Have Humans Affected Atlantic Hurricane Climate?

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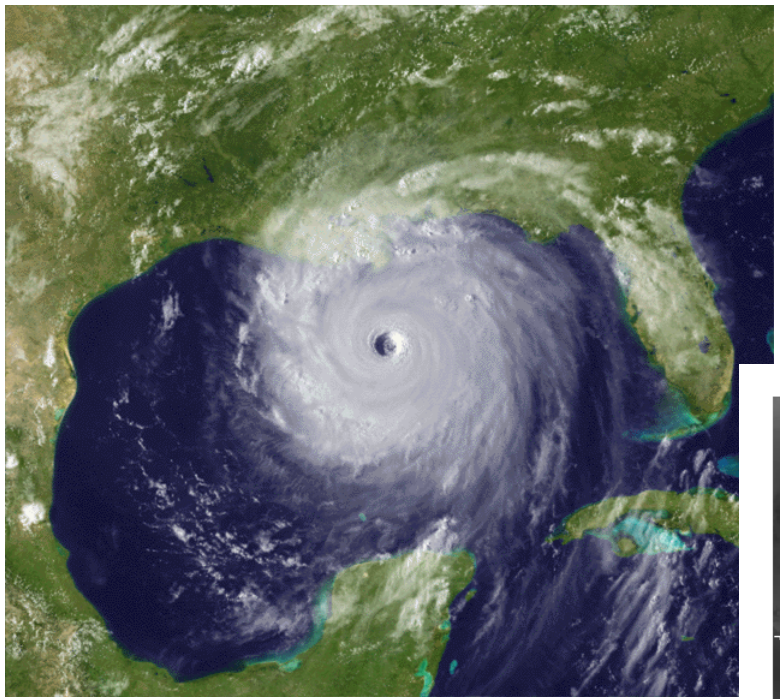
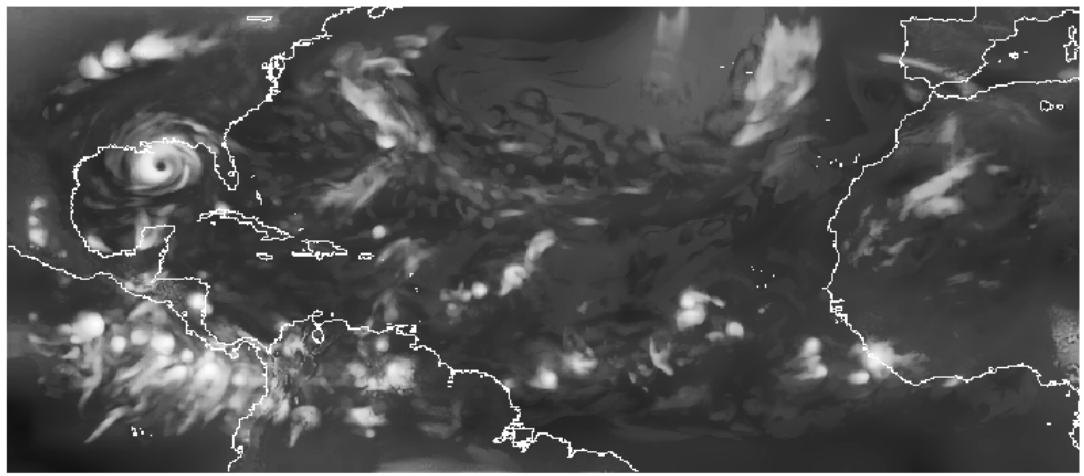


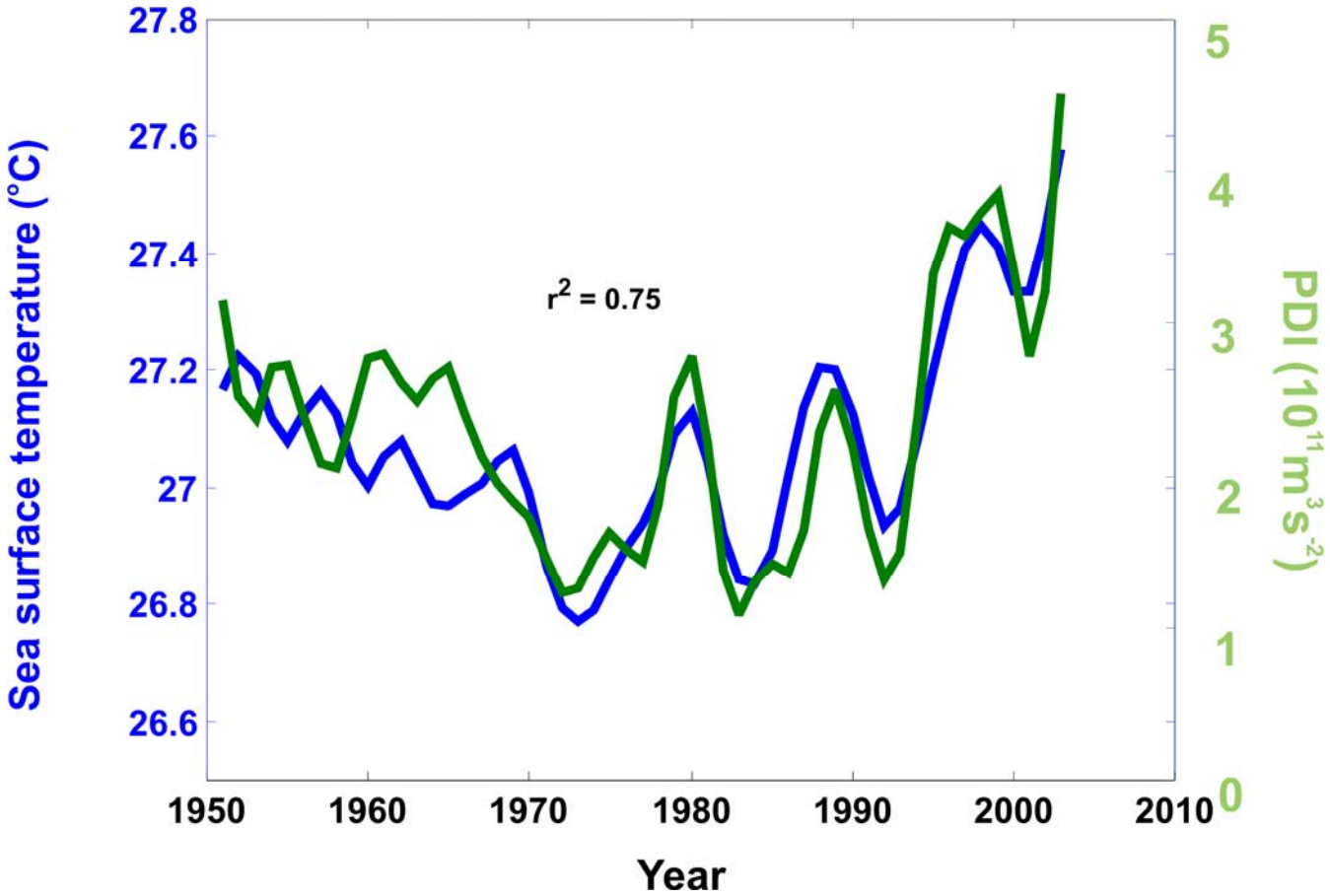
Hurricane Katrina, Aug. 2005



GFDL model simulation of Atlantic hurricane activity

MOTIVATION:

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…



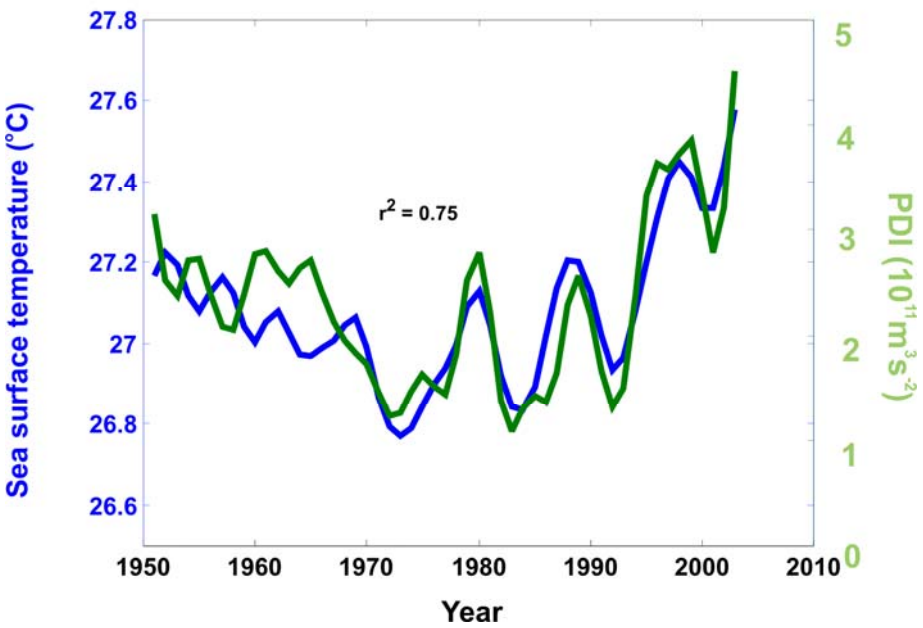
PDI is proportional to the time integral of the cube of the surface wind speeds accumulated across all storms over their entire life cycles.

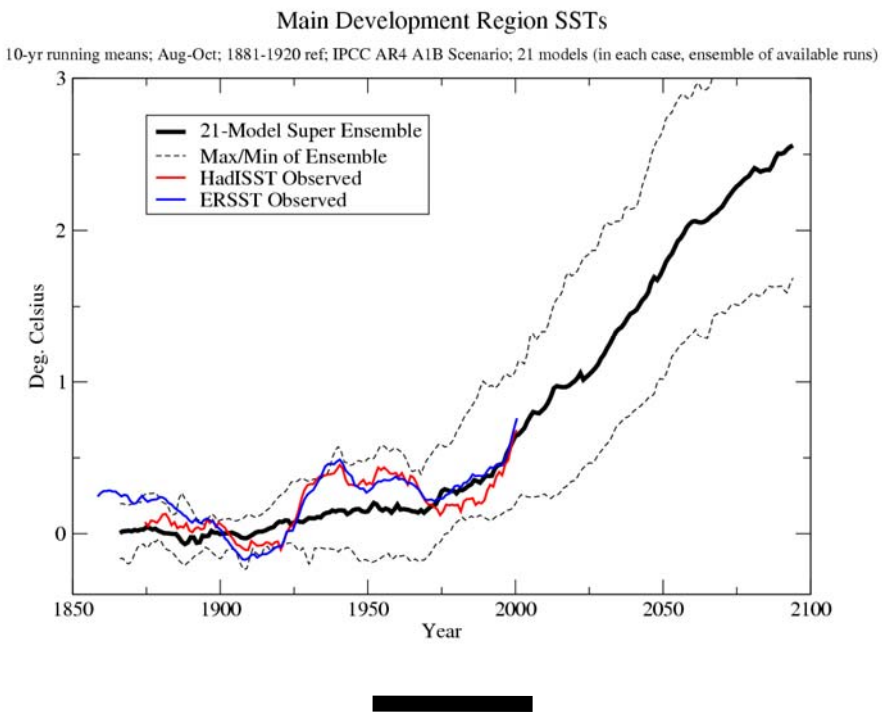
Source: Kerry Emanuel, J. Climate (accepted).

MOTIVATION:

What are the implications of pronounced future warming for Atlantic Power Dissipation Index (PDI)?

Power Dissipation Index vs SST





METHODOLOGY:

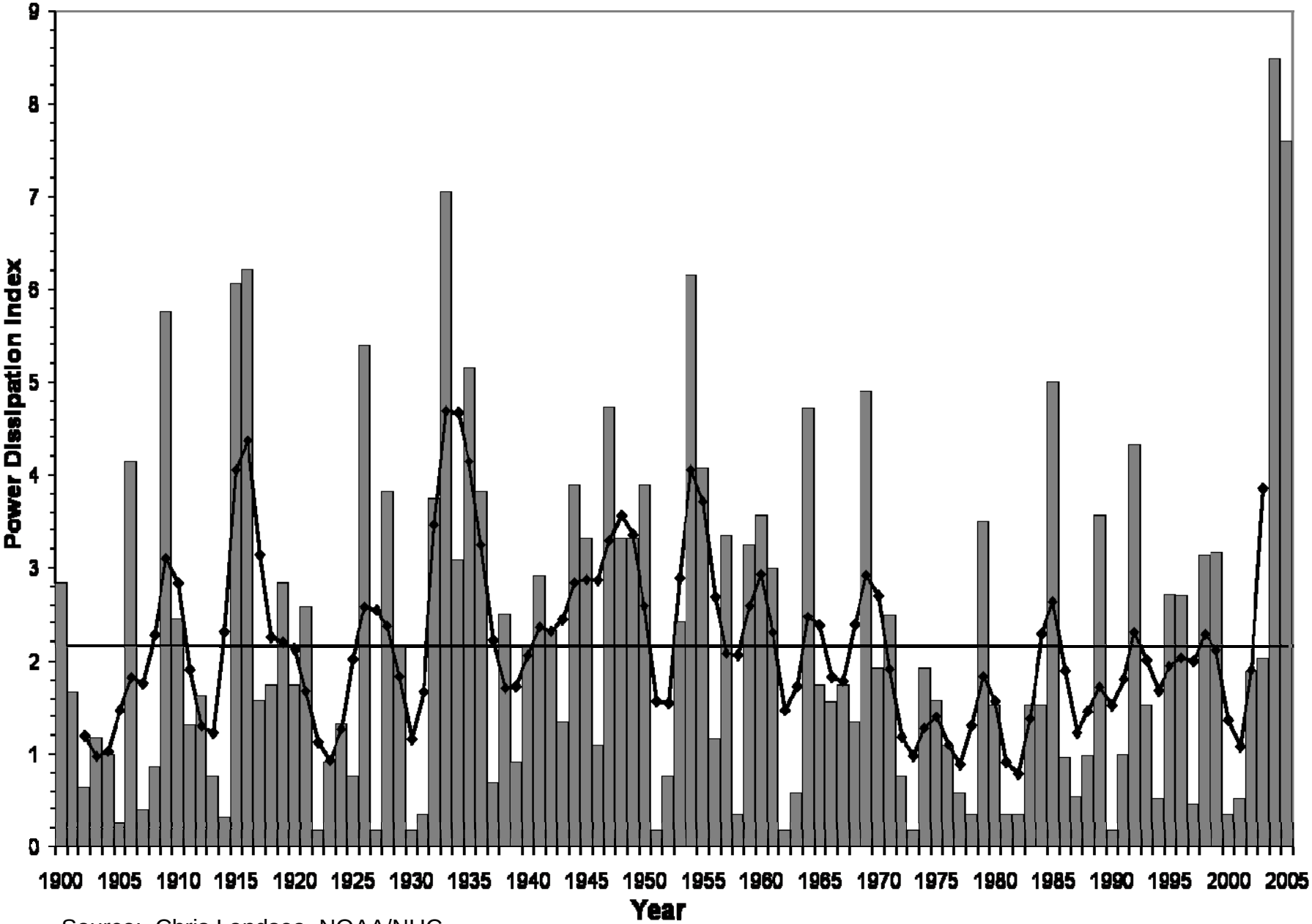
Attribution of hurricane changes to human-induced climate change?

- 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

Summary of Conclusions

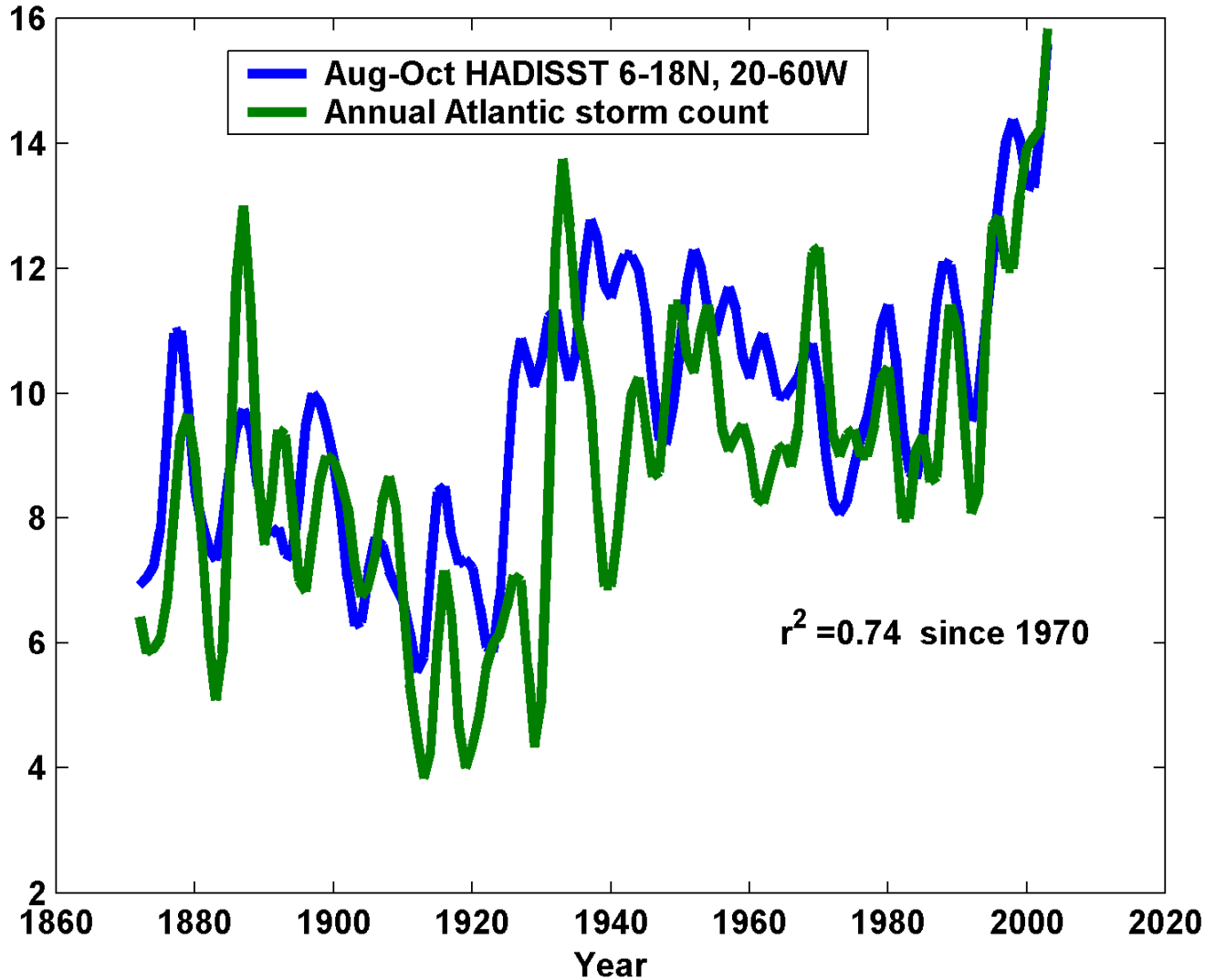
- Some observational studies ***suggest there has already been a substantial human influence on hurricanes*** …while other studies do not.
- A new Atlantic regional model projects ***fewer hurricanes*** during the next century, although with ***increasing intensities and rainfall rates for hurricanes that do occur***.
- Based on the current state of models and ongoing data concerns, ***it is not appropriate at this time to make a likelihood statement attributing past increases in hurricane activity to human-caused climate warming***.

A measure of annual U.S. landfalling hurricane activity shows no clear long-term trend since 1900…



Source: Chris Landsea, NOAA/NHC

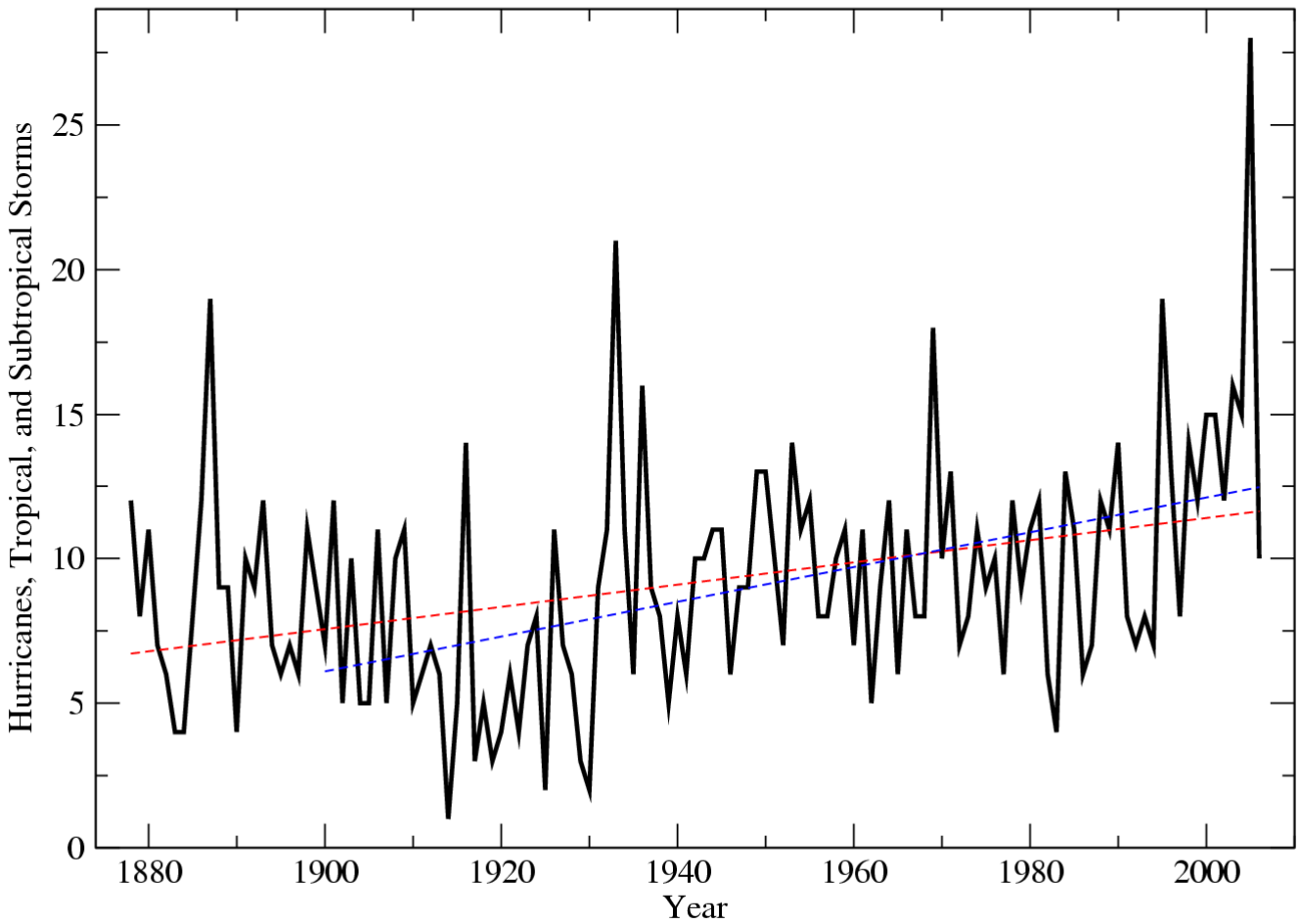
The frequency of recorded storms (low-pass filtered) in the Atlantic basin is well-correlated with tropical Atlantic SSTs



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

HURDAT Atlantic Storms: 1878-2006

Linear Trend: +3.84 storms/century (1878-2006); +6.01 storms/century (1900-2006)



Source: Vecchi and Knutson (in prep)

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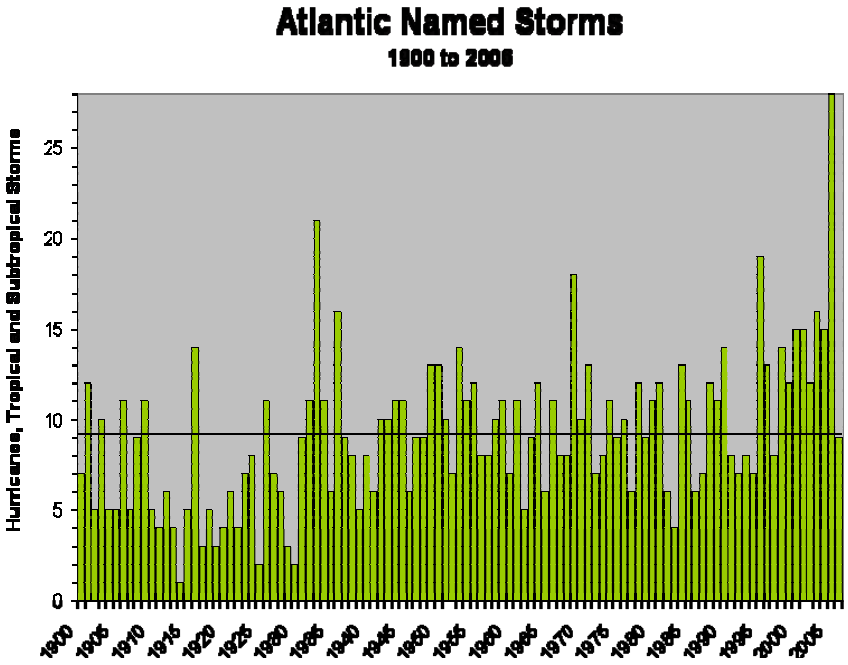
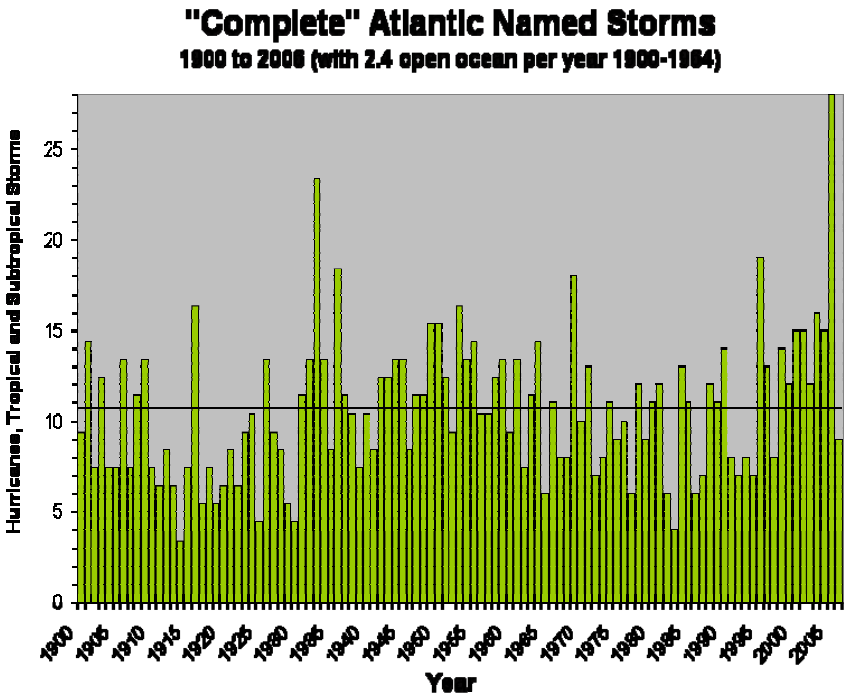
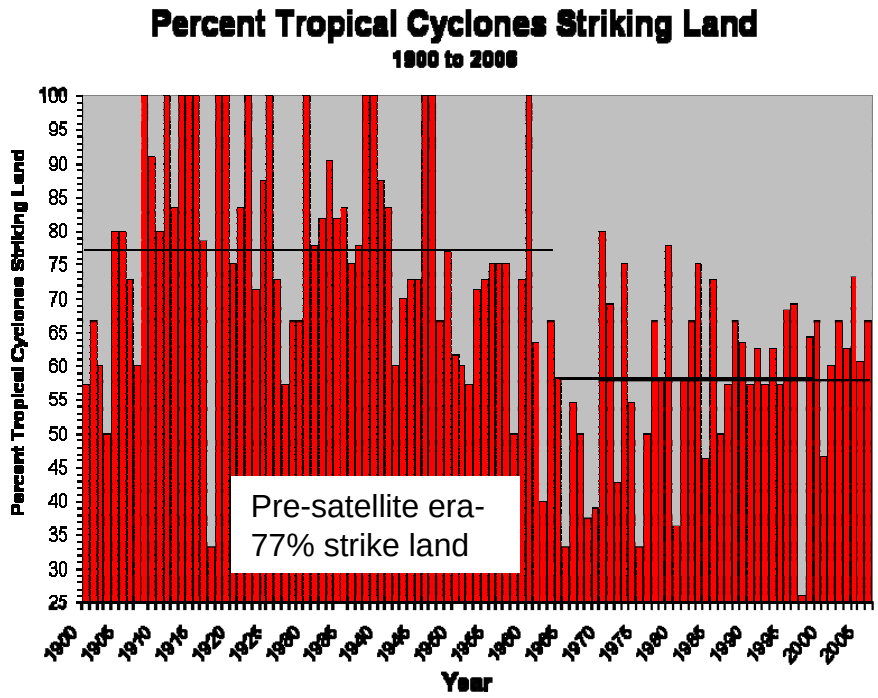
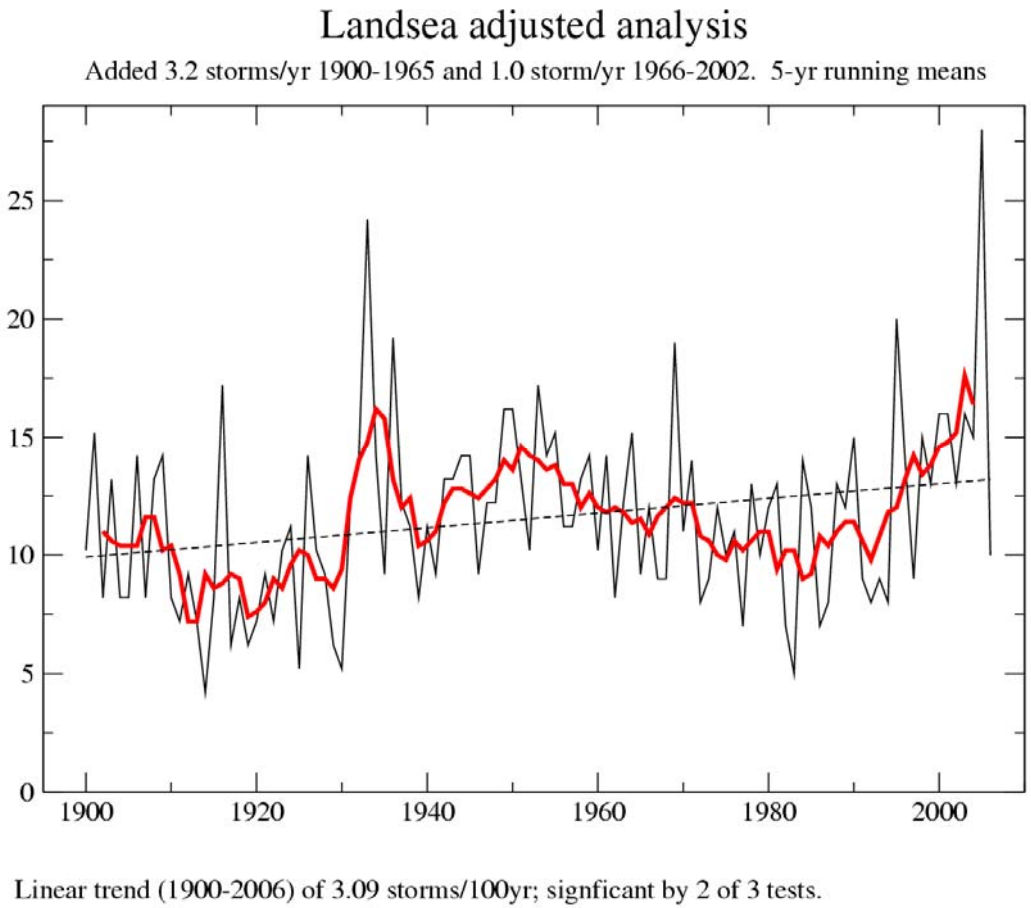
…but some storms may have been missed and not recorded in the database.







Source: Chris Landsea, NHC/NOAA (preliminary version of Landsea, *EOS* (2007))



Landsea: No significant trend from AMO warm phase to warm phase, or cold phase to cold phase.

Holland: Questions assumption of constant landfalling fraction. Multi-decadal variability of fraction??

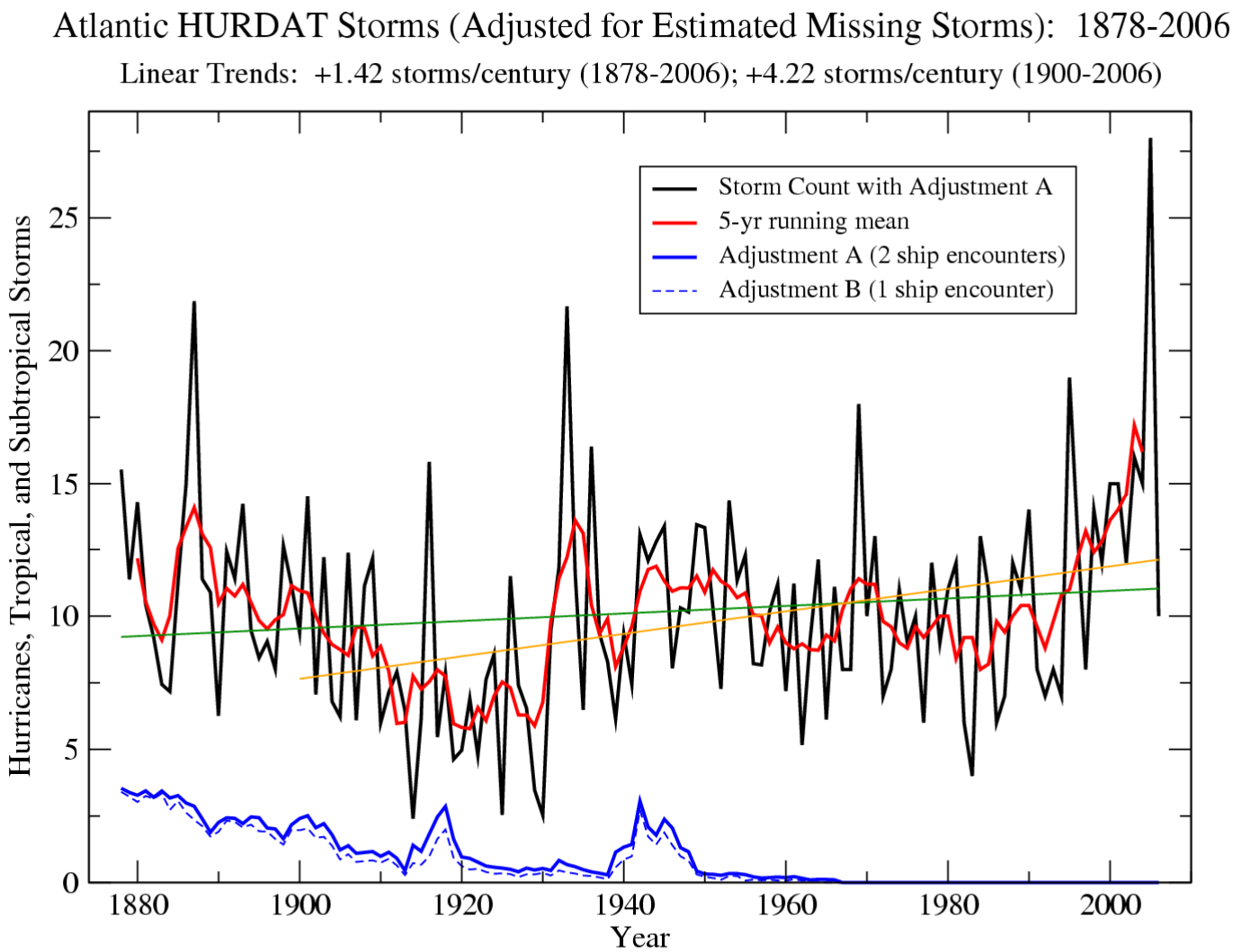
Sabatelli et al. (GRL, 2007). Climate indices as predictors, estimate 1.2 storms / yr were missed (1870-1943).

Source: Adapted from Landsea (2007) *EOS*.

Reconstructing past tropical cyclone counts

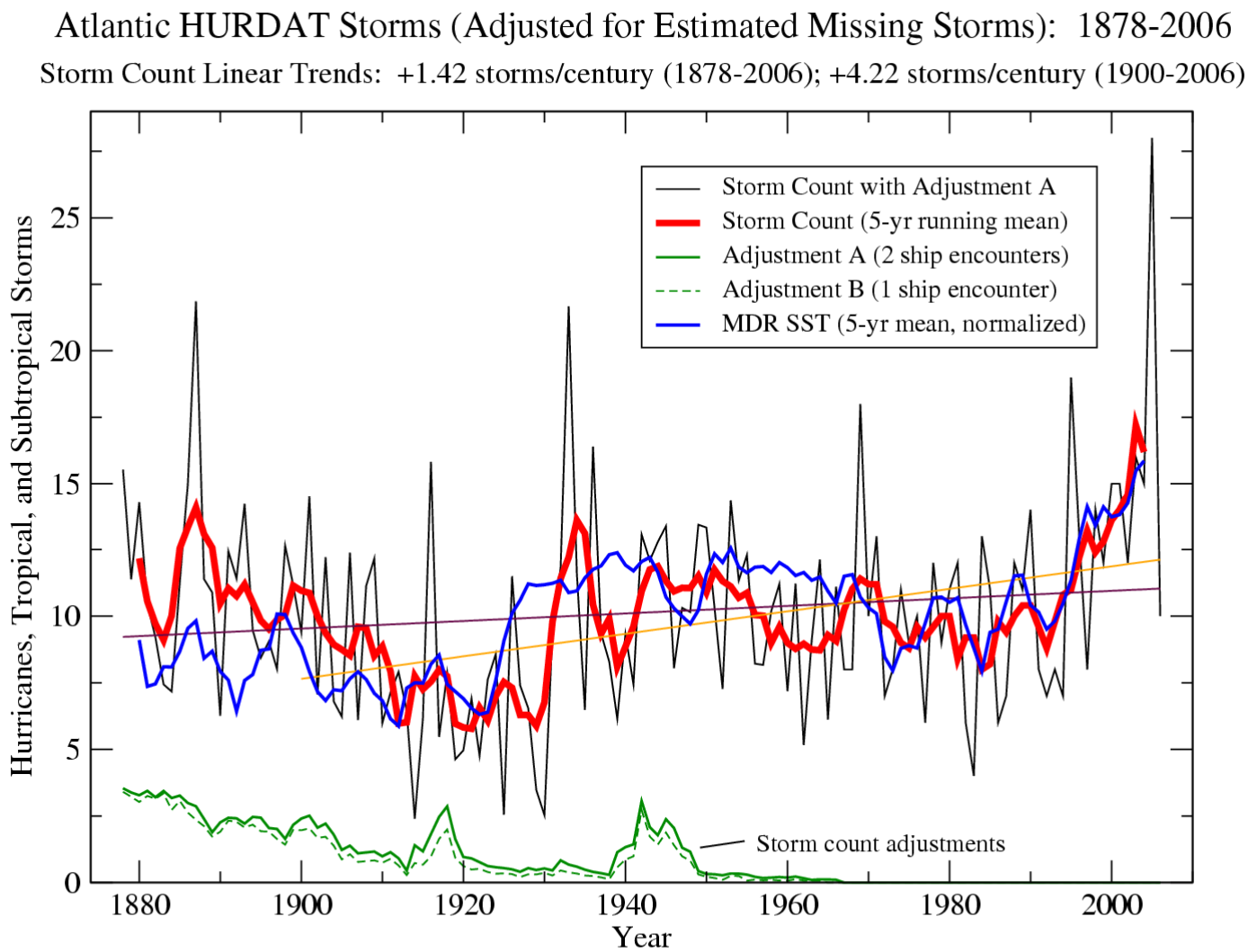
- Satellite-era (1965-2006) storm tracks assumed perfect.
- Apply satellite-era storm tracks to documented ship tracks (ICOADS).
- Storm detected if 2 ship observations within radius of tropical storm force winds (17 m/s). First detection must occur equatorward of 40N. Monte Carlo simulation, varying 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 to further test with additional tracks. (First will look for evidence of storms in “new” ship data.)

Source: Vecchi and Knutson (2007) J. Climate, accepted.



Trend from 1878-2006: Not significant (p=0.05, 2-sided tests)
Trend from 1900-2006: Significant " "

Source: Vecchi and Knutson (2007)



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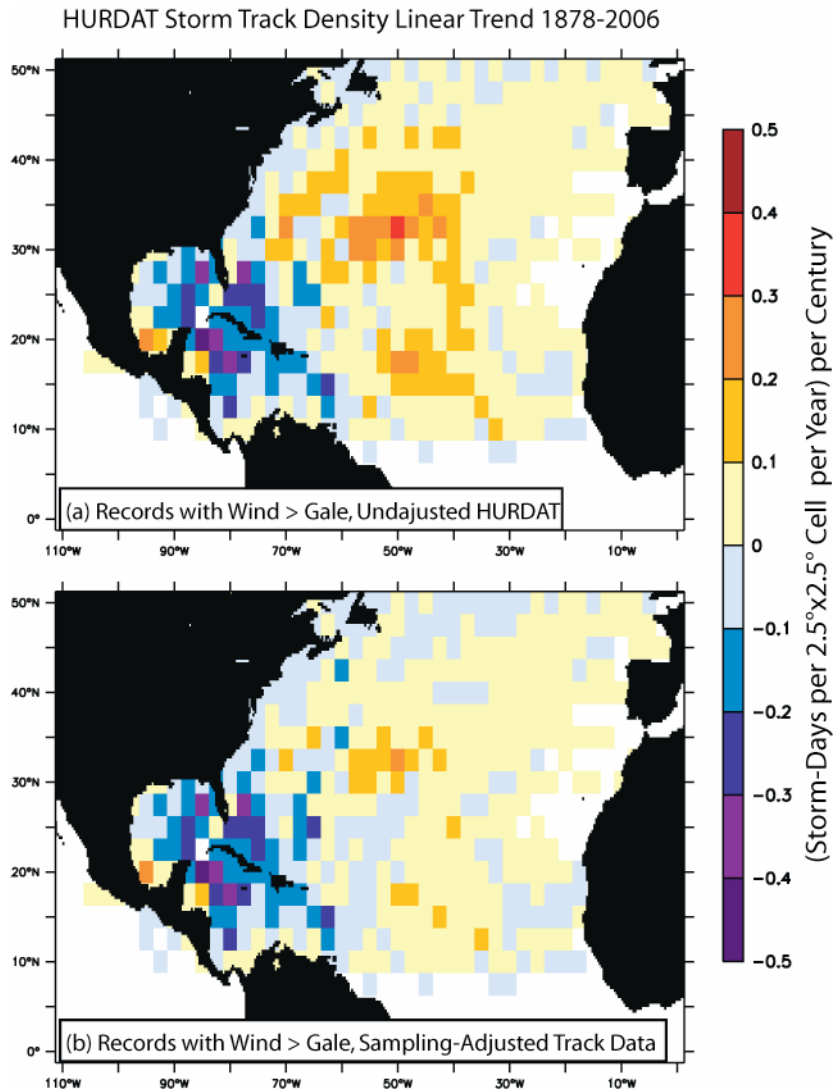
Storm Count Trend from 1878-2006: Not significant (p=0.05, 2-sided tests)
Storm Count Trend from 1900-2006: Significant " "

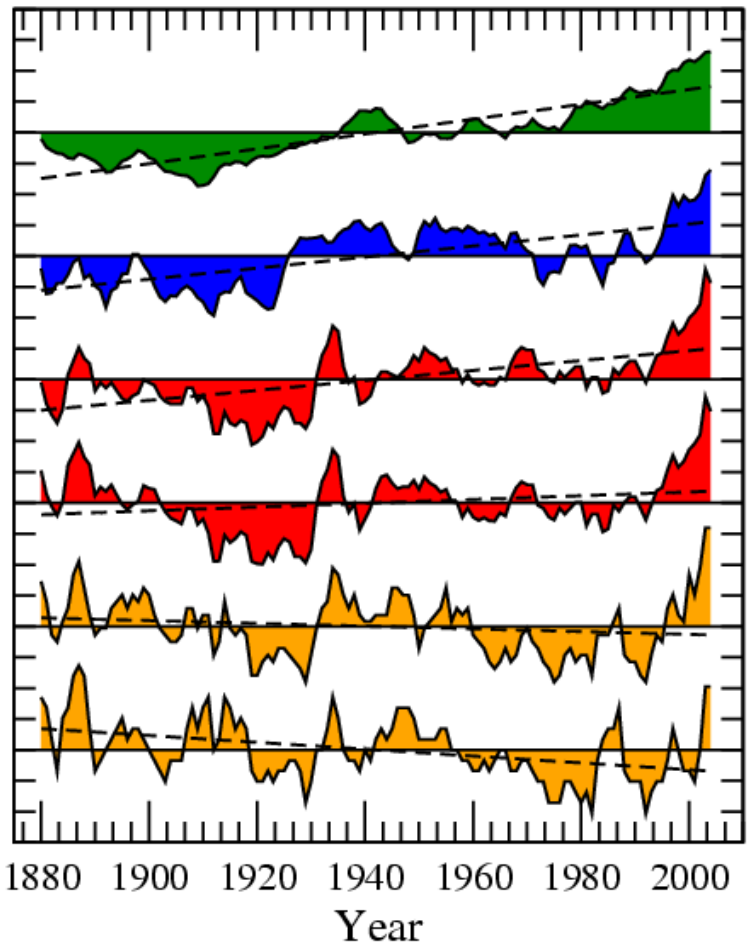
Source: Vecchi and Knutson (2007)

Occurrence Trends: Decrease in Gulf of Mexico and Caribbean Increase (slight) in open Atlantic



Source: Vecchi and Knutson (2007), preliminary version

A comparison of several climate change metrics:



Global Mean Temperature

Tropical Atlantic Sea Surface Temperature

Atlantic Tropical Storm Counts (unadj.)

Atlantic Trop. Storm Counts (Vecchi/Knut. Adj.)

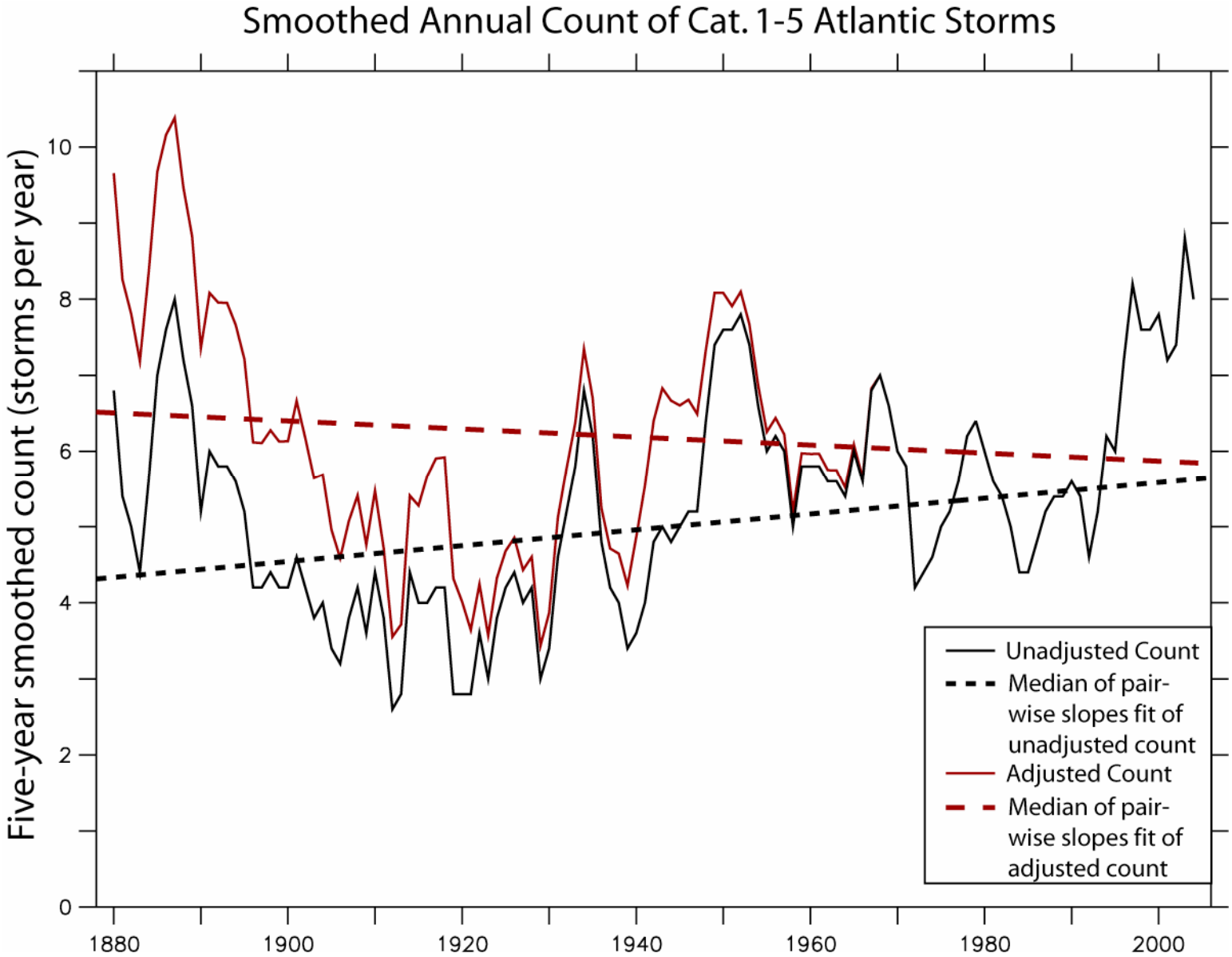
U.S. Landfalling Tropical Storms (unadj.)

U.S. Landfalling Hurricanes (unadj.)

Note: All time series are low-pass filtered (5-yr mean) and normalized to unit standard deviation (y-axis tic marks: 1 st. dev).

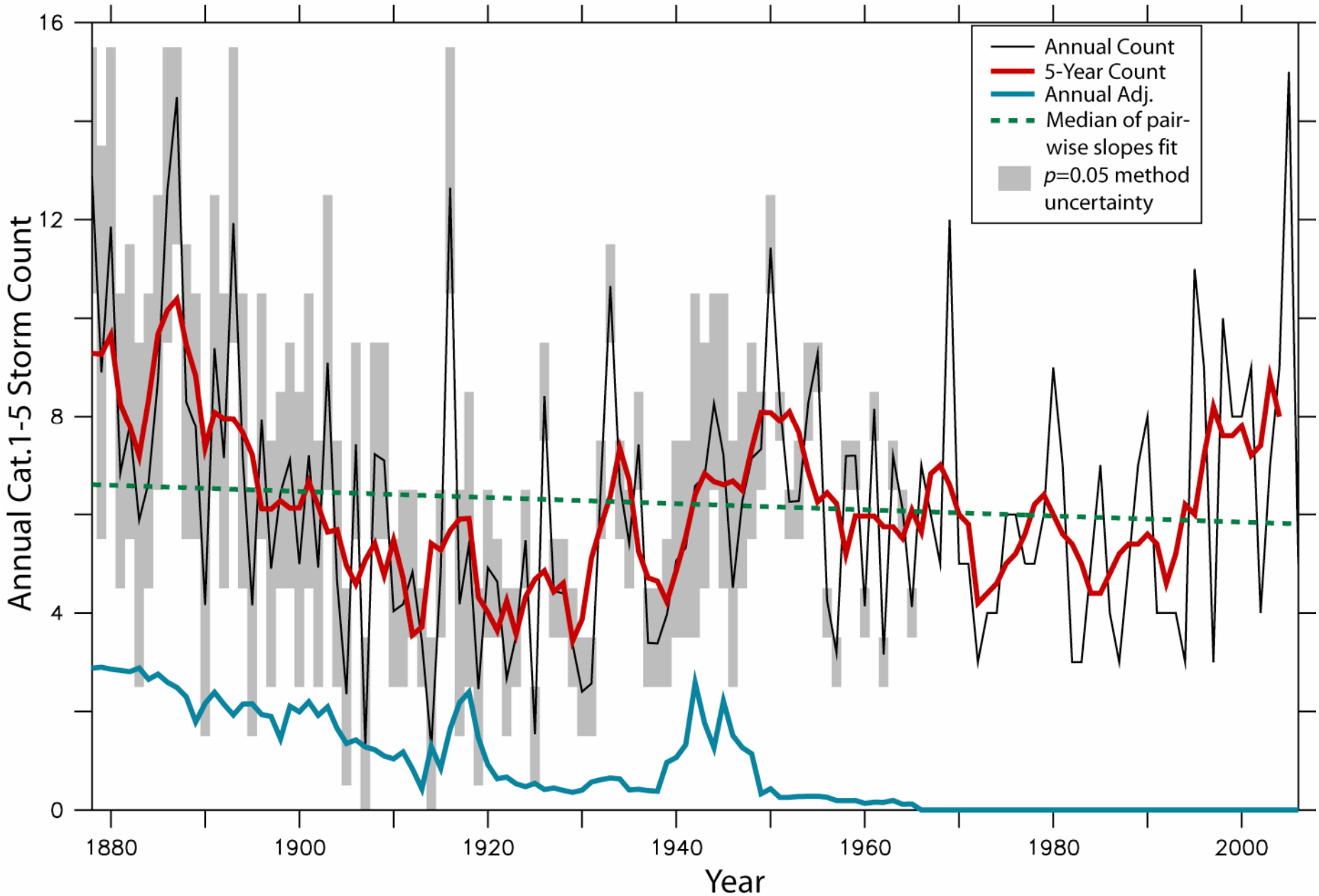
Source: Vecchi and Knutson (2007)

Application of the Vecchi/Knutson approach to Atlantic Hurricane Counts

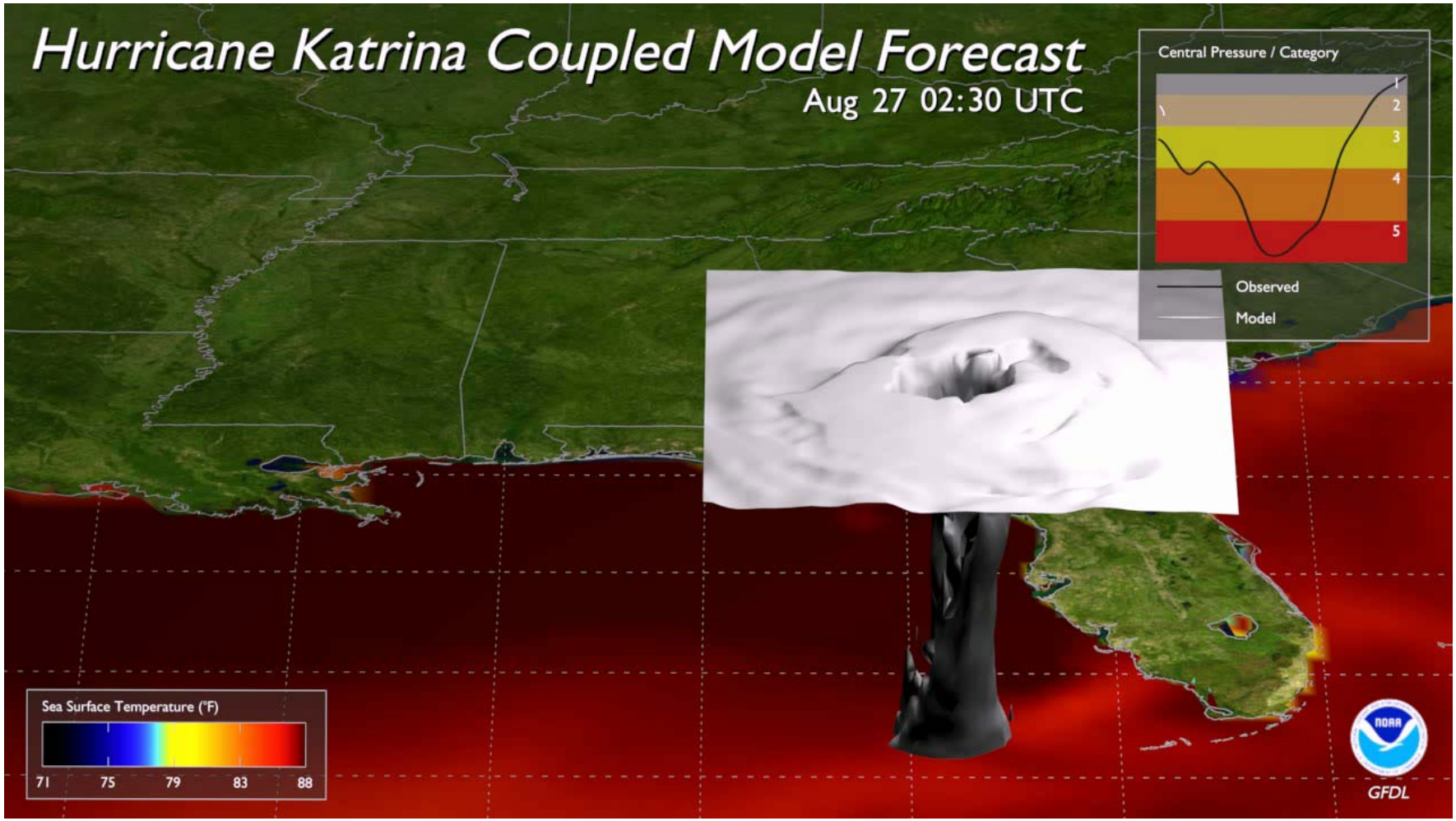


Source: G. Vecchi, personal communtication

Adjusted Annual Count of Hurricanes (Cat 1-5)



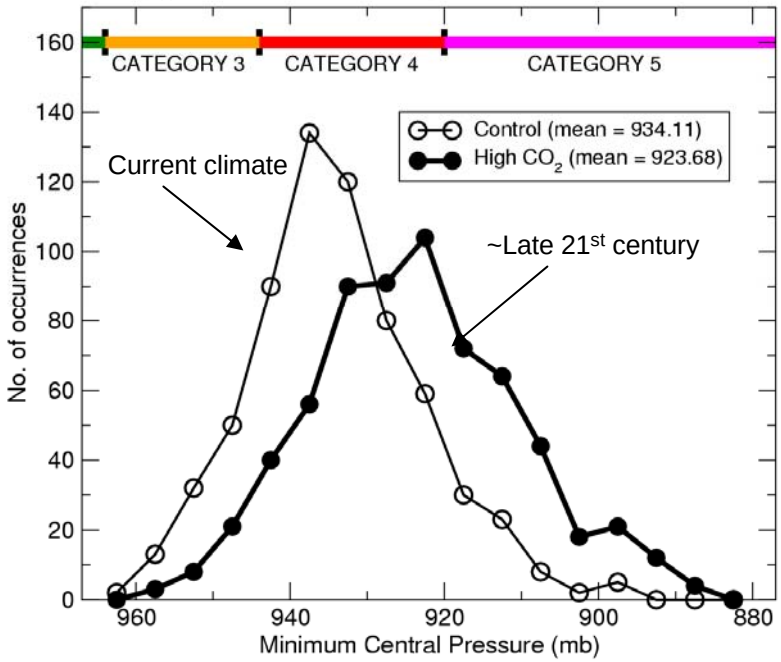
Source: G. Vecchi, personal communtication



Courtesy Morris Bender and Tim Marchok, NOAA/GFDL

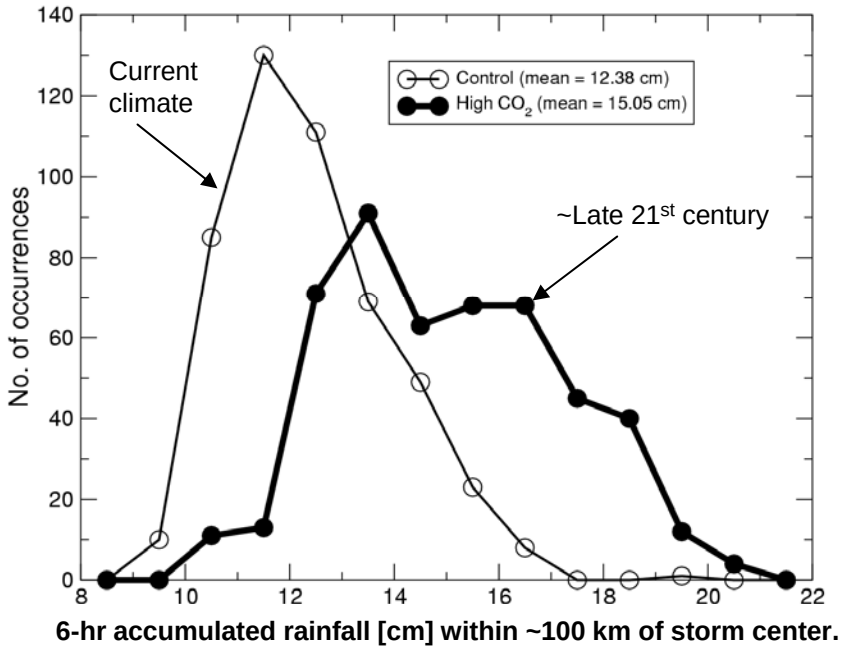
Hurricane models project increasing hurricane intensities and rainfall rates with climate warming ...

Hurricane Intensity



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

Hurricane Rainfall Rates

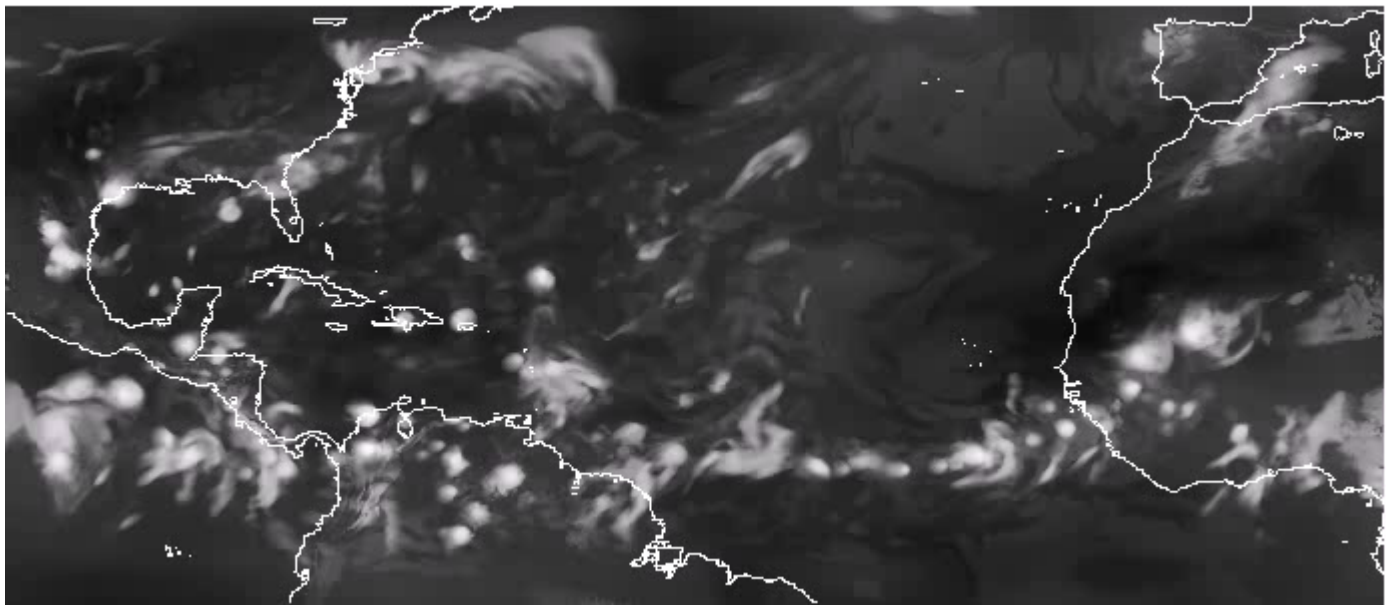


6-hr accumulated rainfall [cm] within ~100 km of storm center.

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

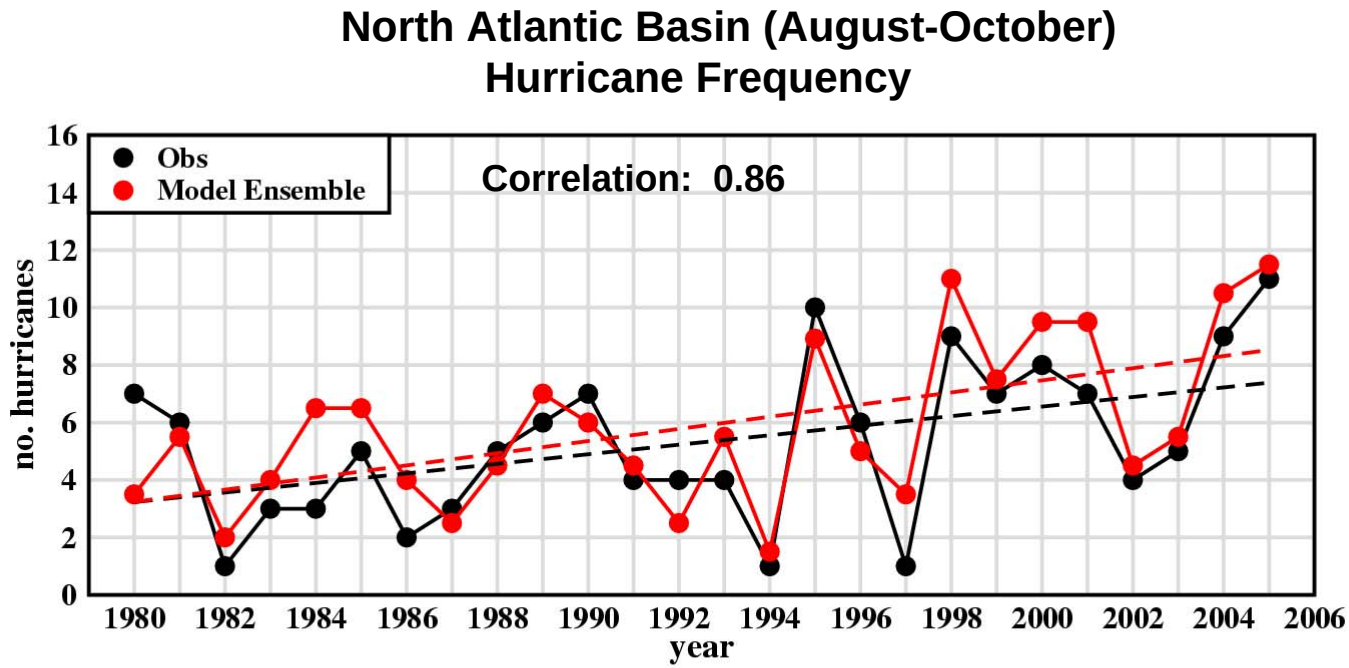
Sources: Knutson and Tuleya, *J. Climate*, 2004 (left); Knutson and Tuleya, 2007; accepted for publication, Cambridge Univ Press (right). See also Bengtsson et al. (*Tellus* 2007) and Oouchi et (*J. Meteor. Soc. Japan,* 2006).

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



- The model runs for entire hurricane seasons.
- The model generates its own sample of hurricanes during each season.
- These experiments push the limits of available computing resources.

The model captures both the increase in hurricane activity since the 1980s and the year-by-year fluctuations….

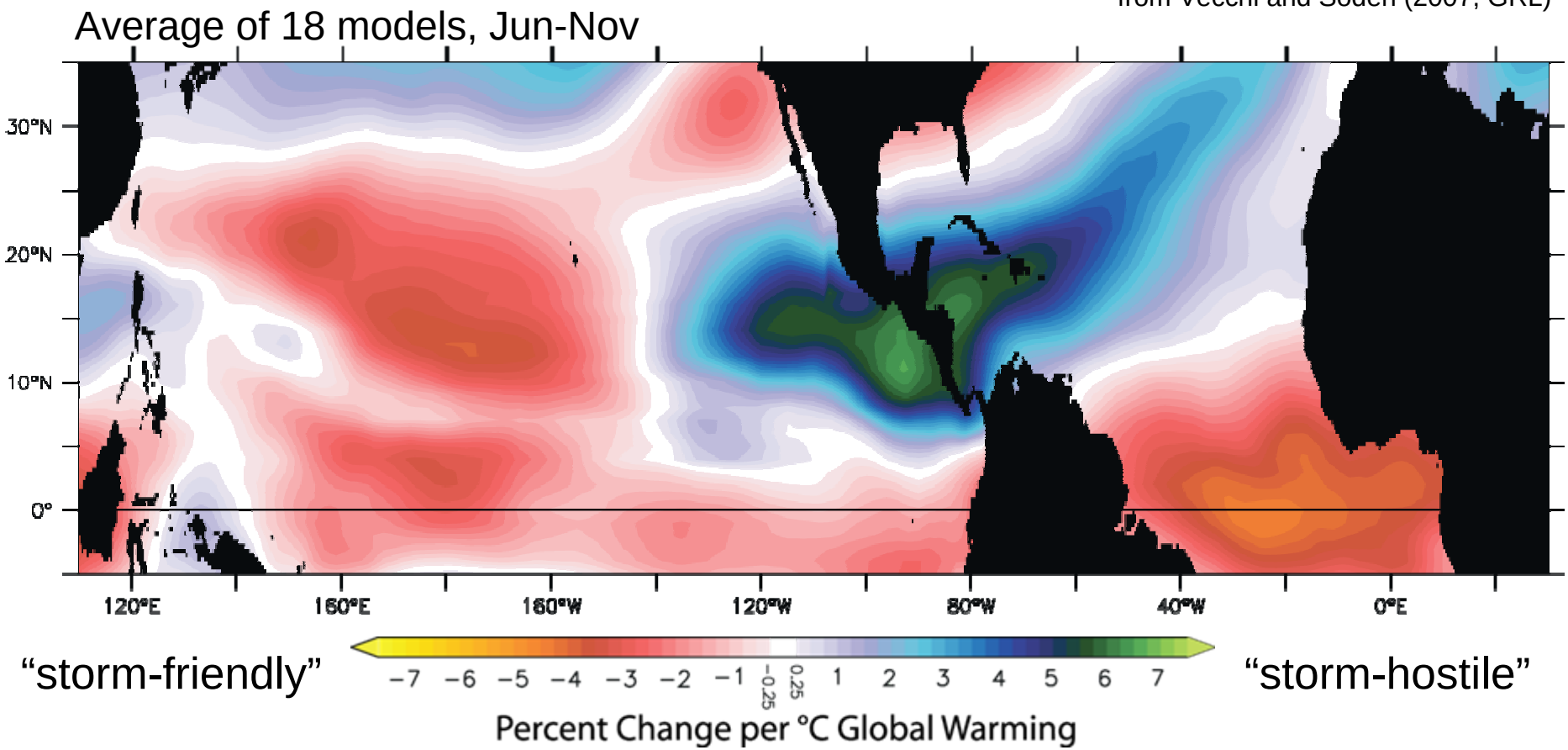


Source: Knutson et al. 2007 (BAMS)

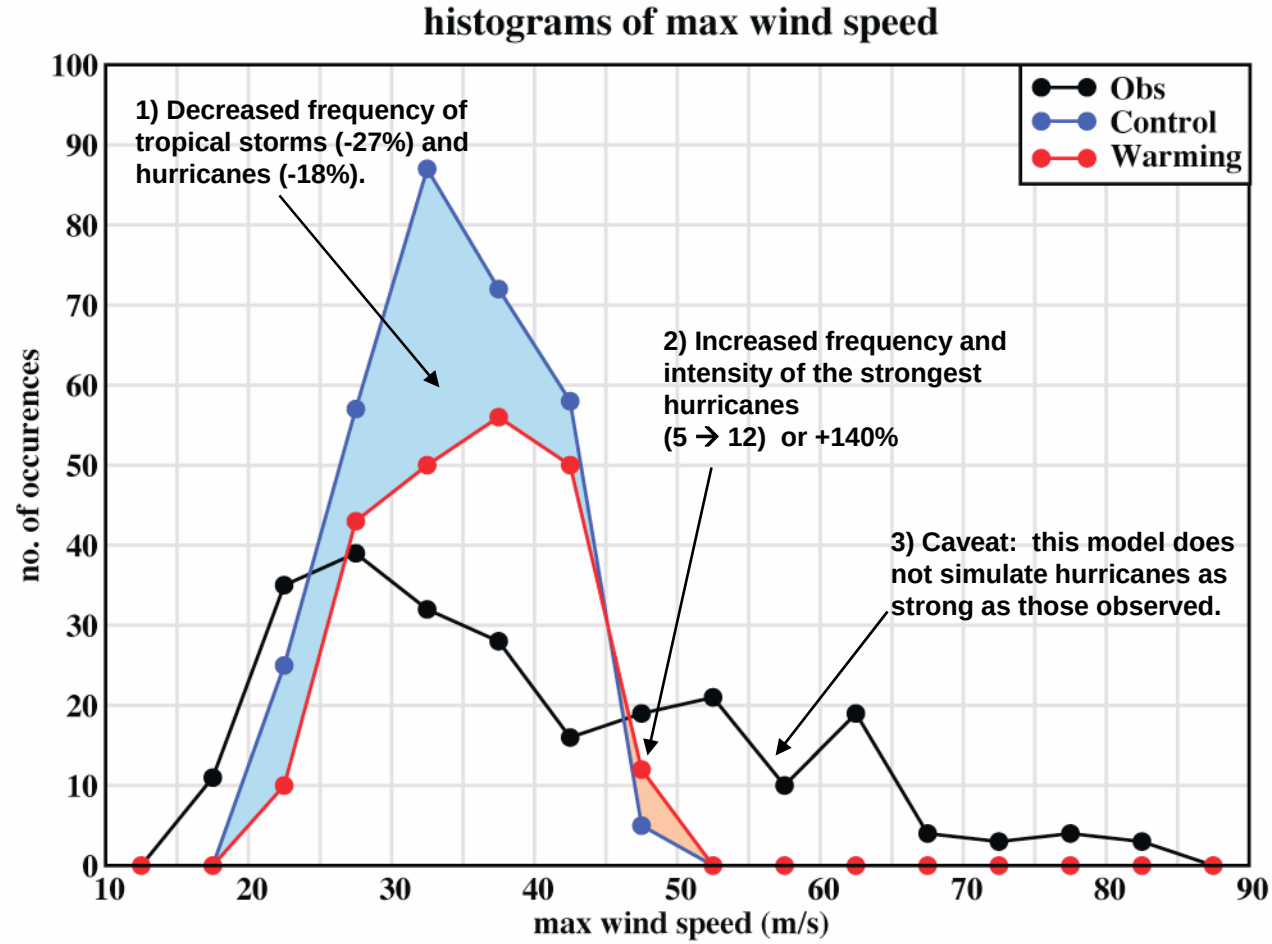
Note: Model uses large-scale interior nudging to NCEP Reanalysis

Late 21st Century projections: increased vertical wind shear may lead to fewer Atlantic hurricanes

from Vecchi and Soden (2007, GRL)

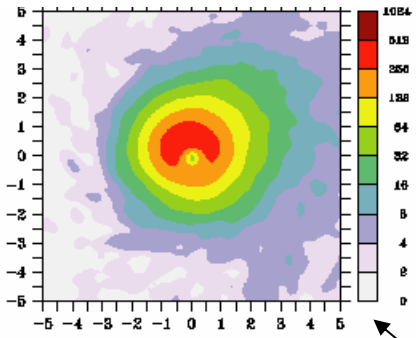


The model provides projections of Atlantic hurricane tropical storm *frequency* changes for late 21st century A1B warming scenario:

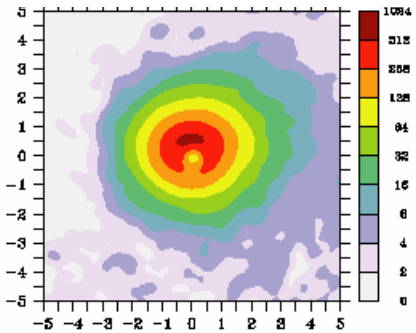


The new model simulates increased hurricane intensities and hurricane rainfall rates in a warmer climate…consistent with previous work…

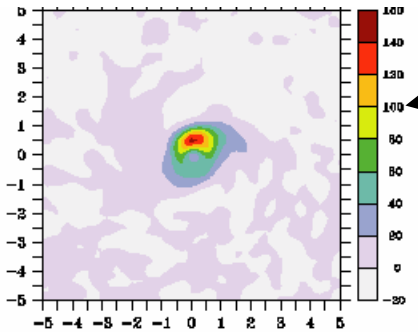
Present Climate



Warm Climate

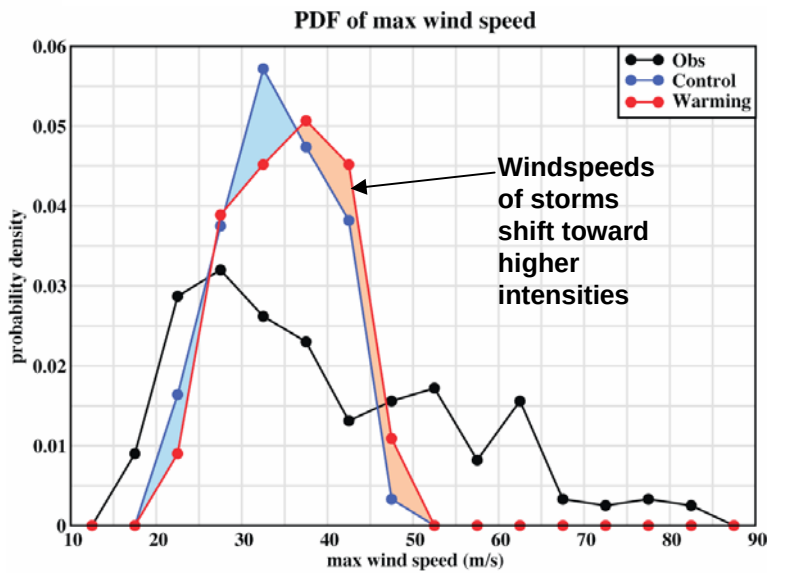


Warm Climate – Present Climate



Rainfall Rates
(mm/day)

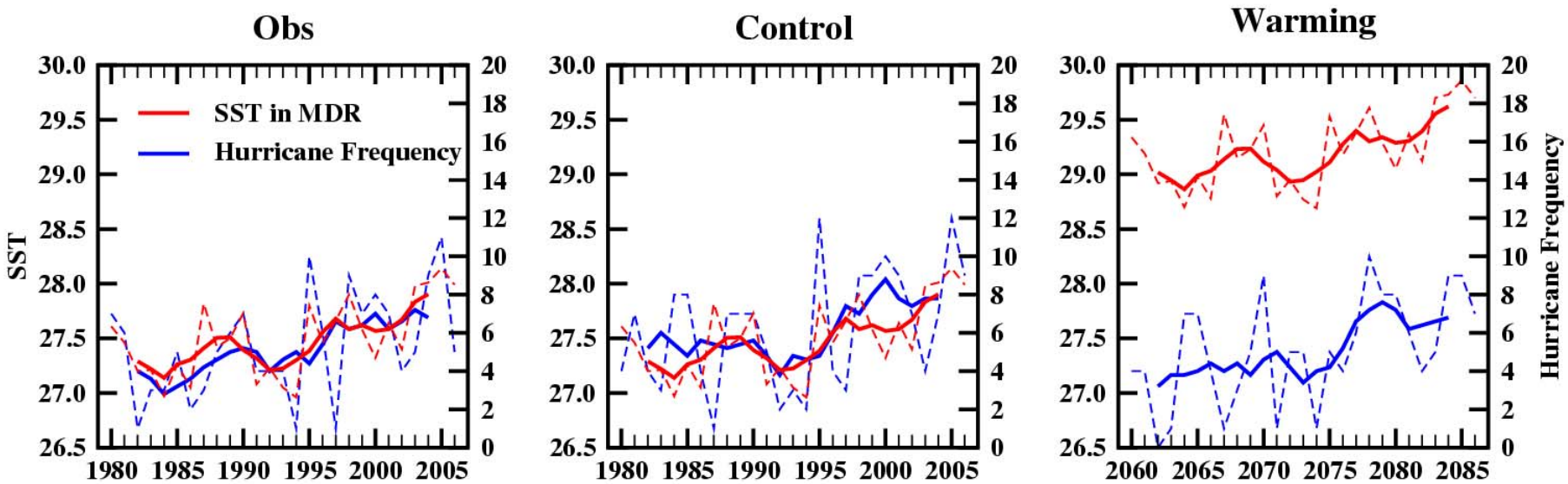
Storm Intensities (Normalized by frequency)



Avg. Rainfall Rate Increases:

50 km radius:	+37%
100 km radius:	+23%
150 km radius:	+17%
400 km radius:	+10%

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 doesn't simulate the hurricanes as intense as observed

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

Conclusions

- Atlantic SST and hurricane “power dissipation” are well correlated on low-frequencies since ~1950. Since studies attribute part of the Atlantic SST warming to increasing greenhouse gases, this ***suggests the possibility of a human influence on hurricanes***.
- Longer tropical cyclone records, including consideration of data problems, give ***conflicting indications*** on whether there have been significant increases in Atlantic tropical storm and hurricane numbers. U.S. landfalling hurricanes show no increase.
- A new Atlantic nested regional model projects ***increased intensities and rainfall rates of hurricanes*** for the late 21st century (in agreement with previous studies), but projects ***fewer hurricanes*** overall. The intensity sensitivity is too small to expect detectability at this time.
- Although increased SSTs are ***strongly correlated*** with increased hurricane activity in both the model and observations since 1980, a much larger projected 21st century SST warming leads to ***decreased hurricane frequency*** in the model. Therefore, the detailed structure (and cause) of a climate warming appears to strongly determine how the warming will influence hurricanes.
- Based on the current state of models and ongoing data concerns, ***it is not appropriate at this time to make a likelihood statement attributing past changes in hurricane activity to increasing greenhouse gases or other human-caused factors***.

Summary Statement on Tropical Cyclones and Climate Change

WMO International Workshop on Tropical Cyclones VI

Highlights (excerpts) of Consensus Statements as of December 2006:

- No firm conclusion yet on whether there is a detectable anthropogenic signal in hurricane activity.

- Detection of trends is made more difficult by changes in hurricane observation methods over time and by strong multi-decadal variability in hurricane activity.

- Some increase in hurricane peak wind speed (and hurricane rainfall) is likely if the climate continues to warm. Projected magnitude: 3-5% increase in wind speed per degree Celsius sea surface temperature increase.

- **Vulnerability to hurricane *storm-surge flooding* will increase if the projected rise in sea level due to global warming occurs.**

Source: WMO (World Meteorological Organization)

Statistical significance testing

- **Method 1:** Linear least-squares regression on annual storm count series. Adjust degrees of freedom for two-sided t-test based on lag-1 autocorrelation.
- **Method 2:** Same as Method 1, but for the ranks rather than the original series. Addresses issue of skewness in storm count annual data.
- **Method 3:** Bootstrap resampling (with replacement) of series sug-segments of length L. Compute linear trends of resampled data sets as a control comparison. L values in range of 2-8 tested. (Recommended value of 2-3 based on Wilks text.)

- The three methods give roughly similar results here, although Method 3 appears a bit more conservative (at least for some L values in range of 2-8).

Research needs for this problem:

- Improved observations: particularly reanalysis efforts to produce “climate quality data” on hurricanes for detection/attribution studies (e.g., PDI error? Adjusted storm counts?)
- Improved hurricane modeling: Higher resolution models, retrospective studies of 20th century hurricane variability that can simulate or infer past hurricane activity
- Observational and modeling studies of Atlantic multidecadal variability (e.g., the Atlantic Multidecadal Oscillation—AMO, and “forced climate change” (past and future) affecting SST, shear, etc. in the basin
- Paleoclimate studies, both for the AMO and for pre-historic hurricane activity.
- Convergence of statistical models (correlations) and dynamical models (hurricane simulation)
- More confident projections of future Atlantic large-scale environment (e.g., reexamination of Vecchi/Soden with future models, improved aerosols, etc.)

Have Humans Affected Atlantic Hurricane Climate?

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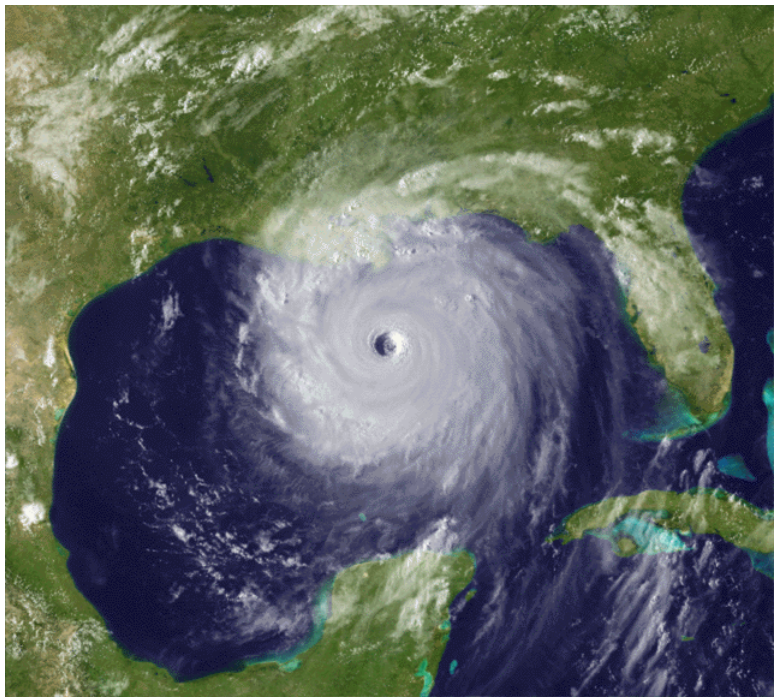
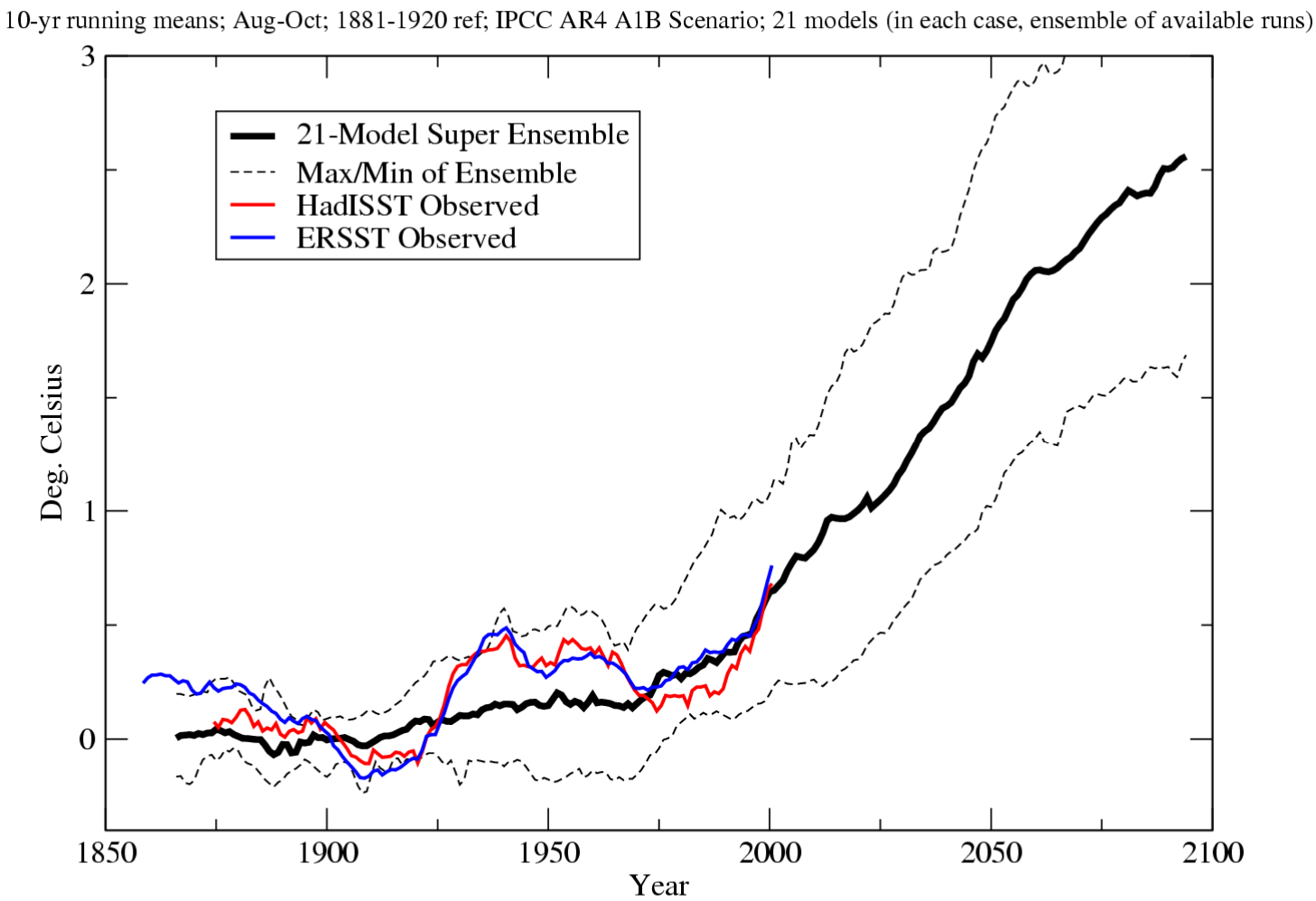


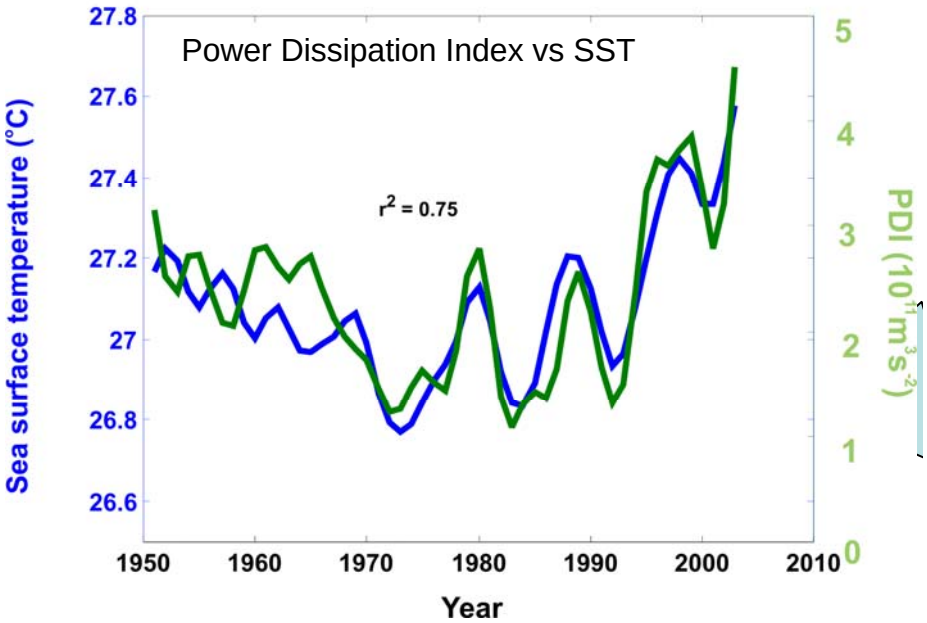
Hurricane Katrina, Aug. 2005

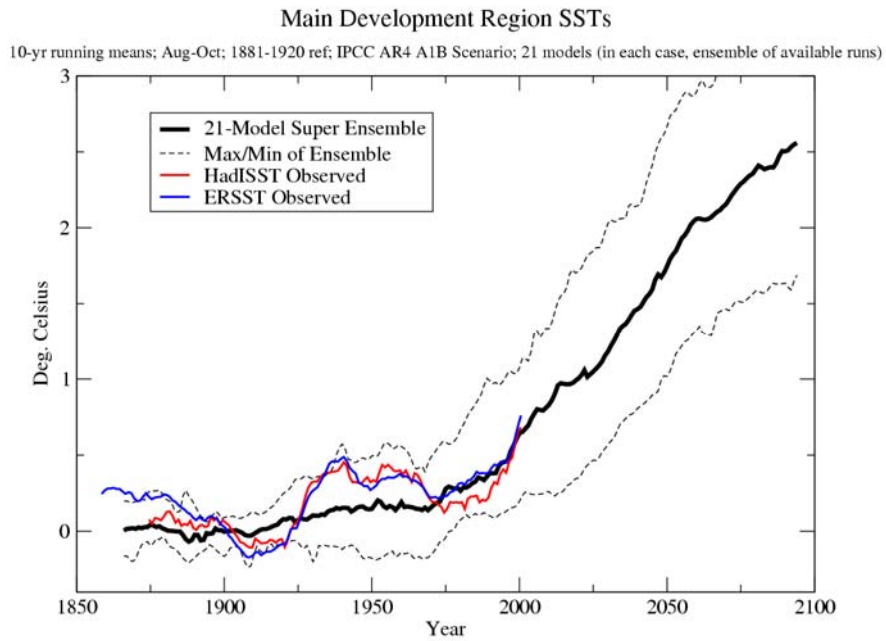
Binger, Oklahoma tornado, May 1981
http://www.spc.noaa.gov/faq/tornado/binger.htm

Sea surface temperatures have increased in the region where Atlantic hurricanes form and intensify, and they are projected to increase much more during the 21st century…



What are the implications of pronounced future warming for Atlantic Power Dissipation Index (PDI)?





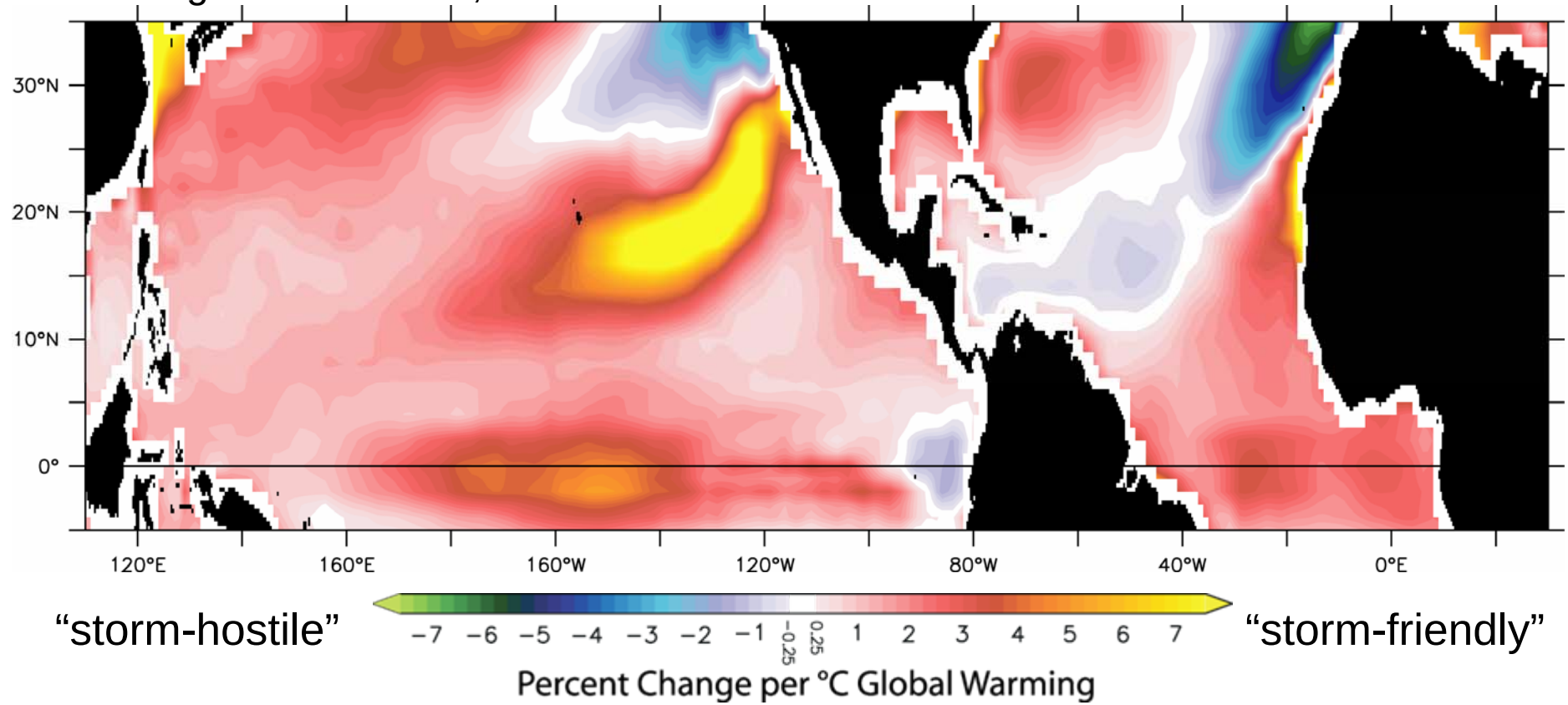
Future Atlantic Hurricane Activity?

- Models indicate increased hurricane intensities with warmer ocean temperatures.
- Increased vertical wind shear may reduce hurricane activity in the Atlantic.
- How do we assess which of these effects will “win out”?

Projected 21st Century Changes in Thermodynamic Potential Intensity of Hurricanes

Average of 18 models, Jun-Nov

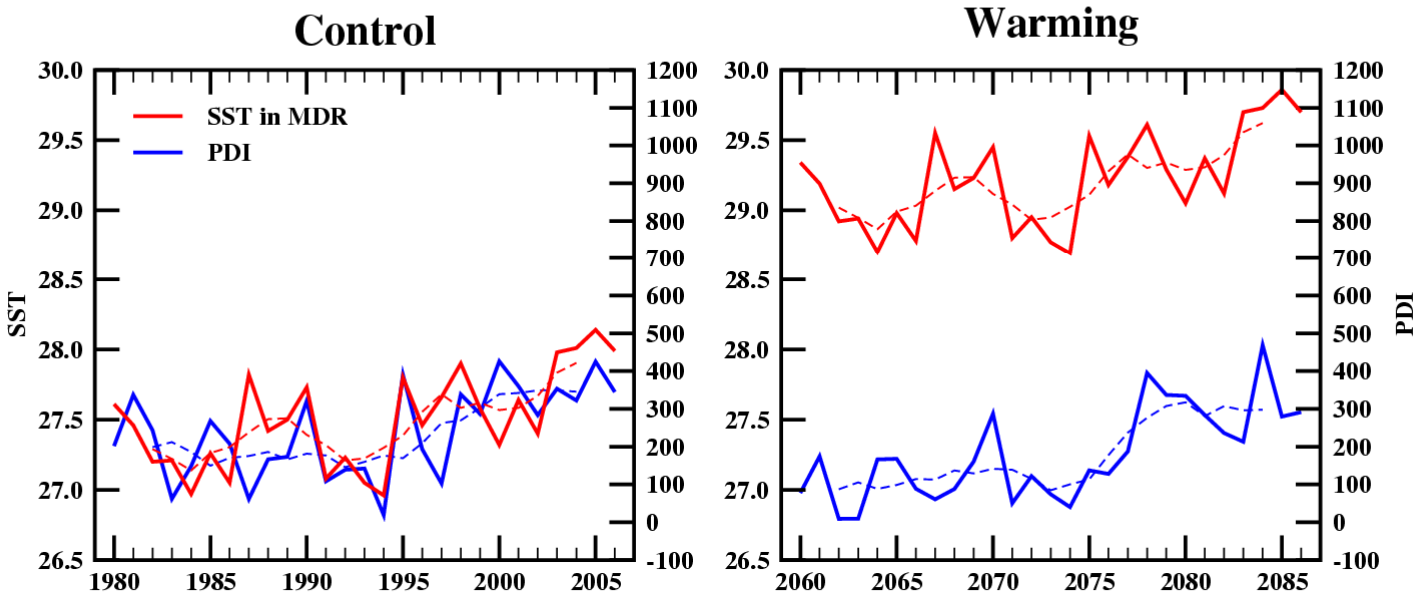
From Vecchi and Soden (2007, GRL)



"storm-hostile"

"storm-friendly"

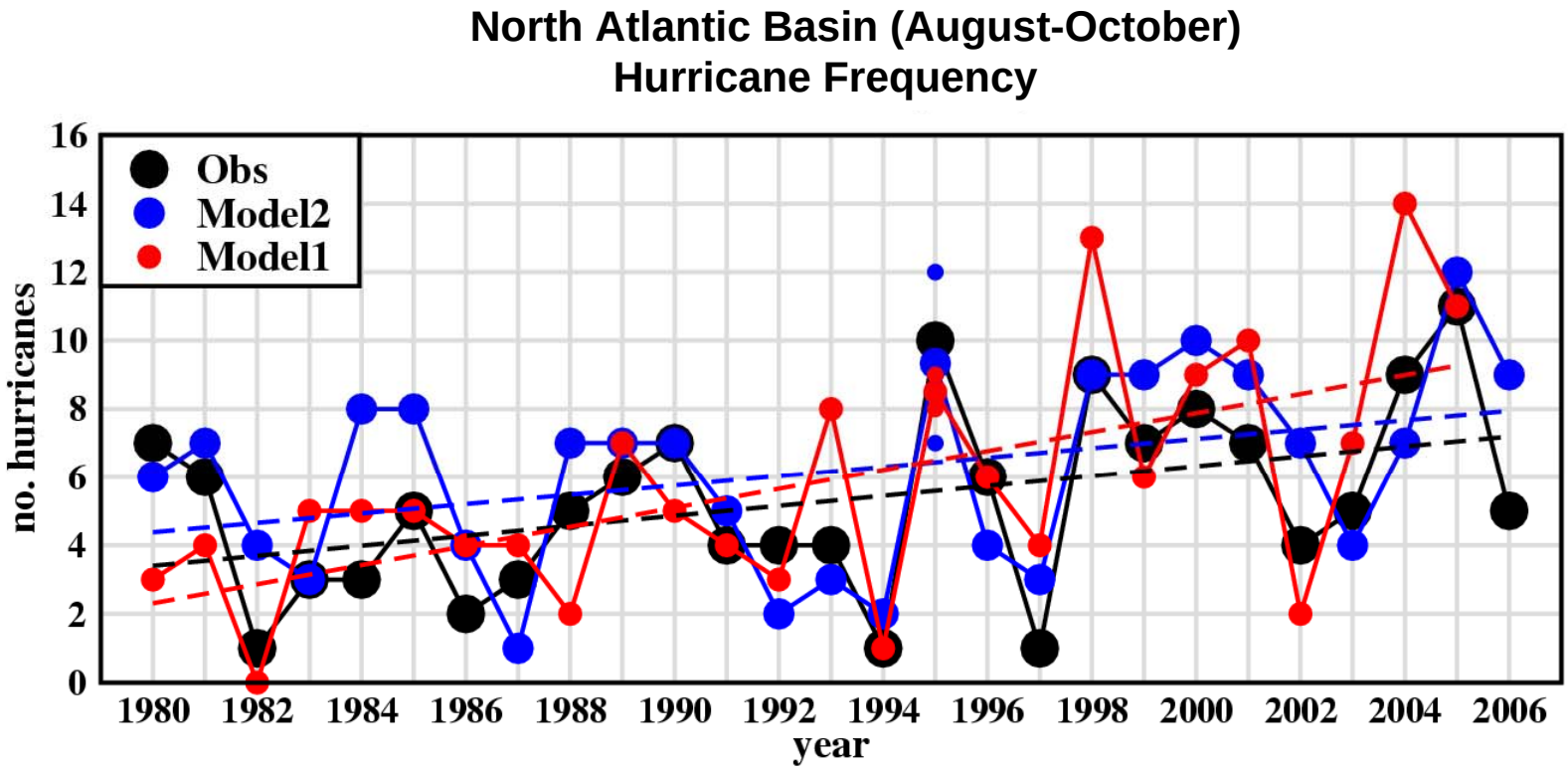
The control model reproduces the observed close relationship between SST and PDI (1980-2006), but this strong relationship does not hold for future human-caused warming in the model.



PDI actually *decreases* by 24% in the warm climate case… although the model doesn't simulate the hurricanes as intense as observed

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

Showing the individual ensemble members (n=2)….



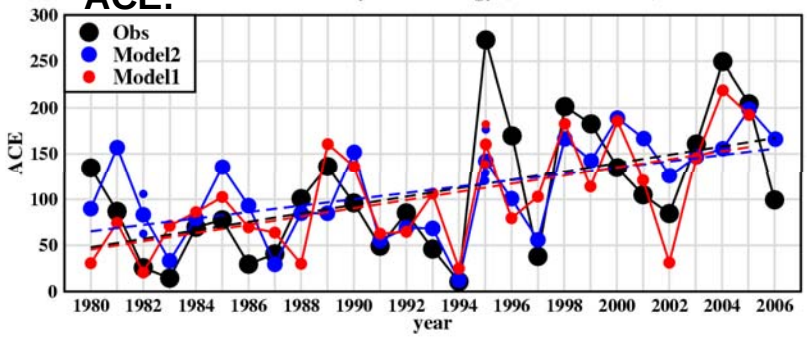
Correlations vs. Obs: Model1: 0.76
Model2: 0.76

Source: Knutson et al. 2007 (BAMS, in press)

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

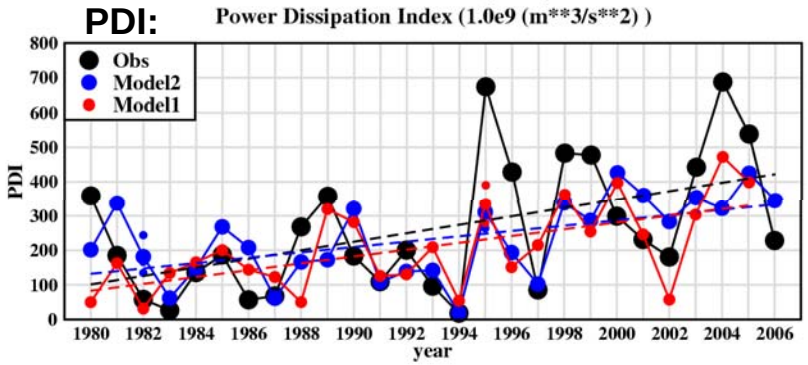
Other hurricane metrics (ACE, PDI) are simulated fairly well, but major hurricanes are under-simulated…

ACE:



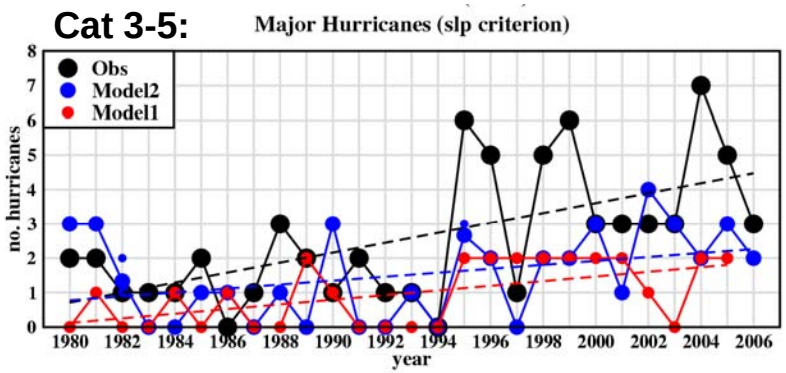
Correlations: Model1: 0.72
Model2: 0.68
Ensem: 0.77

PDI:



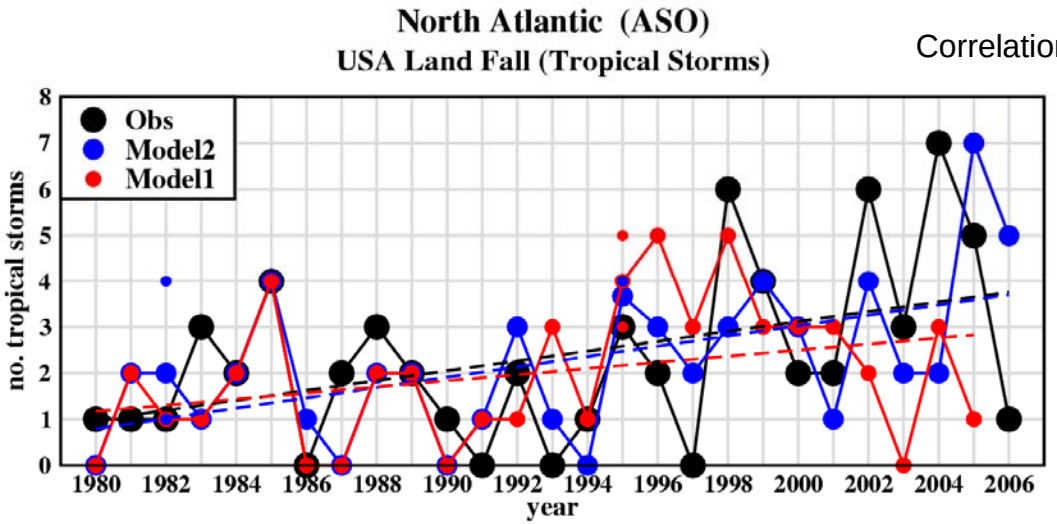
Correlations: Model1: 0.70
Model2: 0.62
Ensem: 0.73

Cat 3-5:

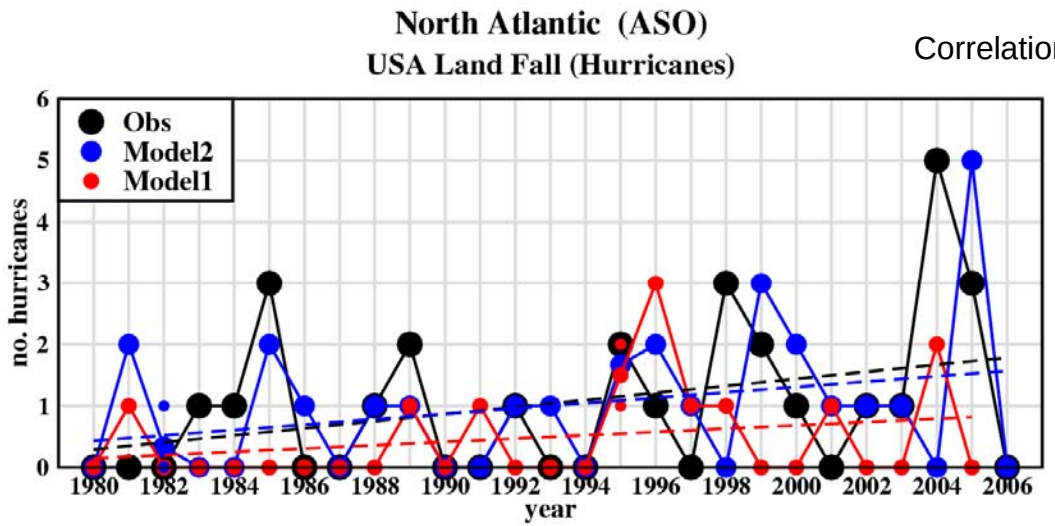


Correlations: Model1: 0.64
Model2: 0.51
Ensem: 0.69

But the model does not correlate as well with observed landfall statistics...

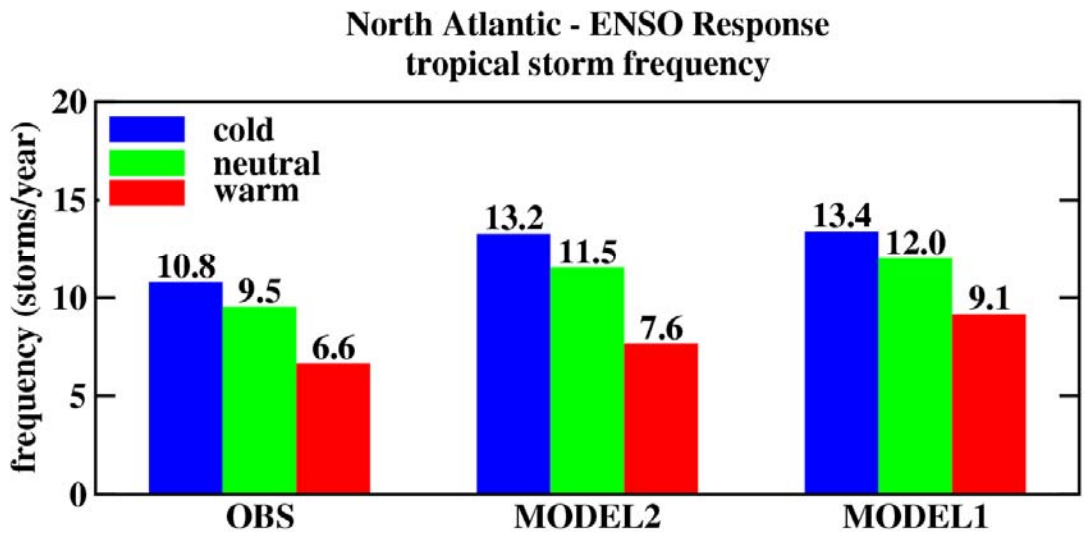


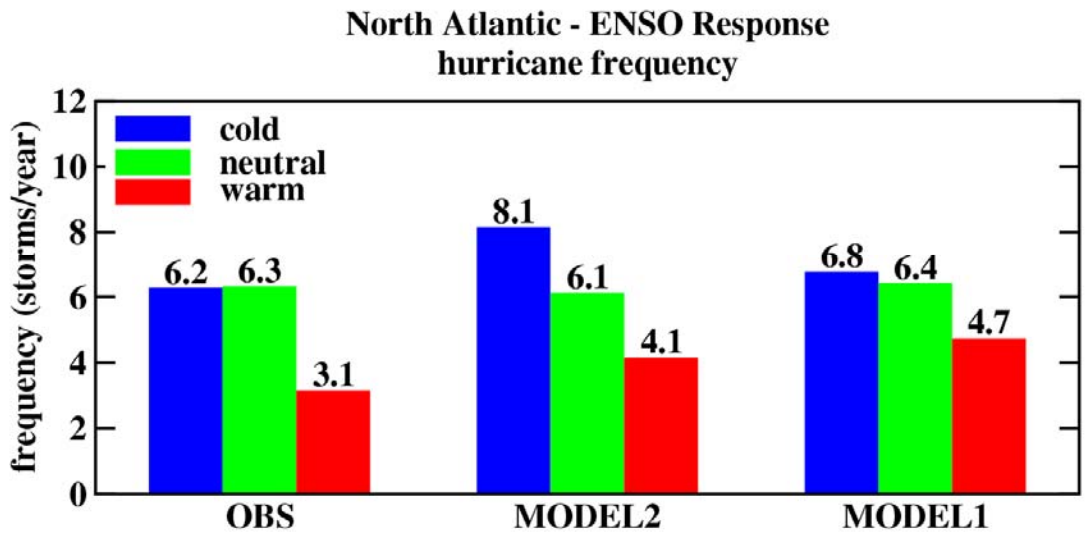
Correlations: Model1: 0.36
Model2: 0.51
Ensem: 0.57



Correlations: Model1: 0.30
Model2: 0.32
Ensem: 0.41

The model also reproduces the observed reduction of Atlantic hurricane activity during El Niño events fairly well…

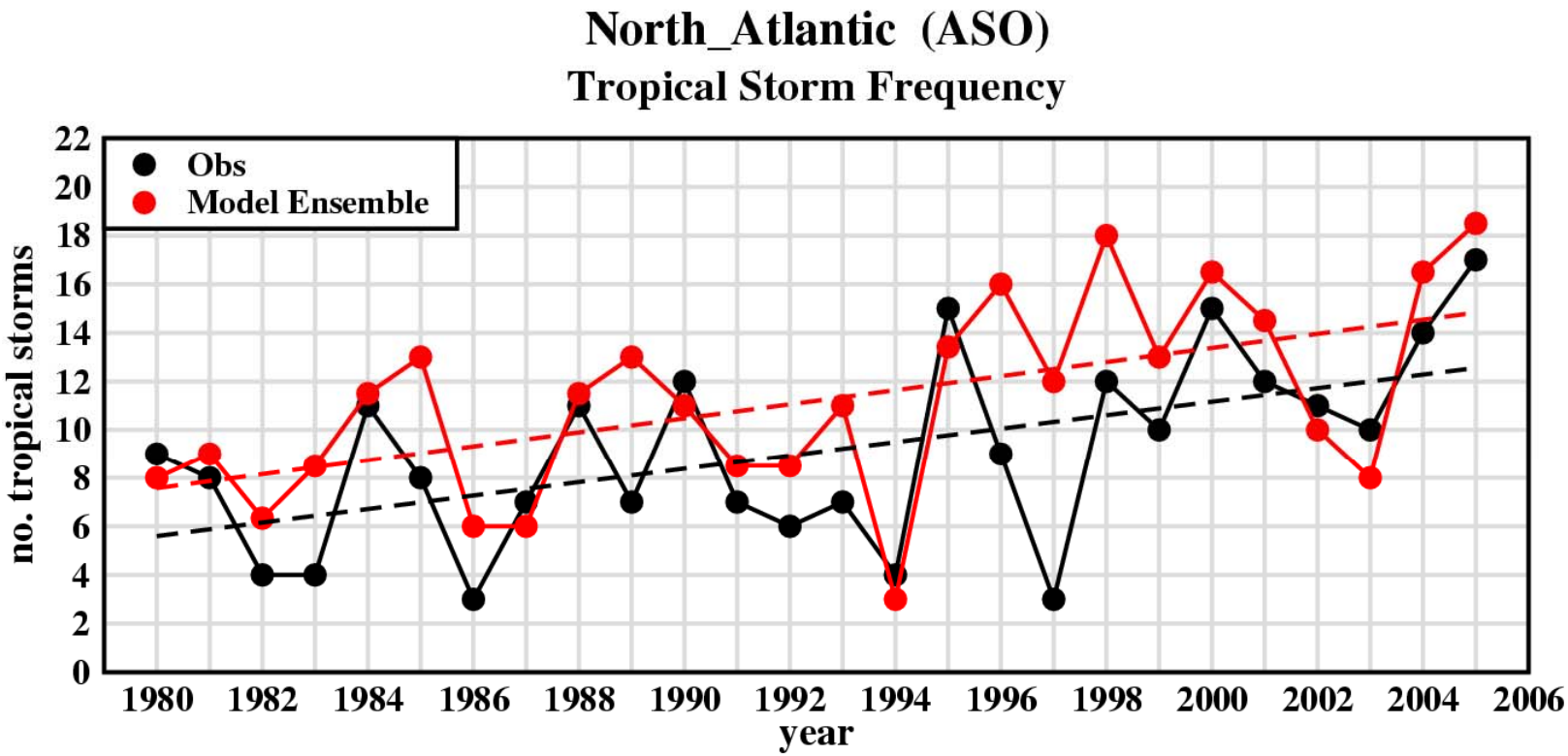




(Alternative) Conclusions

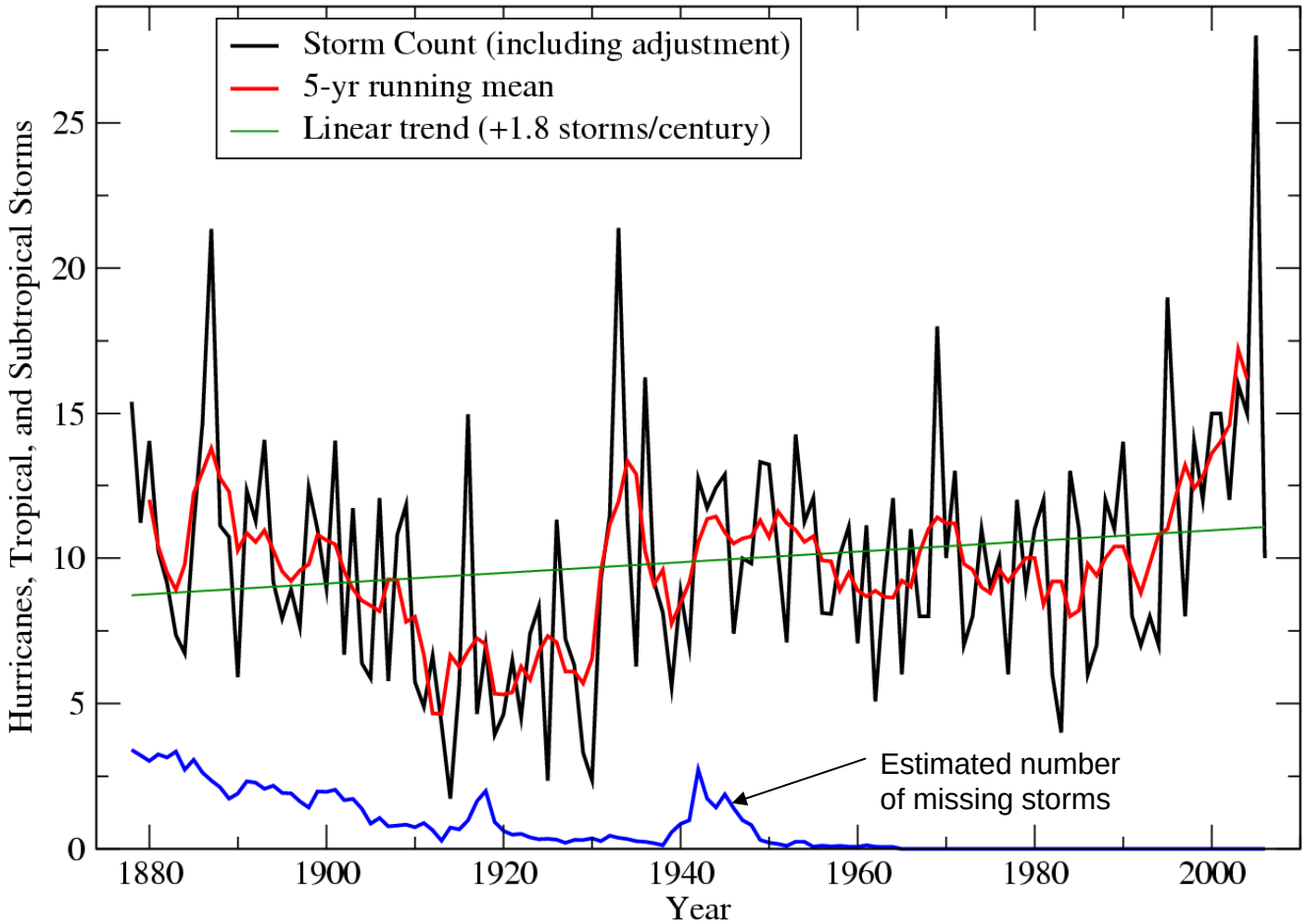
- Observed data, including consideration of data problems, give ***conflicting indications*** on whether there have been significant increases in Atlantic tropical storm and hurricane numbers.
- High resolution models consistently project ***increasing hurricane intensities and rainfall rates*** for the late 21st century, but whether there will be more or fewer hurricanes remains uncertain.
- A new modeling approach ***reproduces many important aspects*** of Atlantic hurricane activity observed since 1980, and thus shows promise as a tool for both understanding past variations and for making more reliable projections of future hurricane activity.

- Other slides (not used in presentation for now)



Correlations vs. Obs: Model Ensemble: 0.73

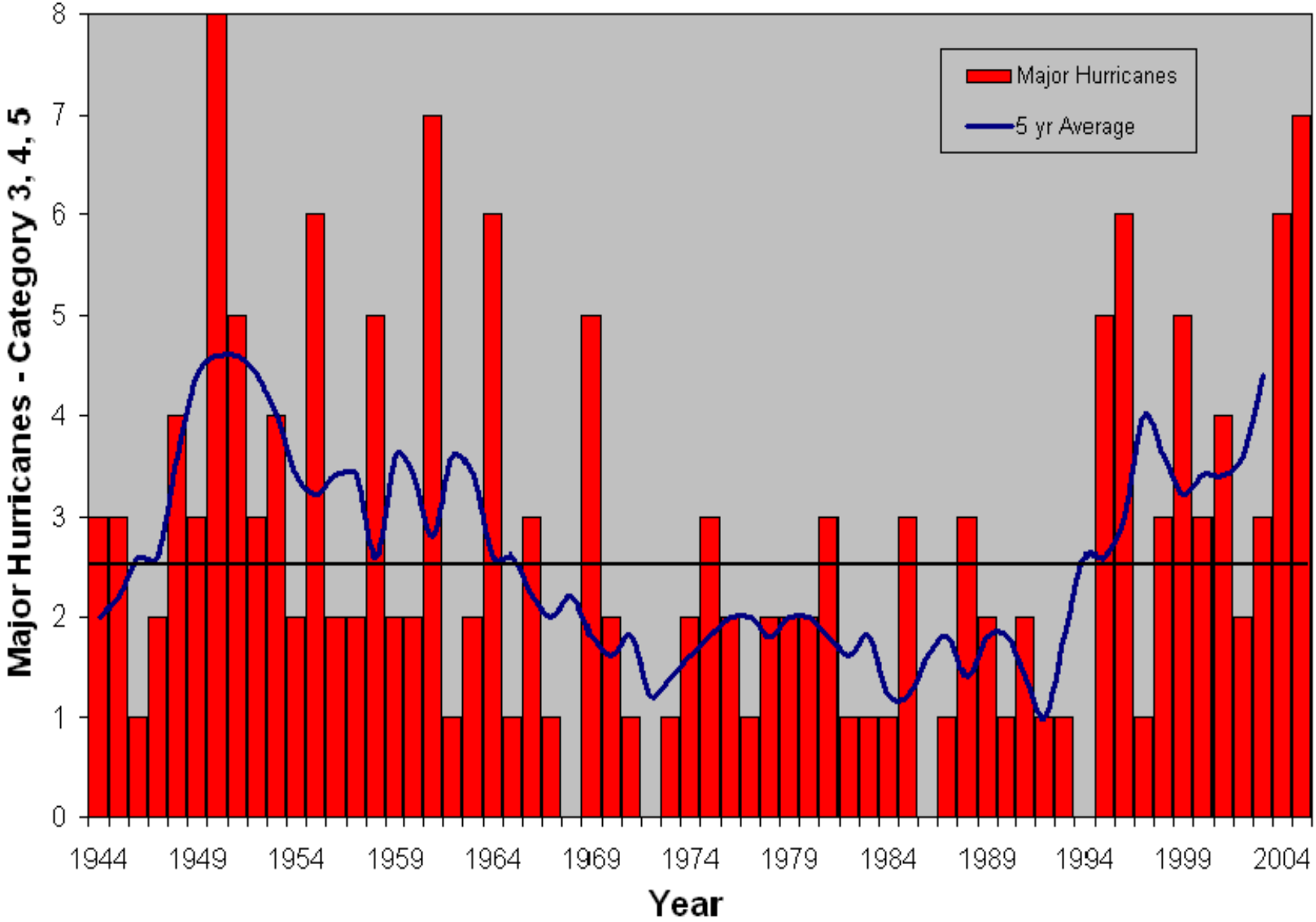
Atlantic basin-wide tropical storm counts, adjusted for missing storms, indicate that 2005 was the most active year in the record, but the trend since 1876 is not assessed to be statistically significant…



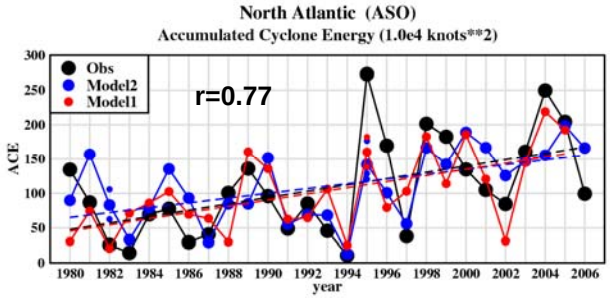
Source: Vecchi and Knutson (in prep)

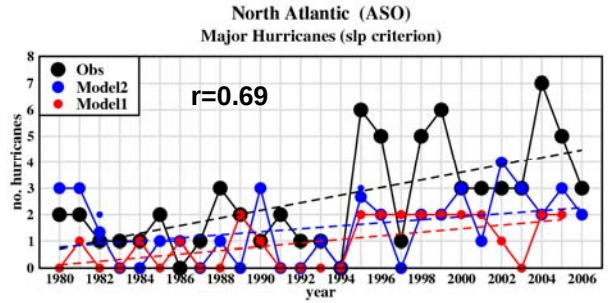
Fri Mar 16 15:14:30 2007

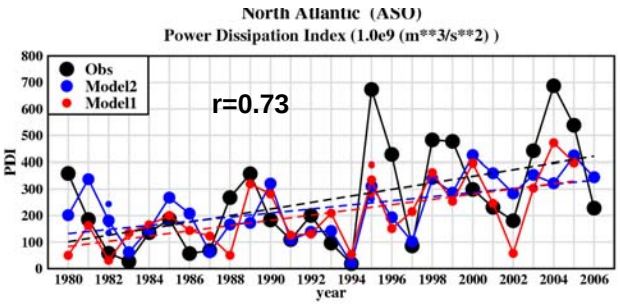
Atlantic Major Hurricane counts (basin-wide) since the mid-1940s: no long-term trend

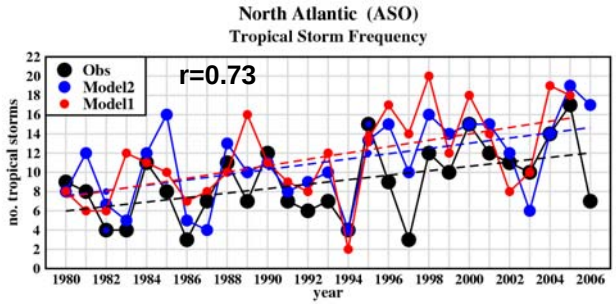


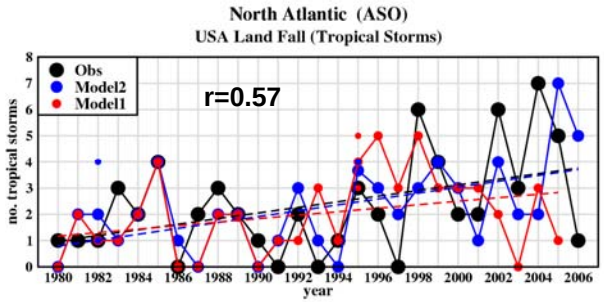
Source: Chris Landsea, NOAA/NHC

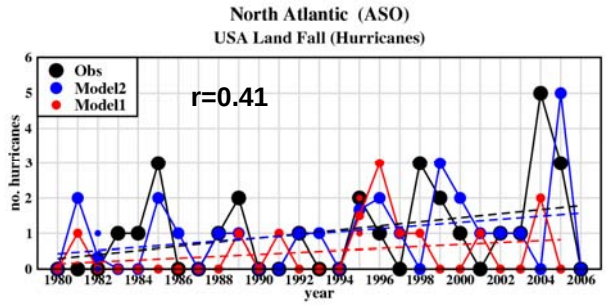


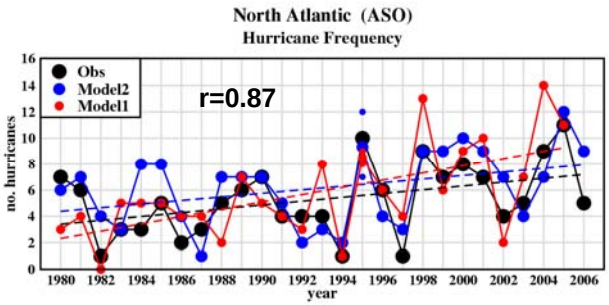


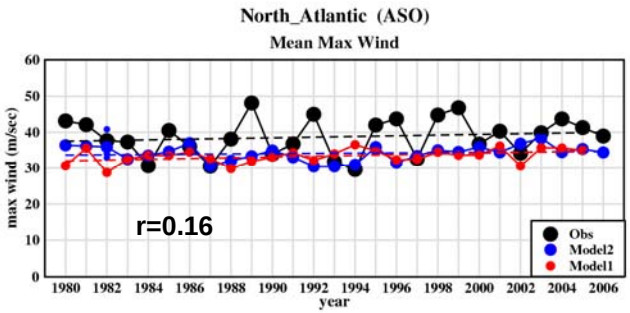








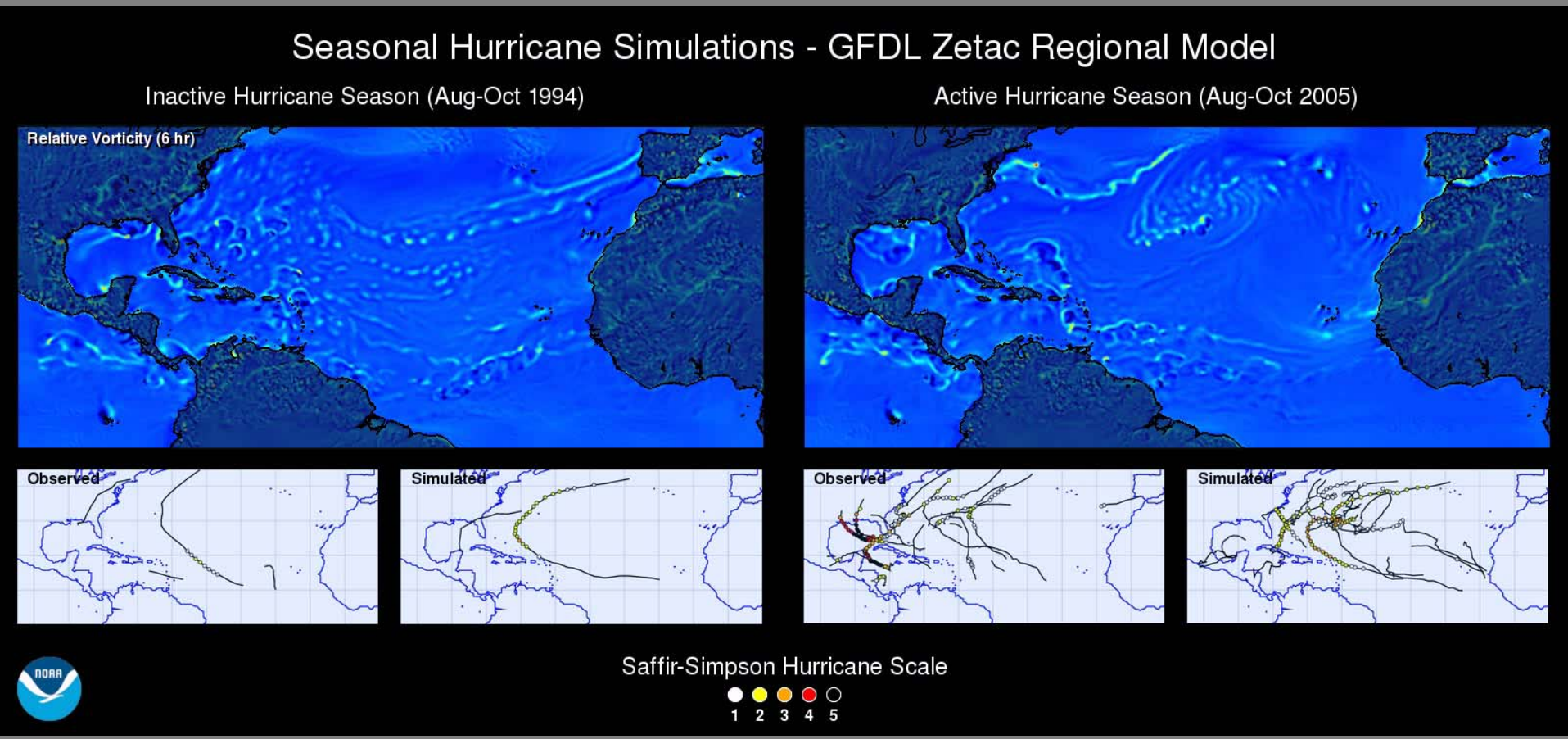




Model performance: various Atlantic hurricane measures

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

Source: Knutson et al. 2007 (in review)



Prototype model for future global hurricane forecasting system…