Atlantic tropical cyclones and climate: observed changes

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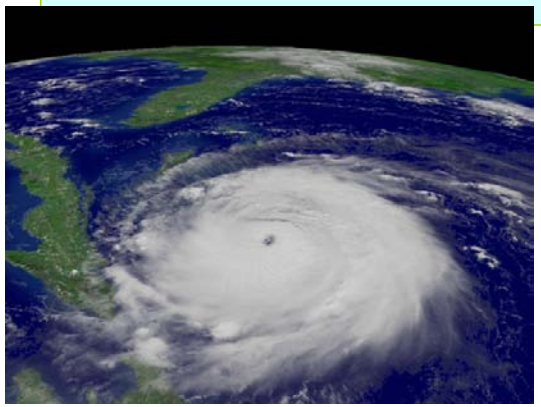
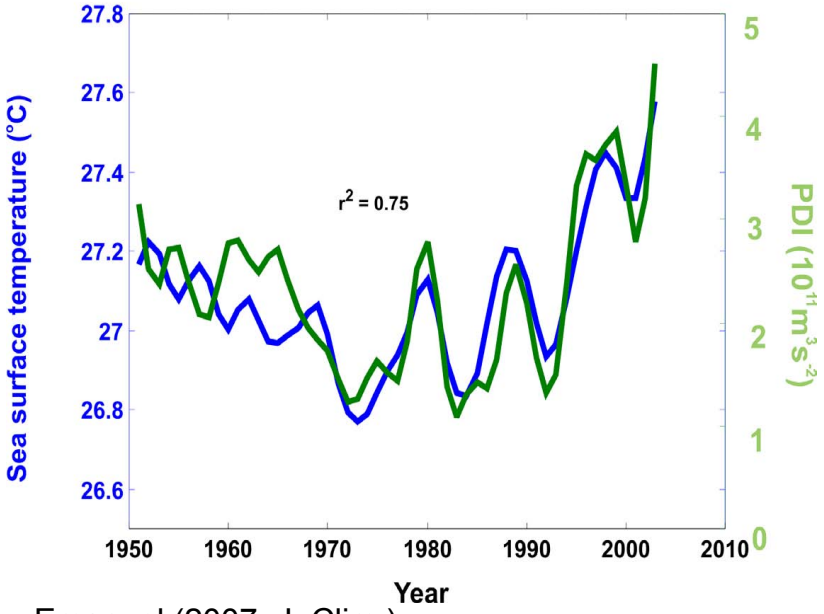
North Atlantic tropical cyclones



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



Emanuel (2007, J. Clim.)

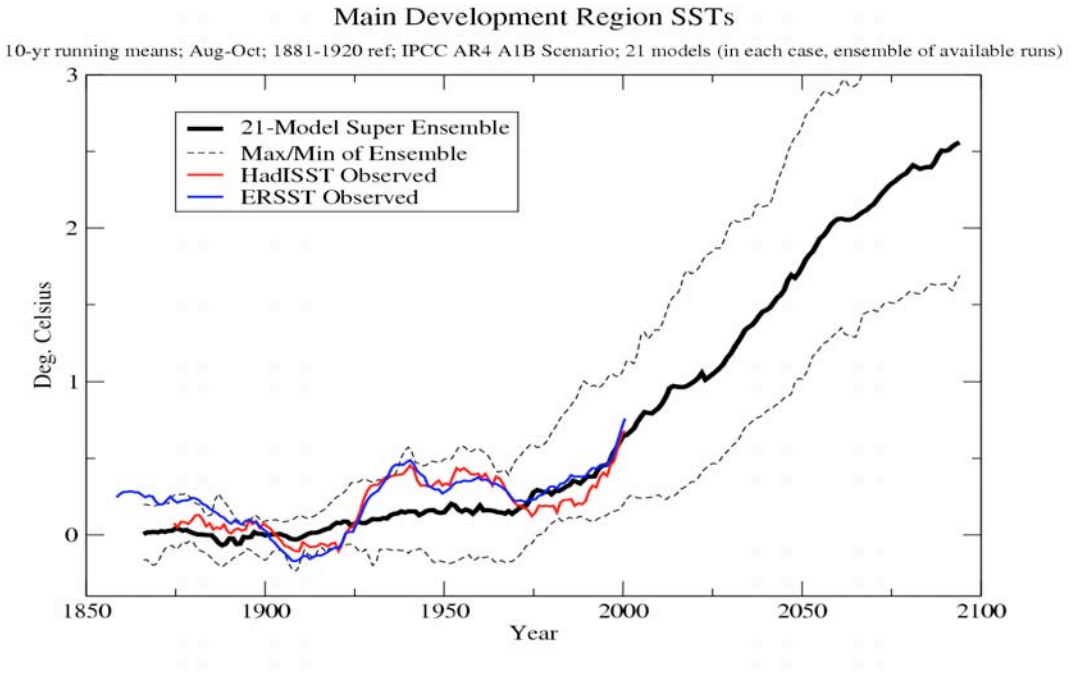
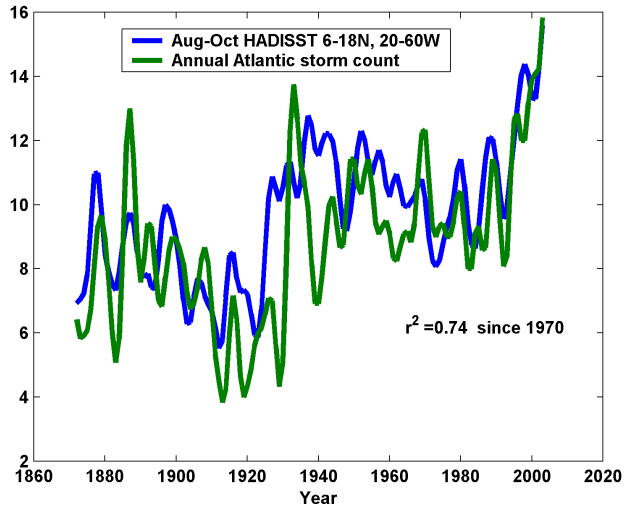
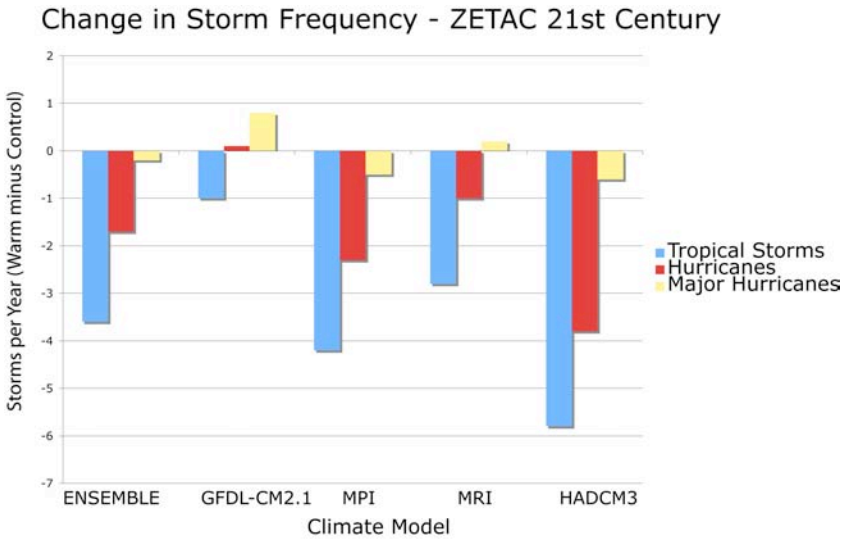


Figure: Tom Knutson

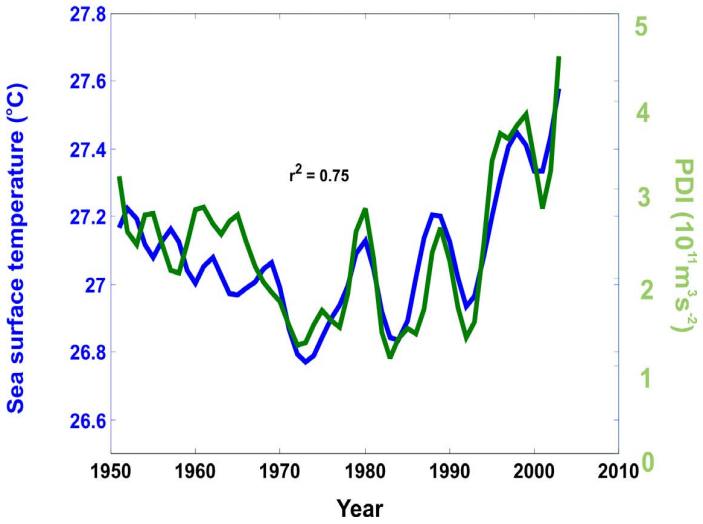
Is the historical Atlantic TS record consistent with dynamical model projections of a weak (and possibly negative) sensitivity to warming?



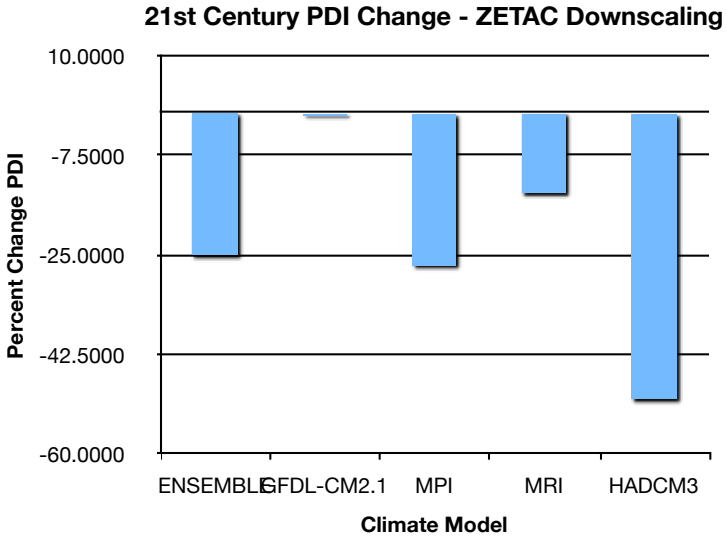
Source: Emanuel (2006); Mann and Emanuel (2006) EOS.
See also Holland and Webster (2007) *Phil. Trans. R. Soc. A*



Source: Knutson et al (2008, Nature Geosci.)
Knutson et al (2010, in prep.)



Emanuel (2007, J. Clim.)



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

Outline

Focus on basin-wide activity measures

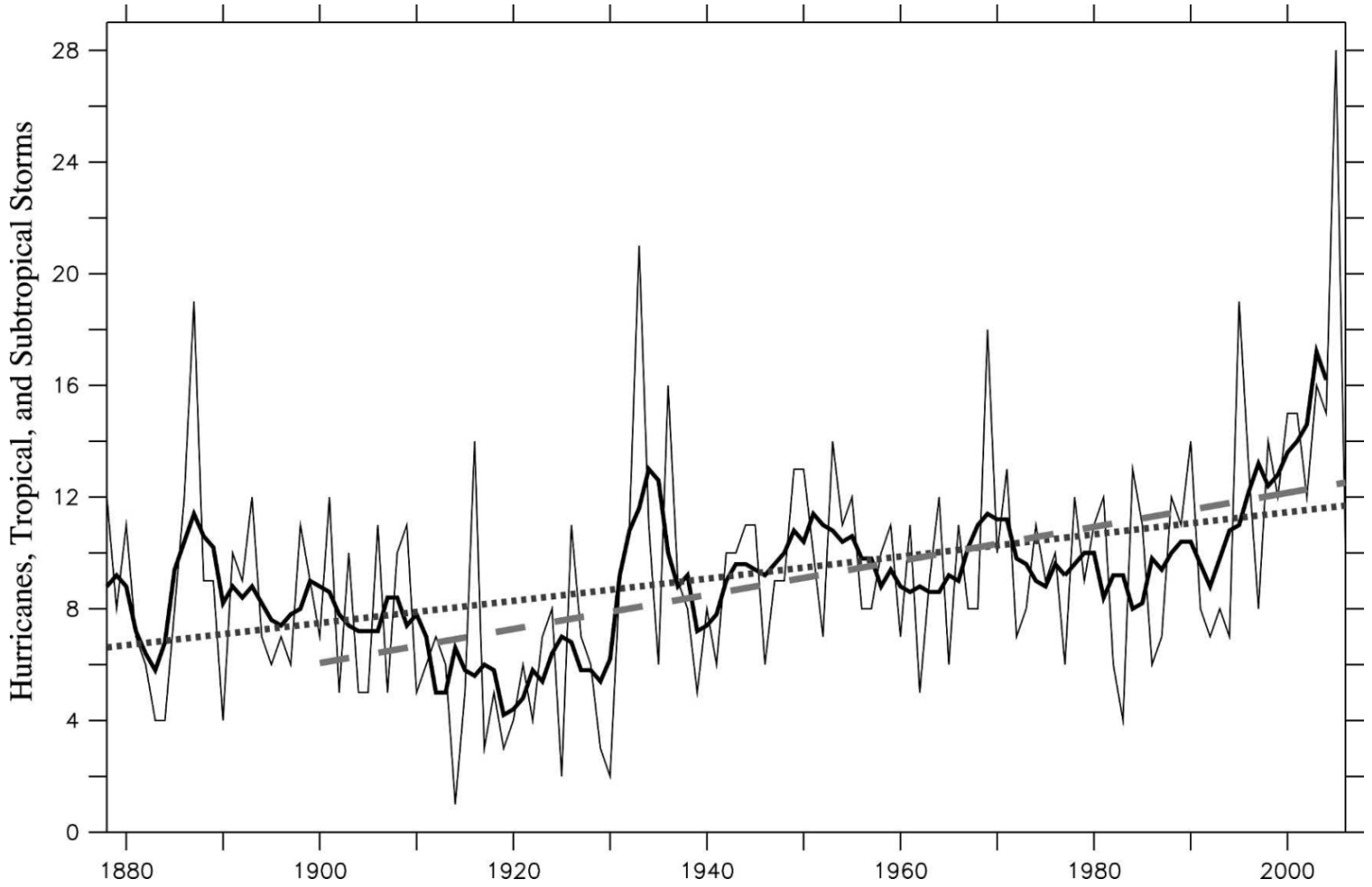
- Tropical Storm: frequency and duration
- Hurricane: frequency and structure

- Power Dissipation Index

- Statistical models of TS frequency

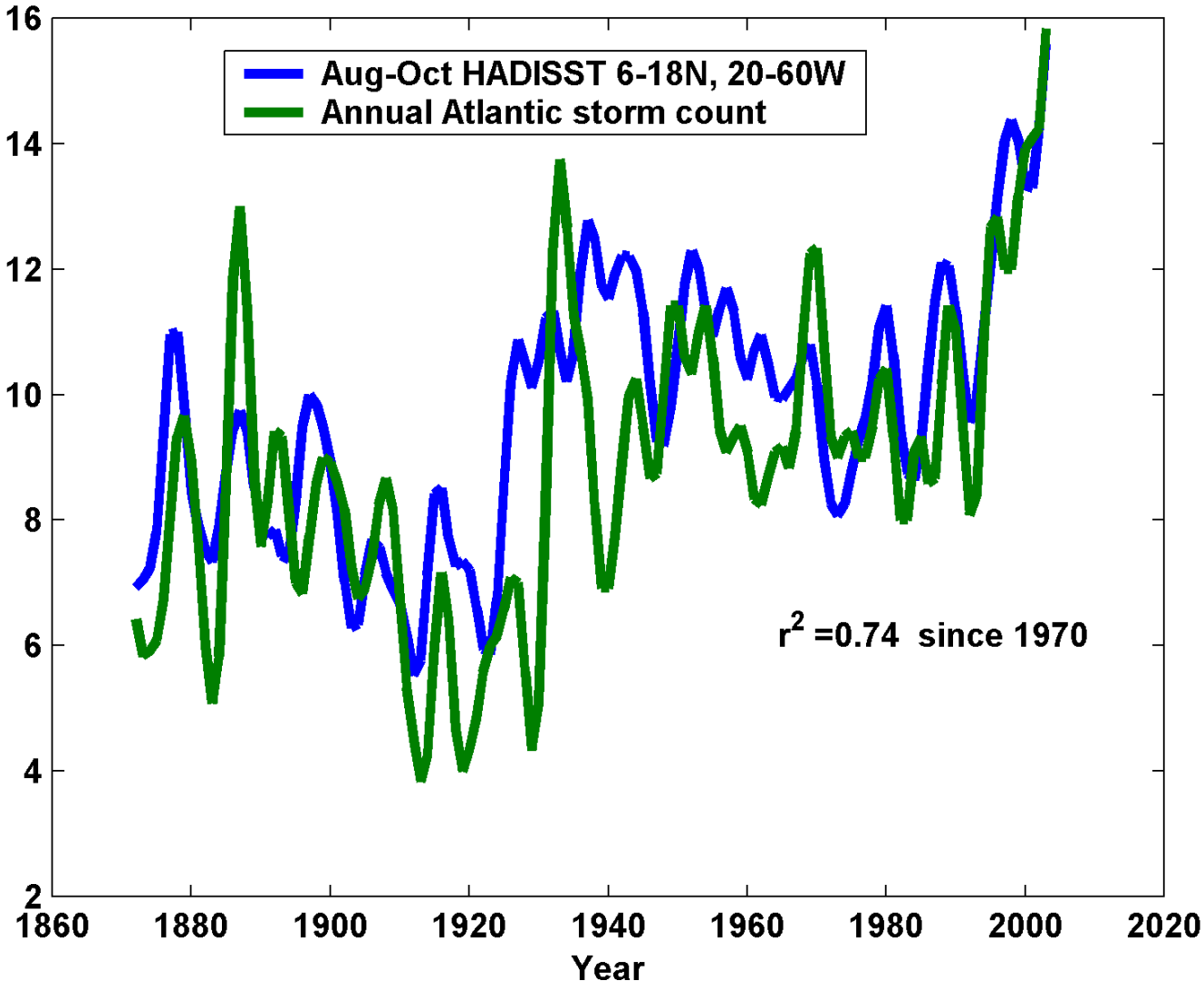
Century-scale changes in TS frequency

Clear increase in recorded number of Atlantic tropical storms since late-19th Cy.



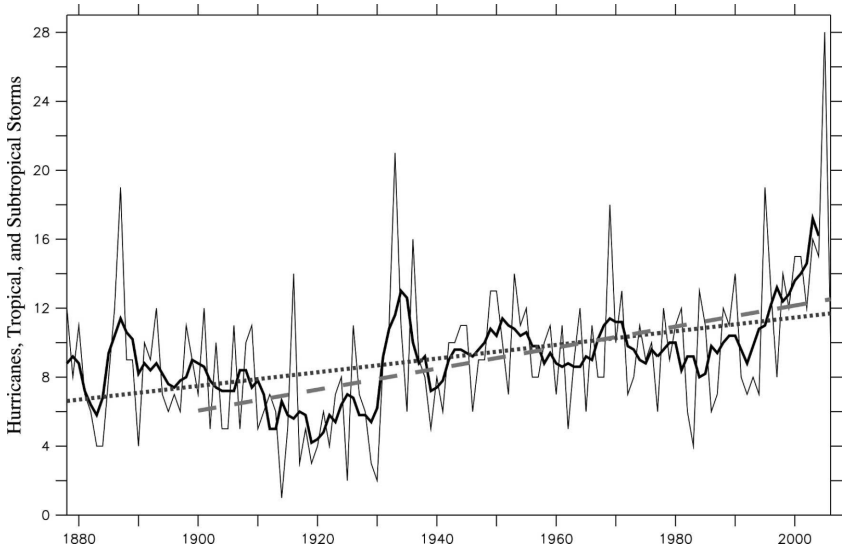
Source: Vecchi and Knutson , J. Climate, 2008.

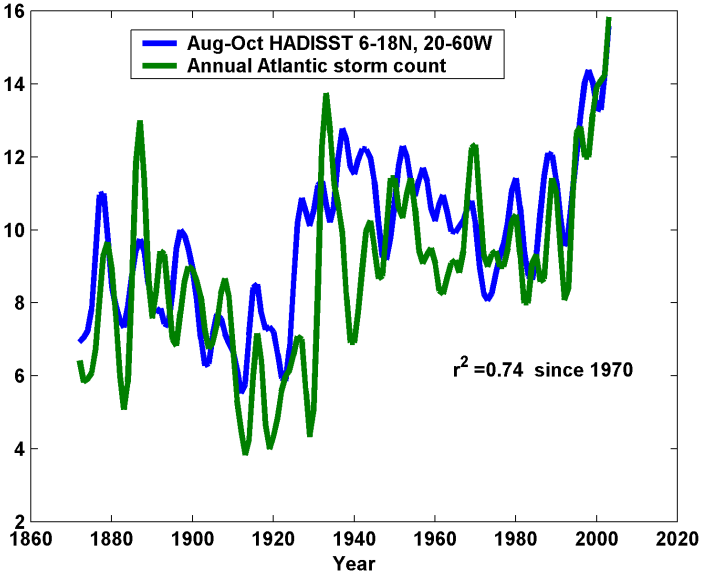
Records of Atlantic TS Frequency well-correlated to Atlantic SST



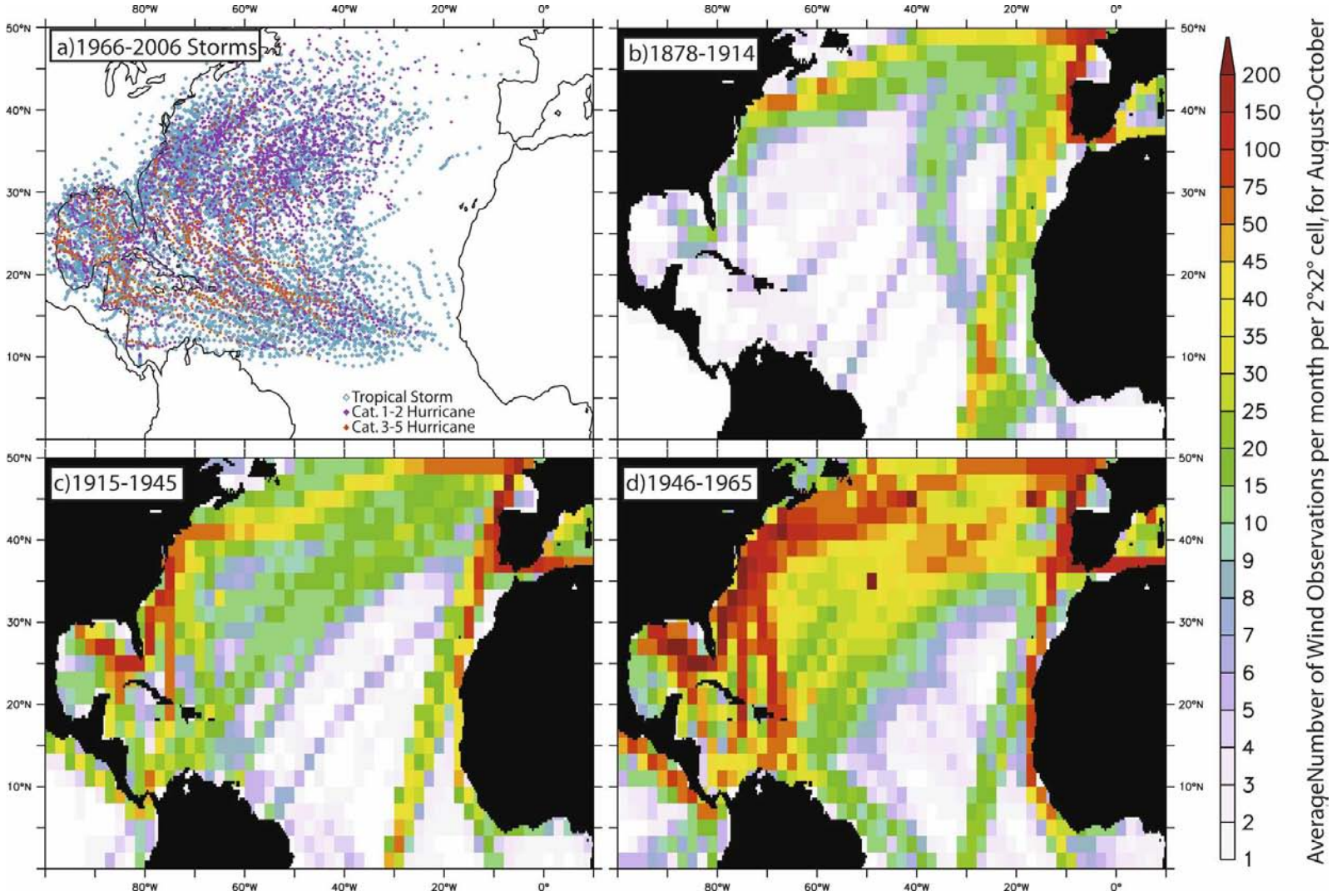
Source: Emanuel (2006); Mann and Emanuel (2006) EOS. See also Holland and Webster (2007) *Phil. Trans. R. Soc. A*

Real change in TS frequency?



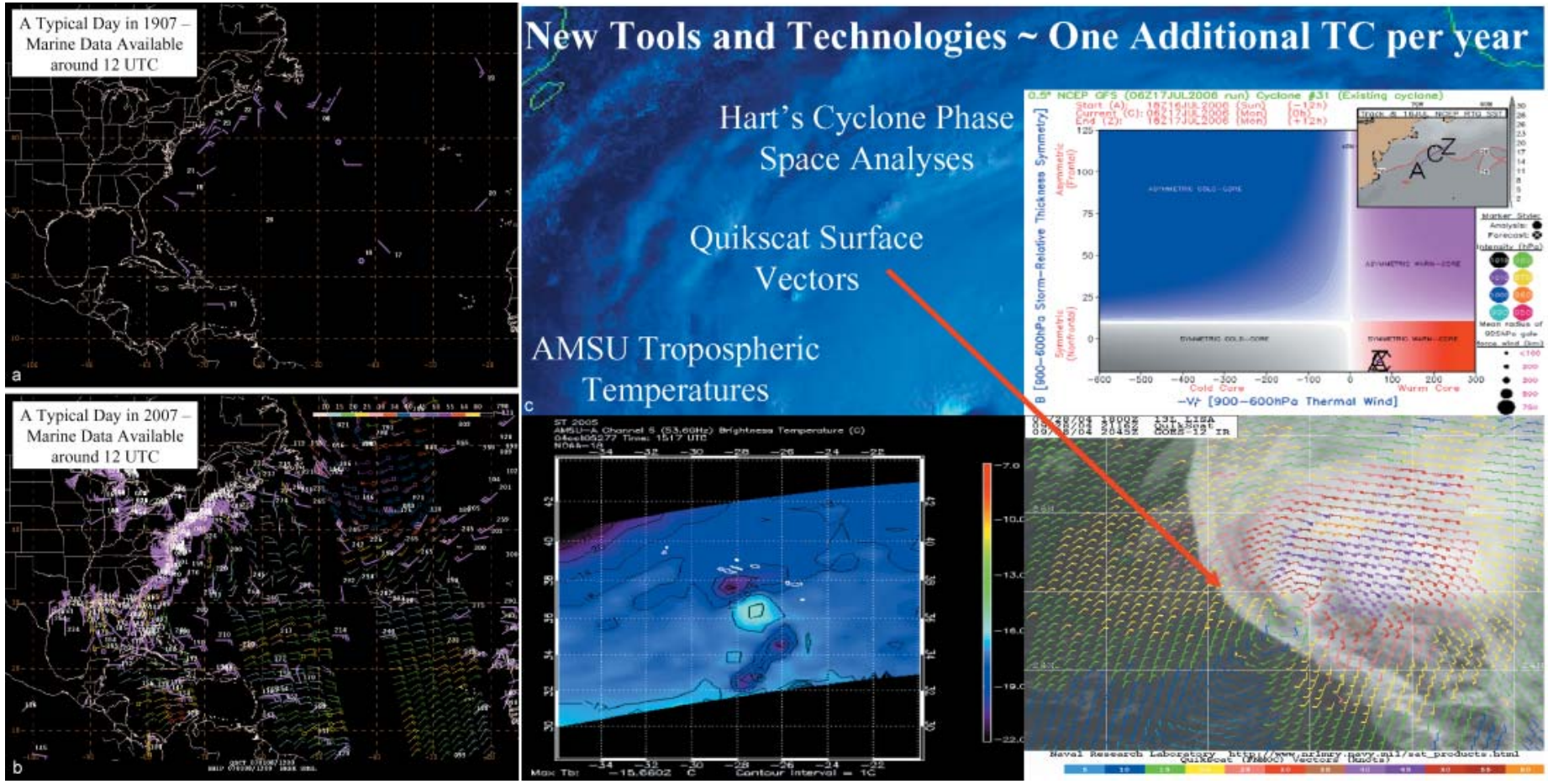


Ability to observe cyclones has also changed with time: e.g., ship track density



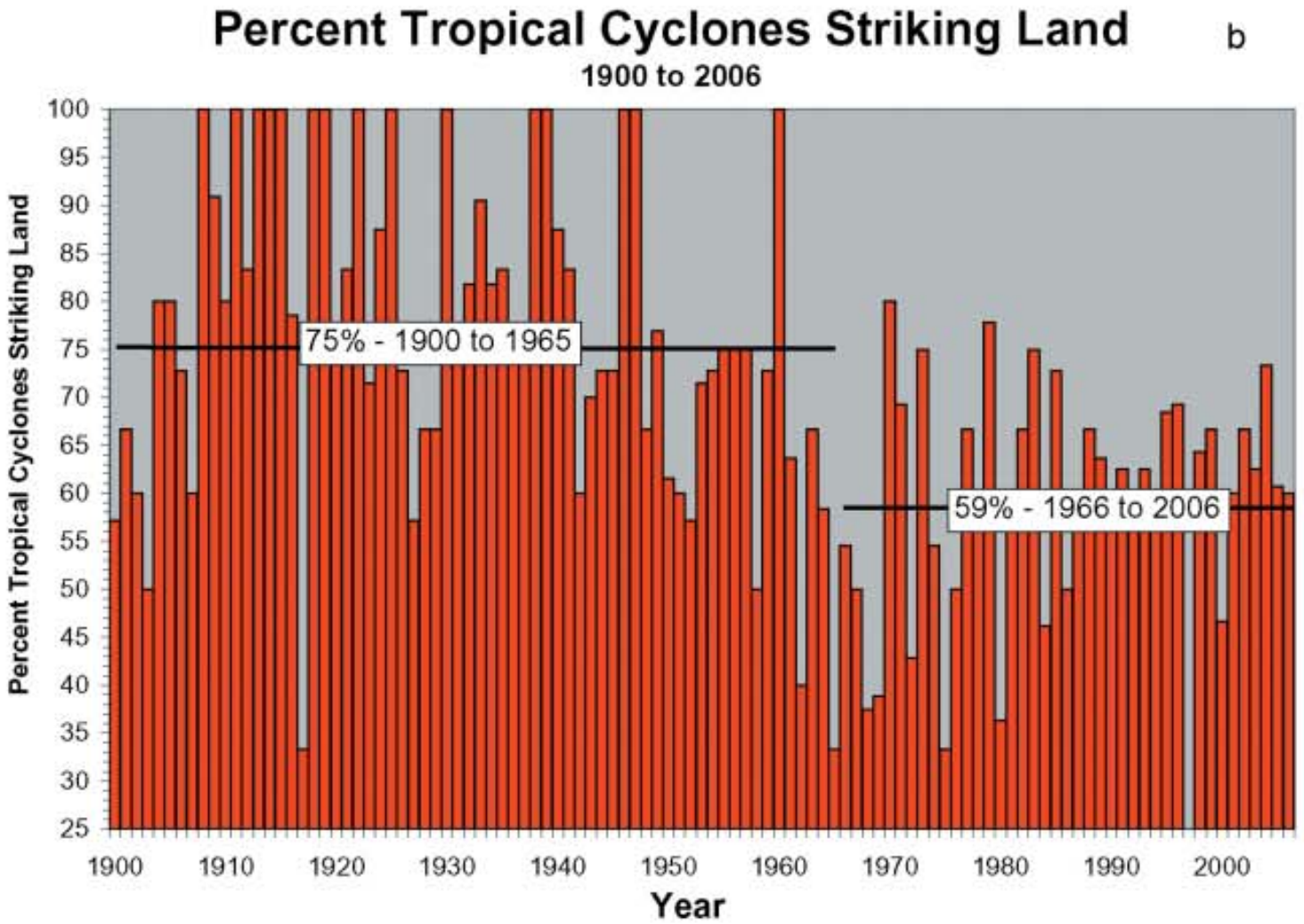
Source: Vecchi and Knutson , J. Climate, 2008.

Ability to observe cyclones has also changed with time: e.g., new technologies



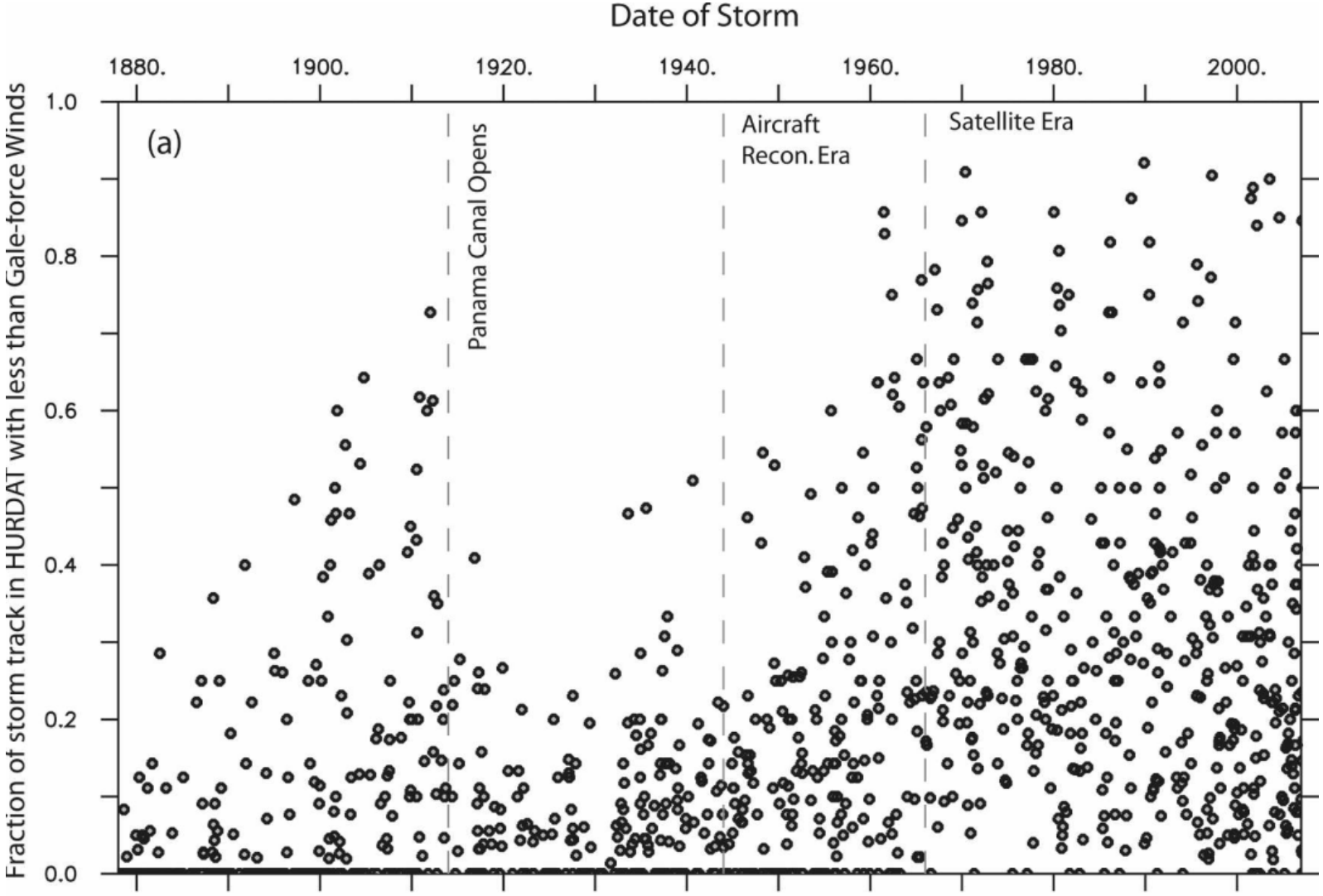
Source: Landsea, EOS, 2007.

Characteristics of recorded storms exhibit strong secular changes, e.g., fraction of storms hitting land



Source: Landsea, EOS, 2007.

Characteristics of recorded storms exhibit strong secular changes, e.g., time as tropical depression



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

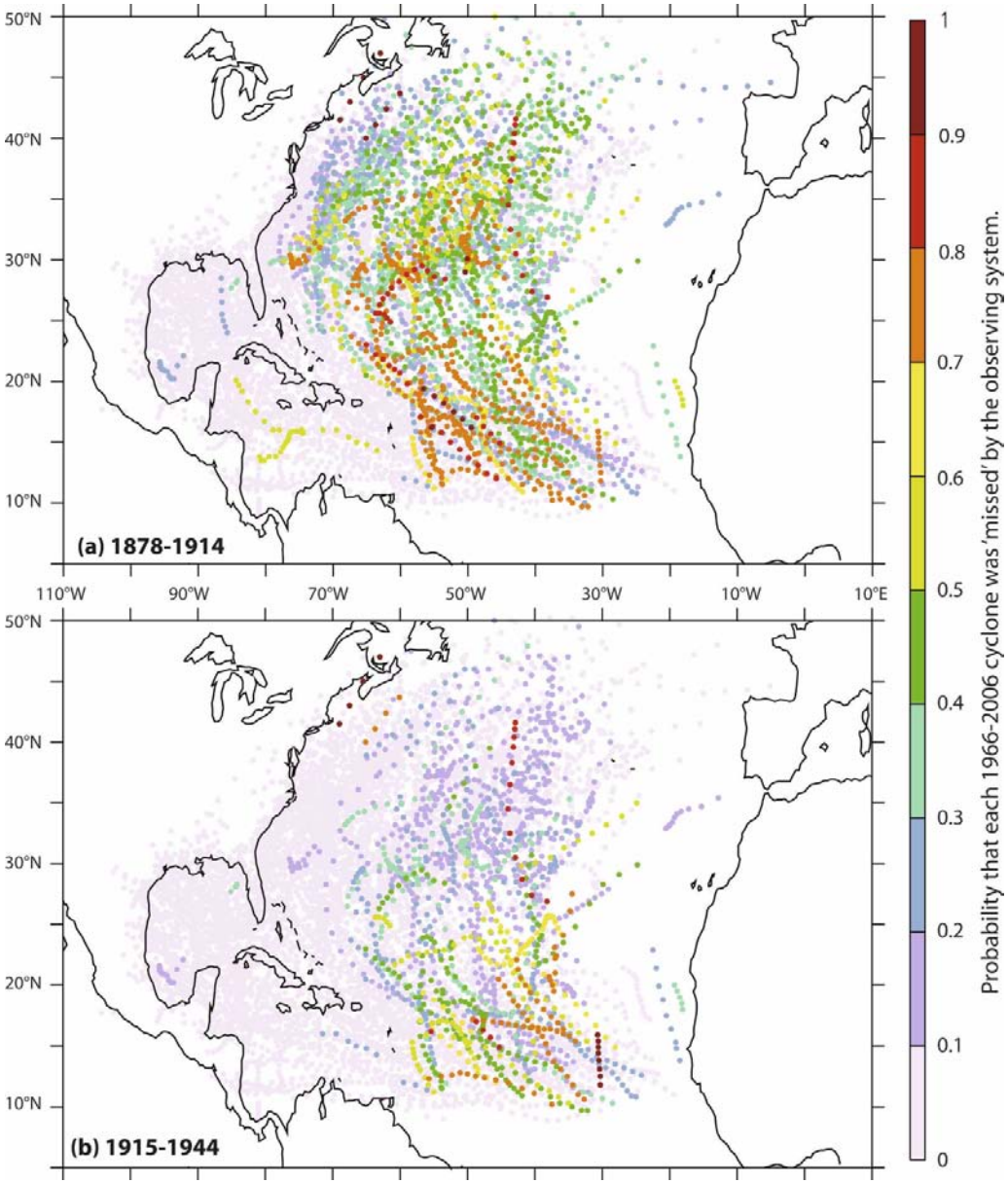
Estimating “missed” past tropical storms:

Vecchi and Kutson (2008, J. Clim)

- 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 equator-ward of 40°N. Monte Carlo simulation, varying storm radii within observationally justified bounds.
- All land assumed to be “perfect detector” of tropical storms (equator-ward of 40°N)—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.)

- **Can we reject hypothesis of no change to TS frequency?**

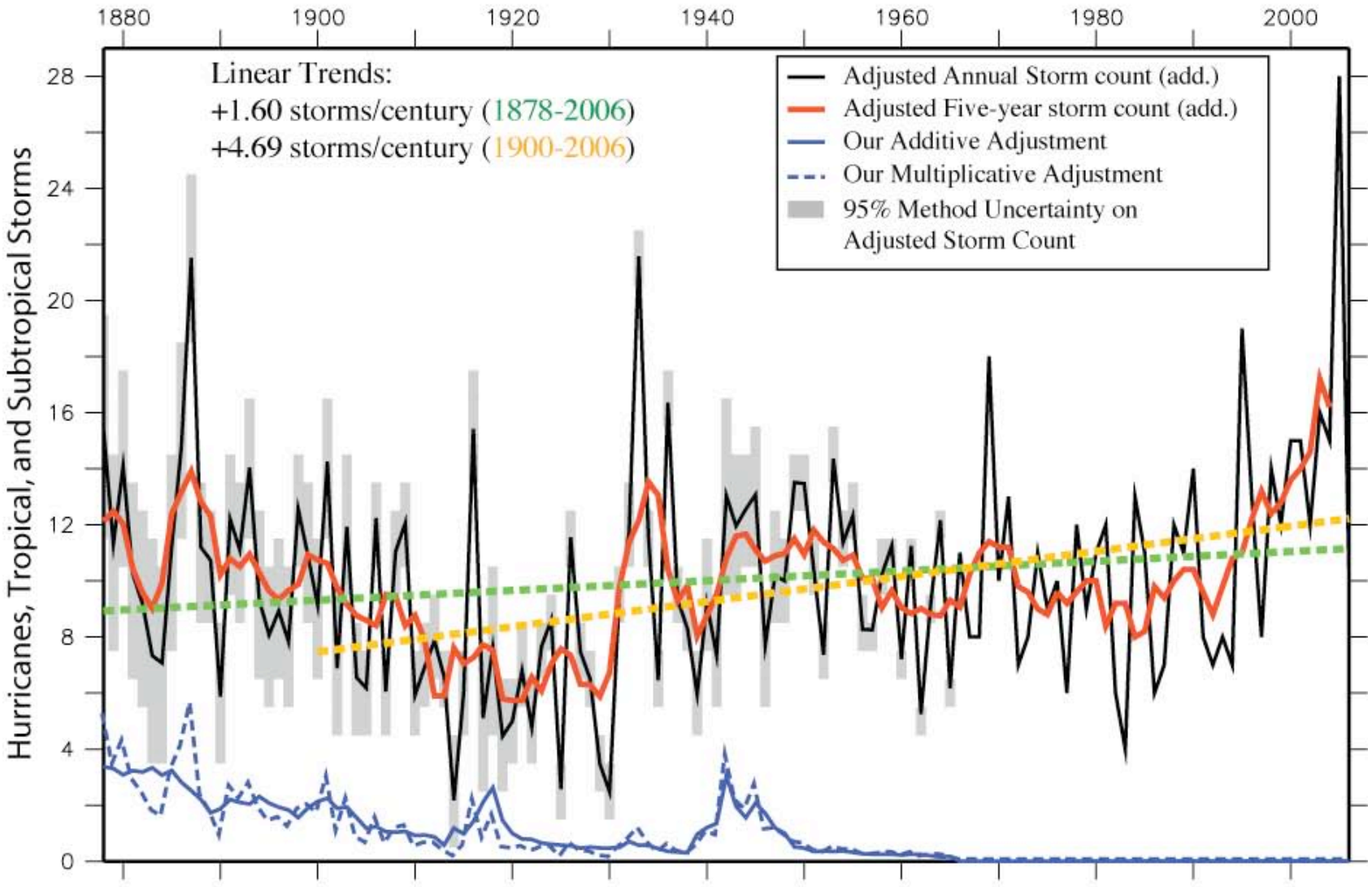
Probability we cannot exclude a storm from having been missed



- Storms near land least likely to have been "missed"
- "Detectability" increases with time.

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

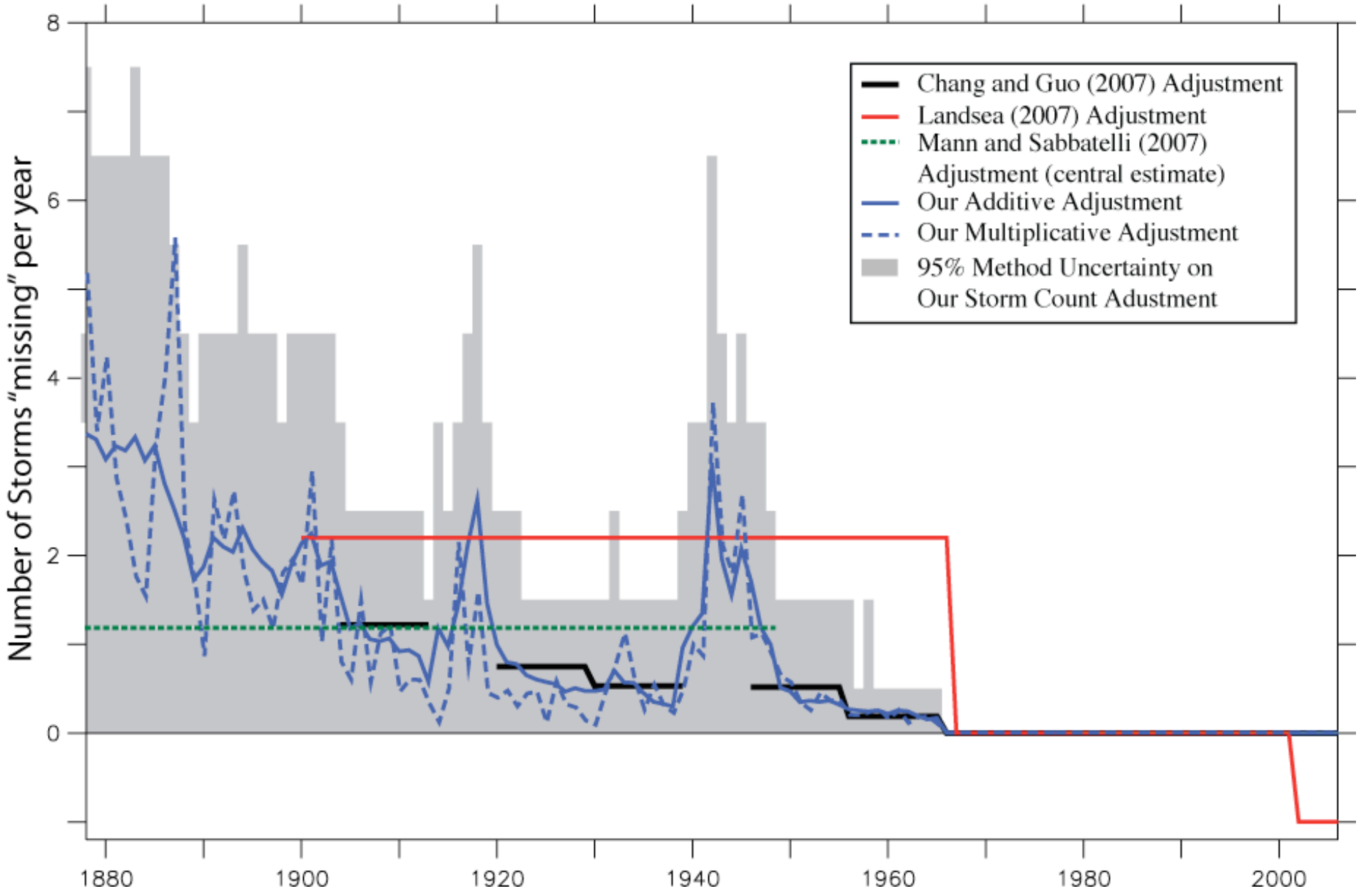
Atlantic Tropical Storm counts show no significant trend from 1878 after adjusting for 'missing storms' based on ship track densities.



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

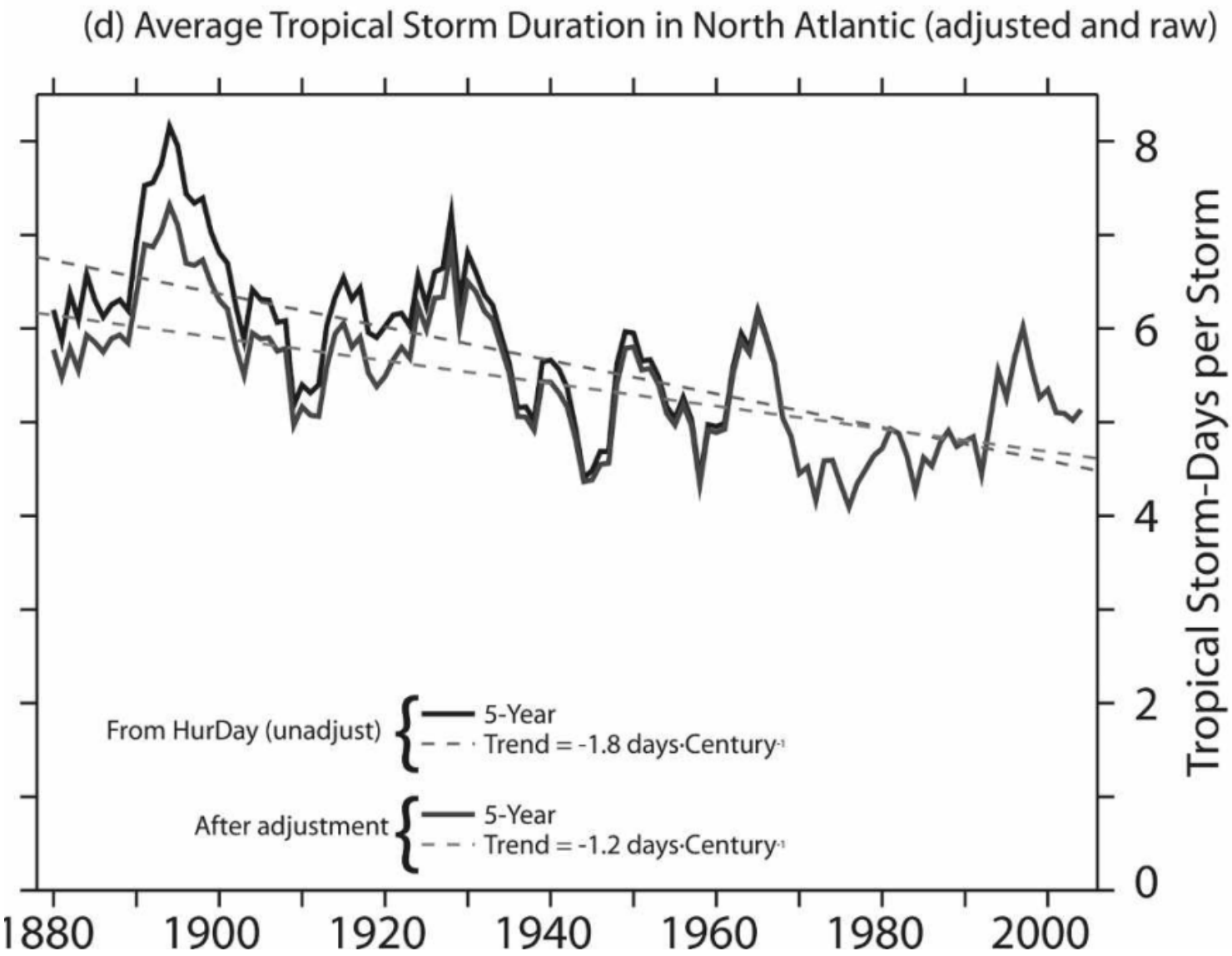
Source: Vecchi and Knutson, J. Climate, 2008.

Missing storm adjustments to HURDAT storms (1878-2007)



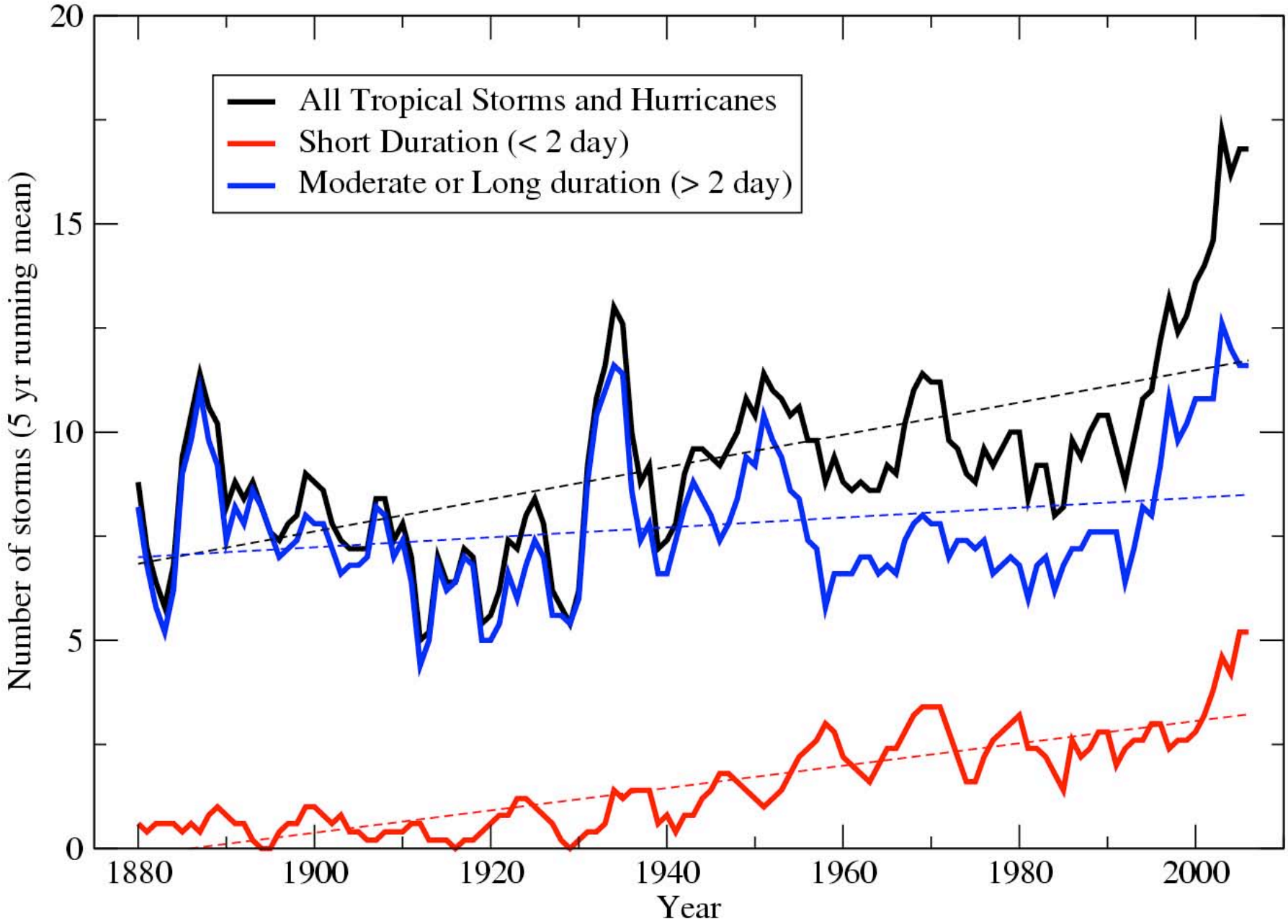
Source: Vecchi and Knutson, J. Climate, 2008.

Tropical storm duration exhibits a large decrease, even with adjustment: why?

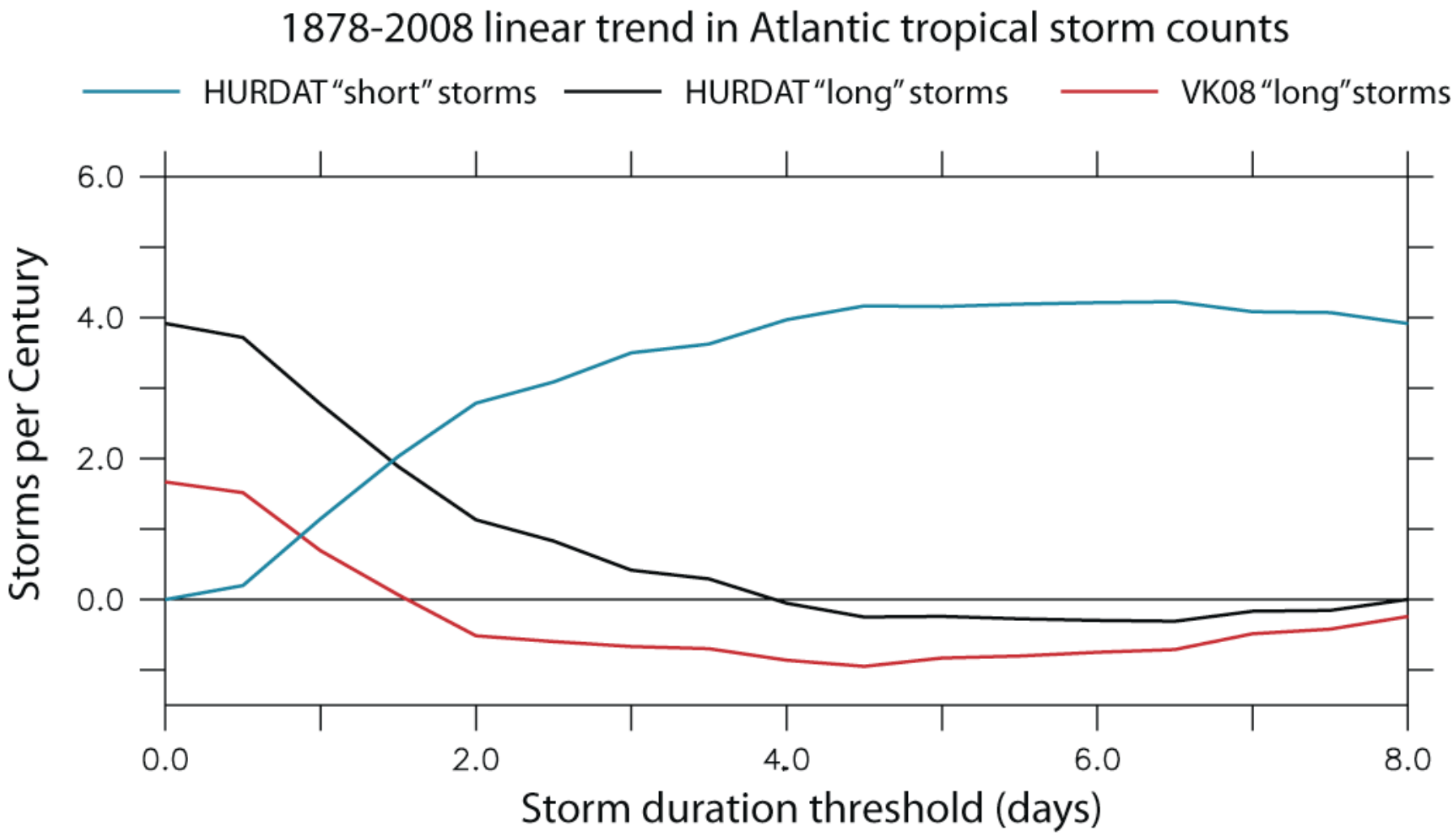


Source: Vecchi and Knutson, J. Climate, 2008.

Recorded increase in storm counts comes from short duration storms

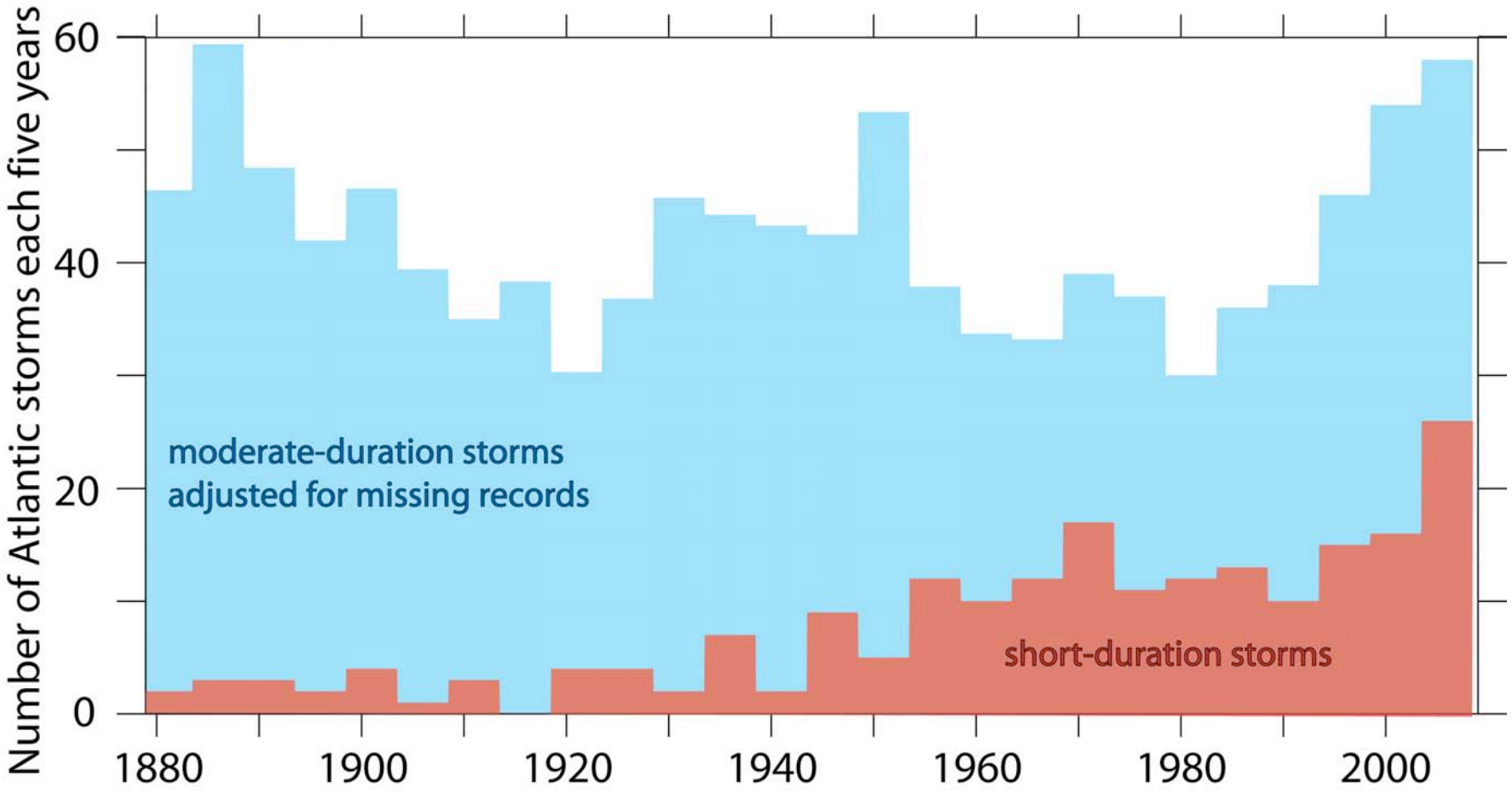


Source: Landsea, Vecchi, Bengtsson and Knutson, J. Climate, 2009.



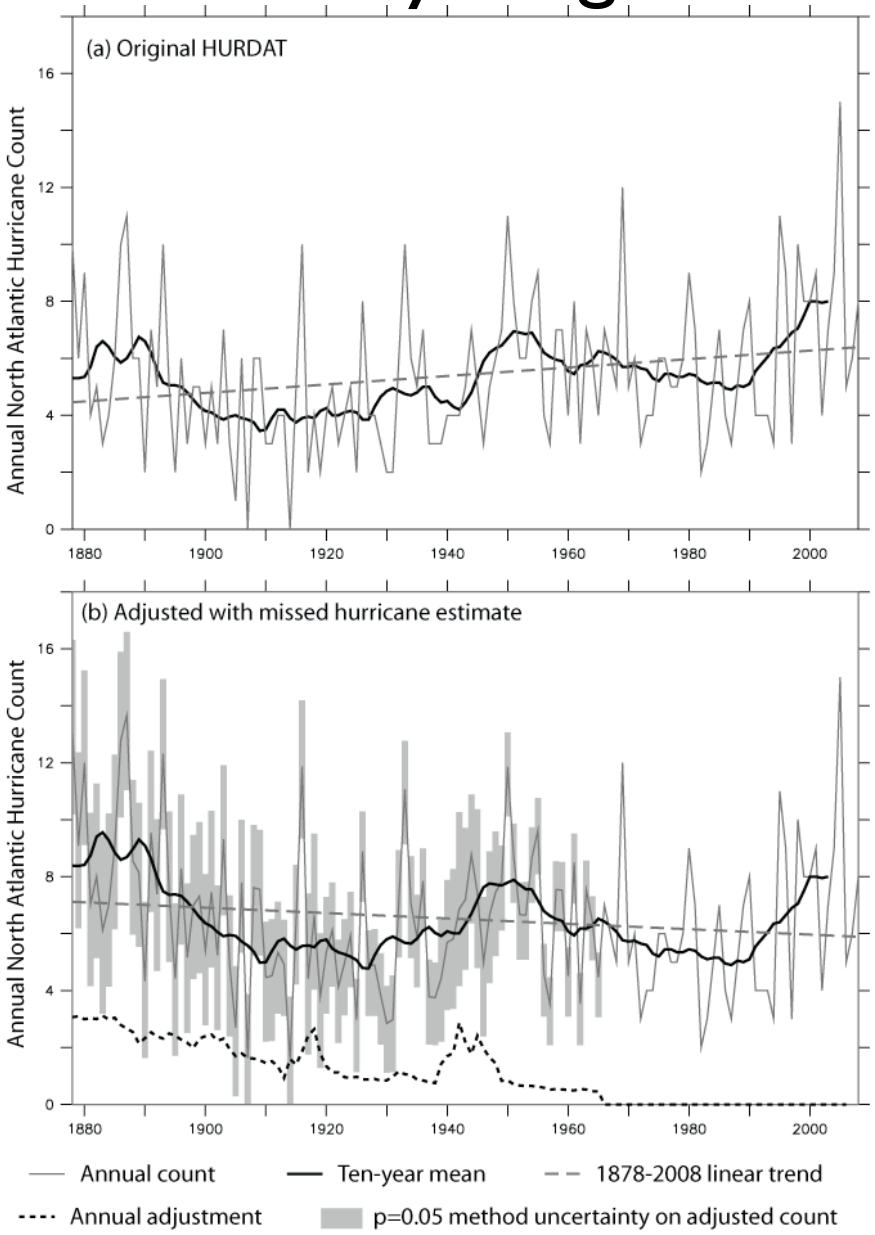
Source: Landsea, Vecchi, Bengtsson and Knutson, J. Climate, 2009.

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.



Hurricane frequency

Adjustment to hurricane counts leads to a nominally long-term decrease in hurricanes.

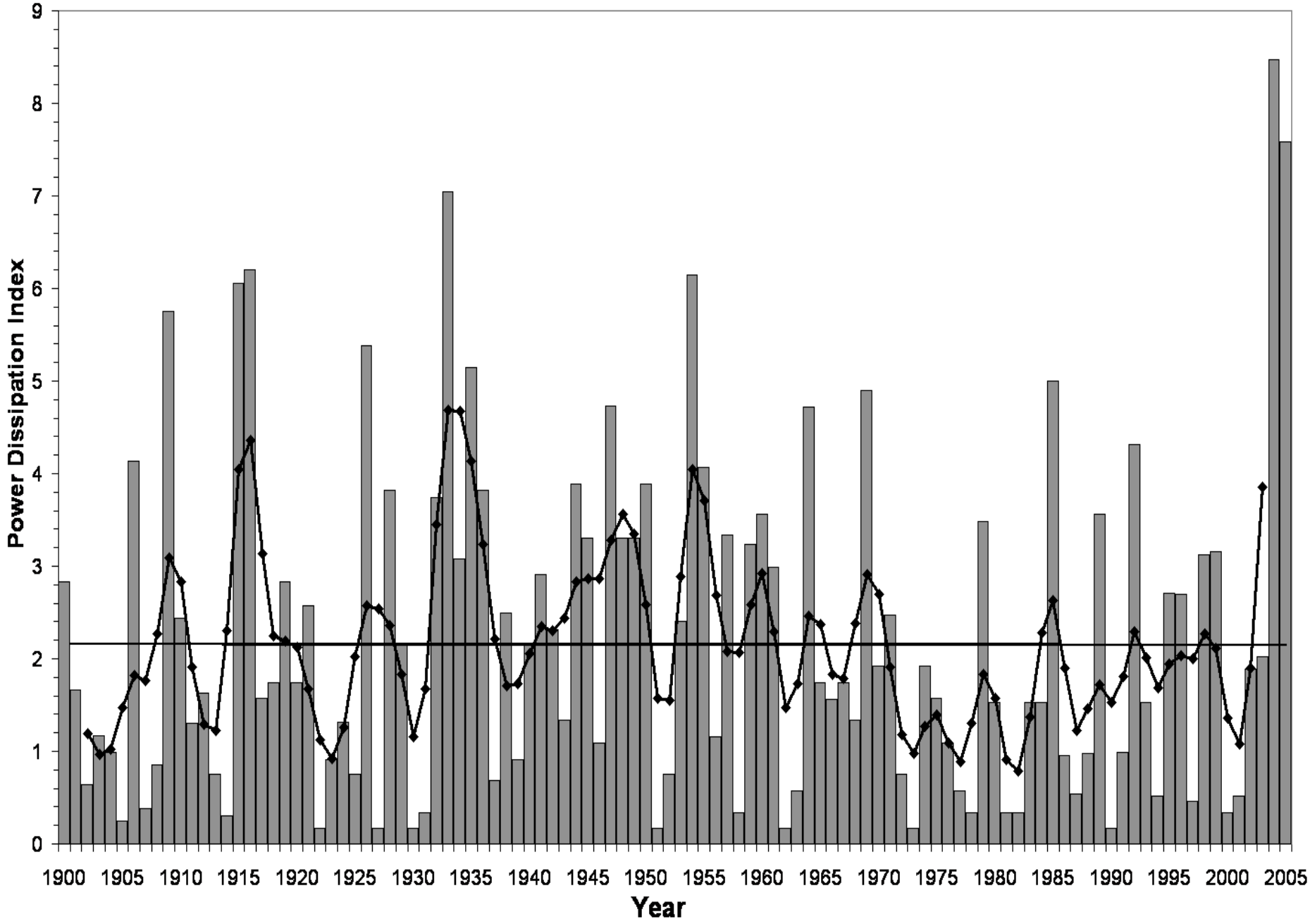


Significant increase in HURDAT recorded hurricane frequency

Accounting for observing system changes, cannot reject null hypothesis of no long-term change in frequency.

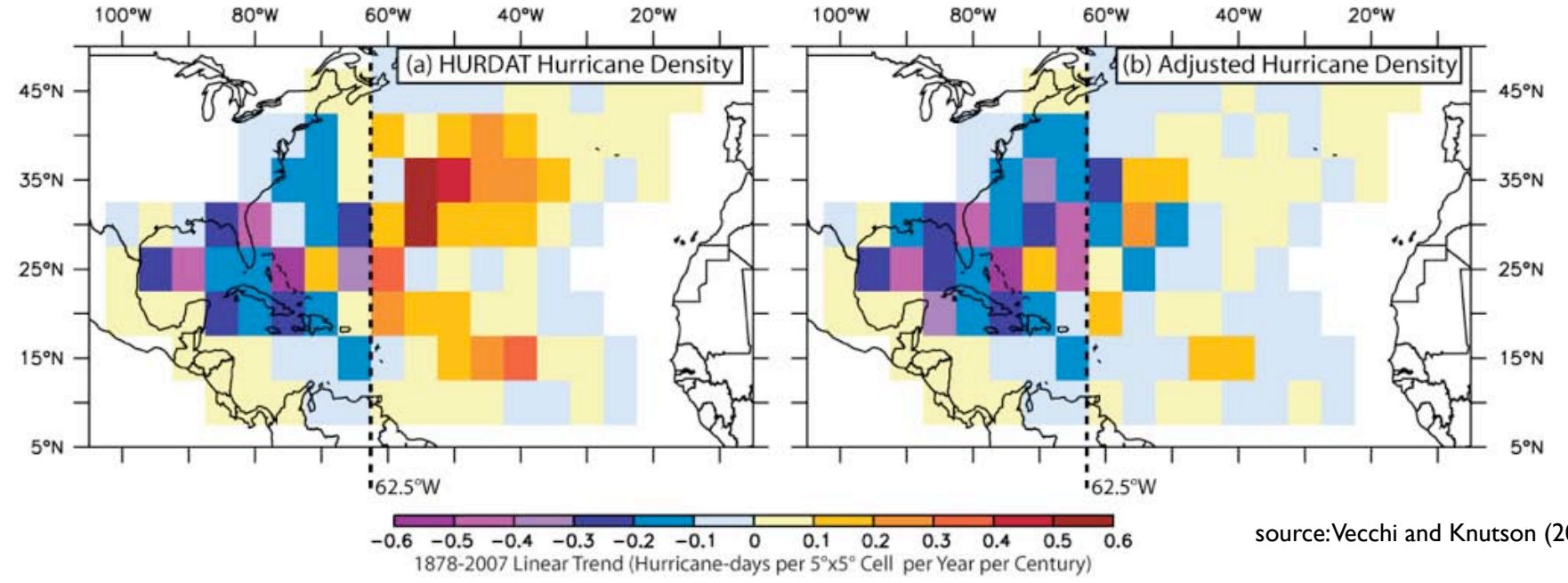
source: Vecchi and Knutson (2010, in prep)

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

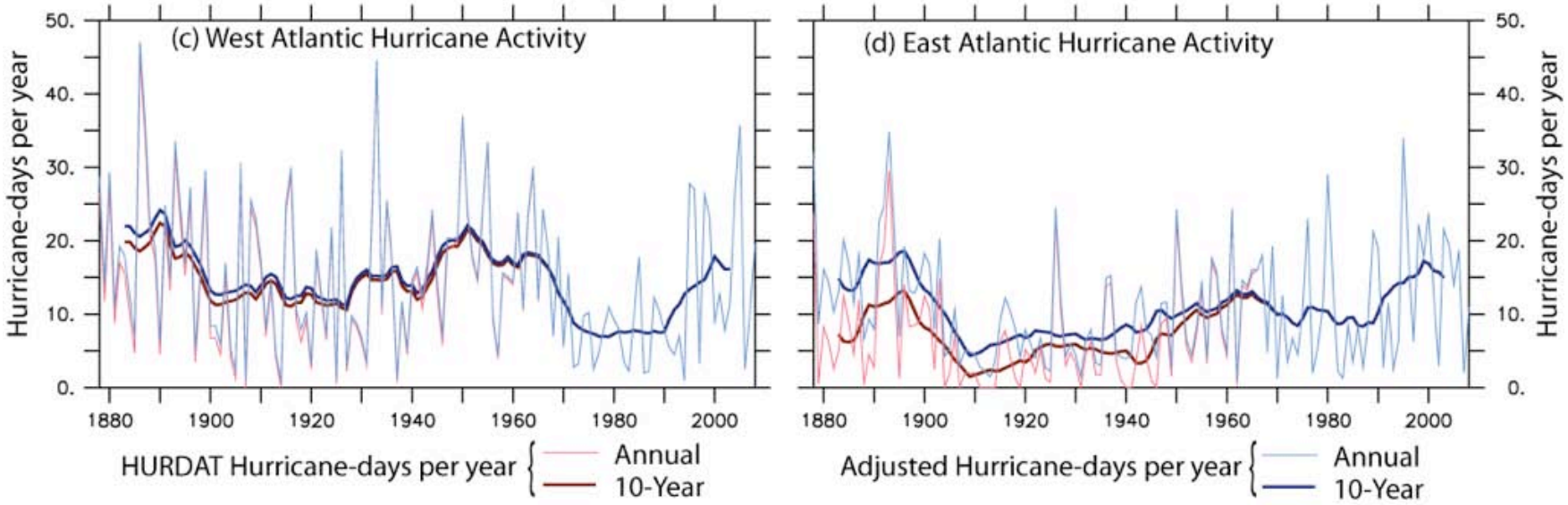


Source: Chris Landsea, NOAA/NHC

Hurricane activity shifts eastward in long-term (similar change in TSs)



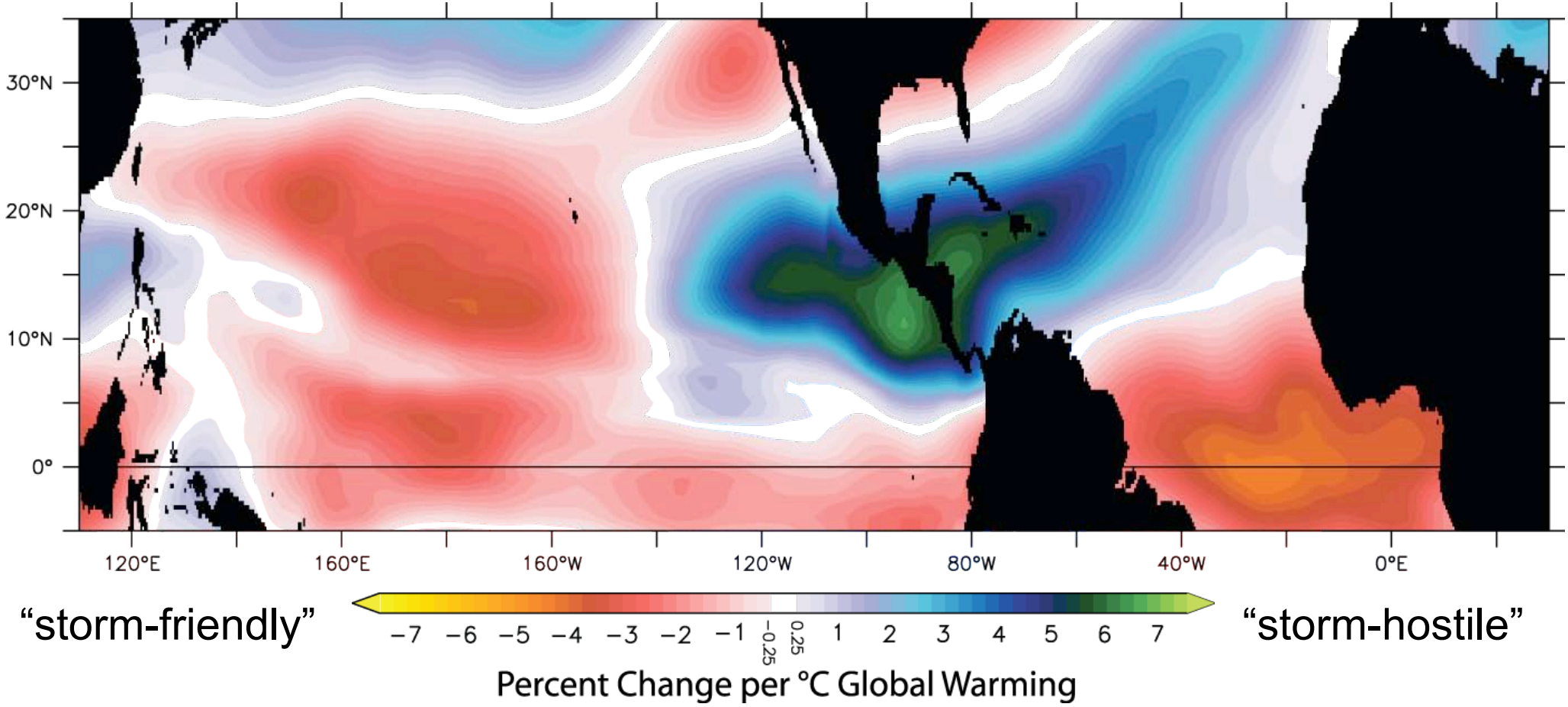
source: Vecchi and Knutson (2010, in prep)



Projected 21st Century Changes in Vertical Wind Shear

from Vecchi and Soden (2007, GRL)

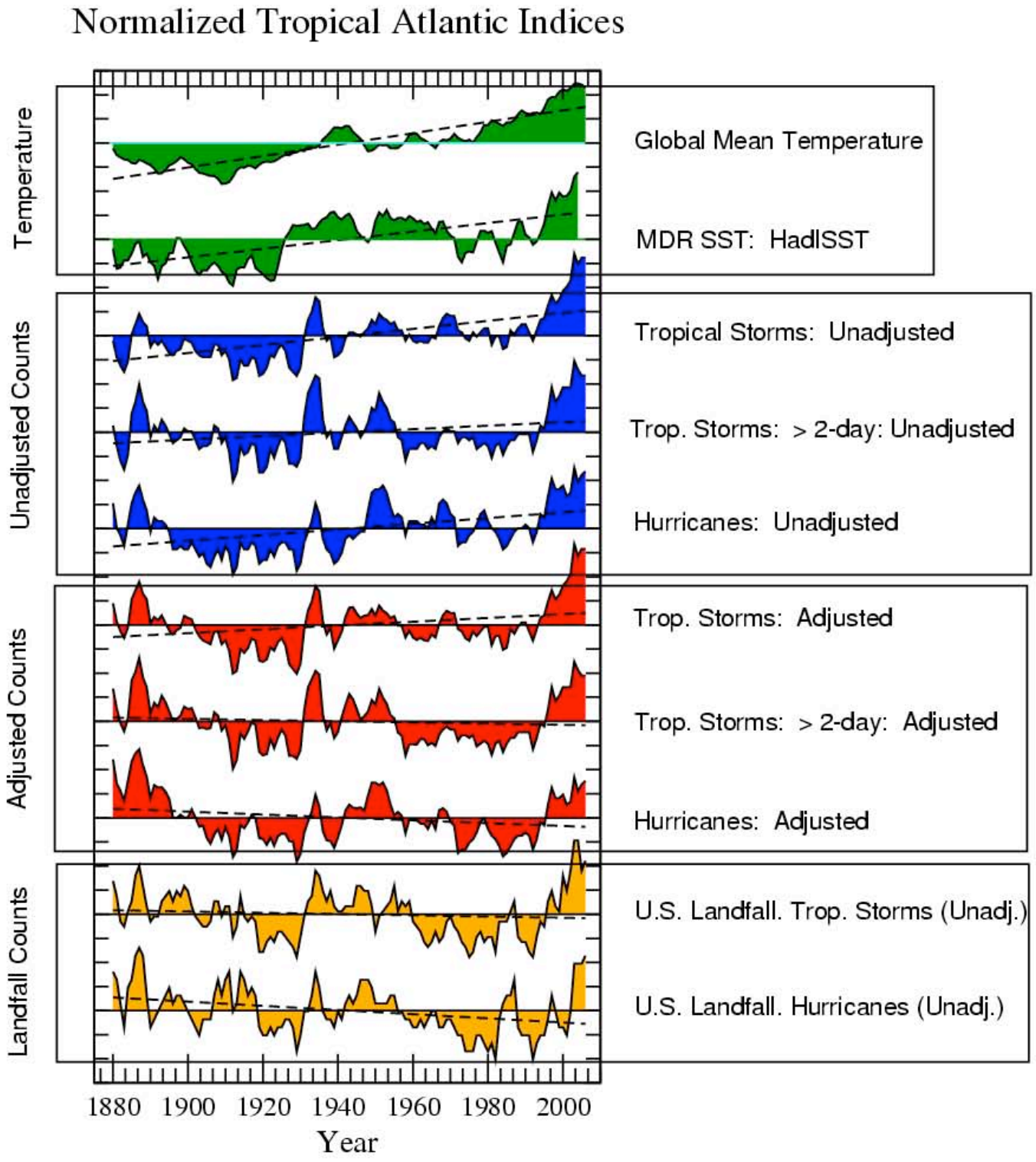
Average of 18 models, Jun-Nov



"storm-friendly" "storm-hostile"

Over swath of tropical Atlantic and East Pacific, increased wind-shear.

If (**big IF**) eastward shift is real, is it response to anthropogenic increase in shear?

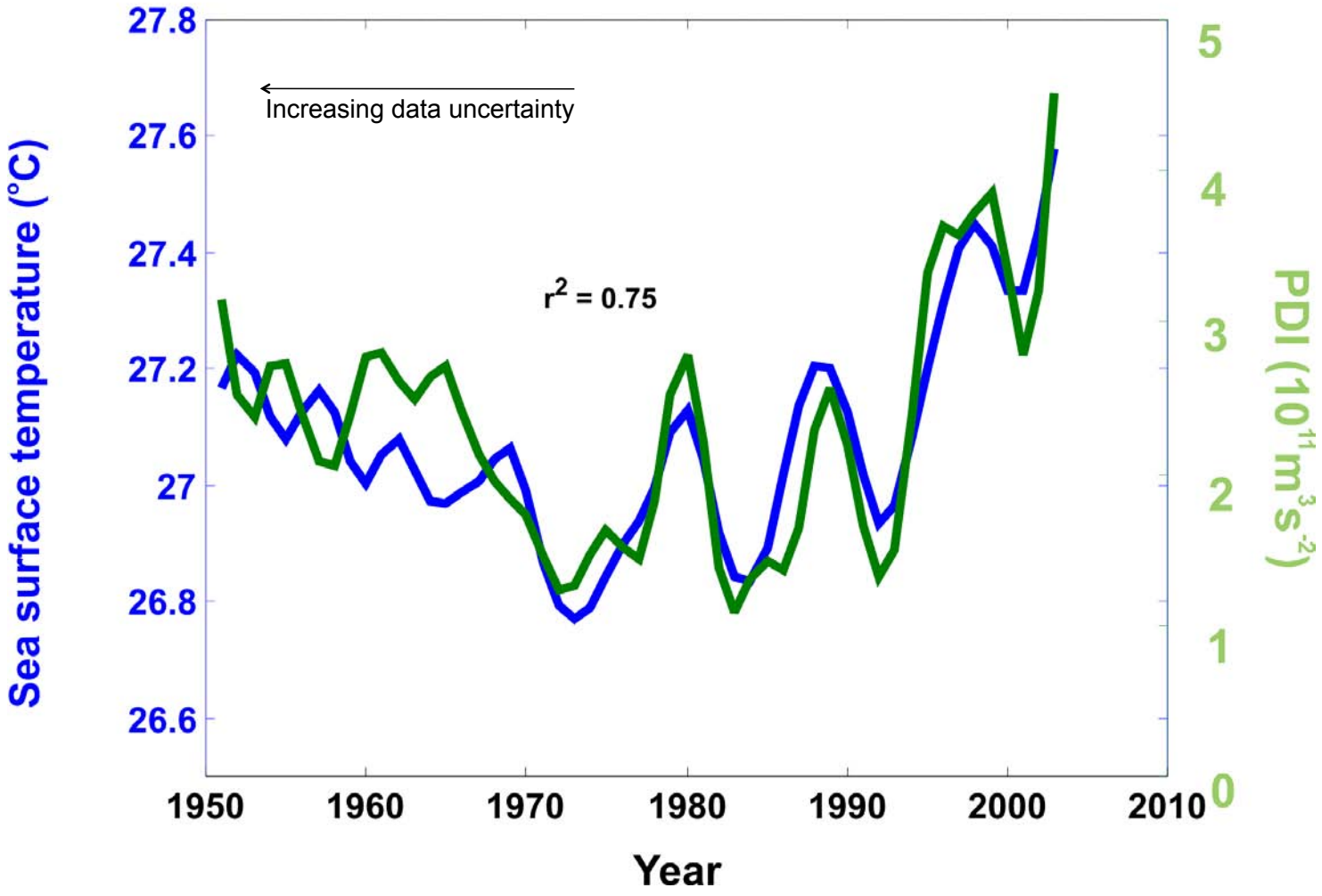


Sources:

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

Changes in Integrated Activity and SST

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…

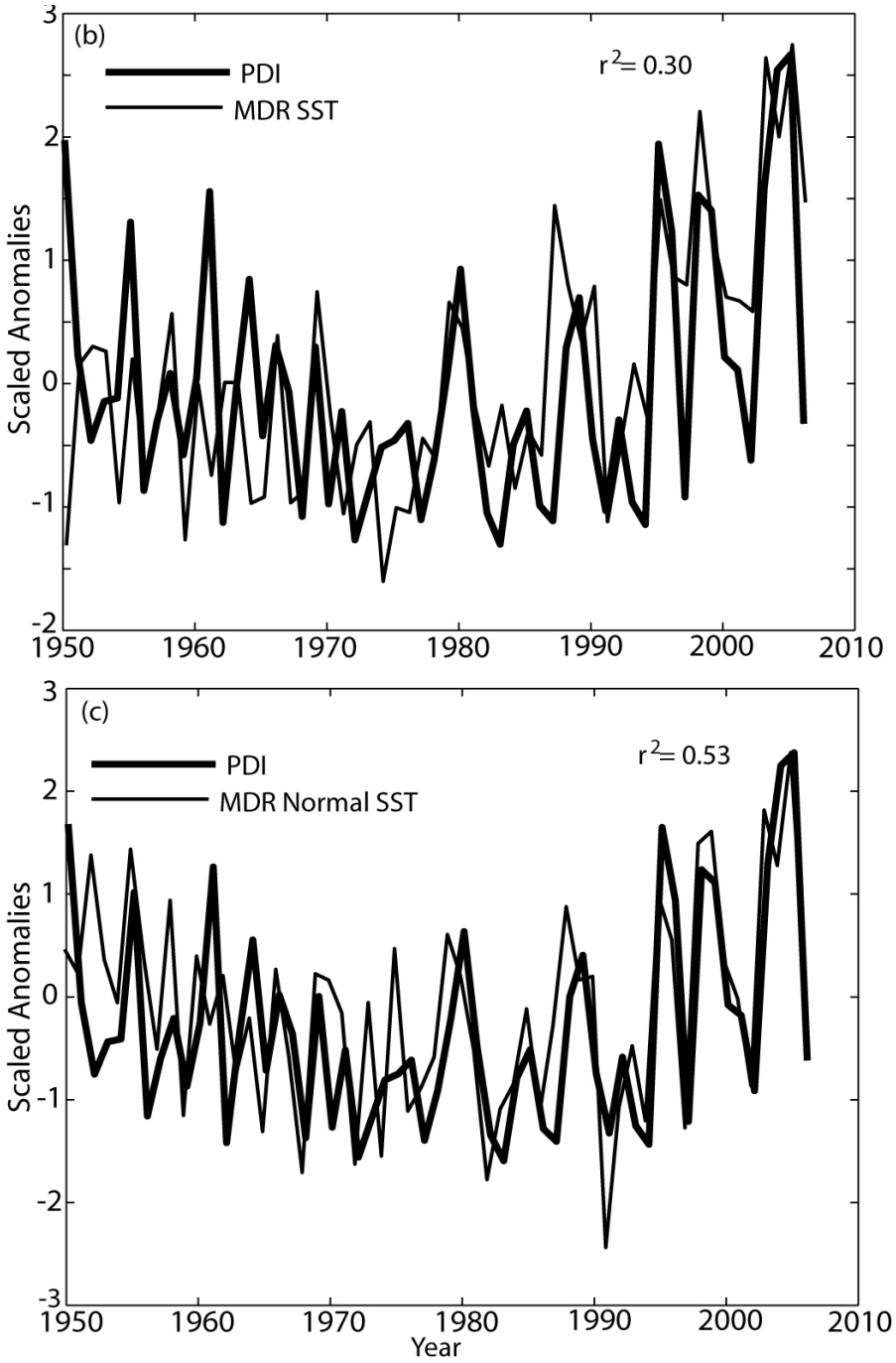


PDI is proportional to the time integral of the cube of the surface wind speeds accumulated across all storms over their entire life cycles.

Source: Emanuel, J. Climate (2007).

Should local Atlantic SST be predictor for PDI?

- Remote SST changes impact Atlantic wind shear:
  - During El Niño (e.g., Gray 1975)
  - Warming-induced weakening of Walker circulation increases shear (Vecchi and Soden 2007)
  - Warming of Indo-West Pacific increases shear (Latif et al 2007, GRL)
- Remote warming acts to increase thermodynamic stability:
  - WTG hypothesis (Sobel et al 2002)
  - Potential intensity described by warming relative to tropical-mean (Vecchi and Soden 2007)
- High-resolution studies indicate warming relative to tropical-mean relevant quantity:
  - Knutson et al (2008)
  - Zhao et al (2009)



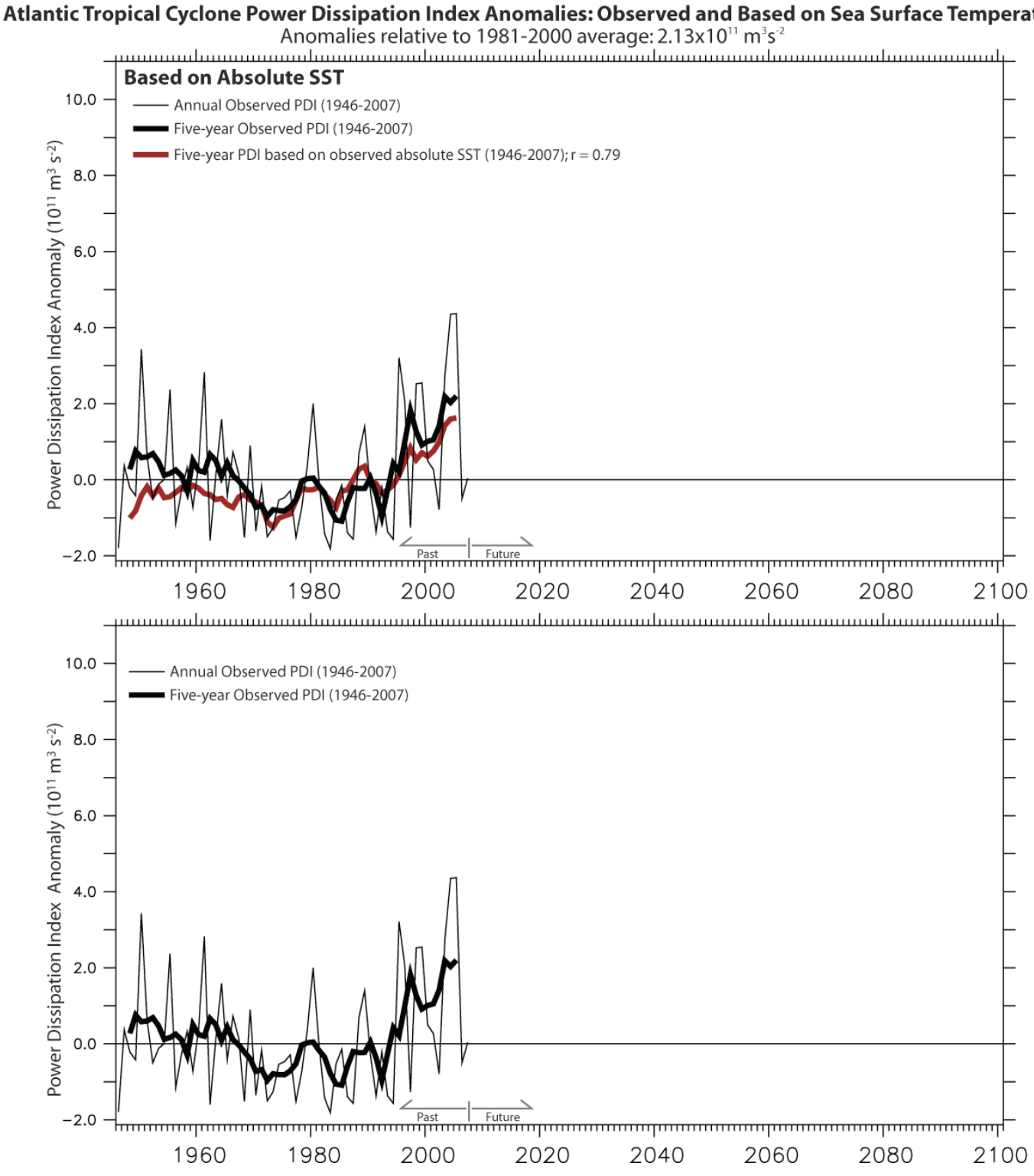
Atlantic hurricane activity (PDI) is correlated with:

- local Atlantic SST (top)

and

- Atlantic SST relative to tropical mean SST (bottom).

Source: Swanson, *G-cubed*, 2008

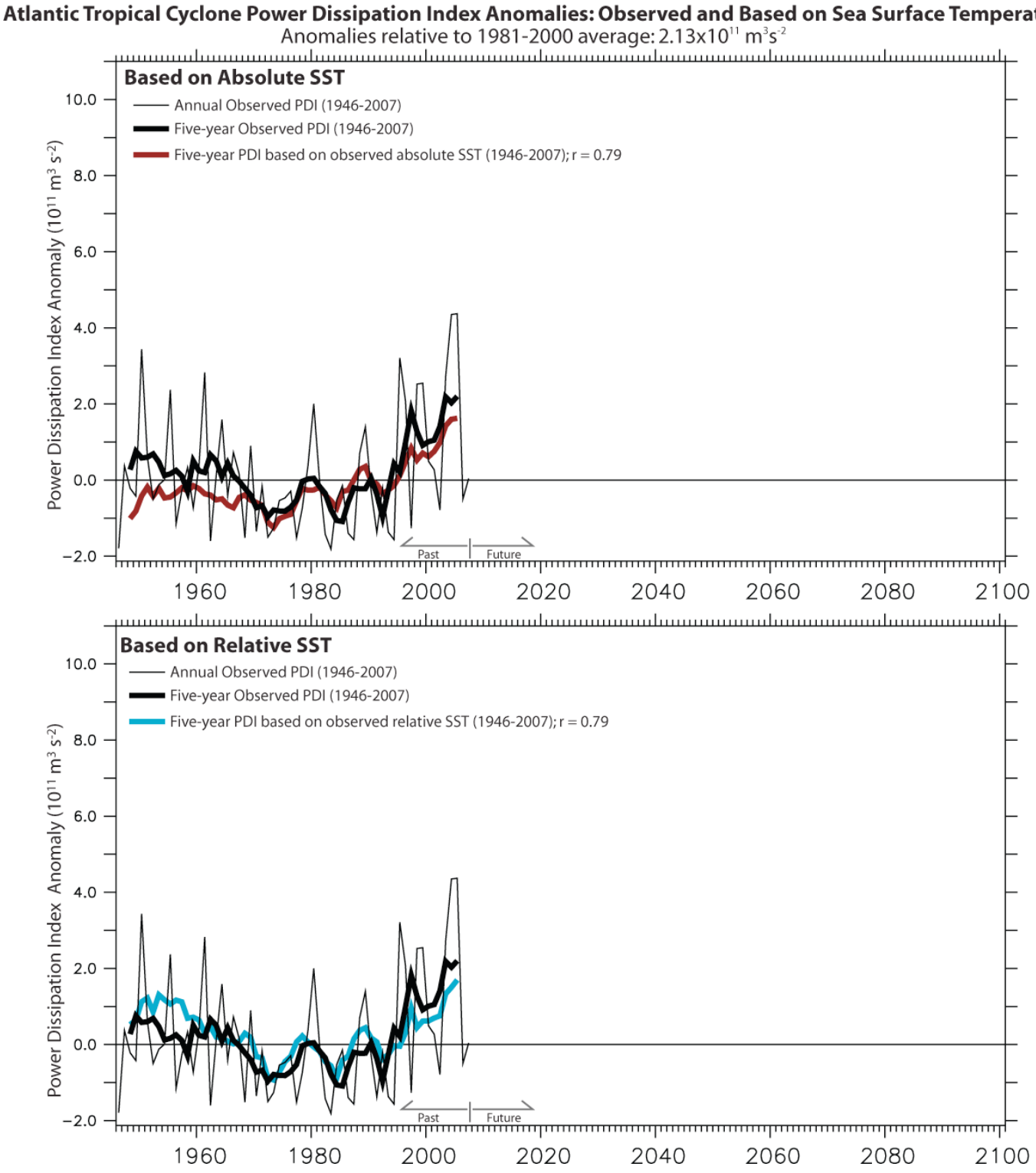


Observed PDI

PDI Regressed on:
Absolute SST

If causal, can attribute.

Vecchi, Swanson and Soden (2008, Science)



Observed PDI

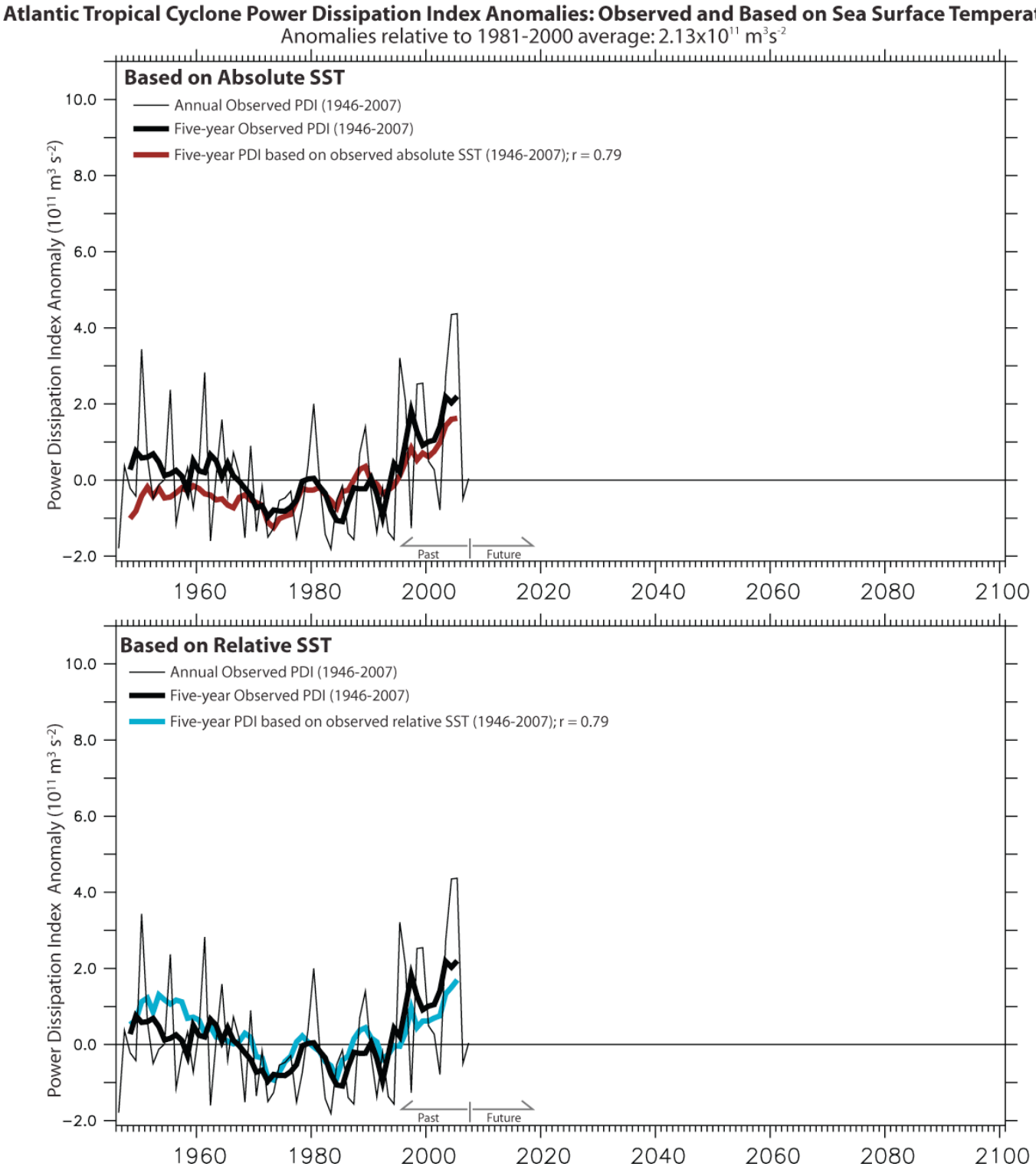
PDI Regressed on:
Absolute SST

If causal, can attribute.

PDI Regressed on:
Relative SST

If causal, **cannot** attribute.

Vecchi, Swanson and Soden (2008, Science)



Observed PDI

PDI Regressed on:
Absolute SST

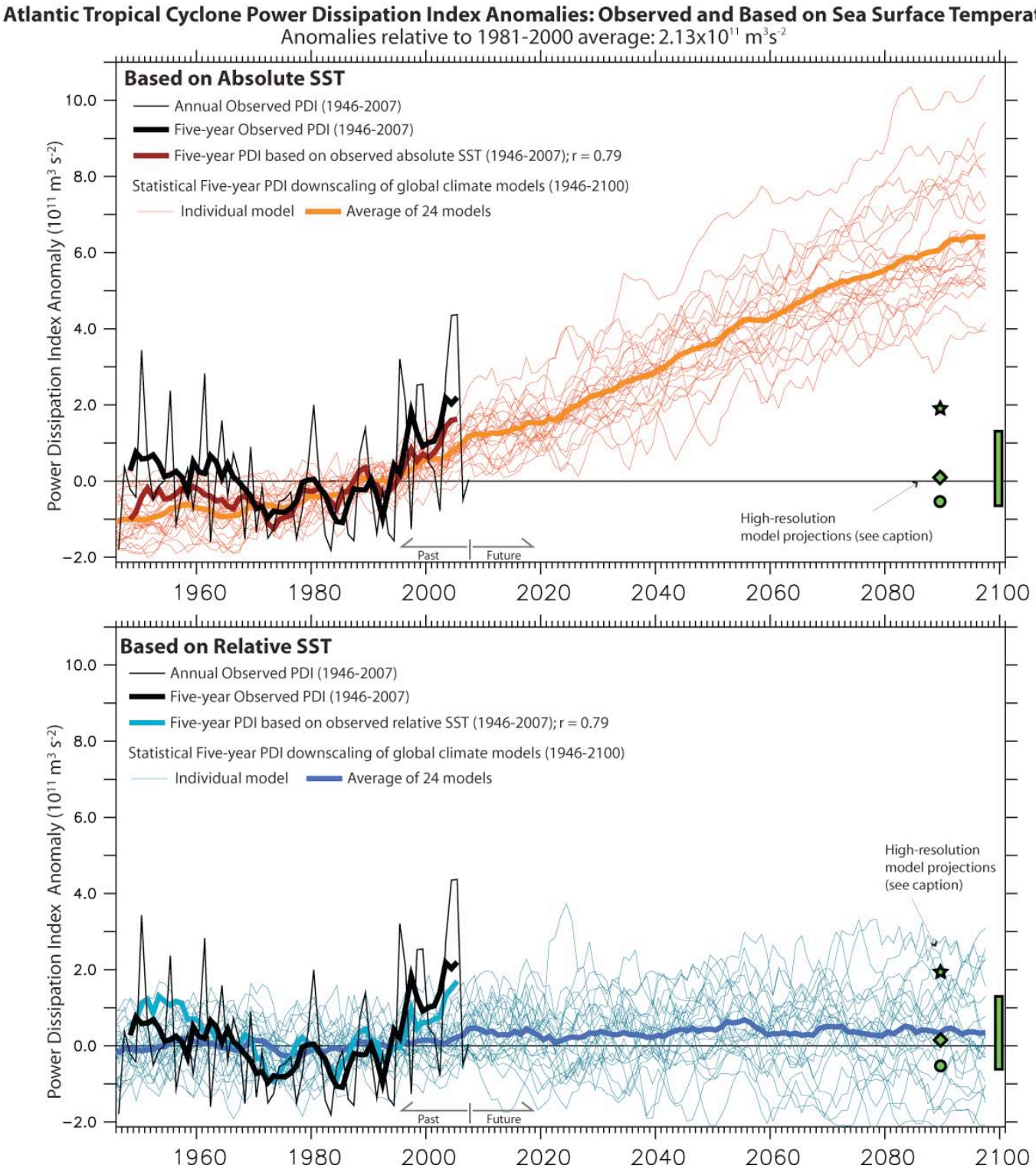
If causal, can attribute.

Correlation does not imply causation!

PDI Regressed on:
Relative SST

If causal, **cannot** attribute.

Vecchi, Swanson and Soden (2008, Science)



Observed PDI

PDI Regressed on:
Absolute SST
Model Abs. SST

High-resolution model activity change

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

PDI Regressed on:
Relative SST
Model Rel. SST

Vecchi, Swanson and Soden (2008, Science)

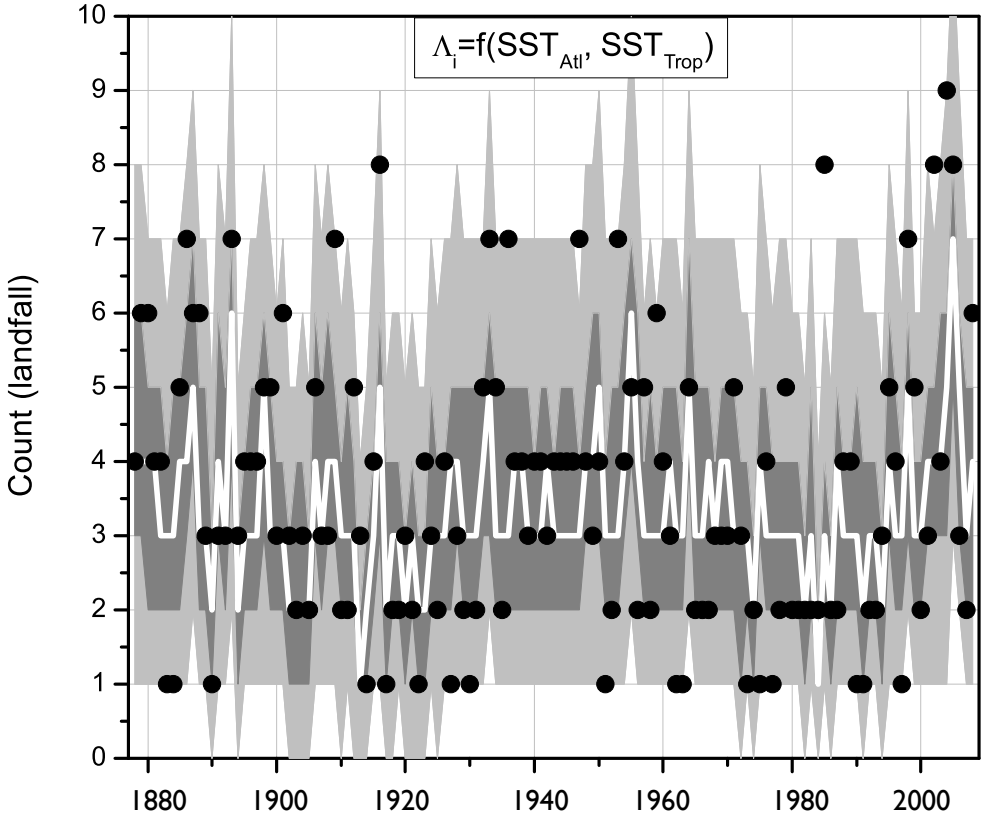
Statistical modeling of tropical storm counts

Collaboration with Gabriele Villarini and Jim Smith
Princeton CEE

Statistical models of TS frequency

- Build statistical models of TS frequency:
  - >2 day duration basin-wide with and without adjustment
  - Landfalling
- Explore range of models:
  - Sensitivity to covariates (NAO, SOI, Atlantic SST, Tropical SST)
  - Sensitivity to model structure (Poisson vs. Negative Binomial).
- Apply to GCM projections and other runs.

U.S. landfalling tropical storms using Atlantic and Tropical-mean SST as covariates



Villarini, Vecchi and Smith (2010, in prep)

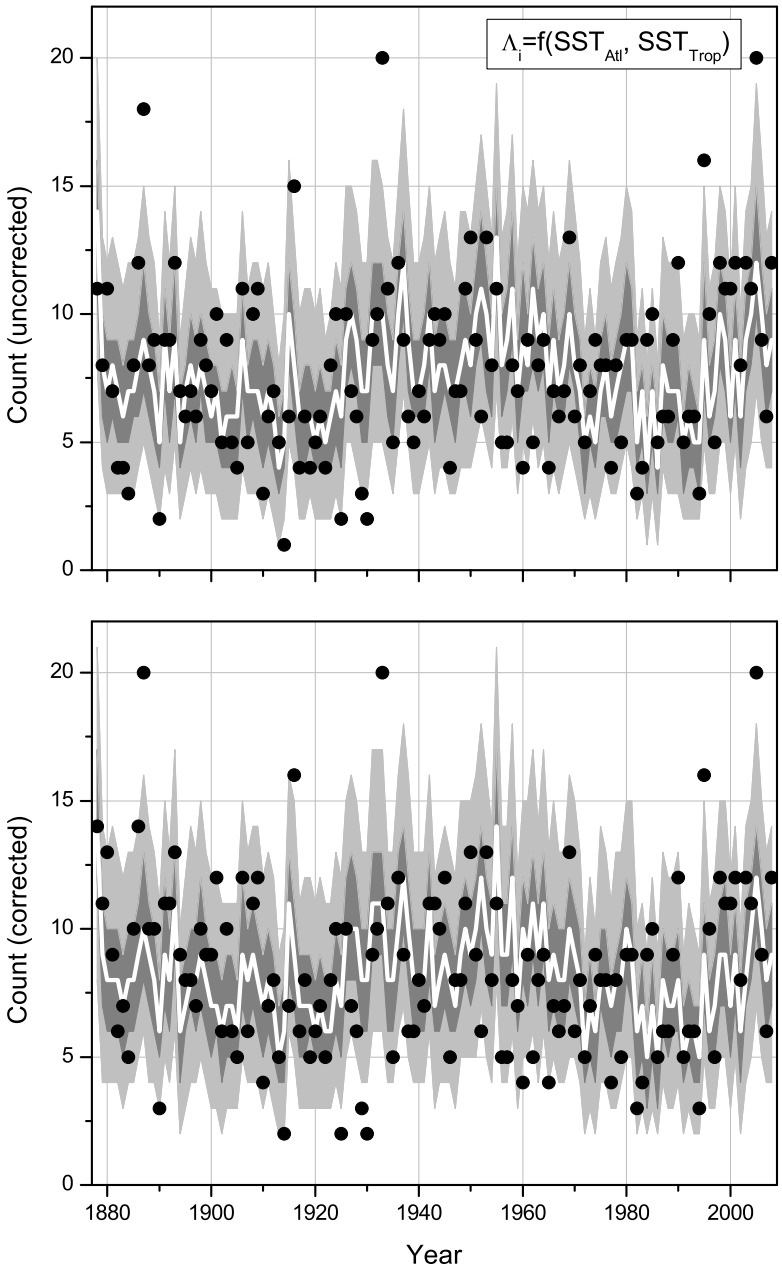
Atlantic SST increases frequency.

Tropical-mean SST reduces frequency.

Factors in fit (w/standard error)

	Landfall
Intercept	1.24 (0.05) 1.24 (0.05)
NAO	- -
SOI	- -
SST_{Atl}	0.89 (0.24) 0.86 (0.22)
SST_{Trop}	-0.89 (0.34) -0.86 (0.30)

Basin-wide tropical storms using Atlantic and Tropical-mean SST as covariates



Atlantic SST increases frequency.

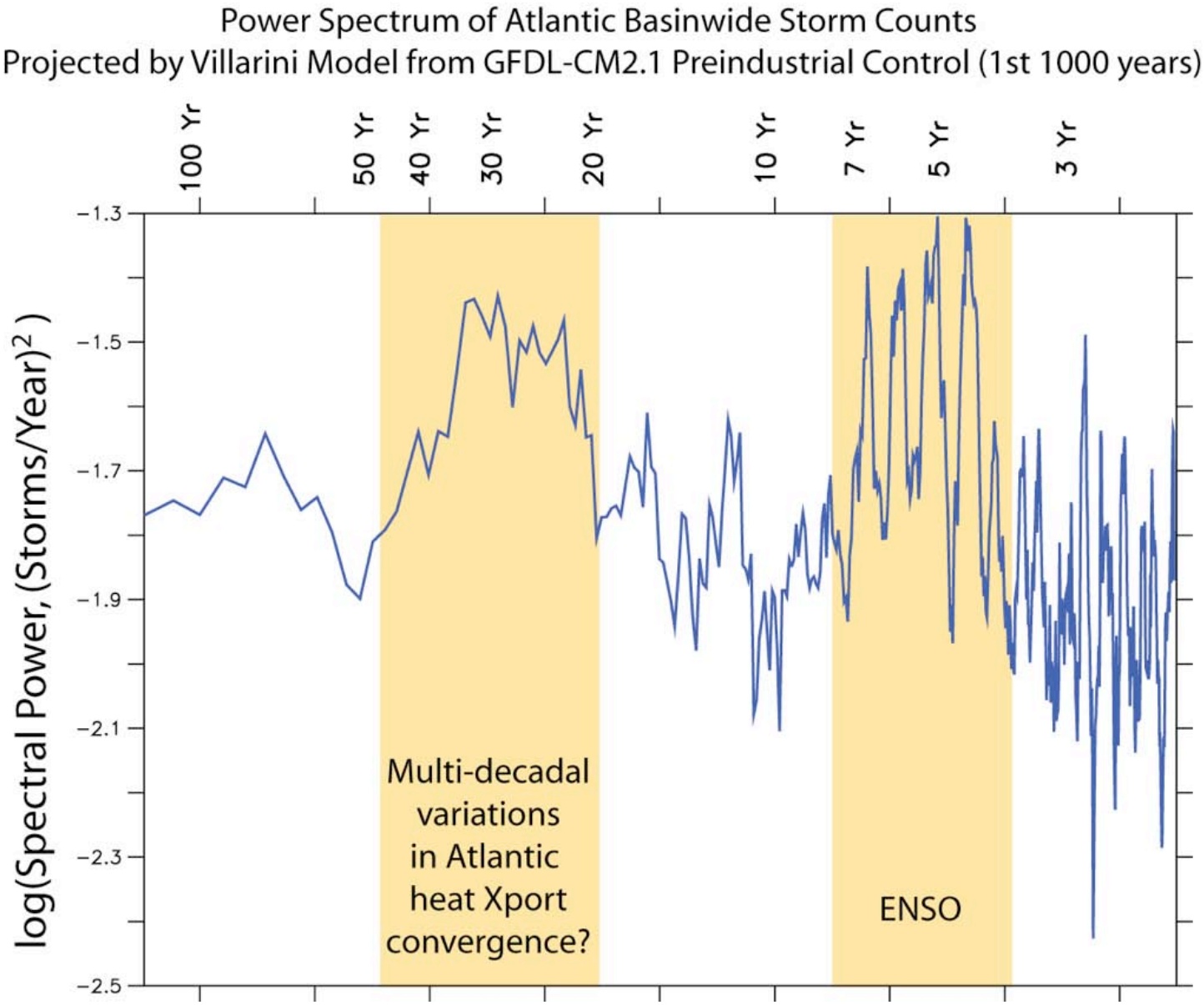
Tropical-mean SST reduces frequency.

Factors in fit (w/standard error)

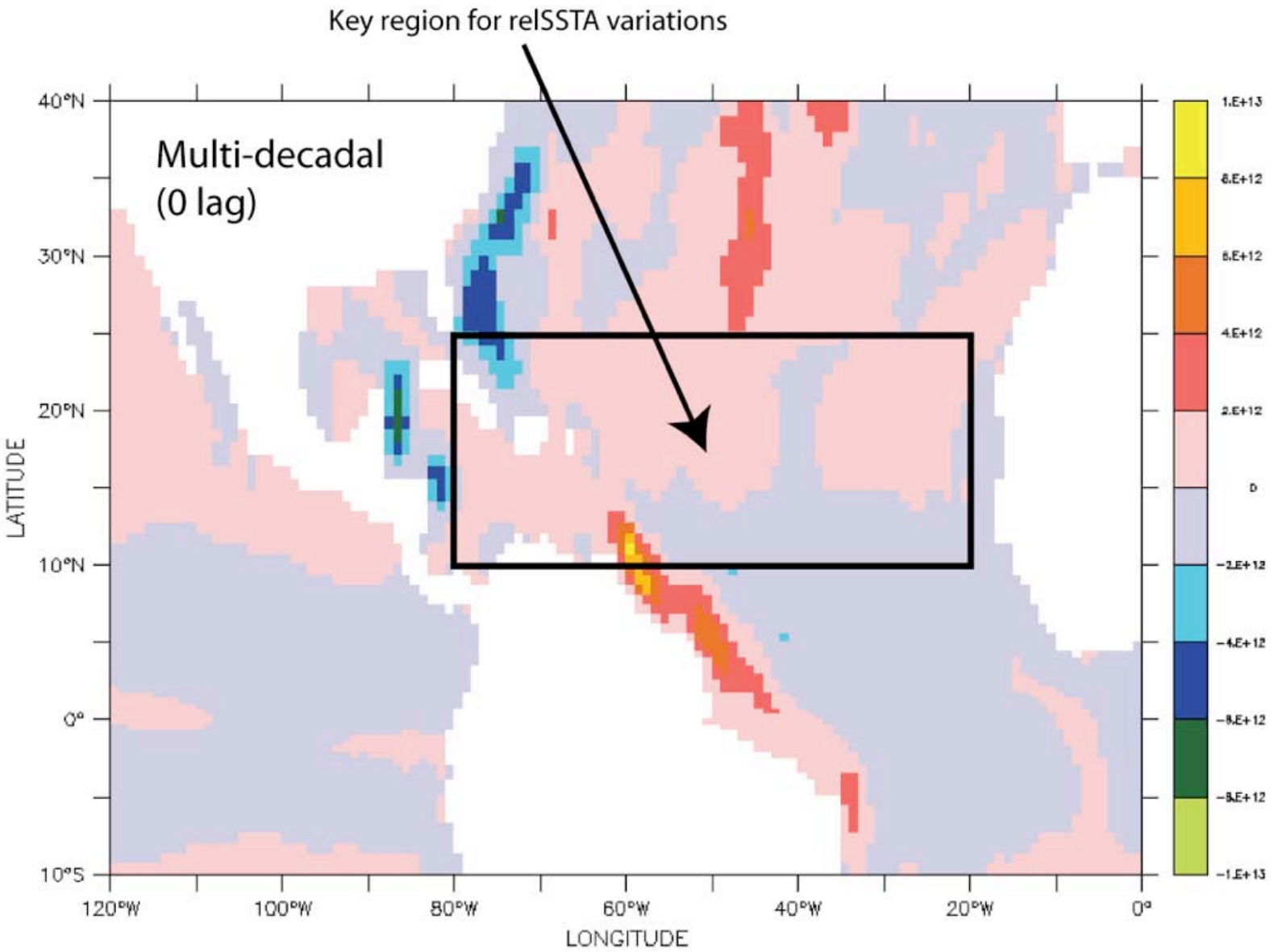
	Uncorrected	Corrected
Intercept	2.03 (0.03) 2.03 (0.03)	2.11 (0.03) 2.10 (0.03)
SST_{Atl}	1.13 (0.20) 1.05 (0.15)	1.05 (0.15) 1.02 (0.14)
SST_{Trop}	-0.98 (0.23) -0.91 (0.20)	-1.22 (0.22) -1.05 (0.19)

Villarini, Vecchi and Smith (2010, in prep)

Statistical downscaling of 2,000 year CM2.1 Control

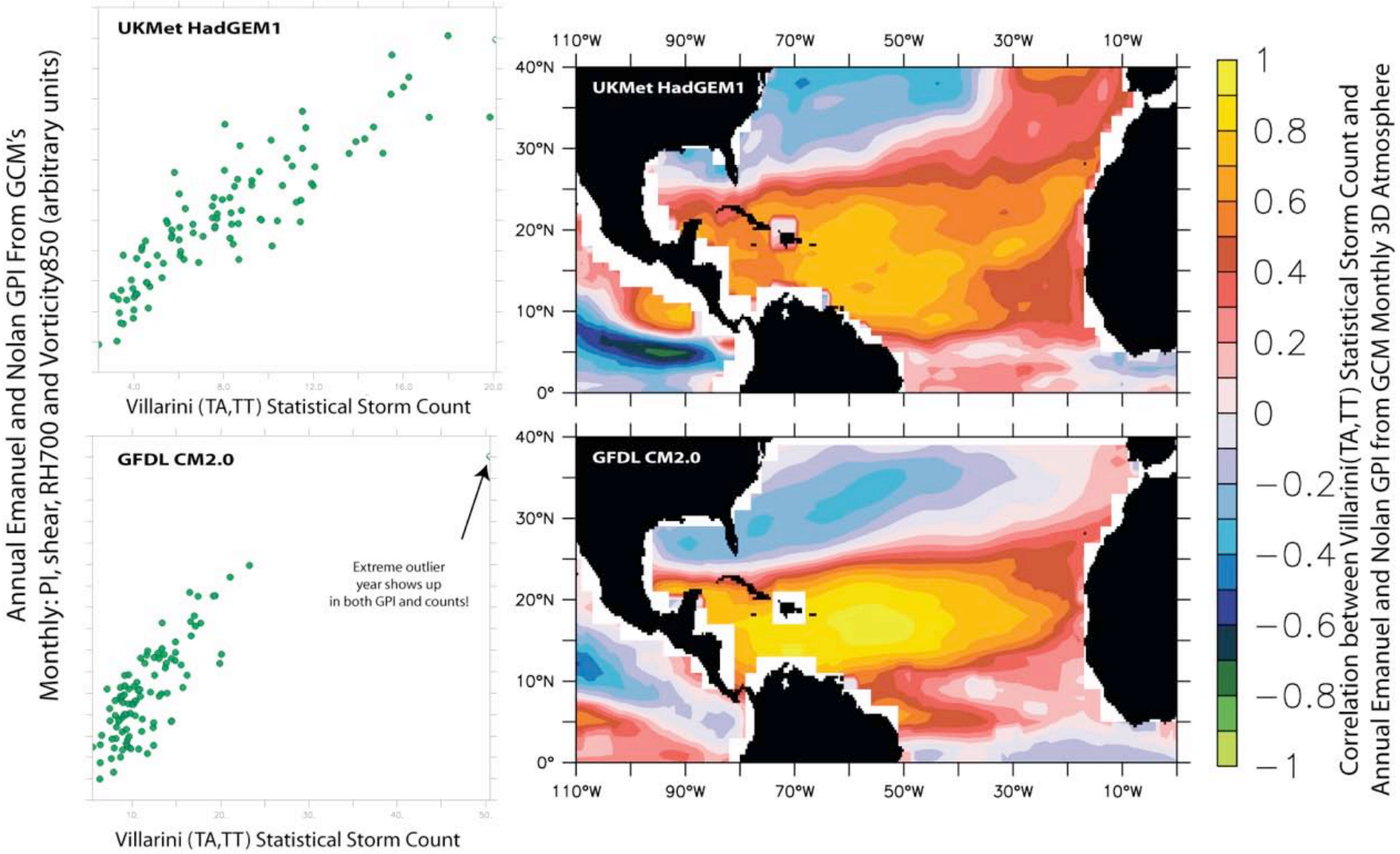


Statistical counts and ocean heat transport

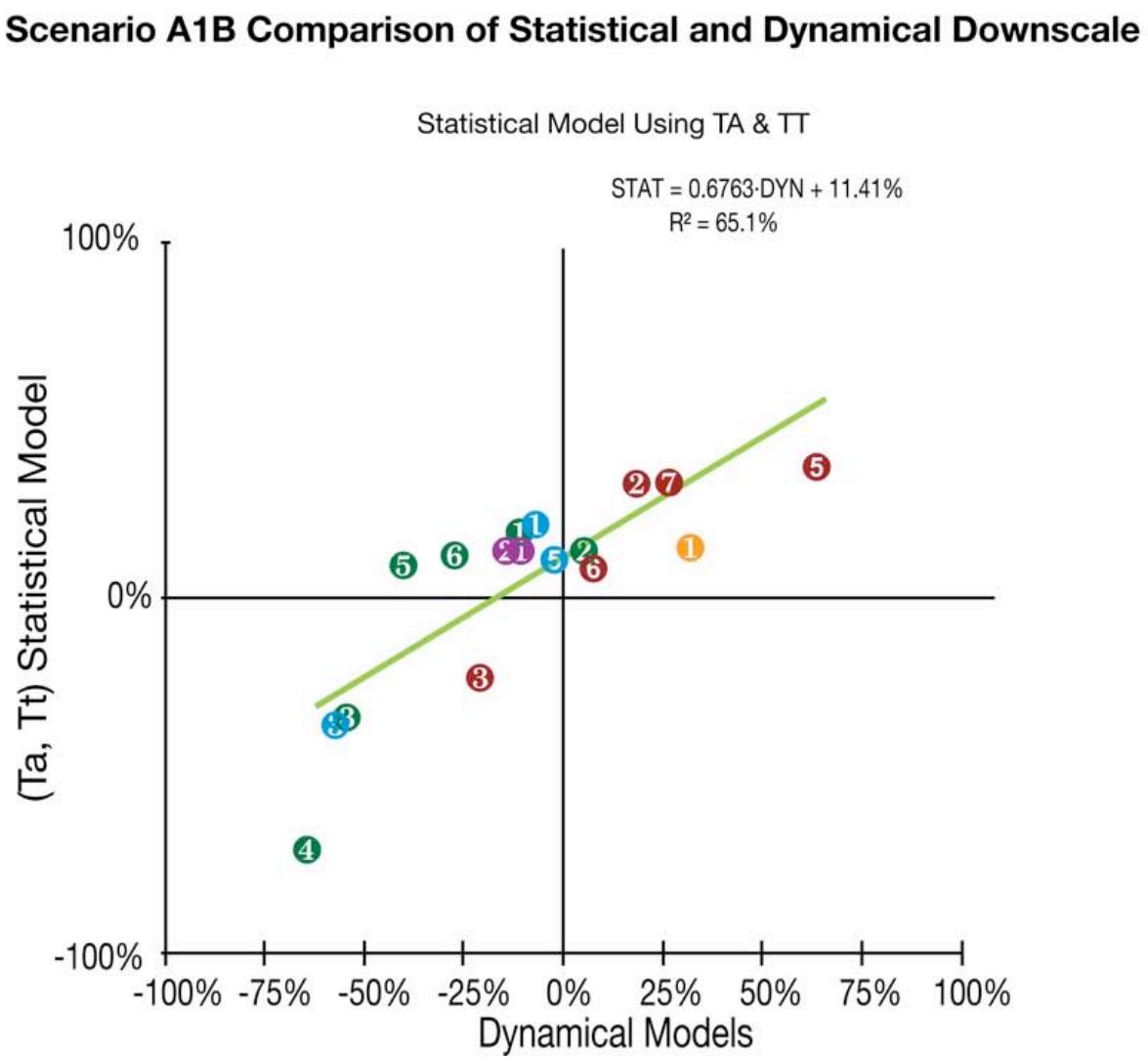


2000-Year Linear Least-squares Regression of Villarini Model Atlantic Basinwide TS Counts onto Vertically-integrated Meridional Ocean Heat Transport - CM2.1 Preindustrial Control

Statistical downscale vs. complex statistical model in GCMs



Downscaling of IPCC-AR4 with statistical model consistent with high-resolution dynamical downscaling techniques



Zhao et al (2009)-
Trends (2001-2100) made 80-year equiv.
1. GFDL CM2.1
3. UKMet HadCM3
5. Max Planck-ECHAM5

Knutson et al (2008), Knutson et al (2010) -
Trends (2001-2100) made 80-year equiv.
1. GFDL CM2.1
2. GFDL CM2.0
3. UKMet HadCM3
4. UKMet HadGEM1
5. Max Planck-ECHAM5
6. MRI CGCM2.3.2

Emanuel et al (2008):
Differences (2181-2200) minus (1981-2000)
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

Bengtsson et al (2007)-
(2071-2100) minus (1961-1990) from MPI-ECHAM5
1. With T213 AGCM
2. With T959 AGCM

Oouchi et al (2005)-
(2081-2099) minus (1979-1998) from MRI

Summary

- It is premature to claim an anthropogenic increase in basinwide Atlantic TS or hurricane frequency.
  - Cannot reject null that frequency has not changed (no detection)
  - Competing dependence on SST (local and remote) prevents two-step attribution
- Since WWII power dissipation index correlates with:
  - Absolute Atlantic SST: suggests partial attribution of PDI increase to greenhouse forcing, implies large future increases.
  - Atlantic SST relative to Tropics: precludes attribution to greenhouse forcing, implies small changes, large variability.
- Homogenized historical record and dynamical models are consistent with relative SST interpretation.
- Statistical models built on homogenized historical record:
  - Consistent with dynamical projections.
  - Can be “cheaply” applied to GCM controls/projections/predictions