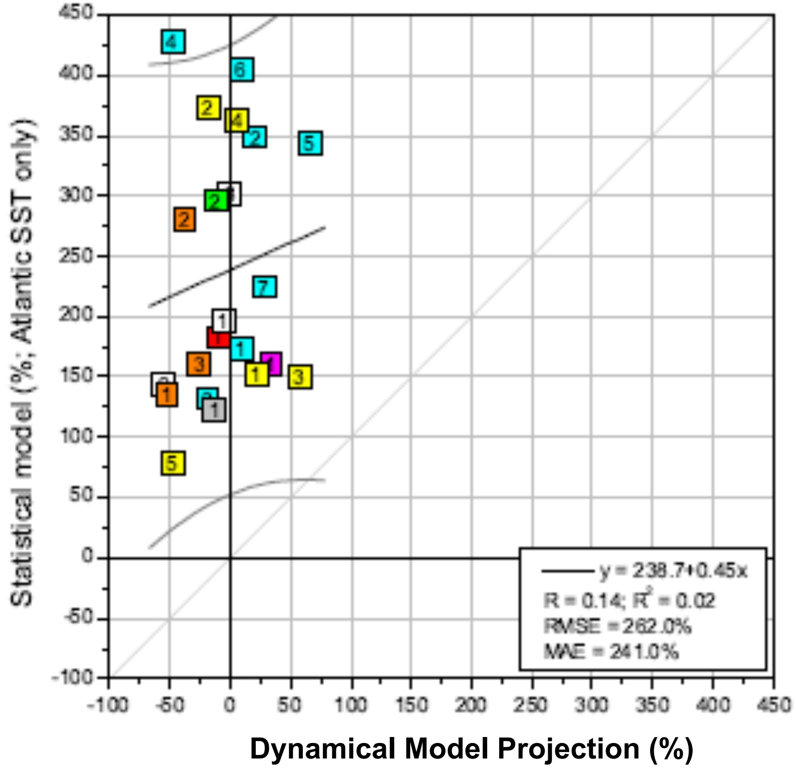
Storm Intensities (Normalized by frequency)
PDF of max wind speed



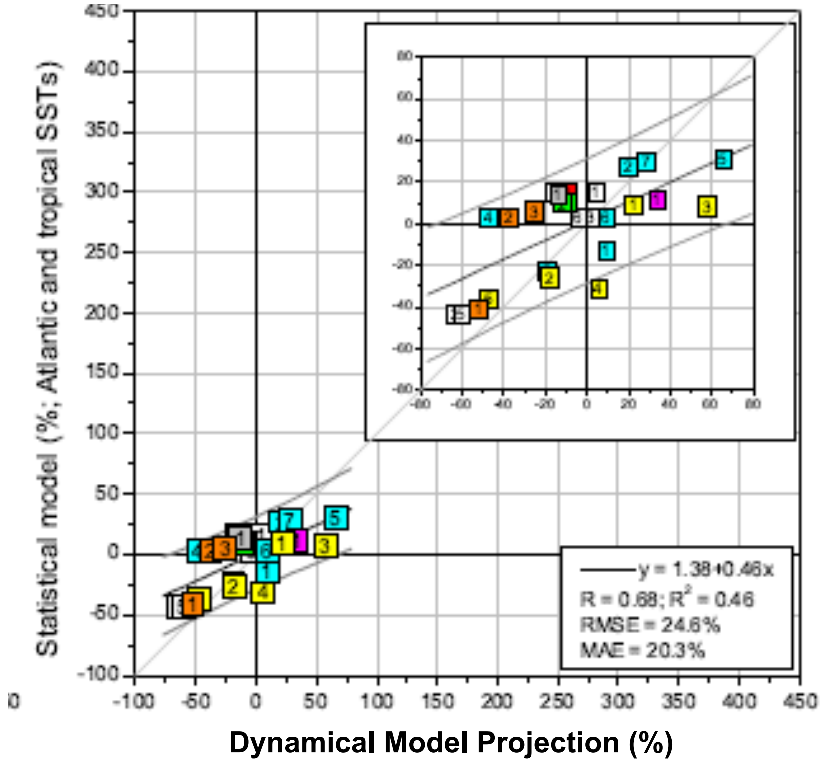
Source: Knutson et al., *2008*, Nature Geoscience.

What environmental variables best ‘explain’ differences in Atlantic Tropical Storm Frequency projections?

Statistical model using local Atlantic MDR SST



Statistical model using Atlantic and Tropical SST



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

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

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

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

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

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

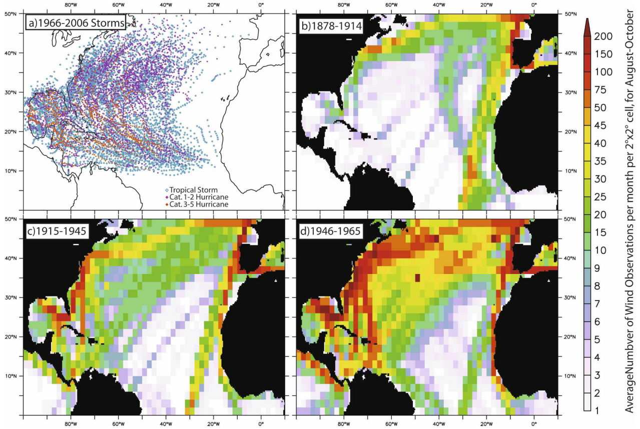
Gualdi et al. (2009)
1. INGV-ECHAM4 $2\times CO_2$

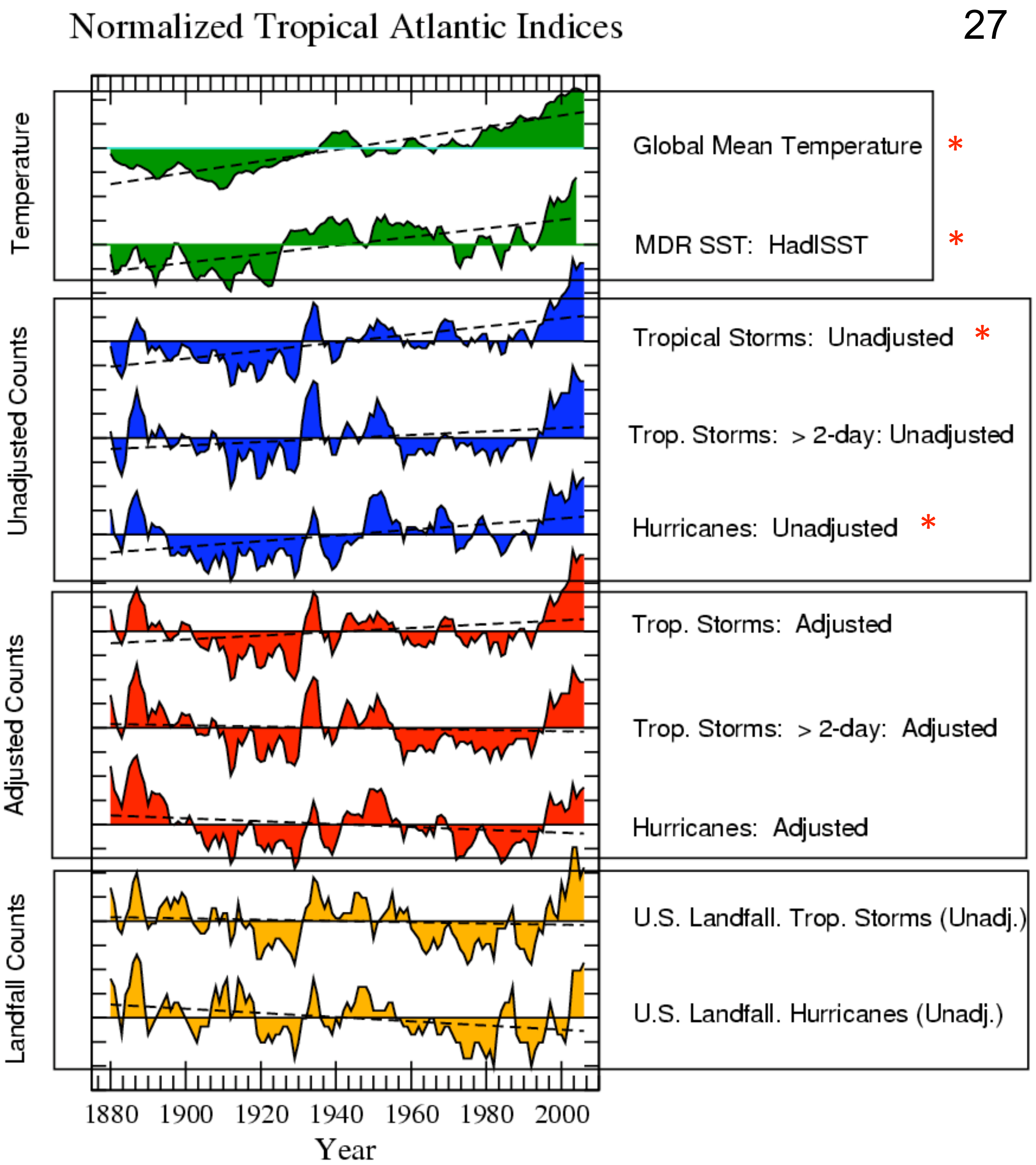
Sugi et al. (2009)
1. MRI CGCM2.3.2 (20 km)
2. MIROC-Hires (20 km)
3. MRI CGCM2.3.2 (60 km)
4. MIROC-Hires (60 km)
5 CSIRO-Mk3.0 (60 km)

Source: Villarini et al. (J. Climate) in press.

* => Significant at p=0.05

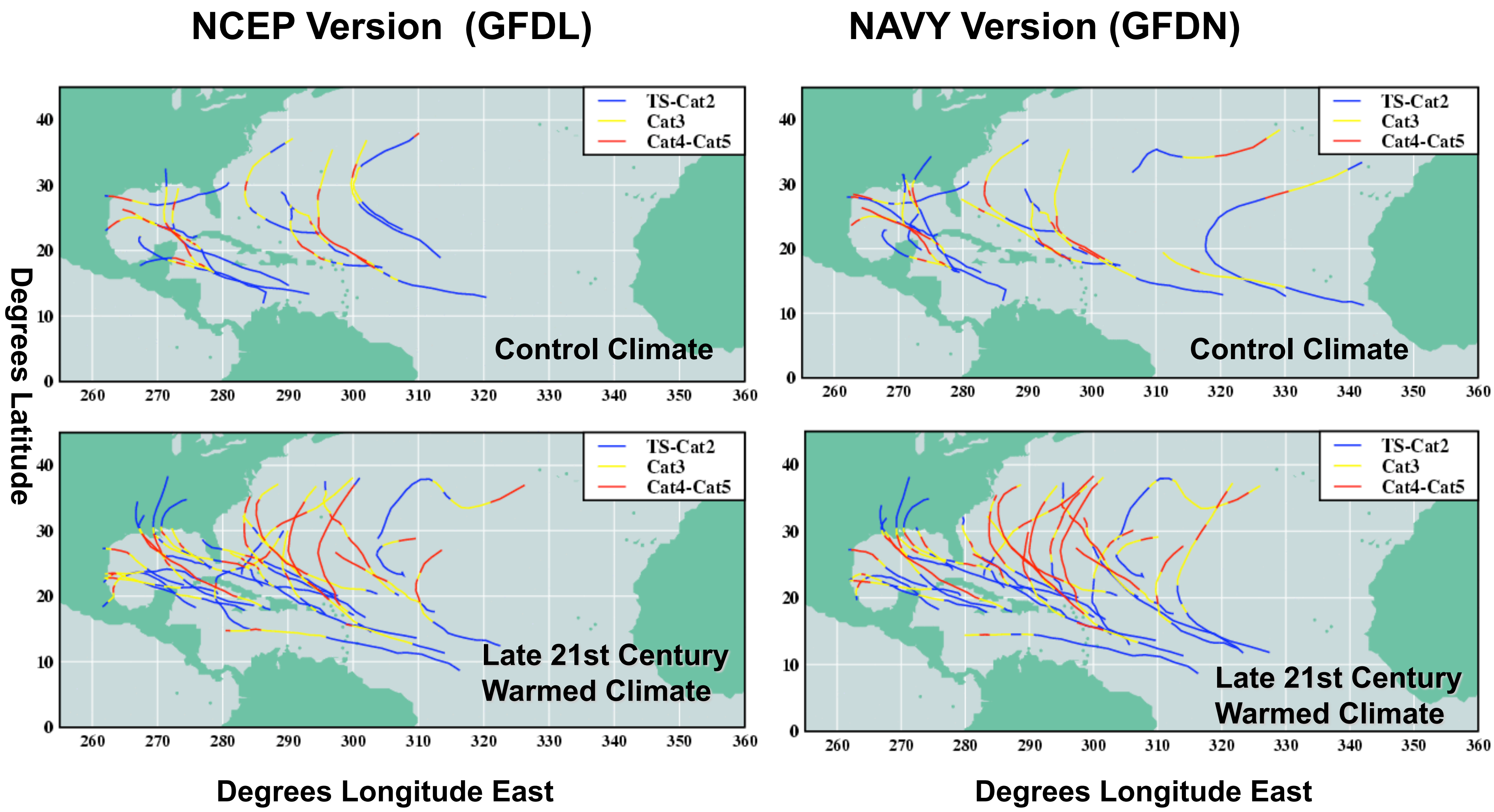
Adjustments to storm counts based on ship/storm track locations and density





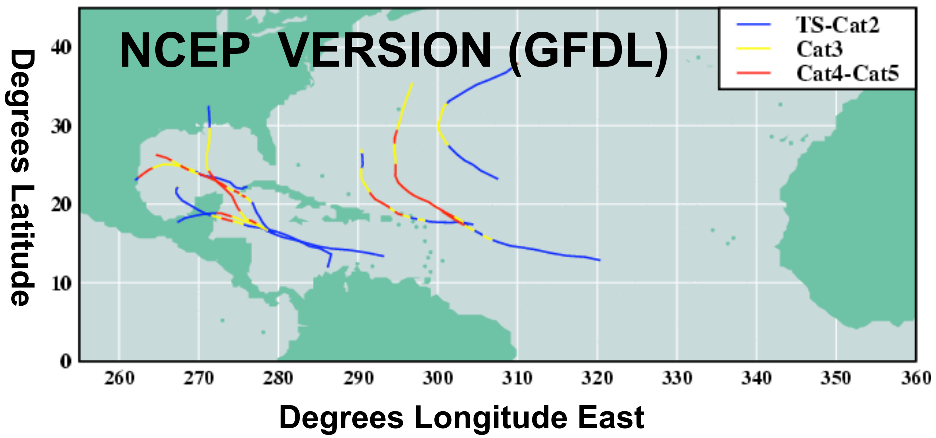
Sources:
Vecchi and Knutson (2008)
Landsea et al. (2009)
Vecchi and Knutson (2011)

Category 4-5 Hurricanes (27 Seasons); GFDL Hurricane Model (2 Versions) Downscale of Zetac Control and CMIP3 Ensemble Climate Change



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

Control Climate

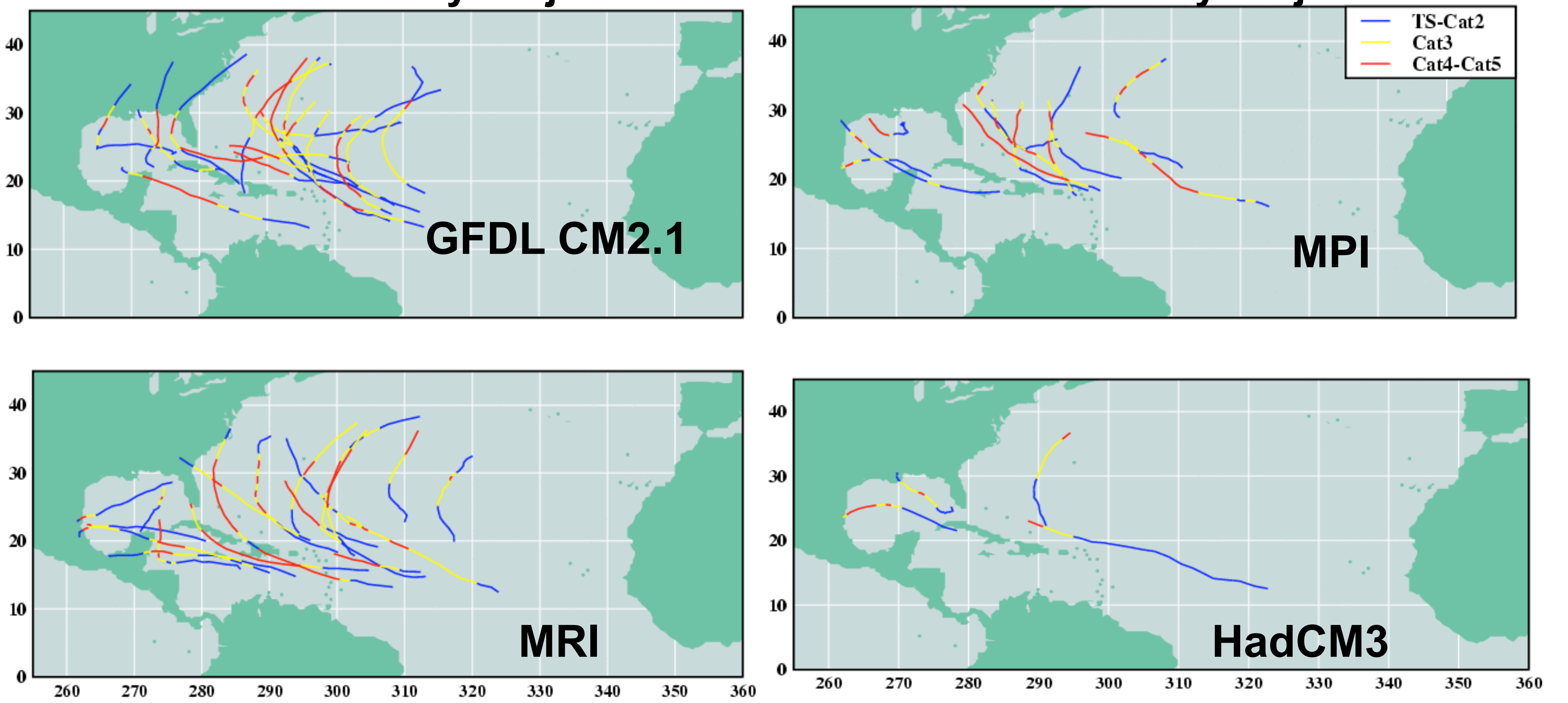


Category 4-5 Hurricanes

(13 seasons, downscaling 4 indiv. CMIP3 models)

Late 21st Century Projections

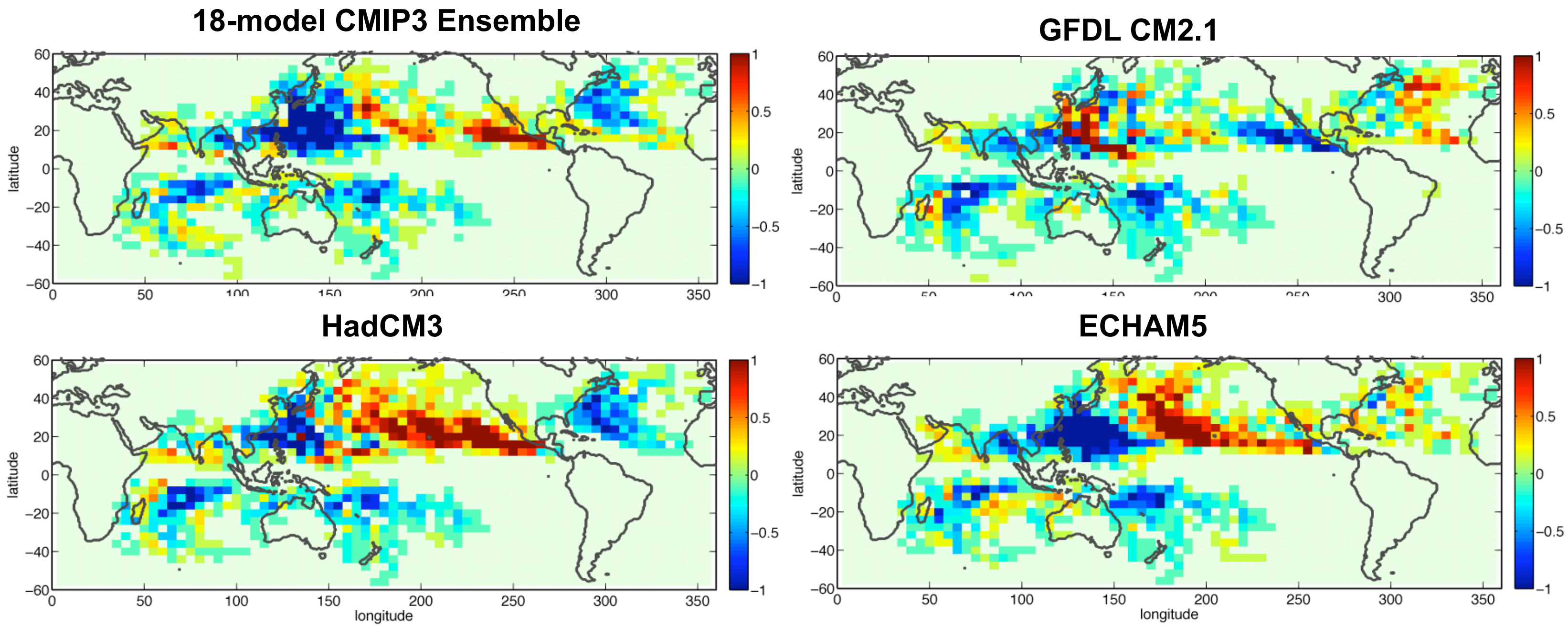
Late 21st Century Projections



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

Tropical cyclone activity: Late 21st century projected changes

GFDL 50-km HIRAM, using four CMIP3-based projections of SSTs.

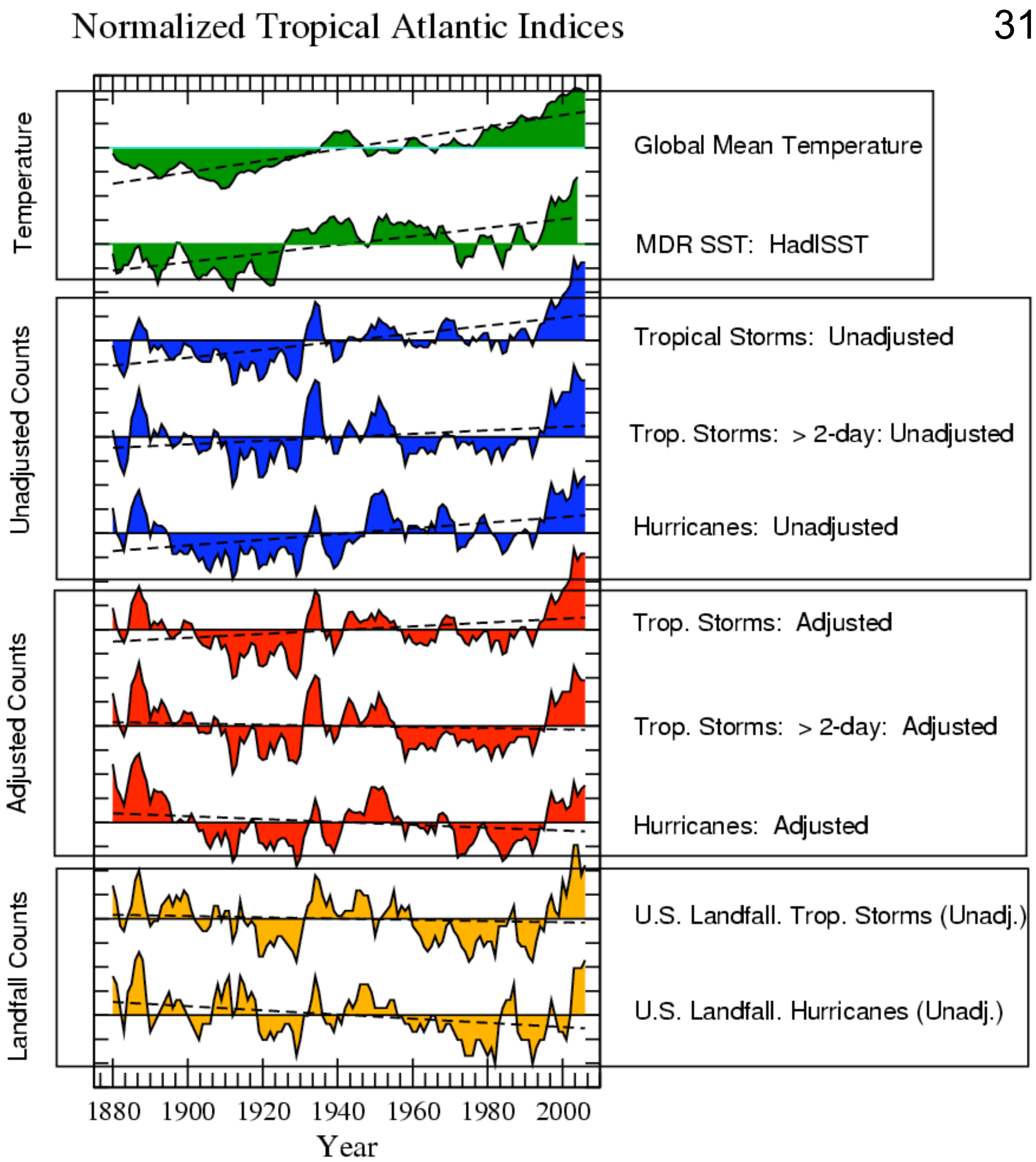


Red/yellow = increase
Blue/green = decrease

Unit: Number per year

- Regional increases/decreases much larger than global-mean changes.
- Pattern depends on details of SST change.

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



Sources:
- Vecchi and Knutson (2008)
- Landsea et al. (2009)
- Vecchi and Knutson (in preparation)

WMO EXPERT TEAM SUMMARY ASSESSMENT:

Detection and Attribution:

It remains uncertain whether past changes in any tropical cyclone activity (frequency, intensity, rainfall, etc.) exceed the variability expected through natural causes, after accounting for changes over time in observing capabilities.

Source: Knutson et al., 2010: Tropical Cyclones and Climate Change. Nature Geoscience, 3, 157-163.

WMO TEAM SUMMARY ASSESSMENT:

Tropical Cyclone Projections: Frequency

It is likely that the global frequency of tropical cyclones will either decrease or remain essentially unchanged due to greenhouse warming. We have very low confidence in projected changes in individual basins. Current models project changes ranging from -6 to -34% globally, and up to ± 50% or more in individual basins by the late 21st century.

"Likely": >67% probability of occurrence, assessed using expert judgment

WMO TEAM SUMMARY ASSESSMENT:

Tropical Cyclone Projections: Intensity

Some increase in mean tropical cyclone maximum wind speed is likely (+2 to +11% globally) with projected 21st century warming, although increases may not occur in all tropical regions. The frequency of the most intense (rare/high-impact) storms will more likely than not increase by a substantially larger percentage in some basins.

"More likely than not": >50% probability of occurrence, assessed using expert judgment

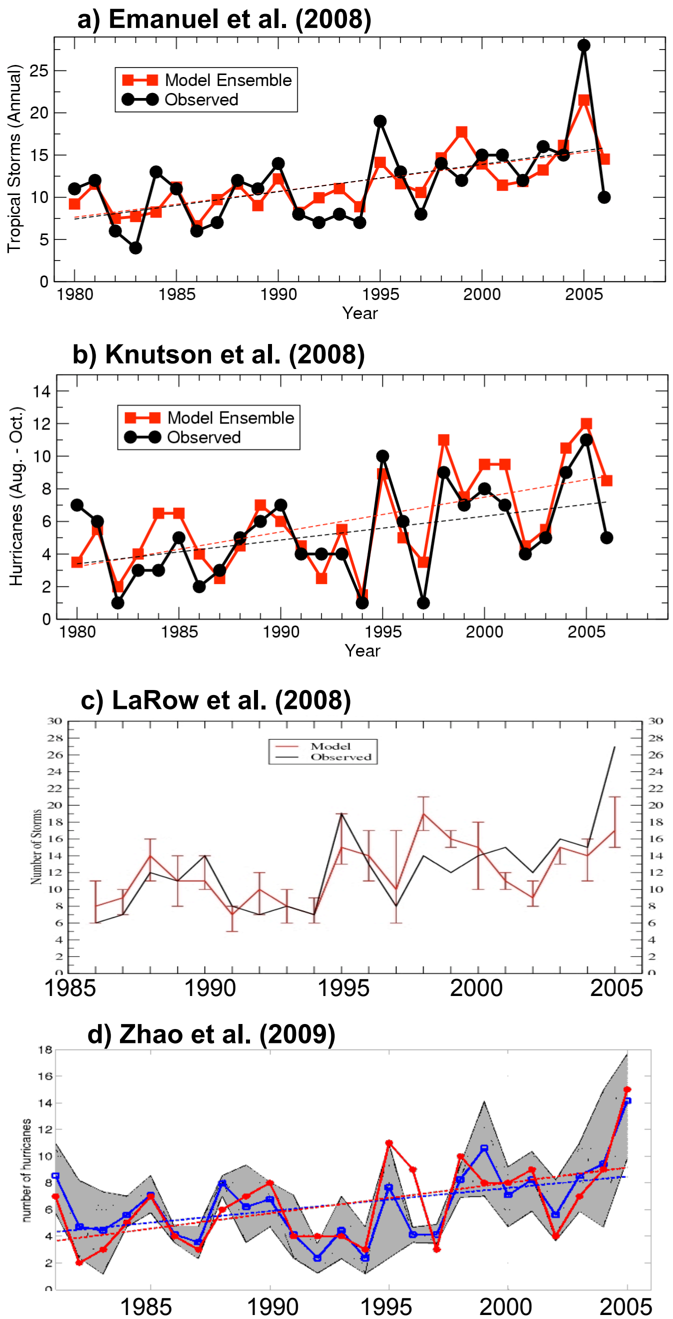
WMO TEAM SUMMARY ASSESSMENT:

Tropical Cyclone Projections: Genesis, Tracks, Duration, and Surge Flooding

We have low confidence in projected changes in genesis location, tracks, duration, or areas of impact. Existing model projections do not show dramatic large-scale changes in these features. The vulnerability of coastal regions to storm surge flooding is expected to increase with future sea level rise and coastal development, although this vulnerability will also depend on future storm characteristics.

Attribution of tropical cyclone (hurricane) changes to anthropogenic forcing?

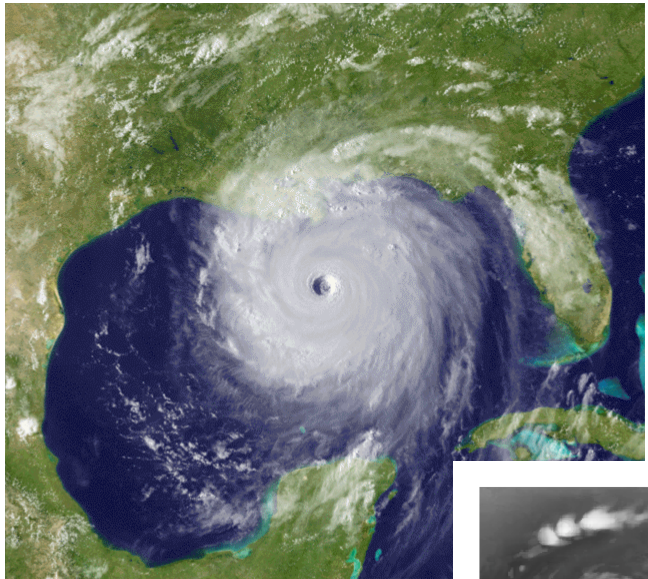
- Detection: is there an observed change that exceeds "internal variability"?
- Attribution: is the observed change consistent with expected anthropogenic influence? And inconsistent with alternative explanations?
- Models/theory must reconcile with observations
- Observations must be assessed for "false trends" based on evolving observational capabilities



Now a more robust result, as several dynamical or statistical-dynamical models can simulate recent Atlantic tropical cyclone interannual variability and trends…

Atlantic Hurricanes and Climate Change

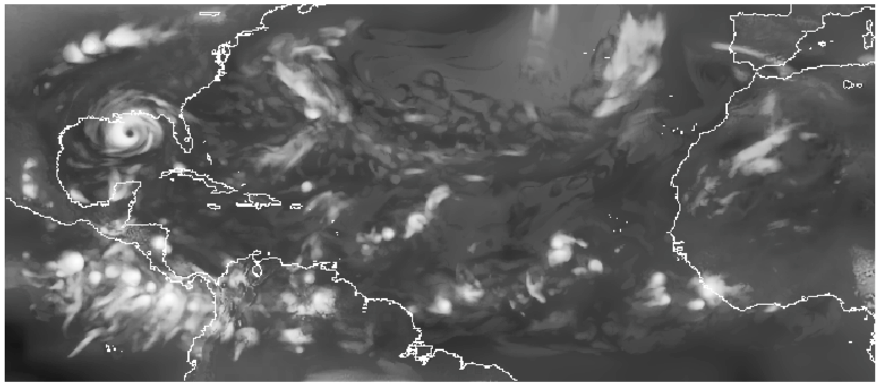
Hurricane Katrina, Aug. 2005



Tom Knutson

Geophysical Fluid Dynamics Lab/NOAA
Princeton, New Jersey

http://www.gfdl.noaa.gov/~tk

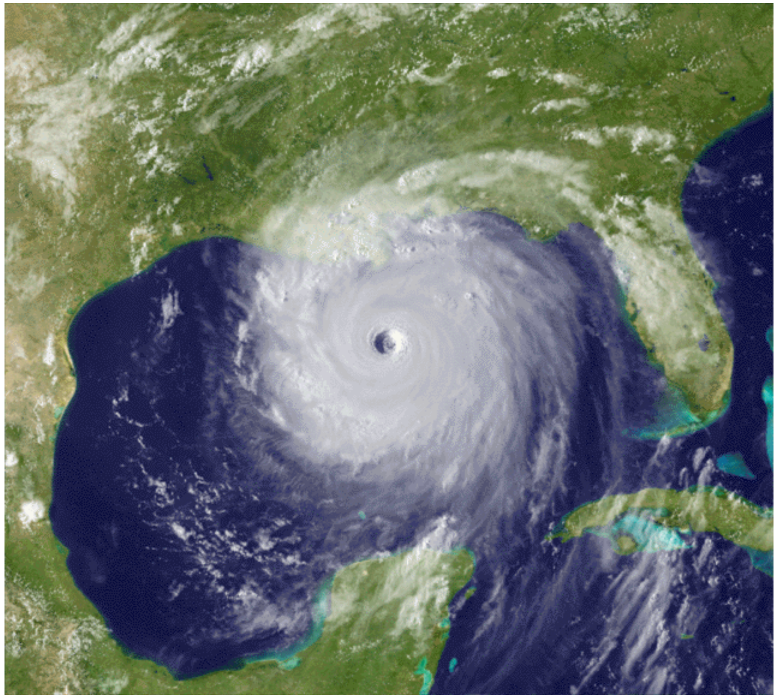


GFDL model simulation of Atlantic hurricane activity

<u>*GFDL Collaborators:*</u>

Joe Sirutis
Isaac Held
Gabe Vecchi
Bob Tuleya
Morris Bender
Steve Garner
Ming Zhao
S.-J. Lin

Tropical Cyclones and Climate Change: An Assessment



WMO Expert Team on Climate Change Impacts on Tropical Cyclones

February 2010

World Meteorological Organization
Weather Research Programme
Working Group on Tropical Meteorology Research

Expert Team Members:

John McBride, Co-Chair — Center for Australian Weather and Climate Research, Melbourne, Australia

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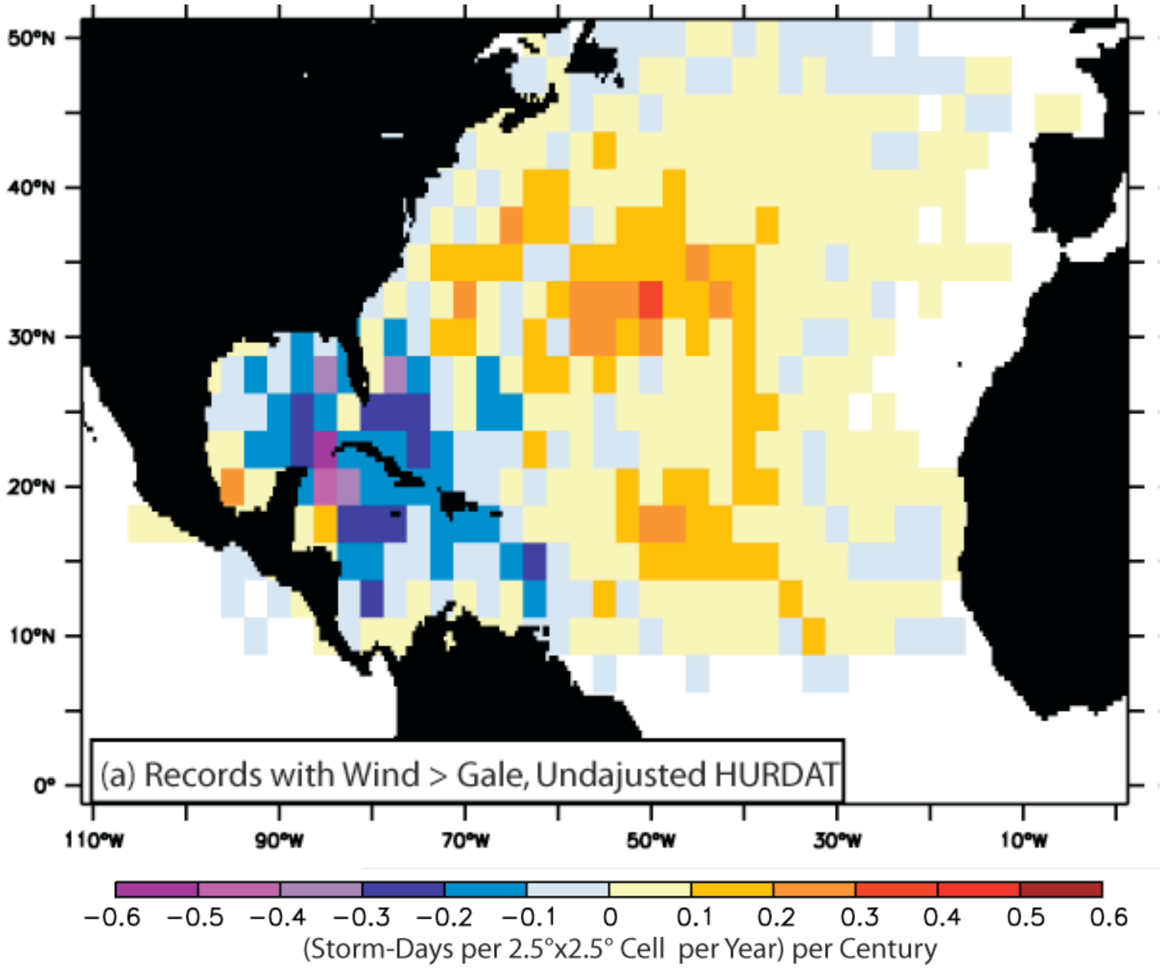
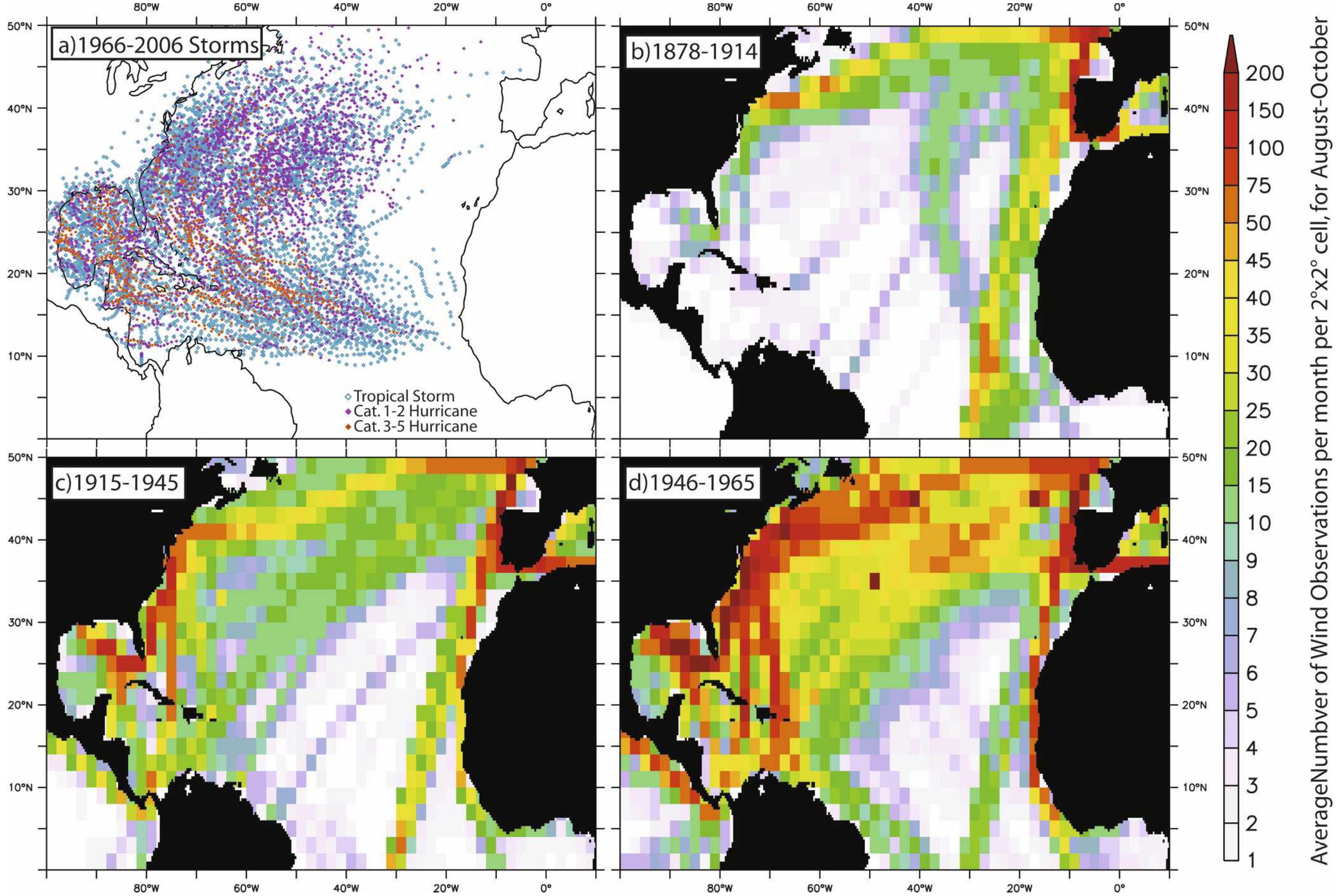
Linear trends in tropical storm track density (1878-2006):
Decreases in the Gulf of Mexico and Caribbean
Increases mostly found in the open Atlantic and off the U.S. East Coast (based on original, unadjusted data)…



Source: Vecchi and Knutson, J. Climate, 2008.

Ship tracks have changed in density and location over time

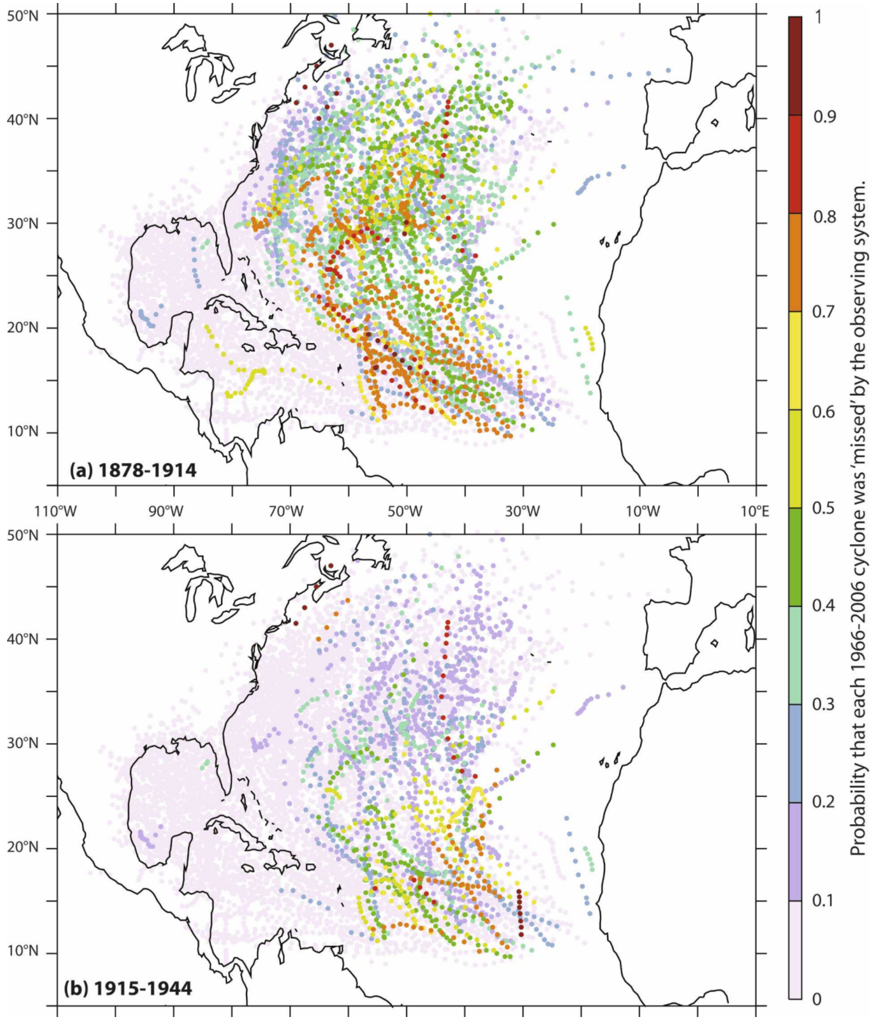


Source: Vecchi and Knutson , J. Climate, 2008.

Reconstructing past tropical cyclone counts

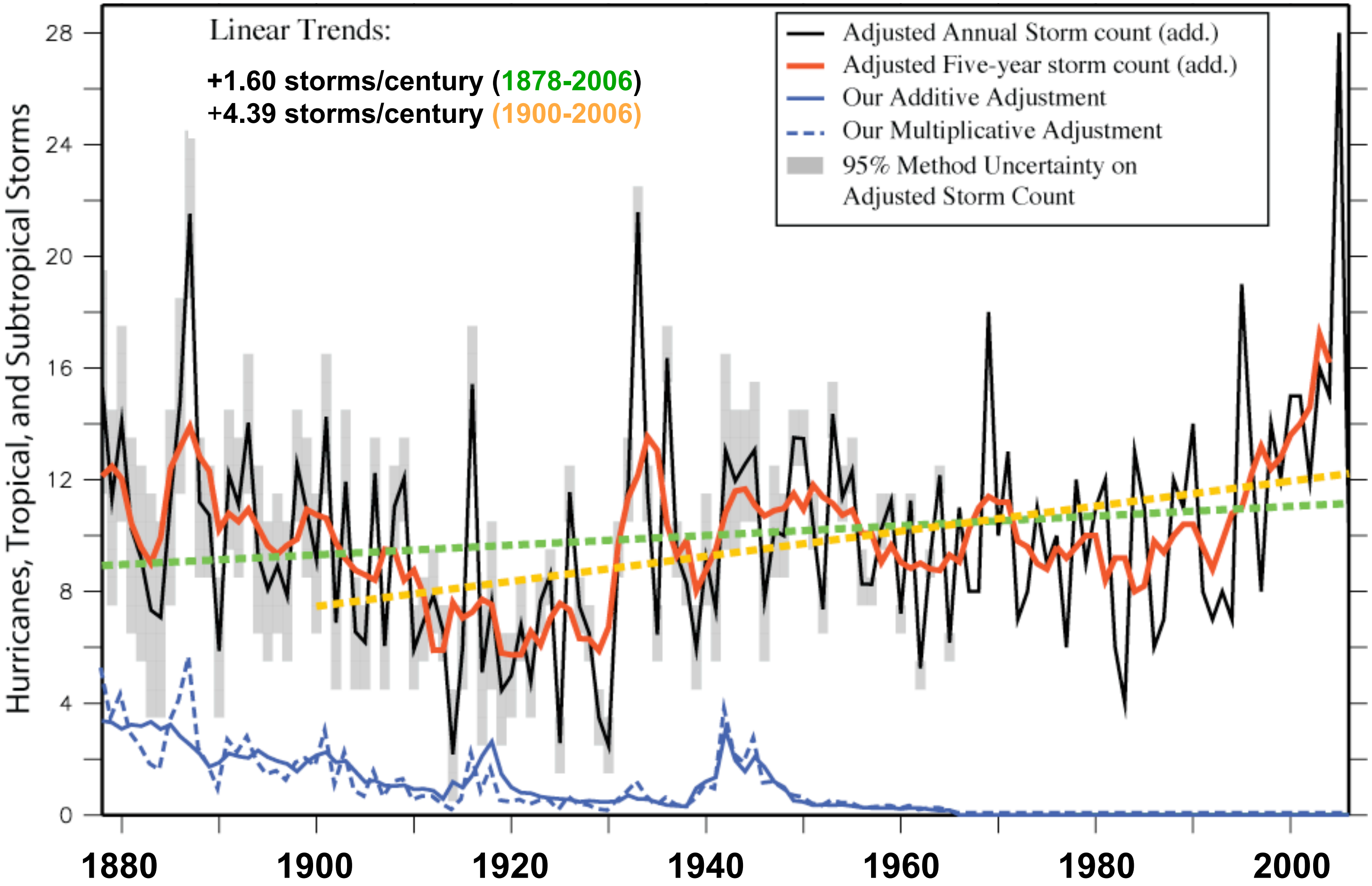
- Satellite-era (1965-2006) storm tracks assumed perfect.
- Apply satellite-era storm tracks to documented ship tracks (ICOADS).
- Storm detected if ship within radius of tropical storm force winds (17 m/s). First detection must occur equatorward of 40N. Monte Carlo simulation, varying storm radii within reasonable bounds.
- All land assumed to be “perfect detector” of tropical storms (equatorward of 40N)—planned to further test…
- Assume all relevant ship tracks are in data base—plan further tests with additional tracks. (First will look for evidence of storms in “new” ship data.)

Estimated probabilities that individual cyclones (1966-2006) were 'missed' by the observing systems for earlier decades…



Source: Vecchi and Knutson , J. Climate, 2008.

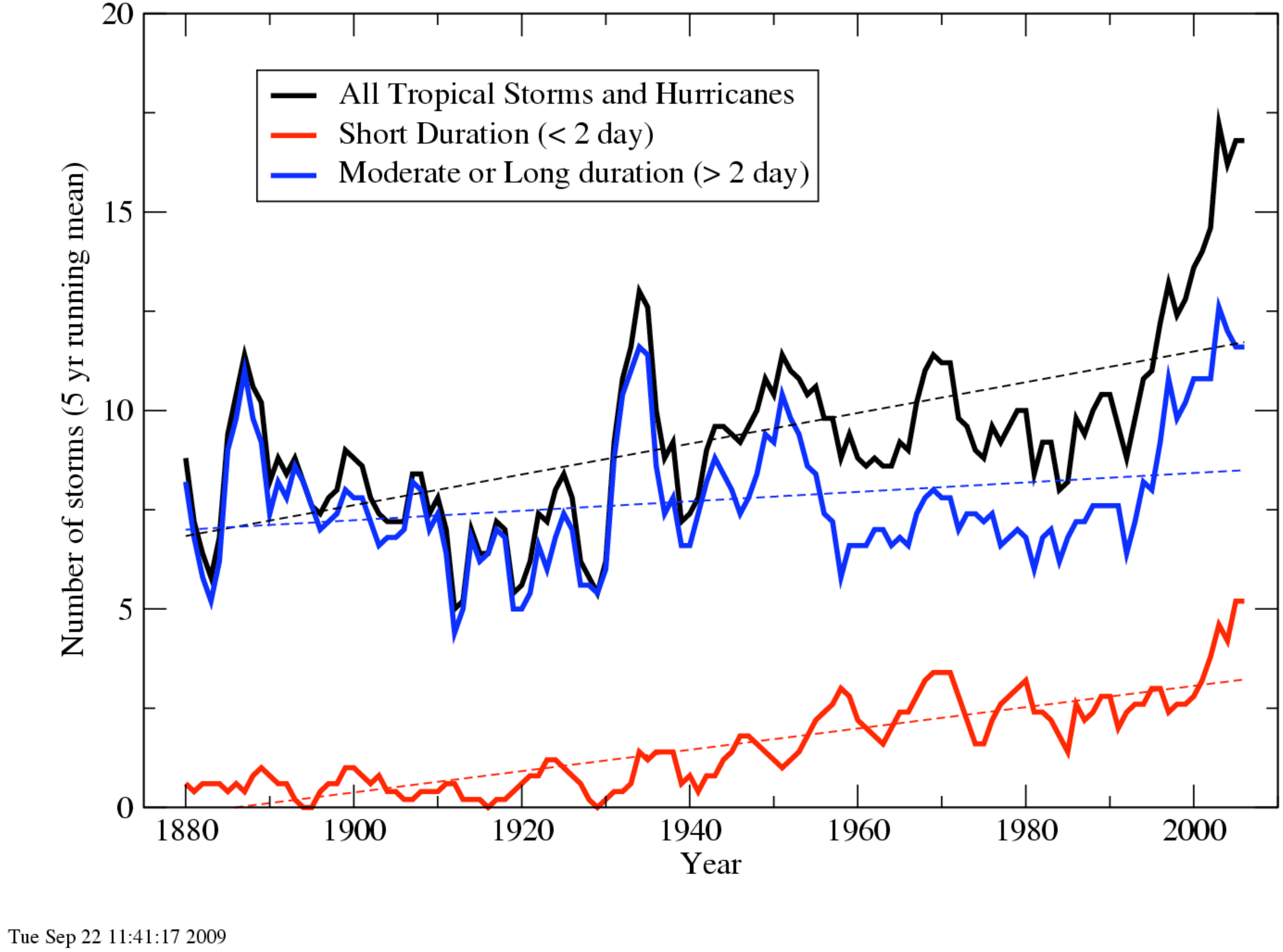
Atlantic Tropical Storm counts show no significant trend from 1878 after adjusting for ‘missing storms’ based on ship track densities.



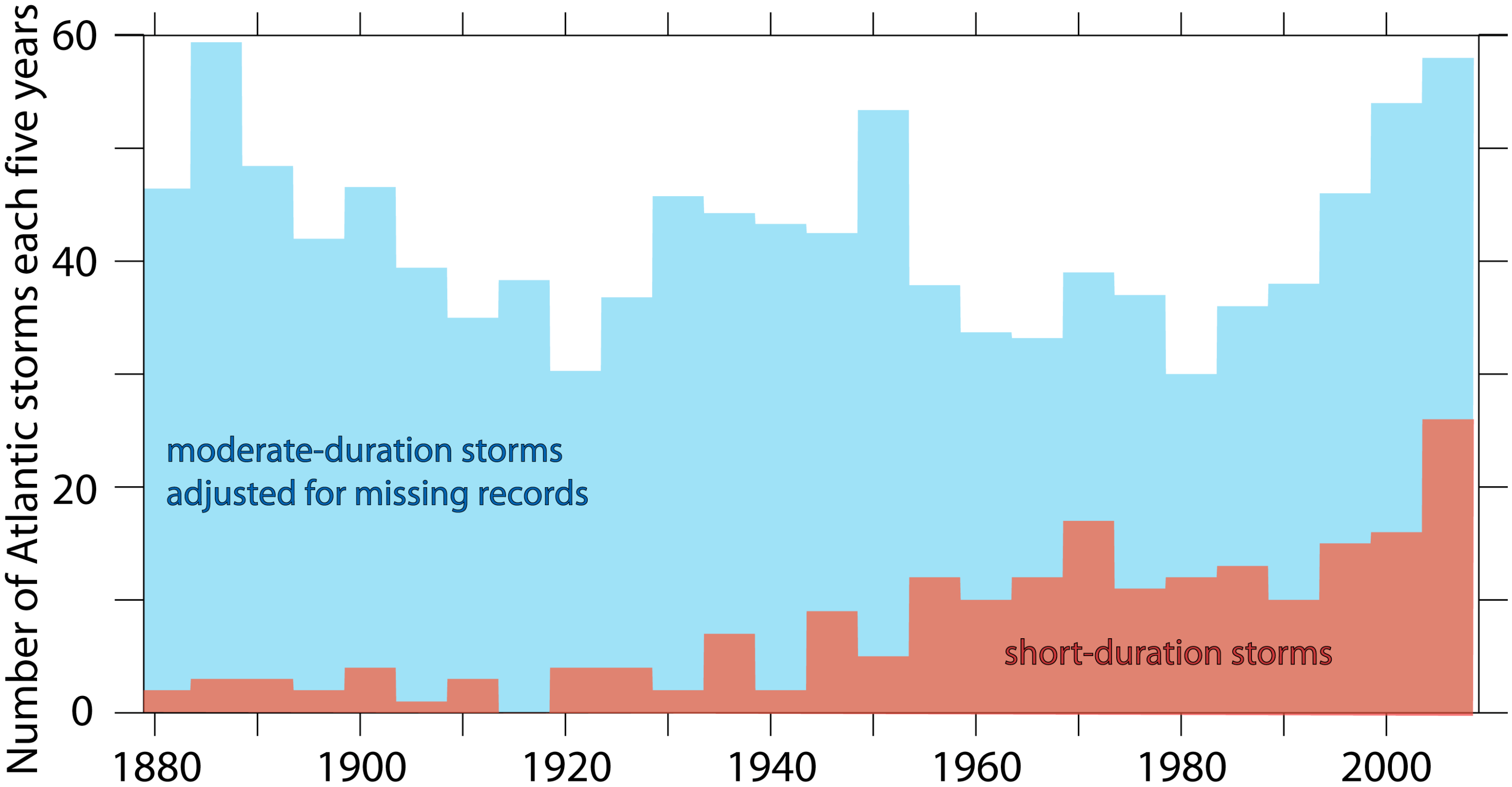
Trend from 1878-2006: Not significant (p=0.05, 2-sided tests, computed p-val ~0.2)
Trend from 1900-2006: Is significant at p=0.05 level

Source: Vecchi and Knutson, J. Climate, 2008.

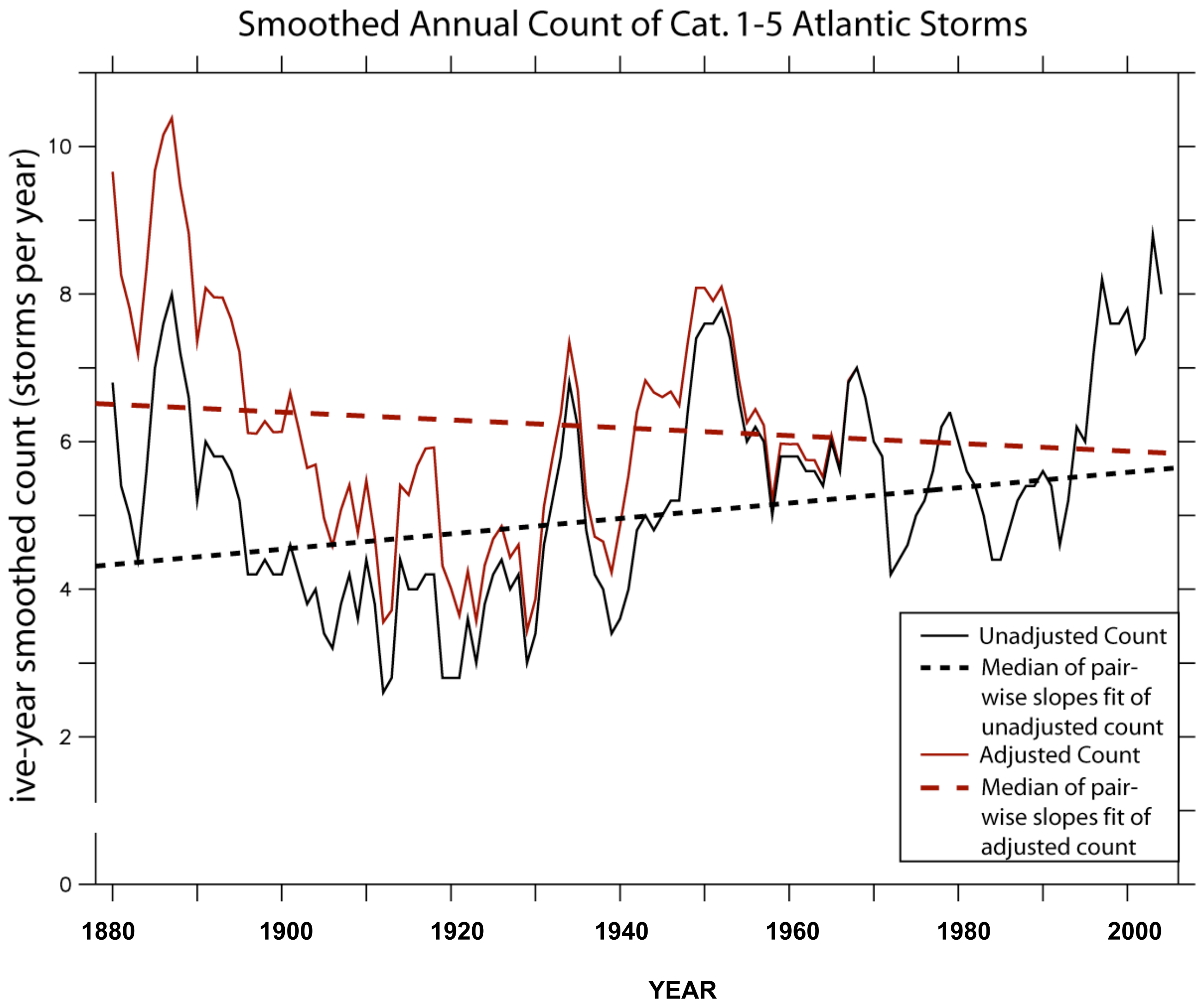
The rising trend in Atlantic tropical storms is due mostly to very short lived storms (< 2 day duration)



Atlantic tropical storms (< 2 day duration) show a strong rising trend, but storms of >2 day duration--adjusted for missing storms--do not show a trend.

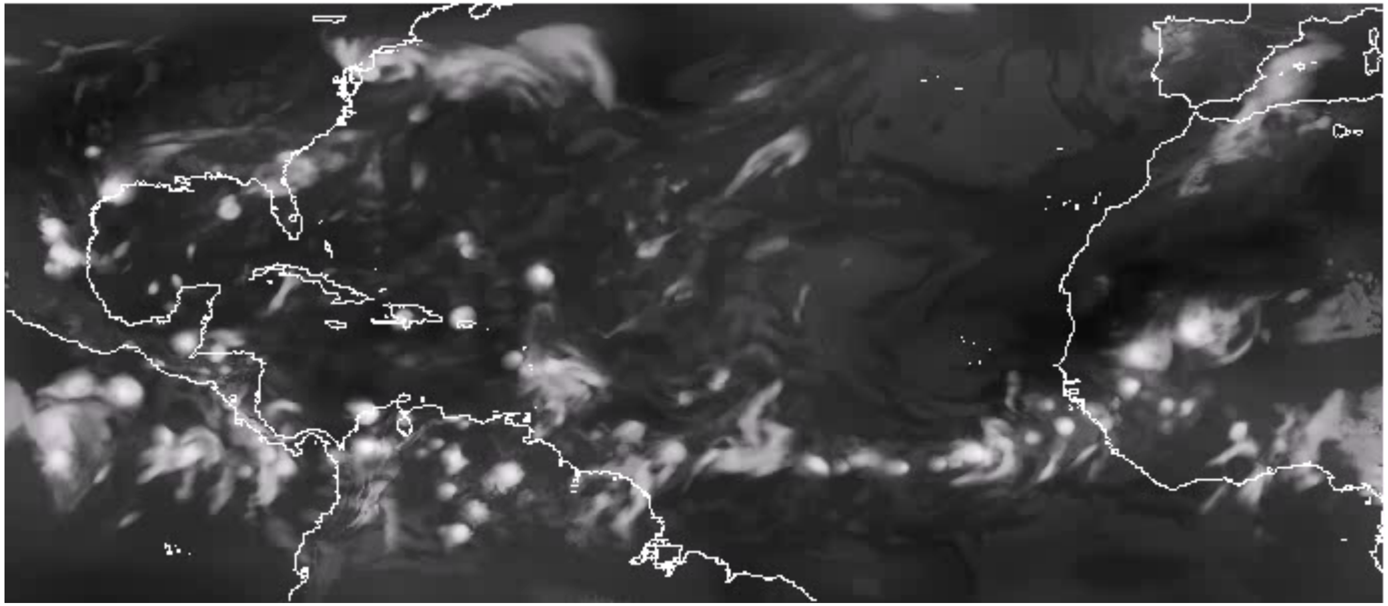


Application of Vecchi/Knutson ship-track methodology to hurricanes



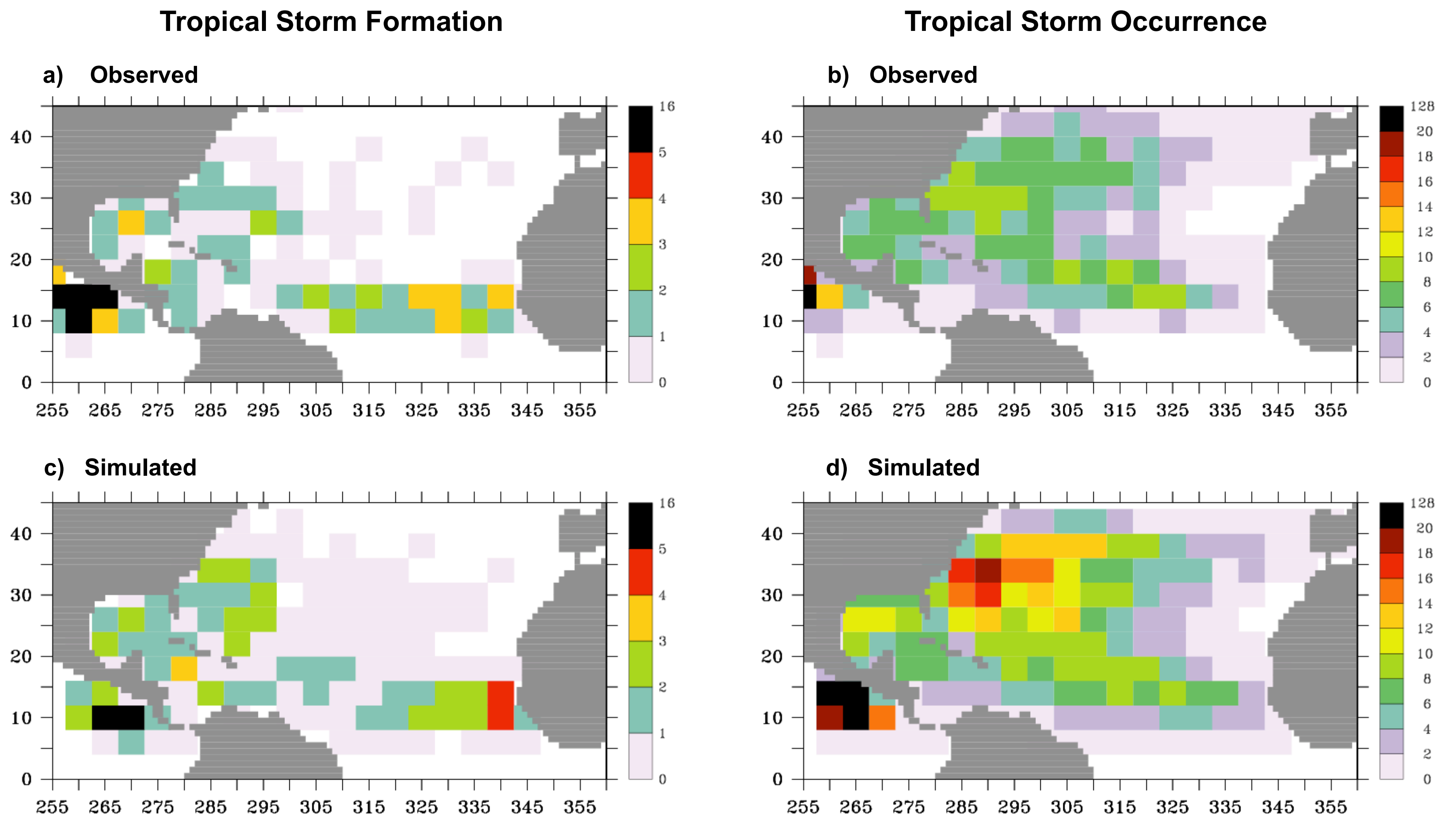
Sources: Vecchi and Knutson, GFDL, manuscript in preparation

GFDL Zetac Model: A new high-resolution regional model for Atlantic hurricane season simulations…



- The model runs for full hurricane seasons, nudged to NCEP reanalyses.
- Model grid spacing: 18km.
- Model does not parameterize moist convection.

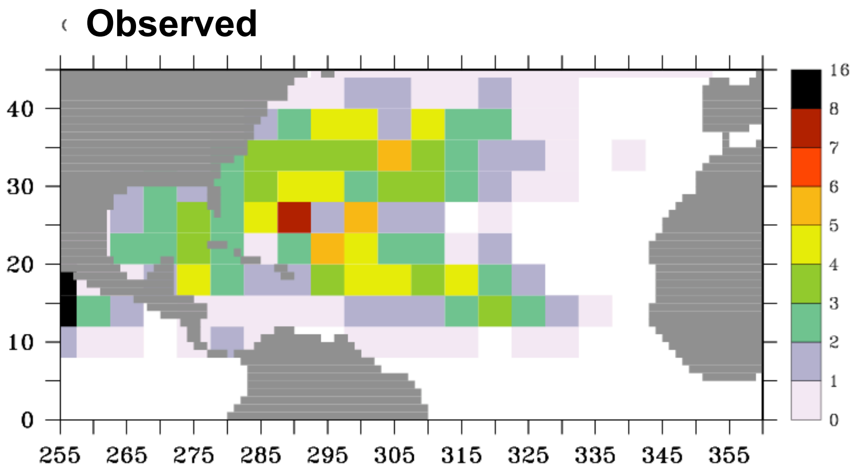
Zetac Regional Model Downscaling: geographical distribution of storms

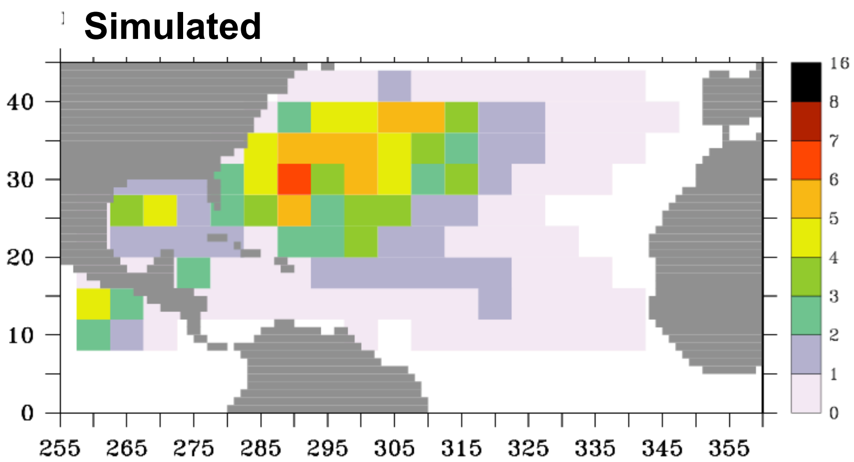


Note: Model uses large-scale interior nudging to NCEP Reanalysis

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

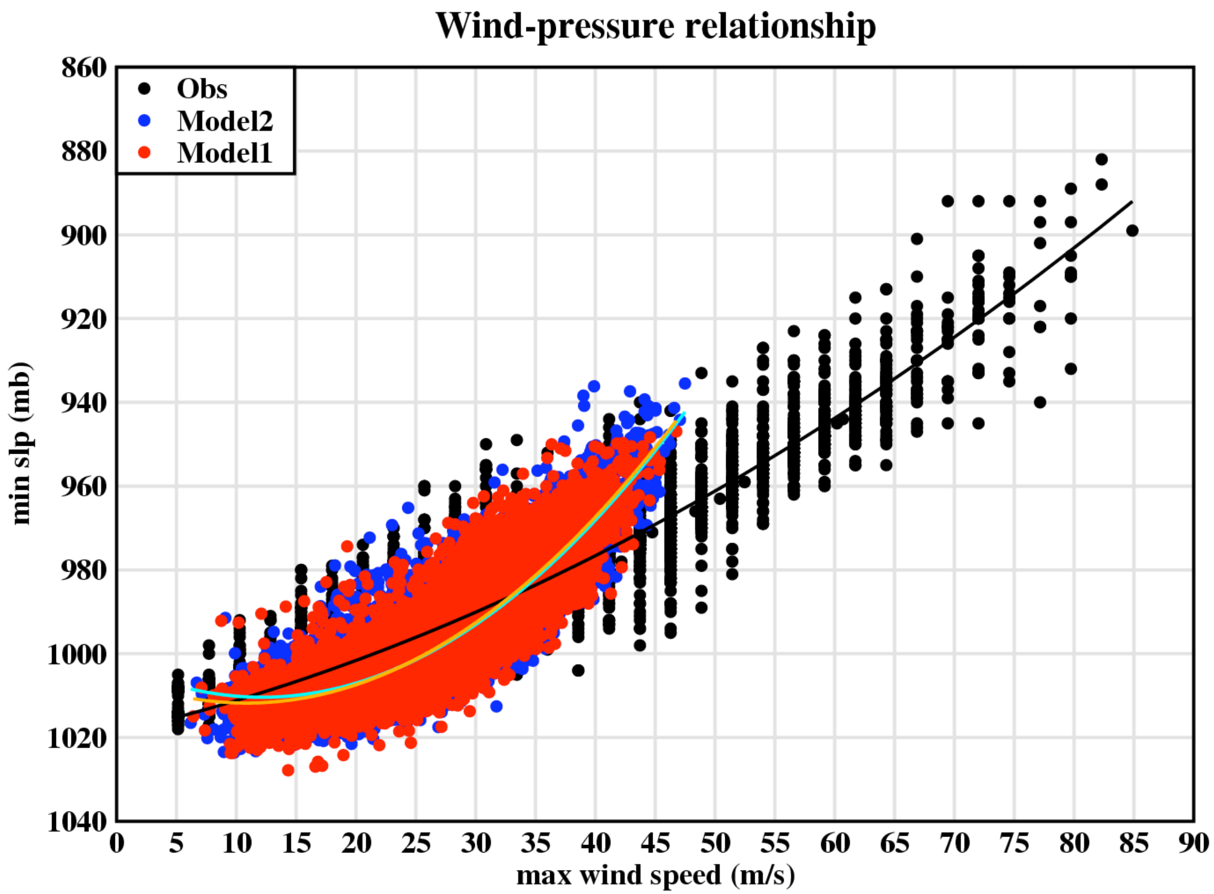
Zetac Regional Model Downscaling: Distribution of hurricane occurrence





Note: Model uses large-scale interior nudging to NCEP Reanalysis

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



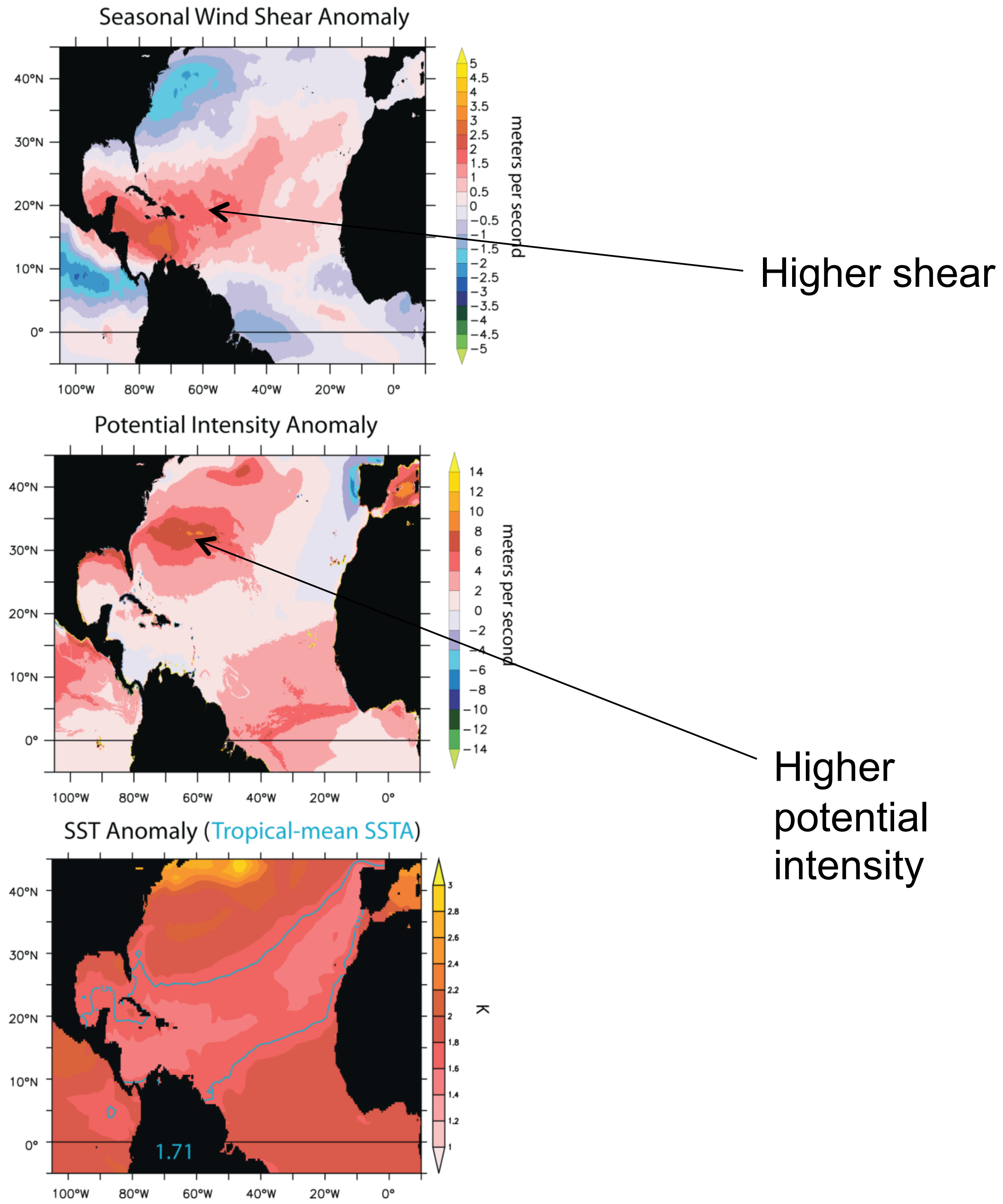
…the 18km grid model's poor wind-pressure relation at lower central pressures leads to maximum near-surface winds of ~47 m/s, considerably lower than observed…

Climate Change Experiments

- Re-run all 27 seasons with the Zetac regional model, but modify the NCEP Reanalysis forcing by a 3-D climate change perturbation field:
  - Multi-model ensemble climate change. IPCC A1B scenarion. 18 CMIP3 climate models (similar to Vecchi and Soden, 2007).
  - Compare modified climate runs with original 26 year control runs.
  - Interannual/decadal variability and weather are unaltered from the control run.
  - Multi-model ensemble climate change approach reduces problems with corruption of climate change signal by internal multi-decadal variability in the models.

Source: Knutson et al., *Nature Geoscience*, 2008.

18-Model CMIP3 Ensemble-Mean Climate Change Projections (A1B Scenario, Late 21st century)



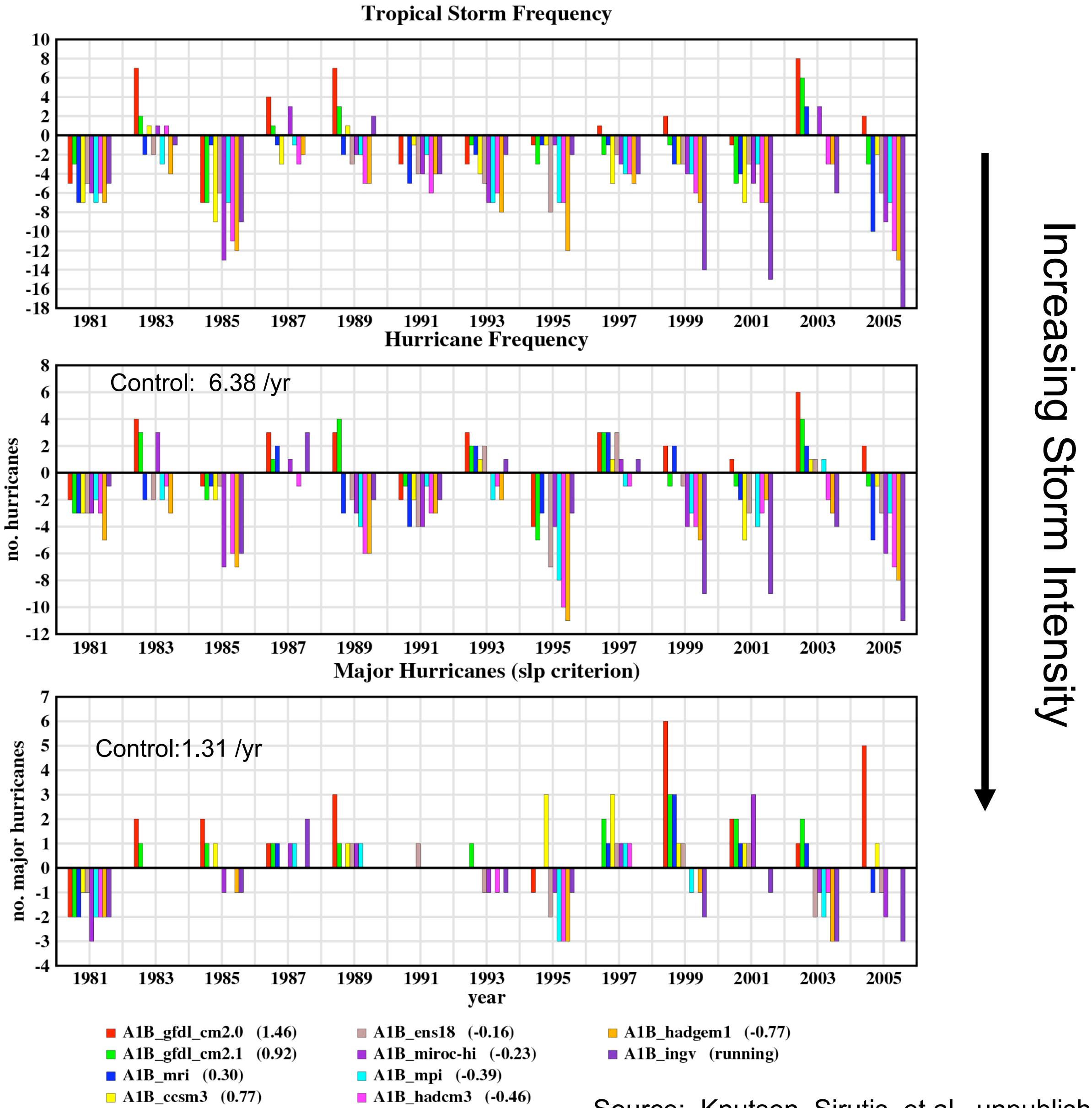
55

Climate Model Dependence: Zetac downscaling (Warm minus Control)

Tropical Storms:
18-model ens.: -33%

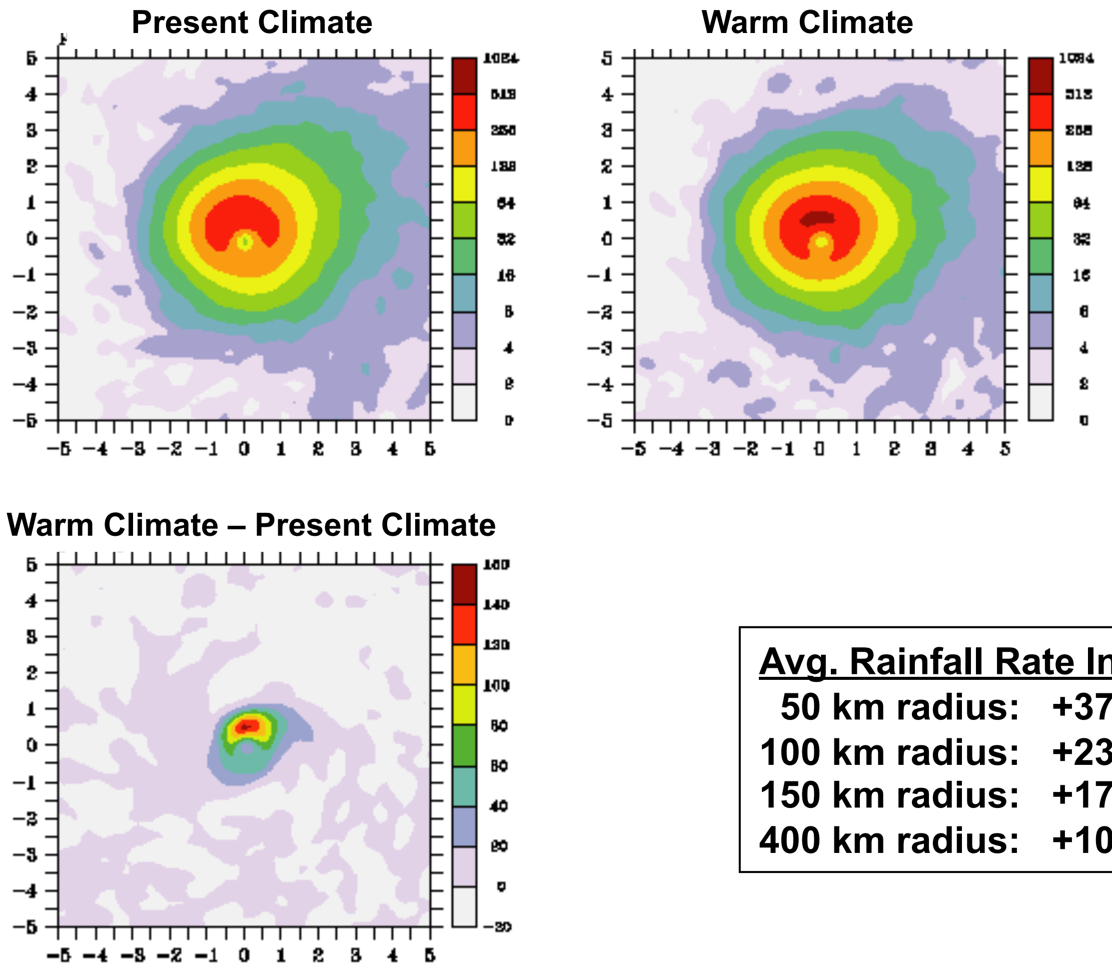
Hurricanes:
18-model ens.: -24%

Major Hurricanes:
18-model ens.: -5%



Source: Knutson, Sirutis, et al., unpublished

The new model simulates increased hurricane rainfall rates in the warmer climate (late 21st century, A1B scenario) … consistent with previous studies…



Rainfall Rates
(mm/day)

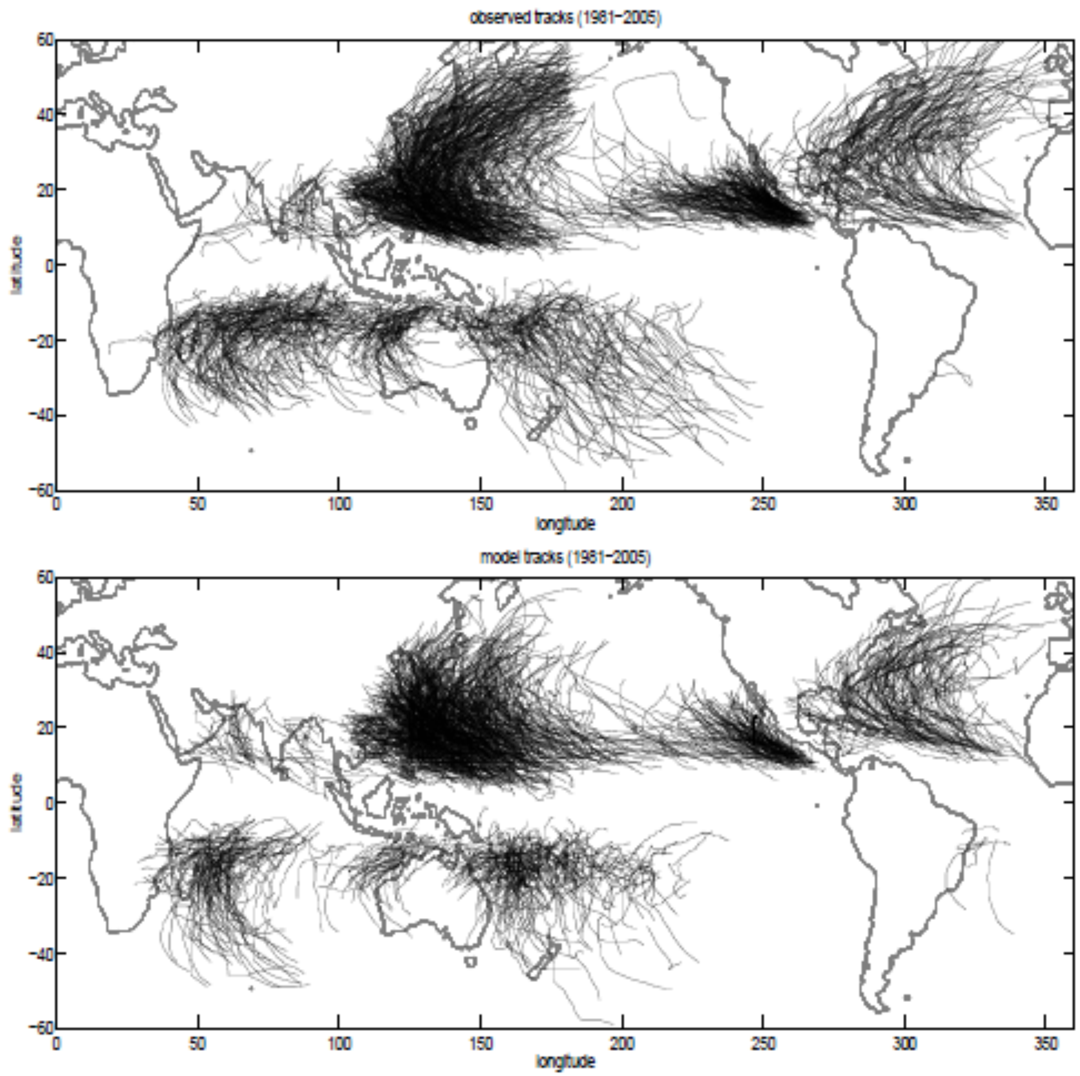
<u>Avg. Rainfall Rate Increases</u>:
50 km radius: +37%
100 km radius: +23%
150 km radius: +17%
400 km radius: +10%

Average Warming: 1.72^{o}C

Source: Knutson et al., *2008*, *Nature Geoscience*.

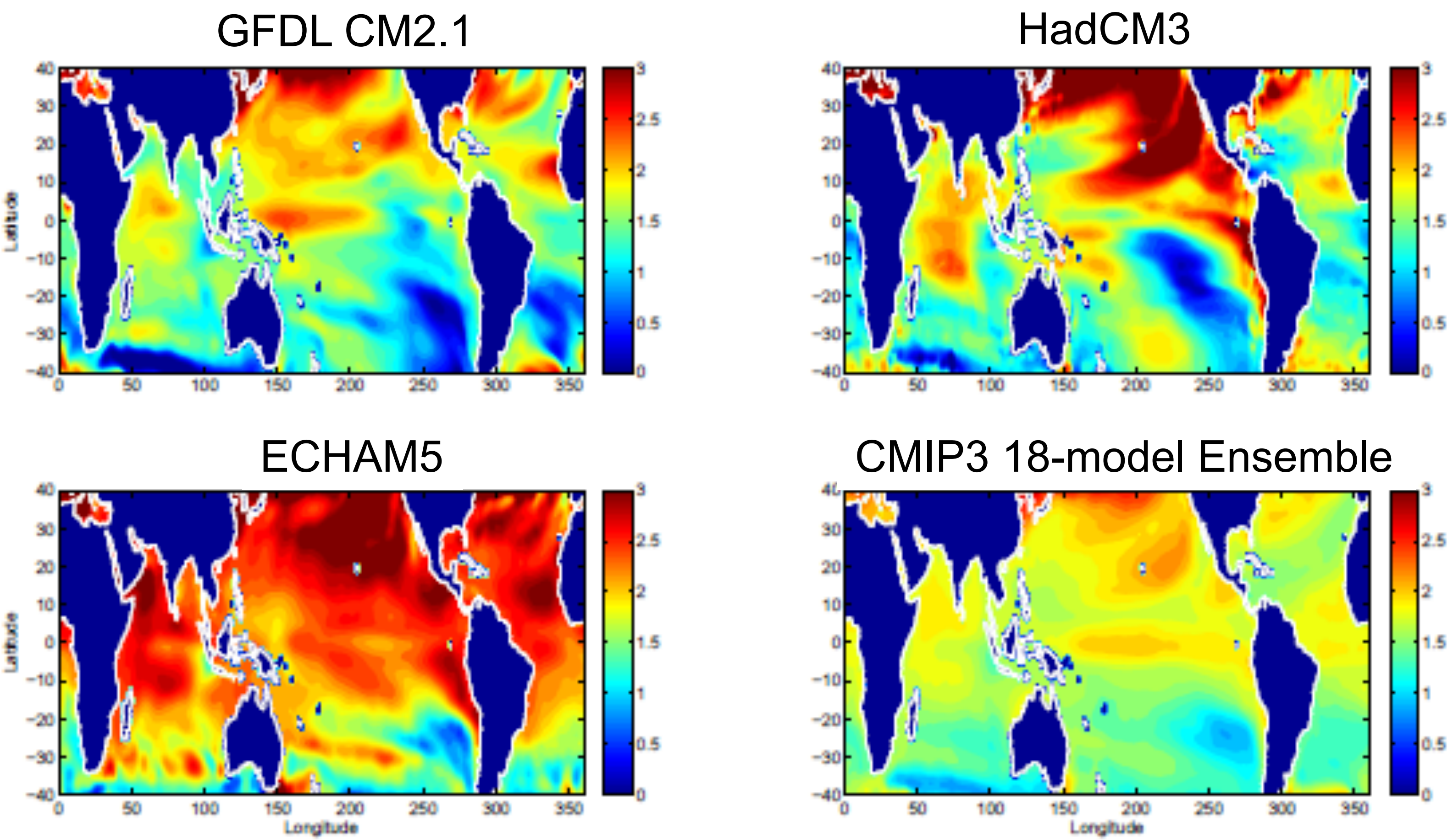
GFDL HIRAM 50km grid global model:

Simulated vs Observed Tropical Storm Tracks (1981-2005)



Source: Zhao et al. J. Climate (2009)

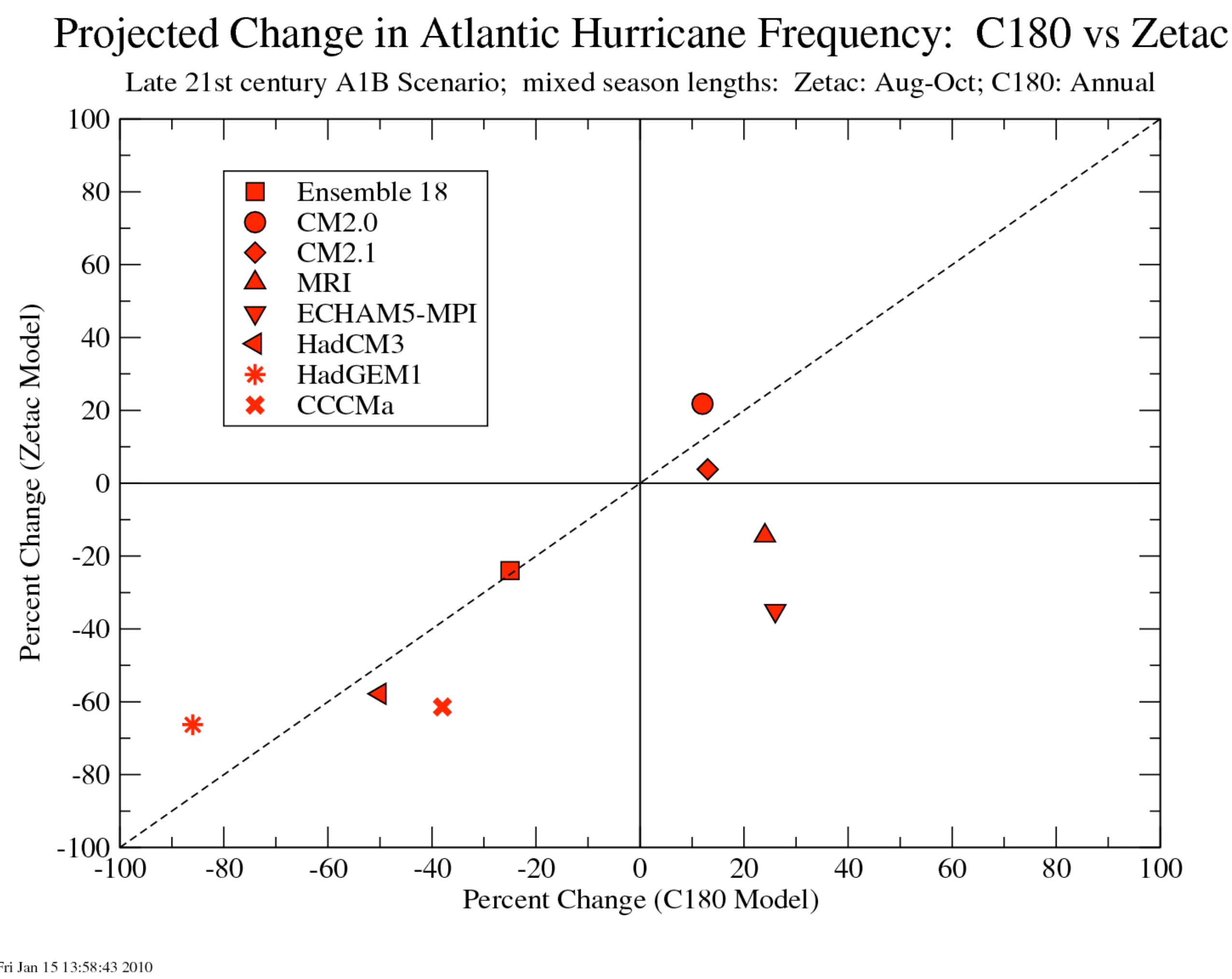
Global Model Tropical Cyclone Climate Change Experiments: Use A1B Scenario late 21st century projected SST changes from several CMIP3 models



Unit: Deg C

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

Zetac and C180 projected hurricane changes are fairly comparable for 6 of 8 common cases tested so far…suggesting that uncertainty due to downscaling may be dominated by the climate model inputs, rather than the downscaling models.



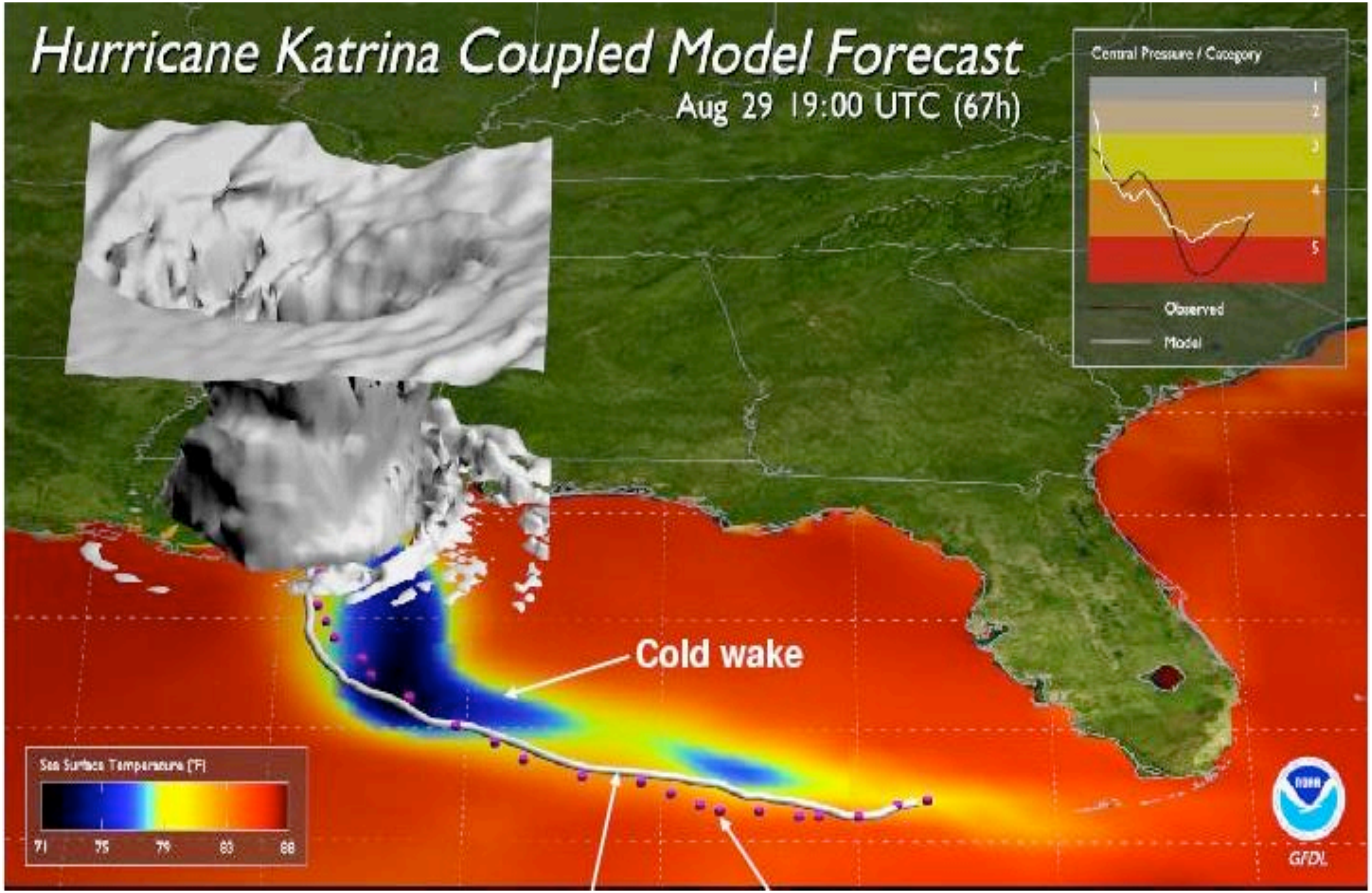
C180 results provided by Ming Zhao, GFDL, see Zhao et al. 2009.

Intensities of the strongest storms?

- 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) to re-simulate all individual storms from the zetac regional climate model runs (control and warm climates).

➡ So far only done for the Atlantic basin…



Hurricane Katrina Coupled Model Forecast
Aug 29 19:00 UTC (67h)
Central Pressure / Category
1
2
3
4
5
Observed
Model
Cold wake
Sea Surface Temperature (°F)
71
75
79
83
88
GFDL

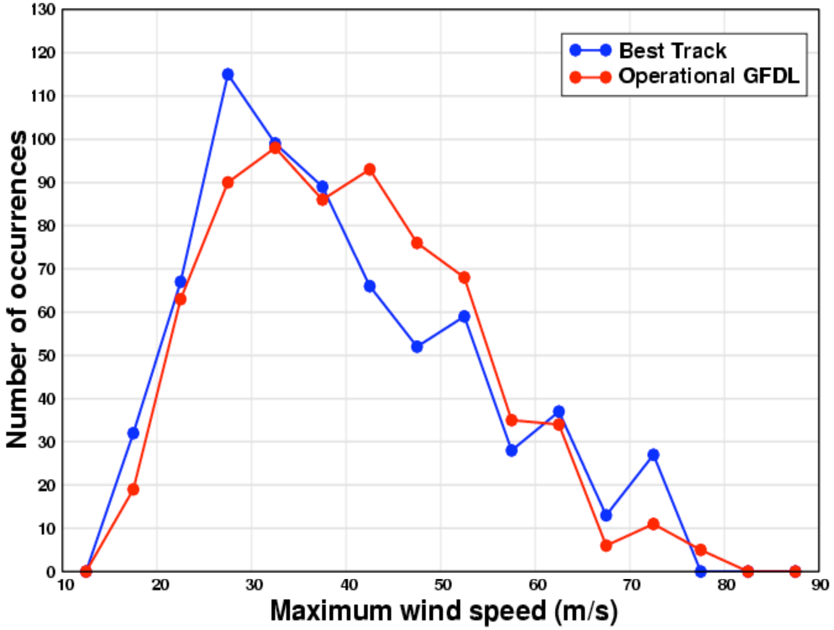
EXPERIMENTAL DESIGN

- Latest version of the GFDL Hurricane Prediction system used for this study (Operational at NCEP and FLEET since 1995).
- Every Zetac Regional Climate model tropical storm was downscaled to the GFDL hurricane prediction model for the 27 years from 1980 to 2006 (***control and warm climate***).
- All forecasts were begun 3 days before maximum intensity obtained by the Zetac model or when Zetac model first designated system as tropical storm (if less then 3 days before maximum intensity).
- GFDL Hurricane Model runs were 5 days duration.

The GFDL Operational Hurricane Prediction System simulates a realistic distribution of TC intensities in both operational and climate mode…

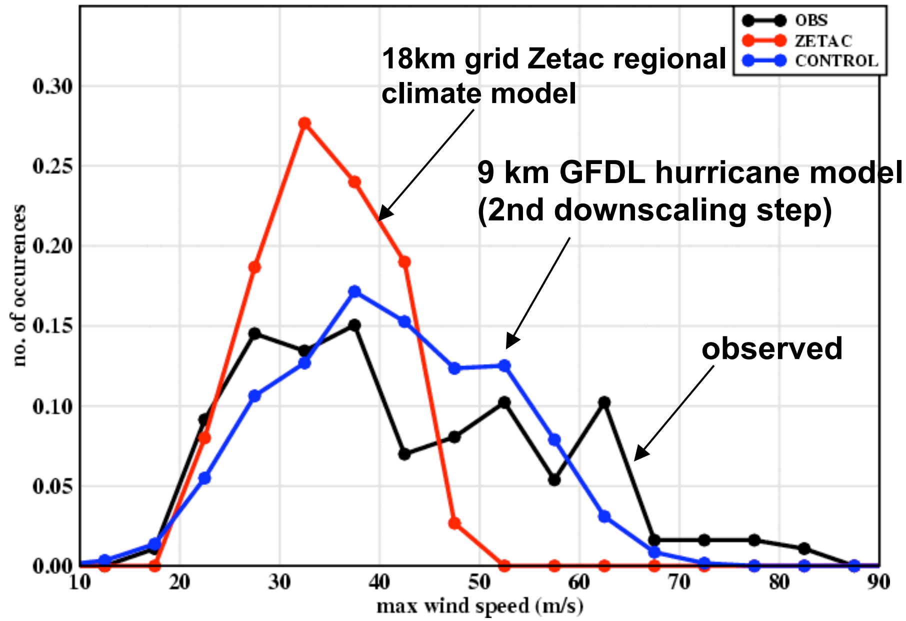
Operational Performance:

Distribution of Maximum Winds Per 120h Forecast Period 2006-2008 Atlantic Seasons



Control climatology of Intensities:

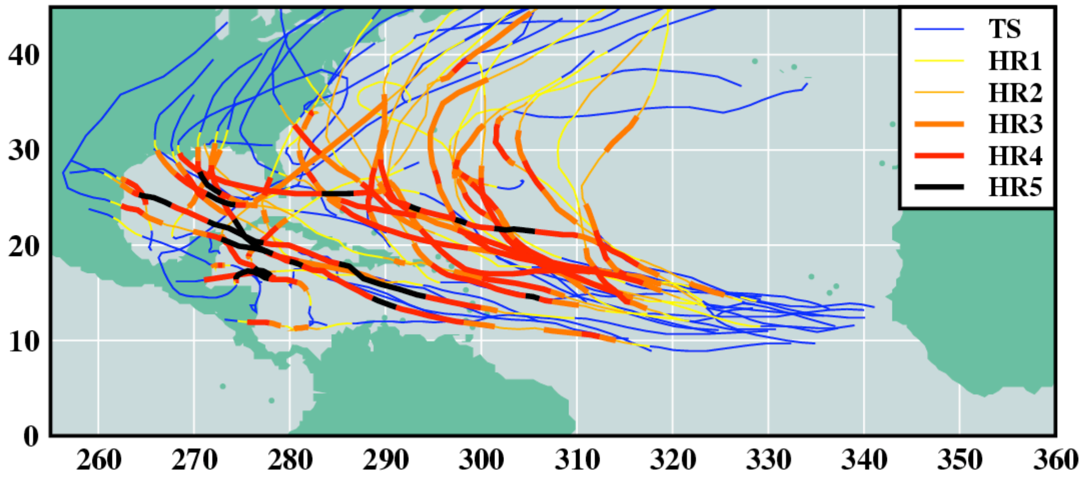
Simulated distributions of maximum wind speeds, downscaling from NCEP Reanalysis



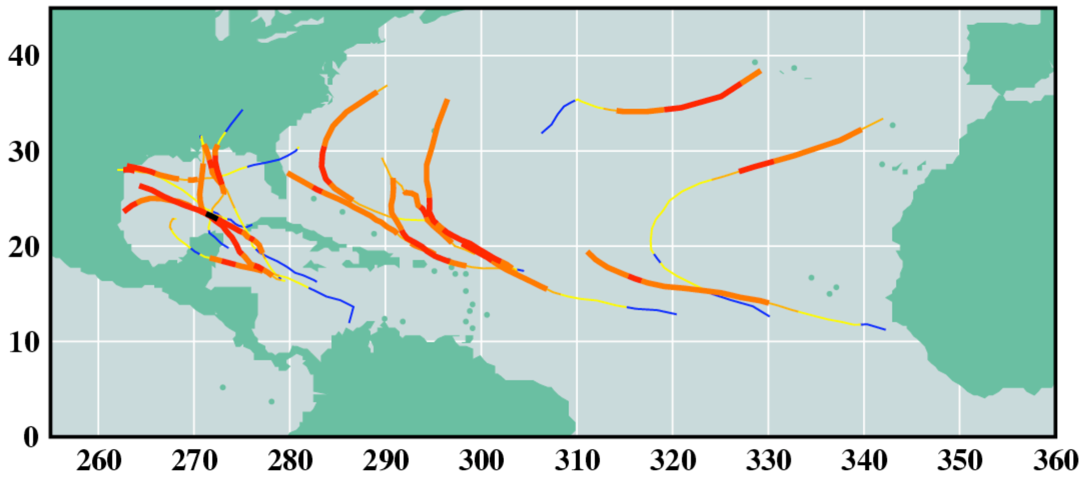
Source: Bender et al., *Science* 2010.

North Atlantic (1980-2006) - Cat 4 & 5 Hurricanes

OBS



control (gfdl downscaling)

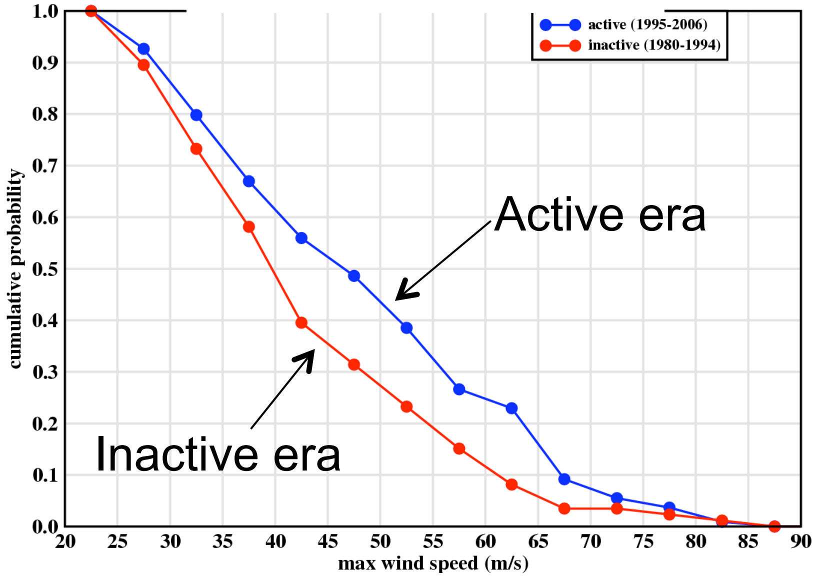


Note: GFDL hurricane model downscaling runs (U.S. Navy version) are limited to 5-day duration.

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

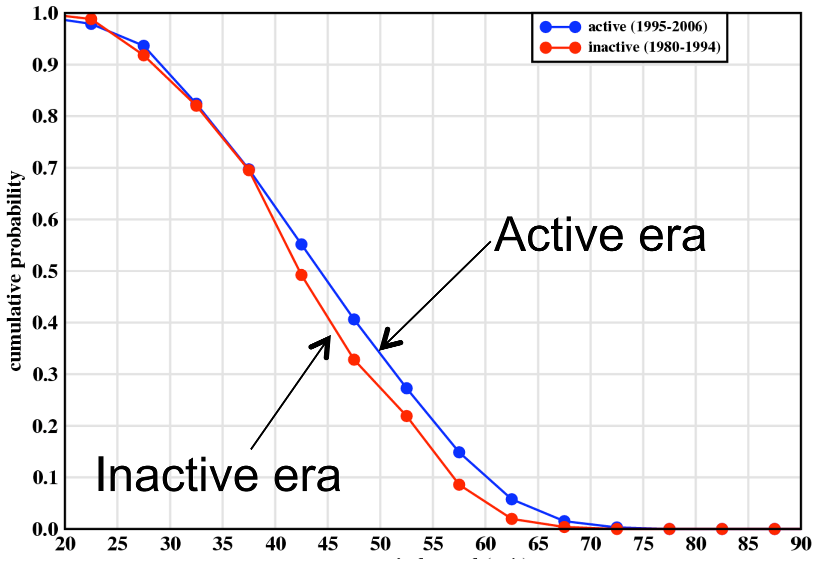
Fraction of storms above indicated intensity

Observed intensities



Fraction of storms above indicated intensity

Simulated intensities



Maximum Wind Speed (m/s)

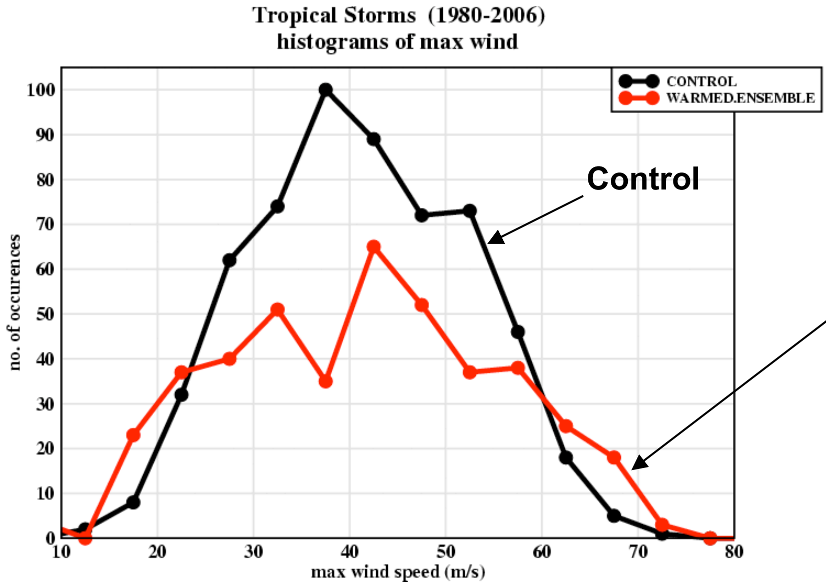
Distributions (CDF's) of Atlantic tropical cyclone intensities (1980-2006).

Red: 1980-1994 (inactive)
Blue: 1995-2006 (active)

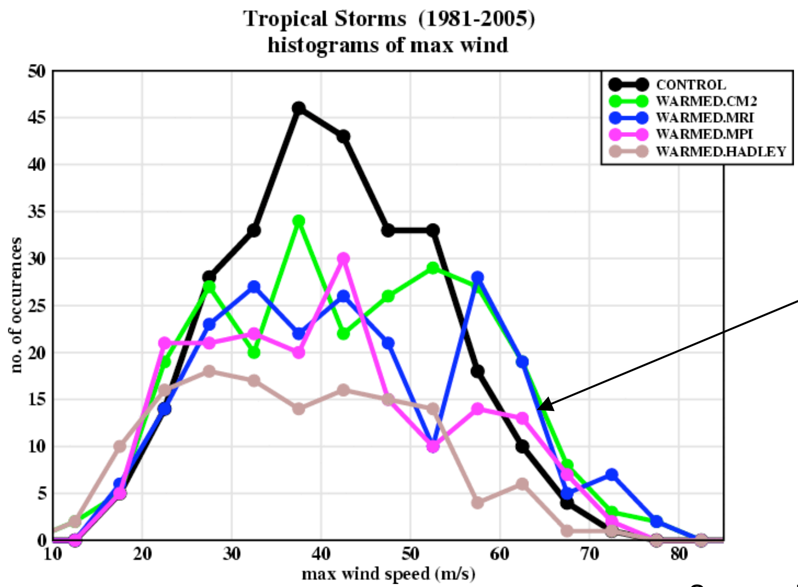
GFDL Hurricane Model intensity distribution is also shifted to higher intensities in active years, but the difference is smaller than observed.

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

In a warmer climate (late 21st century A1B scenario) the hurricane model simulates an expanded distribution of Atlantic hurricane intensities.



The strongest hurricanes increase in number for the downscaled ensemble-mean climate warming…



…and increase for 3 of 4 individual climate models tested.

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

Changes in Atlantic Hurricane Counts by Intensity Class: Late 21st century A1B Projection

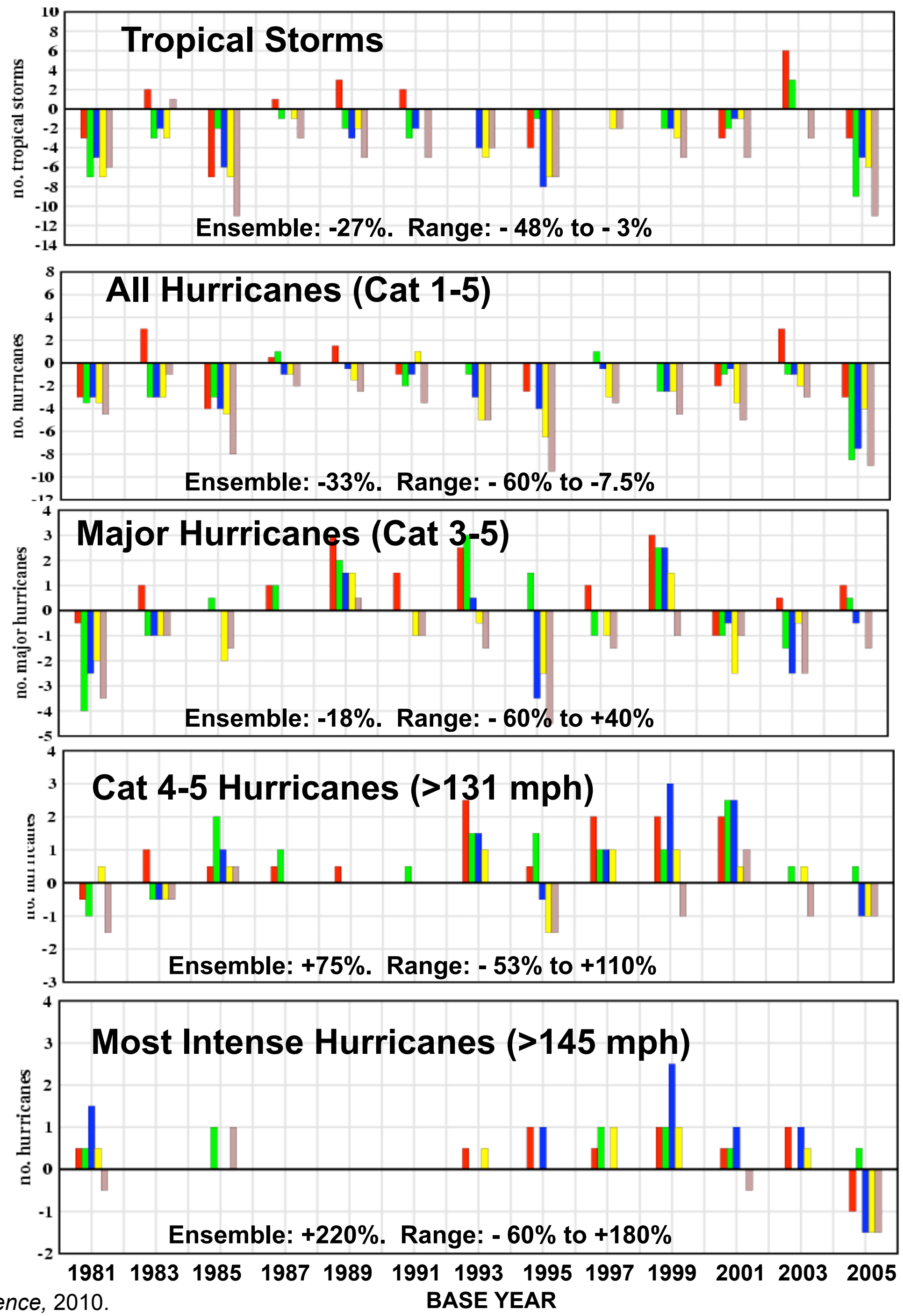
GFDL CM2.1

MRI

18-Model Ensemble

MPI

HadCM3



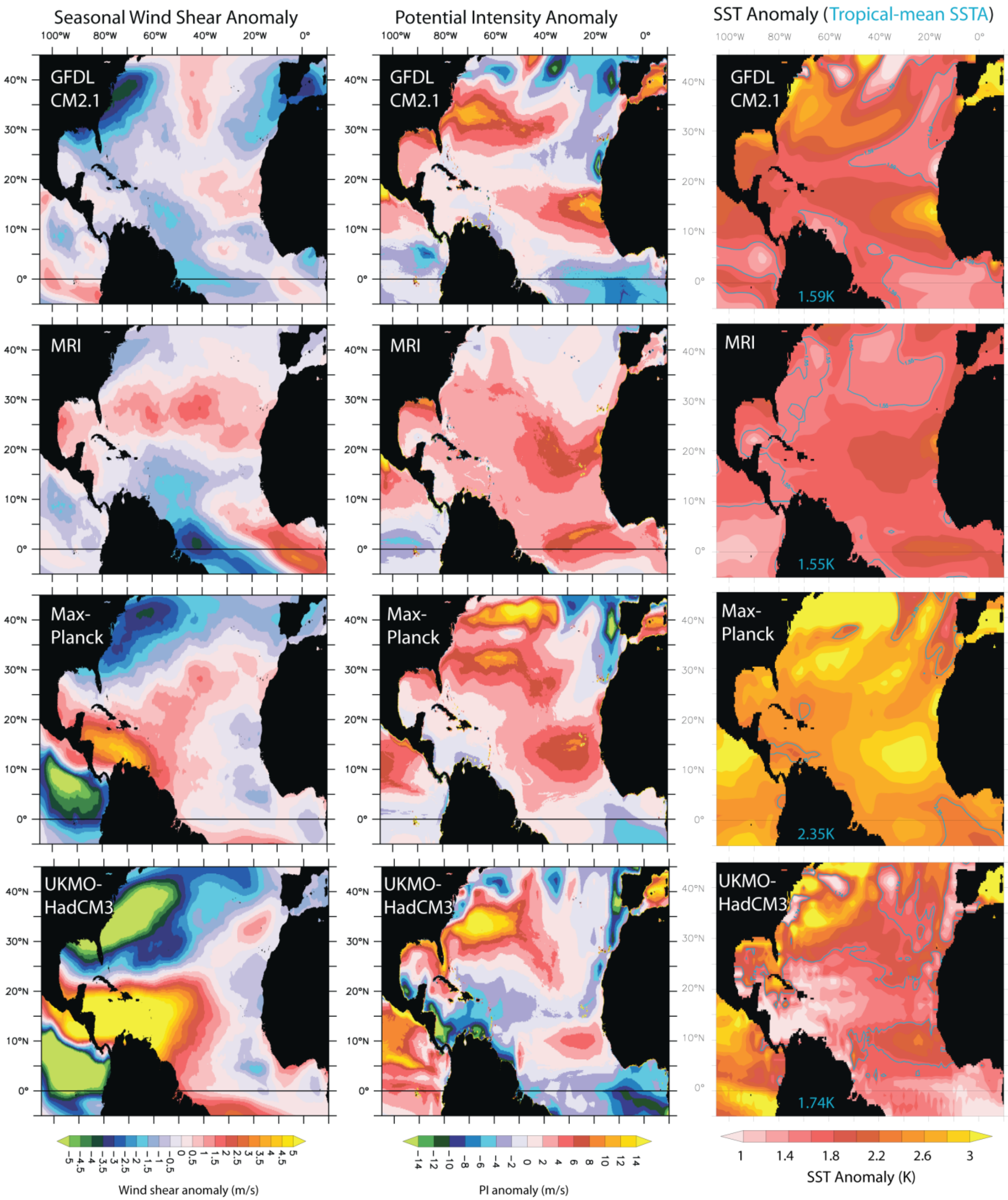
Hurricane Intensity Class

Tropical storms and hurricanes consistently <u>decrease</u> in the number in the warmer climate, but…

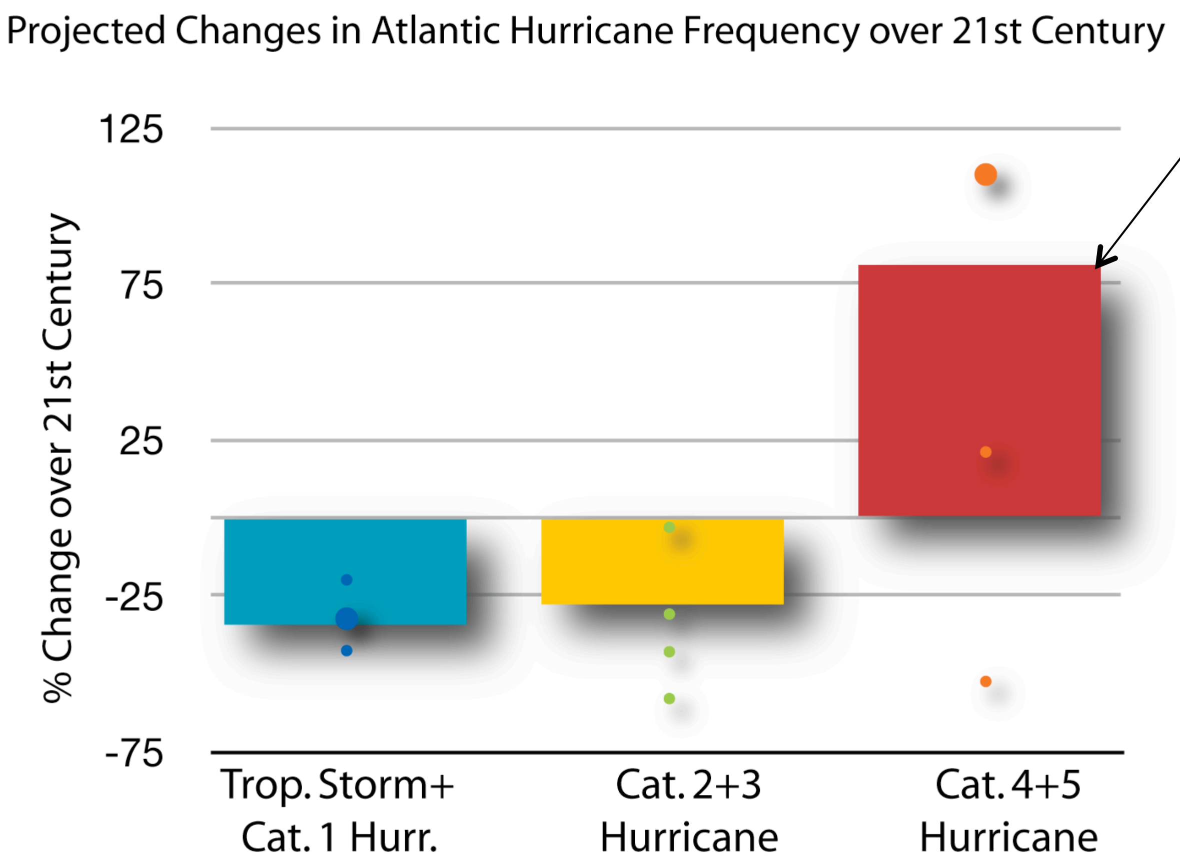
…the rarer <u>most intense</u> simulated hurricanes <u>occur up to 3 times as often</u> in the warmer climate, and increased for 3 of 4 individual models

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

Anomaly Fields from the 4 individual CMIP3 models



SUMMARY OF PROJECTED CHANGE



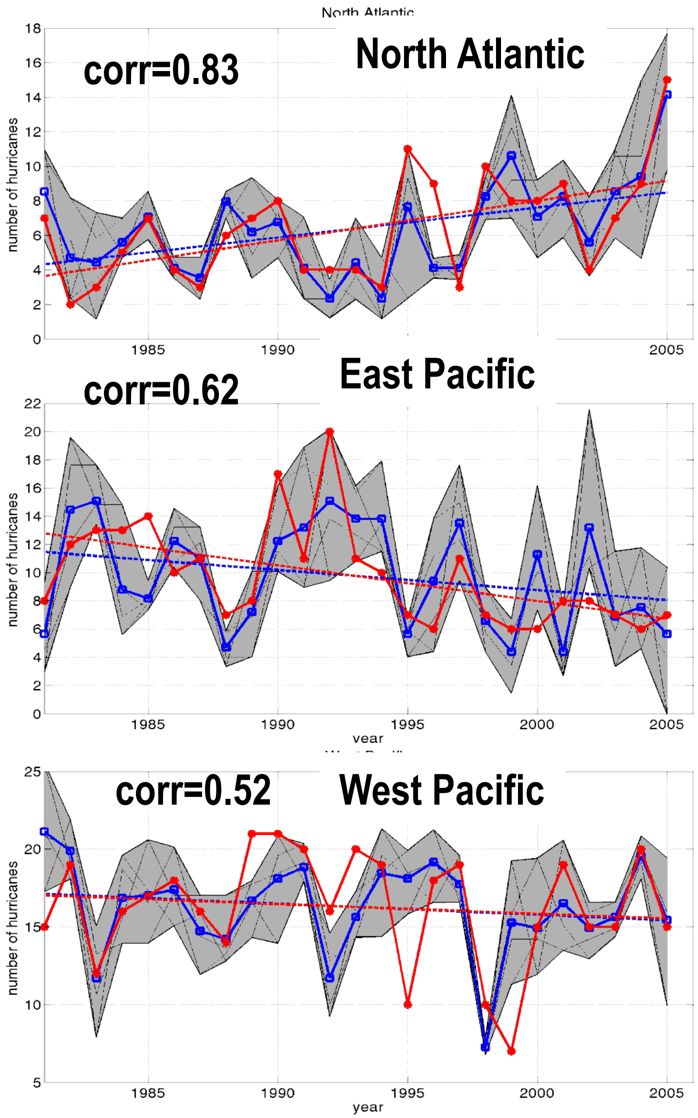
Cat 4+5 frequency: 81% increase, or 10% per decade

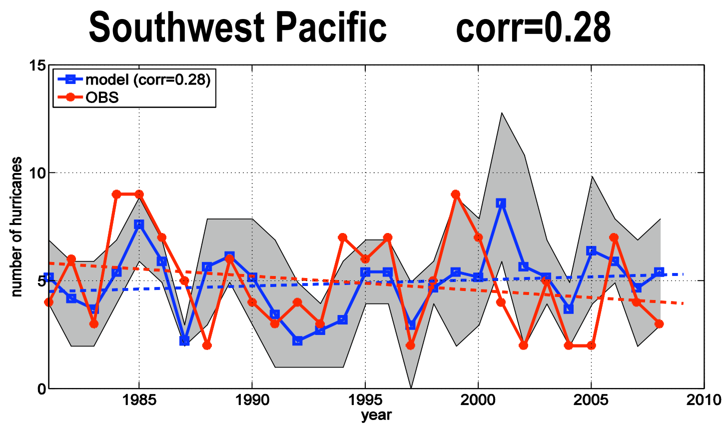
Estimated net impact of these changes on damage potential: **+28%**

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

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

The 50 km grid GFDL HIRAM global model is not systematically under-predicting historical trends in hurricane counts





Hurricane counts for each basin are normalized by a time-independent multiplicative factor

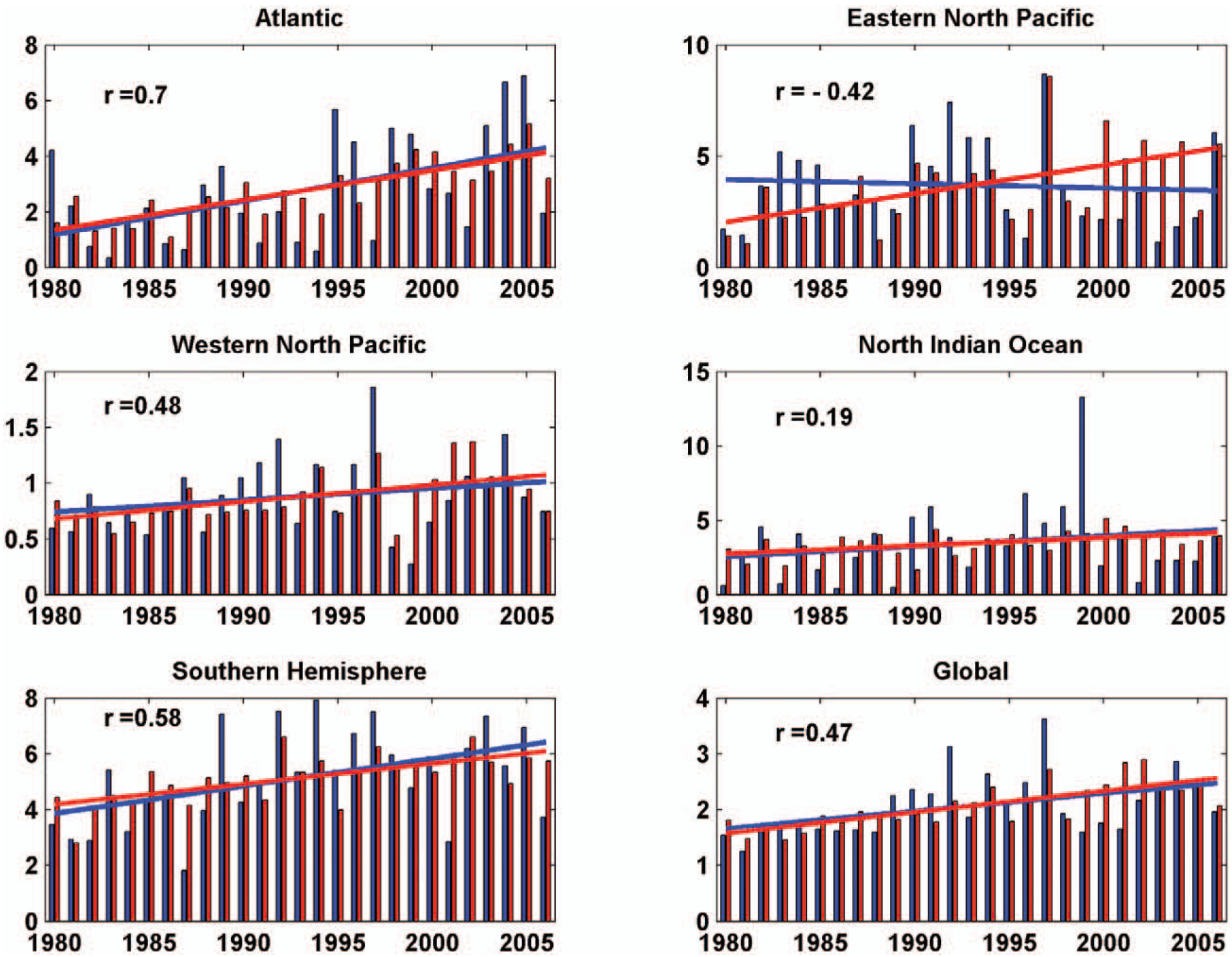
Correlations of model and observed counts are insignificant for the Indian Ocean basins (not shown).

red: observations
blue: HiRAM ensemble mean
shading: model uncertainty

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

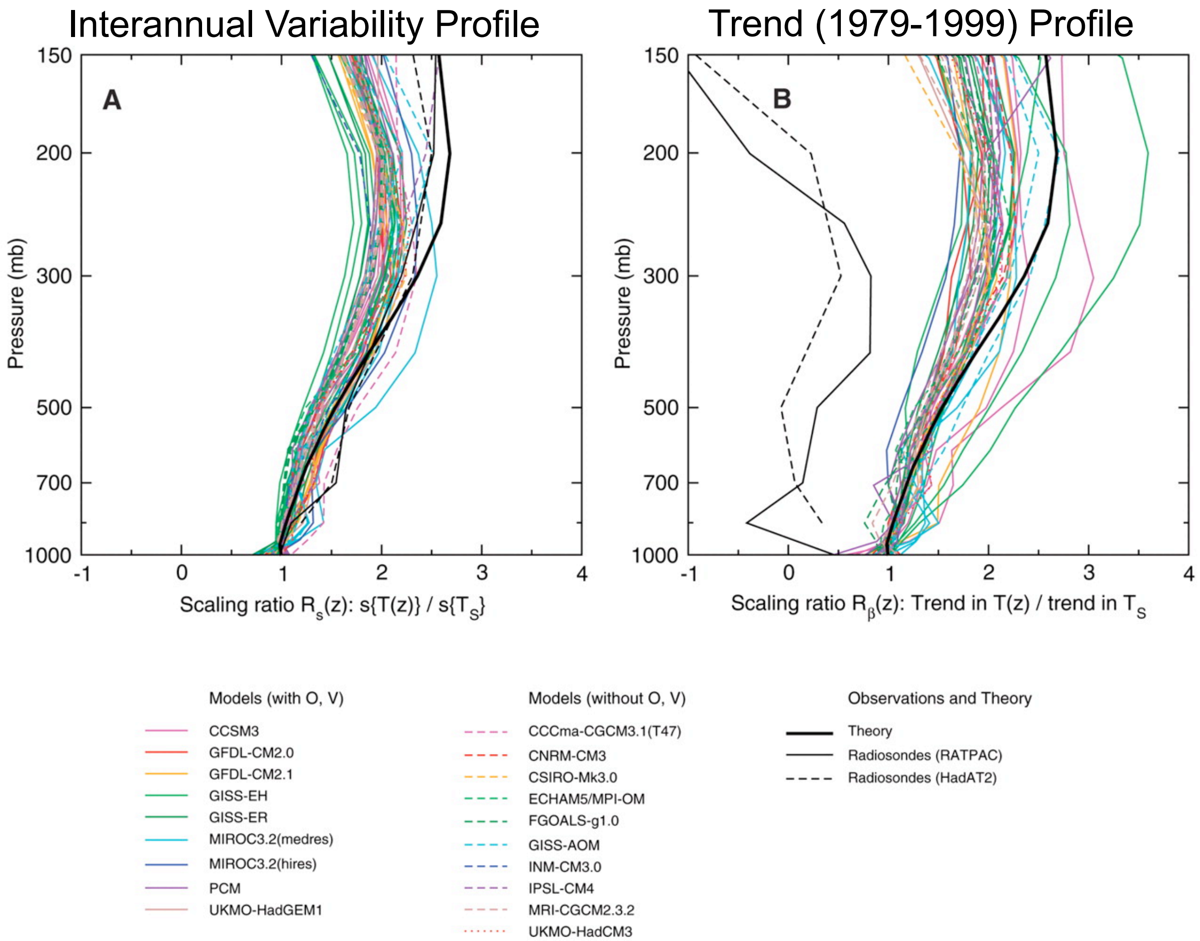
Statistical-Dynamical Downscaling: Simulating Past PDI Variations

Model hindcast (red) uses NCEP Reanalysis. Best track is blue.



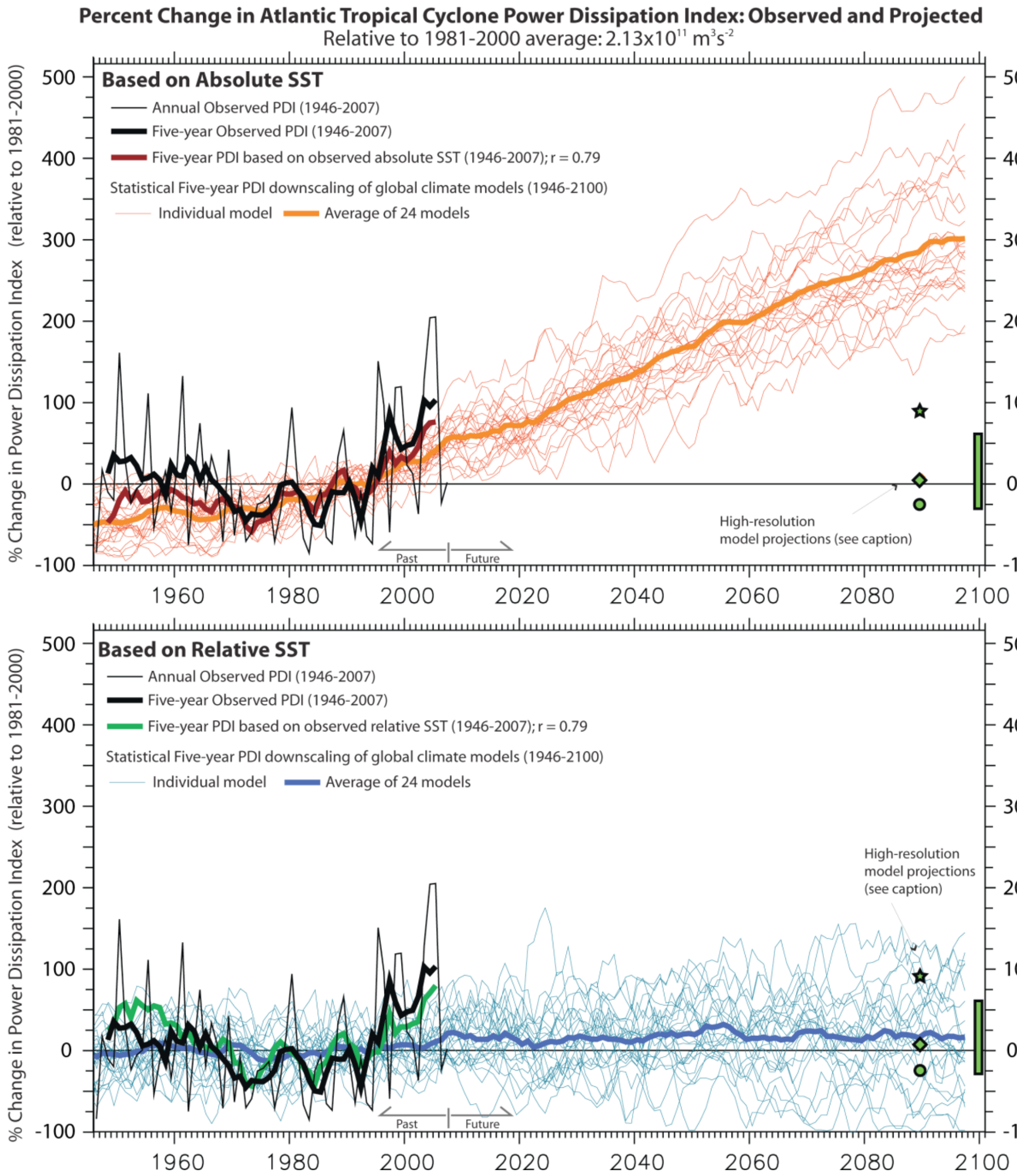
Source: Emanual et al. (2008) Bull. Amer. Meteor. Soc.

Tropical tropospheric temperature variability and trends (1979-1999): Vertical profiles for models and observations



Source: Santer et al., Science 2005. v. 309 1551-1556

Statistical projections of 21st century Atlantic hurricane activity have a large dependence on the predictor used.



Projection 1: Absolute SST

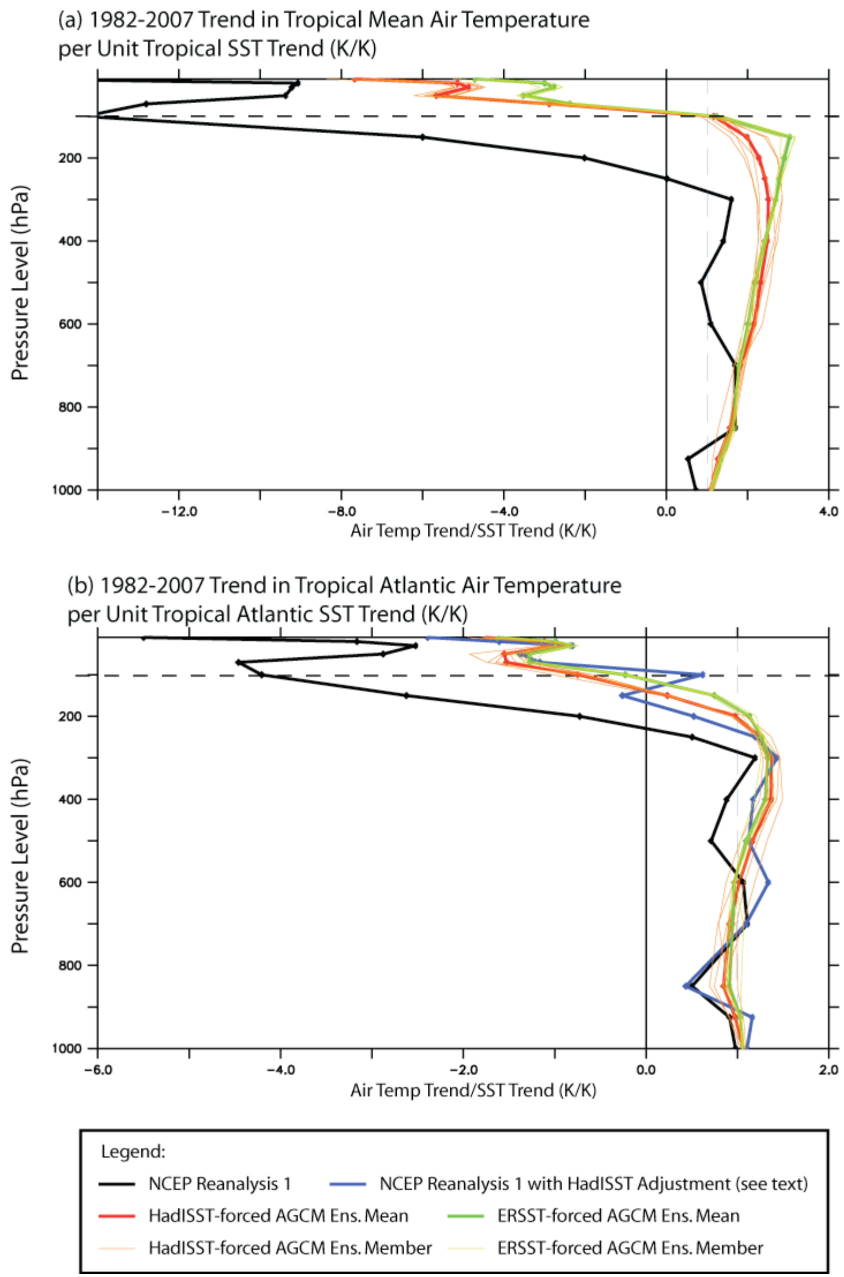
- ~300% projected increase in Power Dissipation
- Indirect attribution: CO_2 → SST → Hurricanes

Projection 2: Relative SST

- Projected change: sign uncertain, +/- 80%
- No Attribution
- <u>Damage potential: +28%</u>

(from Bender et al. Science paper)

Source:
Vecchi et al. *Science* (2008)

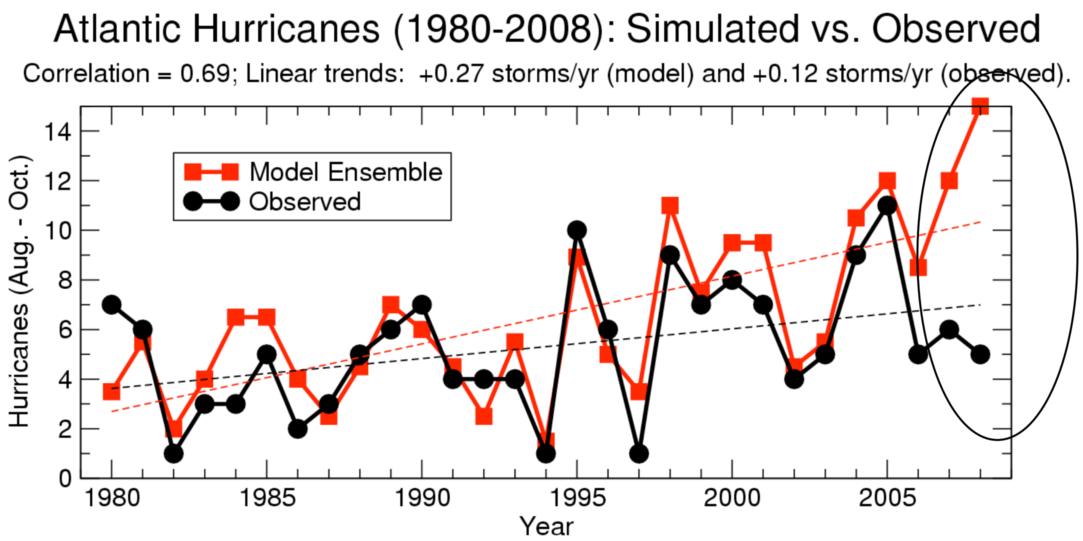


Tropical-mean lapse rate trends are very different in the GFDL HIRAM climate model than in NCEP reanalysis (the latter indicating much more destabilization or increasing potential intensity).

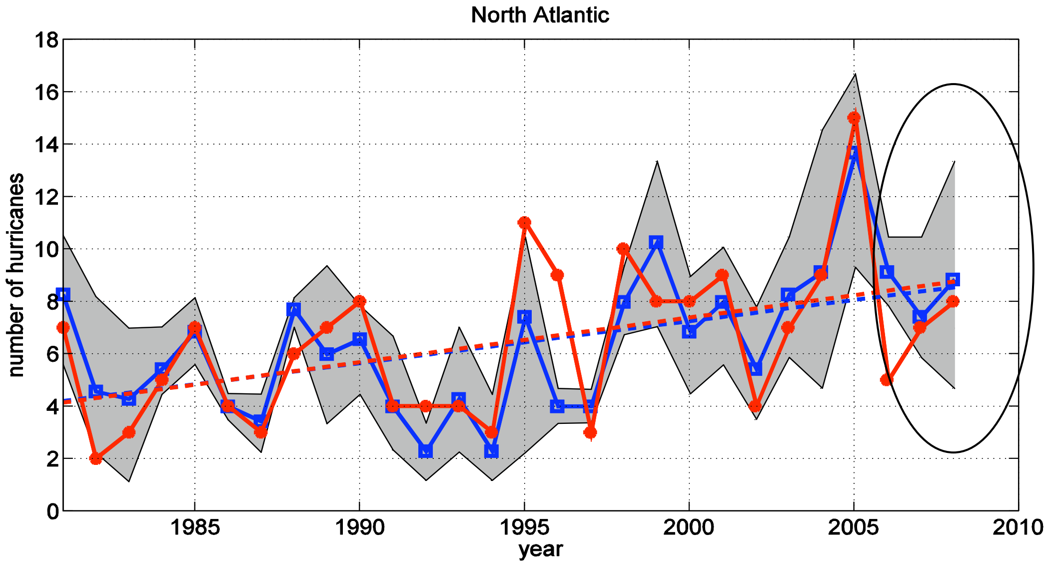
In the tropical Atlantic (1982-2007), NCEP Reanalysis and GFDL HIRAM trends are closer in the troposphere, but quite distinct in the tropopause transition layer near 100mb. Substituting HIRAM's zonal mean temperatures mostly reconciles these differences.

Source: G. Vecchi, manuscript in preparation, 2011.

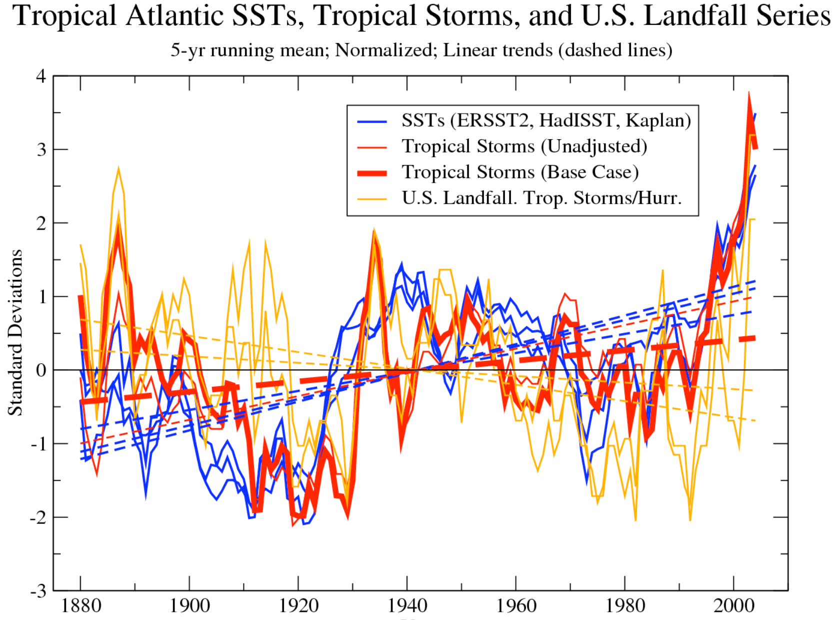
Future Work:
Extension of Atlantic runs through 2007-2008 reveals increasingly unrealistic trend in Zetac model: Possible source: NCEP Reanalysis



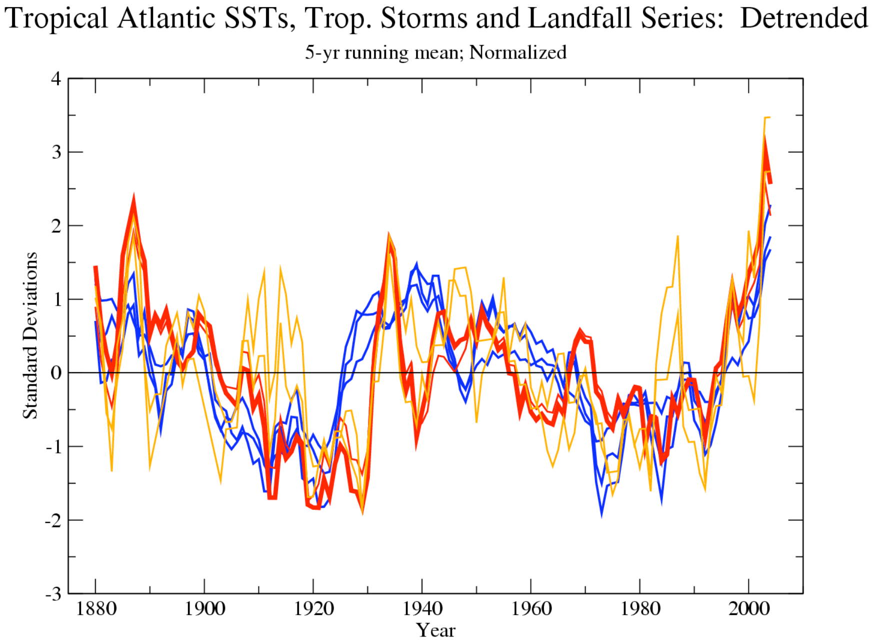
Zetac Regional Model (SST + Reanalysis)



HIRAM 50km global model (SST only)



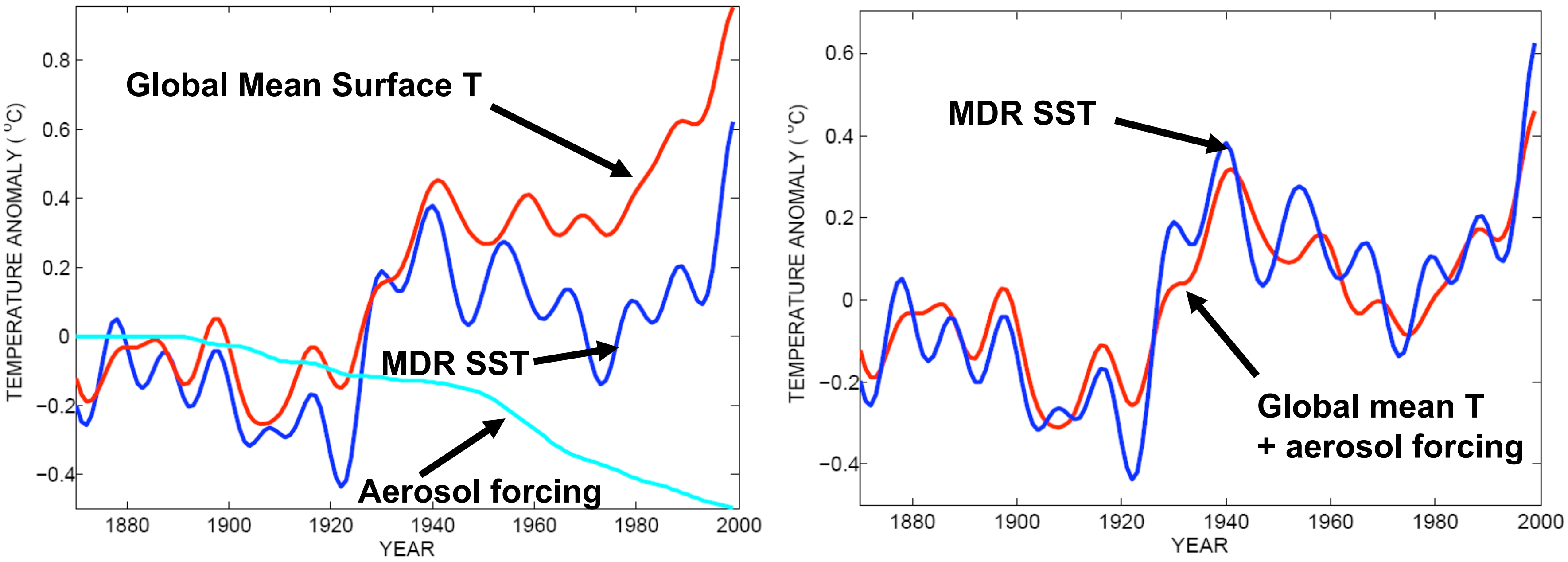
While the century-scale trends in tropical Atlantic series have marked differences…



…the multi-decadal variability (with trend removed) is fairly consistent among the series.

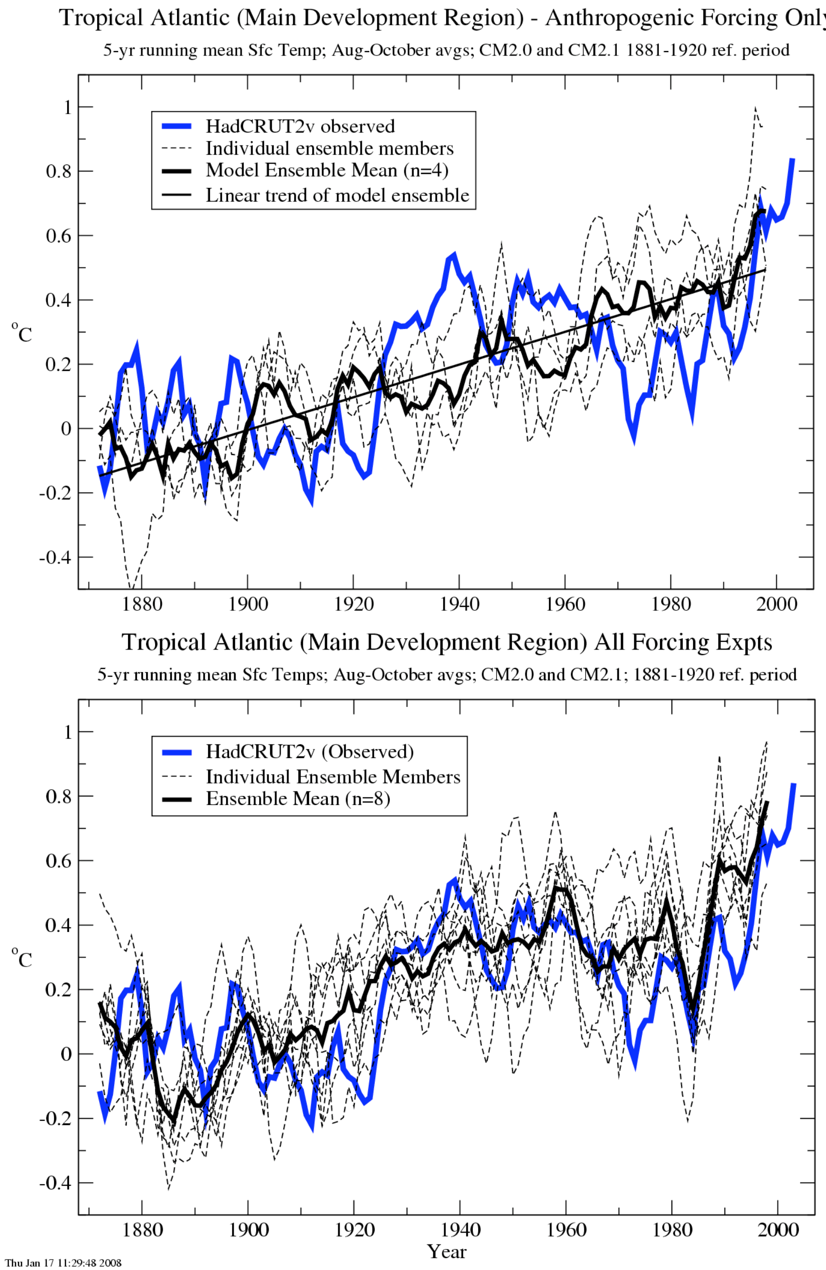
Source: Adapted from Vecchi and Knutson, J. Climate, 2008

Statistical modeling of tropical Atlantic SSTs



Source: Mann and Emanuel, EOS (2006)

What type of SST "anthropogenic signal" should we look for in the tropical Atlantic?

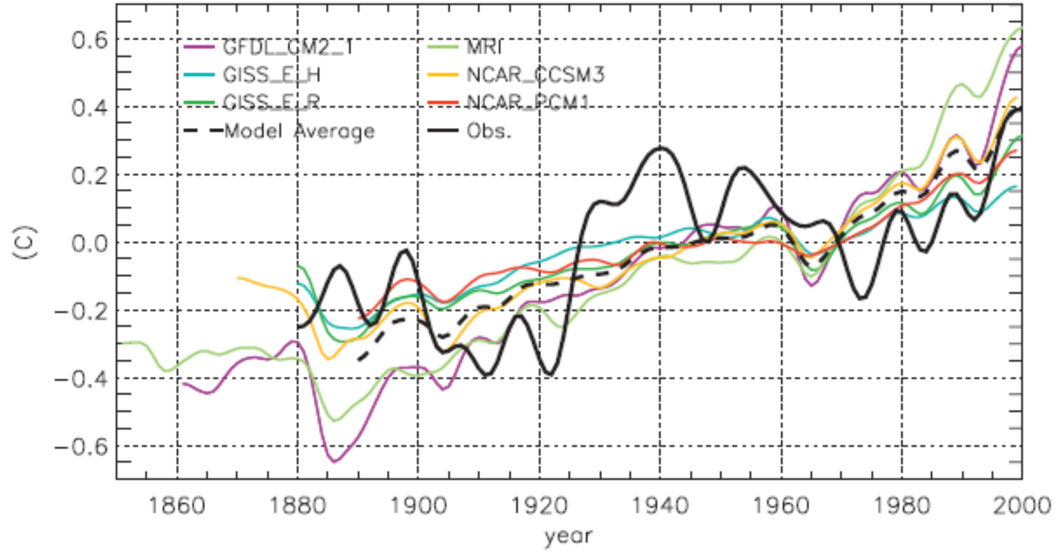


<u>Anthropogenic forcing</u>:
Linear trend-like, but the caveat of no indirect aerosol forcing yet.

<u>Natural + Anthropogenic forcing</u>:
Volcanic/solar/anthropogenic forcing gives a closer fit to observations … Residual (blue – black) = AMO??

Sources: Vecchi and Knutson, J. Climate, 2008. See also Knutson et al. J. Climate, 2006

Fitting Atlantic (MDR) SST changes with climate model all-forcing runs



Estimated contribution of internal variability to Atlantic (MDR) SST changes

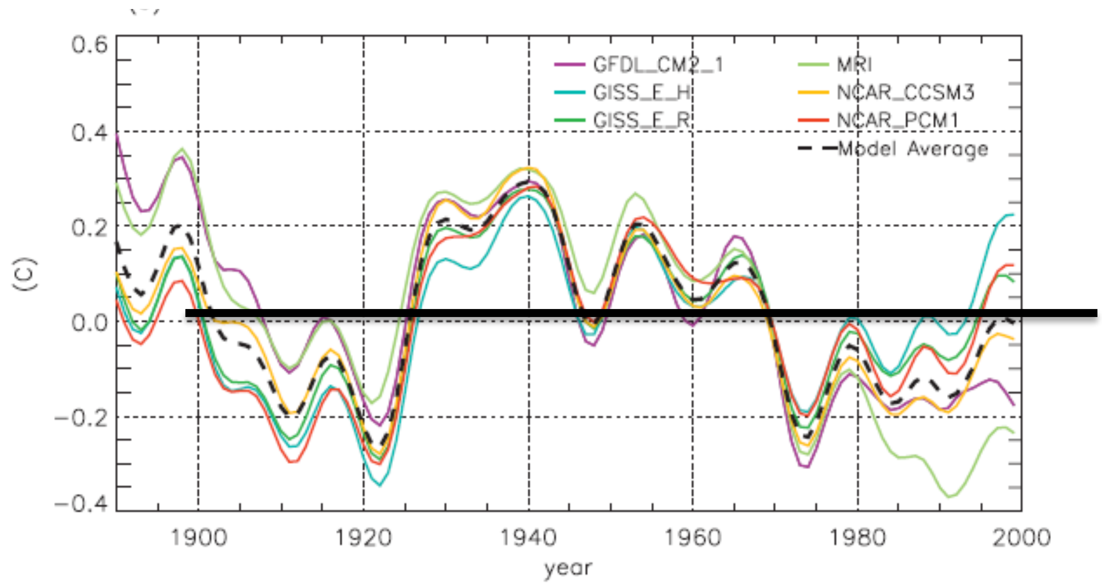
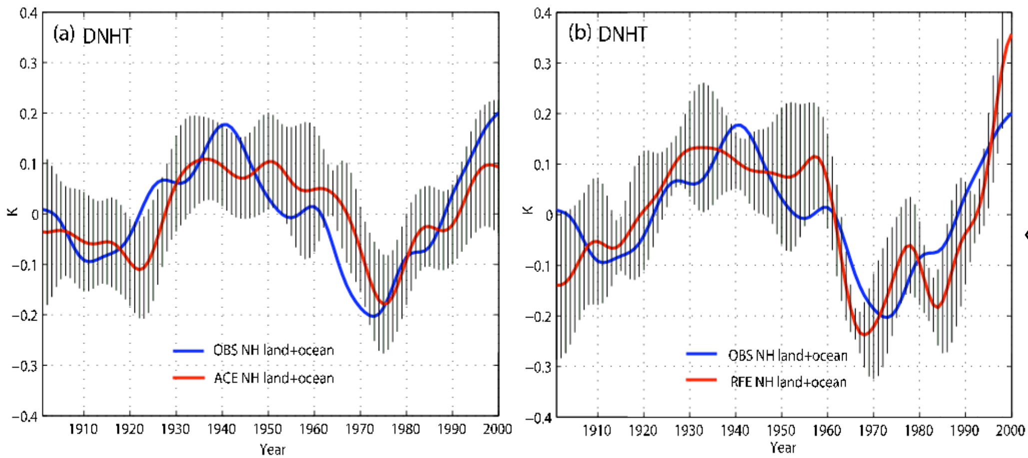


FIG. 6. Same as Fig. 5, but for MDR SST averaged over the 3-month hurricane season, August–October.

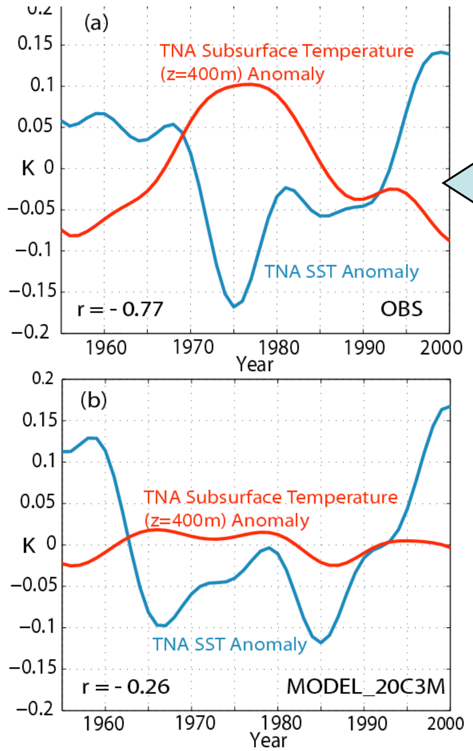
Left: Some model analyses suggest that the AMO may presently be near a neutral state, implying a possible further increase in Atlantic hurricane activity during the next few decades.

Source: Ting et al., J. Climate, 2009

Internal Climate Variability vs Radiative Forcing: Detrended NH Mean Temperatures



Model: Radiative forcing and ocean circulation changes both provide a plausible explanation for the fluctuations in 20th century Northern Hemisphere mean temperature (detrended)



Model: Some tentative evidence in support of a significant role for ocean circulation changes: surface and sub-surface fluctuations are out of phase in observations and modeled AMO-like change.

Regression: Model and obs: Internal (AMO) variability in GFDL model is much more effective at altering tropical Atlantic windshear and potential intensity than is radiatively forced change. So not sufficient to compare size of natural and anthropogenic SST contributions alone.

Sources: Zhang, Delworth and Held (2006)
Zhang (2007) Zhang and Delworth (2009) GRL papers.

Tropical Cyclones Frequency Projections (Late 21st century) - Summary

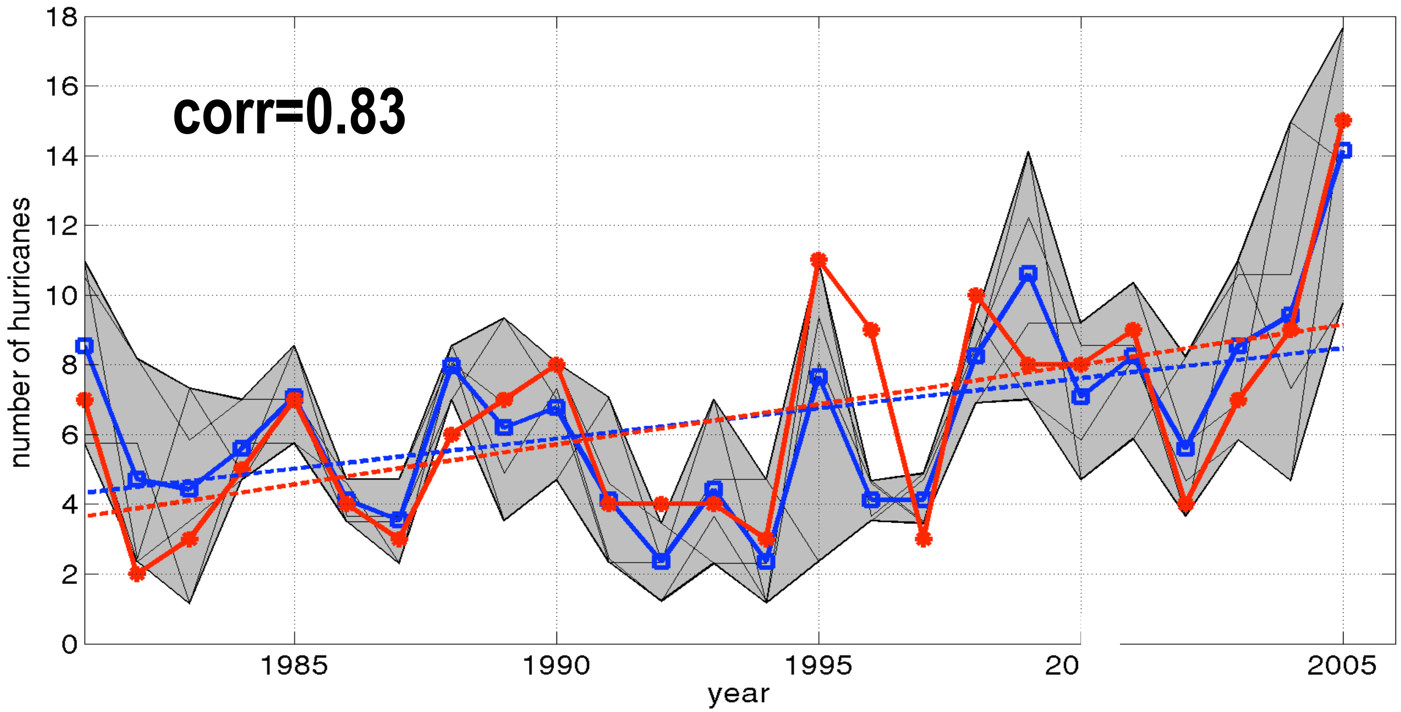
TABLE S1. TC Frequency Projections												
Reference	Model/type	Resolution/	Experiment	Basin								
				Global	NH	SH	N Atl.	NW Pac.	NE Pac.	N Ind.	S. Ind.	SW Pac.
Tropical Storm Frequency Changes (%)												
Sugi et al. 2002 (ref 32)	JMA Timeslice	T106 L21 (~120km)	10y 1xCO2, 2xCO2	-34	-28	-39	+61	-66	-67	+9	-57	-31
McDonald et al. 2005 (ref 50)	HadAM3 Timeslice	N144 L30 (~100km)	15y IS95a 1979-1994 2082-2097	-6	-3	-10	-30	-30	+80	+42	+10	-18
Hasegawa and Emori 2005 (ref 51)	CCSR/NIES/FRC GC timeslice	T106 L56 (~120km)	5x20y at 1xCO2 7x20y at 2xCO2					-4				
Yoshimura et al. 2006 (ref 52)	JMA Timeslice	T106 L21 (~120km)	10y 1xCO2, 2xCO2	-15								
Oouchi et al. 2006 (ref 10)	MRI/JMA Timeslice	TL959 L60 (~20km)	10y A1B 1982-1993 2080-2099	-30	-28	-32	+34	-38	-34	-52	-28	-43
Chauvin et al. 2006 (ref 31)	ARPEGE Climat Timeslice	~50 km	Downscale CNRM B2 Downscale Hadley A2				+18 -25					
Stowasser et al. 2007 (ref 53)	IPRC Regional		Downscale NCAR CCSM2, 6xCO2					+19				
Bengtsson et al. 2007 (ref 13)	ECHAM5 timeslice	T213 (~60 km)	2071-2100, A1B		-13		-8	-20	+4	-26		
Bengtsson et al. 2007 (ref 13)	ECHAM5 timeslice	T319 (~40 km)	2071-2100, A1B		-19		-13	-28	+7	-51		
Emanuel et al. 2008 (ref 11)	Statistical-deterministic	---	Downscale 7 CMIP3 mods.: A1B, 2180-2200 Average over 7 models	-7	+2	-13	+4	+6	-5	-7	-12	-15
Knutson et al. 2008 (ref 12)	GFDL Zetac regional	18 km	Downscale CMIP3 ens. A1B, 2080-2100				-27					
Leslie et al. 2007 (ref 54)	OU-CGCM with high-res. window	Up to 50 km	2000 to 2050 control and IS92a (6 members)									~0
Gualdi et al. 2008 (ref 28)	SINTEX-G coupled model	T106 (~120 km)	30 yr 1xCO2, 2xCO2, 4xCO2	-16 (2x) -44 (4x)			-14	-20	-3	-13	-14	-22
Semmler et al. 2008 (ref 55)	Rossby Centre regional model	28 km	16 yr control and A2, 2085-2100				-13					
Zhao et al. 2009 (ref 29)	GFDL HIRAM timeslice	50 km	Downscale A1B: CMIP3 n=18 ens. GFDL CM2.1 HadCM3 ECHAM5	 -20 -20 -11 -20	 -14 -14 +5 -17	 -32 -33 -42 -27	 -39 -5 -62 -1	 -29 -5 -12 -52	 +15 -23 +61 +35	 -2 -43 -2 -25	 -30 -33 -41 -13	 -32 -31 -42 -48
Sugi et al. 2009 (ref 45)	JMA/MRI global AGCM timeslice	 20 km 20 km 20 km 20 km 60 km 60 km 60 km 60 km	Downscale A1B: MRI CGCM2.3 MRI CGCM2.3 MIROC-H CMIP3 n=18 ens. MRI CGCM2.3 MIROC-H CMIP3 n=18 ens. CSIRO	 -29 -25 -27 -20 -20 -6 -21 -22	 -31 -25 -15 -21 -21 0 -19 -29	 -27 -25 -42 -19 -17 -16 -25 -11	 +22 +23 -18 +5 +58 +6 +4 -37	 -36 -29 +28 -26 -36 +64 -14 +13	 -39 -30 -50 -25 -31 -42 -33 -49	 -39 -29 +32 -15 -12 +79 +33 -7	 -28 -25 -24 -5 -22 +10 -18 -22	 -22 -27 -90 -42 -8 -69 -36 +10

Blue = decrease

Red = increase

Source: Knutson et al. 2010

GFDL HIRAM (50-km grid global model) reproduces Atlantic hurricane interannual variability and trend (1981-2005) *using observed SSTs alone*



red: observations
blue: HiRAM ensemble mean
shading: model uncertainty

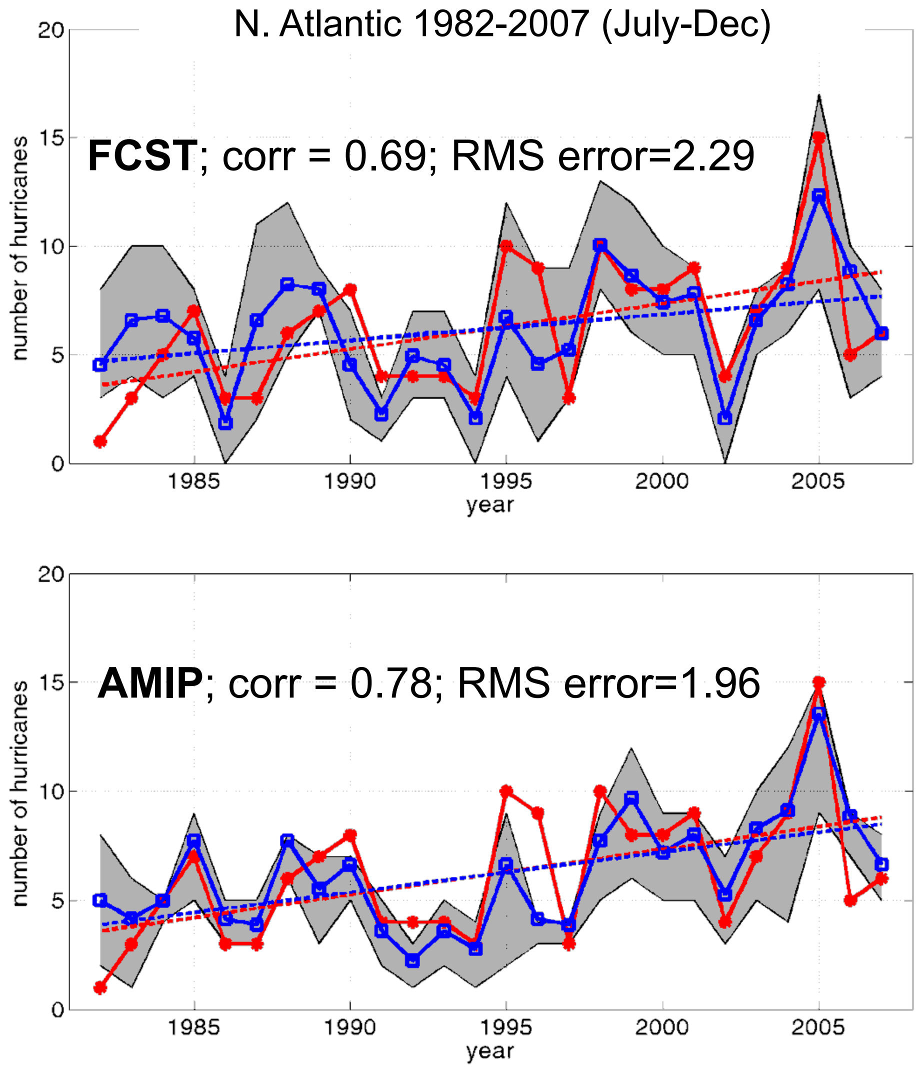
Hurricane counts are normalized by a time-independent multiplicative factor

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

Predicting hurricane activity a season ahead or more…

Simply persisting SST anomalies from June, the GFDL HIRAM model retains skill for its forecast of the Atlantic hurricane season

5-member ensemble hindcasts of hurricane counts for each year during 1982-2007



Source: Ming Zhao, GFDL/NOAA

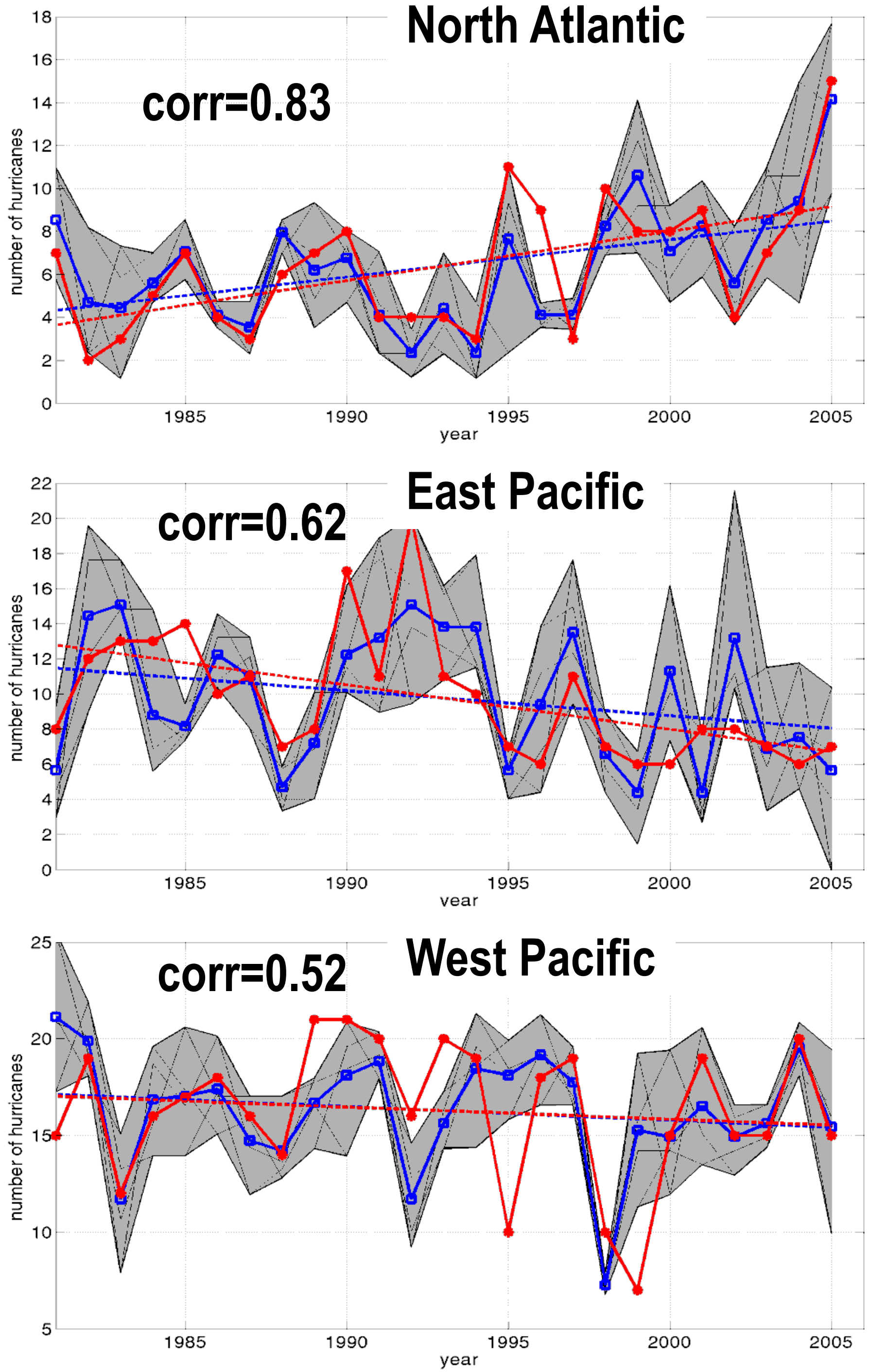
HIRAM 50 km grid model TC correlations for several basins

red: observations
blue: HiRAM ensemble mean
shading: model uncertainty

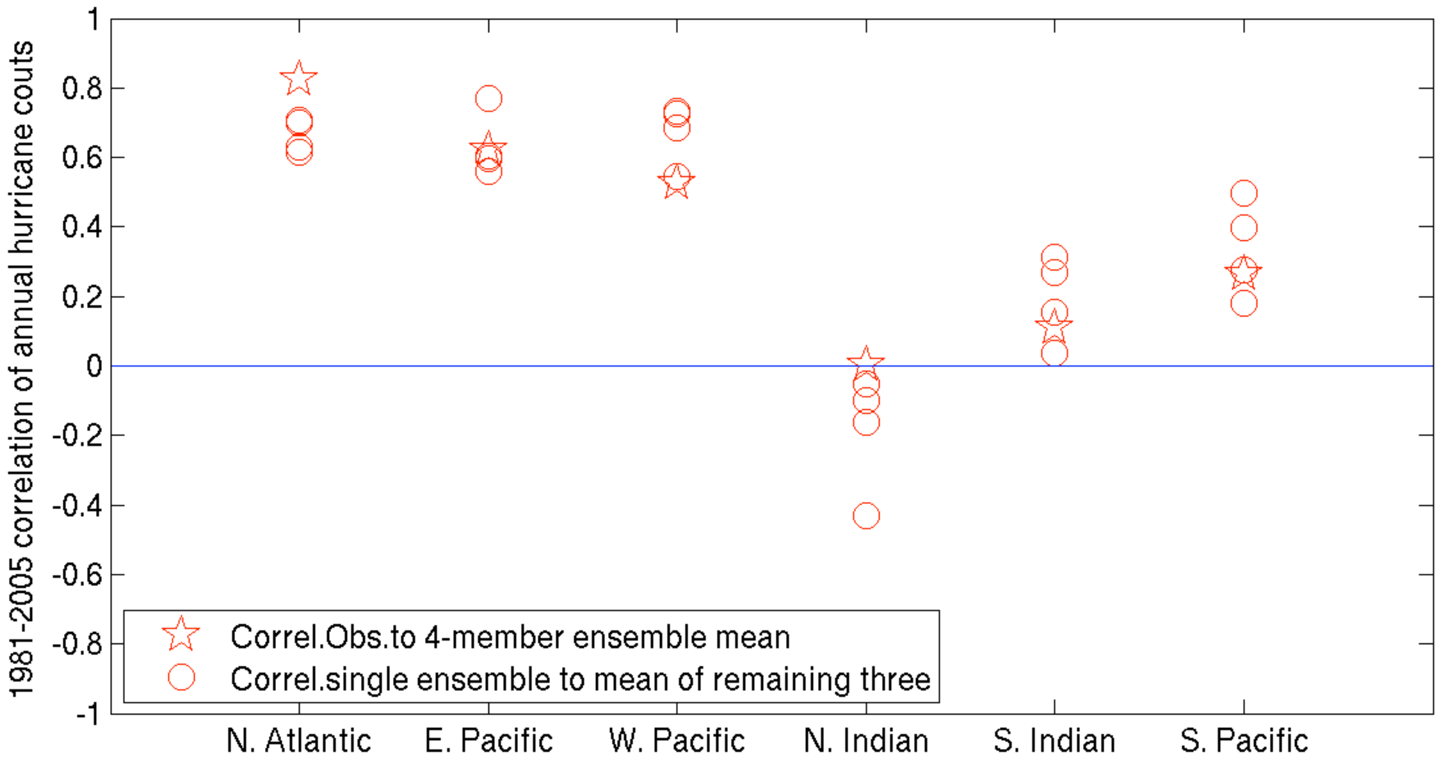
Hurricane counts for each basin are normalized by a time-independent multiplicative factor

Correlation for the South Pacific is ~0.3 and insignificant for the Indian Ocean

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

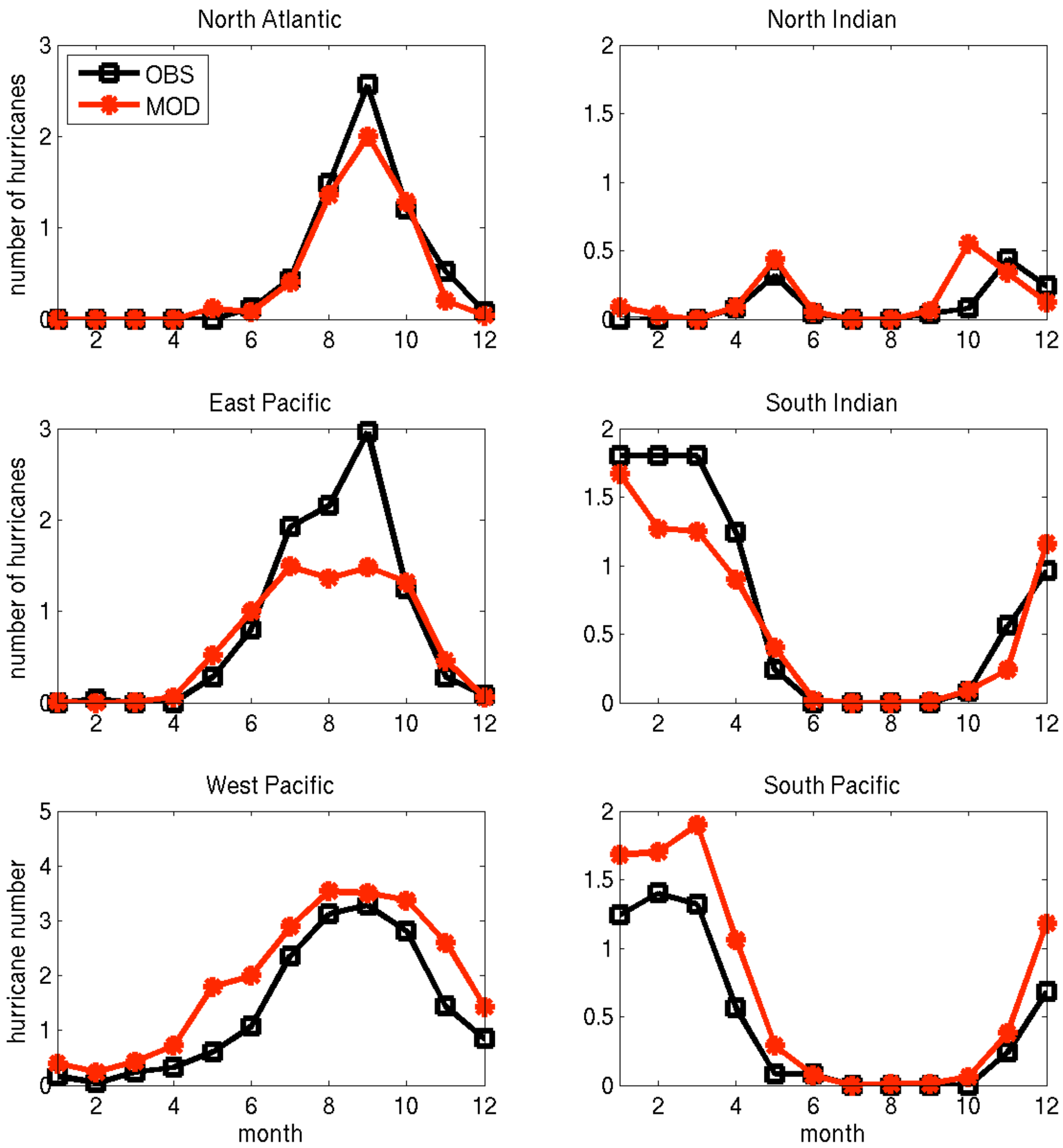


In basins where the HIRAM 50km grid model has low correlation with observations, the correlation of individual model runs with other ensemble members is also low (implying little predictable signal).



Source: Zhao et al. J. Climate, (2009)

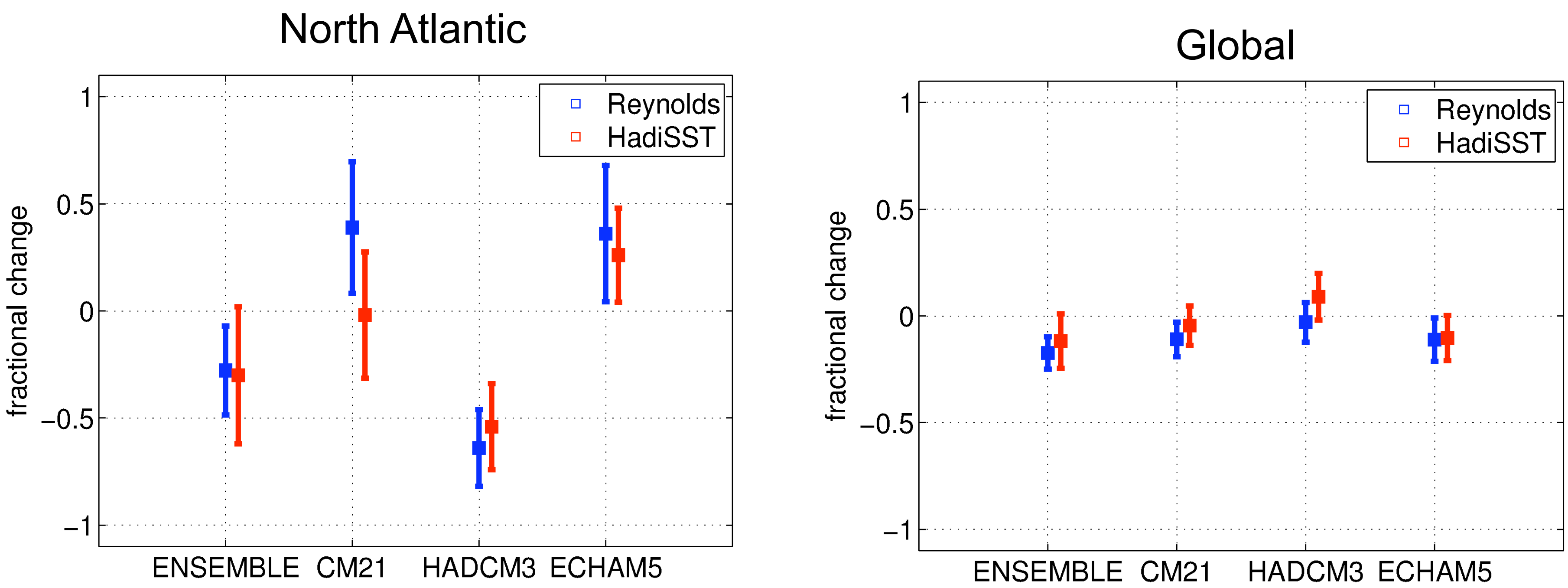
HIRAM 50-km grid model: realistic seasonal cycles of TCs



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

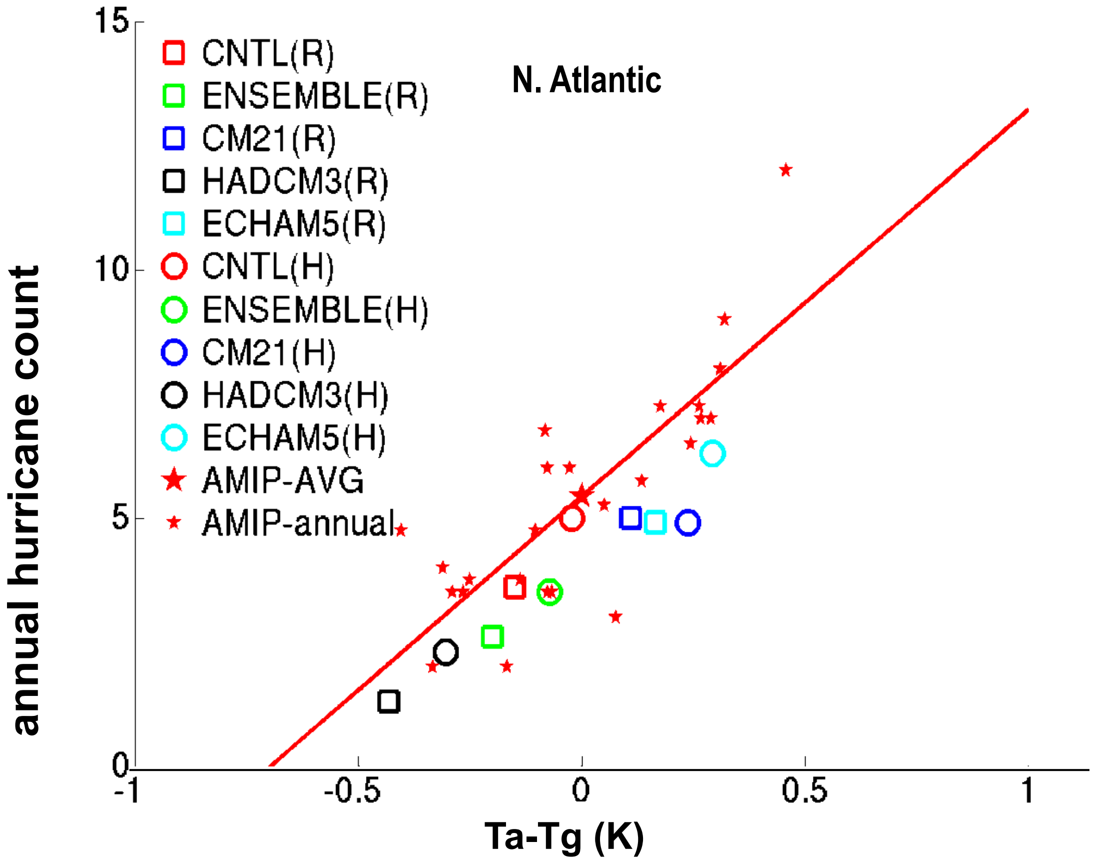
Change of hurricane frequency:

GFDL HIRAM (50 km grid); Late 21st Century Projection



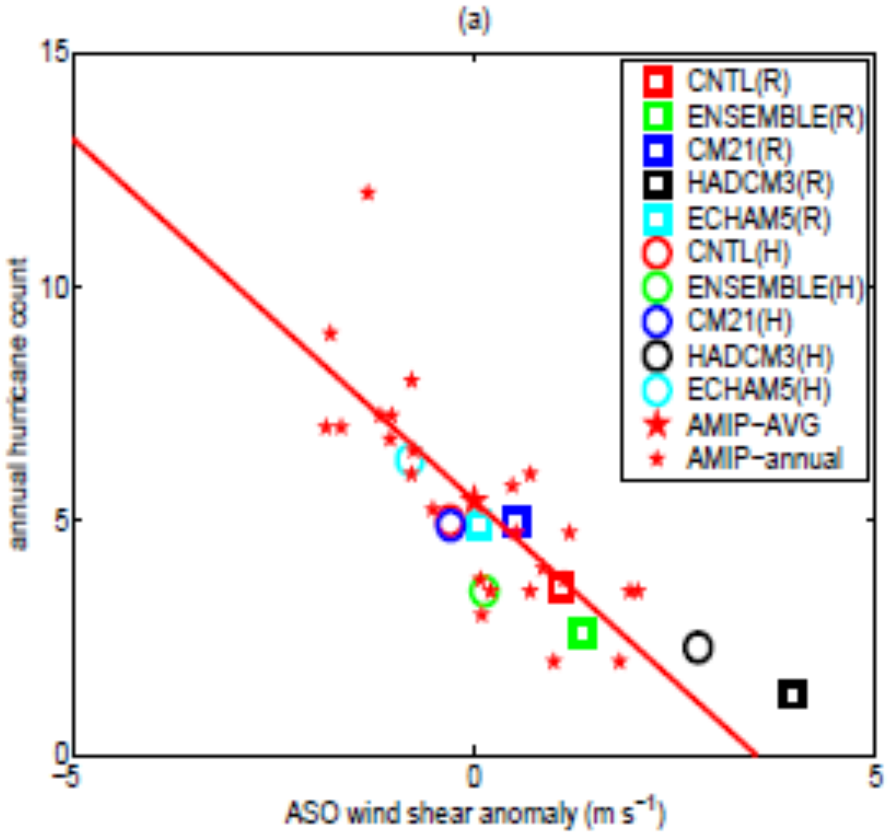
Source: Zhao, Held, Lin, and Vecchi (J. Climate, 2009)

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).



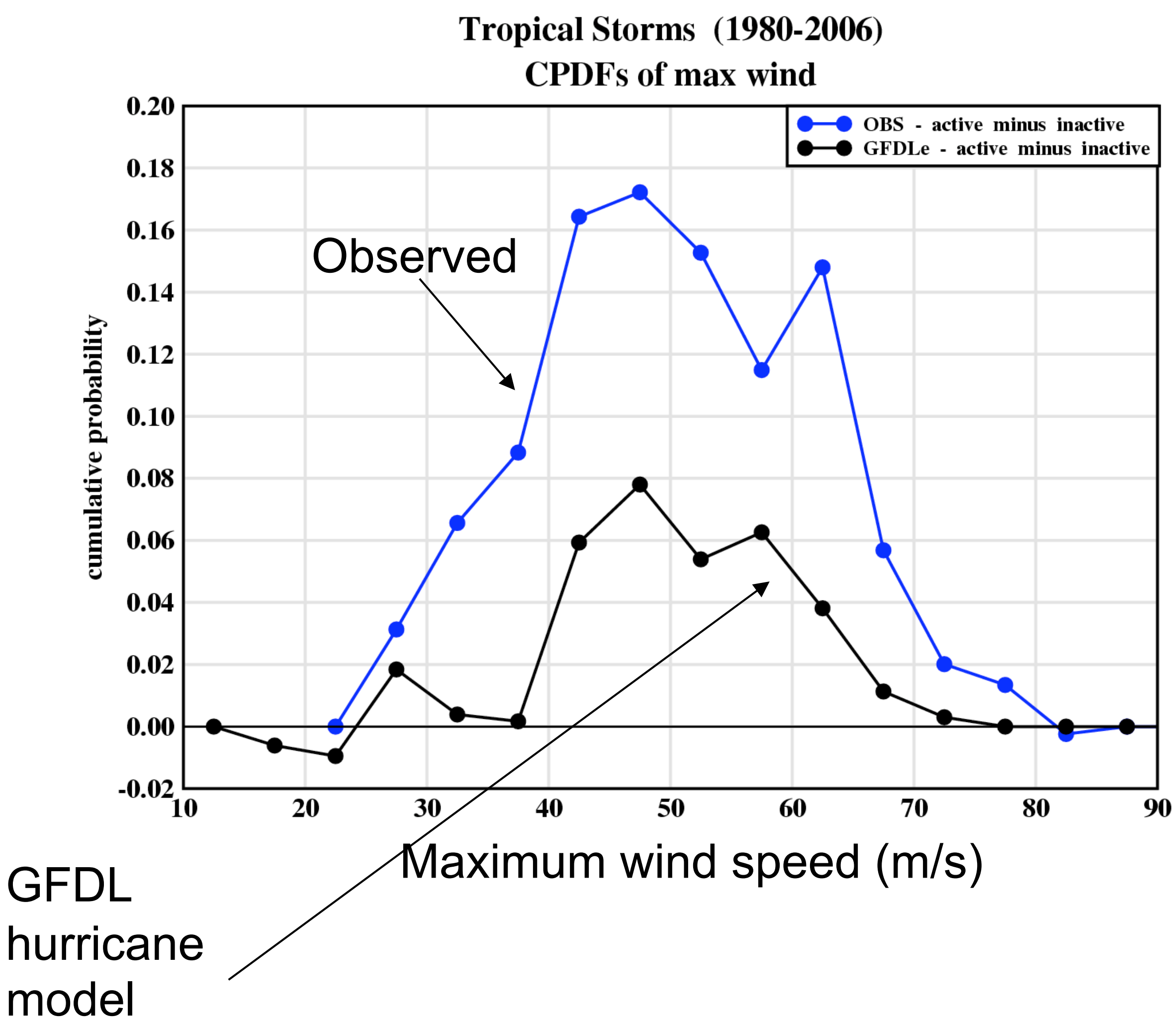
Source: Zhao, Held, Lin, and Vecchi (J. Climate, 2009)

The HIRAM 50-km grid model hurricane count changes (interannual and A1B scenario) are consistent with expectation based on tropical Atlantic vertical wind shear anomalies



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

Cumulative Distribution Functions of Atlantic TC Intensities (1980-2006).



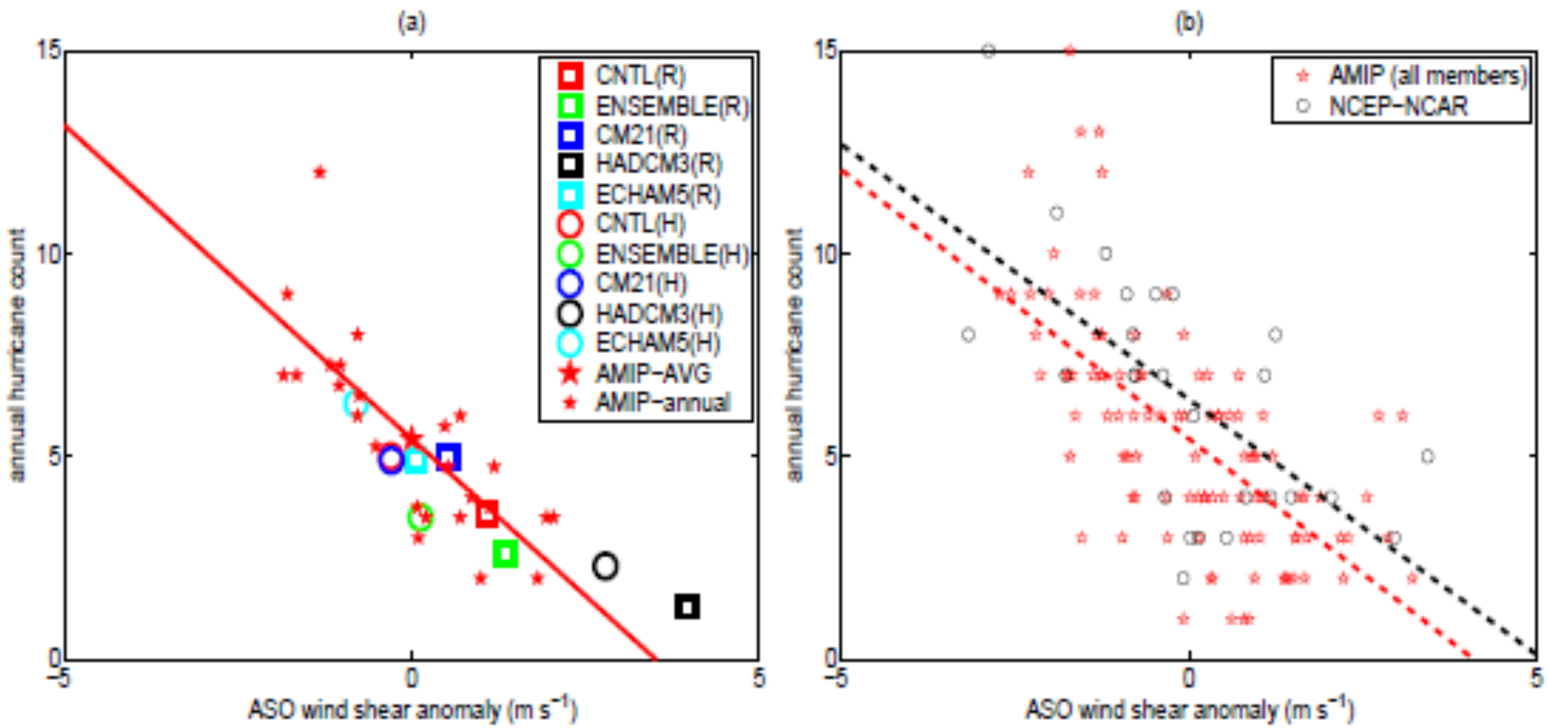
CDF Difference:
1995-2006 era minus 1980-1994 era.

Hurricanes are more intense on average in the active era.

For this set of active/ inactive years the hurricane model intensity *is less sensitive than observed.*

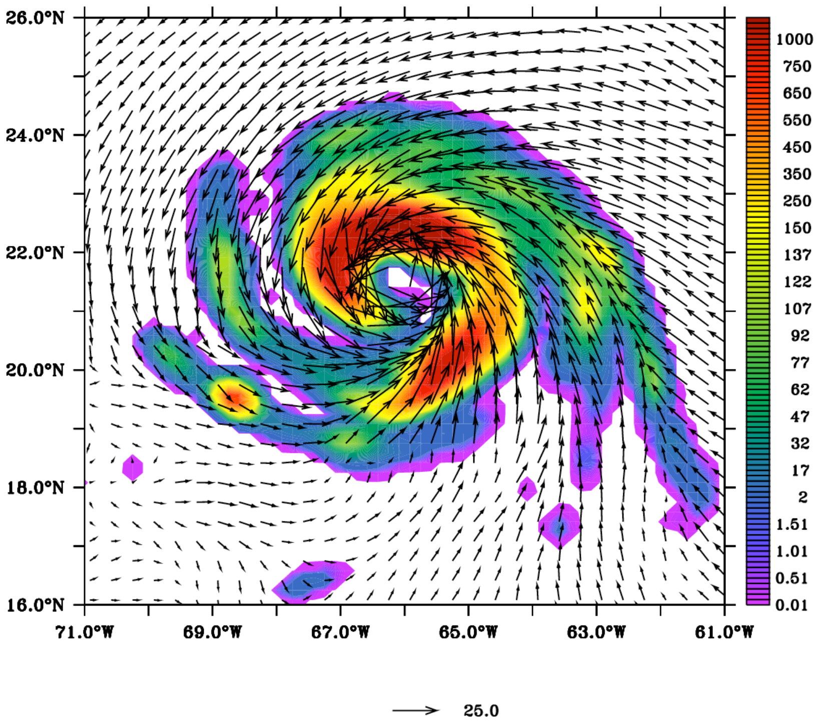
Source: Bender et al., submitted, 2009

The HIRAM 50-km grid model hurricane count changes (interannual and A1B scenario) are consistent with expectation based on tropical Atlantic vertical wind shear anomalies

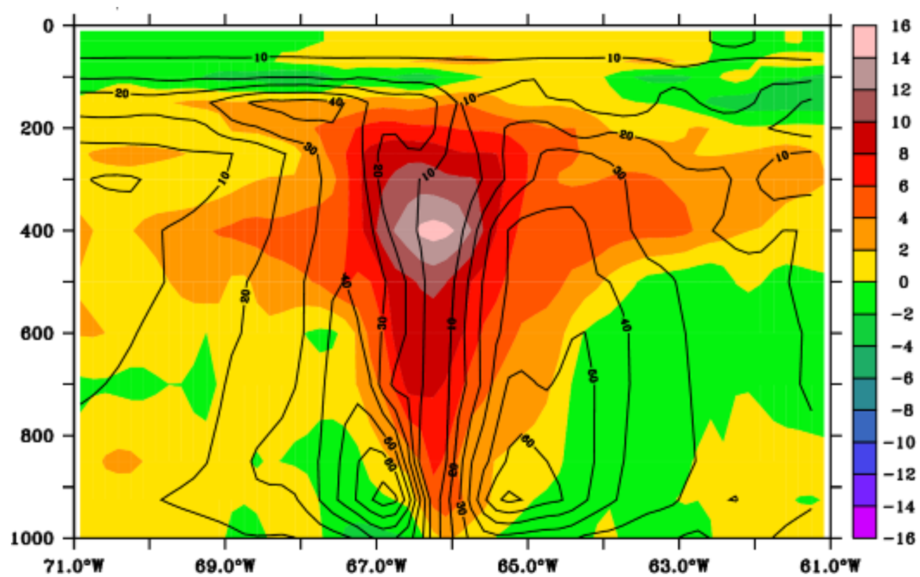


Source: Zhao, Held, Lin, and Vecchi (J. Climate, in press)

Sample hurricane from the Zetac 18-km grid model



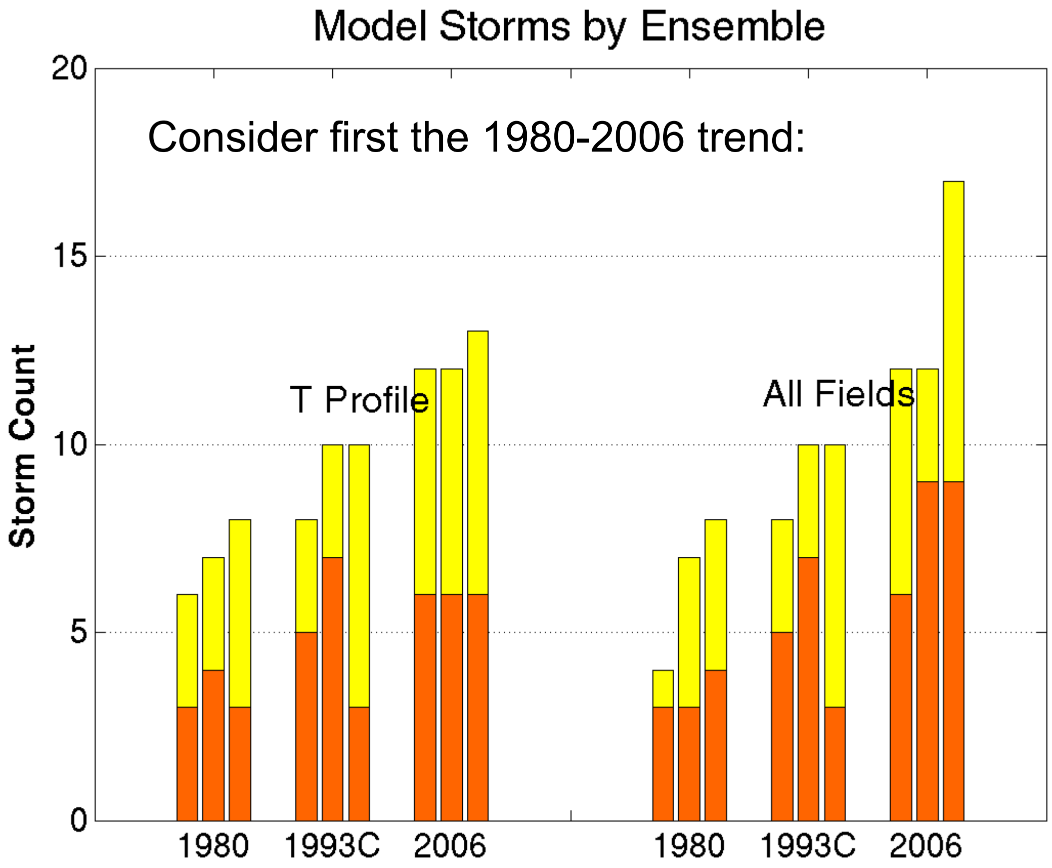
Surface winds (m/s) and rainfall (mm/day)



Atmospheric “warm core” and wind speeds

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

Why did the number of storms decrease in the climate change runs?



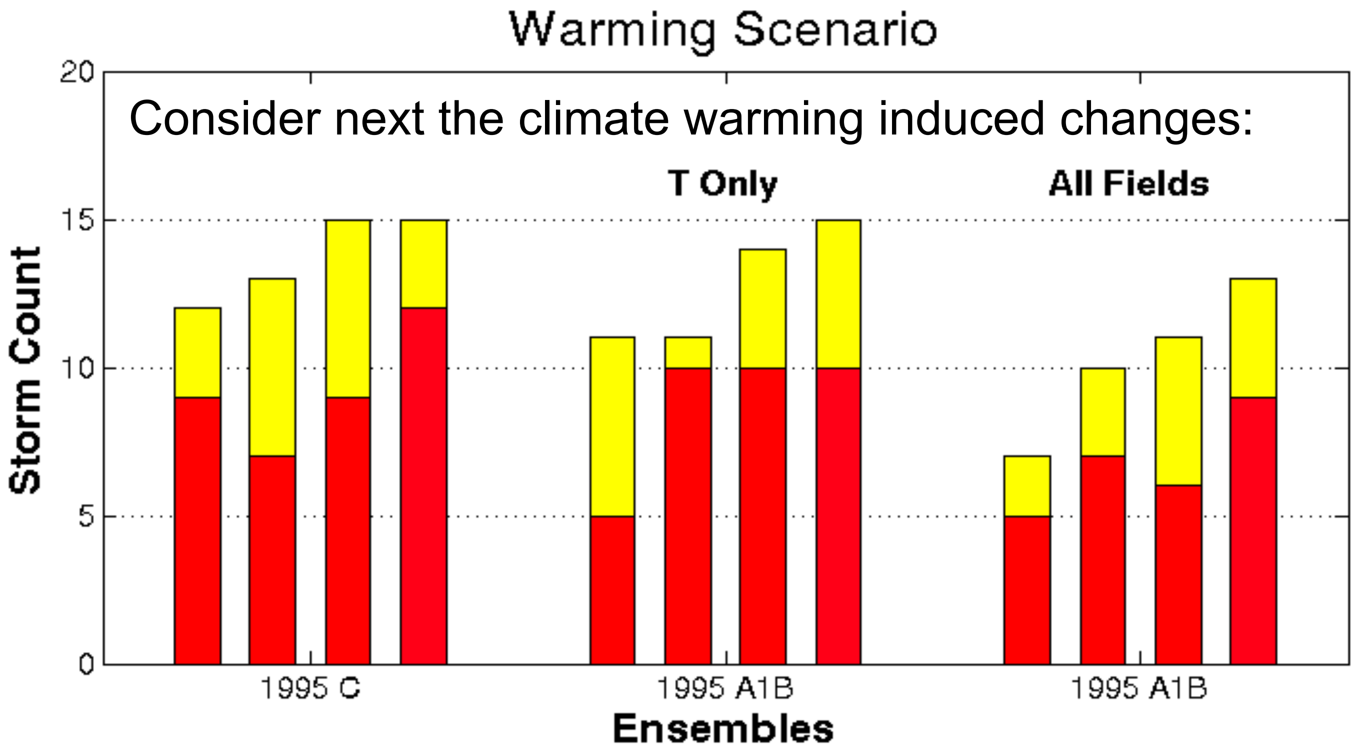
Yellow: Tropical storms

Red: Hurricanes

a) Changing the mean atmospheric temperature profile alone reproduces a substantial part (~half) of the trend over the 1980-2006 period.

Source: Garner, Held, Knutson, and Sirutis, J. Climate, in press.

Why did the number of storms decrease in the climate change runs?

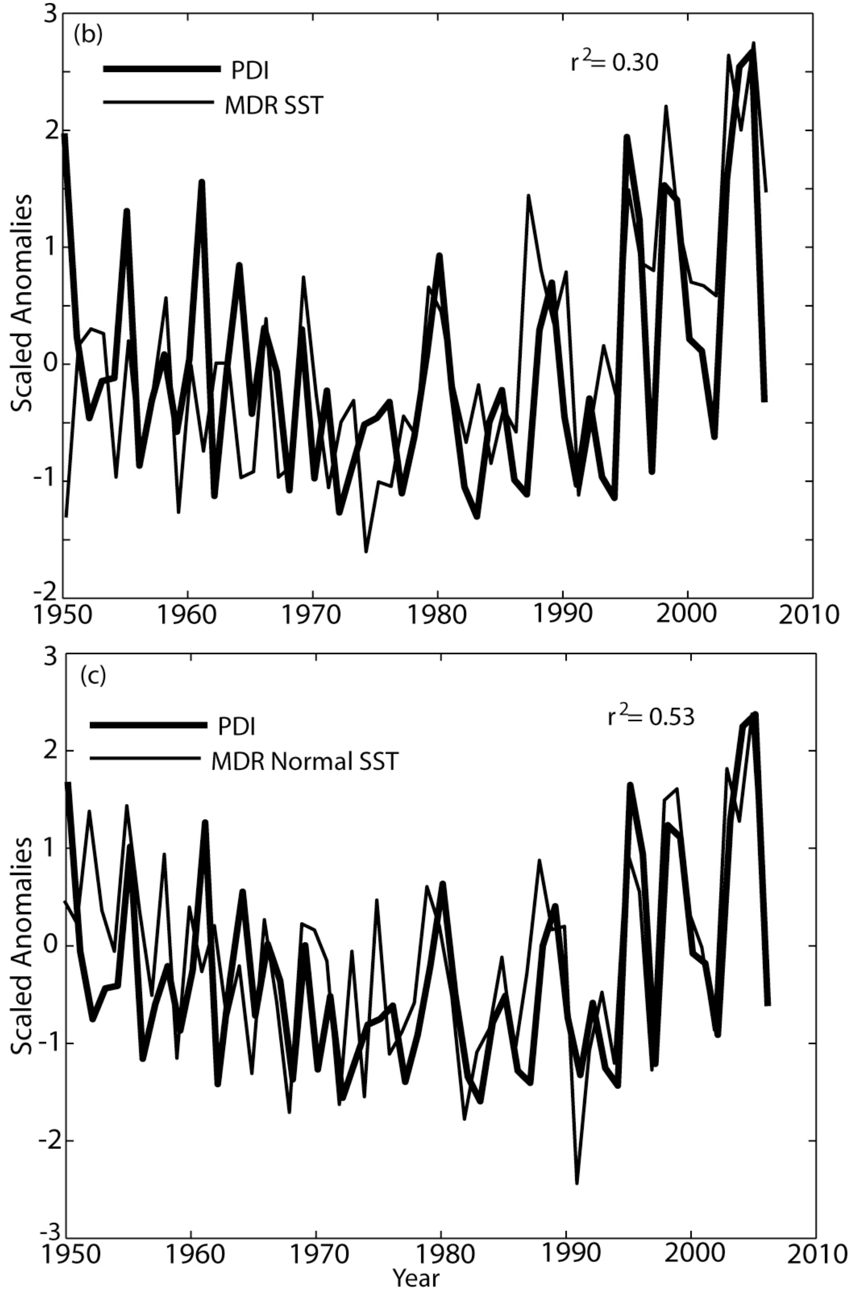


Yellow: Tropical storms

Red: Hurricanes

b) Changing the temperature profile alone reproduces only a small change compared to that produced by all fields. Therefore, we infer that circulation changes (e.g., shear) are probably the dominant contributor to the climate warming-induced reduction of storm count.

Source: Garner, Held, Knutson, and Sirutis, J. Climate, in press.

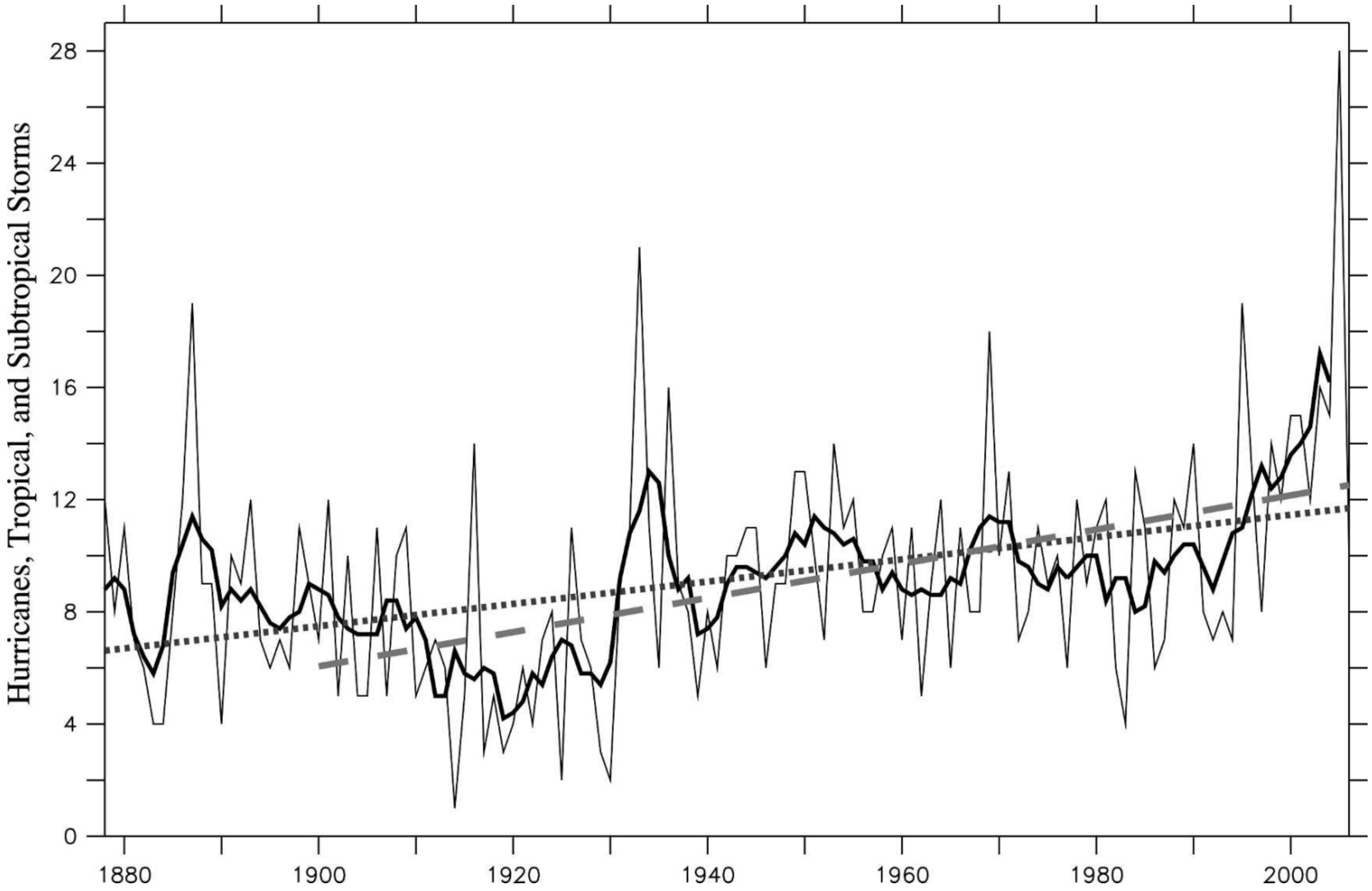


Atlantic hurricane activity (PDI) is correlated with local Atlantic SST (top) and with Atlantic SST relative to tropical mean SST (bottom).

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.

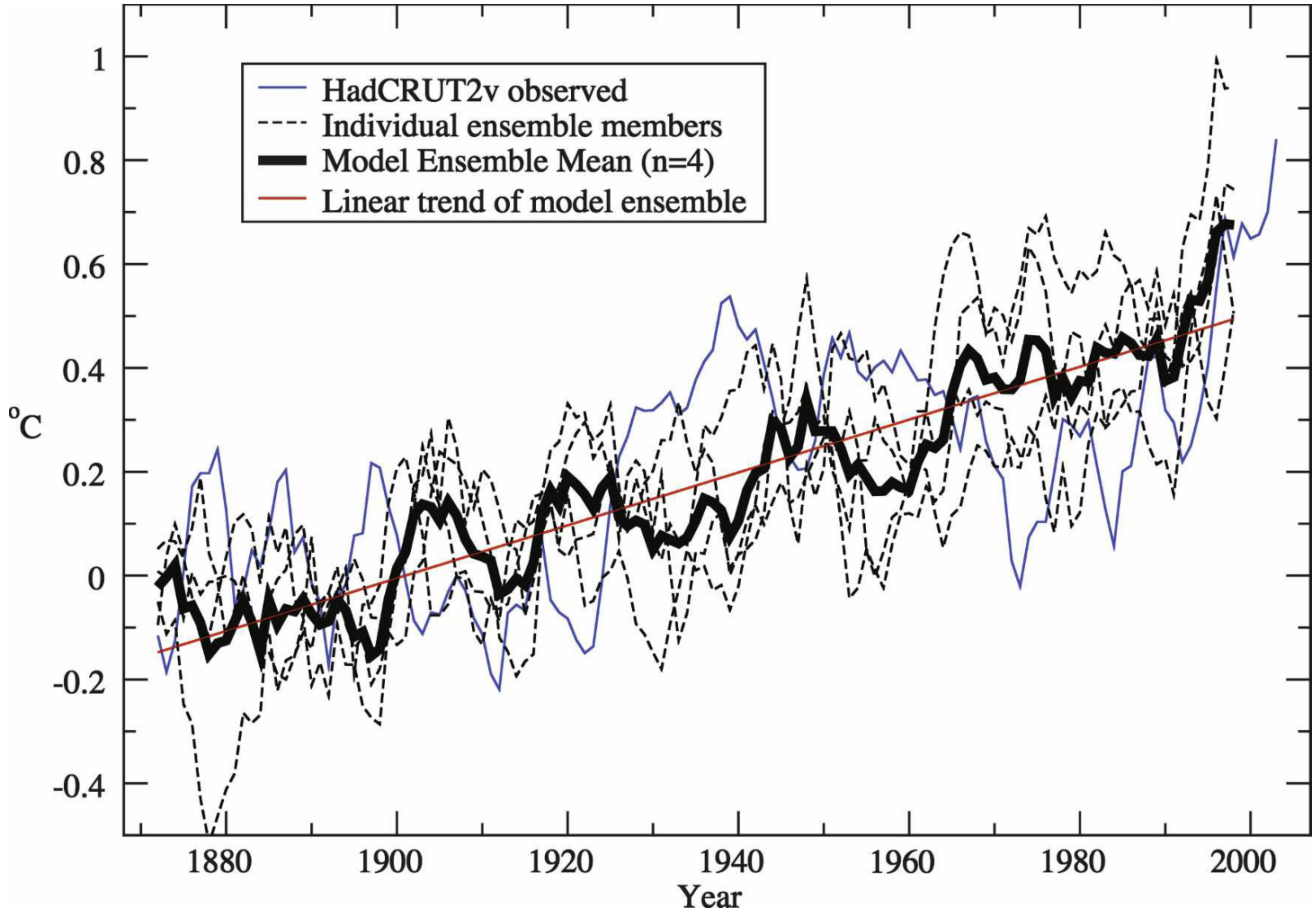
Source: Swanson, *G-cubed*, 2008

Unadjusted tropical storm counts have significant trends since 1900 and since 1878



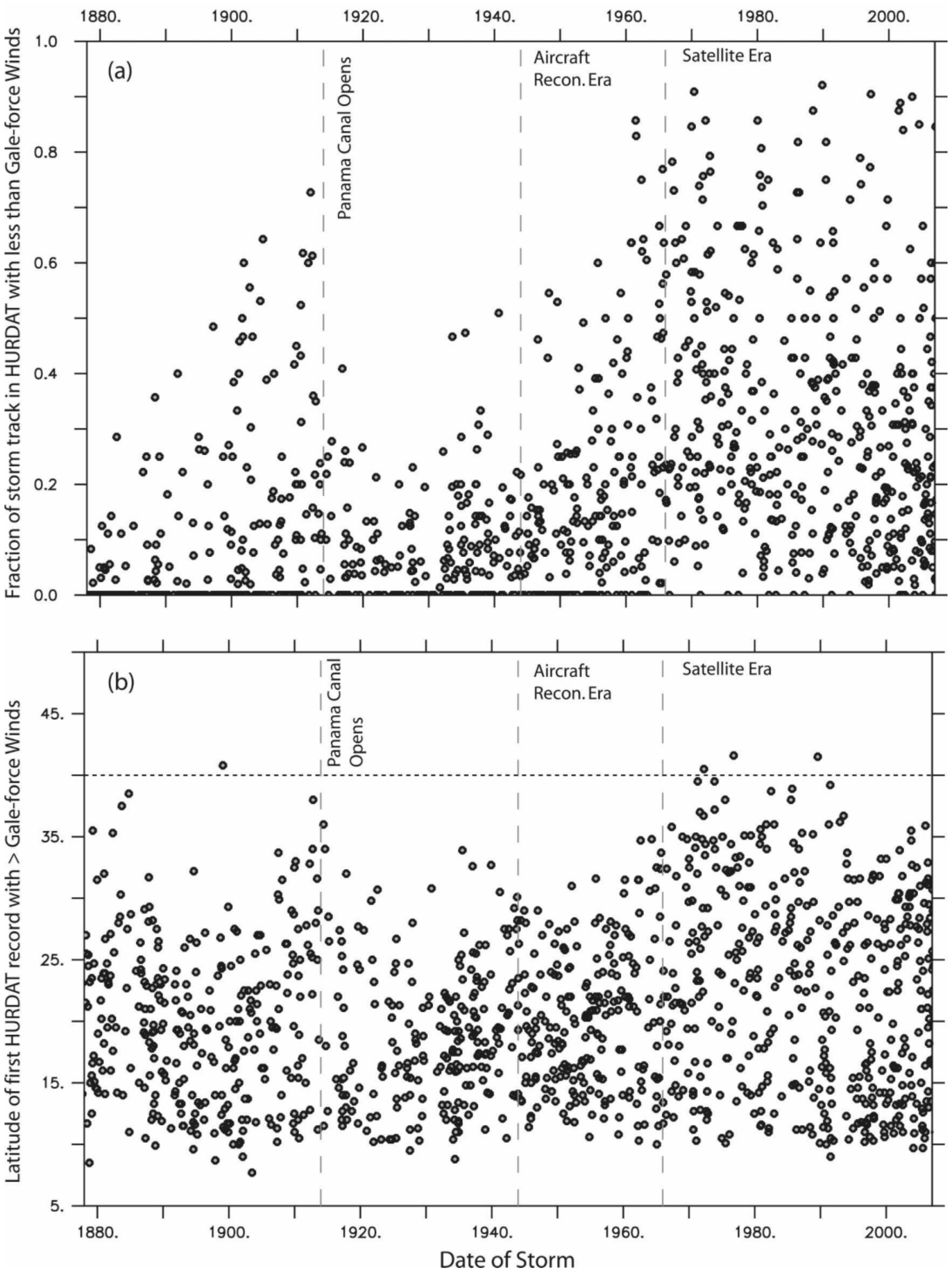
Source: Vecchi and Knutson , J. Climate, 2008.

Why examine linear trends?

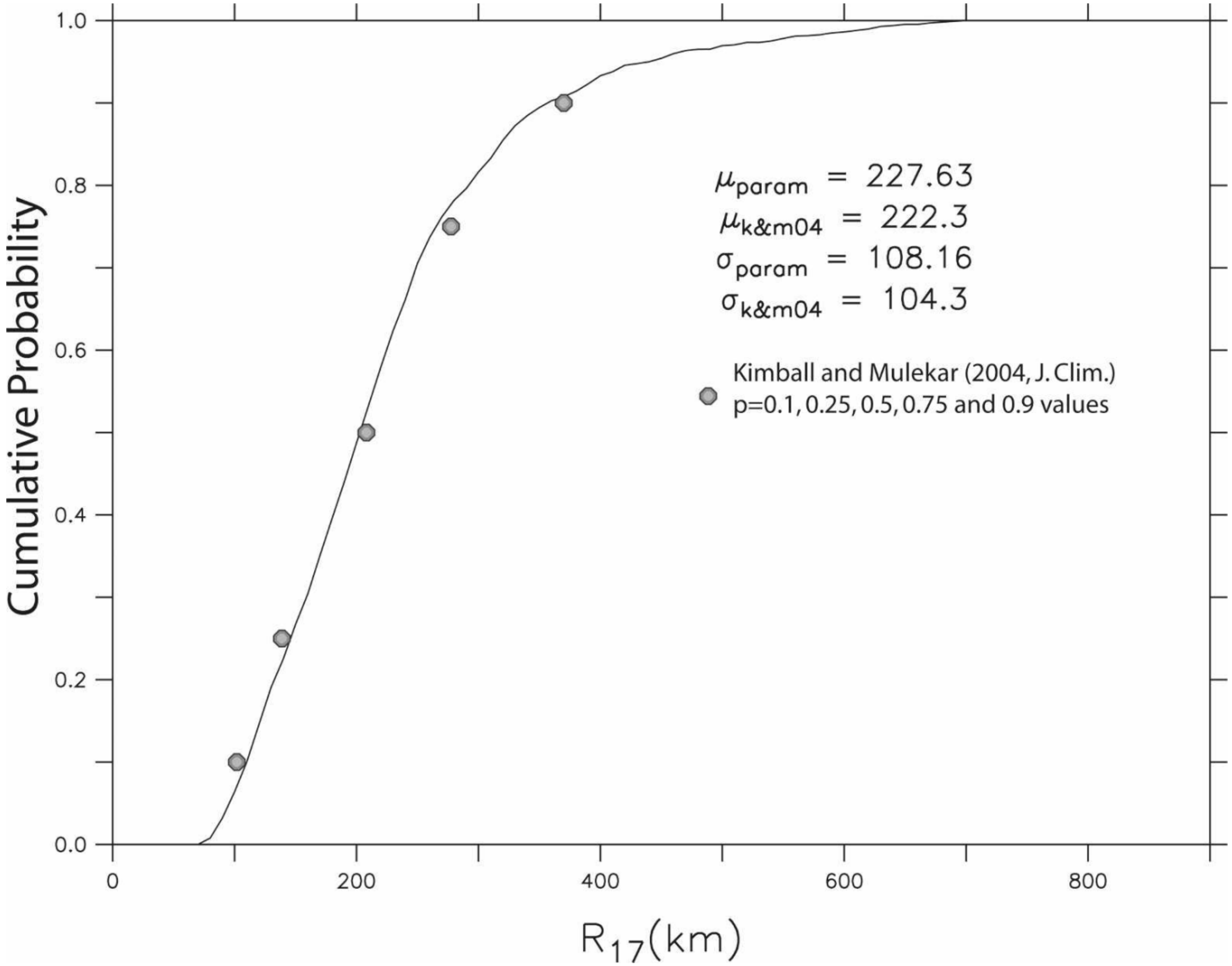


Source: Vecchi and Knutson , J. Climate, 2008.

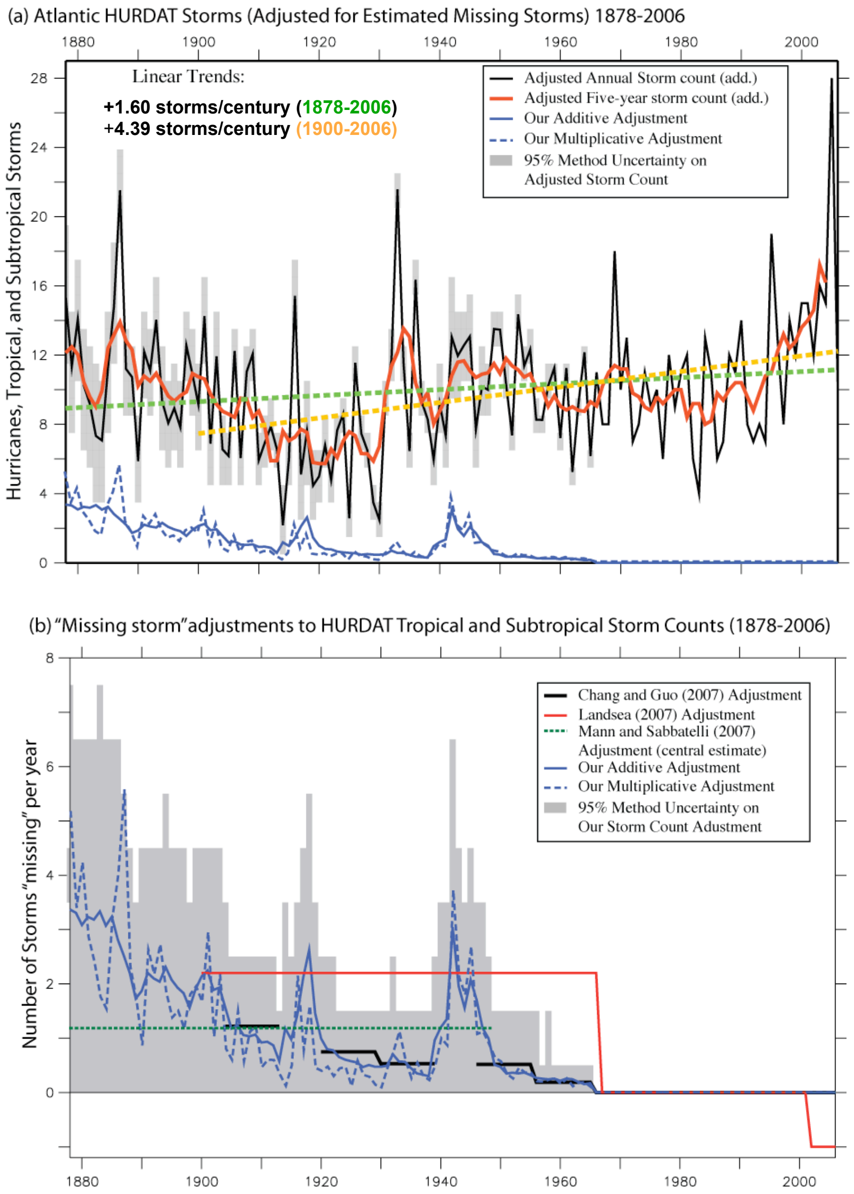
Other evidence for inhomogeneities…tropical depression fraction



Source: Vecchi and Knutson , J. Climate, 2008.



1.0
0.8
0.6
0.4
0.2
0.0
0
200
400
600
800
Cumulative Probability
R_{17}(km)
μ_{param} = 227.63
$\mu_{k\&m04}$ = 222.3
σ_{param} = 108.16
$\sigma_{k\&m04}$ = 104.3
Kimball and Mulekar (2004, J. Clim.)
p=0.1, 0.25, 0.5, 0.75 and 0.9 values



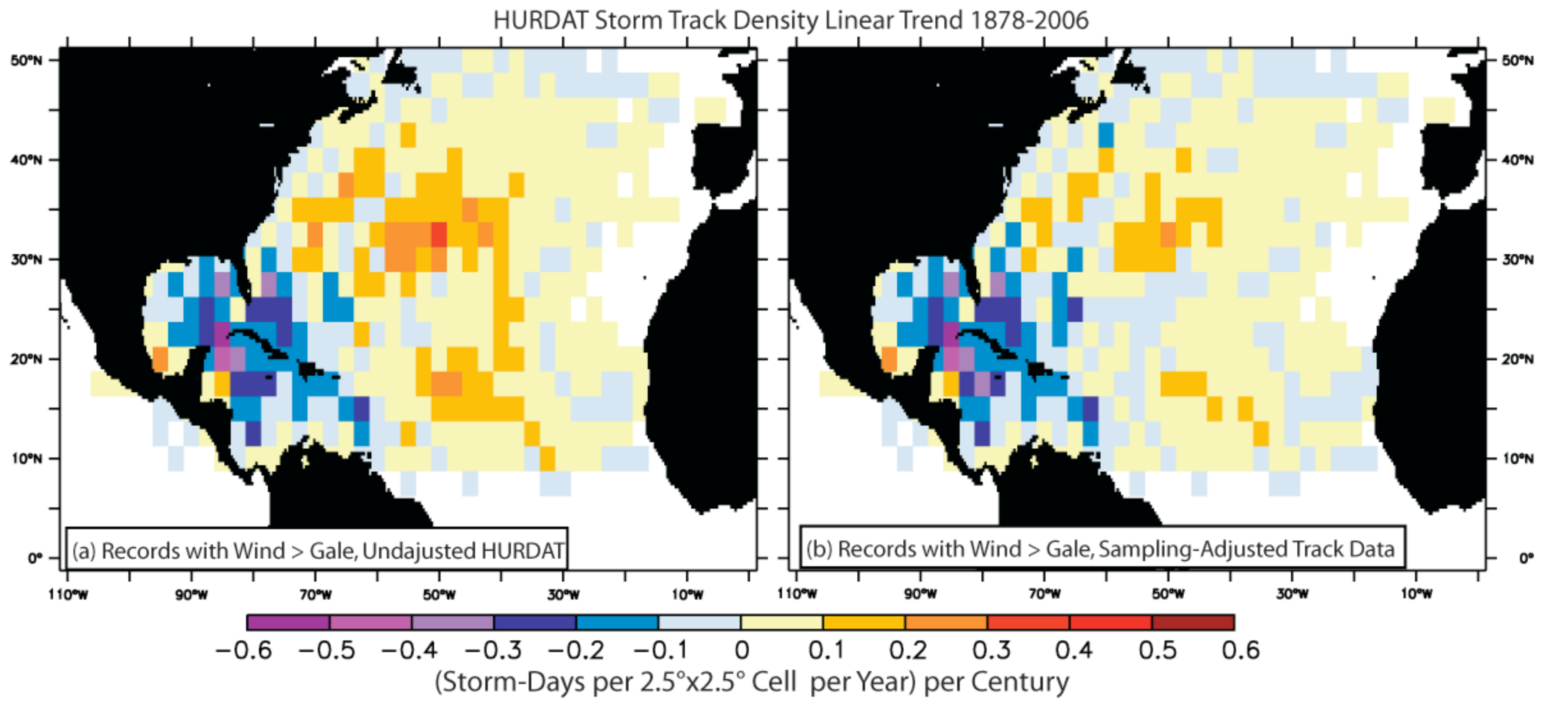
Trend from 1878-2006: Not significant (p=0.05, 2-sided tests, computed p-val ~0.2)

Trend from 1900-2006: Is significant at p=0.05 level

Other estimates of missing Atlantic tropical storms…

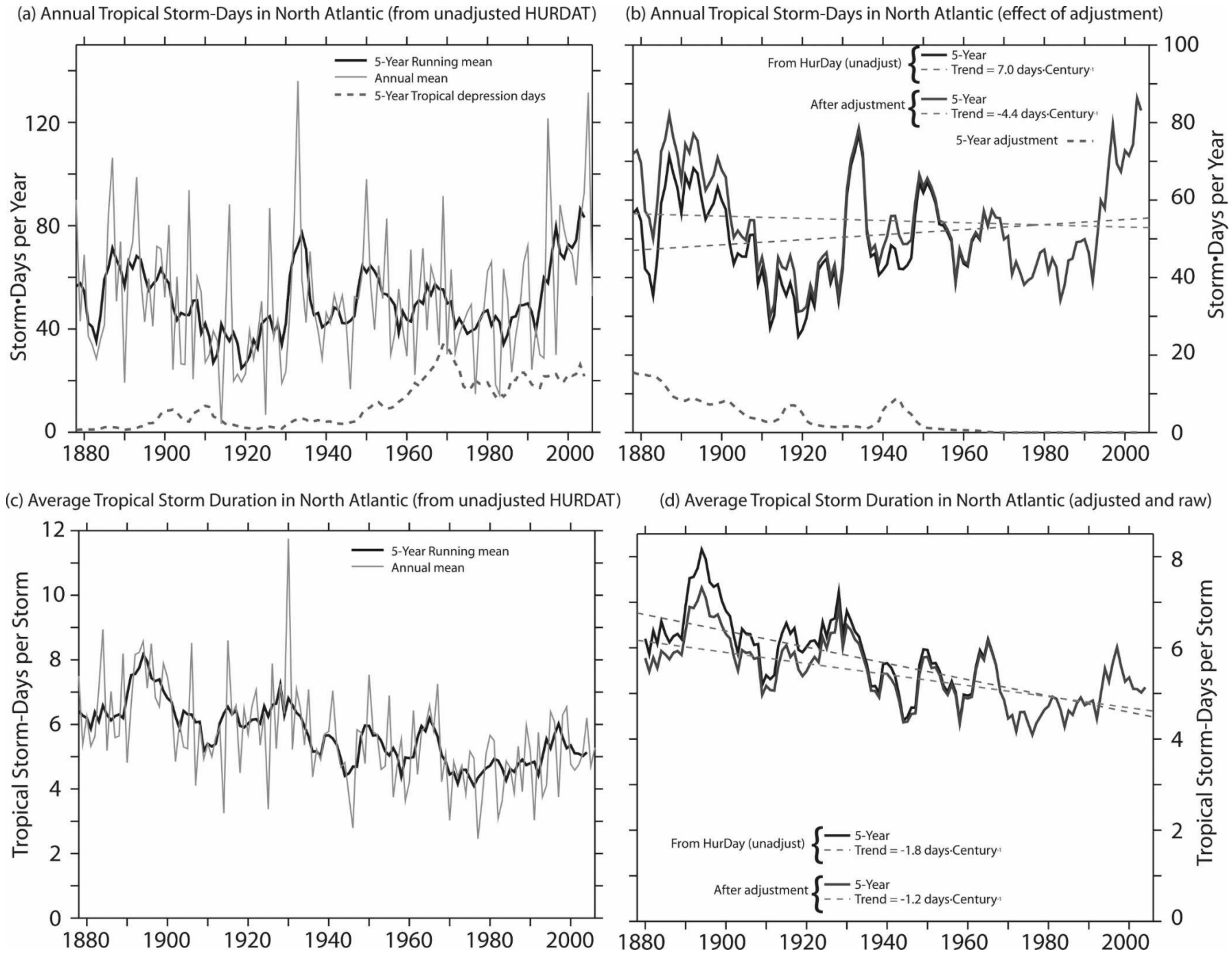
Source: Vecchi and Knutson, J. Climate, 2008.

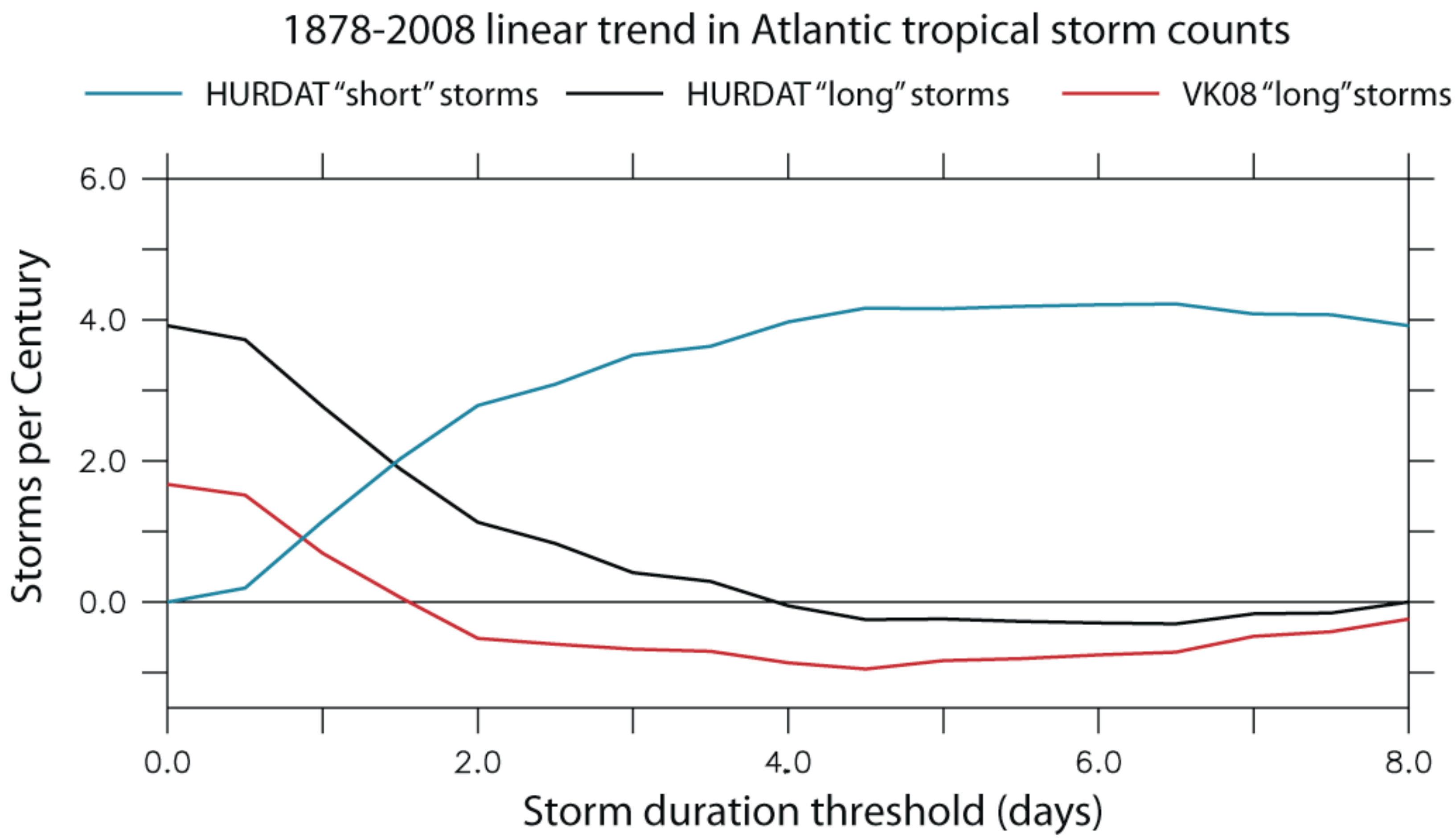
Tropical storm occurrence has apparently decreased in the Gulf of Mexico and Caribbean…Increases are mostly located in the open Atlantic and off the U.S. East Coast (in original, unadjusted data)…

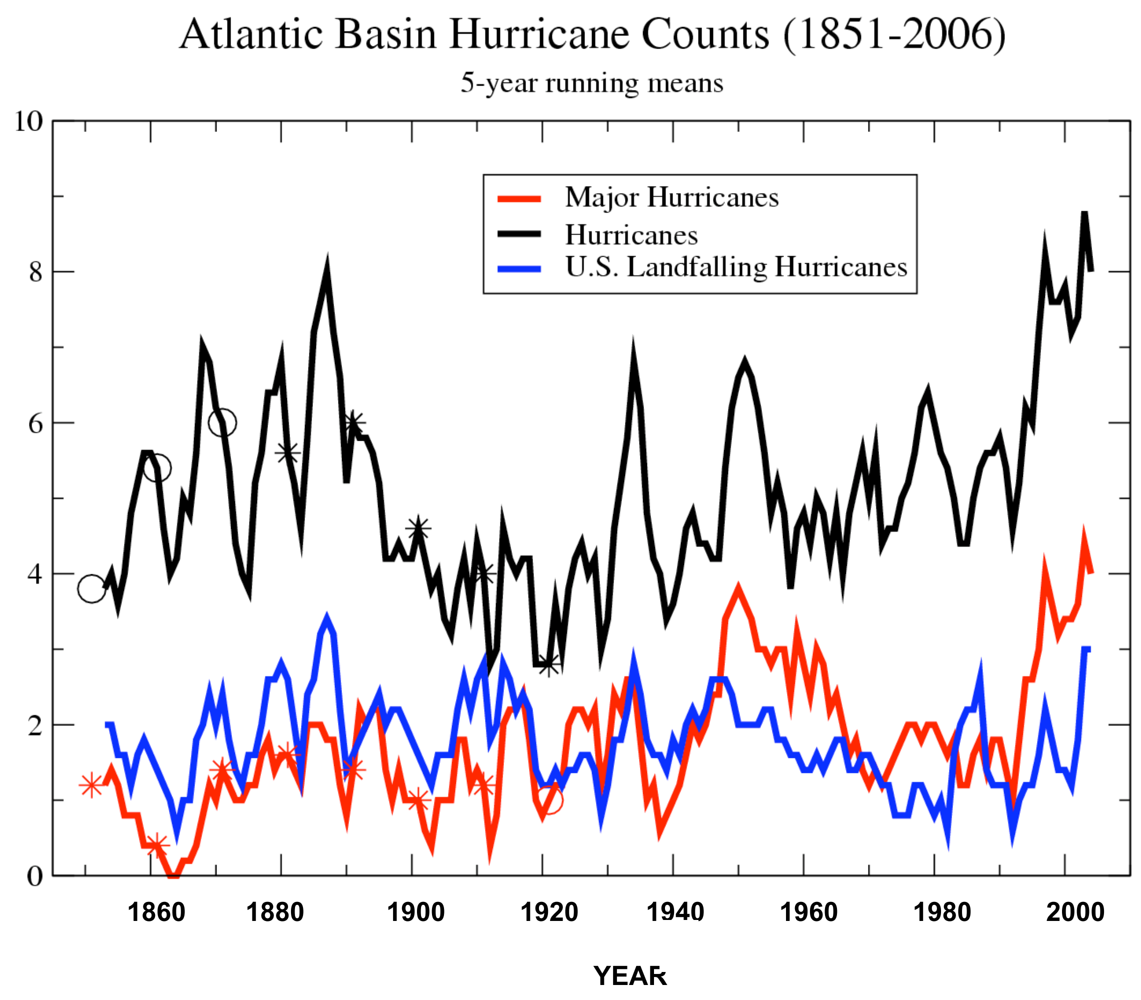


Source: Vecchi and Knutson, J. Climate, accepted for publication.

Tropical Storm Duration Issues

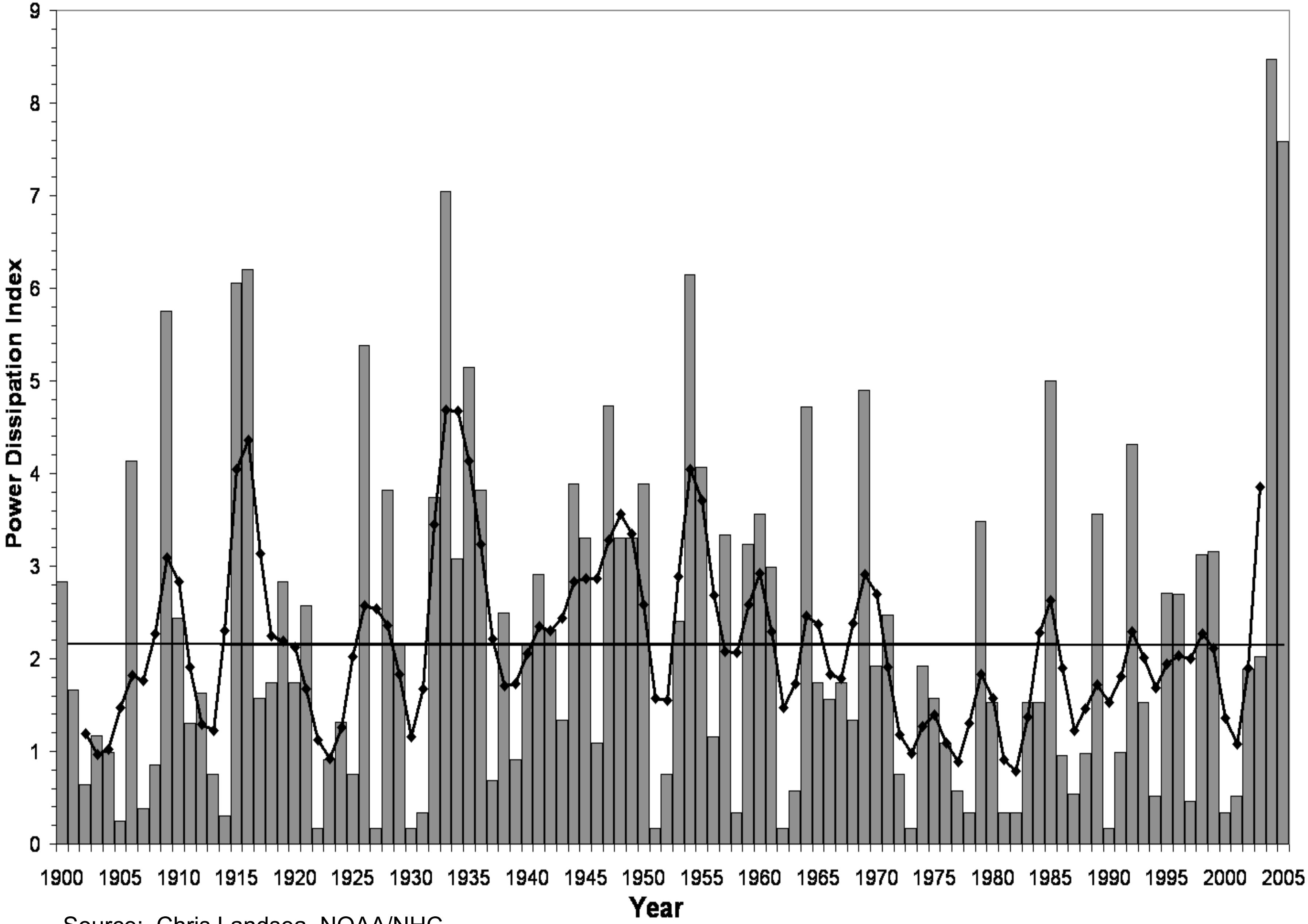



1878-2008 linear trend in Atlantic tropical storm counts
HURDAT "short" storms
HURDAT "long" storms
VK08 "long" storms
Storms per Century
6.0
4.0
2.0
0.0
0.0
2.0
4.0
6.0
8.0
Storm duration threshold (days)



Source: CCSP 3.3 Report

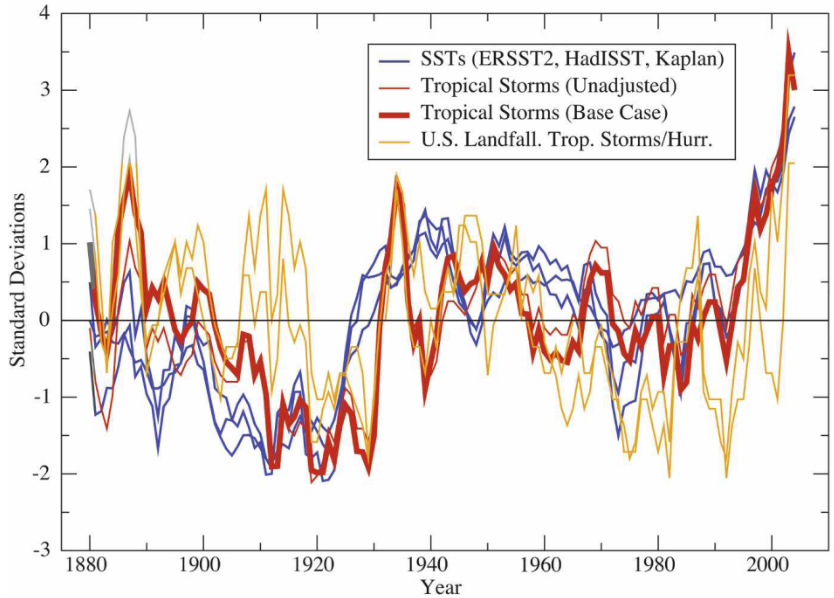
Landfalling storms: U.S. landfalling PDI shows no clear long-term trend since 1900…



Source: Chris Landsea, NOAA/NHC

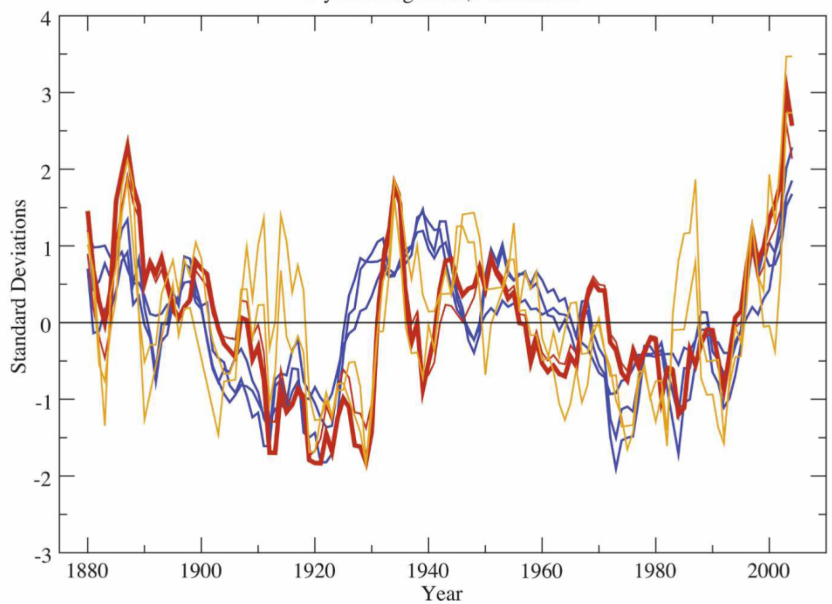
(a) Tropical Atlantic SSTs, Tropical Storms, and U.S. Landfall Series

5-yr running mean; Normalized

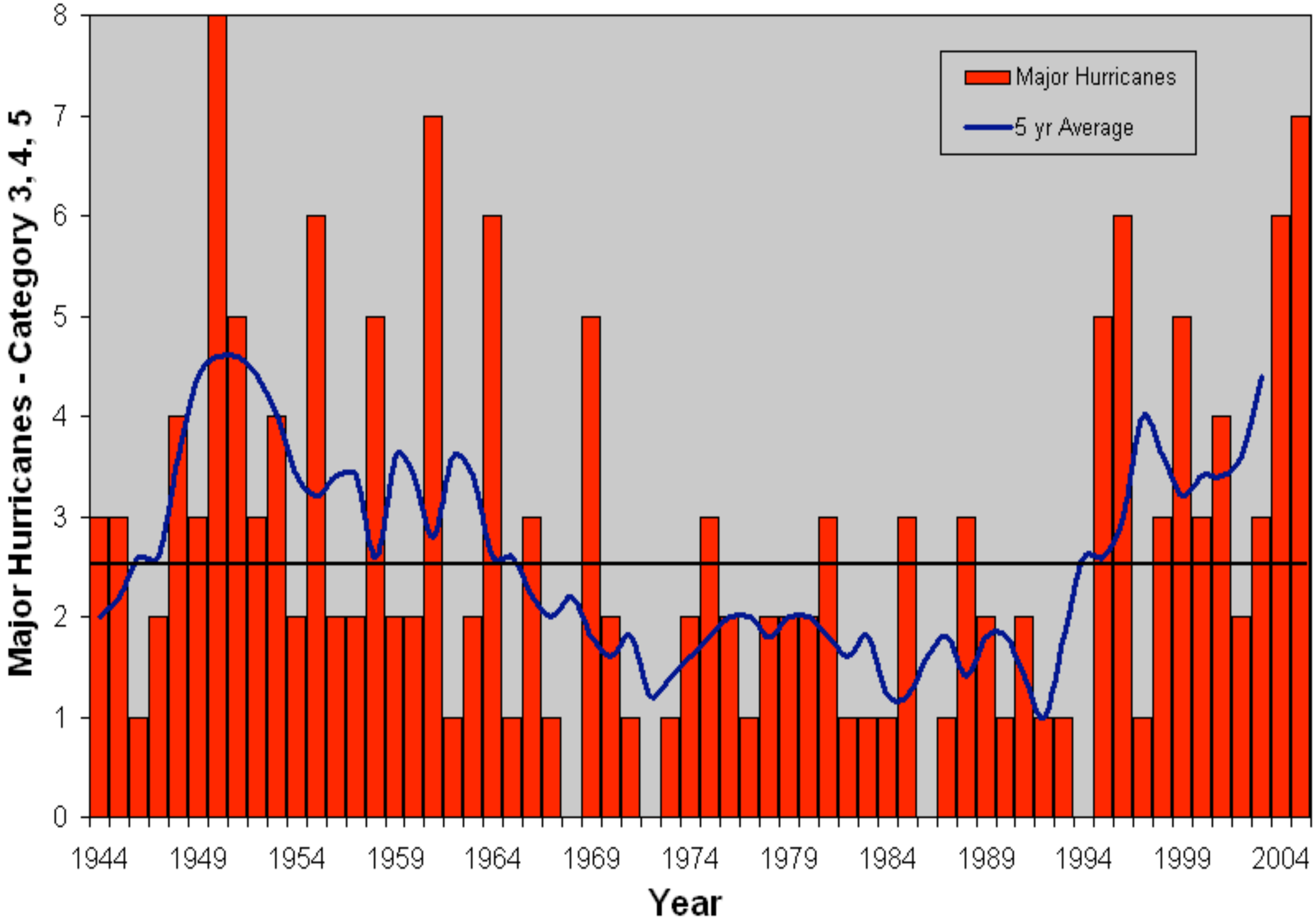


(b) Tropical Atlantic SSTs, Trop. Storms and Landfall Series: Detrended

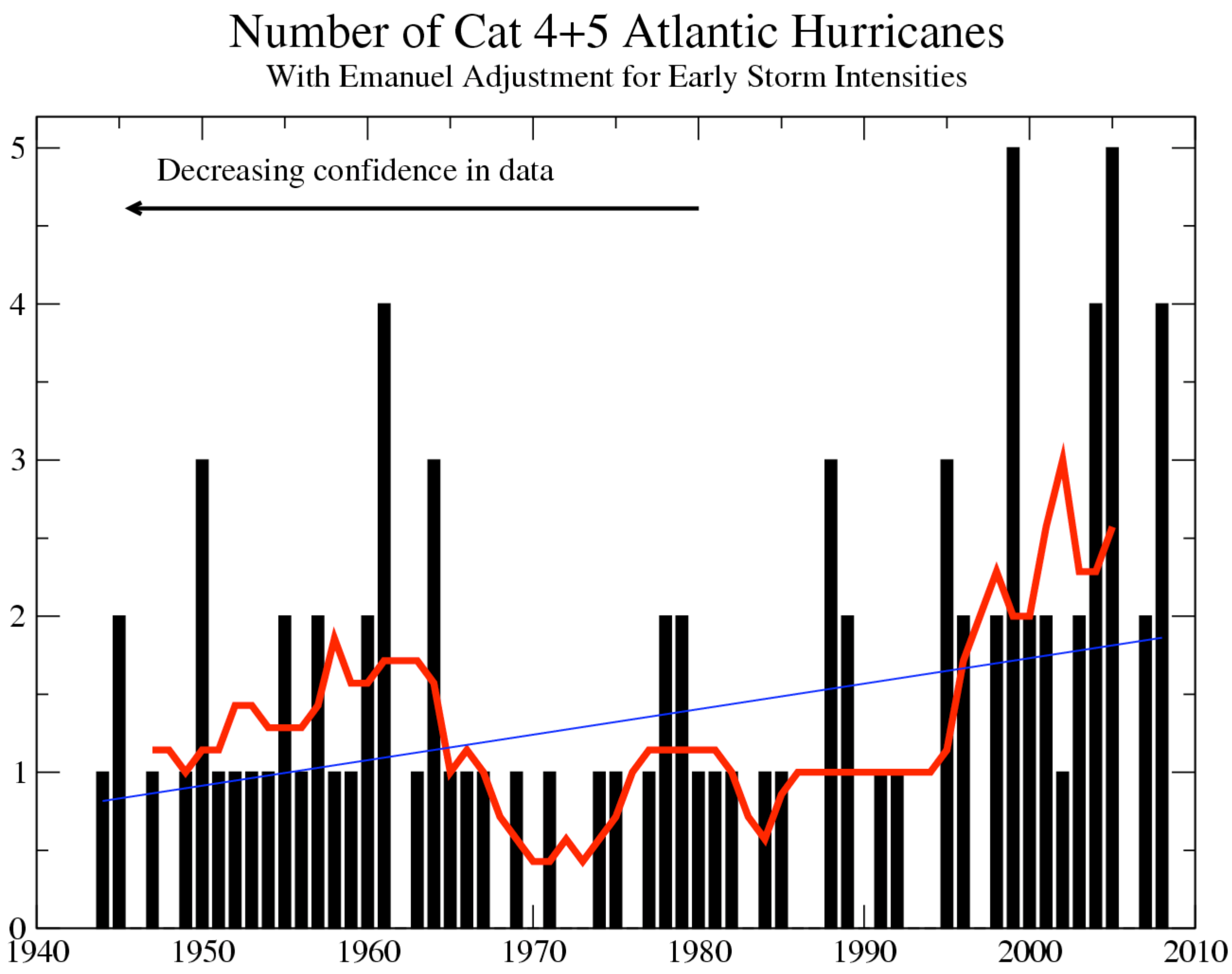
5-yr running mean; Normalized



Atlantic Major Hurricane counts (basin-wide) since the mid-1940s: no long-term trend



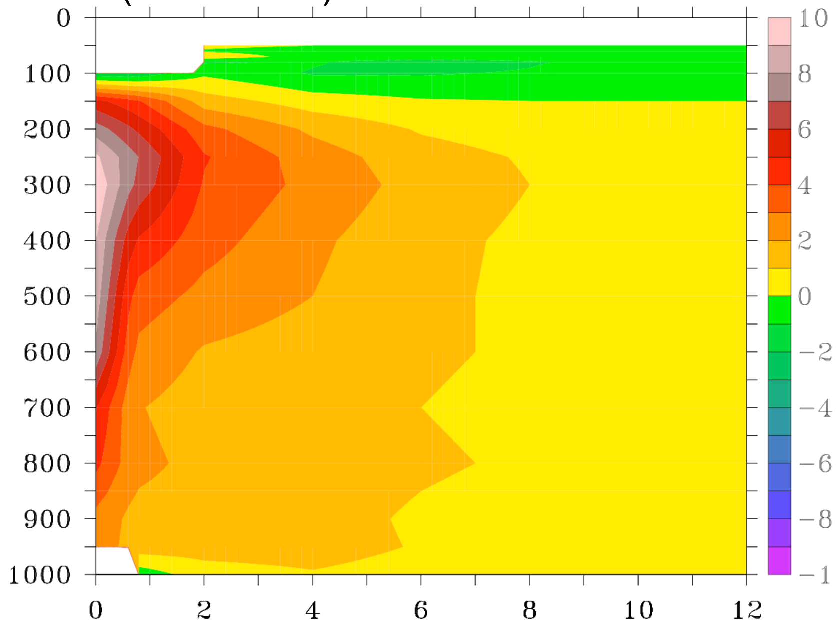
Source: Chris Landsea, NOAA/NHC



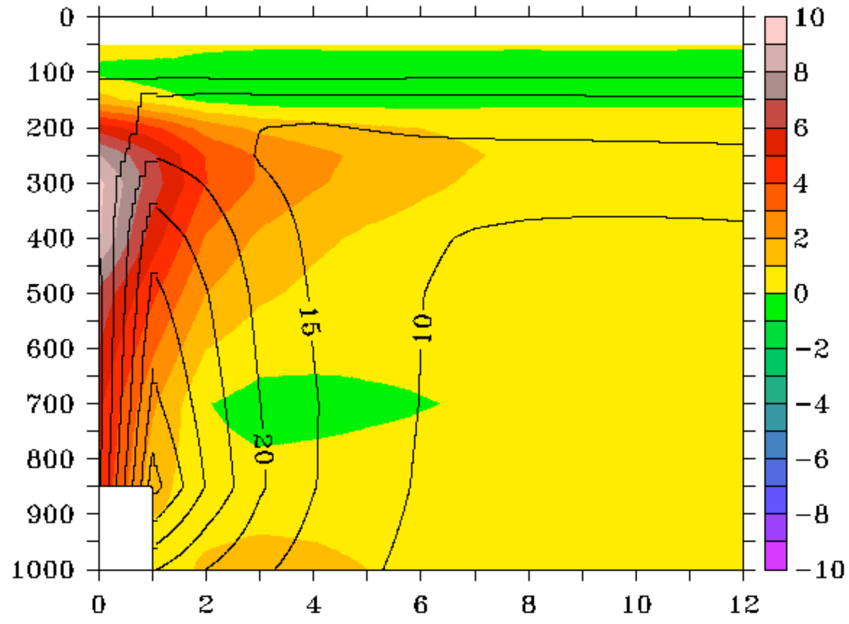
Source: Bender et al., submitted, 2009.

Zetac model hurricanes have a fairly realistic warm core structure

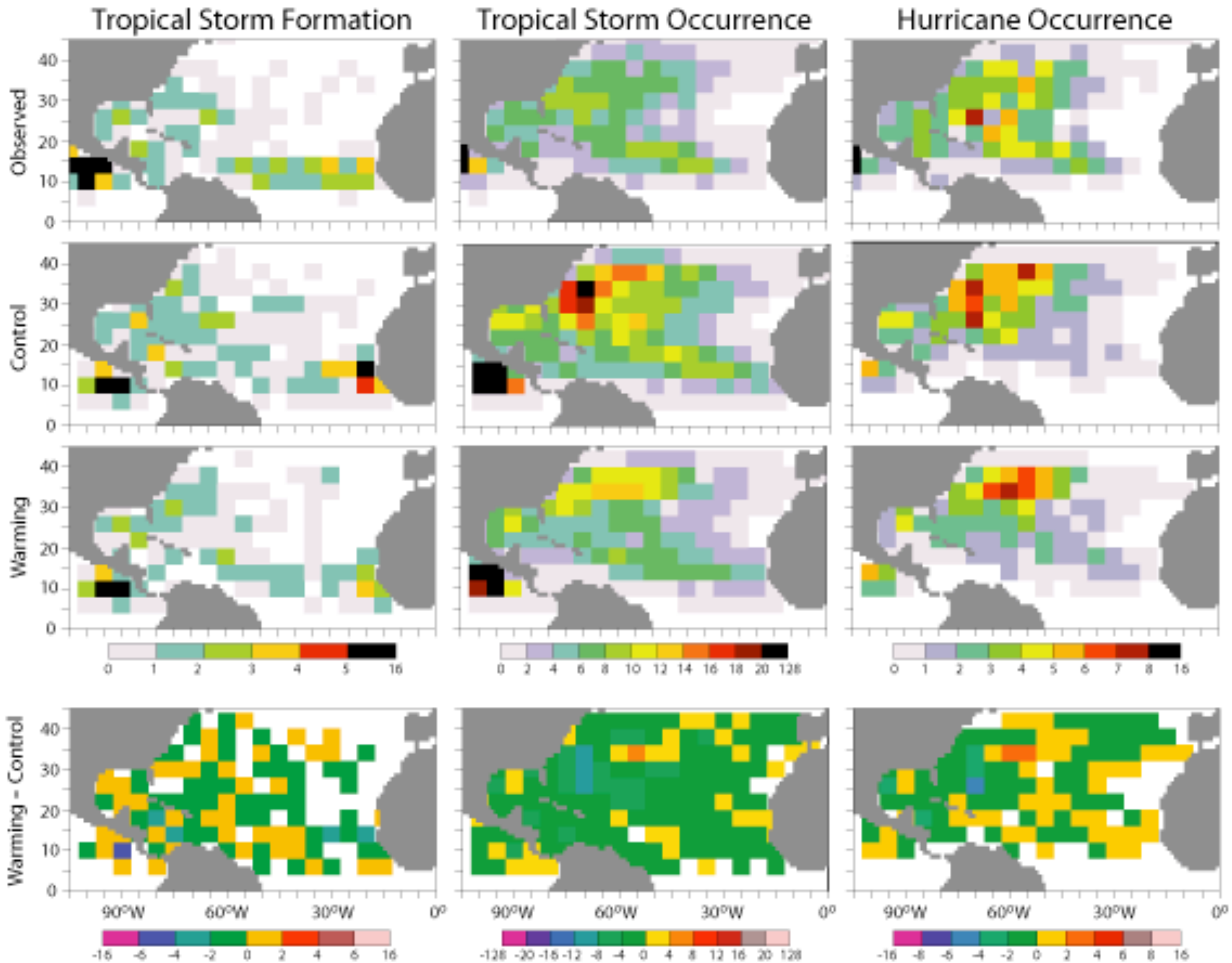
Observed composite temperature anomaly for steady-state typhoon (Frank 1977)



Model hurricane composite temperature anomaly and wind speed:



Influence of pronounced greenhouse warming on distribution of hurricane occurrence:



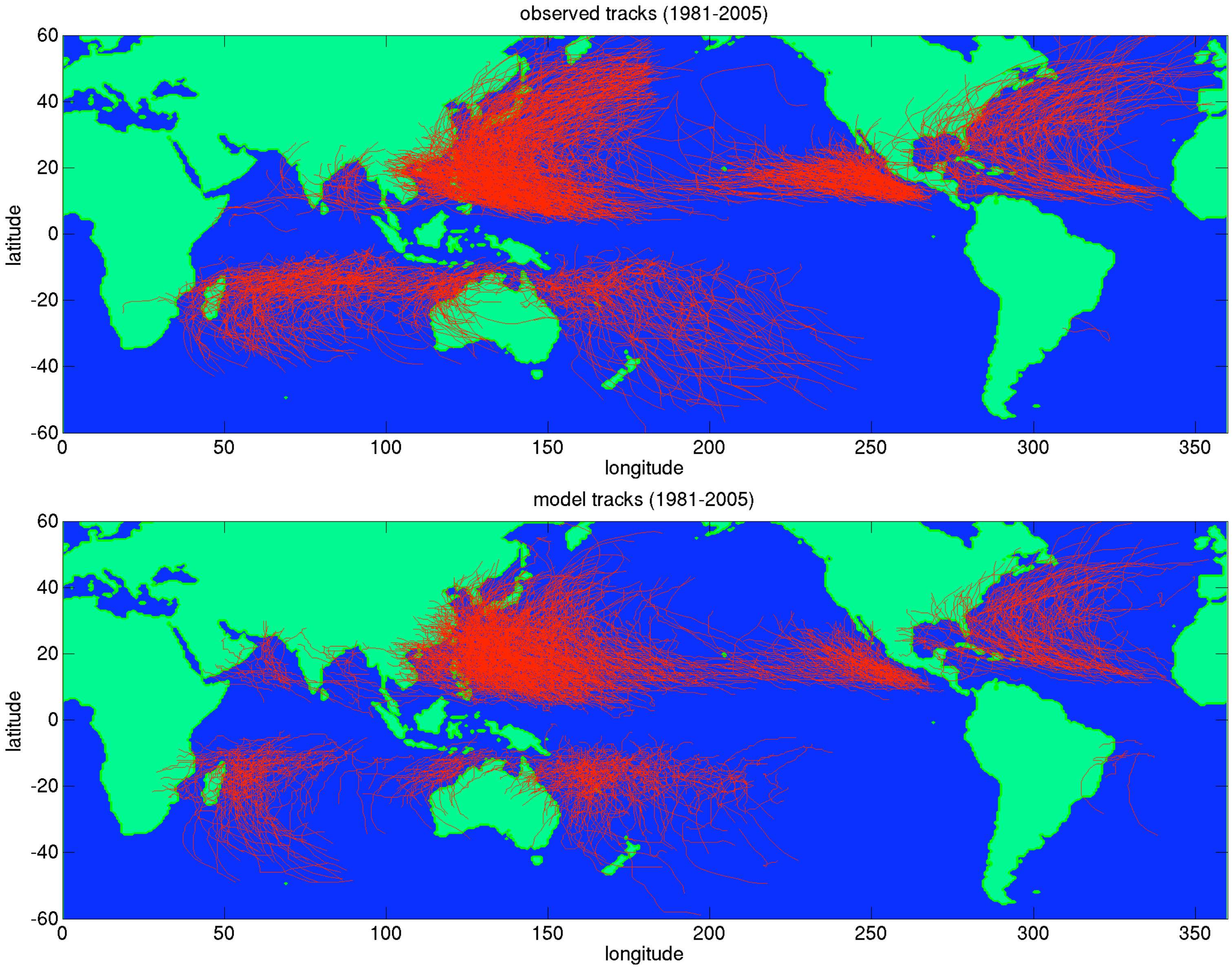
Some biases in hurricane occurrence may distort climate change projection

A hint of an eastward shift in hurricane occurrence…

Climate Model Dependence?

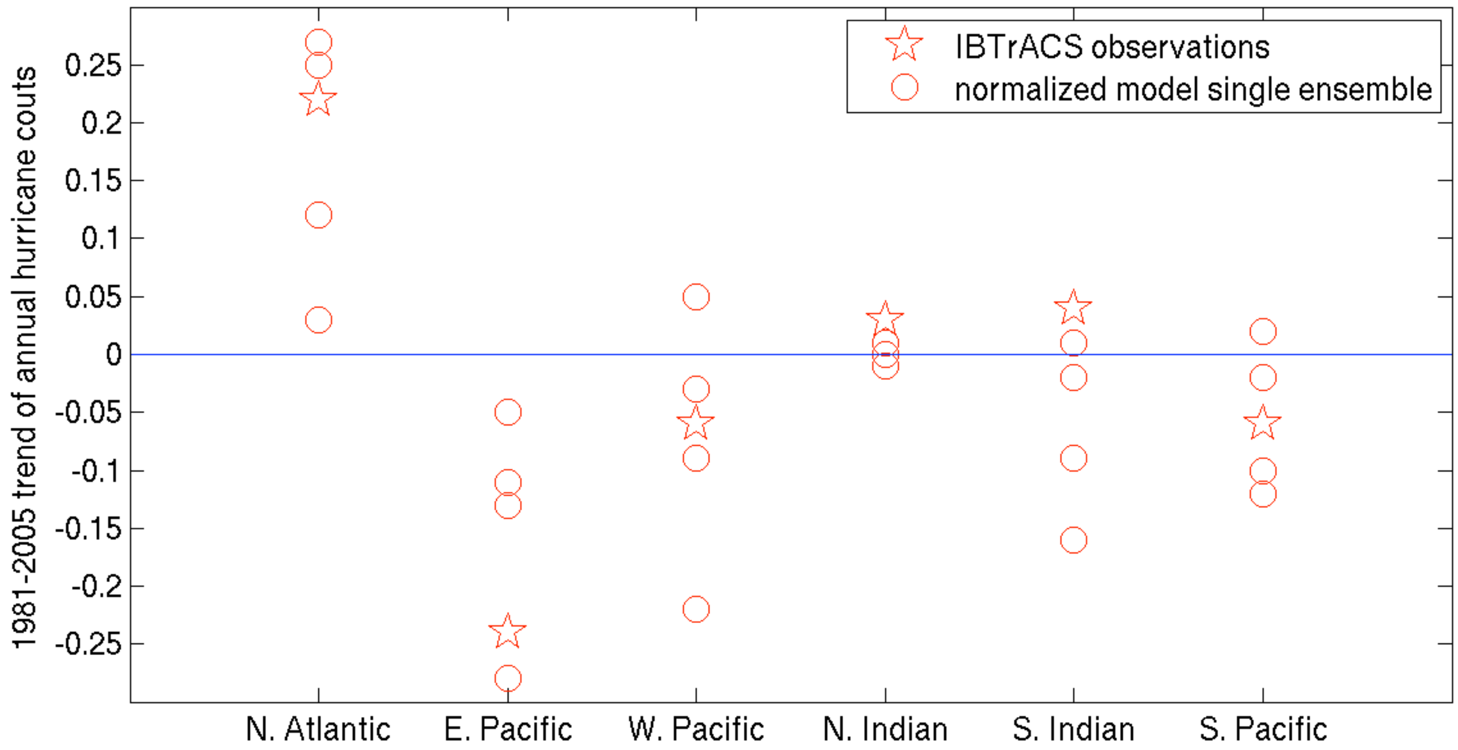
- Rather than an average climate change perturbation derived from multiple models, consider the change from individual CMIP3 models separately.
  - For each model, use linear trend analysis to extract the A1B scenario 21st century climate change perturbation field.
  - Models include GFDL CM2.1, MPI, MRI, HadCM3 (so far).
  - Selection of models attempts to capture extremes of the distribution of model responses.

Tropical Storm Tracks (1981-2005): HIRAM 50km Grid Model vs Observed

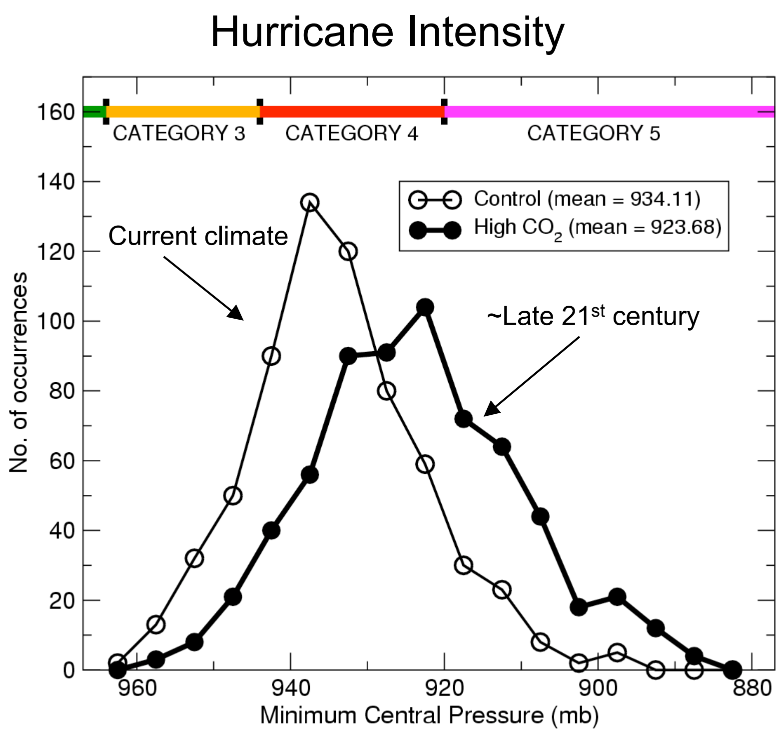


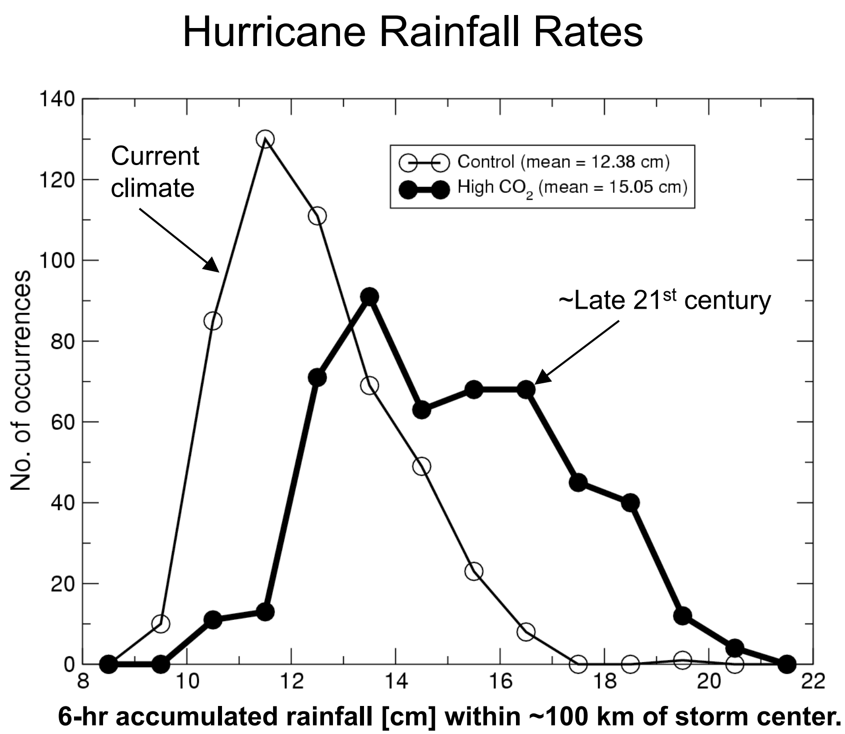
Source: Zhao et al. J. Climate, in press (2009)

Trends in hurricane counts (1981-2005) are fairly realistic in HIRAM 50 km grid model (within range of the model ensemble) in most basins.



Hurricane models project increasing hurricane intensities and rainfall rates with climate warming… …but probably not detectable at present.



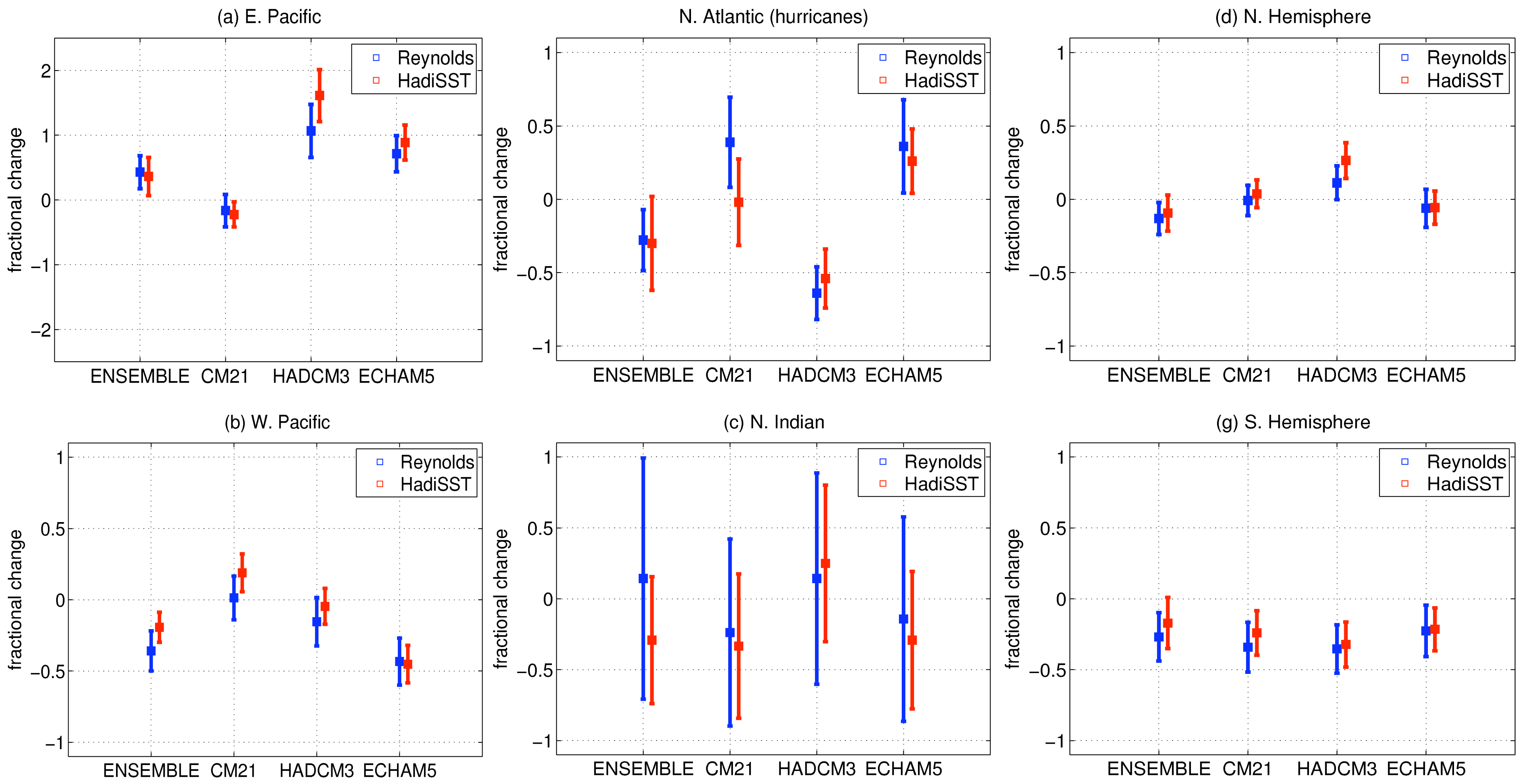


Sensitivity: ~4% increase in wind speed per ^{o}C SST increase

Sensitivity: ~12% increase in near-storm rainfall per ^{o}C SST increase

Sources: Knutson and Tuleya, *J. Climate*, 2004 (left); Knutson and Tuleya (2008) Cambridge Univ Press (right). See also Bengtsson et al. (*Tellus* 2007) and Oouchi et (*J. Meteor. Soc. Japan,* 2006); Walsh et al. (2004) Stowasser et al. (2007).

Fractional change of hurricane frequency – indiv. basins

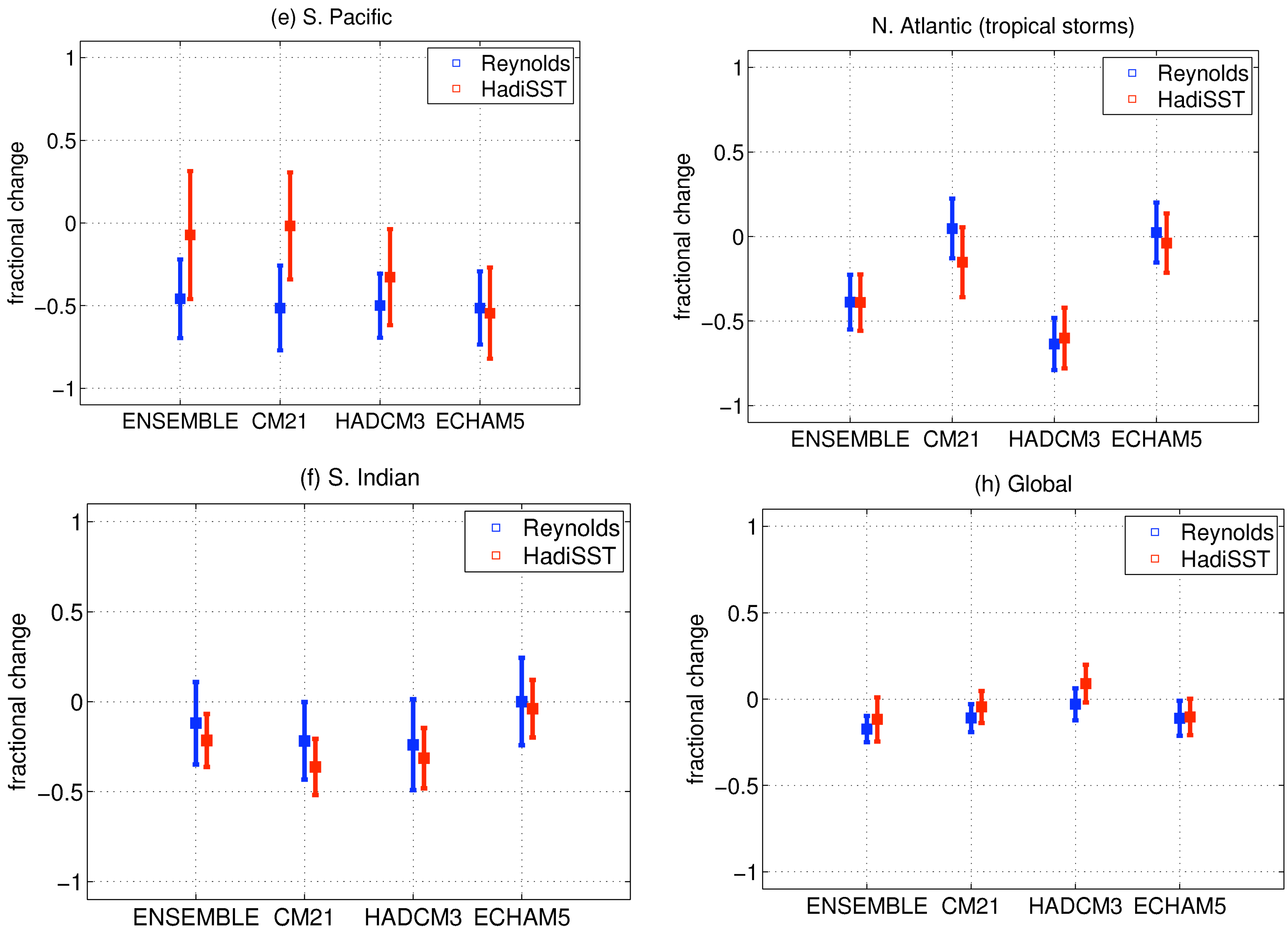


Source: Zhao, Held, Lin, and Vecchi (J. Climate, in press)

Zetac Model Characteristics

- 1/6 degree (18 km) grid; 45 vertical levels
- Non-hydrostatic
- Resolved convection or Relaxed Arakawa-Schubert convection
- Lin Microphysics
- Mellor-Yamada boundary layer formulation
- Atlantic Basin domain (105W-10E; 10S-45N)
- Boundary forcing: Observed SSTs + NCEP 4x daily Reanalyses
- Large-scale (waves 0-2) interior spectral nudging of all variables toward Reanalysis with a timescale of 36 hours (48 hours in Model1).
- Interactive land model (with spun-up initial condition based on reanalysis forcing
- Time step: 30 sec
- CPU requirements: ~300 CPU hr / simulated day (Altix – 90 CPUs) or 750,000 CPU hours for 27 three-month seasons.
- Typically Aug 1 – Oct 31 simulations (+ 3-day spin-up)

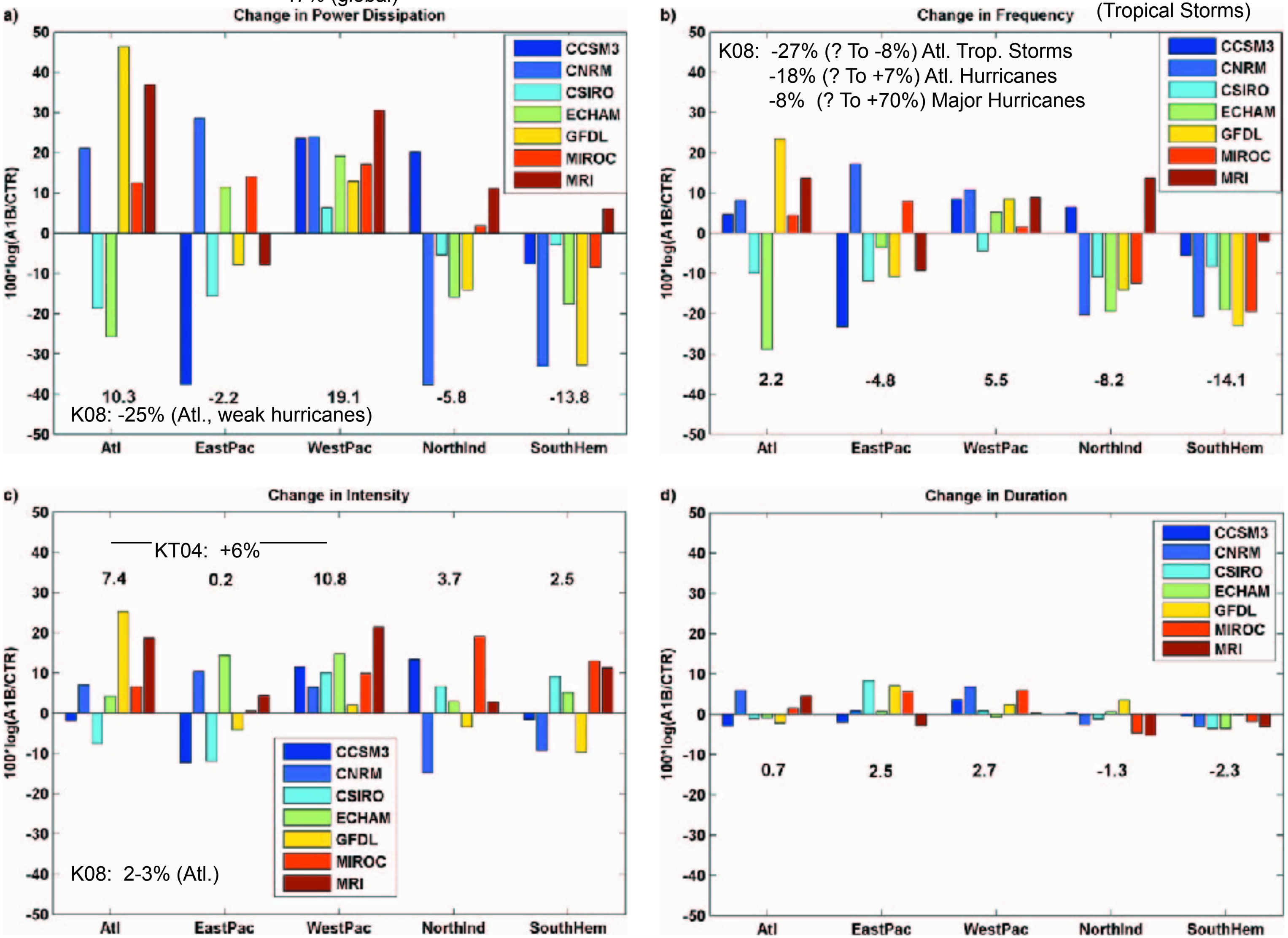
Fractional change of hurricane frequency – indiv. basins



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

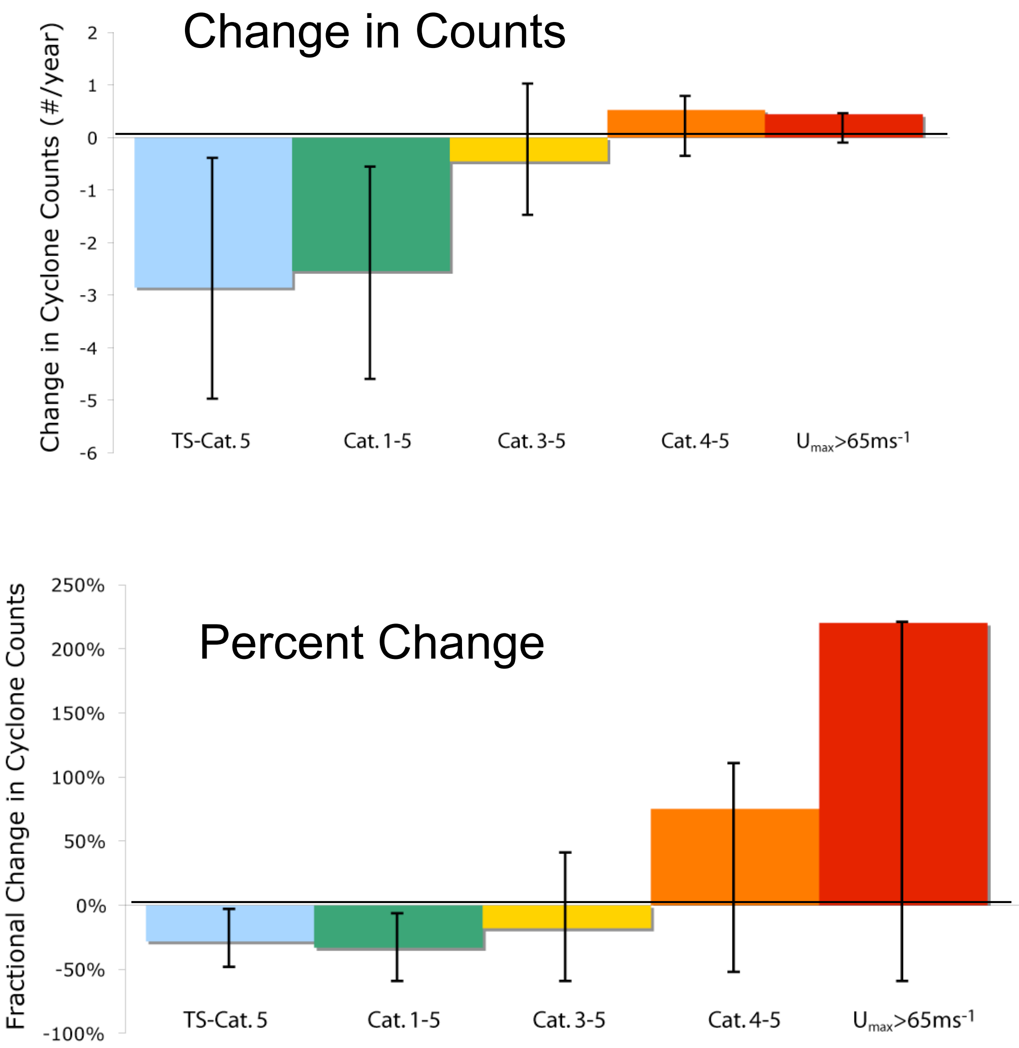
Alternative Downscaling Approach: Emanuel et al. (2008)

Emanuel "Obs." Last 25 yr: +250% (Atl.)
+47% (global)



…with some selected rough comparisons to other modeling studies

The GFDL hurricane model projects a large fractional increase in the occurrence of very intense Atlantic hurricanes in a warmer climate.



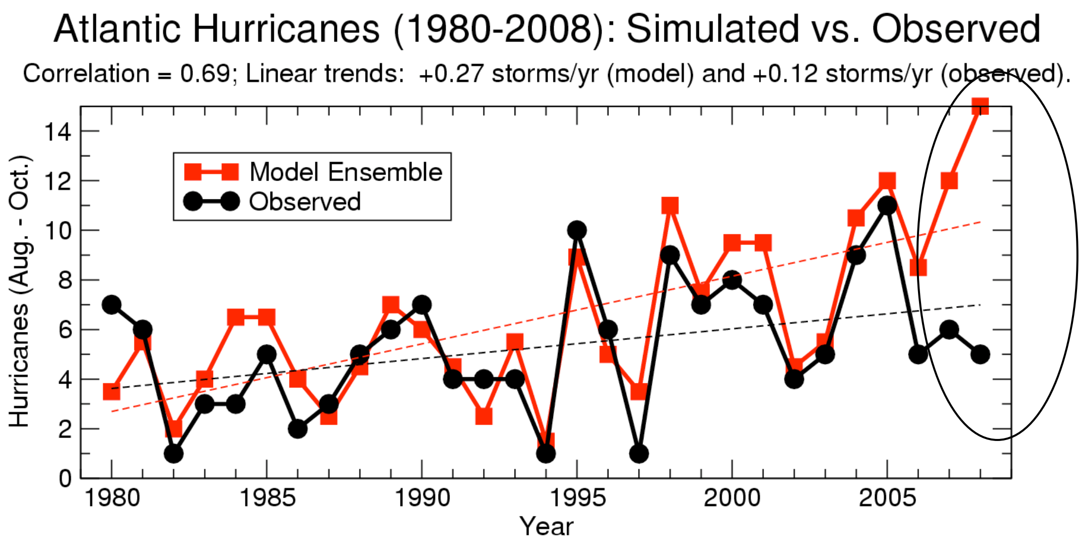
- All cases are downscaled from the Zetac regional model into the GFDL hurricane model, which can simulate hurricanes up to category 5 intensity.

- Colored bars show changes for 18 CMIP3 model ensemble; whiskers show range of changes across 4 individual CMIP models and the ensemble.

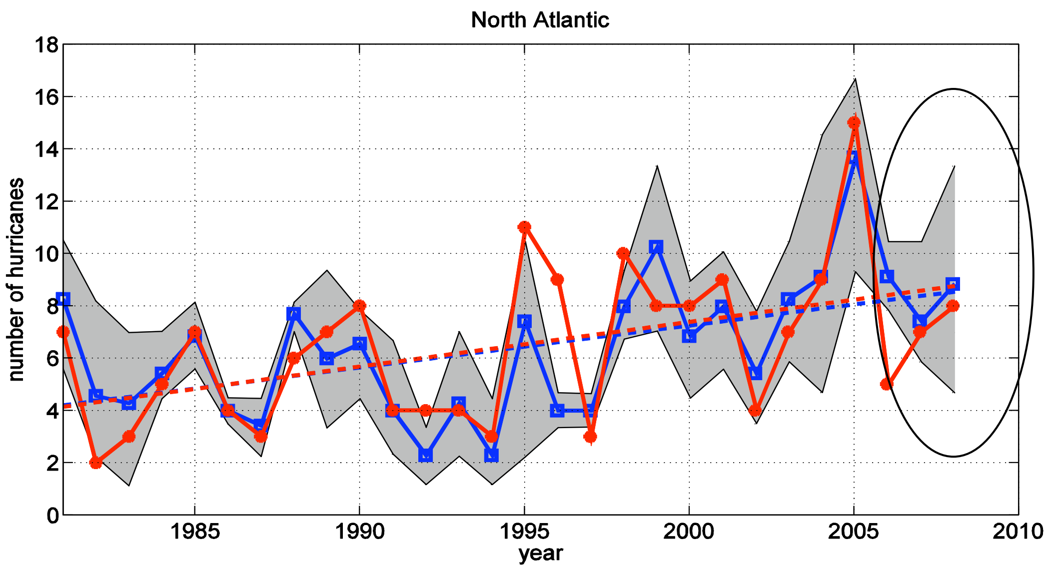
Source: Bender et al., submitted, 2009

Future Work:

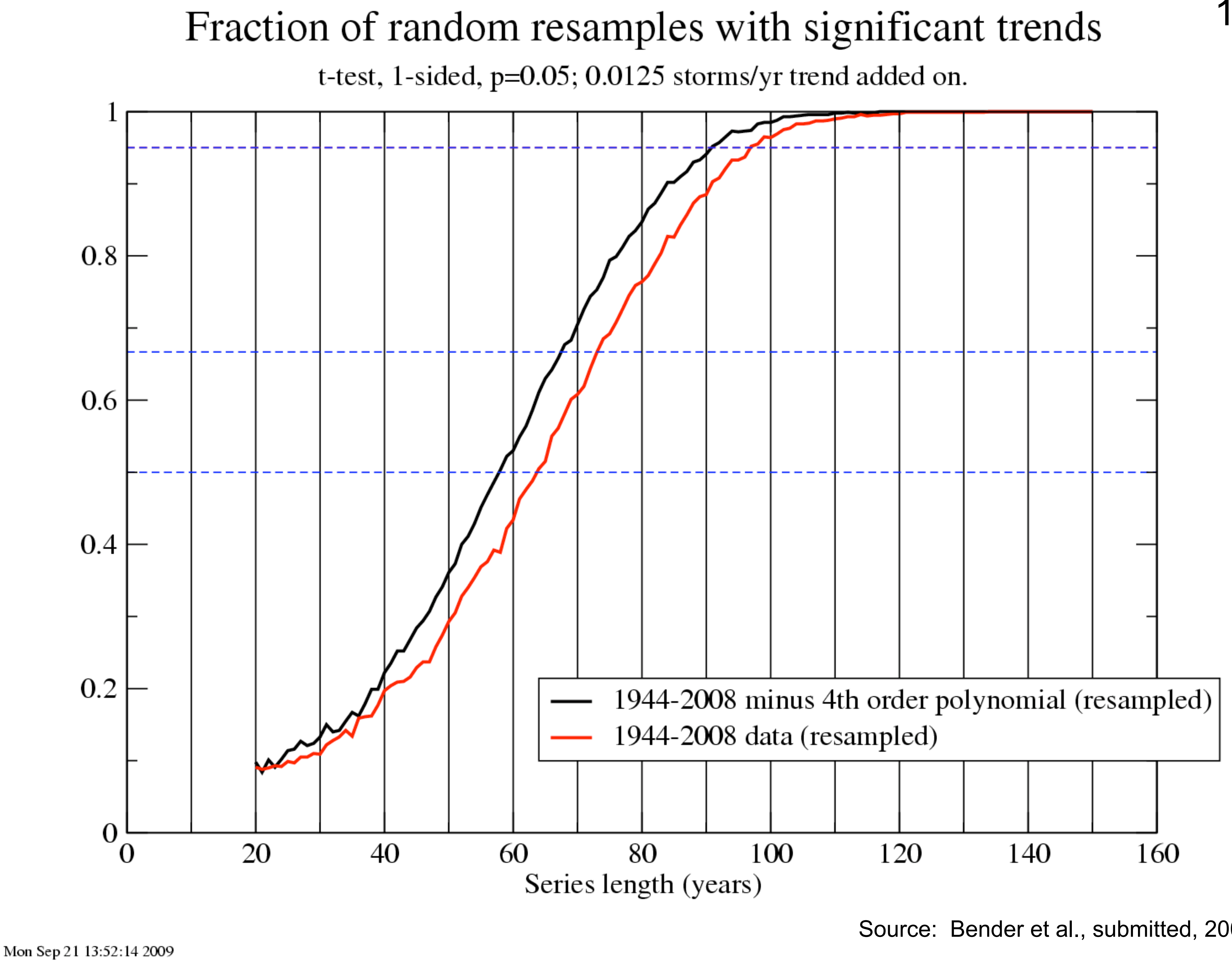
Extension of Atlantic runs through 2007-2008 reveals increasingly unrealistic trend in Zetac model: Possible source: NCEP Reanalysis



Zetac Regional Model (SST + Reanalysis)



HIRAM 50km global model (SST only)

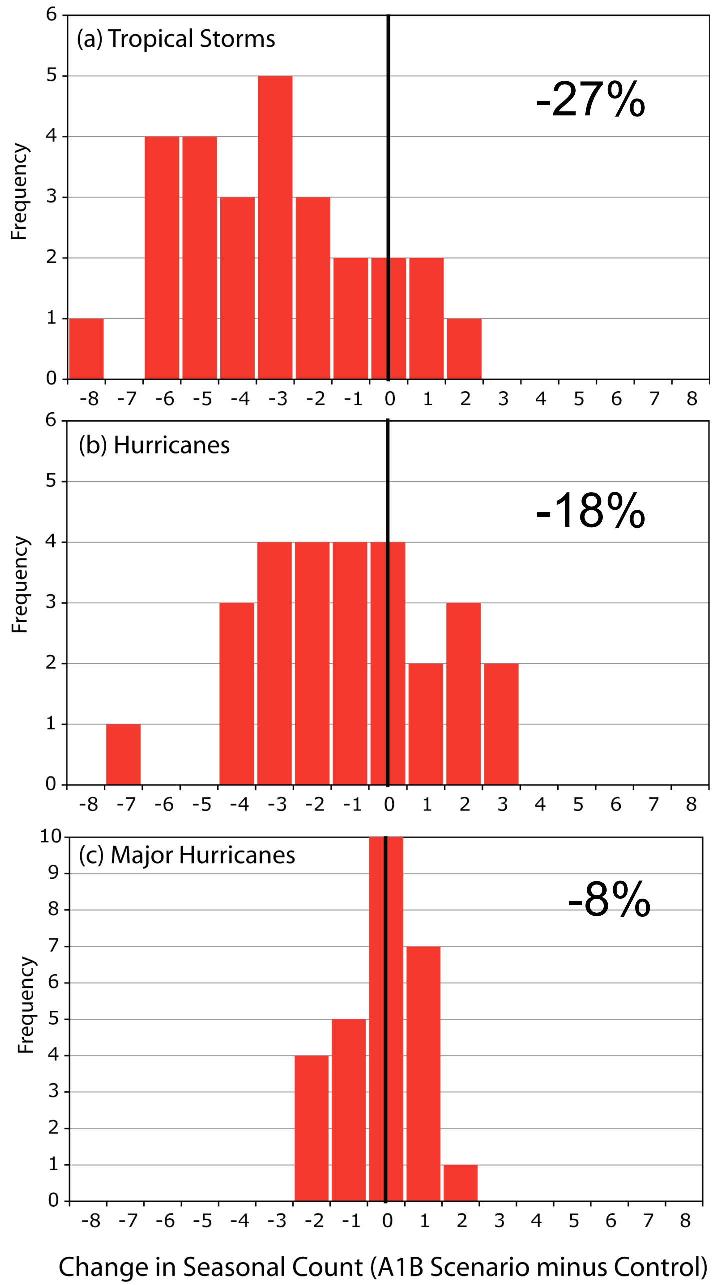


Source: Bender et al., submitted, 2009.

Conclusions:

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

1. **Atlantic tropical storm and hurricane counts--after adjustment for estimated missing storms--do not show significant increasing trends since the late 1800s.**
2. **The main contributors to positive tropical storm trends are: i) storms far from US landfall regions (US landfalls have not increased) and/or ii) storms of relatively brief recorded duration (e.g., < 2 days).**
3. **Latest model projection: cat 4-5 Atlantic hurricanes may increase by 9%/decade (A1B scenario; 18-model ensemble) with also 3 of 4 individual models tested so far showing an increase. However, this change may not be detectable for many decades due to high noise levels.**
4. **Some evidence for increasing intensities of strongest observed storms (particularly in Atlantic), but the short records (26 yr) and climate model limitations (e.g., indirect aerosols) preclude a confident attribution of different influencing factors at this time.**
5. **Caveats: Assumptions in ‘missing storm’ estimates need further examination; remaining data and modeling uncertainties.**



Projected changes in Atlantic hurricane/tropical storm numbers:

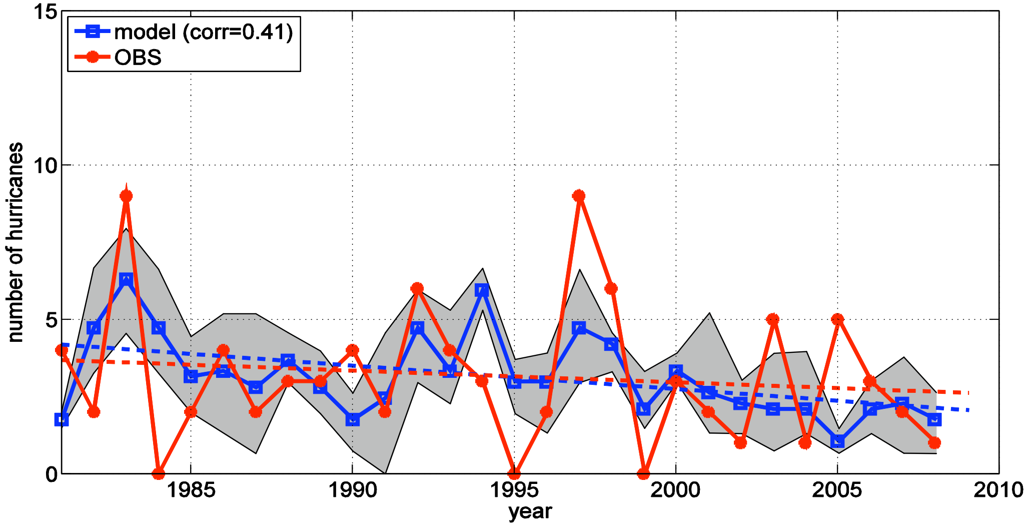
Late 21st century; Zetac regional model downscaling of CMIP3 multi-model ensemble climate change signal.

Note: U.S. Landfalling hurricanes: -30%

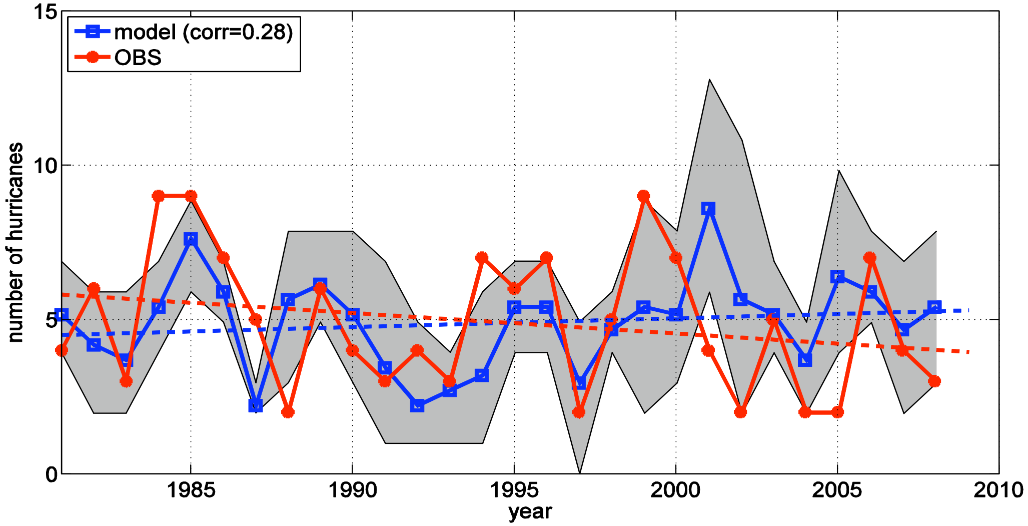
What about even stronger storms??

Source: Knutson et al., *2008*, *Nature Geoscience*.

Simulated tropical cyclone (>33 m/s) counts are better correlated with observed counts in the eastern part of the SW Pac basin the Australia region.

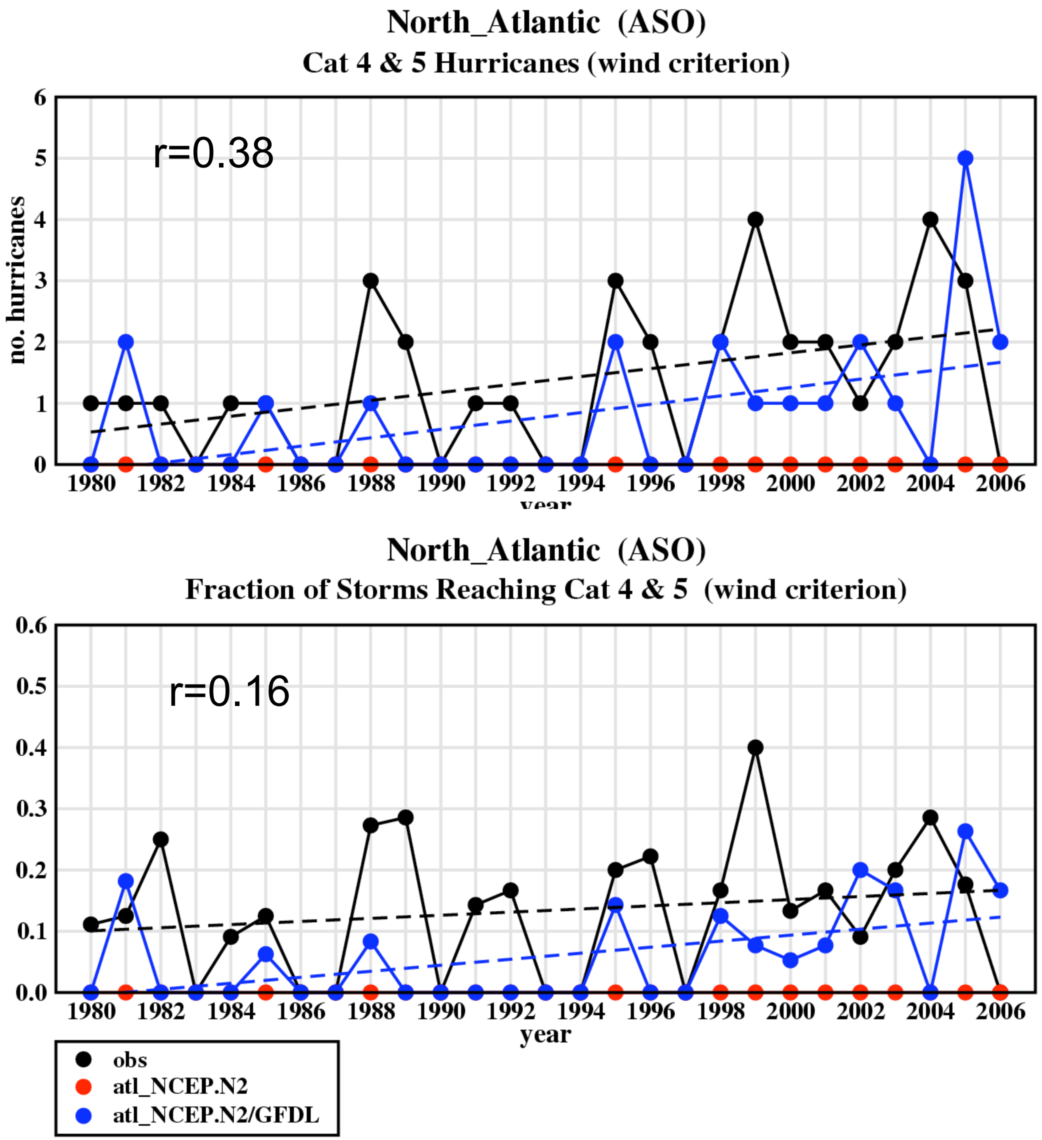


SW Pacific Basin
(East of 168E)
r = 0.41



Australia Region
(105E-168E)
r=0.28

Control Run: Skill in simulating Cat 4-5 numbers?



Unlike Zetac,
The GFDL hurricane model downscaling has some hindcast skill at simulating interannual variations of Cat 4-5 hurricane counts (with low bias overall).

…although this 'skill' arises mainly from the total storm count, not an ability to hindcast the fraction of storms achieving Cat 4-5 each year…

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