Tropical Cyclones and Climate Change: What Do We Know?

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What is our physical understanding of how TCs respond to climate change? Part I: TC wind-intensity

Two primary factors dictate how strong a TC's winds *can* get, all other factors optimal. This is called **TC potential intensity** (Emanuel 1987).

1) Ocean surface temperature (and heat content).
2) The temperature and moisture state of the atmosphere.

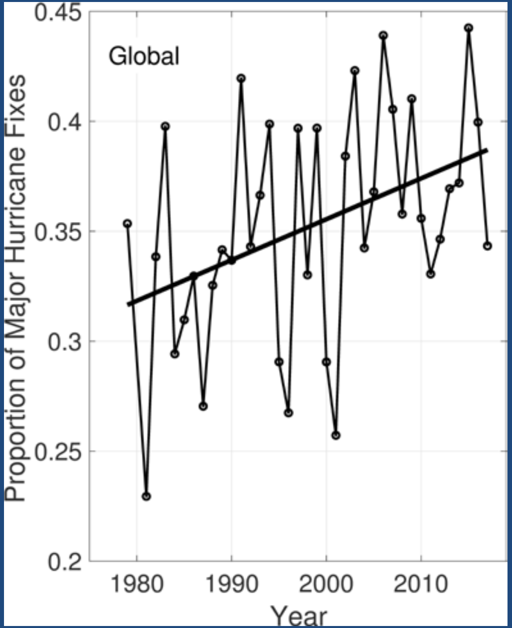
Potential intensity depends on the *moist thermodynamic* state of the atmosphere / ocean. The theory is based on the Carnot cycle heat engine.

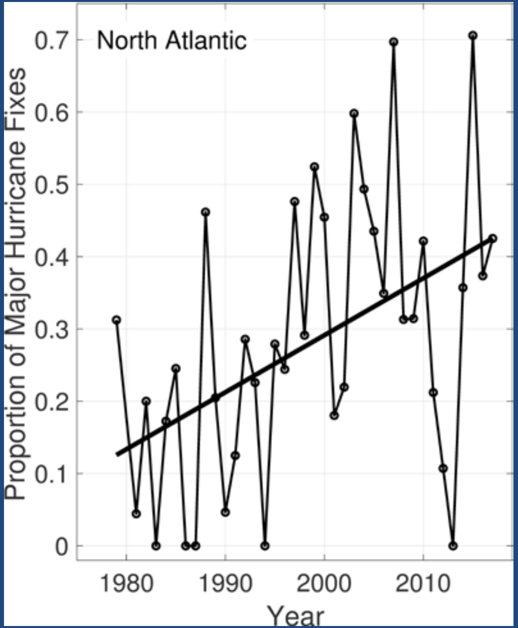
Other factors can keep a TC from reaching its potential intensity (e.g. vertical wind shear), by disrupting the efficiency of the heat engine.

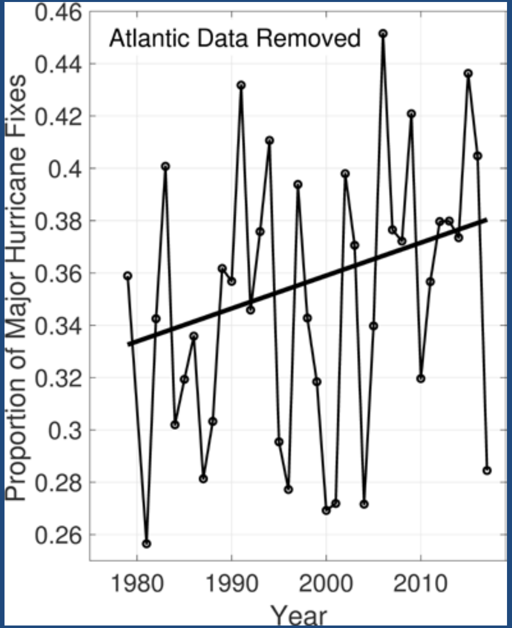
If climate change increases TC potential intensity and other factors don't counteract this, then we should see a shift towards stronger storms. Do we?

Emanuel, K. A., 1987: The dependence of hurricane intensity on climate. *Nature*, **326** , 483–485.

Yes, the strongest TCs have become stronger over the past 4 decades







Globally, it's about 25% more likely now that a TC will be at major TC intensity (Category 3, 4, 5) than four decades ago.

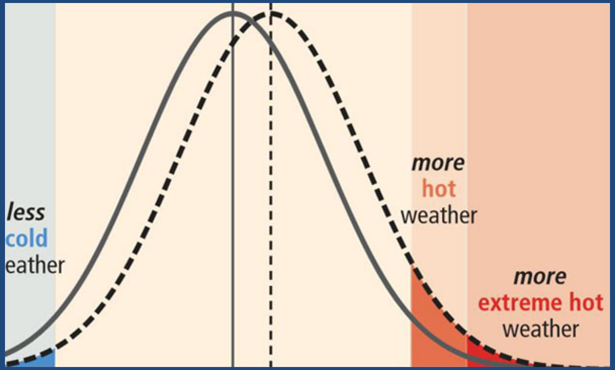
In the Atlantic the proportion has more than doubled.

Almost all mortality and damage is caused by major TCs.

Kossin, J. P., K. R. Knapp, T. L. Olander, and C. S. Velden, 2020: Global increase in major tropical cyclone exceedance probability over the past four decades. *Proceedings of the National Academy of Sciences*, **117**, 11975-11980

And yes, the strongest TCs are projected to get stronger with warming.

We have high confidence that the global average TC intensity will increase. The mean projected increase in lifetime-maximum surface wind speeds is about 5% under 2°C warming. **A small change in the mean often comes with a large change in the extremes.**



We have high confidence that the global proportion of very intense (category 4–5) TCs will increase. The median projected change is about +13%. Again, **these are the storms that are responsible for the greatest damage and mortality rates.**

Knutson, T., S. J. Camargo, J. C. L. Chan, K. Emanuel, C.-H. Ho, J. Kossin, M. Mohapatra, M. Satoh, M. Sugi, K. Walsh, and L. Wu, 2020: Tropical cyclones and climate change assessment: Part II. Projections. *Bull. Amer. Meteor. Soc.*, **101**, E303–E322.

What is our physical understanding of how TCs respond to climate change? Part 2: TC rain-rates

TC rain-rates increase with warming of the atmosphere, simply because warmer air holds more water vapor, which increases by about 7% per °C of warming. TCs are very good at turning this additional water vapor into rain.

But measuring past changes in TC rain-rate is difficult for a number of reasons, so this signal has not been confidently observed yet. Still, just based on physics, it's highly likely that TC rain-rates have increased.

And we have high confidence that TC rain rates will increase by at least 14% under 2°C of warming.

What else could lead to more rainfall?
(Hint: think of Hurricane Harvey over Texas)

So far, we've discussed the physical links between climate change and TC wind intensity and rain rates (we'll talk about TC frequency later).

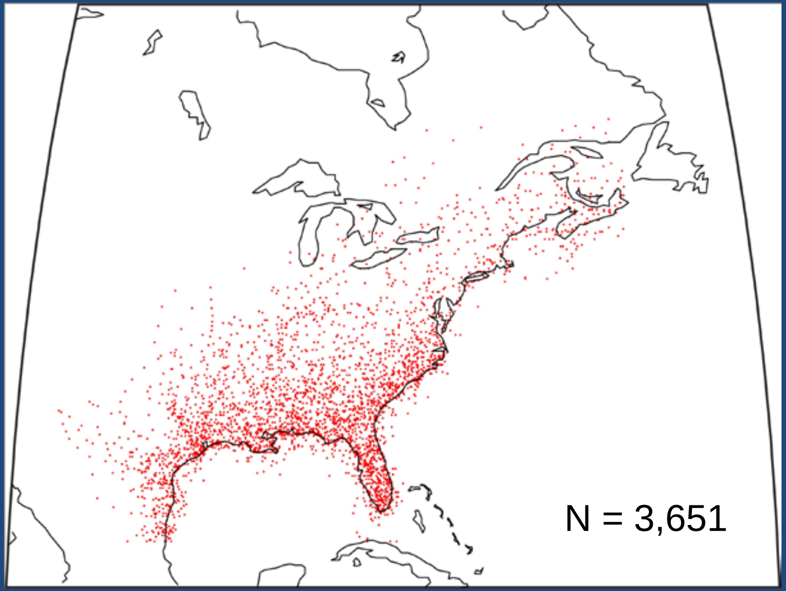
Another very important question is whether TC tracks will be affected by climate change.

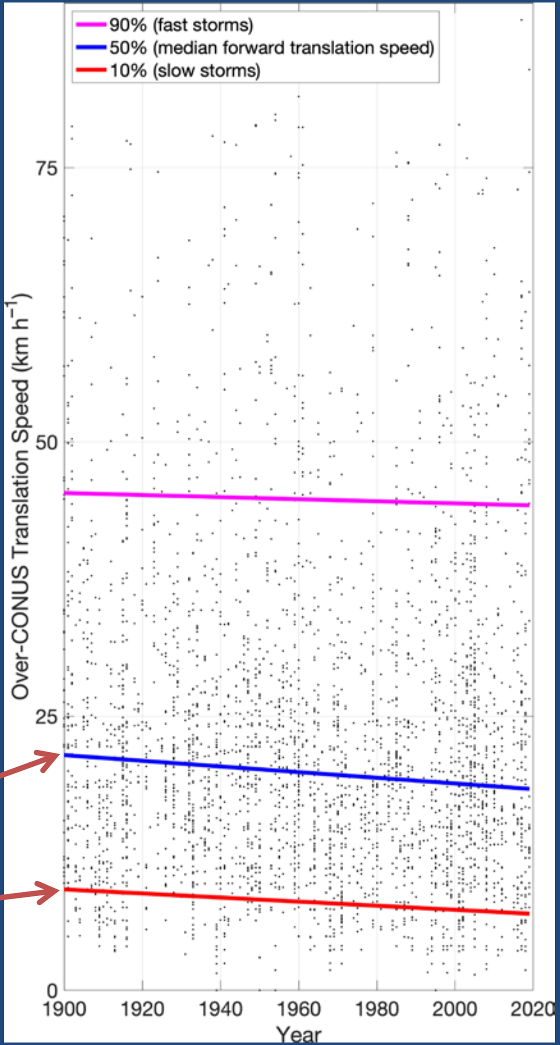
1) Changes in the speed of forward motion along the tracks
2) Track shifts

Changes in forward speed can have profound effects on local rainfall amounts, as well as wind damage due to changes in wind-event duration.

Track shifts can have profound effects on TC exposure patterns.

Slowdown over CONUS since 1900





14% slowdown of the median

24% slowdown of the slowest 10th percentile

Hurricane rain-rate increases by about 7% per °C of warming, as warmer air holds more water vapor.

There's been about 1°C warming since 1900.

$$\text{local rainfall} \sim \frac{\text{rain-rate}}{\text{speed of motion}}$$

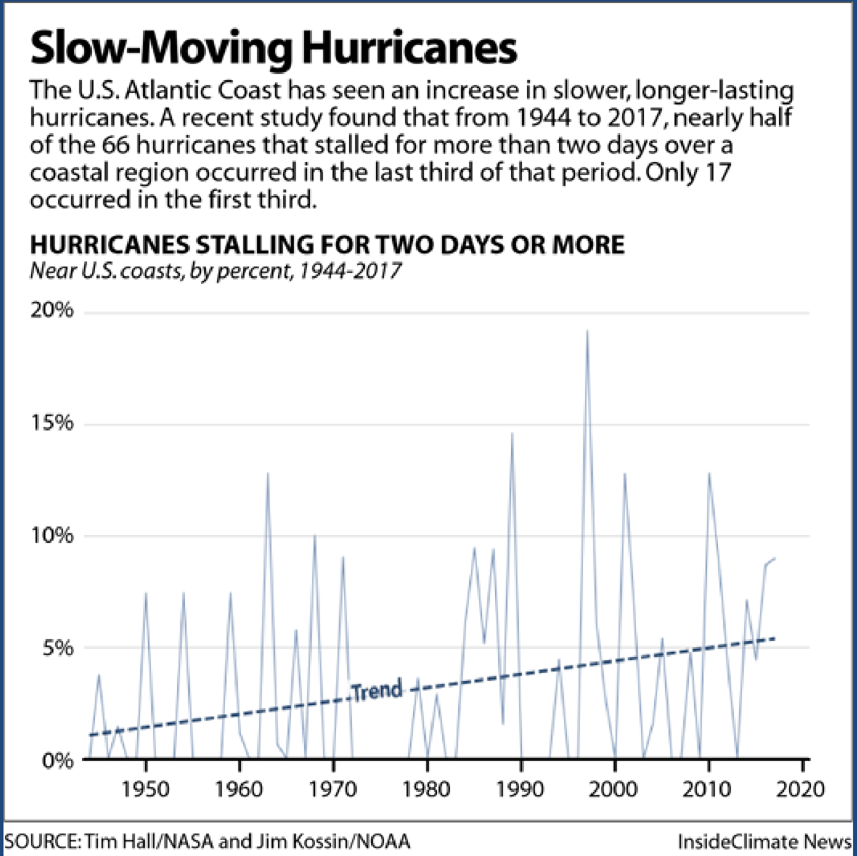
$$\text{change in local rainfall} \sim \frac{(1+7\%)}{(1-24\%)}$$

41% increase of local rainfall due to the combined effect of 7% more water vapor and 24% slower moving hurricanes

Adapted from Kossin, J. P., 2019: Matters Arising, *Nature*, **570,** E16-E22.

J. Kossin, 26 Apr 2021

TCs are "stalling" more often



The increase in frequency of stalling events over the US is linked to increased rainfall.

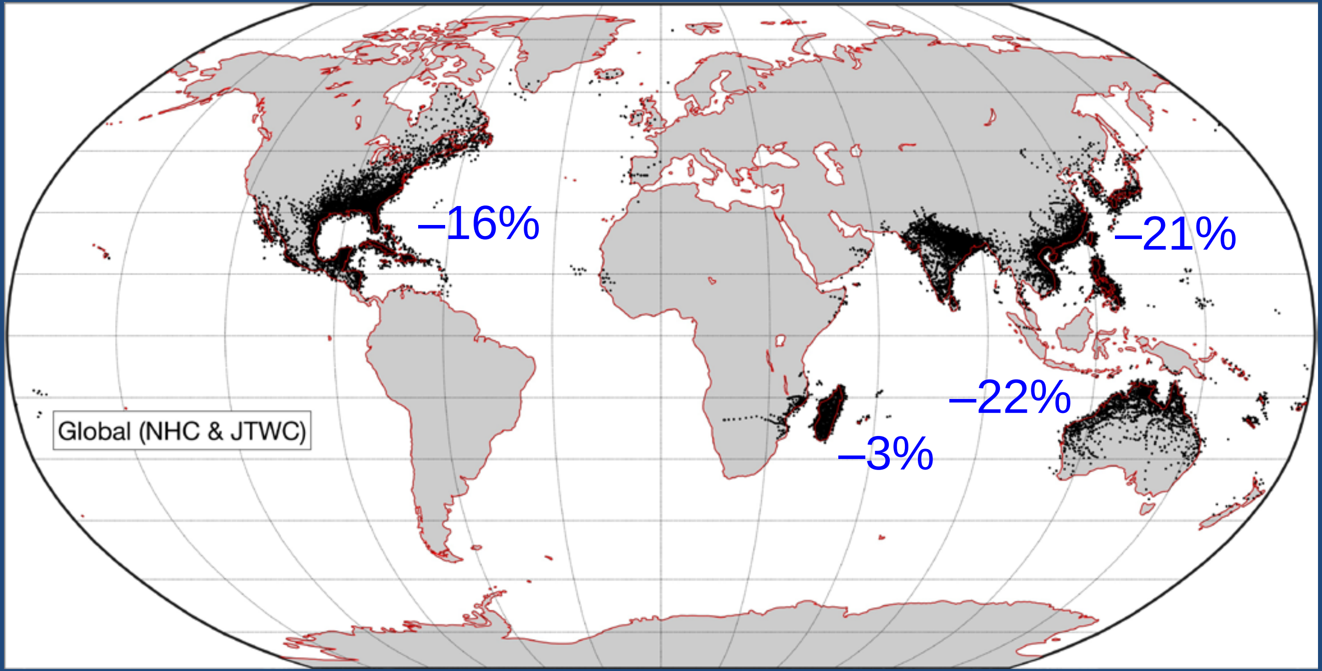
Recent examples:

Hurricanes Sally & Eta (2020)
Hurricane Dorian (2019)
Hurricane Florence (2018)
Hurricane Harvey (2017)

Hall, T. M., and J. P. Kossin, 2019: Hurricane stalling along the North American coast and implications for rainfall. *Nature Climate and Atmospheric Science*, **2**, doi:10.1038/s41612-019-0074-8

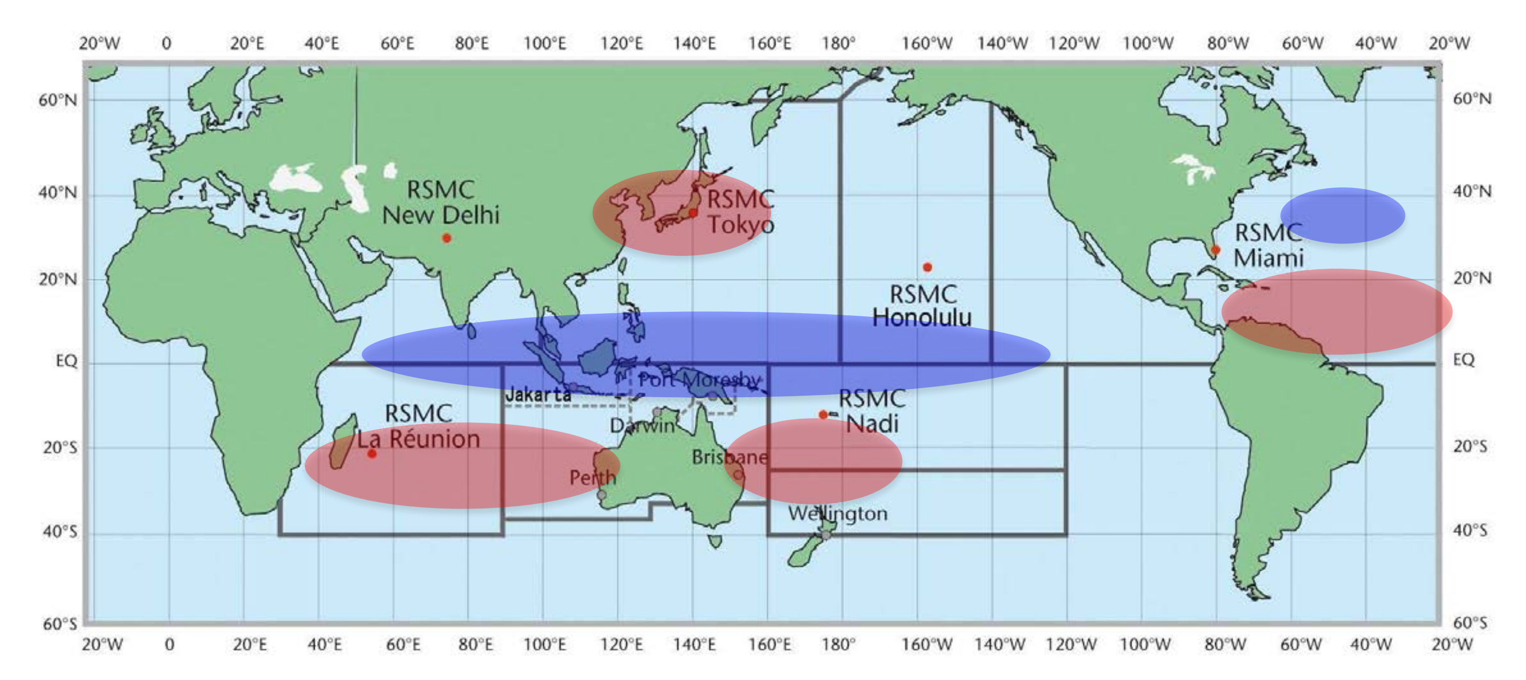
The slowdown over land appears to be occurring globally.

The physical links are not clear yet, but it may be due to arctic amplification reducing the summertime steering winds in the subtropics and mid-latitudes. Some models project this into the future, and some don't.



Kossin, J. P., 2018: A global slowdown of tropical cyclone translation speed. *Nature*, **558**, 104-108.

Track shifts: TCs have migrated poleward in most regions as the tropics have expanded.



Increased TC exposure in less prepared populous regions.

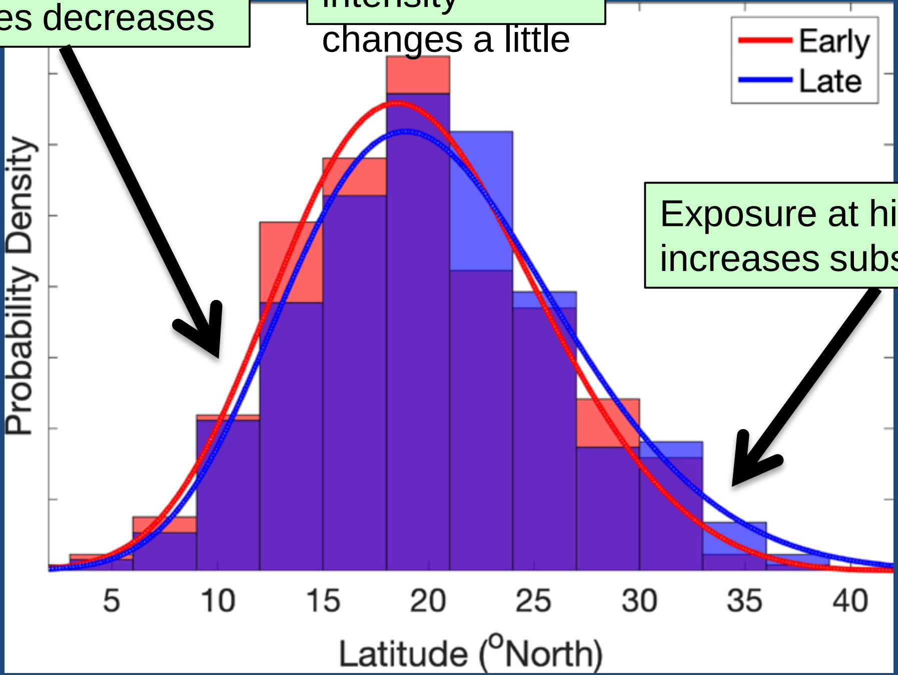
Kossin, J. P., K. A. Emanuel, and G. A. Vecchi, 2014: The poleward migration of the location of tropical cyclone maximum intensity. *Nature*, **509**, 349-352.

The poleward shift is particularly pronounced in the western North Pacific Ocean

Exposure at low latitudes decreases

Average latitude of peak intensity changes a little

Exposure at high latitudes increases substantially



Philippines **Taiwan** **Japan, Korea**

Eastern China

Kossin, J. P., K. A. Emanuel, and S. J. Camargo, 2016: Past and projected changes in western North Pacific tropical cyclone exposure. *Journal of Climate*, **29**, 5725-5739.

What is our physical understanding of how TCs respond to climate change? Part 3: TC genesis

1. Warming raises ocean temperature and increases heat content (simple).

2. The atmosphere responds to warming differently, depending on what caused the warming (complicated).

Well-mixed greenhouse gas warming warms the oceans, but also tends to stabilize and dry the atmosphere, which tends to suppress TC genesis (formation).

Local warming (e.g., reduction of aerosol concentration) affects the atmosphere differently and generally causes increased genesis frequency. This is likely what has been happening in the Atlantic.

There is no clear evidence, nor clear expectation, that TC genesis rates have increased or will increase due to increasing greenhouse gas concentration.

Emanuel, K., and A. Sobel, 2013: Response of tropical sea surface temperature, precipitation, and tropical cyclone-related variables to changes in global and local forcing. *J. Adv. Model. Earth Syst.*, **5**, 447–458.

What other aspects of TCs have been linked to climate change?

TCs are intensifying more rapidly

In the early 1980s, the chance of having a hurricane intensification event of 35 mph or more in a 24 hour period was about 1/100. 30 years later, the chance has gone up by a factor of 5 to about 1/20.

The most rapid 24-hour intensification events (top 95%) are becoming even more rapid, by about an additional 5mph per decade.

What about TC size? No clear evidence and a general lack of studies.

Bhatia, K., G. Vecchi, T. Knutson, H. Murakami, J. Kossin, K. Dixon, and C. Whitlock, 2019: Recent increases in tropical cyclone intensification rates. *Nature Communications*, **10**, doi:10.1038/s41467-019-08471-z.

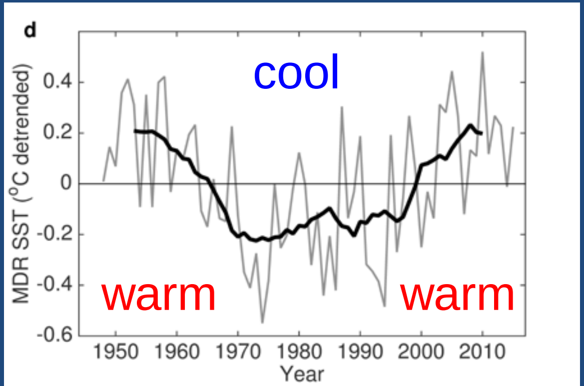
So, what do we know about TCs and climate change?

It's not clear that we will have more TCs forming, but once a TC *does* form we have high confidence that it is more likely to

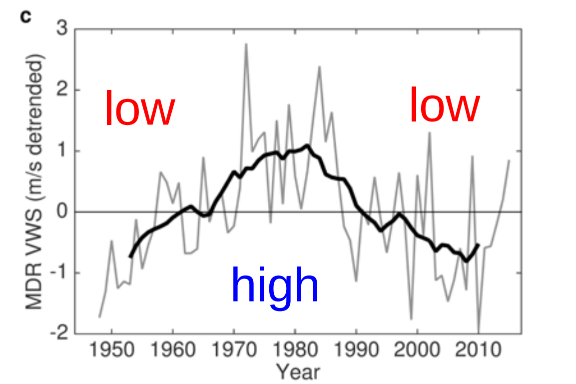
- ✧ Be at major hurricane intensity.
- ✧ Have greater rain-rates.
- ✧ Intensify rapidly.

There is also good evidence that tracks change. TC forward speed slows over land and TCs are more likely to stall. Exposure to TCs changes as tracks shift.

Multi-decadal variability in the tropical North Atlantic, and basin-wide Atlantic major hurricane activity

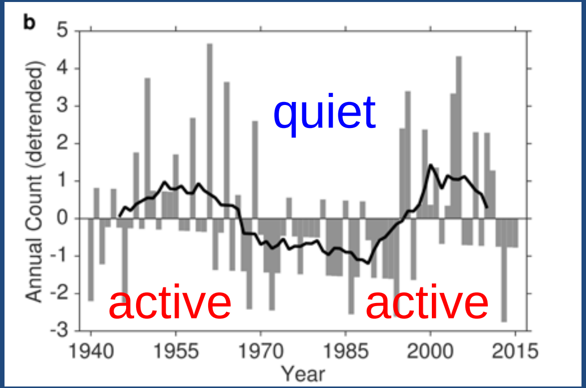


SST



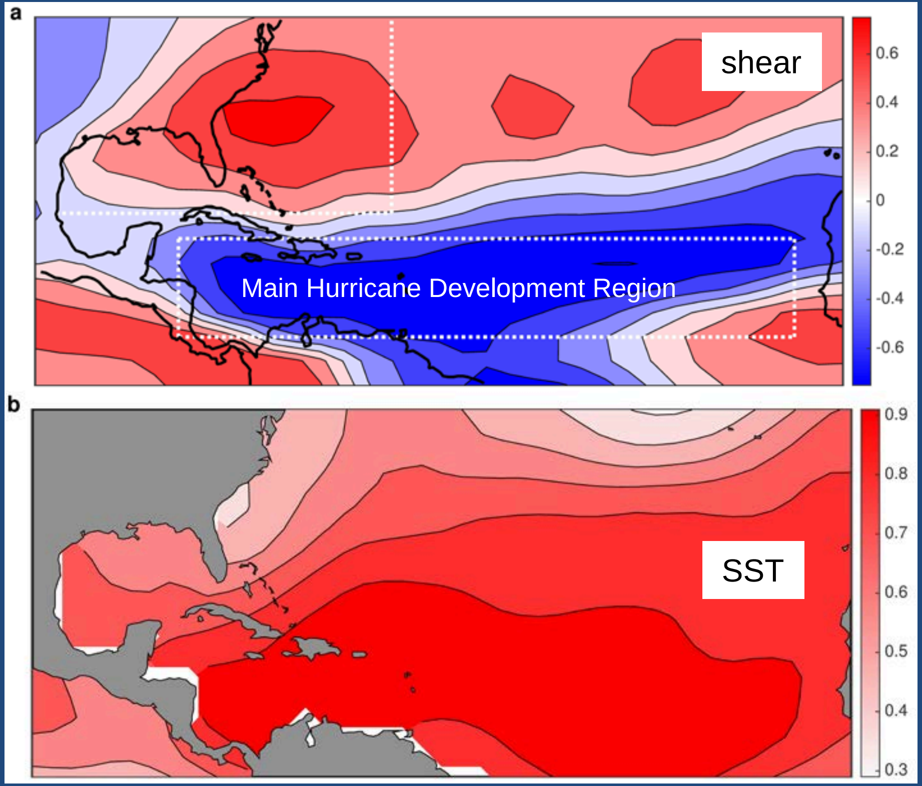
Vertical wind shear

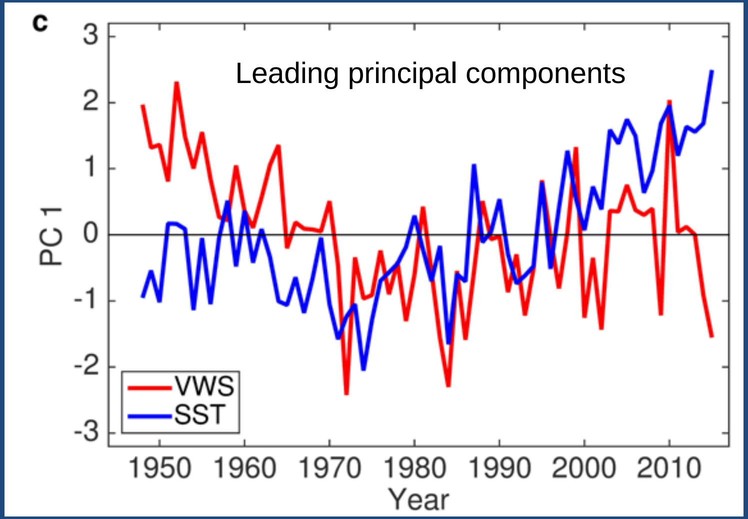
Major hurricanes



Are there regional patterns of variability that may be important for regional risk, but are missing from these types of analyses?

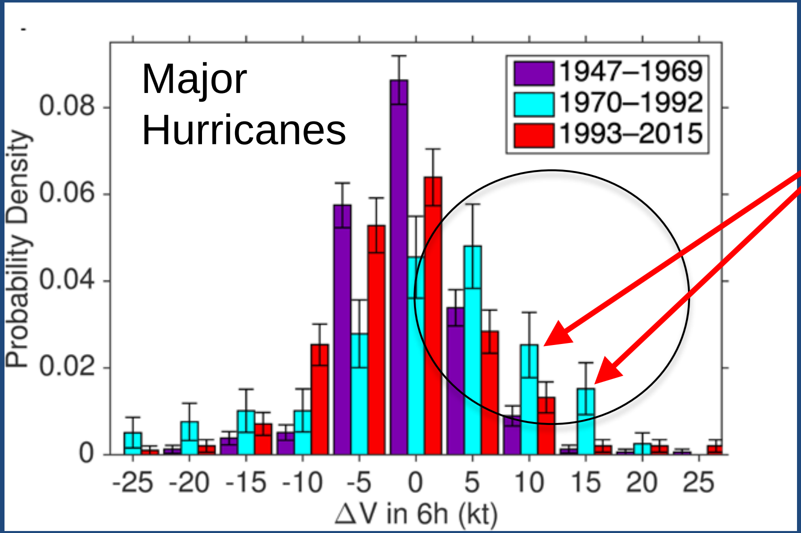
Leading patterns of variability of shear and SST (1948–2015)



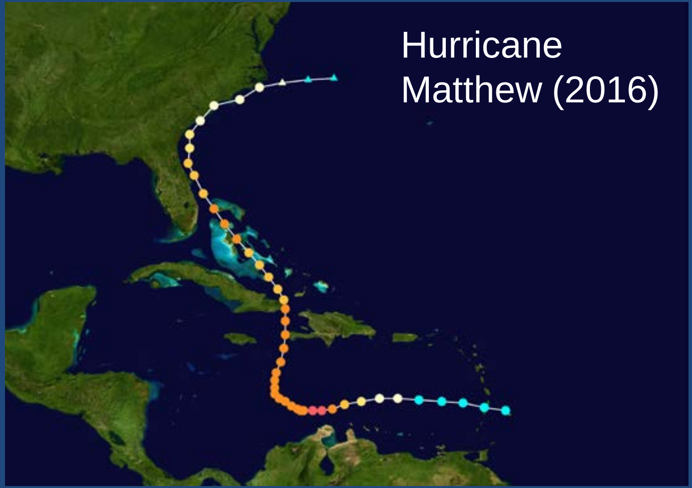


Kossin, J. P., 2017: Hurricane intensification along United States coast suppressed during active hurricane periods. *Nature*, **541**, 390-393.

Hurricane intensity change near/along the U.S. coast



very dangerous



$$\text{Pr (Rapid Intensification of U.S. Major Hurricane)} = \begin{cases} 10 \pm 7\% \text{ (last cool phase)} \\ 3 \pm 2\% \text{ (current warm phase)} \end{cases}$$

Major hurricanes that approach or move along the U.S. east coast were 3 times less likely to rapidly intensify during active warm periods (e.g., Hurricane Matthew 2016).

Fewer hurricanes during cool periods, but they're more dangerous and harder to forecast.
Overall risk is lower, but singular events can pose greater risk (e.g., Andrew 1992).

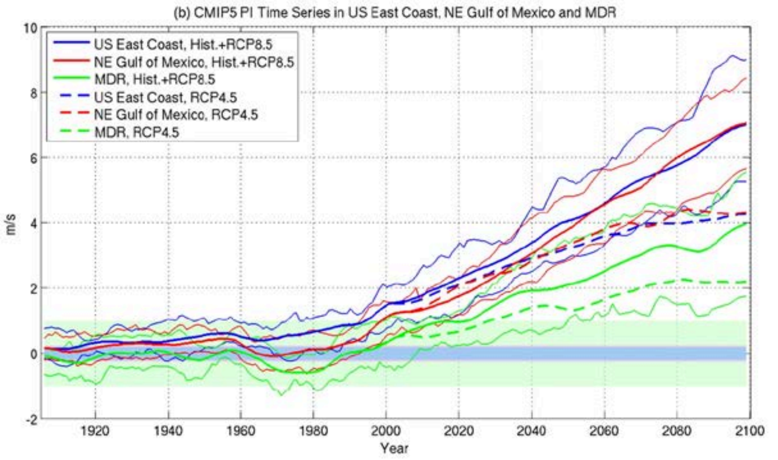
There is a natural barrier that helps protect regions near and along the U.S. east coast during periods of heightened overall hurricane peril.

This is tremendously fortunate.

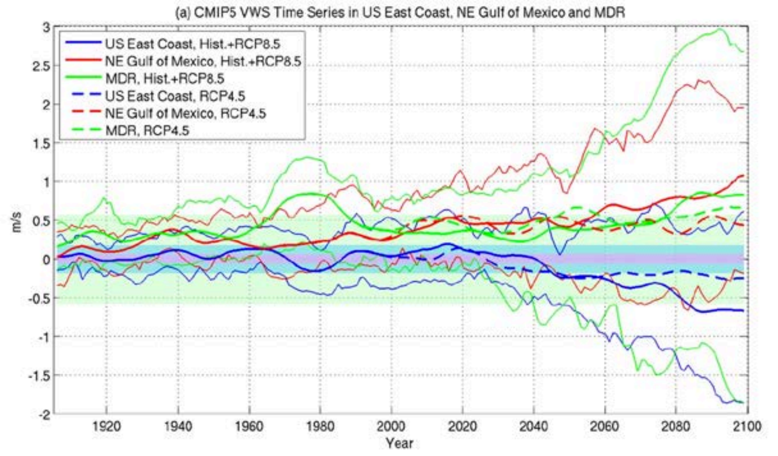
Is this barrier sensitive to greenhouse gas warming?

If so, does greenhouse gas warming enhance or degrade the barrier?

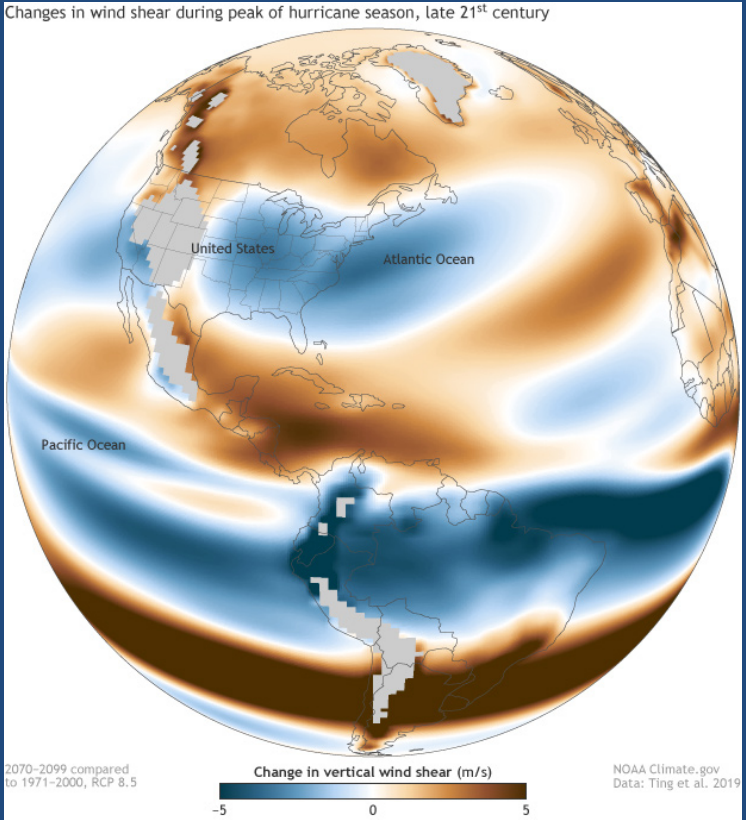
Patterns of projected shear change



PI



VWS



Ting, M., J. P. Kossin, S. J. Camargo, and C. Li, 2019: Past and future hurricane intensity change along the U.S. East Coast. Scientific Reports, 9:7795, 10.1038/s41598-019-44252-w

J. Kossin, 26 Apr 2021

The natural shear barrier along the U.S. east coast has been reducing major U.S. hurricane risk for decades. The more conducive the tropics are for elevated hurricane peril, the stronger the barrier to any hurricanes that approach or move along the coast.

This pattern is projected to erode with increasing greenhouse gas concentrations. By 2050, following the RCP8.5 business-as-usual scenario, the amplitude of the shear decrease along the coast is projected to be twice the amplitude of the natural barrier of increased shear.

All other factors equal, such a trend will substantially increase U.S. hurricane risk on an individual hurricane basis, although overall risk may increase at a lesser rate.

In the Antilles, shear is projected to increase, which should offset the increase in potential intensity to some extent.

Questions?