Climate Change and Tropical Cyclones

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January 5, 2017

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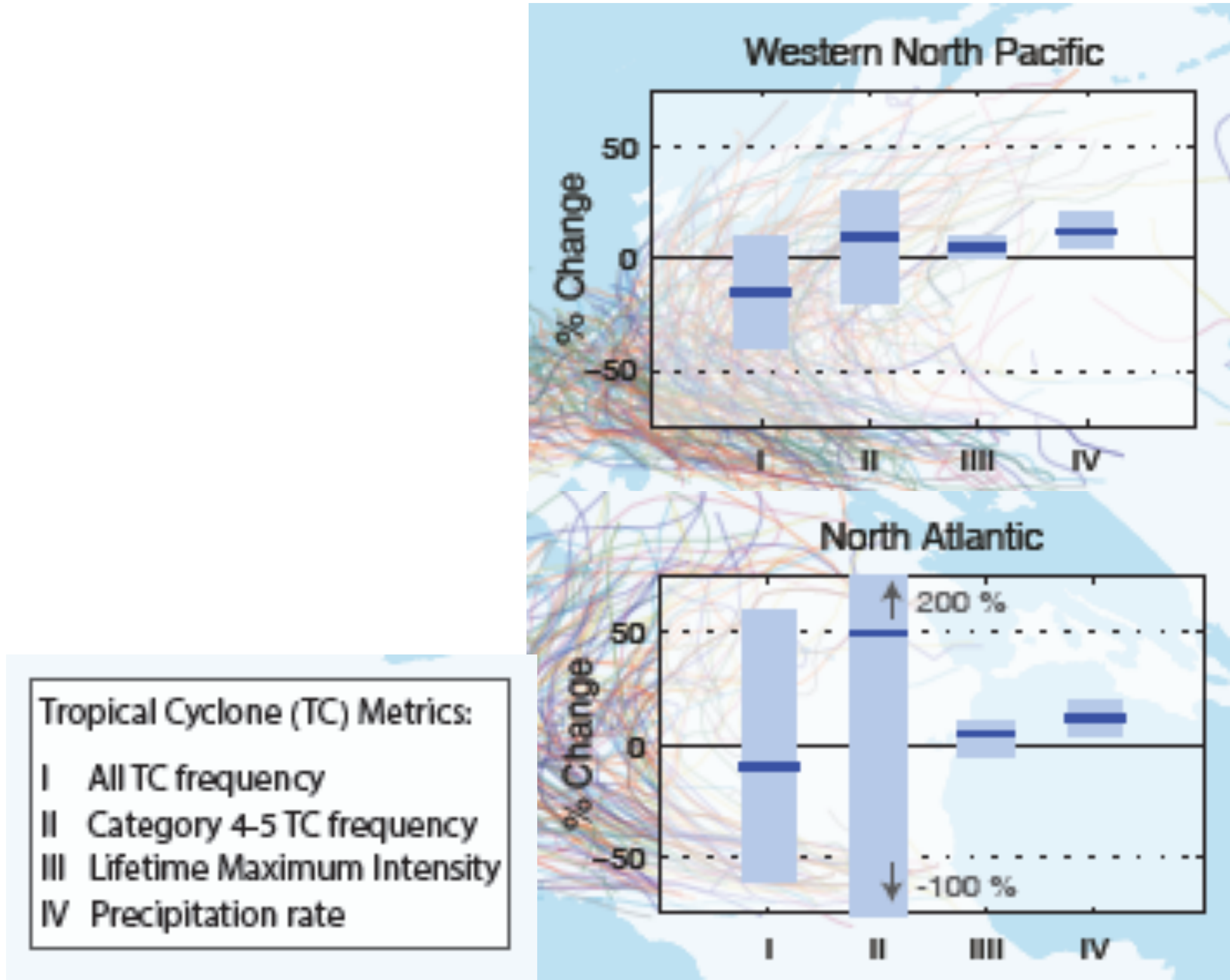
IN THE CITY OF NEW YORK

As climate warms, TC intensity is projected to increase.
With larger uncertainty, TC frequency is projected to decrease.



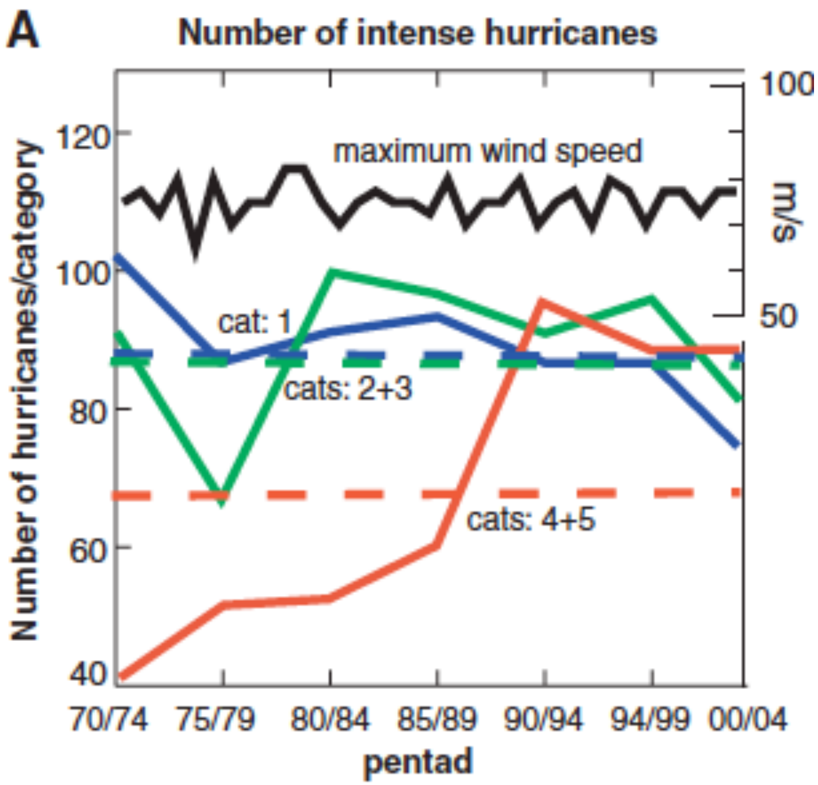
IPCC AR5

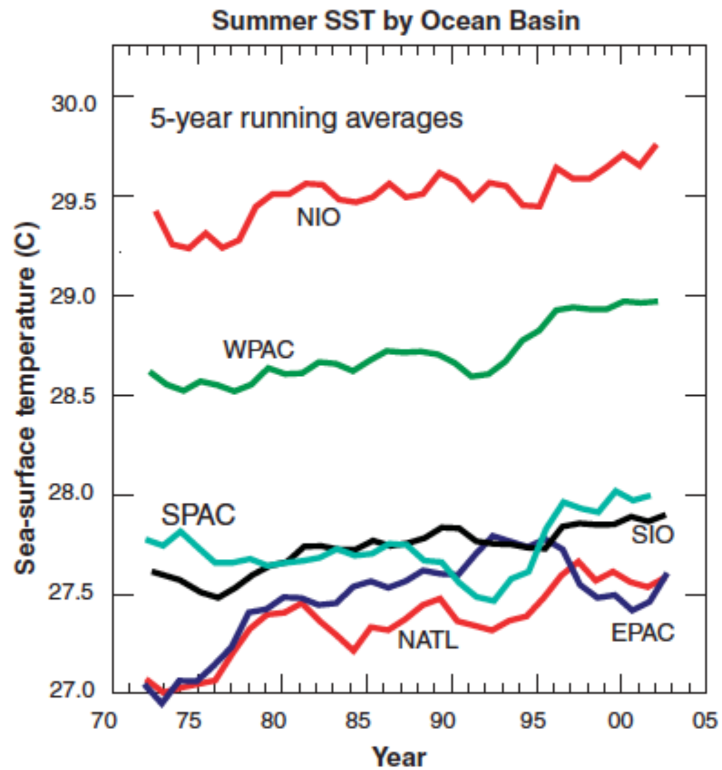
Outline

- Have TCs already become stronger, due to warming up to the present? (Sobel et al. 2016, *Science*)
- What are the reasons for the projected future decrease in TC frequency? (Camargo et al. 2014, *J. Climate*)

Part 1: Has climate change already caused increases in TC intensity?

2005: A couple very prominent studies say tropical cyclones are getting stronger, due to sea surface temperature (SST) increases.

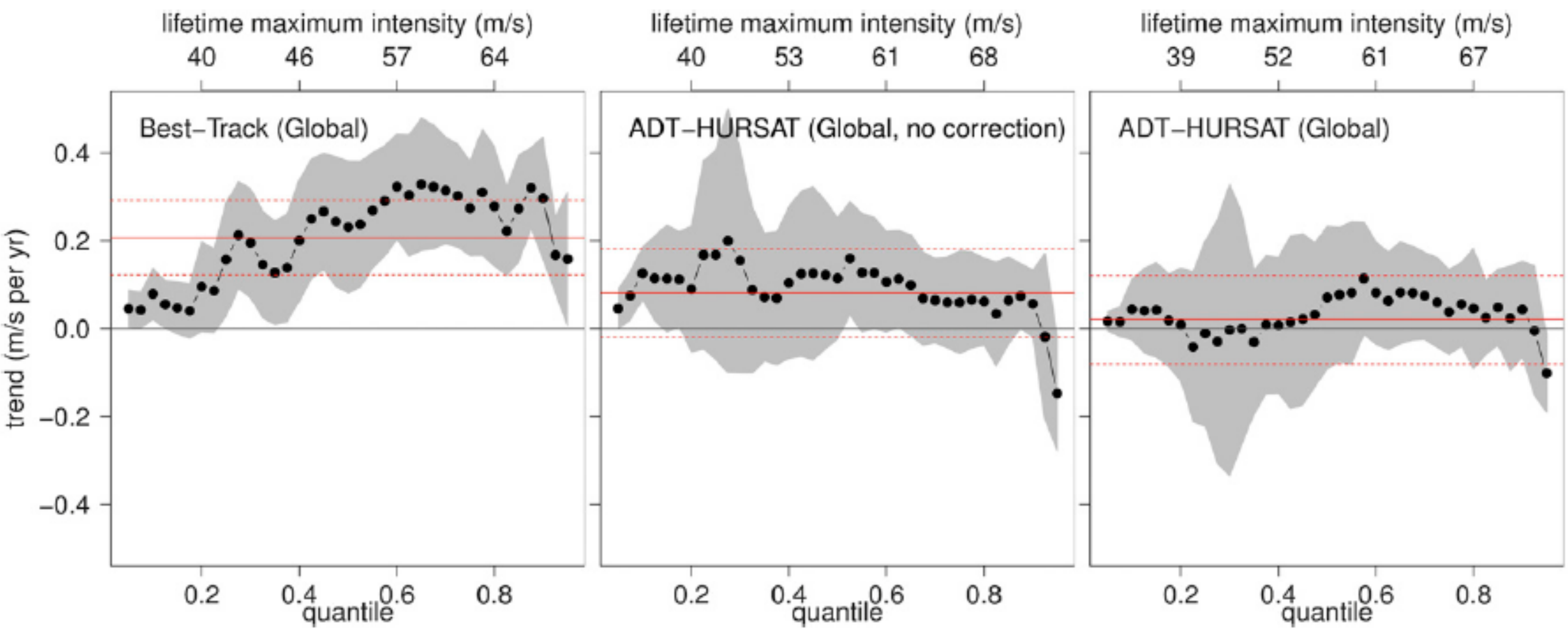




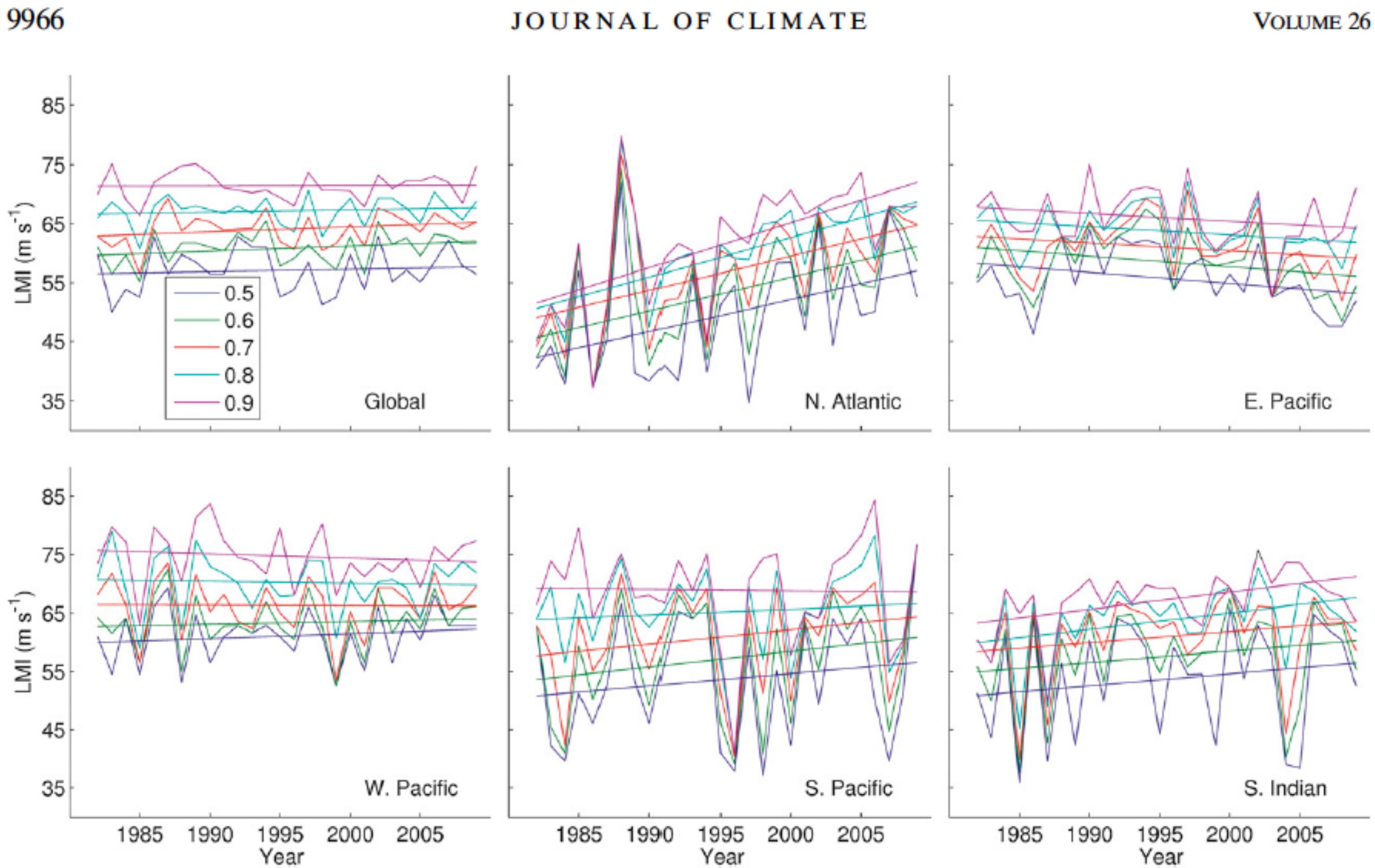
Webster et al. 2005, *Science*

More recently: some studies/data sets say TCs are getting stronger, but not all.

15 December 2013 KOSSIN ET AL. 9967



Low-frequency natural variability is large, making trend-fitting tricky.



Kossin et al. 2013

Why do we expect TC intensity to increase?

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The reasons have become a little more subtle with time.

It has long been known that sea surface temperature is important to TCs. They generally don’t form over water below 26-27C.

map we can clearly see that *all regions without hurricanes are characterized by relatively low water temperature.* Very characteristic is the entire area

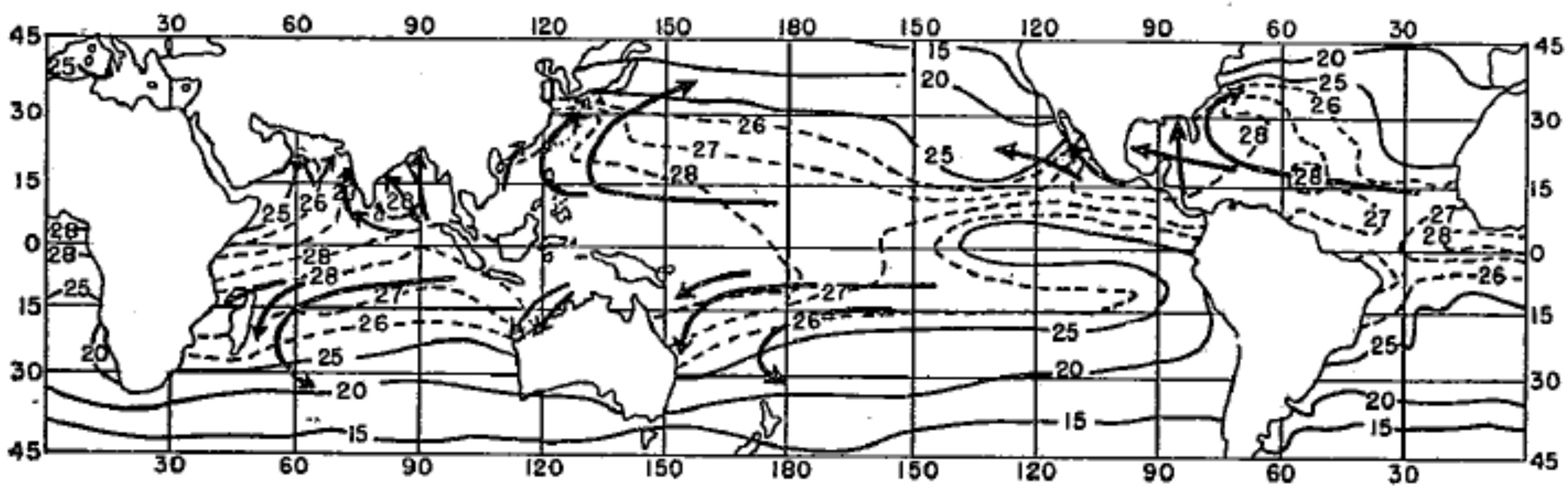
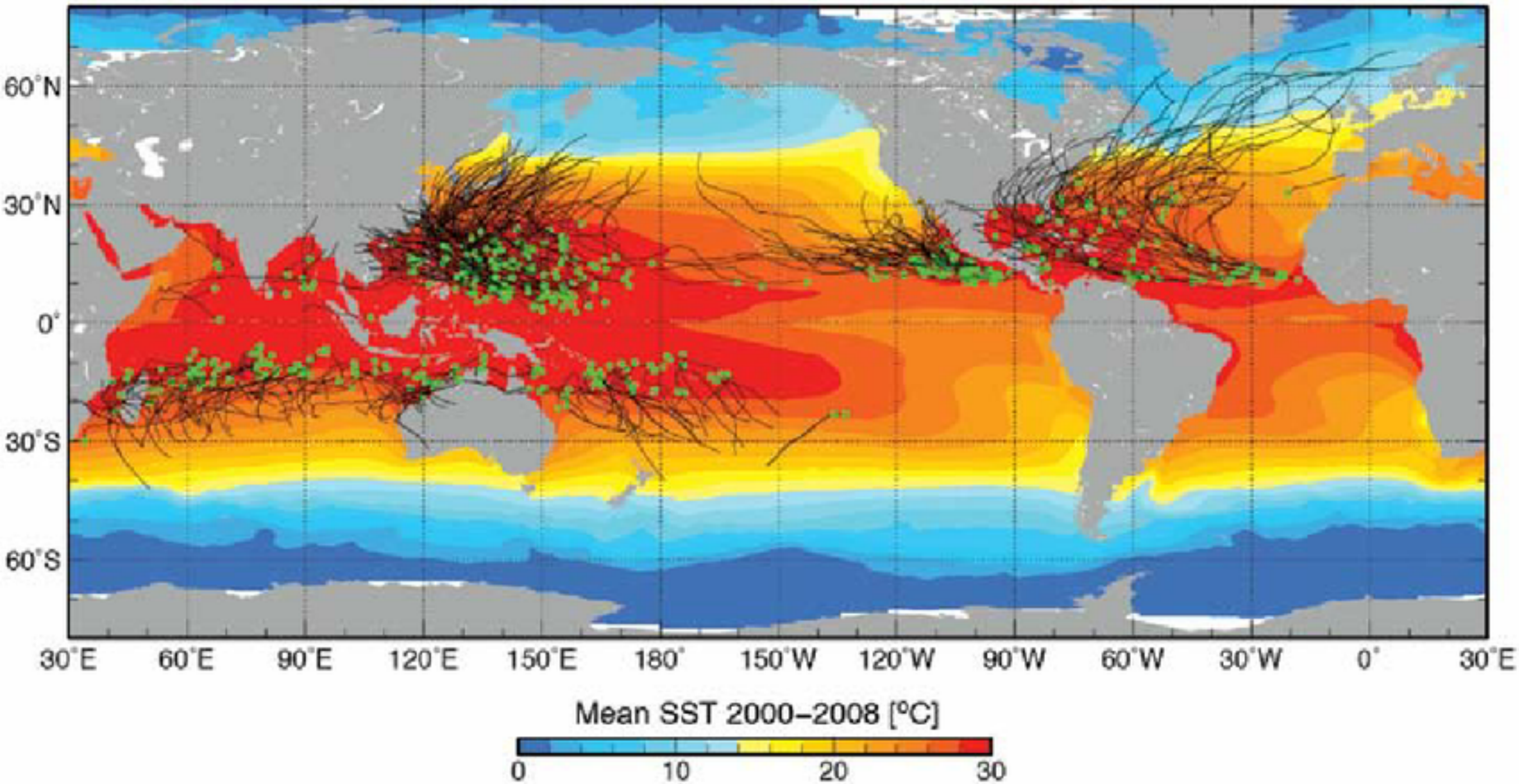


Fig. 4. Principal hurricane paths and surface water temperature during the warmest season.

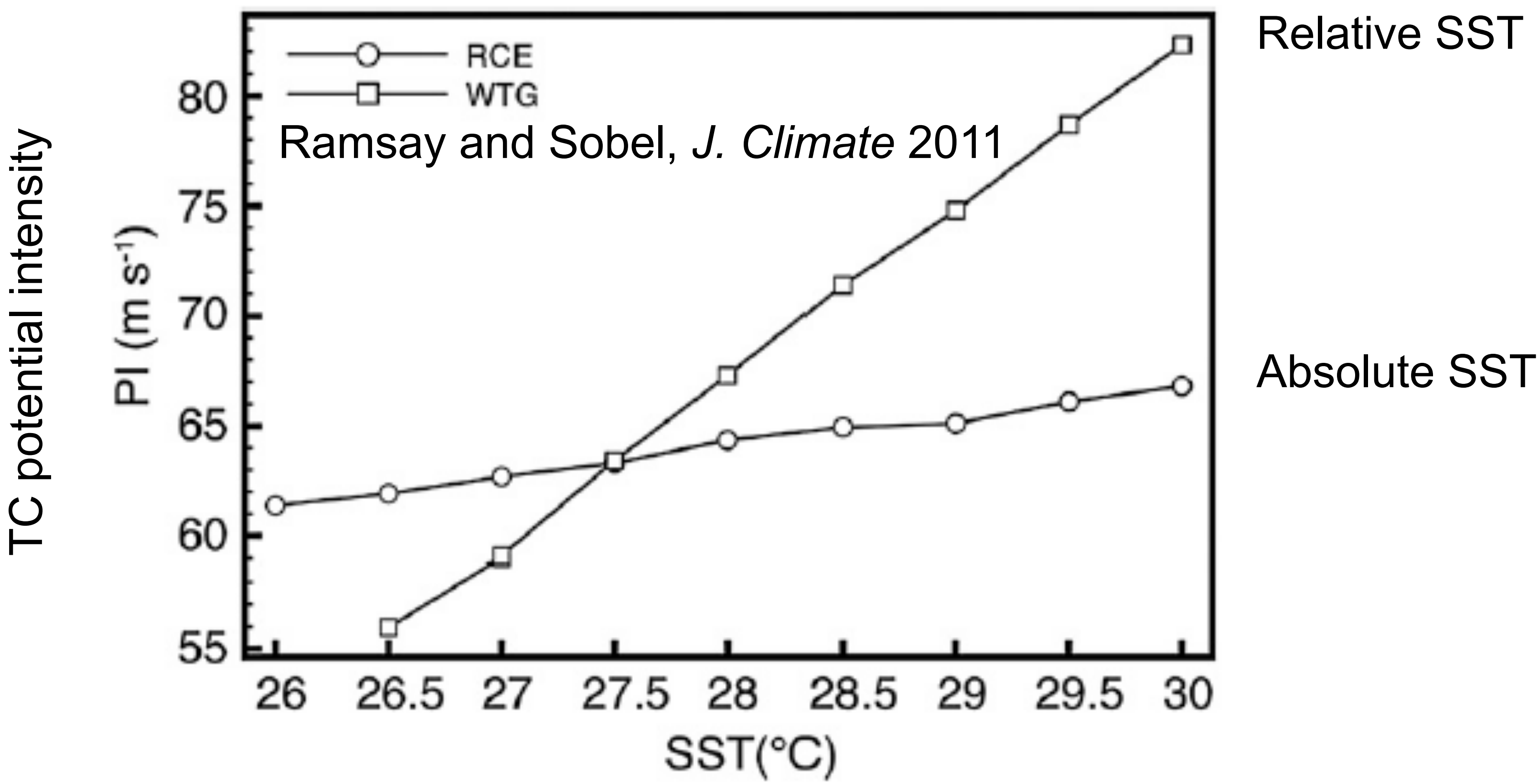
Palmen, 1948

So higher SST means more & stronger TCs, right?



Gustavo et al. 2009

Maybe not. R*elative SST (*compared to the tropical mean) matters more than absolute SST.



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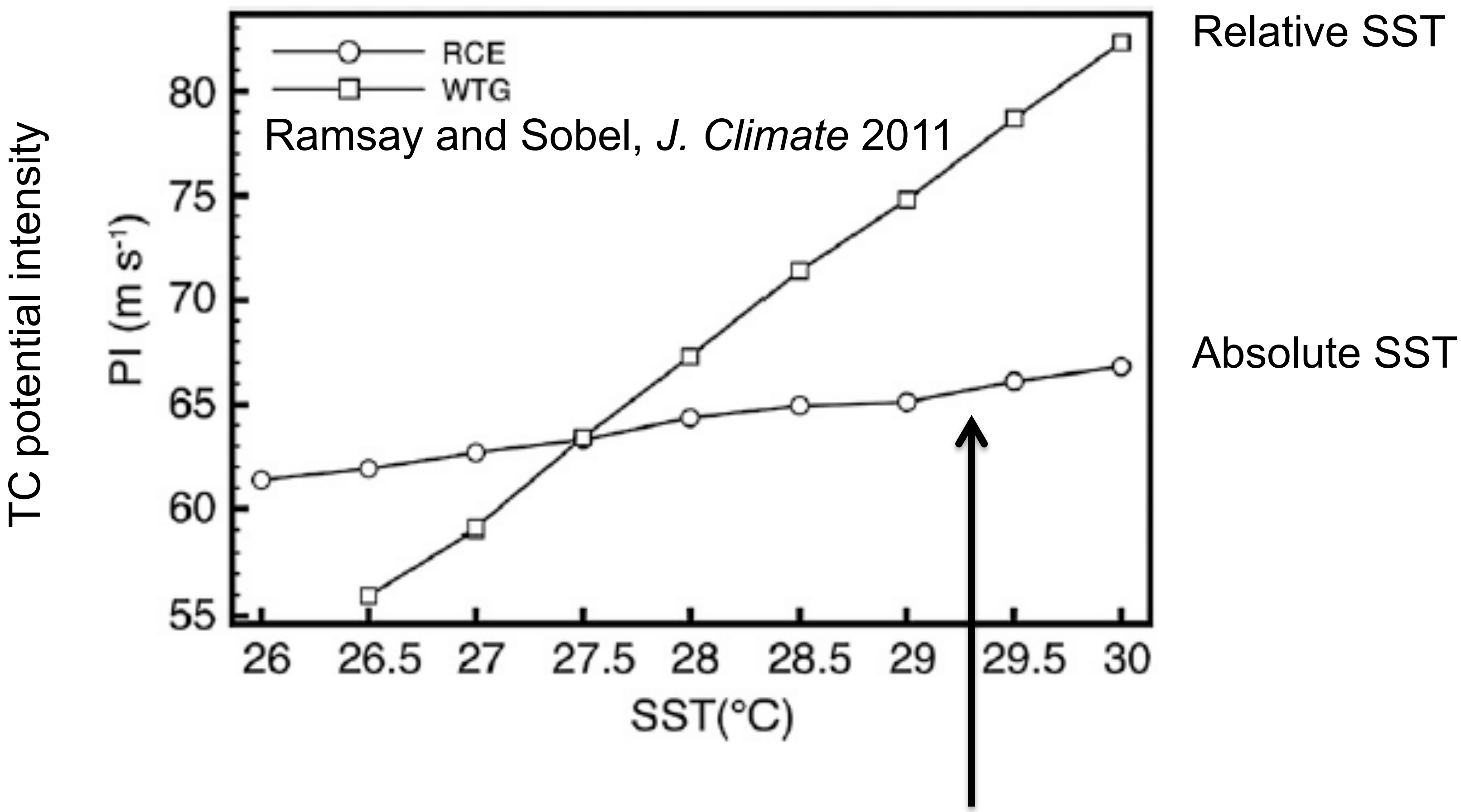


Though absolute SST still has some effect.

In potential intensity theory, the hurricane can be viewed as an ideal (Carnot) heat engine (K. Emanuel, MIT)

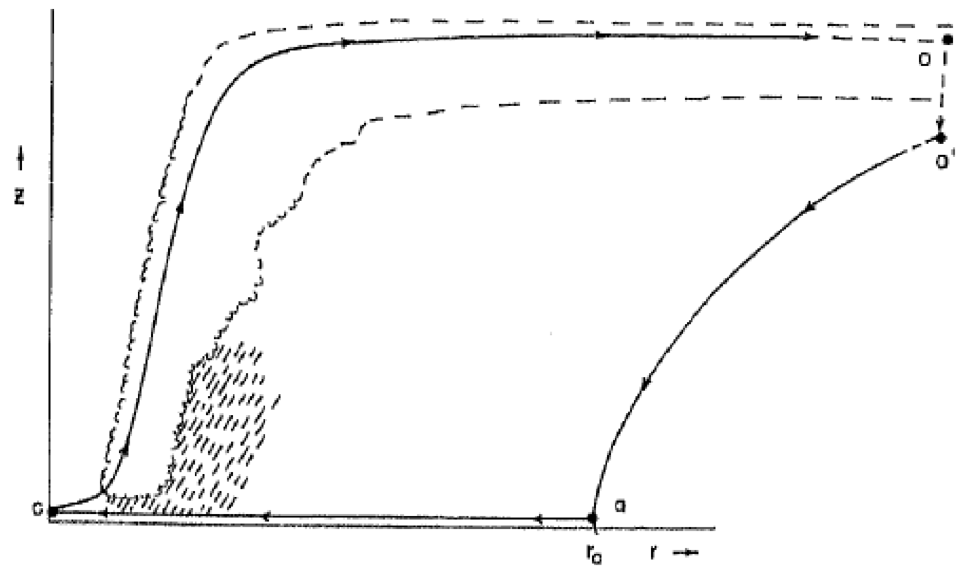


Figure 1 The hurricane Carnot cycle. Air begins spiraling in toward the storm center at point *a*, acquiring entropy from the ocean surface at fixed temperature T_s. It then ascends adiabatically from point *c*, flowing out near the storm top to some large radius, denoted symbolically by point *o*. The excess entropy is lost by export or by electromagnetic radiation to space between *o* and *o'* at a much lower temperature T_o. The cycle is closed by integrating along an absolute vortex line between *o'* and *a*. The curves *c*–*o* and *o'*–*a* also represent surfaces of constant absolute angular momentum about the storm's axis.

Efficiency $\eta = (T_{surf} - T_{trop})/T_{surf} \approx 1/3$

This theory gives successful predictions of the maximum intensity a TC can reach

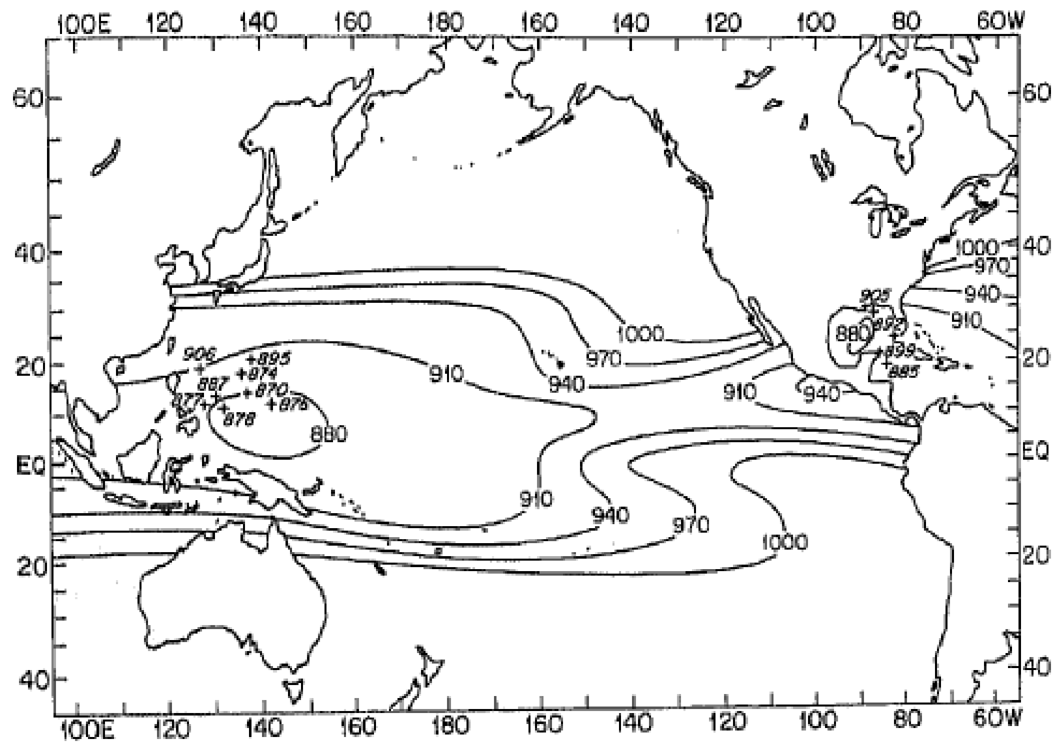
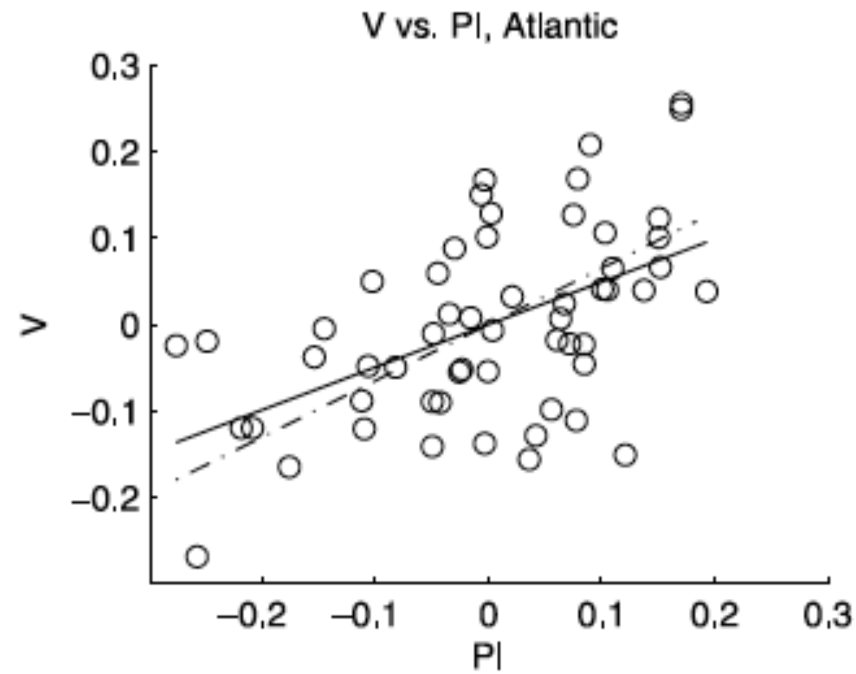
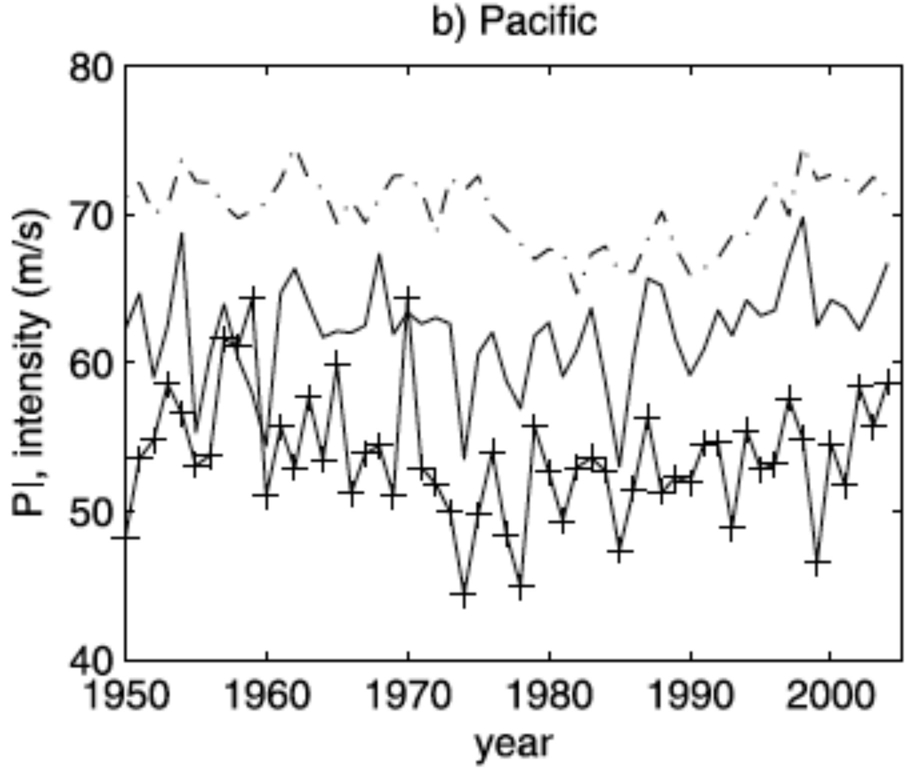


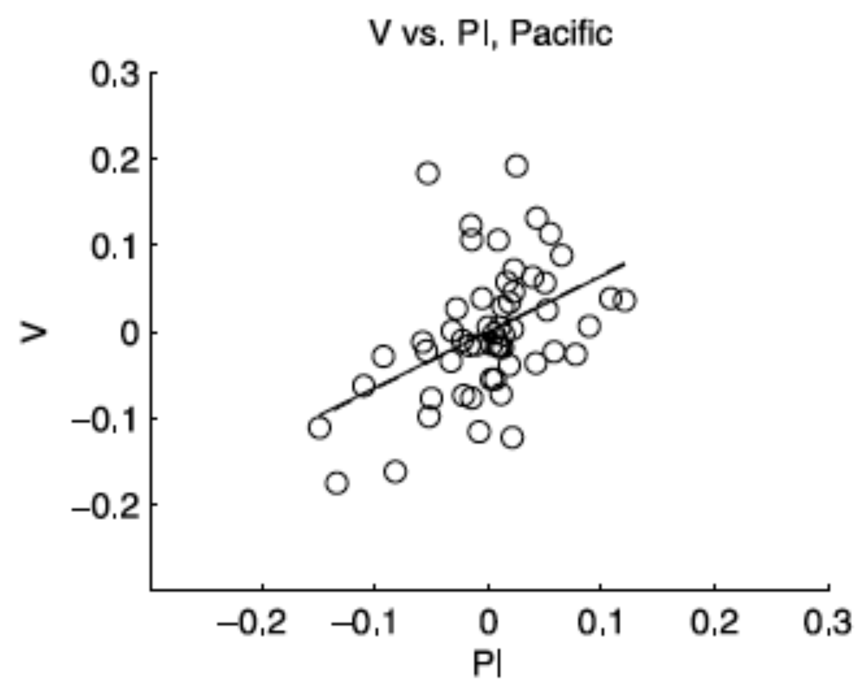
Figure 3 Minimum sustainable central pressure of tropical cyclones (in millibars) under September climatological conditions. The central pressures of some of the most intense tropical cyclones on record are shown by italicized numbers and crosses.

Emanuel, 1986

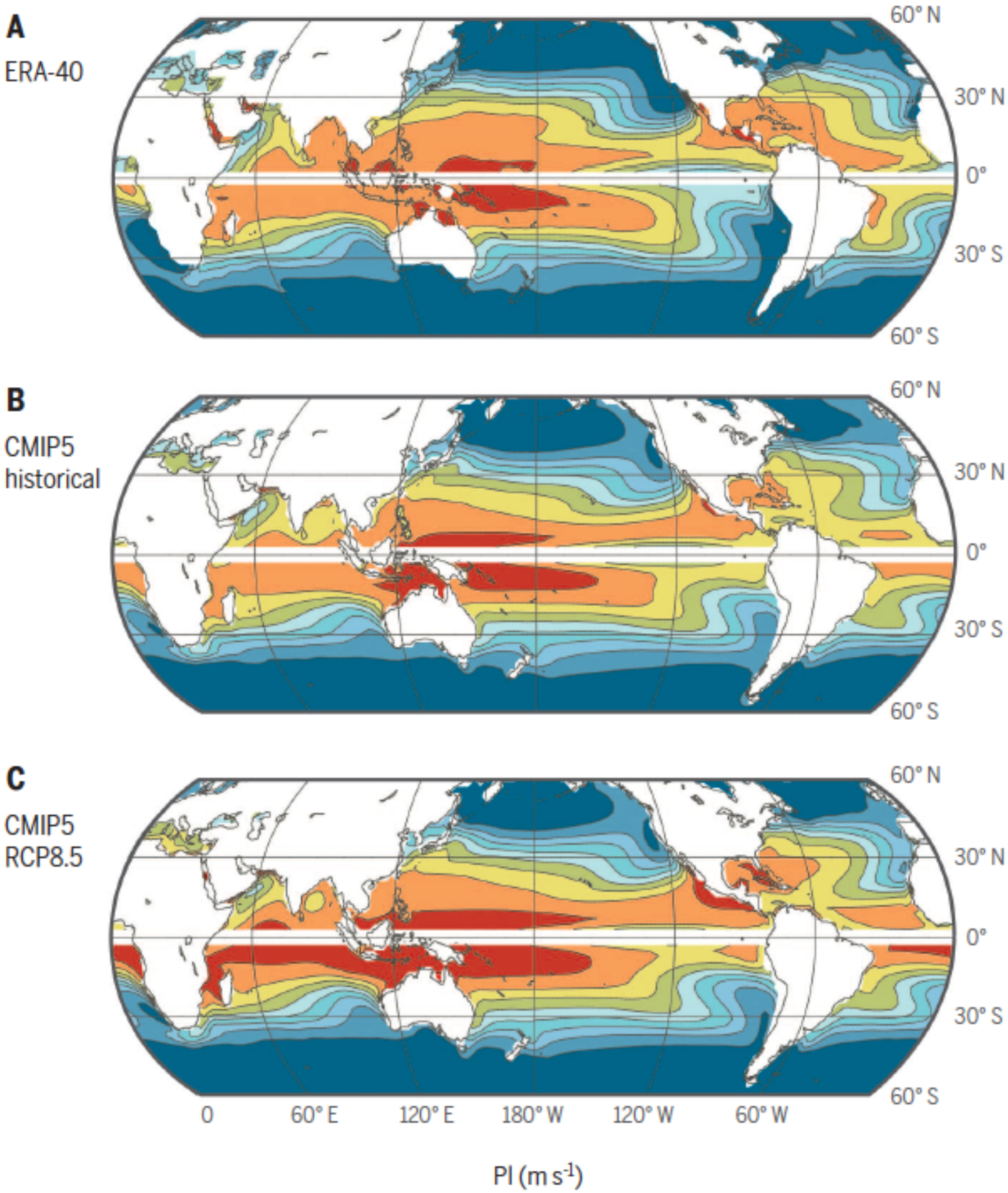
PI theory has some success at predicting variability in TC intensity, given the tracks
(Wing, Camargo, Sobel, 2007, *GRL*)





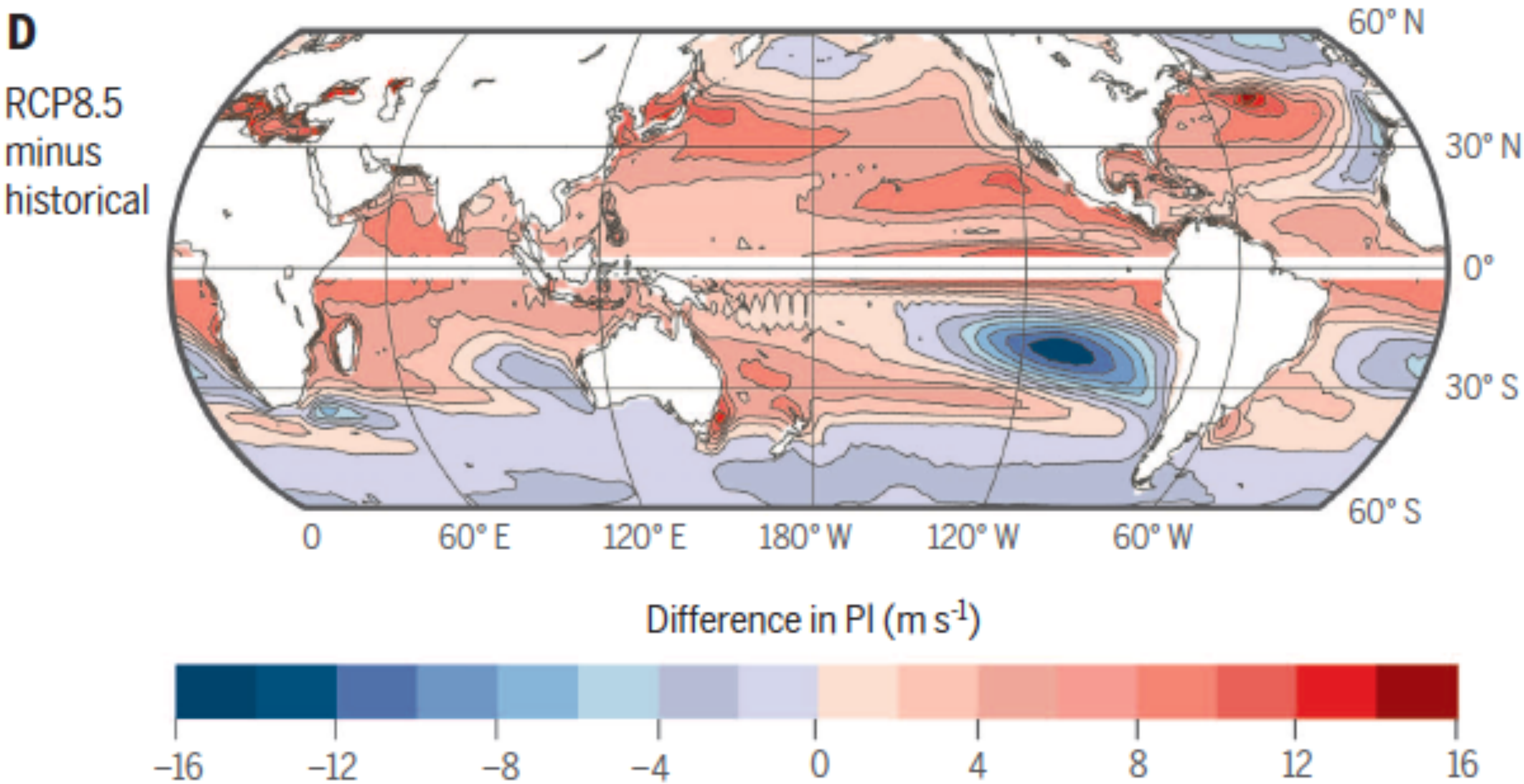


PI is projected to increase in the future as climate warms.



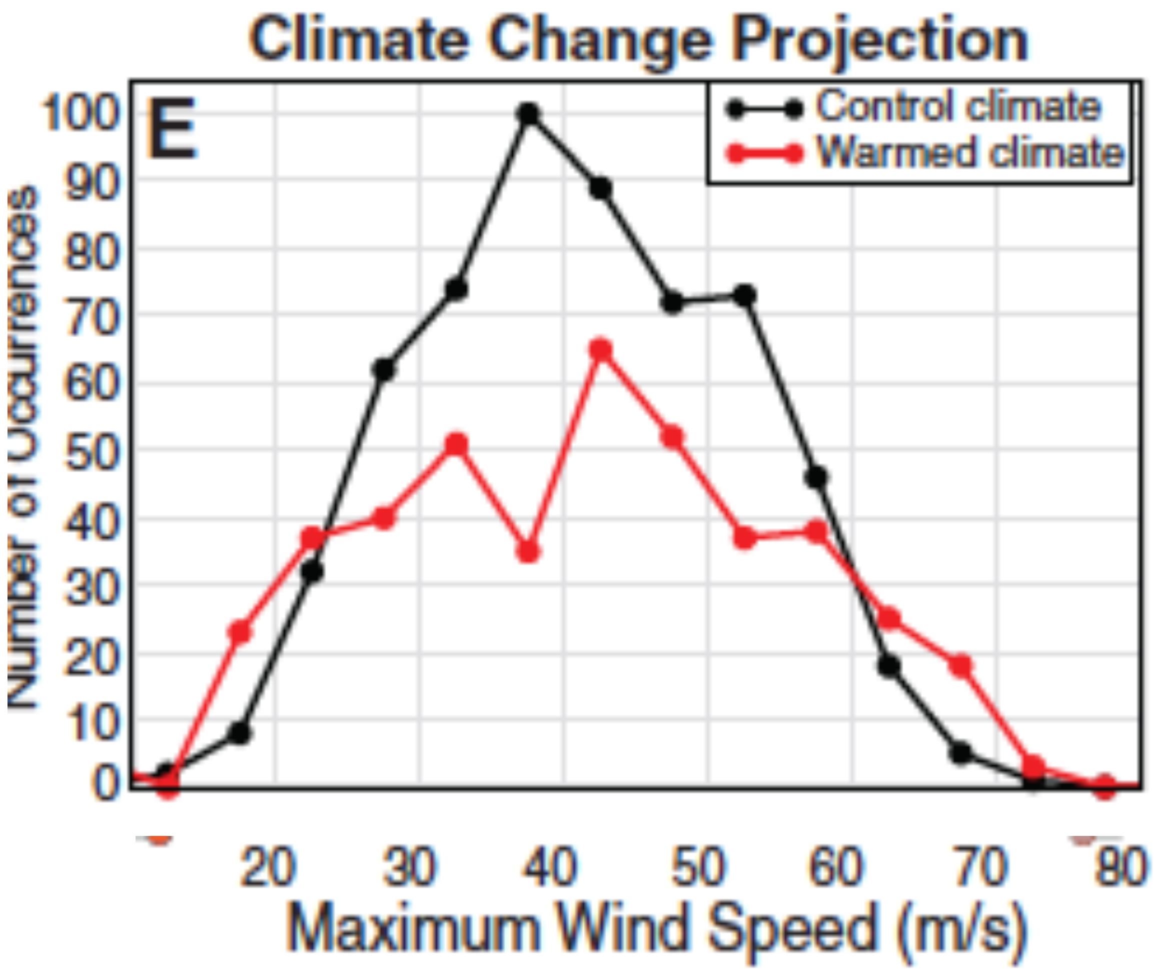
Sobel et al. 2016

Change in PI, late 21c-20c, CMIP5



Sobel et al. 2016

High-resolution models support PI theory and project increasing intensities.



Bender et al. 2010

But PI trends in observations are not entirely clear or consistent (except in the Atlantic).

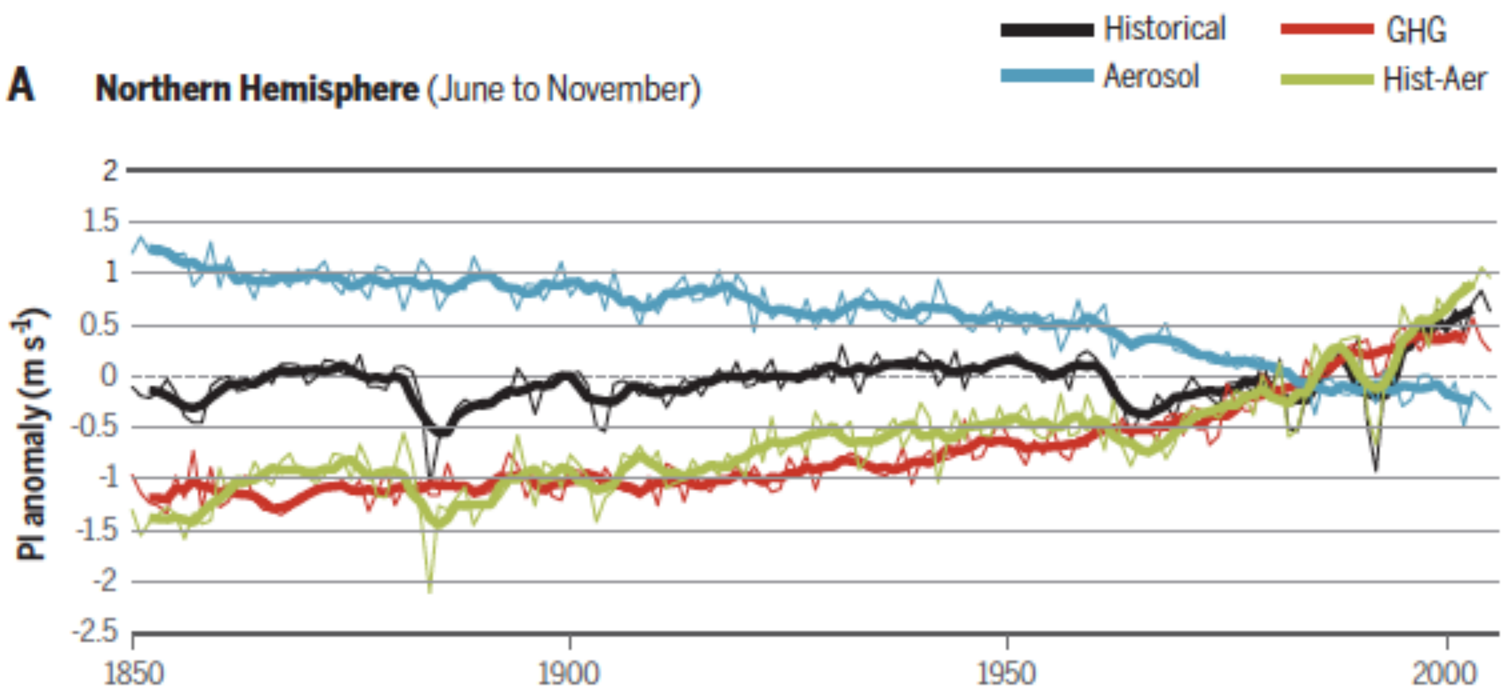
Table 2. Contribution to Decadal Trend in Potential Intensity (m s^{-1} decade^{-1})[a]

Basin	Contribution From Disequilibrium Trend	Contribution From Efficiency Trend	Total Trend	Efficiency as Percent of Total
		North Atlantic		
ERA-Interim	**1.04**	0.08	**1.12**	7%
MERRA	0.41	0.23	**0.64**	36%
San Juan	**1.47**	**0.62**	**2.10**	30%
		Eastern North Pacific		
ERA-Interim	−0.11	−0.14	−0.25	57%
MERRA	**−1.13**	−0.04	**−1.17**	3%
Hilo	−0.27	0.06	−0.21	−31%
		Western North Pacific		
ERA-Interim	**0.77**	−0.05	**0.72**	−6%
MERRA	−0.37	0.01	−0.35	−4%
Koror	**0.61**	−0.08	0.53	−16%
Chuuk	**0.58**	−0.01	0.57	−2%
Majuro	0.26	**0.24**	0.50	48%
Marcus	**0.97**	0.00	**0.98**	0%
		North Indian		
ERA-Interim	0.30	0.00	0.30	0%
MERRA	**−1.02**	0.08	**−0.94**	−9%
		Southern Hemisphere		
ERA-Interim	**1.07**	0.00	**1.07**	0%
MERRA	0.05	0.11	0.17	69%
Darwin	−0.26	**0.25**	−0.01	−1727%

[a]Contributions from the last two terms in equation (2), for the ERA-Interim and MERRA reanalyses, and RATPAC station data averaged over the months and regions defined in Table 1. Trends that are significant at the 95% confidence level are in bold font, and negative percentages indicate that the efficiency trend and total potential intensity trend are of opposite sign.

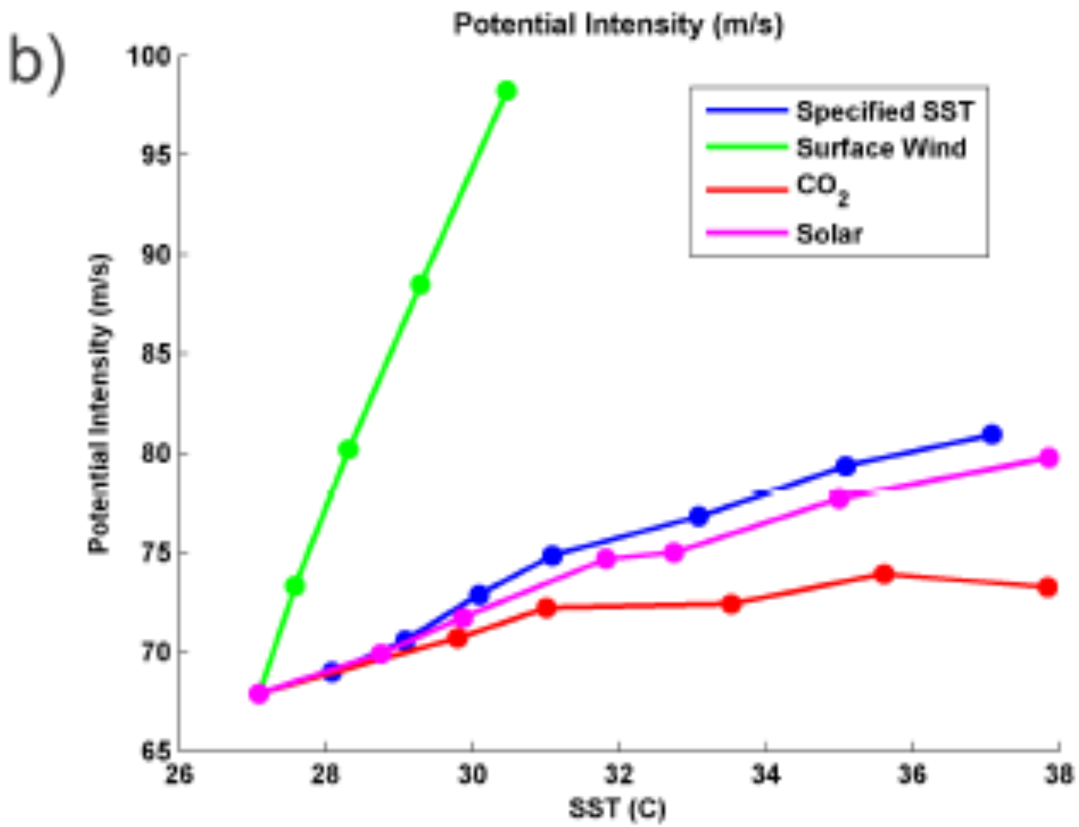
Wing et al. 2015

In fact, CMIP5 models suggest that PI *should not have* increased much yet, due to aerosols.



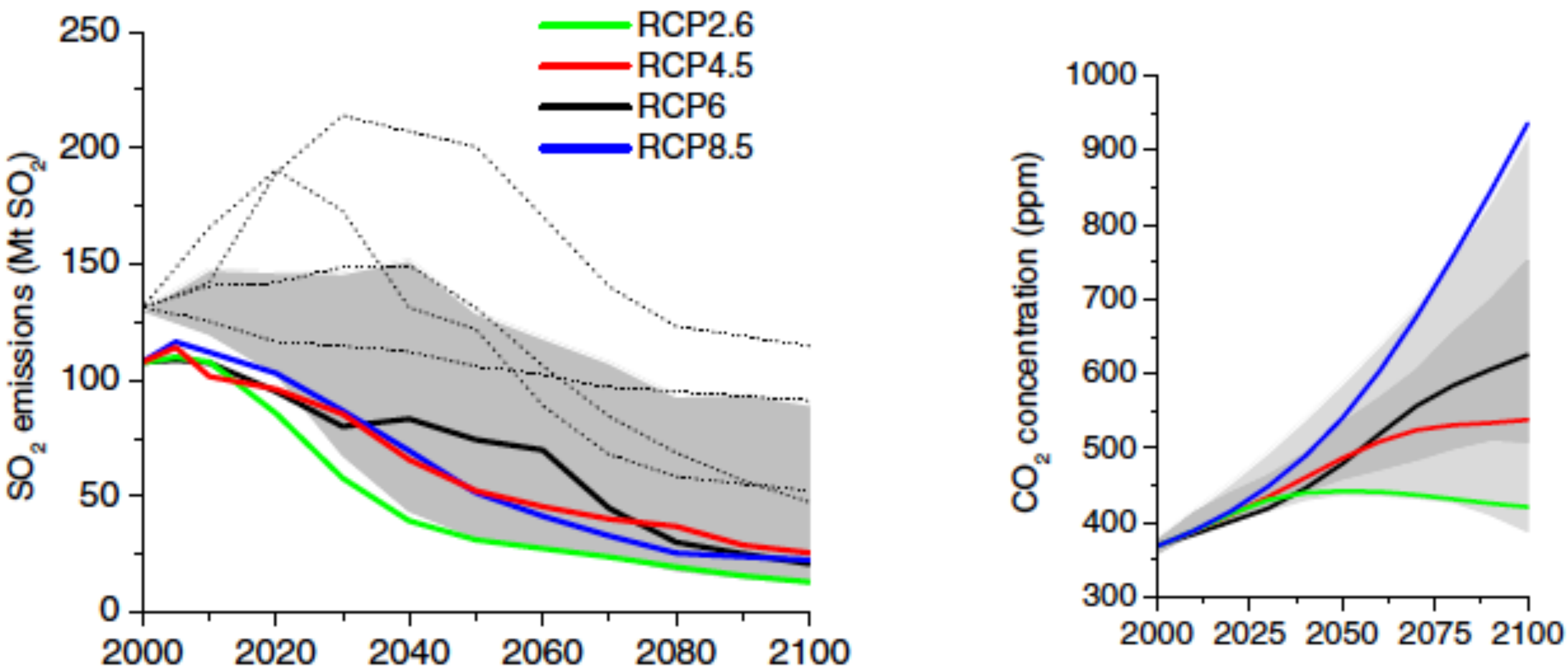
Sobel et al. 2016

Aerosol forcing < greenhouse forcing (hence global warming) but shortwave forcing appears more effective at changing PI, for the same SST change, than longwave.



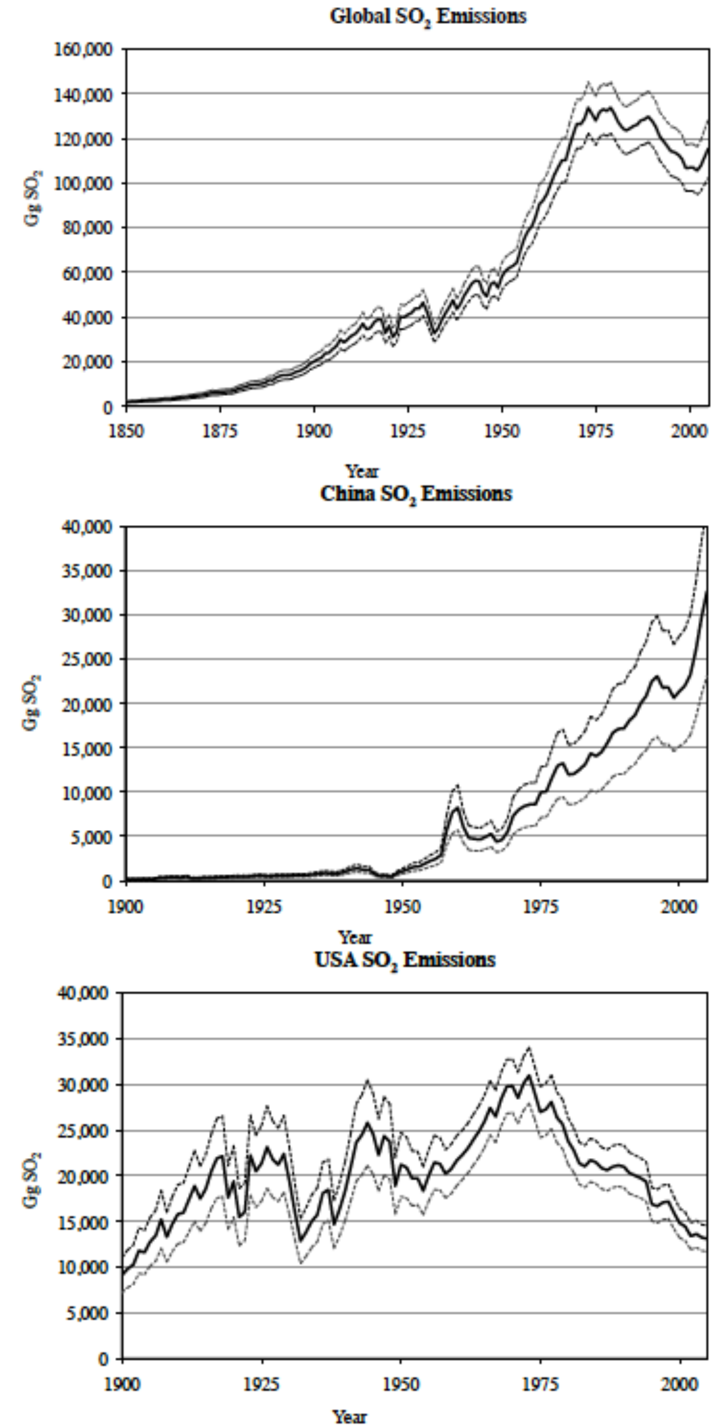
Emanuel and Sobel 2013

Aerosol forcing is projected to decrease (due to cleanup of sulfate emissions) but greenhouse forcing (hence global warming) is very likely to increase at least for a few more decades.



Van Vuuren et al. 2011

Aerosol forcing already shows signs of having reached a plateau.



Smith et al. 2011

Conclusions, part 1

- We expect tropical cyclones to become more intense as the climate warms, because greenhouse warming generally increases PI.
- But aerosol cooling decreases PI, more efficiently (per degree SST).
- Thus although greenhouse gas warming > aerosol cooling, so the climate has warmed (~1° C), aerosol cooling has kept PI (and, likely, actual TC intensities) from increasing much, at least til recently.
- In recent decades, aerosol cooling has begun to plateau while greenhouse warming has continued to increase. Thus the intensity increases are coming.

Part 2: Why do models project decreases in TC frequency?

Potential intensity theory tells us something about TC intensity,
But does not tell us whether a TC will exist in the first place!
We have no systematic theory for *genesis*, thus we have none for TC *frequency* (number/year)

So we develop empirical genesis indices following early work of W. Gray

E.g., Emanuel GPI (Emanuel and Nolan, 2004; Camargo, Emanuel and Sobel 2007)

$$GP = |10^5 \eta|^{3/2} (\mathbf{H}/50)^3 (V_{pot}/70)^3 (1+0.1V_{shear})^{-2}$$

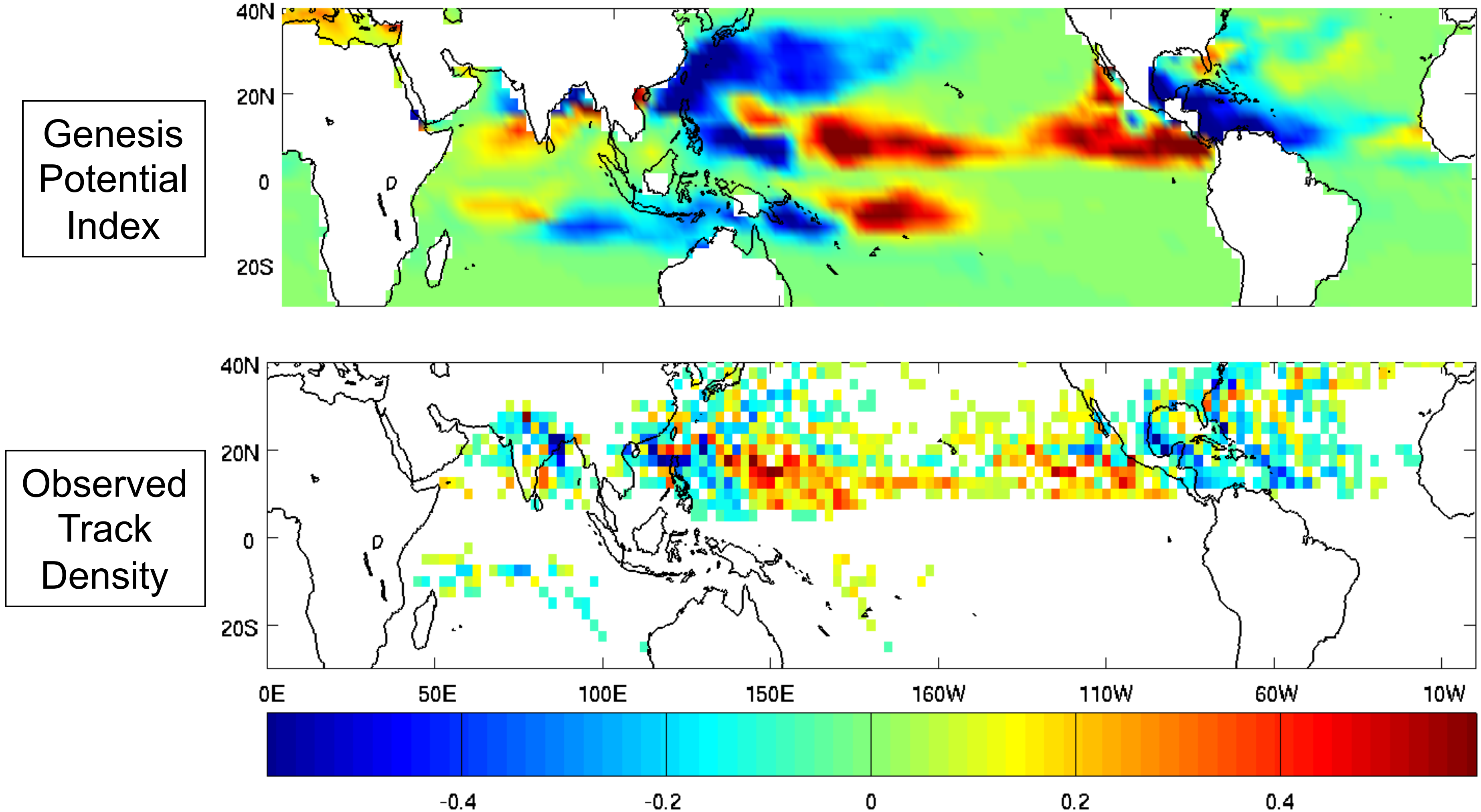
η = absolute vorticity at 850hPa (s^{-1})

H = relative humidity at 700hPa (%)

V_{pot} = potential intensity (m/s)

V_{shear} = magnitude of the vertical wind shear between 200 and 850hPa (m/s).

Though genesis indices are empirical, they can be tested on natural variability (which is not used to derive the index). E.g. here we show composites, El Niño minus La Niña



Camargo, Emanuel & Sobel, J. Climate 2007

More recently we developed a new genesis index, using Poisson regression – allows easy re-derivation if new/different predictors are defined (Tippett, Camargo, and Sobel 2011, *J. Climate* 2011)

- Best fit TCG index:

$$TCGI = \exp(-11.96 + 1.12 \min(|\eta|,3.7) + 0.12\, H + 0.46\, RSST - 0.13\, V_S + \log \cos\Phi)$$

$|\eta|$ = absolute vorticity (850hPa) x 10^5

H = column relative humidity

RSST = relative SST (SST - mean tropical SST)

V_S = vertical shear (200hPa and 850hPa)

In the process of fitting the data to obtain the index, we learn new physics; here that environmental absolute vorticity (~latitude) only helps up to a point (Tippett, Camargo, and Sobel, *J. Climate* 2011)

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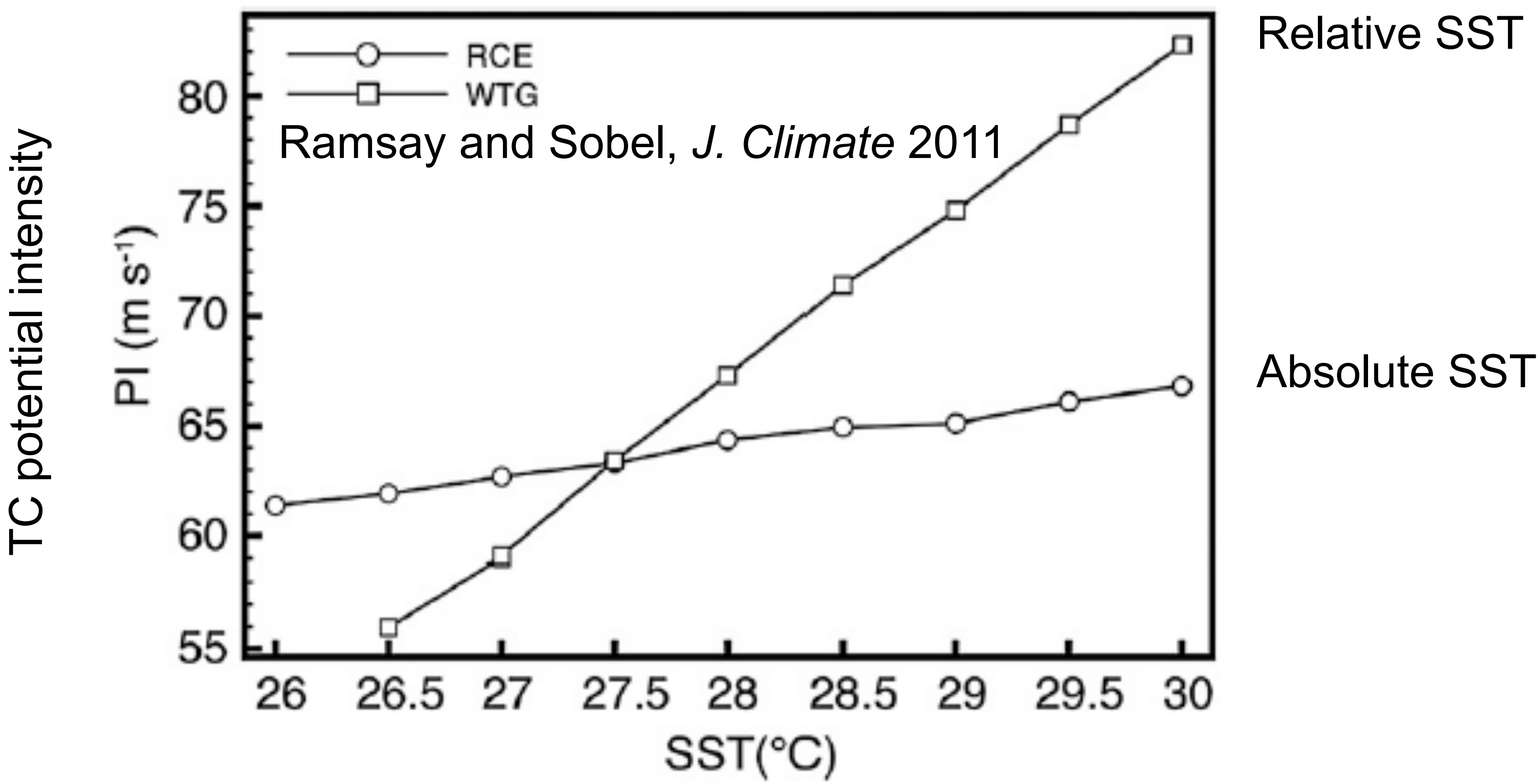
One must be very careful using genesis indices for climate change. They are derived from spatial and seasonal variations in the present climate, so global warming is out of sample.

For example, the SST threshold for TC formation almost certainly will change as climate does – thus one should not use absolute SST as a predictor (cf. Vecchi and Soden 2007)



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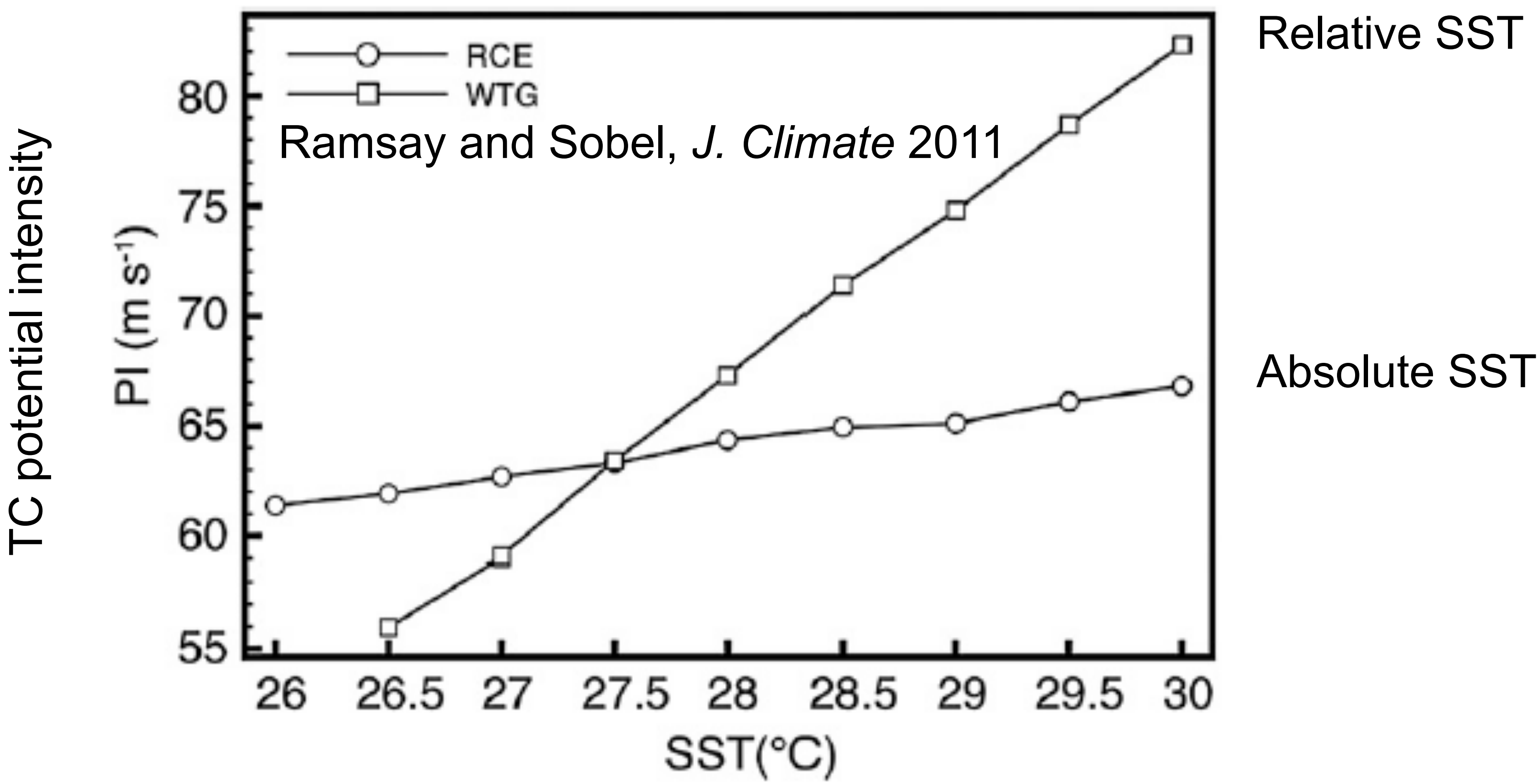
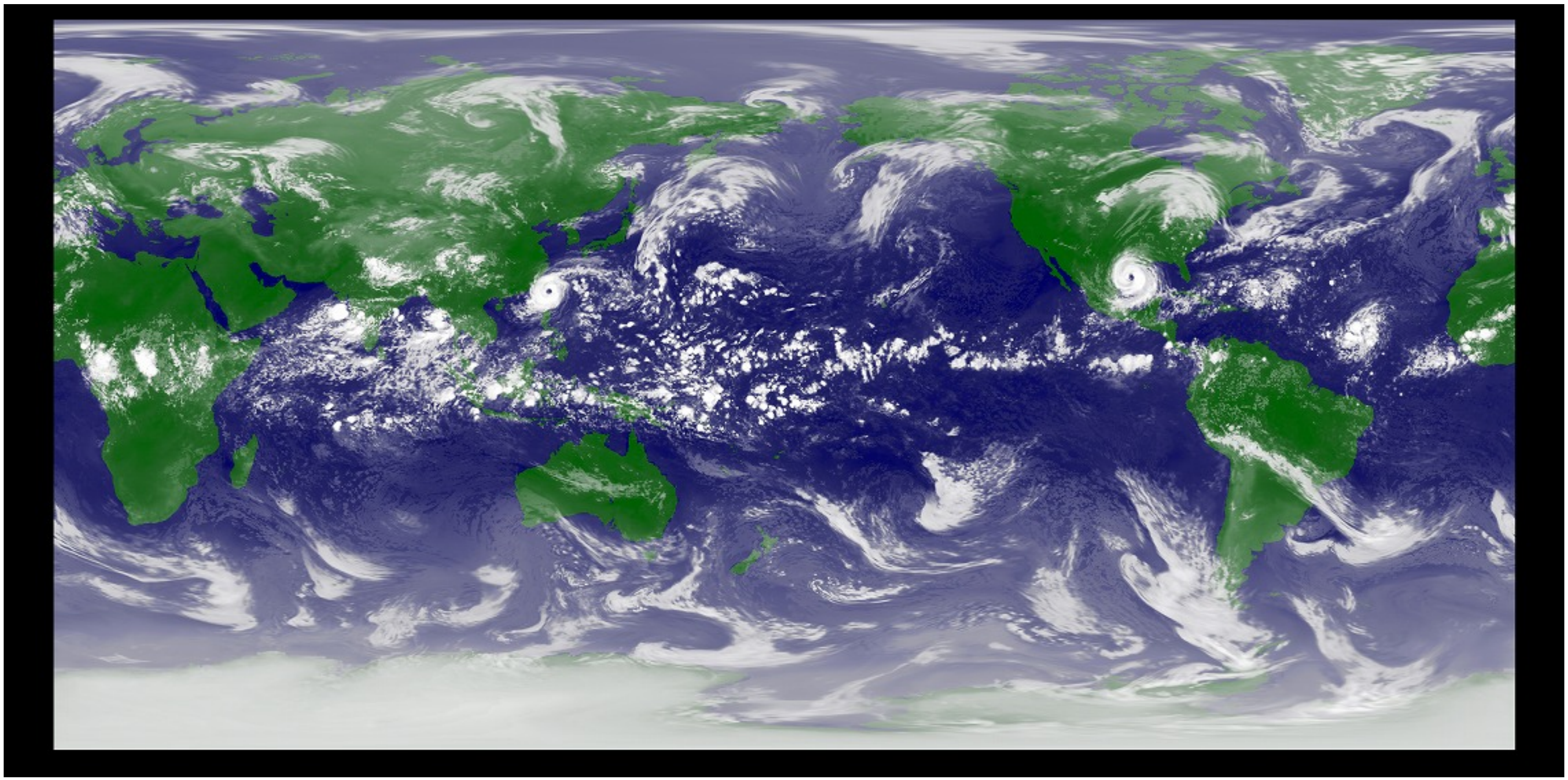


(However, relative SST also is limited as an indicator; e.g. it can't tell us anything about changes due to uniform warming.)

The major new development in TC-climate studies in the last ~decade is global “high-resolution” (~10-50 km grid spacing) models



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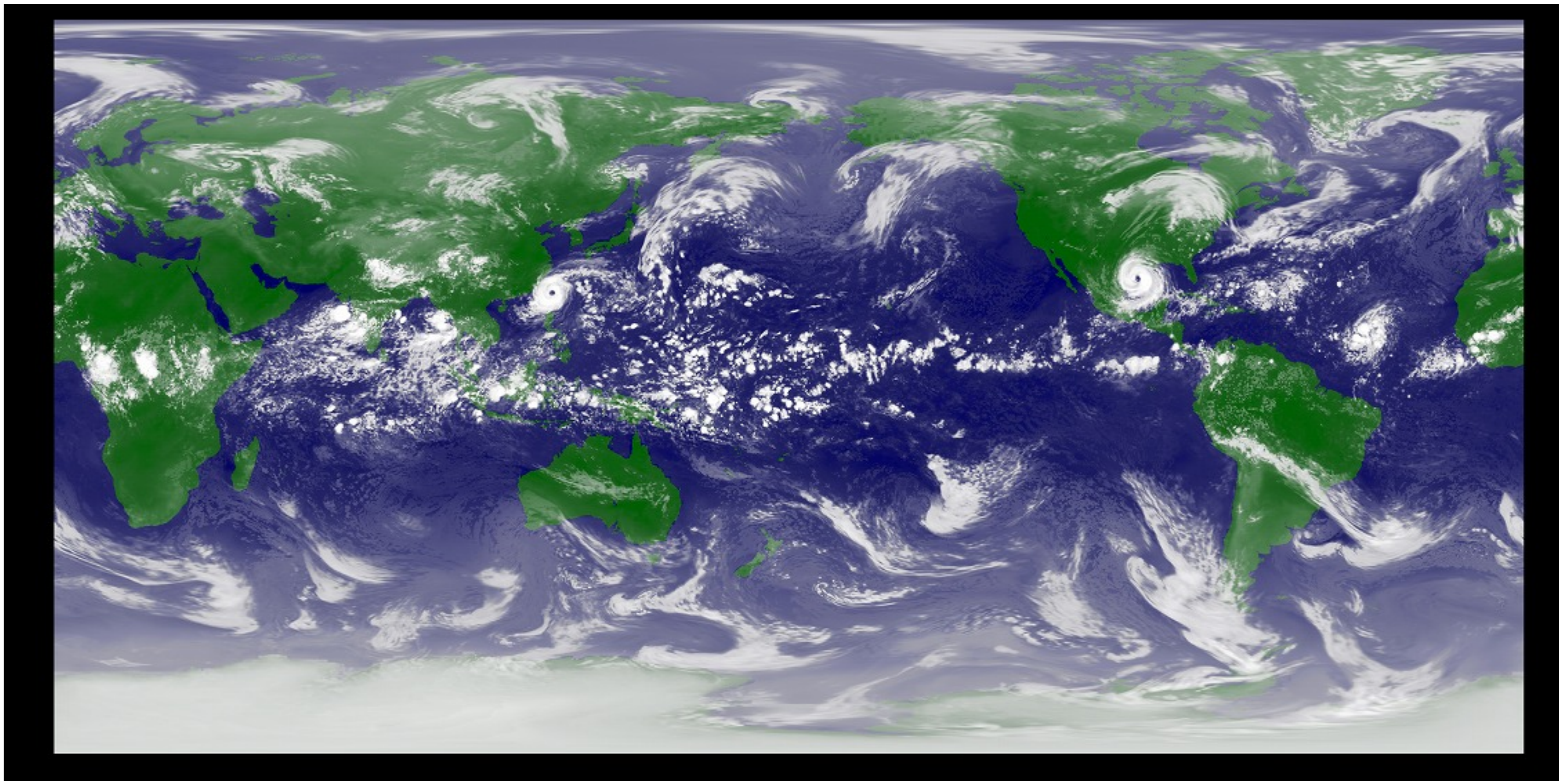
Though there is not complete agreement, these models seem to indicate for the most part that TC frequency will *decrease* globally in a warmer climate.



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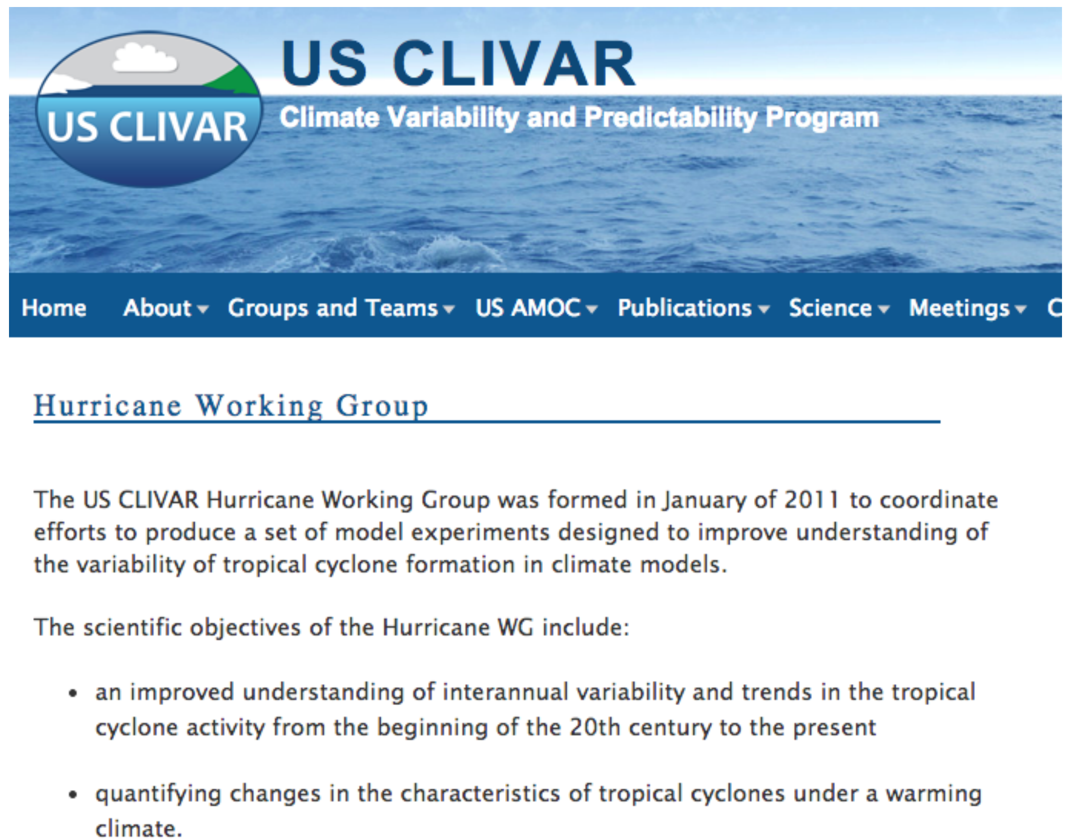
Though there is not complete agreement, these models seem to indicate for the most part that TC frequency will *decrease* globally in a warmer climate.

To understand this and other results from these models better, we have been doing an intercomparison under US CLIVAR
http://www.usclivar.org/working-groups/hurricane


US CLIVAR
Climate Variability and Predictability Program

Home About Groups and Teams US AMOC Publications Science Meetings

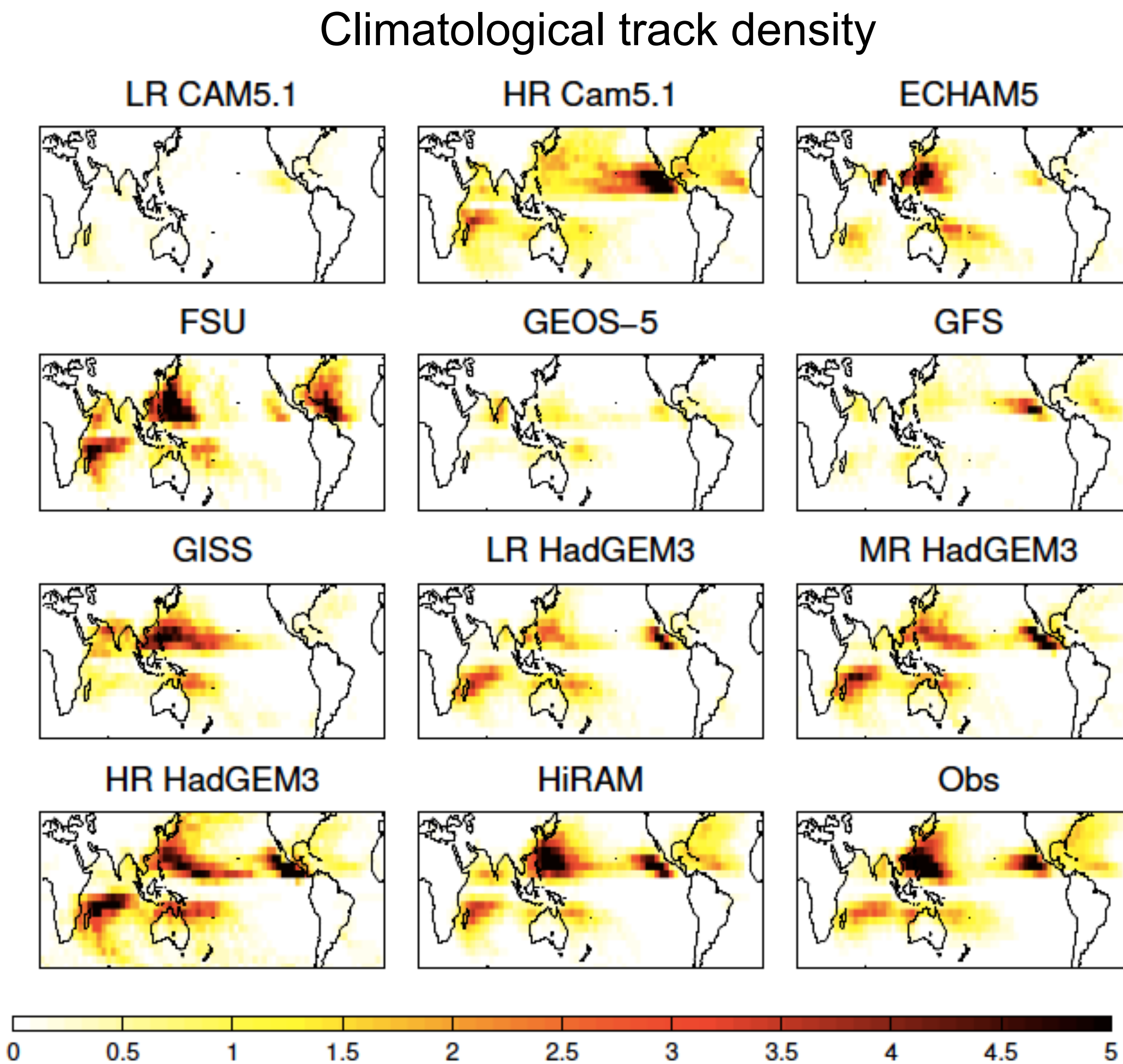
Hurricane Working Group

The US CLIVAR Hurricane Working Group was formed in January of 2011 to coordinate efforts to produce a set of model experiments designed to improve understanding of the variability of tropical cyclone formation in climate models.

The scientific objectives of the Hurricane WG include:

- an improved understanding of interannual variability and trends in the tropical cyclone activity from the beginning of the 20th century to the present
- quantifying changes in the characteristics of tropical cyclones under a warming climate.

The NOAA/GFDL HiRAM model arguably emerges as the best one.



, Shaevitz et al. 2014, *J. Adv. Model Earth. Sys.*

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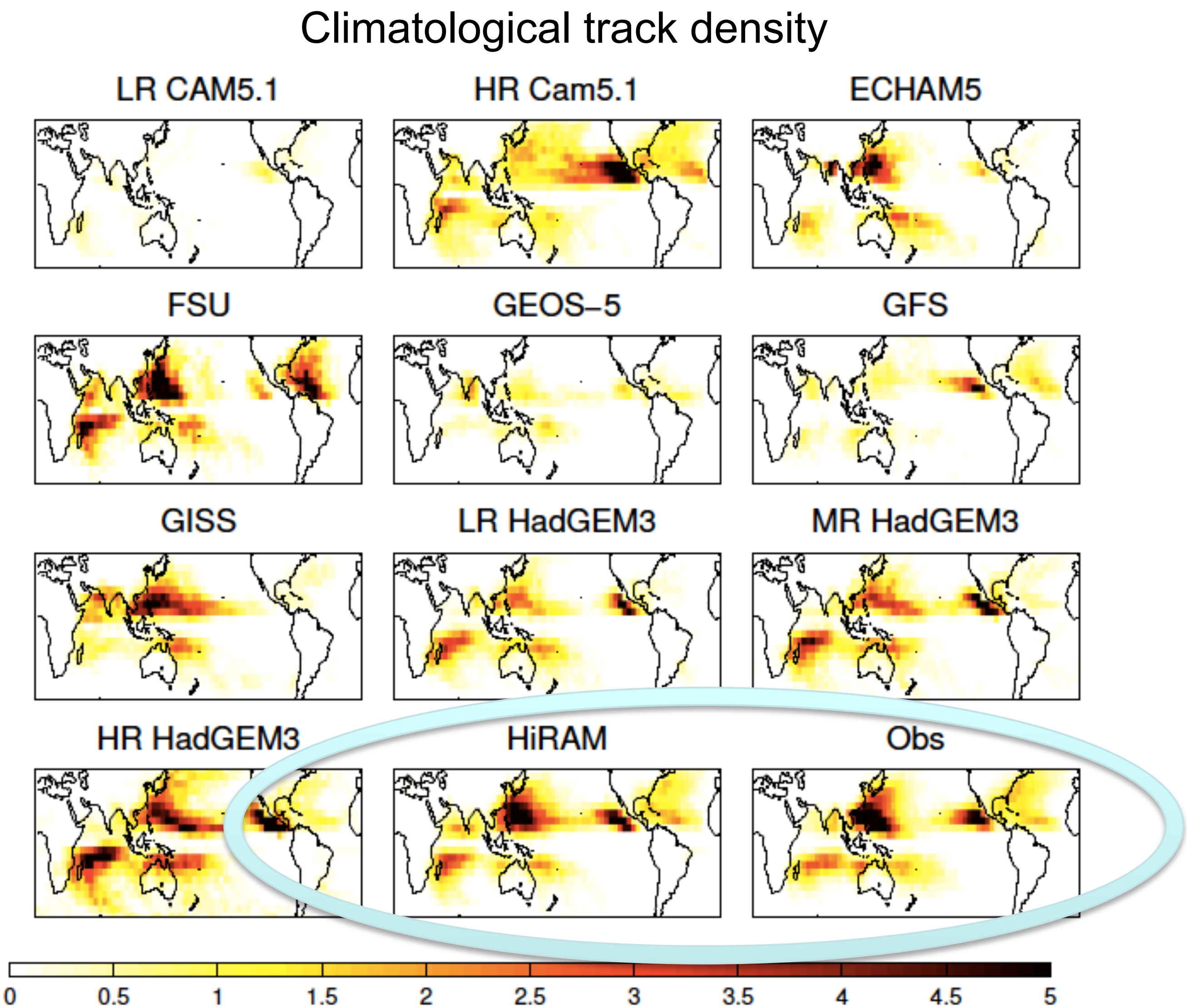

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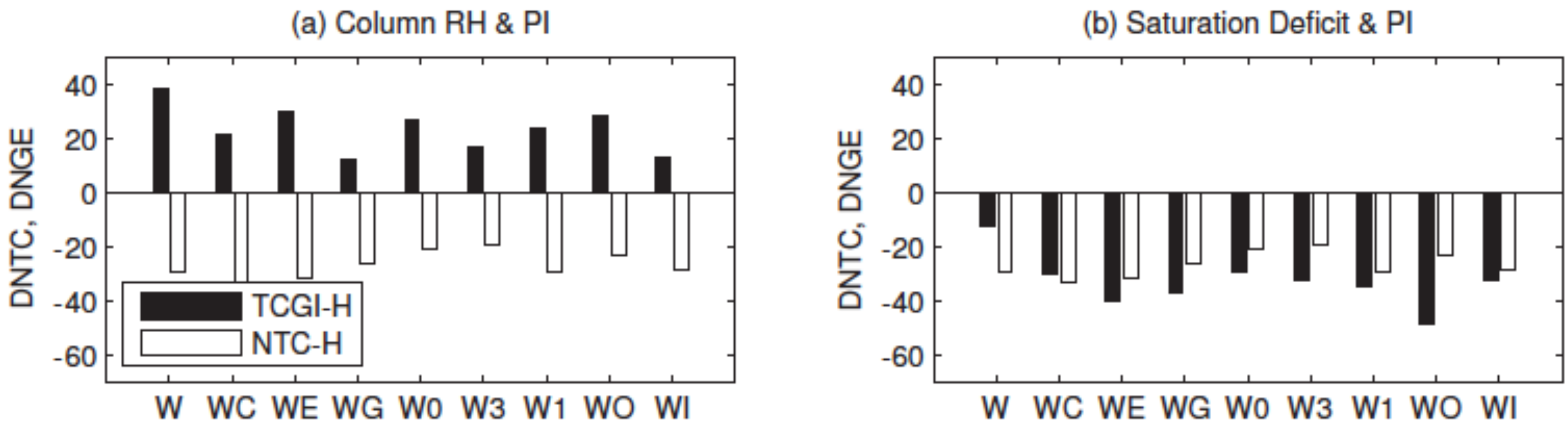
We use this model to test: 1. the genesis index methodology for use in global warming; 2. Our understanding of the reasons behind the simulated decrease in frequency.

We first derive a genesis index (using Poisson regression) from the model's own TC statistics and large-scale environment, in simulations of the recent historical climate.

Then, we test whether that index correctly captures the frequency changes in the warmer climate in the same model.

This is a "perfect model" approach.

We find that we get good results only if we replace *relative humidity* by *saturation deficit.*



SST warming patterns taken from different climate models

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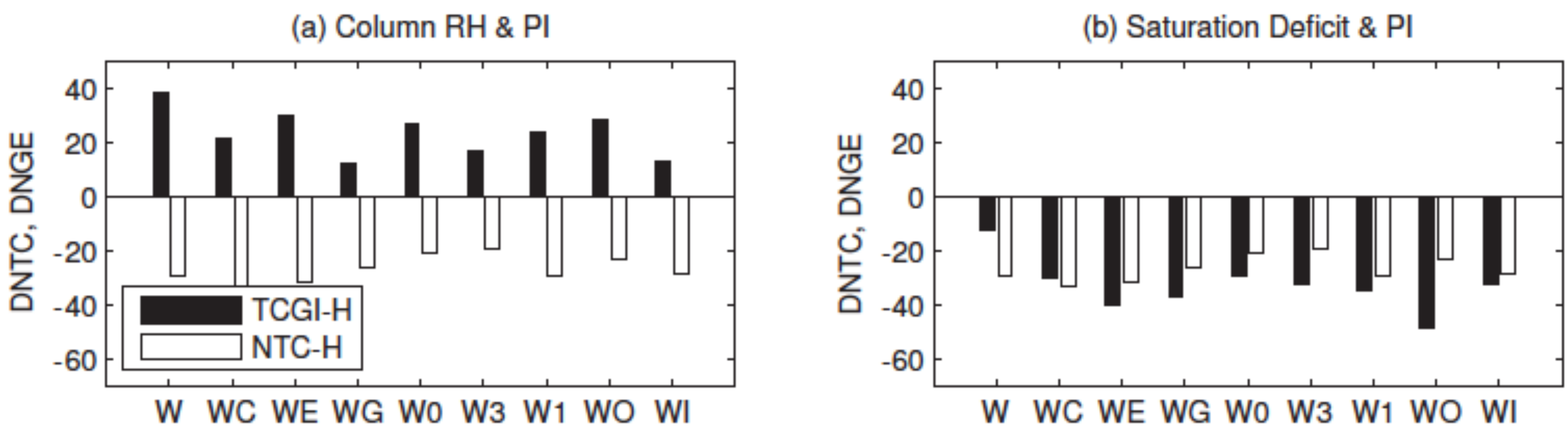

One is the ratio of specific humidity to its saturation value, the other is the difference. Their space/time variations in the present climate are almost identical.

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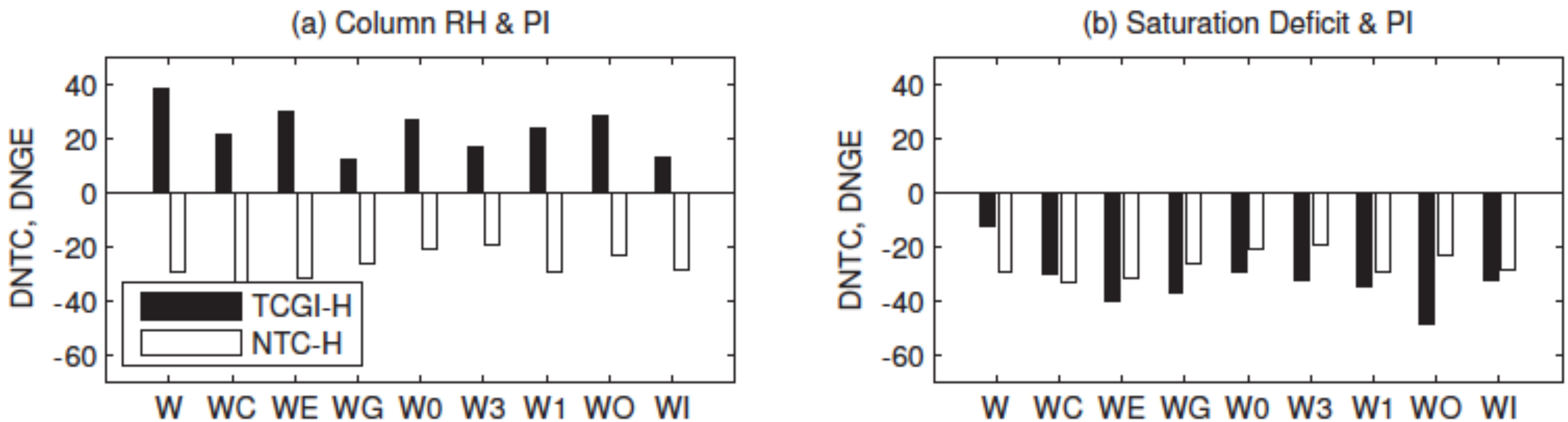
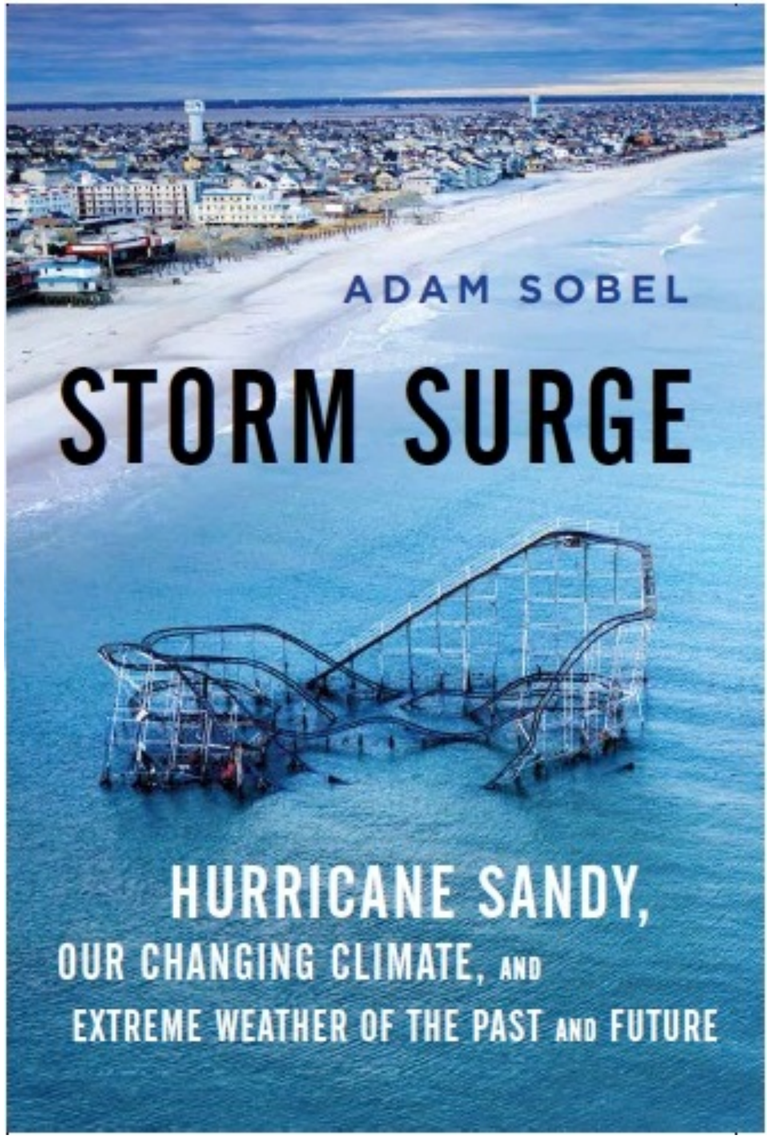


At fixed RH, saturation deficit increases with temperature. Thermodynamically, there is reason to think saturation deficit should matter – it's the absolute entropy the ocean has to supply.

Conclusions

- Models suggest aerosol cooling has kept TC potential intensity changes small so far, even though globe has warmed.
- Our empirical genesis indices are able to capture natural variability, e.g., ENSO, in TC frequency.
- Model-simulated decrease in TC number with warming appears related to the saturation deficit increase – a consequence of constant relative humidity under warming.

Book on Sandy (HarperCollins)



Columbia page: www.columbia.edu/~ahs129/home.html
Blog: adamsobel.org
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Potential intensity theory gives broadly successful predictions of the maximum intensity a TC can reach in the present climate.

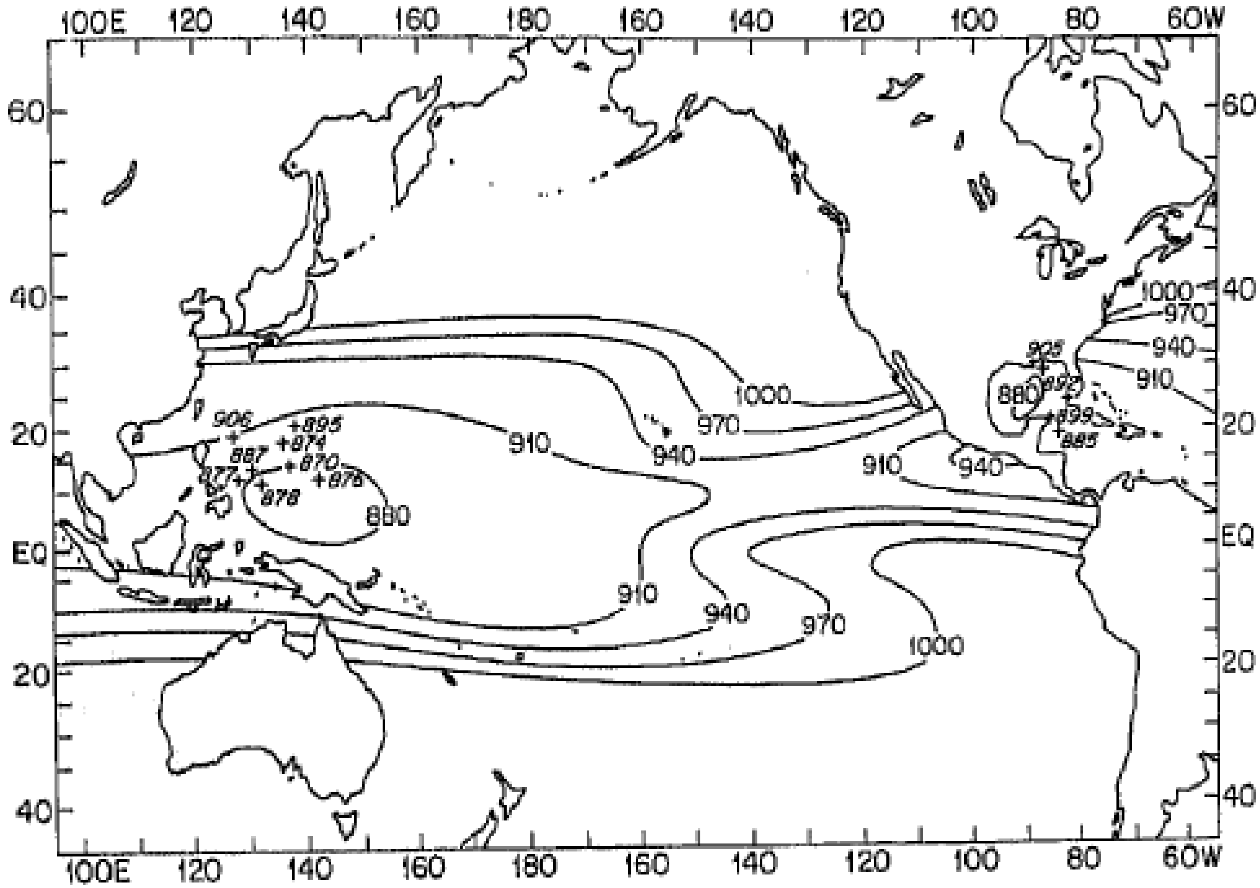

Figure 3 Minimum sustainable central pressure of tropical cyclones (in millibars) under September climatological conditions. The central pressures of some of the most intense tropical cyclones on record are shown by italicized numbers and crosses.