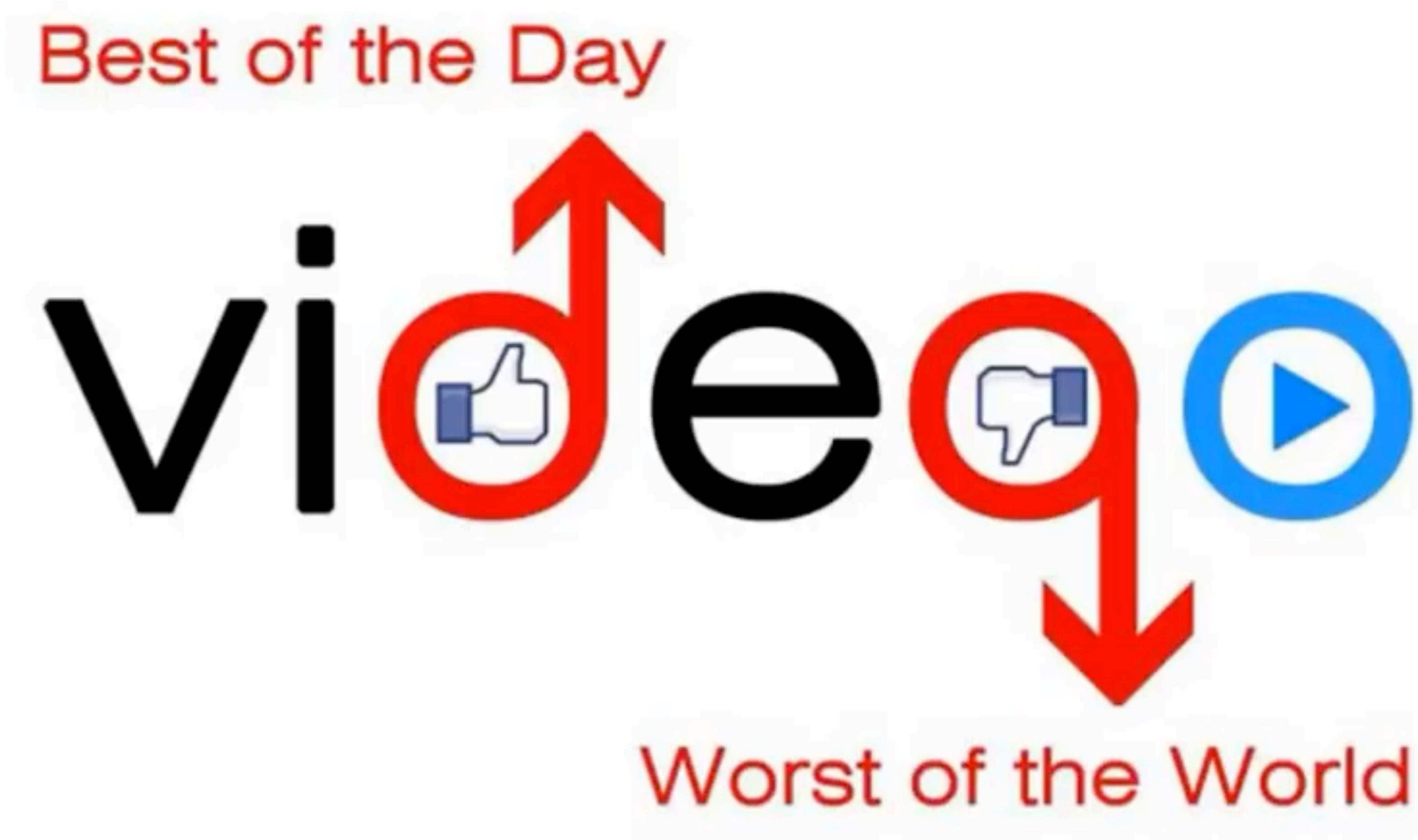
Hurricanes

Global Warming Science

https://courses.seas.harvard.edu/climate/eli/Courses/EPS101/

Hurricane Irma, 2017



https://www.youtube.com/watch?v=KVciUq72gpk

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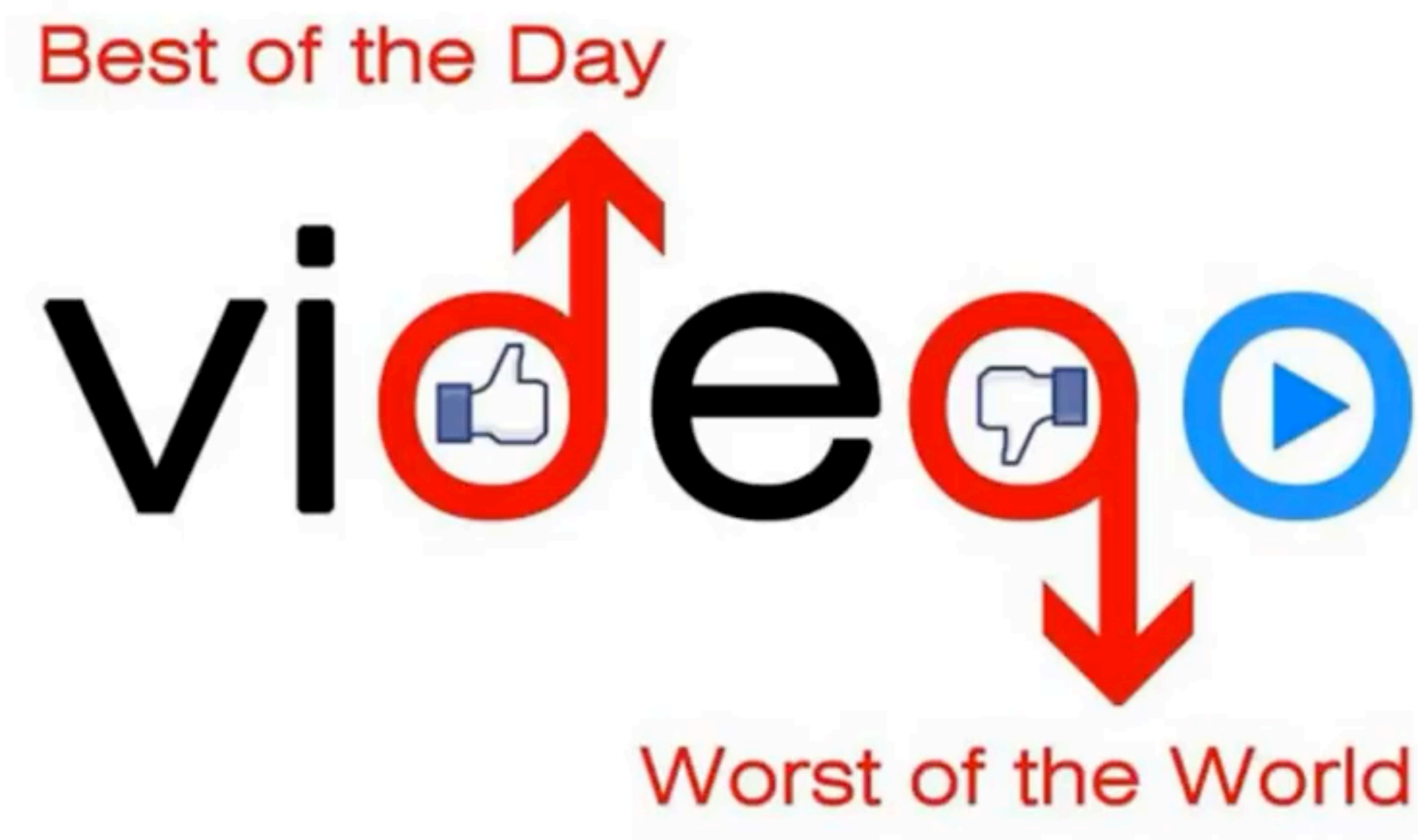
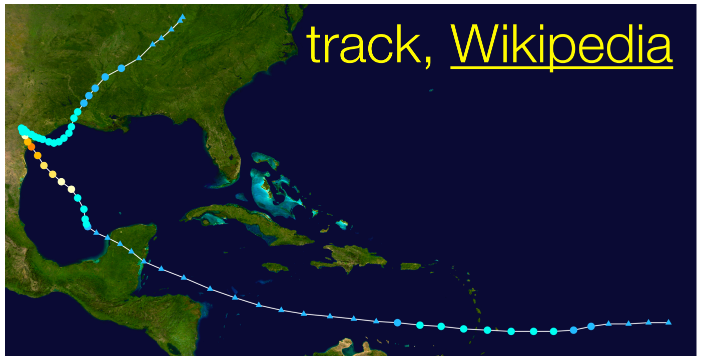


https://www.youtube.com/watch?v=KVciUq72gpk

Hurricane Harvey, 2017



https://www.houstonchronicle.com/local/hc-investigations/harvey/one-year-later/

see also: https://www.houstonchronicle.com/news/houston-weather/hurricaneharvey/article/Then-and-now-photos-show-how-Hurricane-Harvey-13155174.php

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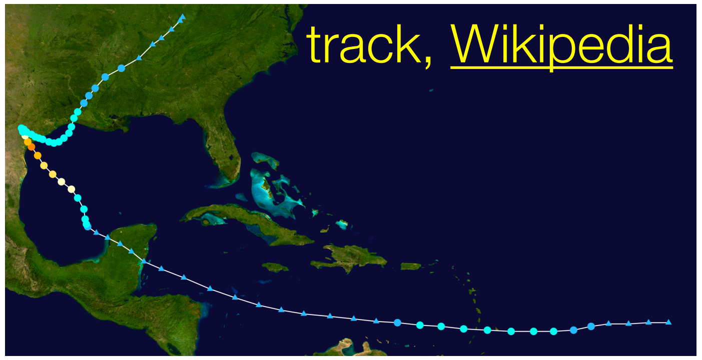

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Katrina, August 2005

NOAA image of Hurricane Katrina, Aug. 29, 2005 at 10:15 AM workshop 1a,b

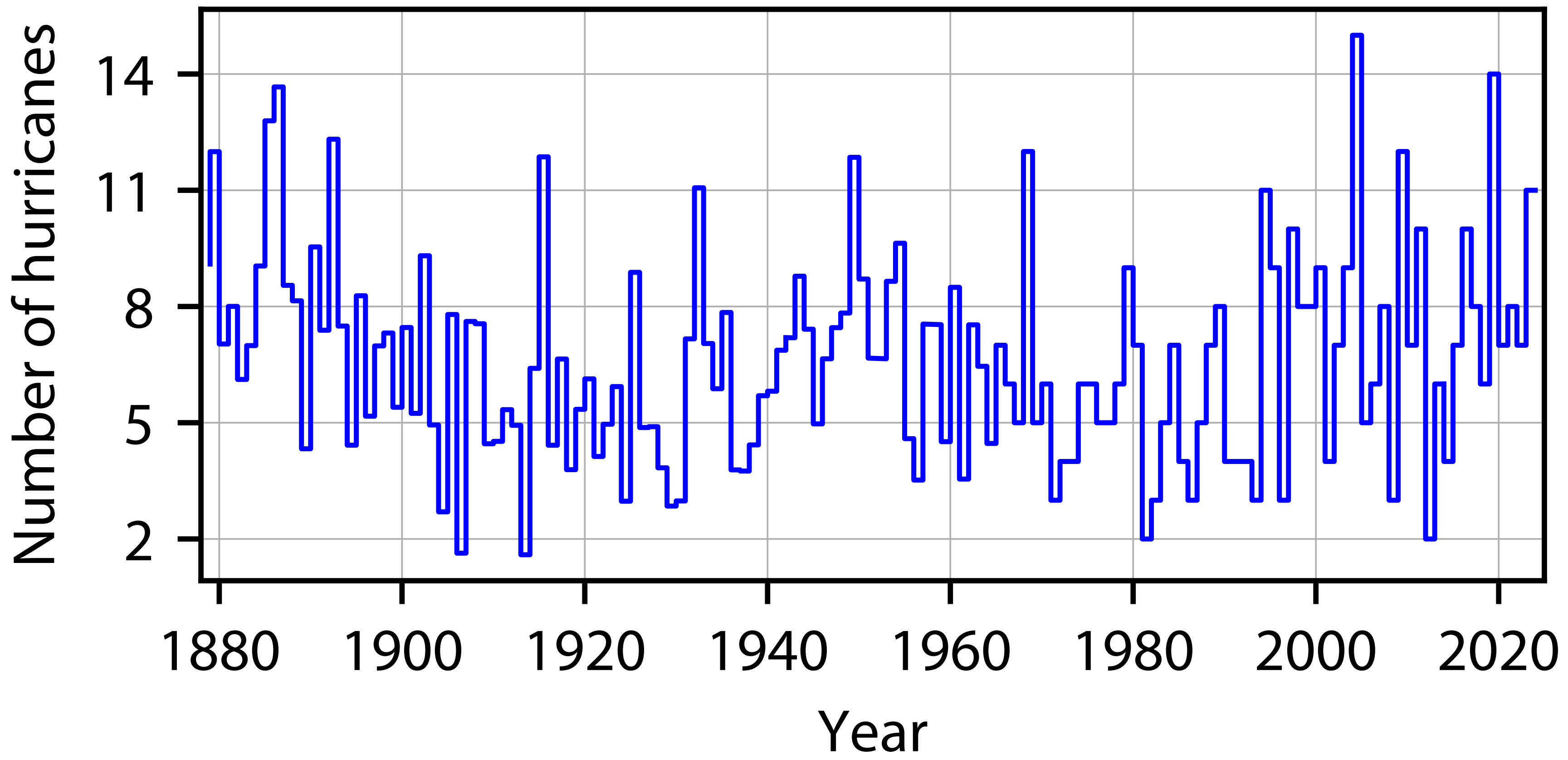
Did Hurricanes get stronger/more frequent already?

Plot time series of
(a) number of Atlantic hurricanes
(b) proxy for destructiveness of hurricanes (PDI, or the "power dissipation index")

Are Hurricanes getting more frequent? Stronger?

Number of Atlantic hurricanes per year

(data: Vecchi & Knutson 2011)



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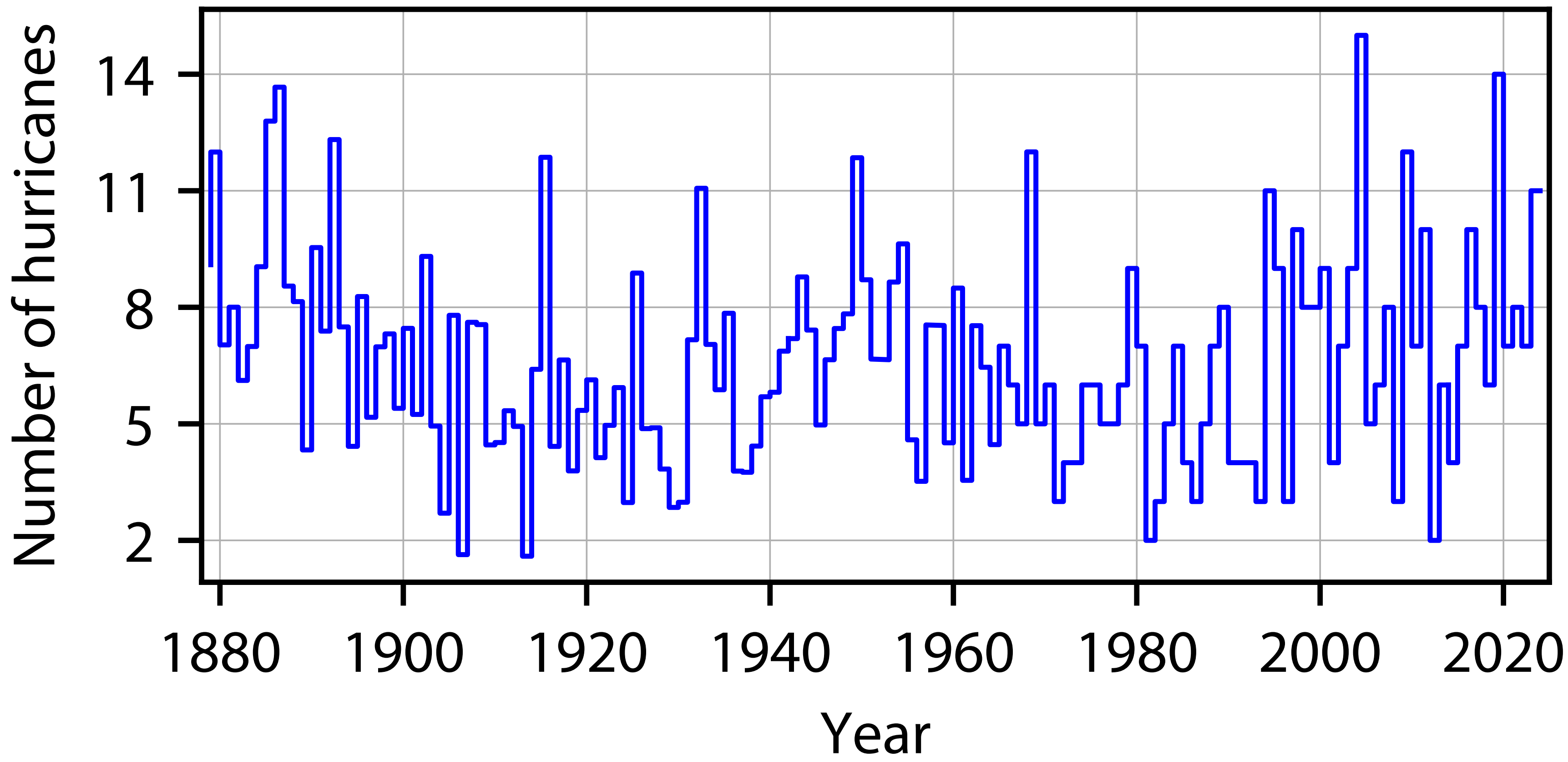
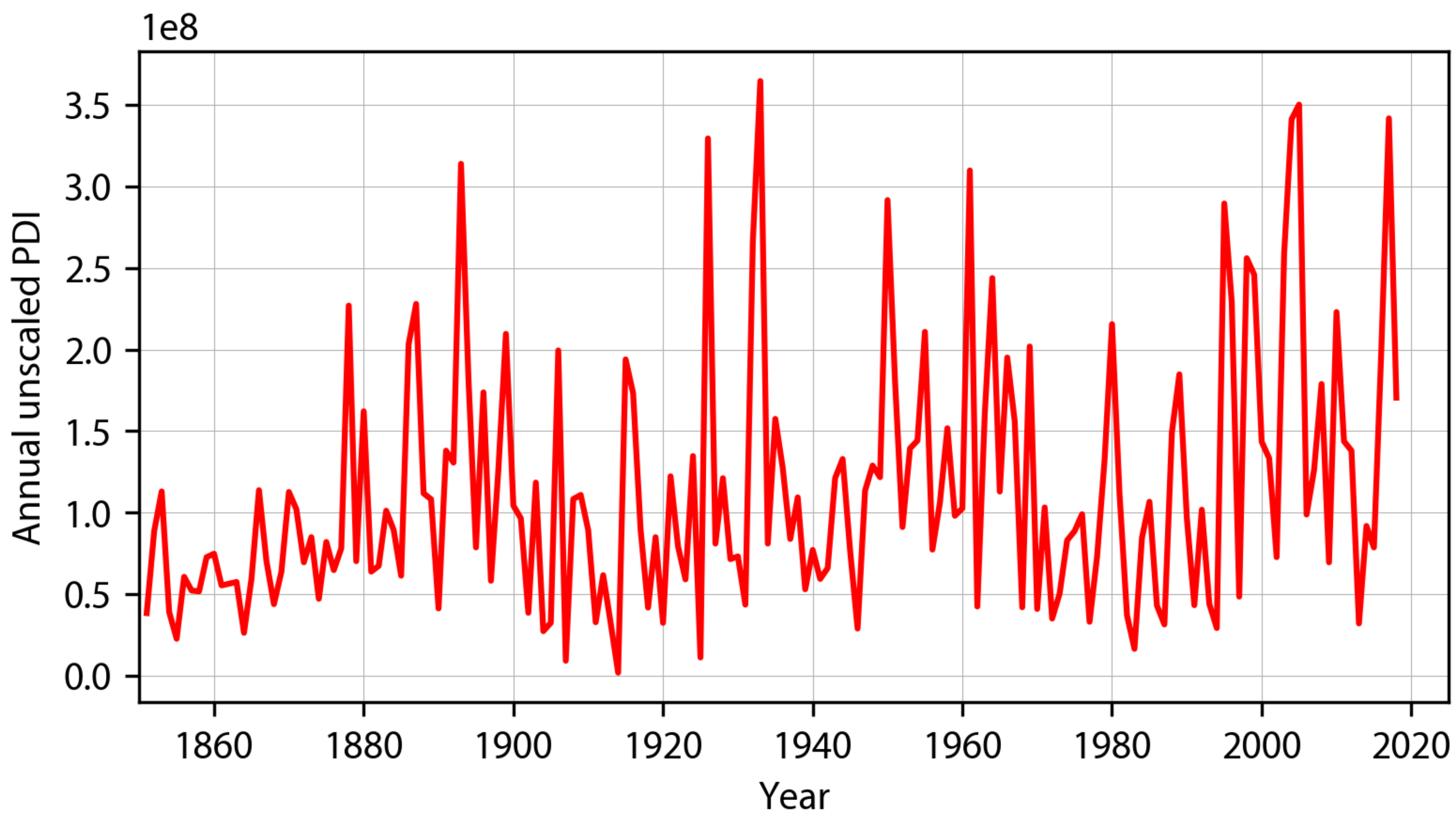
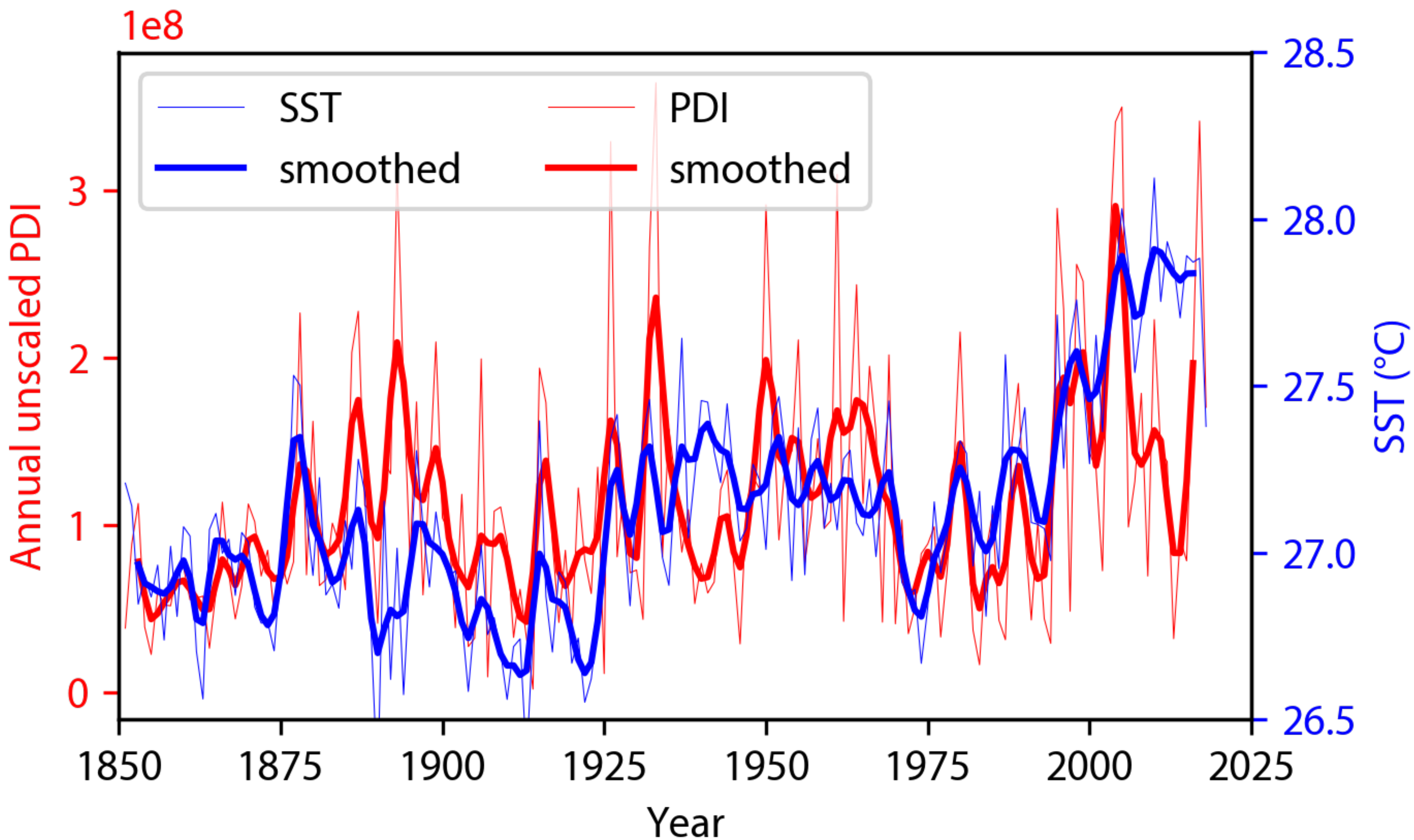


A measure of hurricanes magnitude (PDI)



Are hurricanes getting stronger?

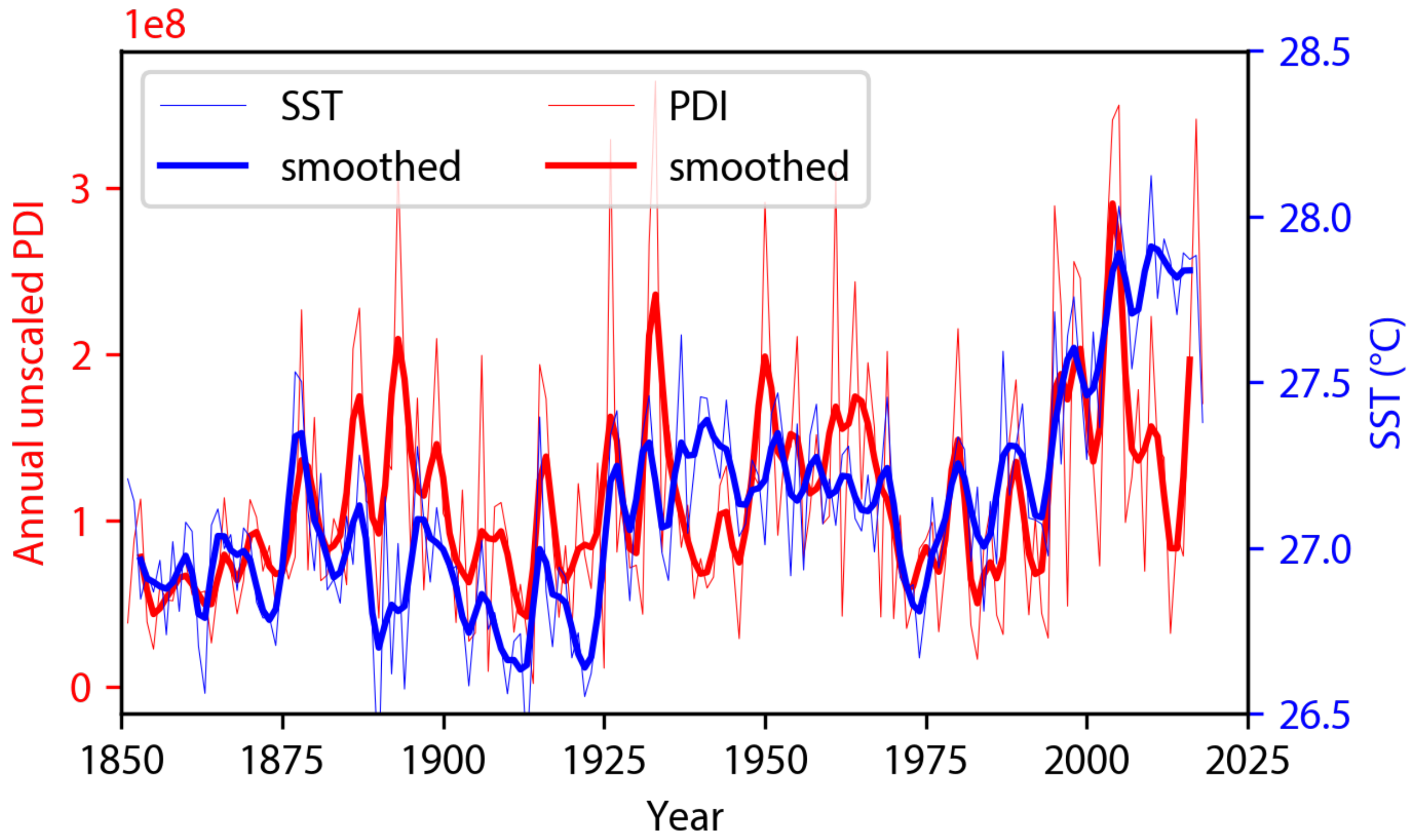
Power dissipation index vs SST, (PDI to be defined more precisely shortly)



r^2 of PDI/SST (unsmoothed):	0.1846
r^2 of PDI/SST (unsmoothed, 1950–today):	0.1693
r^2 of PDI/SST (smoothed):	0.3125
r^2 of PDI/SST (smoothed, 1950–2005):	0.6533
r^2 of PDI/SST (smoothed, 1950–today):	0.3191

Following Emanuel 2005

Smoothing time series



r^2 of PDI/SST (unsmoothed): 0.1846
r^2 of PDI/SST (smoothed): 0.3125

If the data represent some slowly varying “signal” and a rapidly varying “noise”, the smoothing will remove the noise, leaving only the signal:

- smoothing an already smooth slowly varying signal has no effect.
- smoothing a rapidly varying signal removes it to a large degree.

This is used as a justification for smoothing before calculating correlations.

Workshop: (**1c,d**): Calculate the correlation between SST and "hurricane strength" (PDI)

Leave for homework

Hurricane strength (PDI, dash) & Atlantic SST (solid)

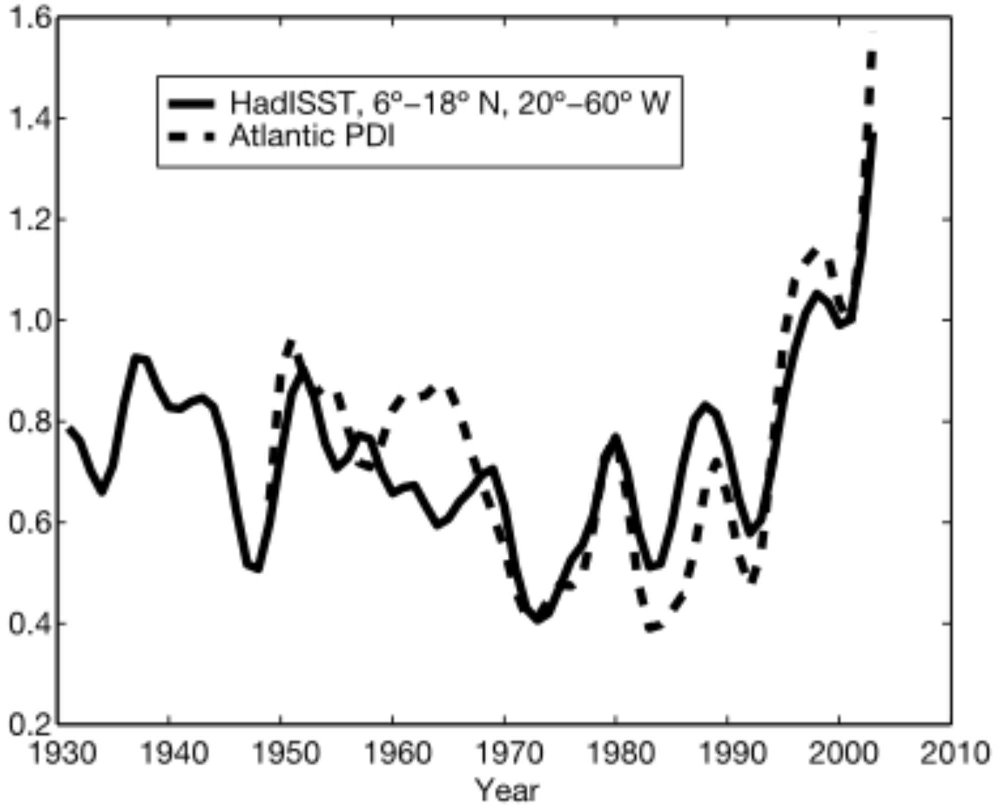


Figure 2 | Annually accumulated PDI for the western North Pacific, compared to July–November average SST. The HadISST (with a constant offset) is averaged over 58N–158 N, 130E–180E. Both time series have been smoothed twice. Power dissipation by western North Pacific tropical cyclones has increased by about 75% in the past 30 yr.

Emanuel 2005

Hurricanes development

https://www.youtube.com/watch?v=4f45jA5UxB0

How a Hurricane Is Born | The Science of Superstorms | BBC

Hurricanes development

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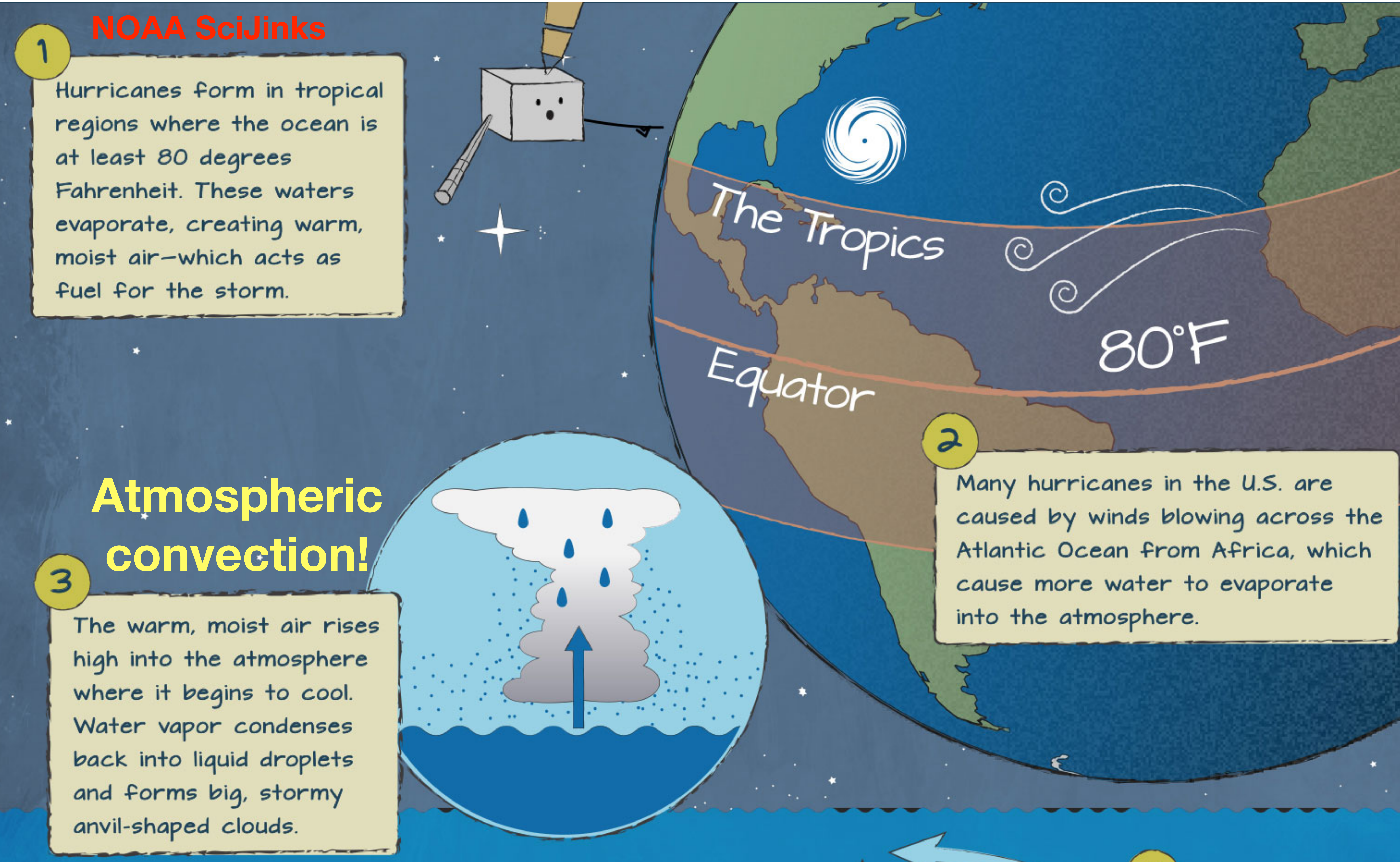

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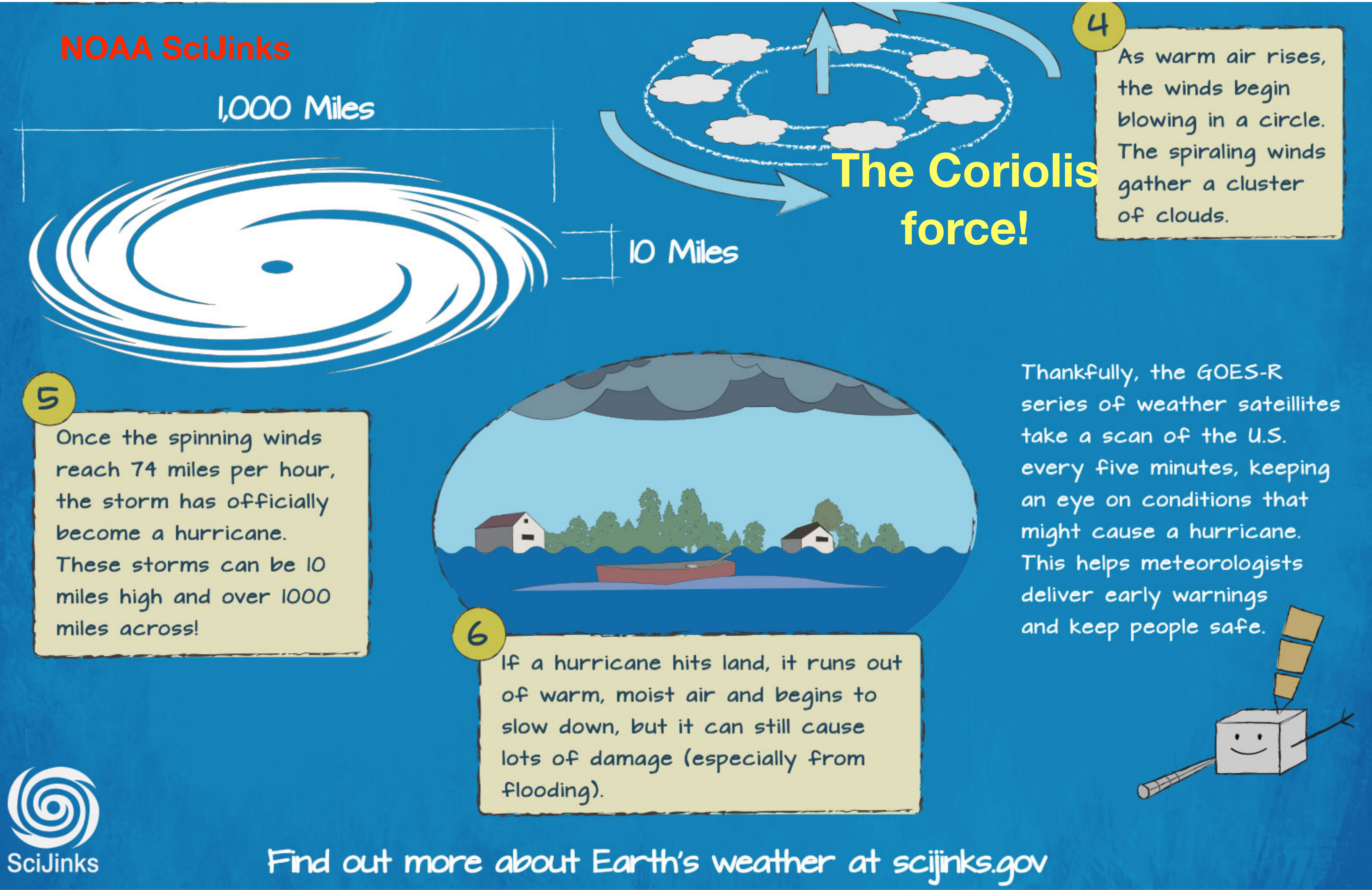

Hurricanes categories

Categories of hurricane

	Category 1	Category 2	Category 3	Category 4	**Category 5**
Wind	74-95mph	96-110mph	111-130mph	131-155mph	**Over 155mph**
Storm surge	4-5ft	6-8ft	9-12ft	13-16ft	**Over 18ft**

Minimal: No real structural damage; some flooding	**Moderate:** Material damage to buildings; small craft break moorings	**Extensive:** Structural damage to small houses; inland flooding	**Extreme:** Major structural damage & heavy flooding; evacuation necessary	**Catastrophic:** Massive damage to buildings; small structures blown over or away

Source: Saffir Simpson scale

PA

The Saffir-Simpson Scale for measuring the size and effects of hurricanes in the Atlantic. Credit: PA Graphics

https://phys.org/news/2019-09-hurricane-dorian-destructive.html

Notes section 8.2:
Potential Intensity & Hurricane Power Dissipation/ Power Dissipation Index (PDI)

(use following slide)

Why are Hurricanes expected to get stronger in a warmer climate?

How do we calculate expected hurricane intensity from SST?

Potential intensity (K. Emanuel)

Use hurricane energetics to estimate its wind magnitude as a function of SST

Potential intensity (K. Emanuel)

Use hurricane energetics to estimate its wind magnitude as a function of SST

Energy source: evaporated ocean water that condenses within the atmosphere and releases latent heat (energy per unit time per unit area).

$$G = \epsilon L \rho_{air} C_k V_s \cdot (q^*(T, p_s) - q_a) = \epsilon L \rho_{air} C_k V_s \cdot q^*(T, p_s)(1 - RH)$$

Efficiency of conversion of heat to kinetic energy (for idealized Carnot cycle):

$$\epsilon = (T_H - T_C)/T_H \approx 1/3$$

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Sink: dissipation due to friction with surface: (again energy per time per area): force*distance/time:

$$D = C_D \rho_{air} V_s^2 \times V_s = C_D \rho_{air} V_s^3 \quad \frac{\mathrm{J}}{\mathrm{s\ m^2}}$$

Source=Sink: *D*=*G*

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Source=Sink: *D*=*G*

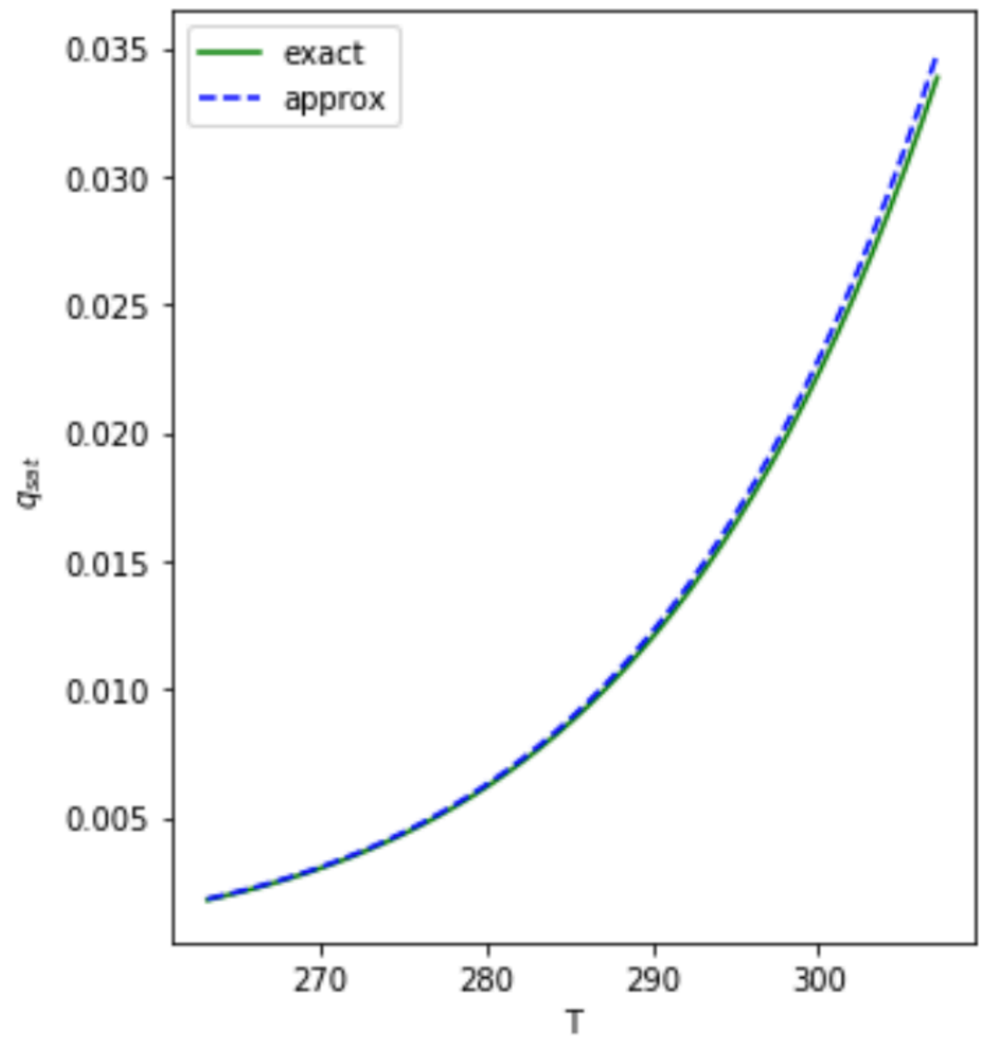
➨ "potential intensity": $$V_s^2 = \frac{SST - T_C}{SST} L\, q^*(T, p_s)\, (1 - RH)$$

Due to *q*(T) factor*, this is exponential in SST, increasing about 6–7% per °C

Clausius Clapeyron

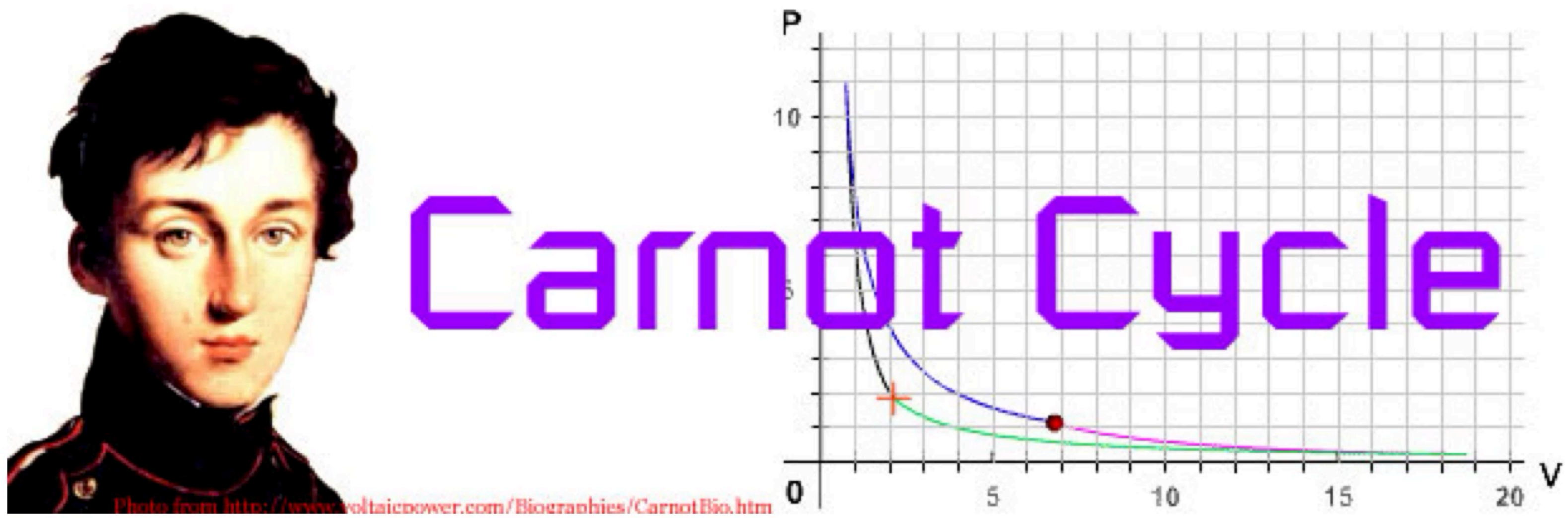
$$q^*(T) = 1577 \cdot 10^3 e^{-5415/T}$$

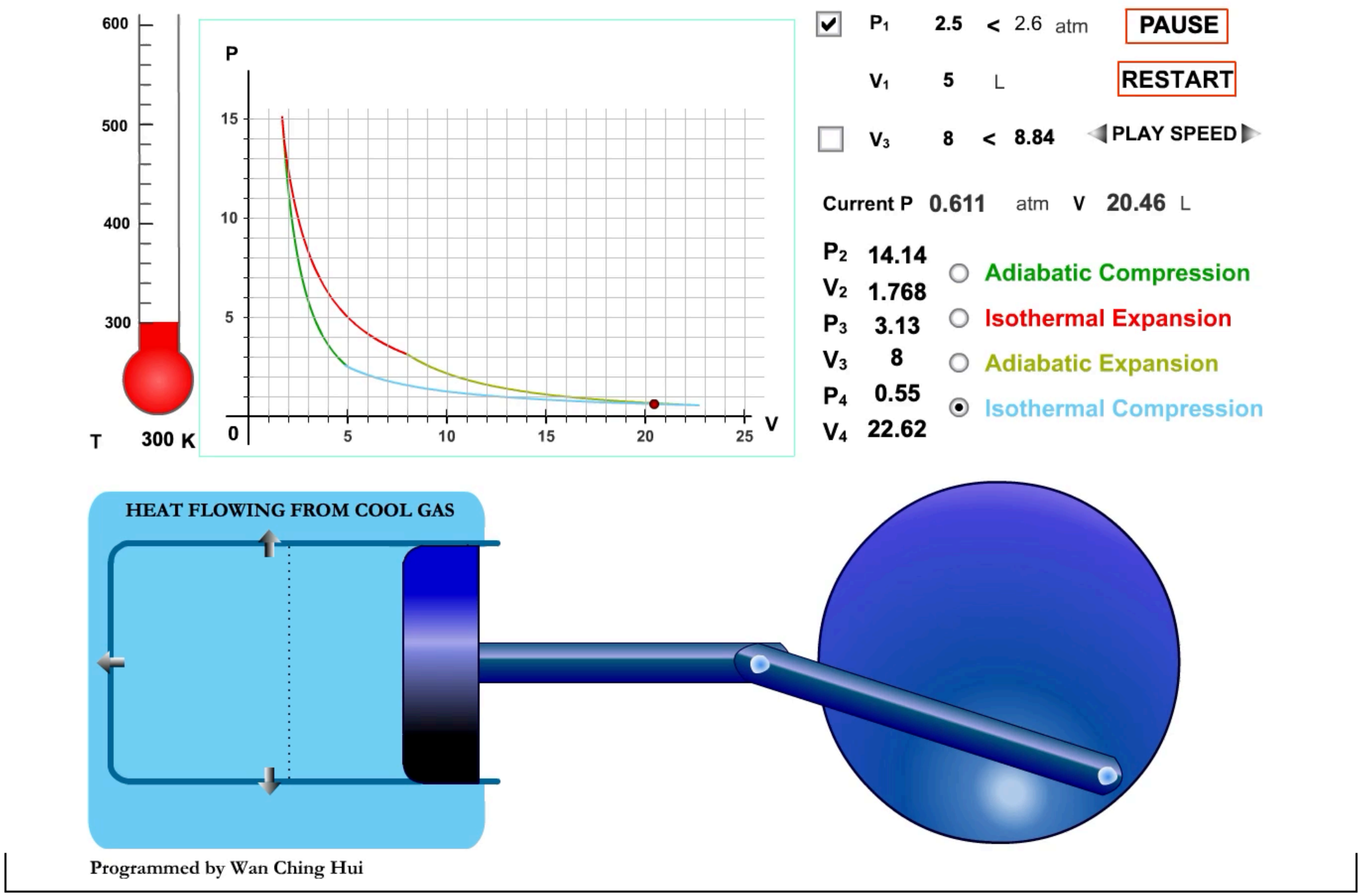
Saturation specific humidity, in kg moisture/kg moist air, at sea level pressure (1000 mb)



exponential in SST,
~7% increase per degree C

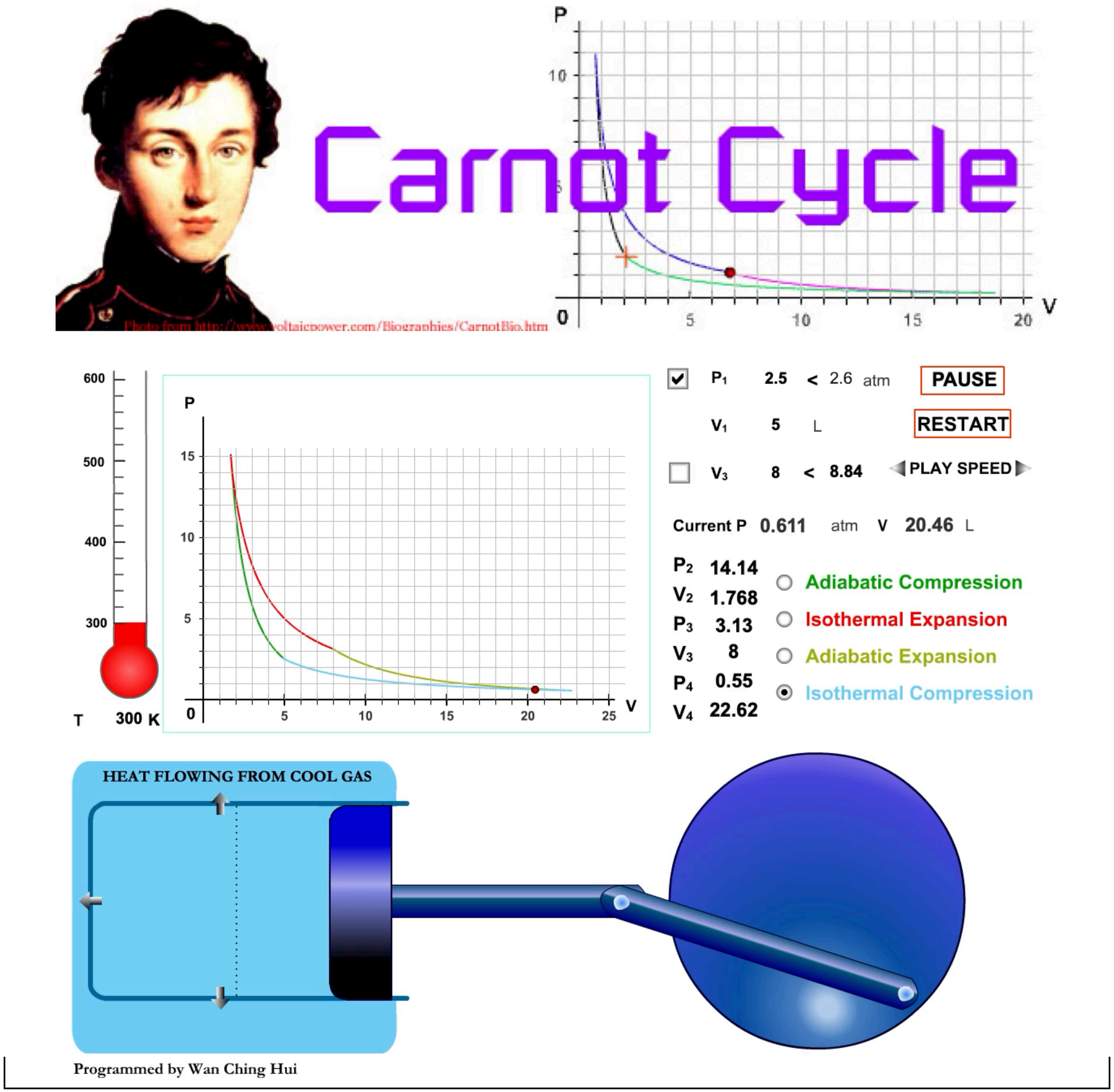
Converting heat to Kinetic energy: Carnot Heat Engine





http://galileoandeinstein.phys.virginia.edu/more_stuff/flashlets/carnot.htm

Converting heat to Kinetic energy: Carnot Heat Engine



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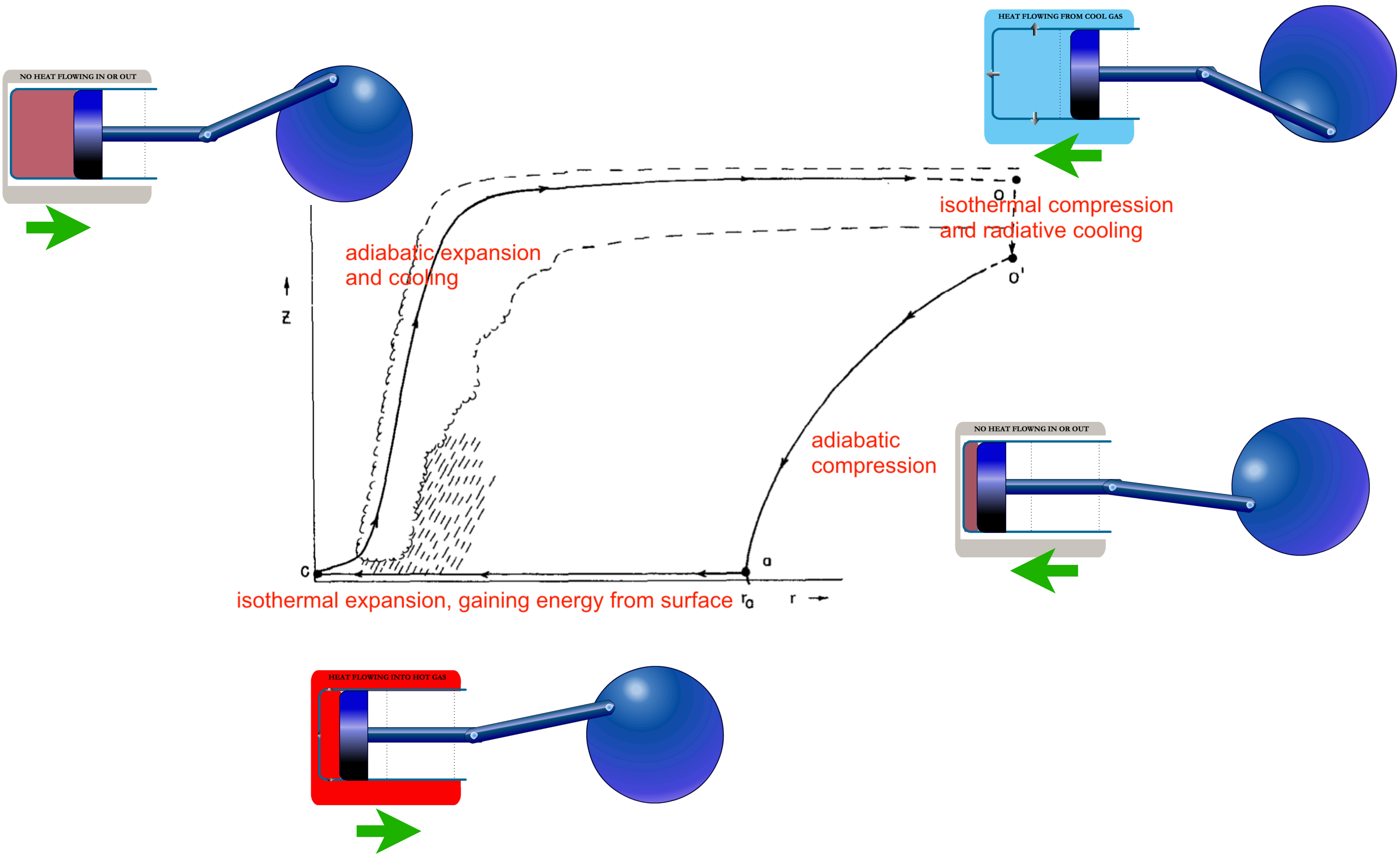
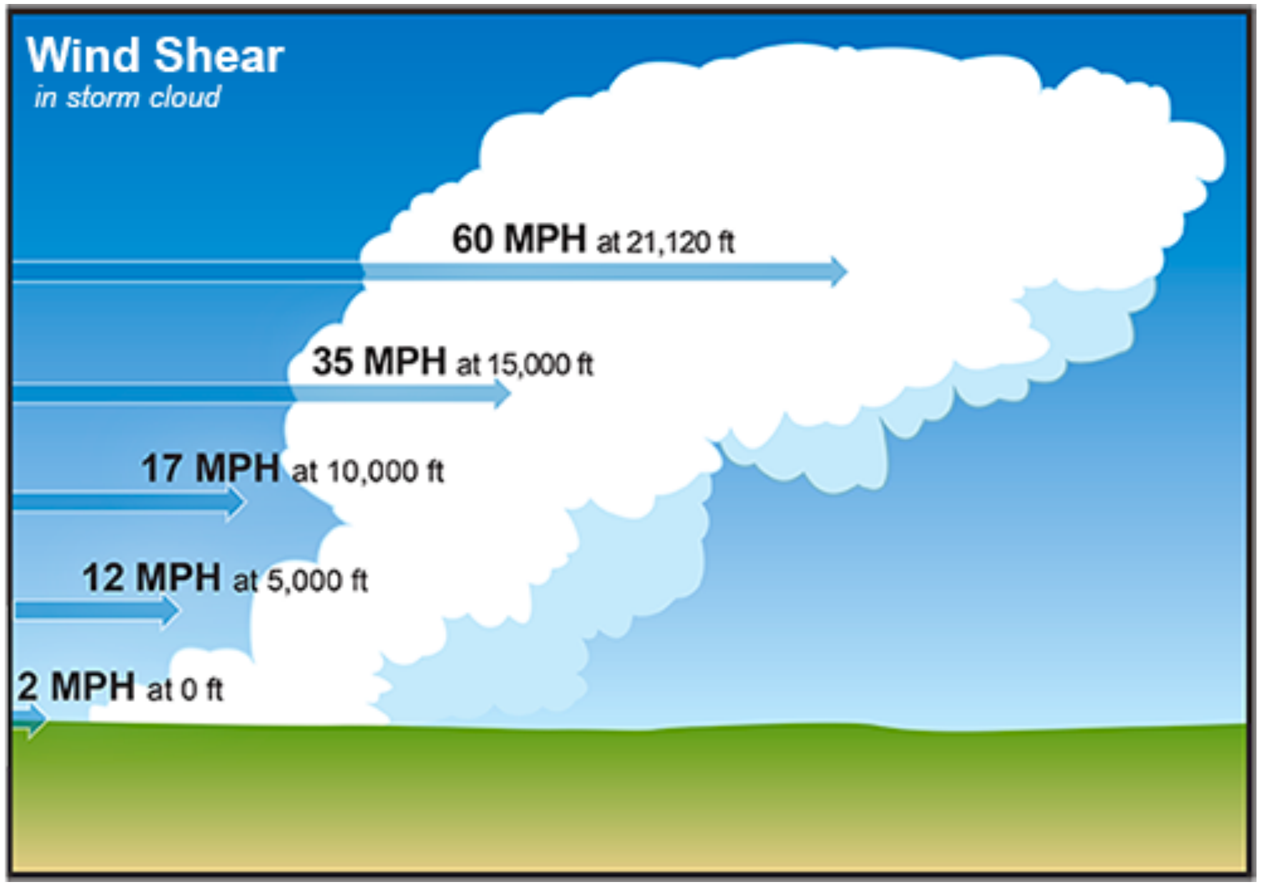
Hurricane as a Carnot Engine (K. Emanuel)



K. Emanuel (1991) + http://galileoandeinstein.phys.virginia.edu/more_stuff/flashlets/carnot.htm

Wind Shear

Wind shear: what is it? effect on Hurricanes



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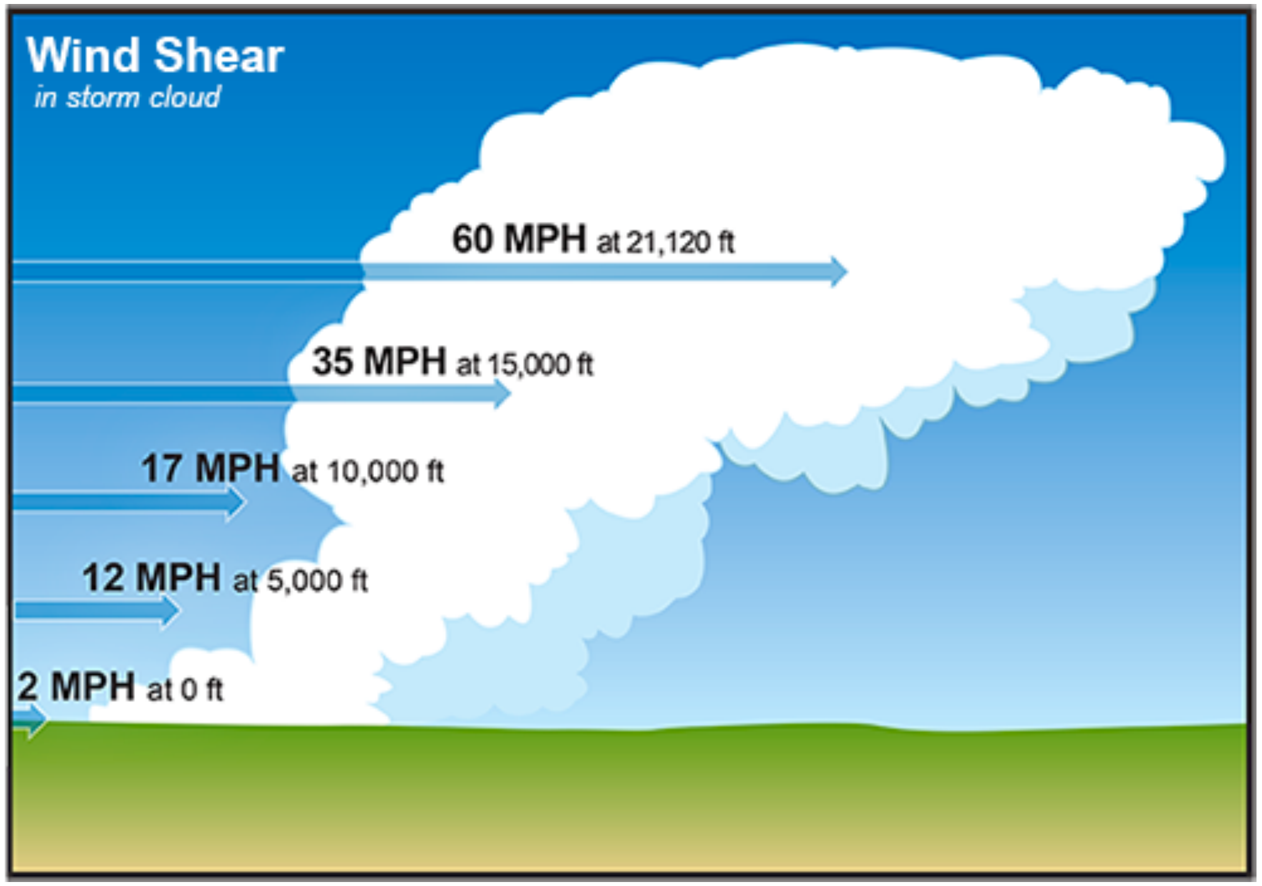

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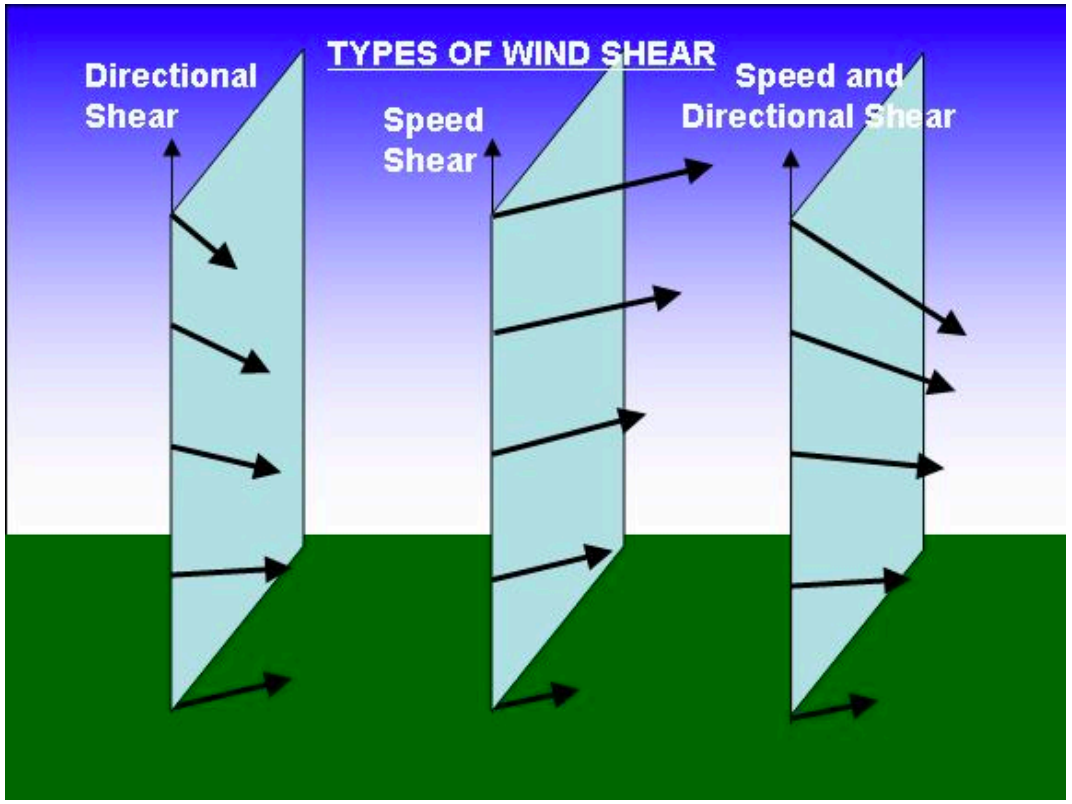

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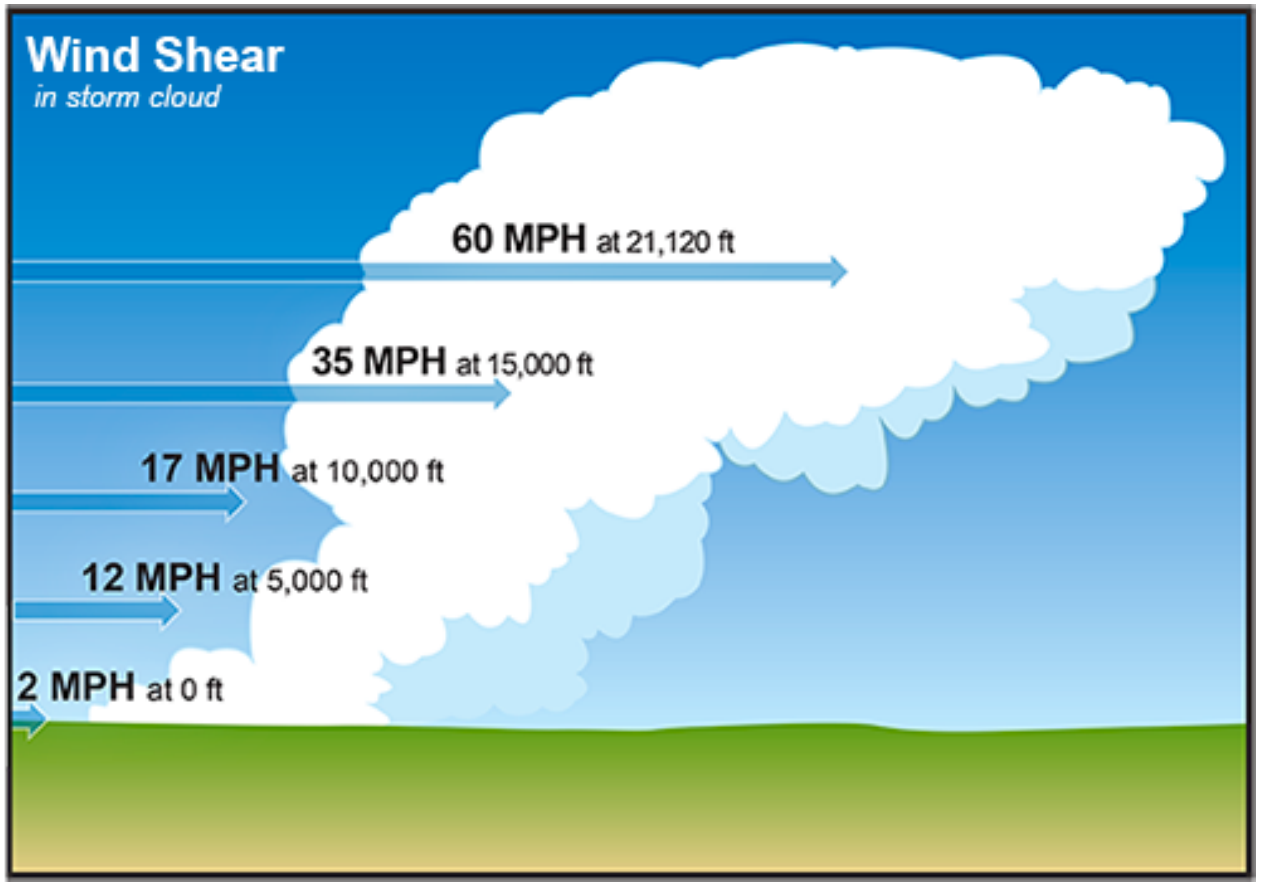

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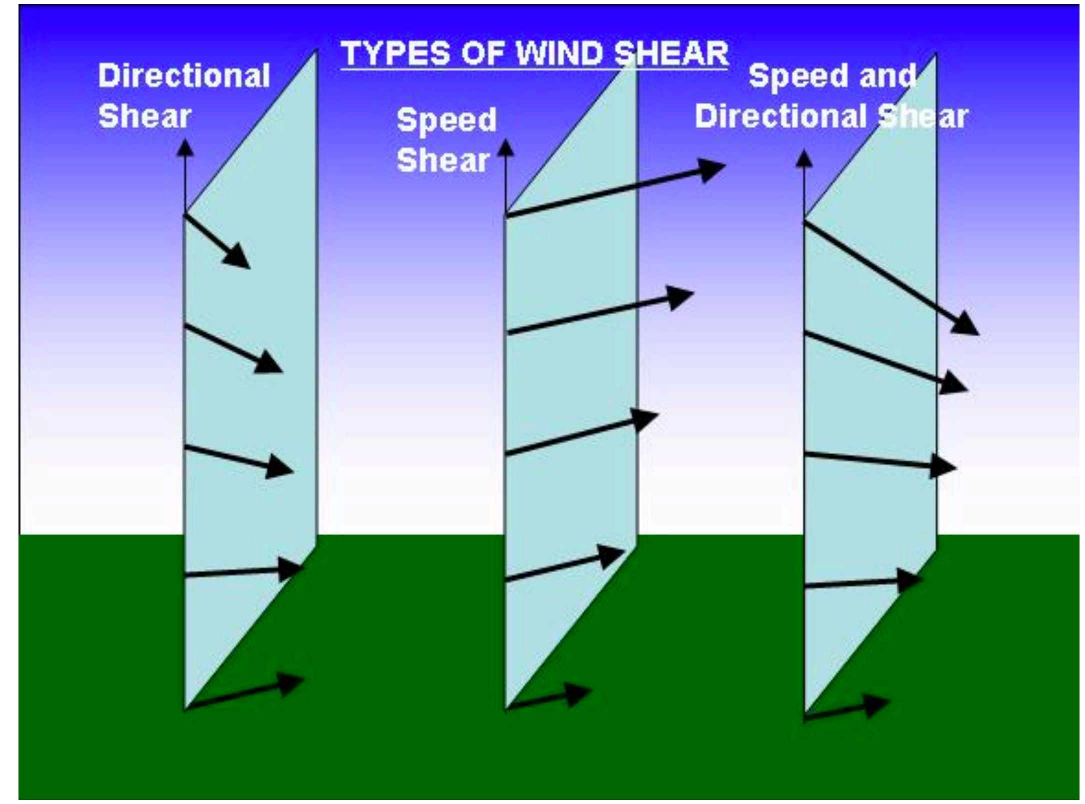

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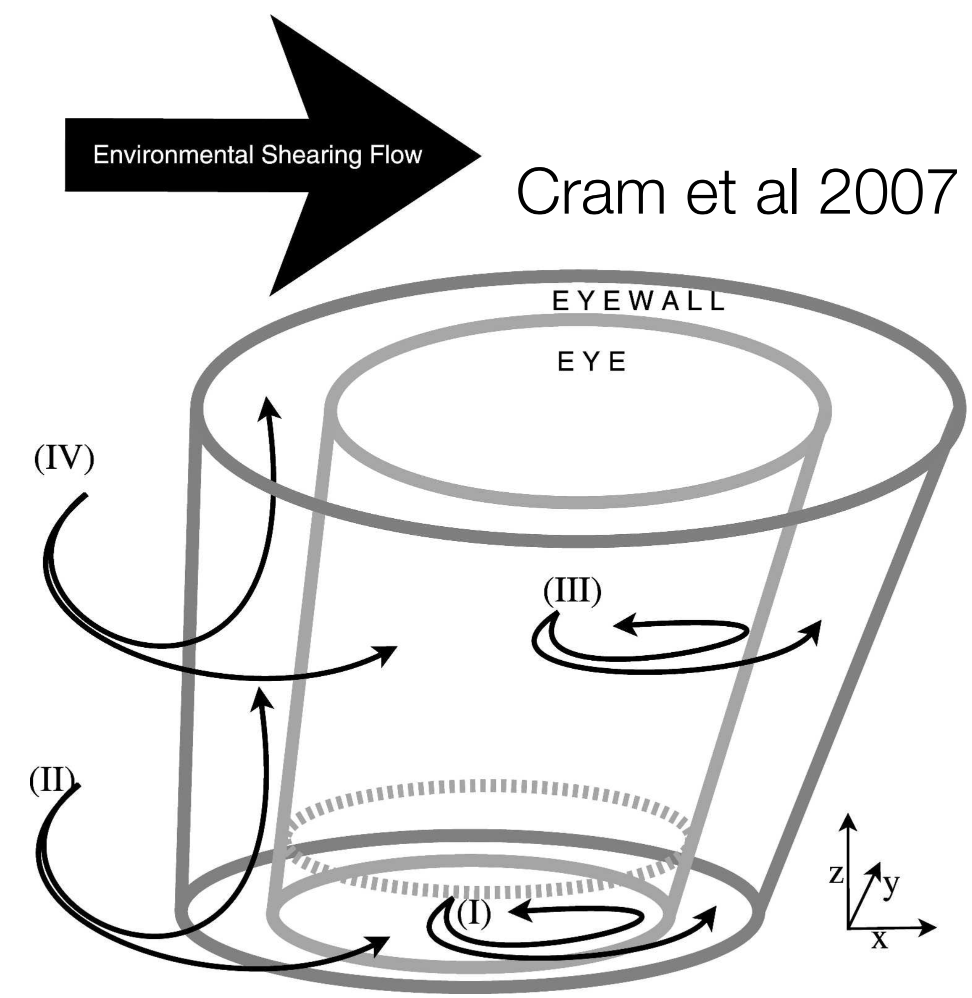
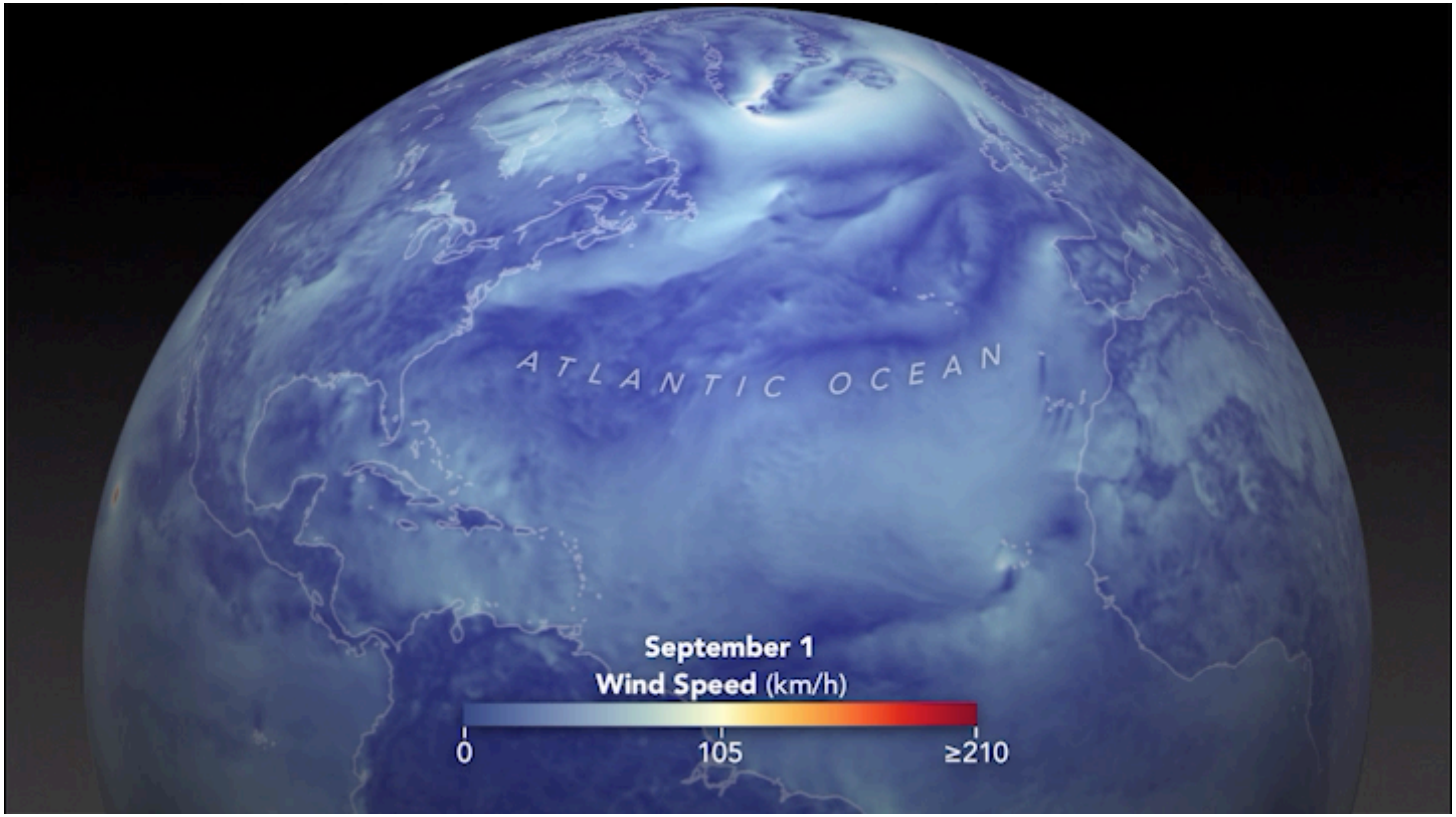
Why hurricanes are weakened by wind shear

(1) The moist convection & latent heat release that drive the hurricane winds can be weakened by a “ventilation” by dry air brought in by the shear. This dry air can flow into the hurricane core at mid-level or into the lower 1–2 km air that flows toward the hurricane center. **(2)** The central low pressure can be weakened via a dilution of the upper-level warm core of the storm by mixing it with the cooler surrounding air, again driven by the shear.



Cram et al 2007

Wind shear: the complex evolution of hurricane Florence



https://earthobservatory.nasa.gov/images/92757/the-complex-evolution-of-florences-winds

"Florence emerged off Africa on September 1 2018, intensified to hurricane status on Sept 4 with peak winds of 120 km/ hour. By Sept 5, it became a Category 4 storm (225 km/hour). A few days of increasing wind shear forced the storm into an asymmetrical shape and began to tear it apart. By Sept 7, Florence's peak winds had dropped back down to 100 km/ hour, no longer a hurricane. On Sept 9, it entered a zone of particularly low wind shear and high sea surface temperatures, intensified rapidly again and by Sept 10, was back to Category 4 status!"

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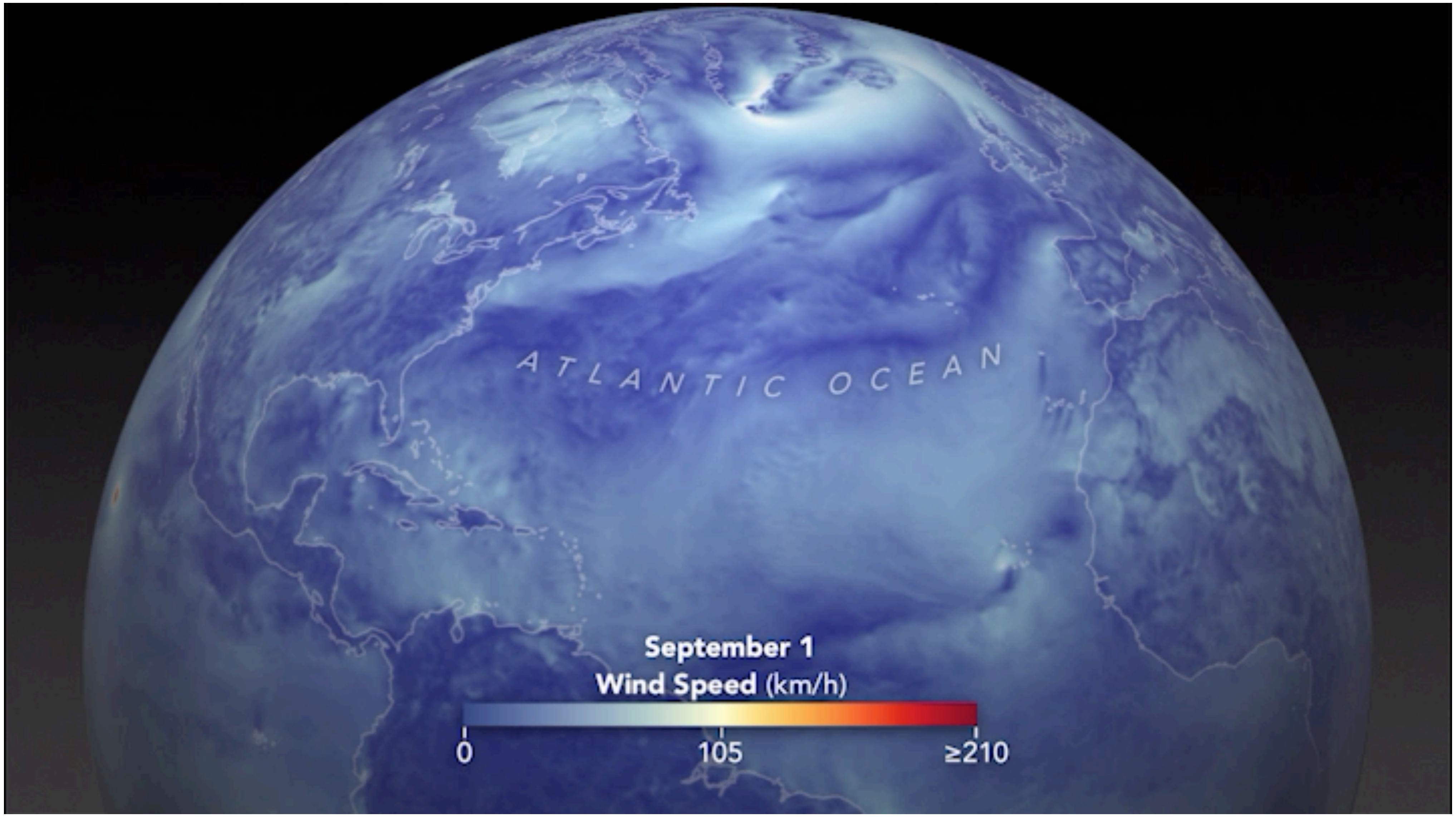

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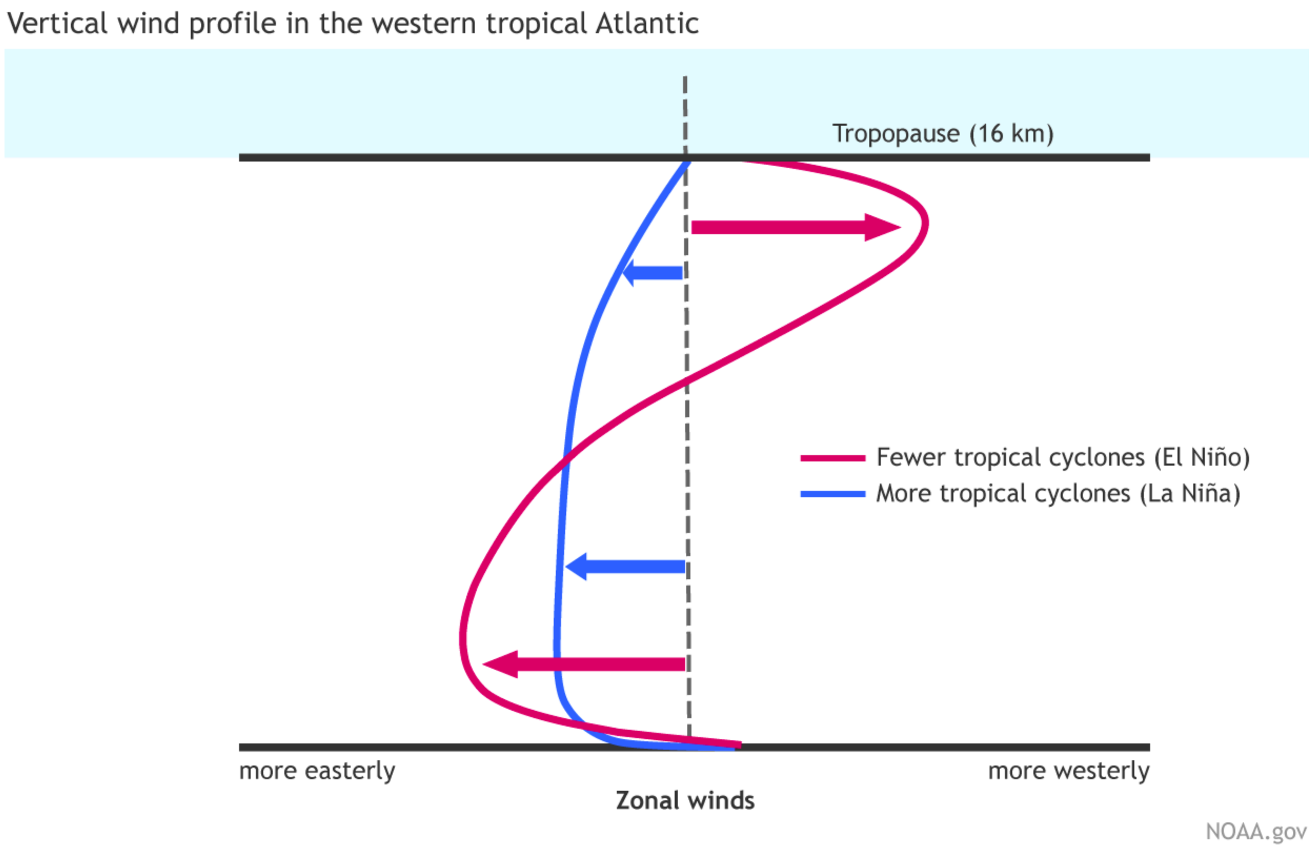
Wind shear: what's affecting it?



NOAA climate.gov

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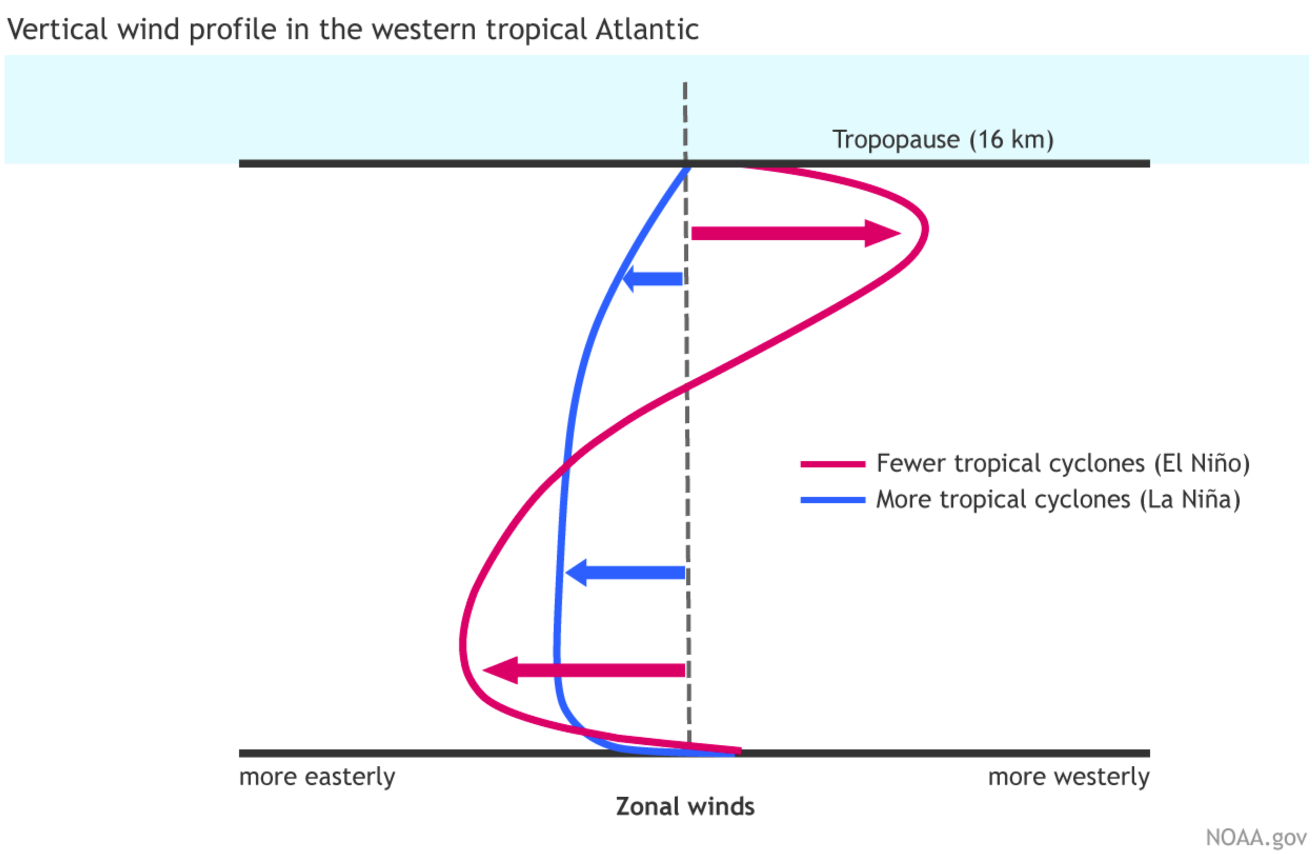

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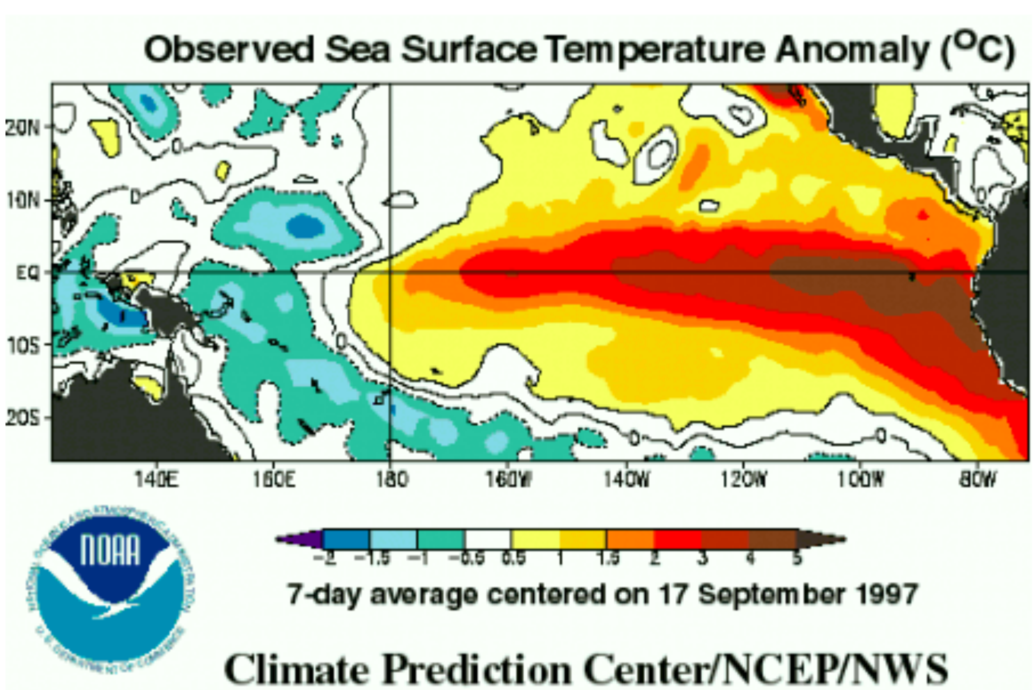

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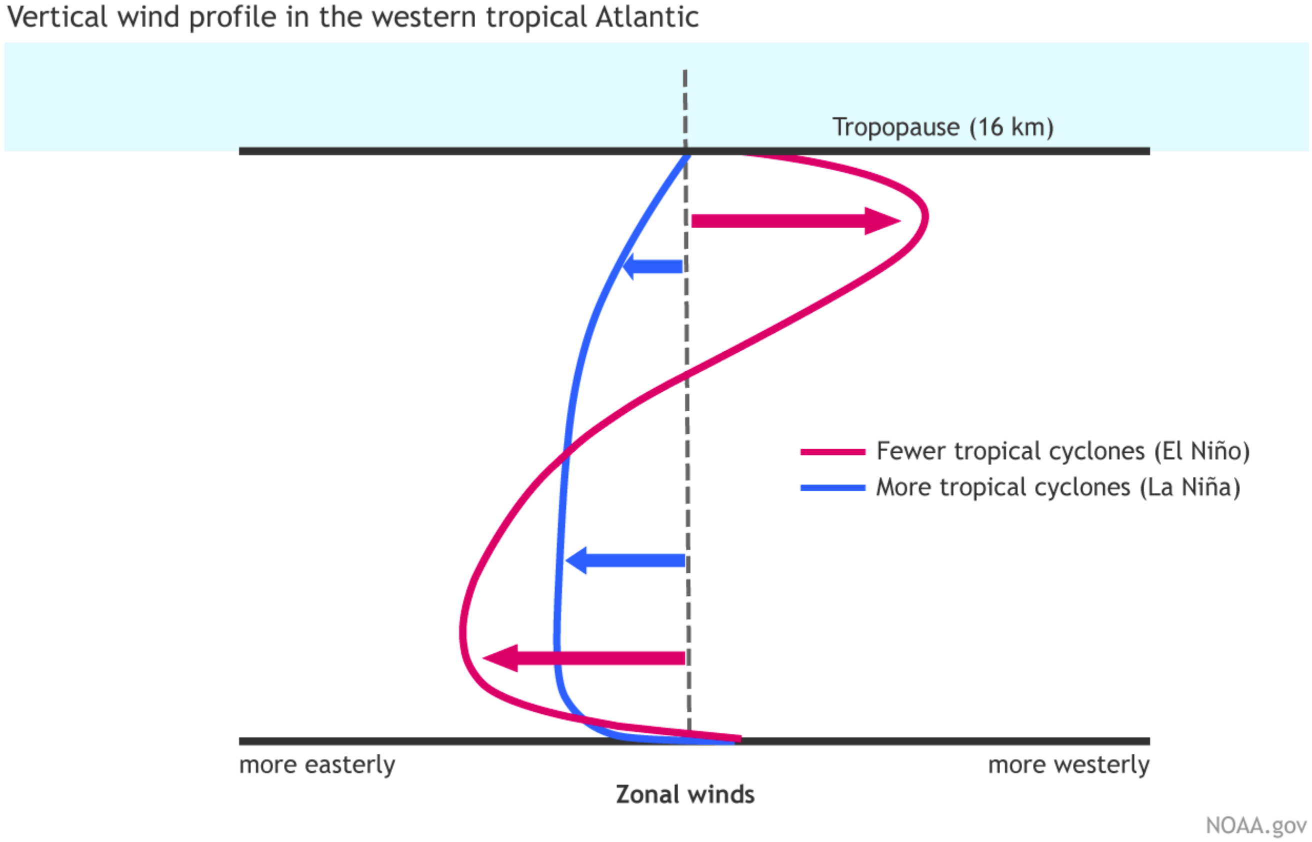

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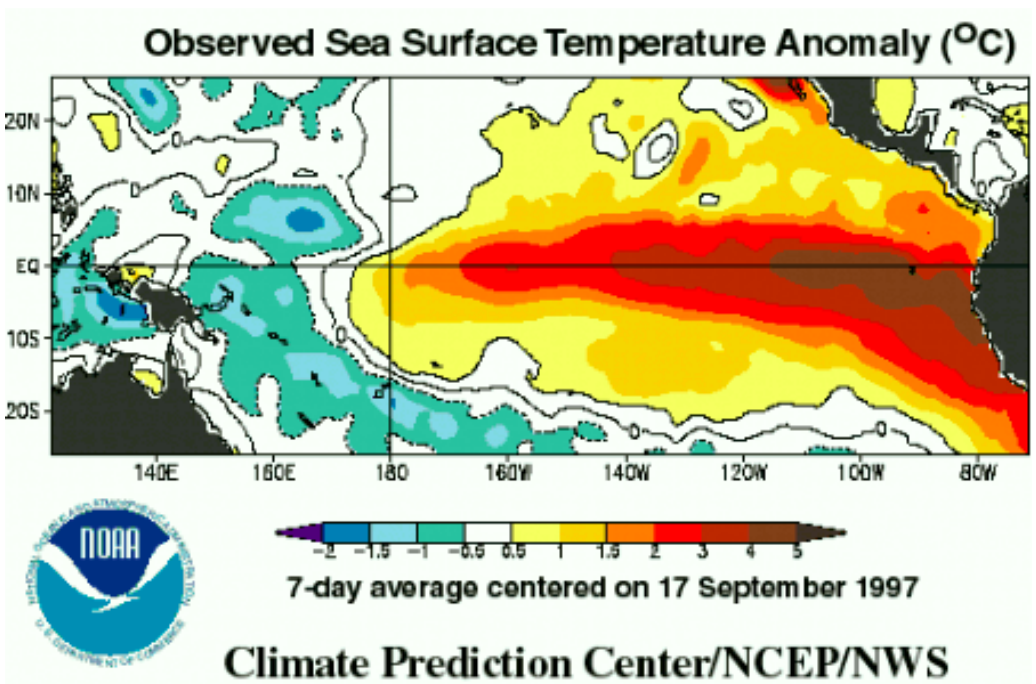
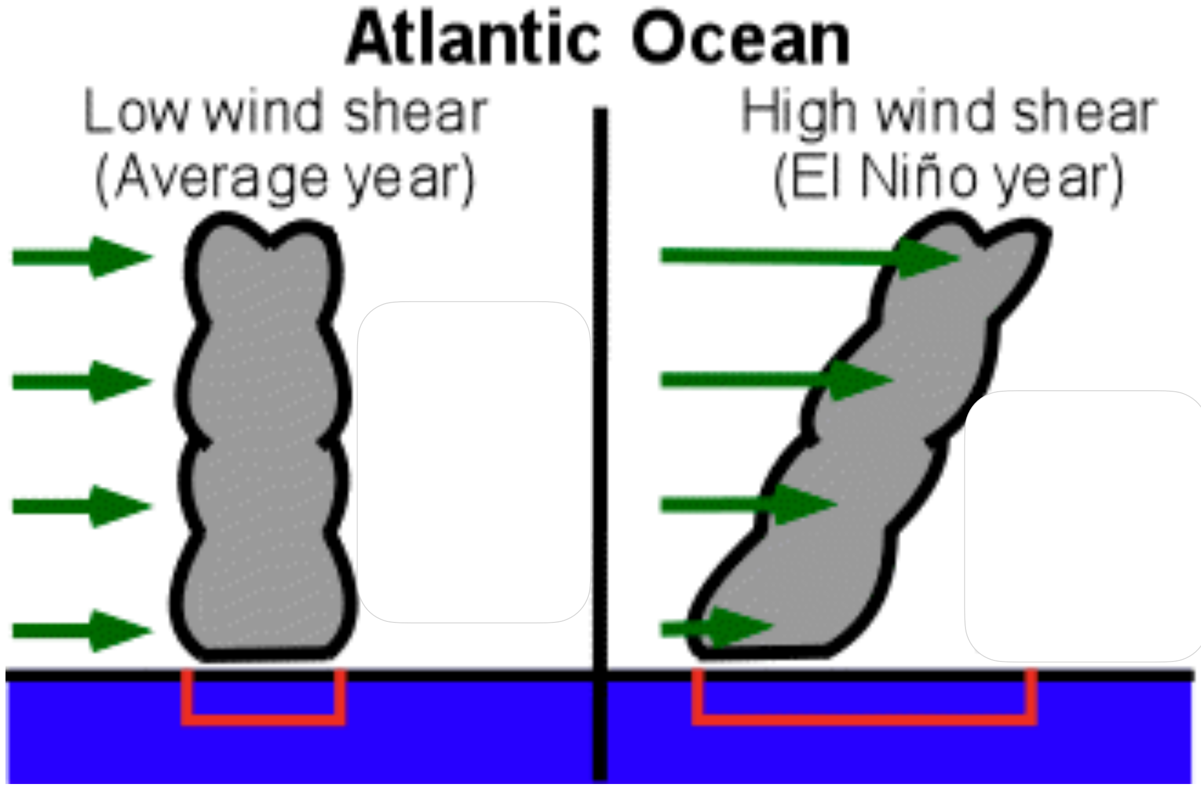


During El Niño events, a strong wind shear over the Atlantic reduces the number of named storms and Hurricanes



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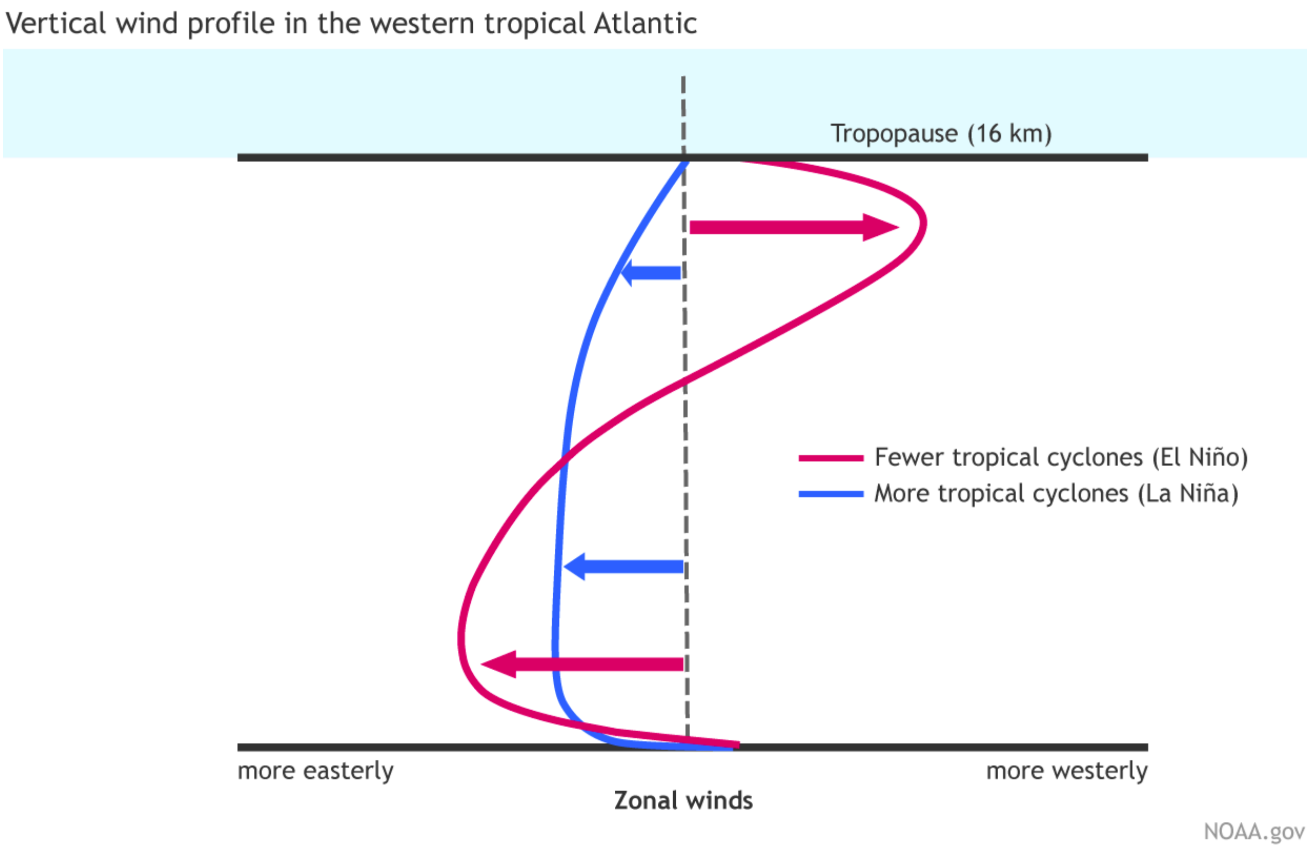

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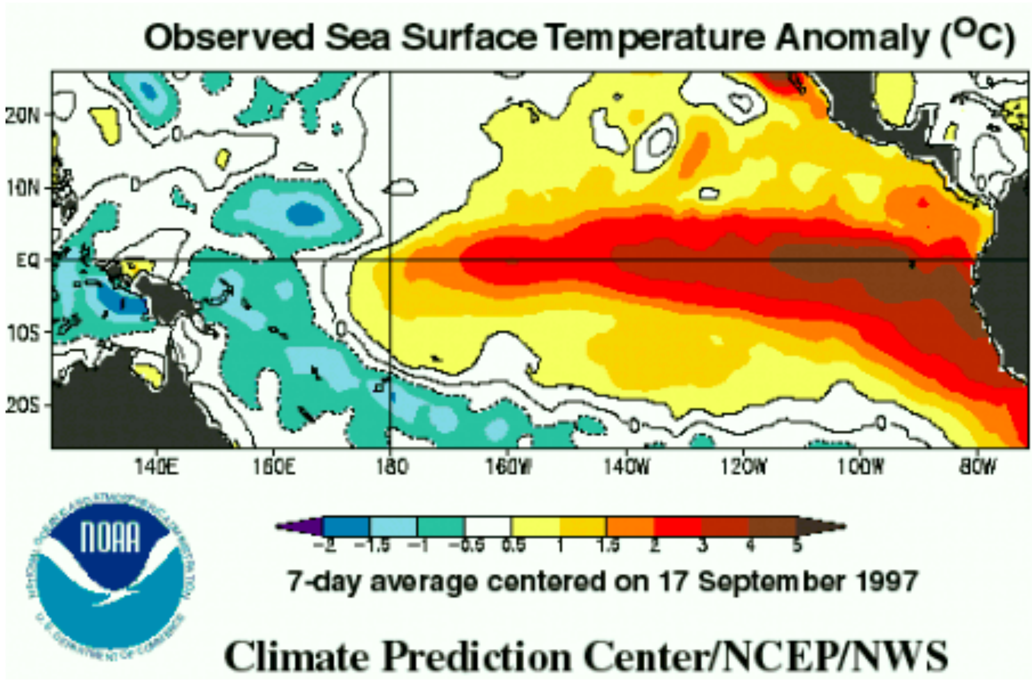

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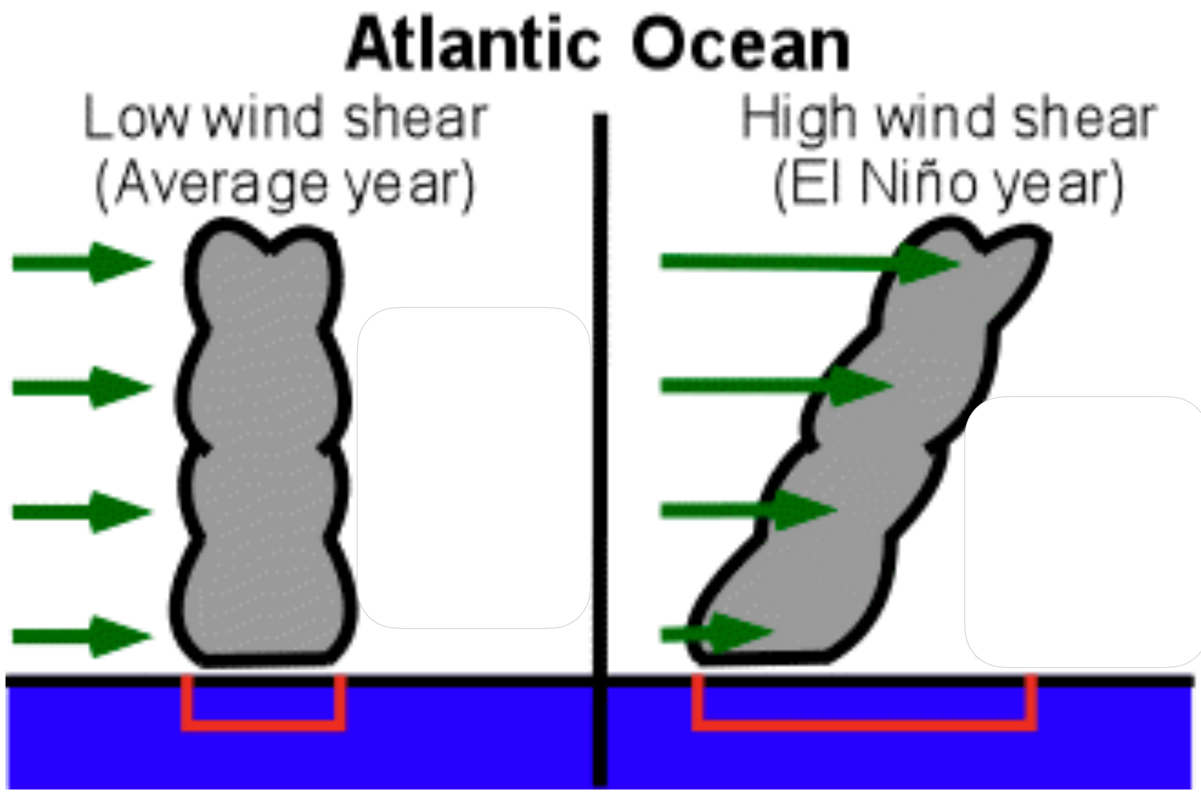


http://ww2010.atmos.uiuc.edu/(Gh)/guides/mtr/hurr/enso.rxml

	Atlantic		Eastern Pacific	
	Average	El Niño Avg.	Average	El Niño Avg.
Named storms	9.4	7.1	16,7	17.6
Hurricanes	5.8	4.0	9.8	10.0
Intense Hurricanes	2.5	1.5	4.8	5.5

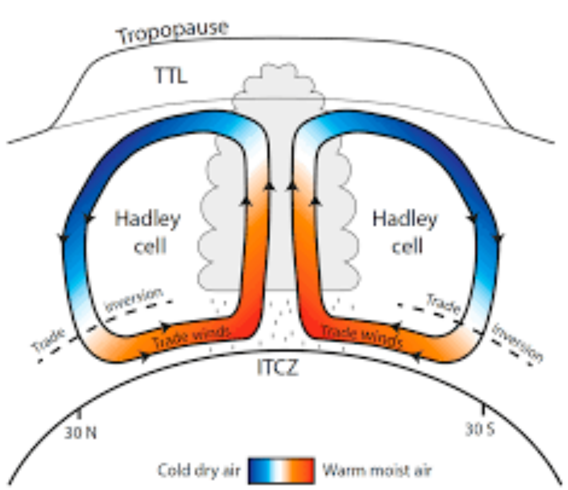
http://ww2010.atmos.uiuc.edu/(Gh)/guides/mtr/hurr/enso.rxml

Wind shear: how does El Nino affect it?

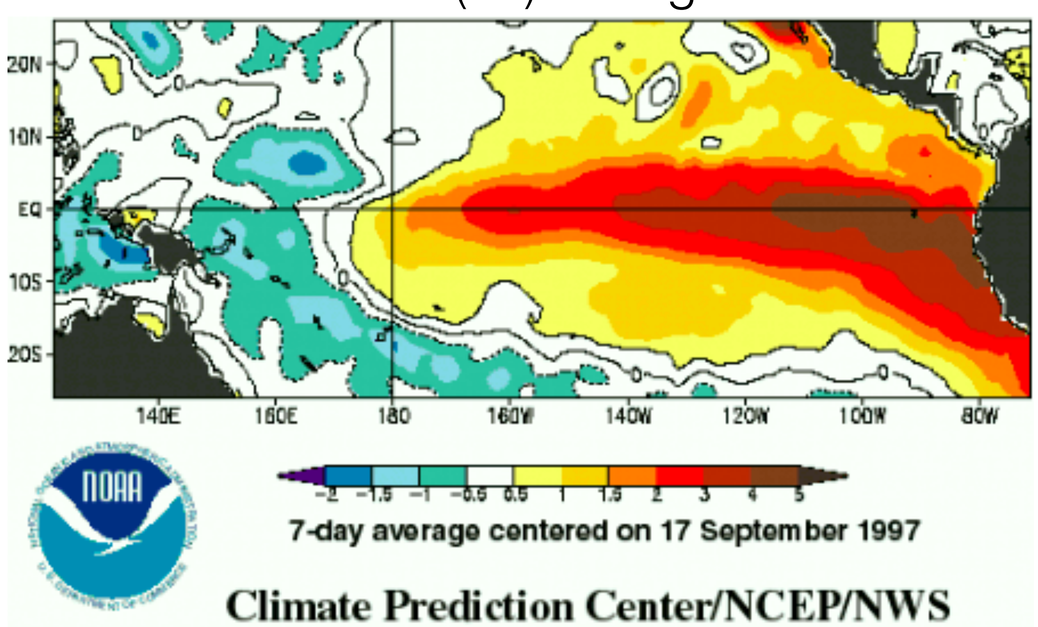
http://www.bitsofscience.org/wind-shear-el-nino-atlantic-hurricanes-jet-stream-6691/

"During El Niño the Pacific subtropical jet stream is fueled by a more powerful Hadley Cell (due to larger convection over warmer tropical ocean waters). A stronger jet stream can lead to stronger shear over the Atlantic and weaken Hurricanes there."

Hadley cell



SST anomalies (°C) during 1997 El Niño



NOAA climate.gov

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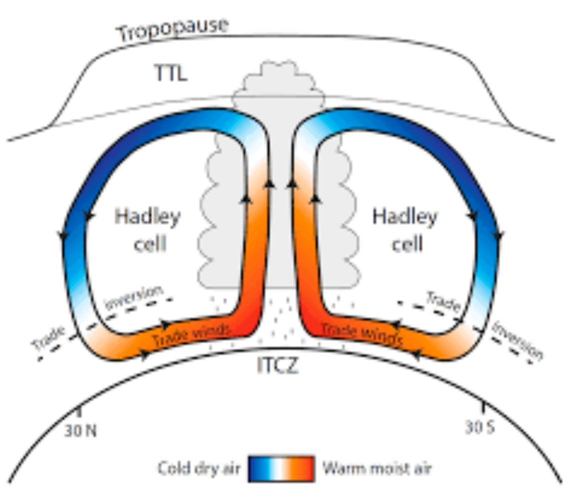
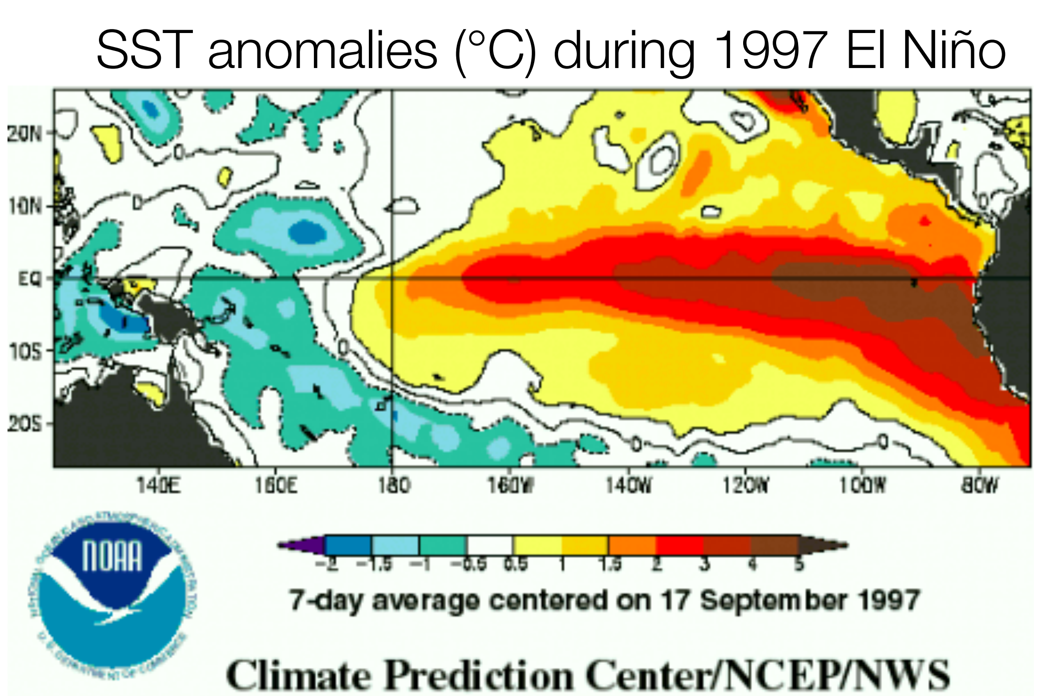
Hadley cell





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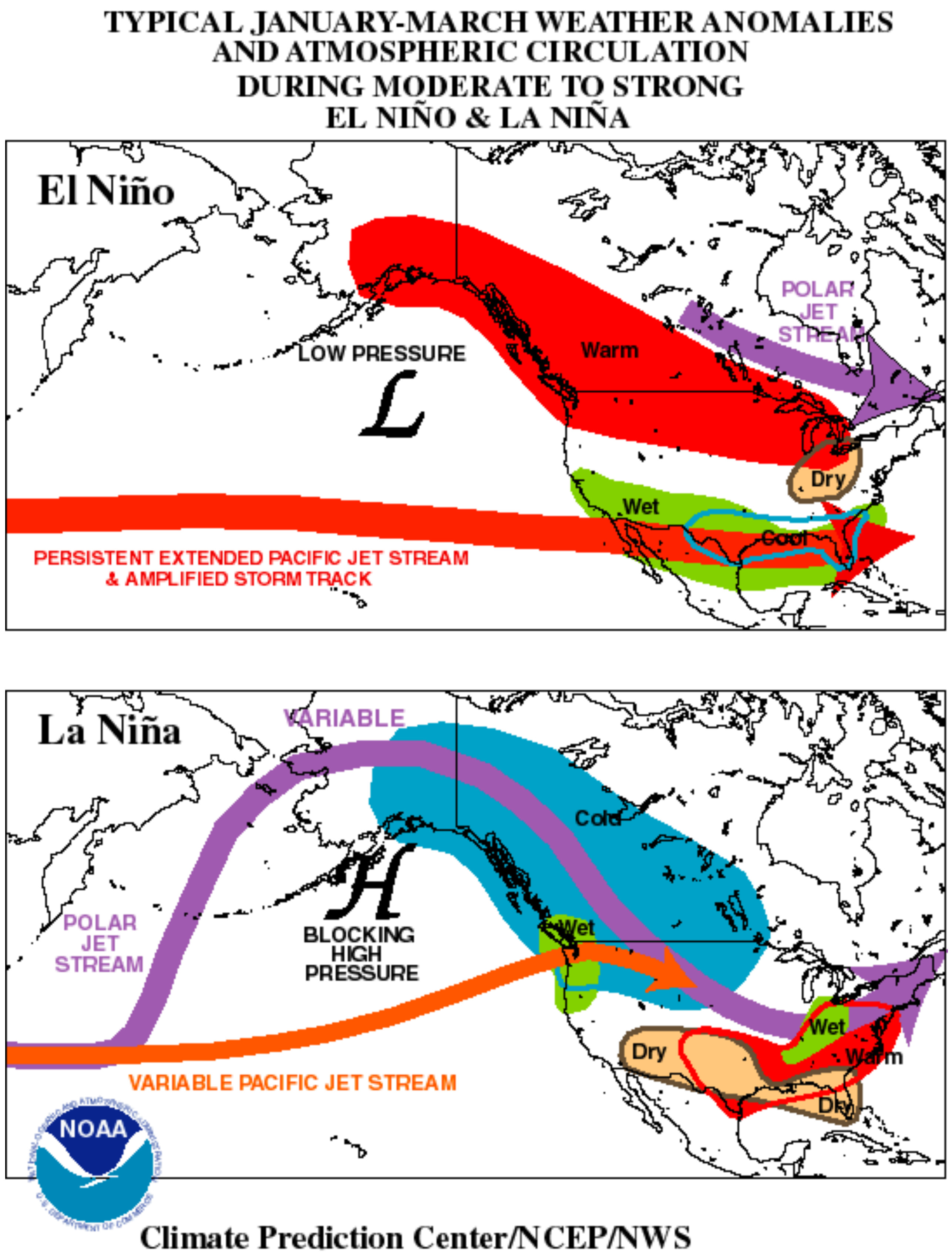
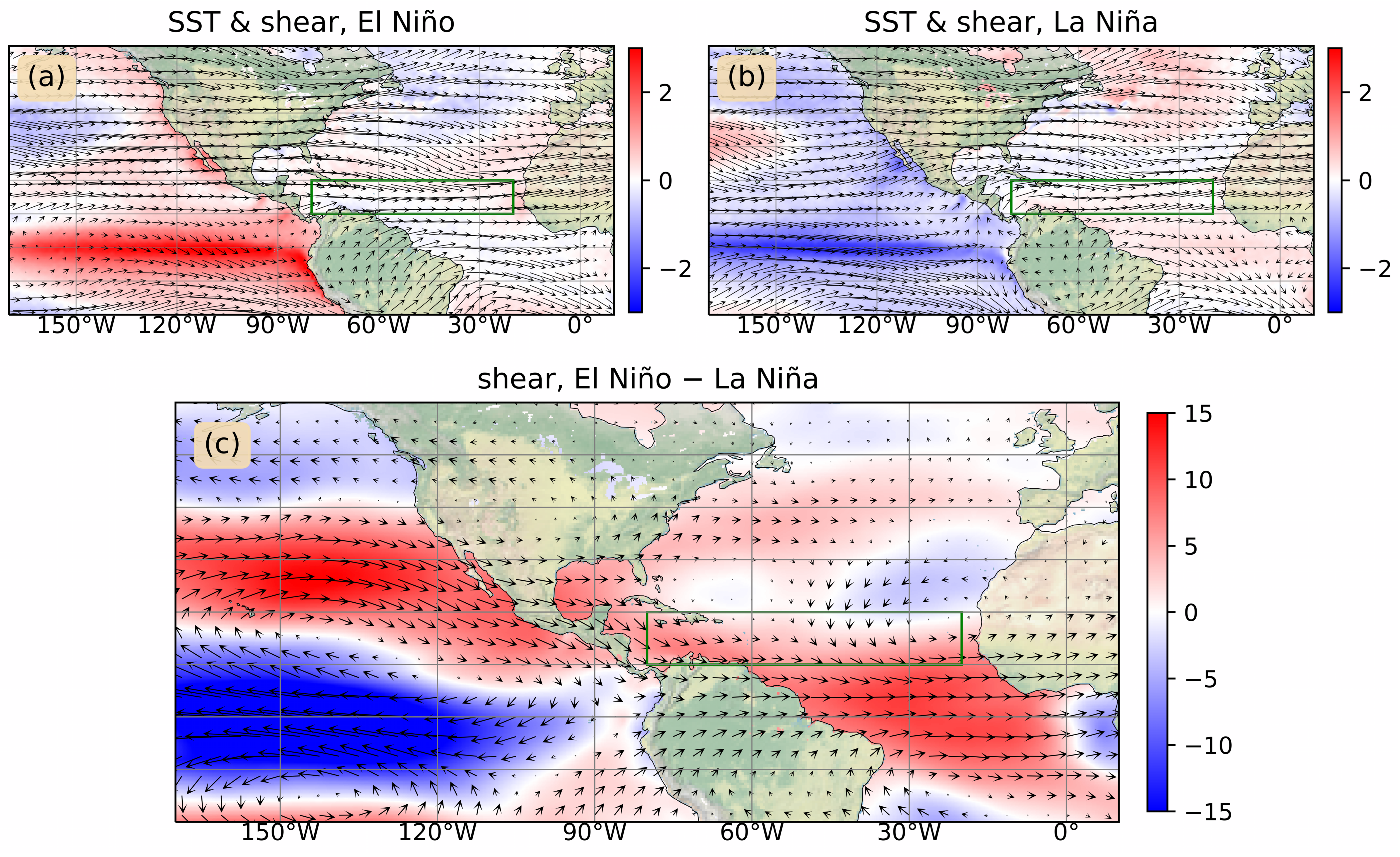


Wind shear: The El Nino/ La Nina signal



(a) SST anomaly from monthly climatology (colors) & wind shear $(\delta U,\delta V) = (U(200\text{ mb}) - U(850\text{ mb}), V(200\text{ mb}) - V(850\text{ mb}))$ during El Niño events, U = zonal wind, V meridional. (b) Same, La Niña. (c) shear $(\delta U,\delta V)$ during El Niño minus that during La Niña shown by vectors. Colors show the magnitude of shear, sqrt $(\delta U)^2 + (\delta V)^2$ for El Niño minus La Niña events. Green box: North Atlantic MDR.

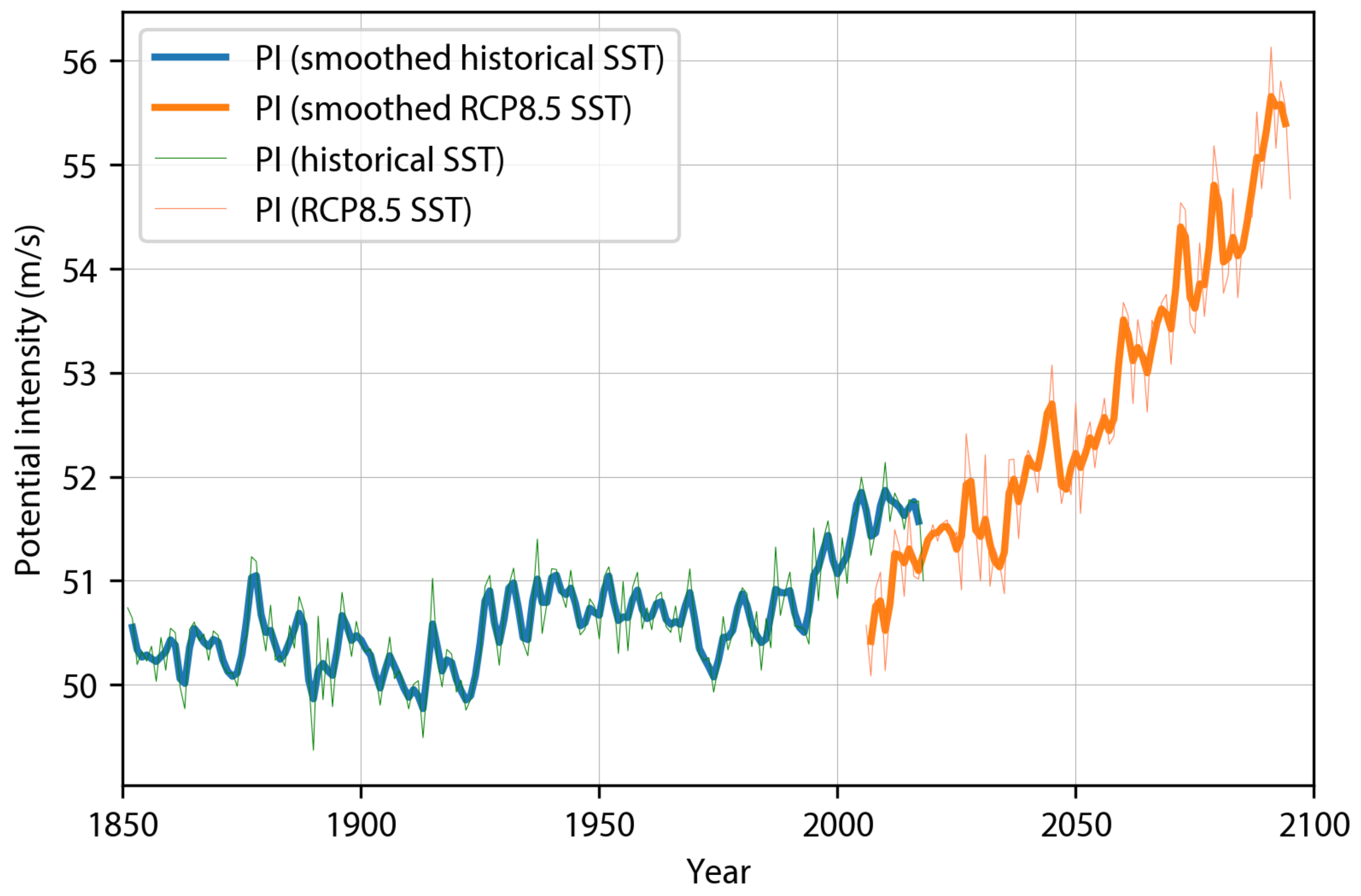
Workshop 2: Potential intensity

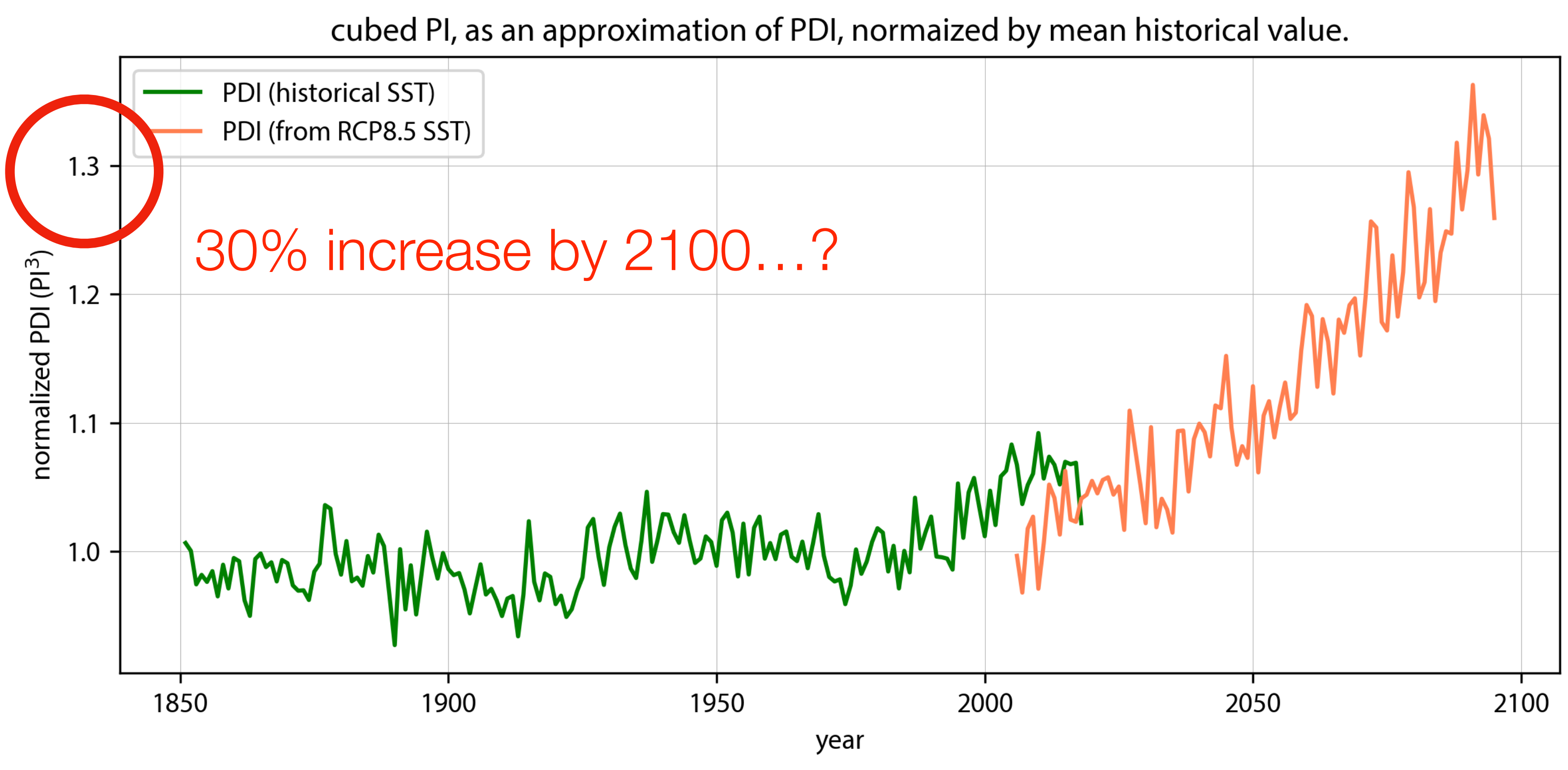
A. Plot the saturation specific-humidity as a function of time, based on the observed MDR SST and the SST increase projected by 2100 under the RCP8.5 scenario.

B. Calculate and plot the expected potential intensity as a function of time for the observed (historical) MDR SST and for the projected MDR SST increase by year 2100 under the RCP8.5 scenario (plotting the raw PI, with the smoothed time series superimposed).

C. Calculate and plot time series of the cube of the PI to approximate the PDI, and normalize by the mean of the PDI calculated from the historical SST. What is the expected percentage increase in PDI by the end of the century? Remember that PDI is a measure of hurricane destructiveness.

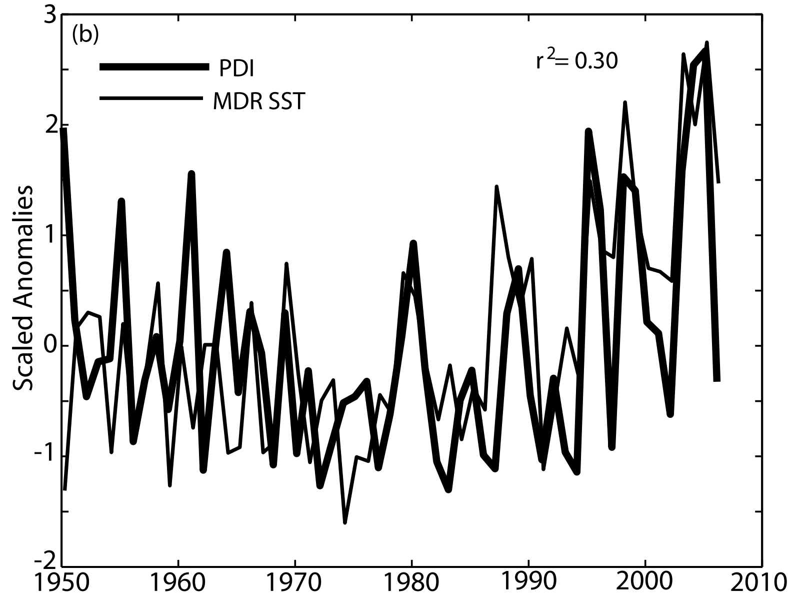
Workshop 2 results: Projected potential intensity





Will Hurricanes get stronger? A statistical approach

Hurricane strength (thick) & Atlantic SST (thin)

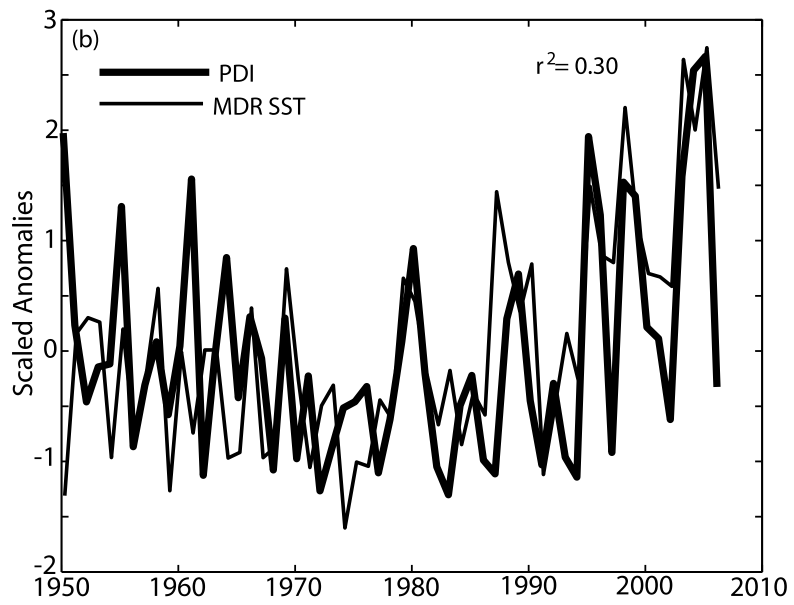


(Swanson 2008)

(Vecchi et al 2008)

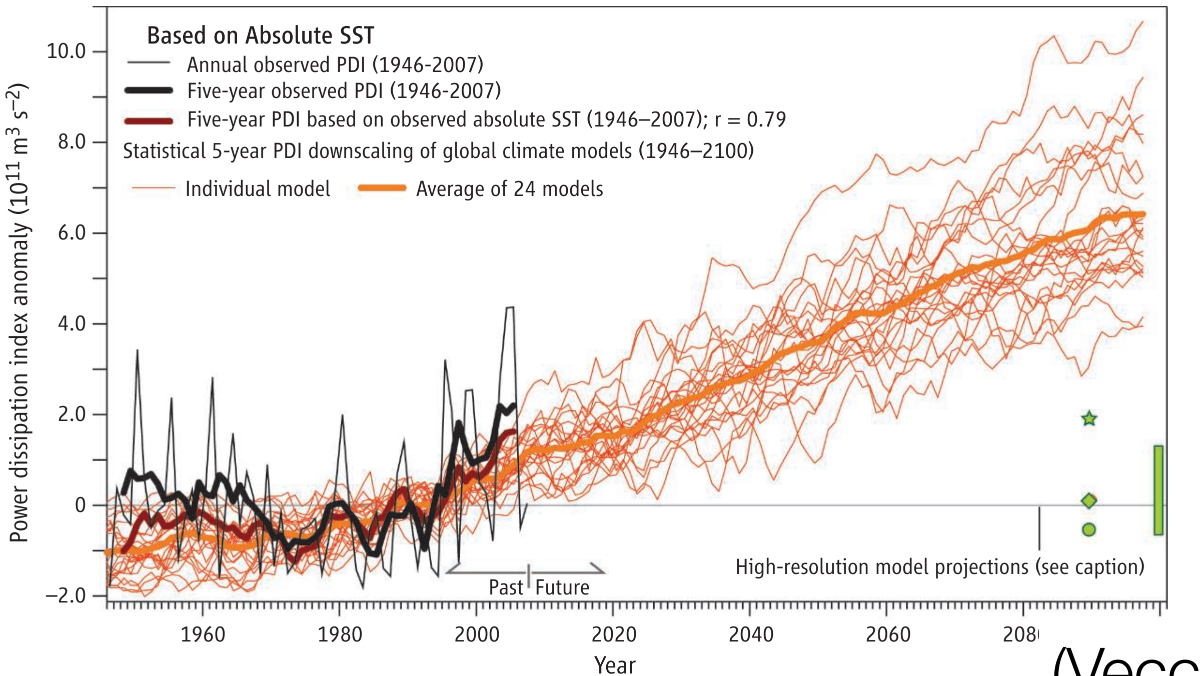
Will Hurricanes get stronger? A statistical approach

Hurricane strength (thick) & Atlantic SST (thin)



(Swanson 2008)

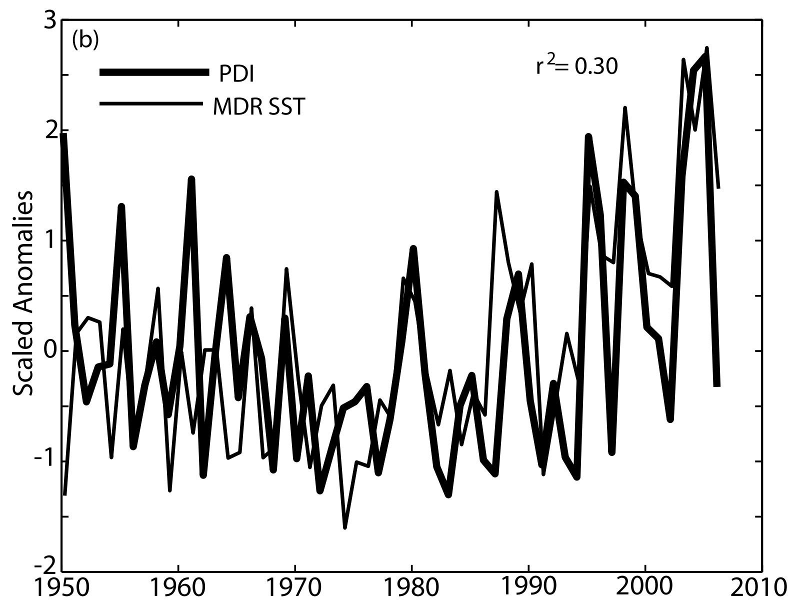
➔ **Hurricanes strengthen dramatically in a global warming scenario**



(Vecchi et al 2008)

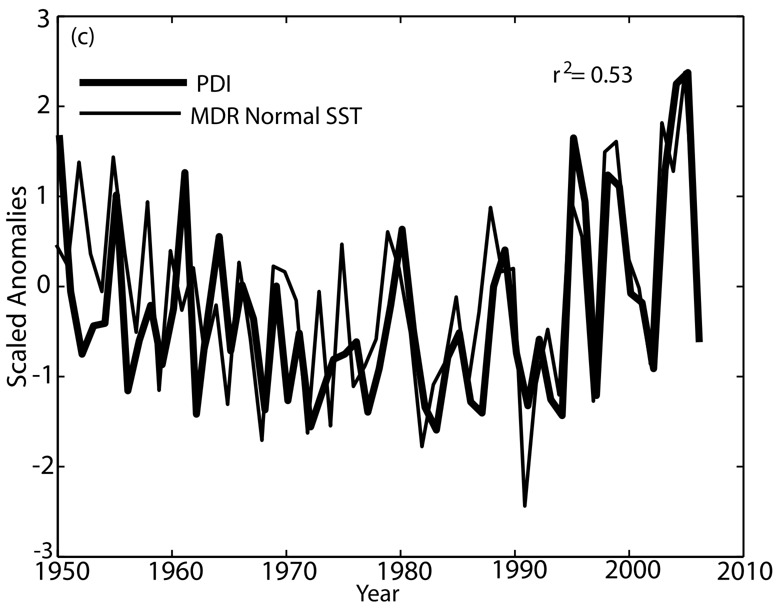
Will Hurricanes get stronger? A statistical approach

Hurricane strength (thick) & Atlantic SST (thin)

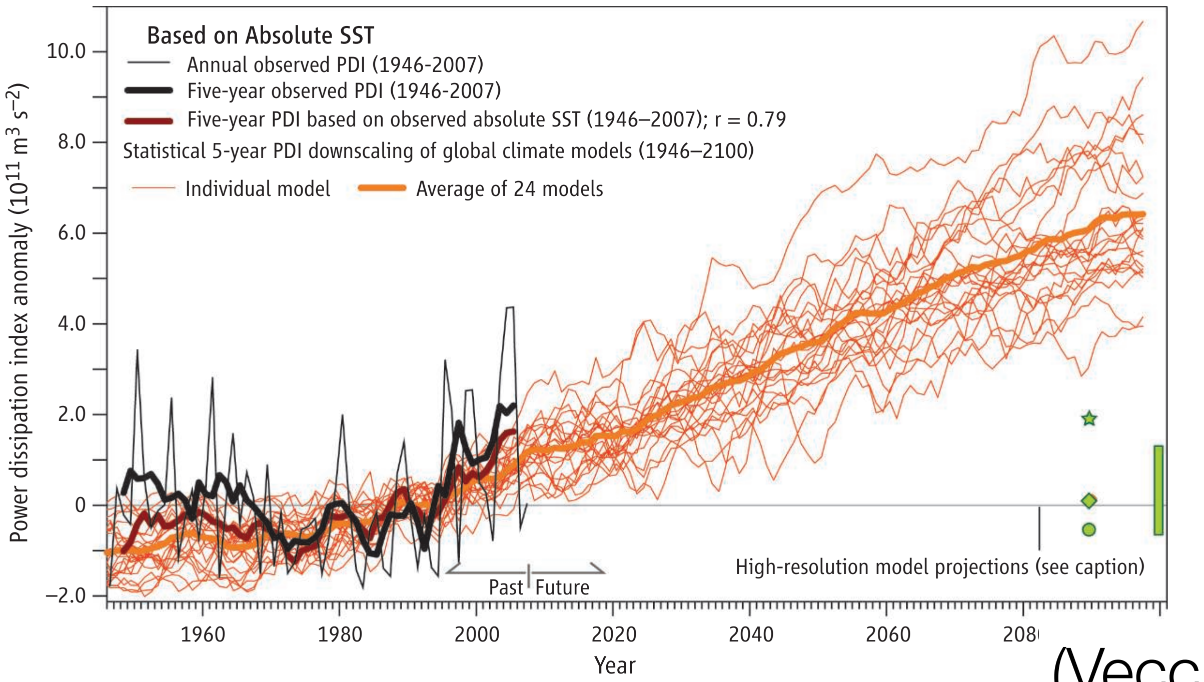


(Swanson 2008)

Hurricanes (thick), & Atlantic minus tropical SST (thin)



➔ **Hurricanes strengthen dramatically in a global warming scenario**

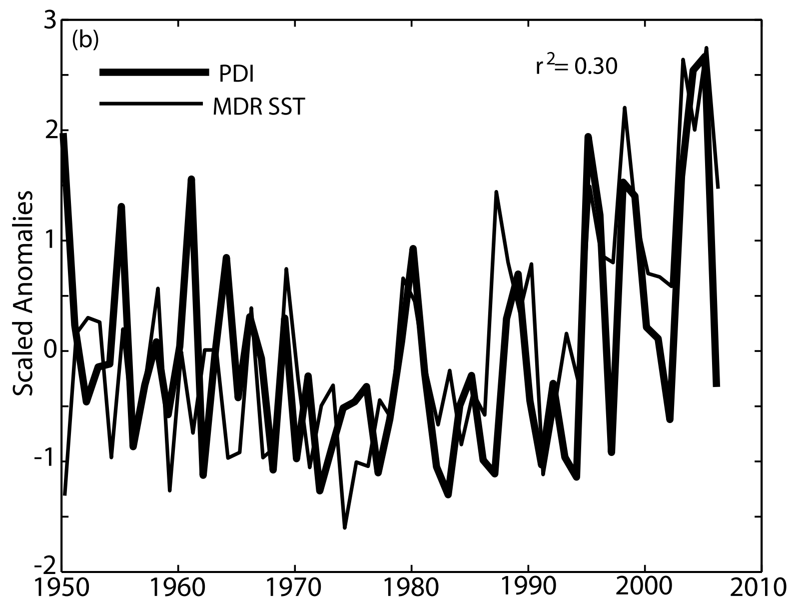


(Vecchi et al 2008)

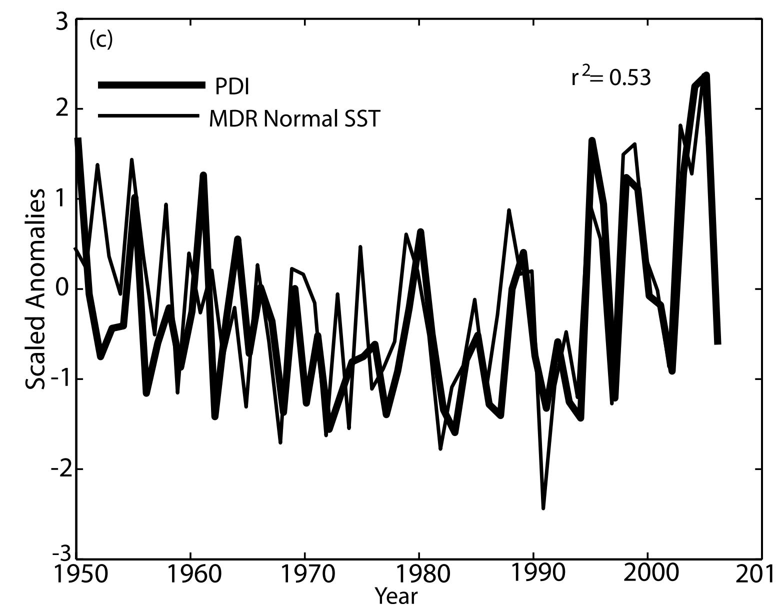
Will Hurricanes get stronger? A statistical approach

Hurricane strength (thick) & Atlantic SST (thin)

Hurricanes (thick), & Atlantic minus tropical SST (thin)

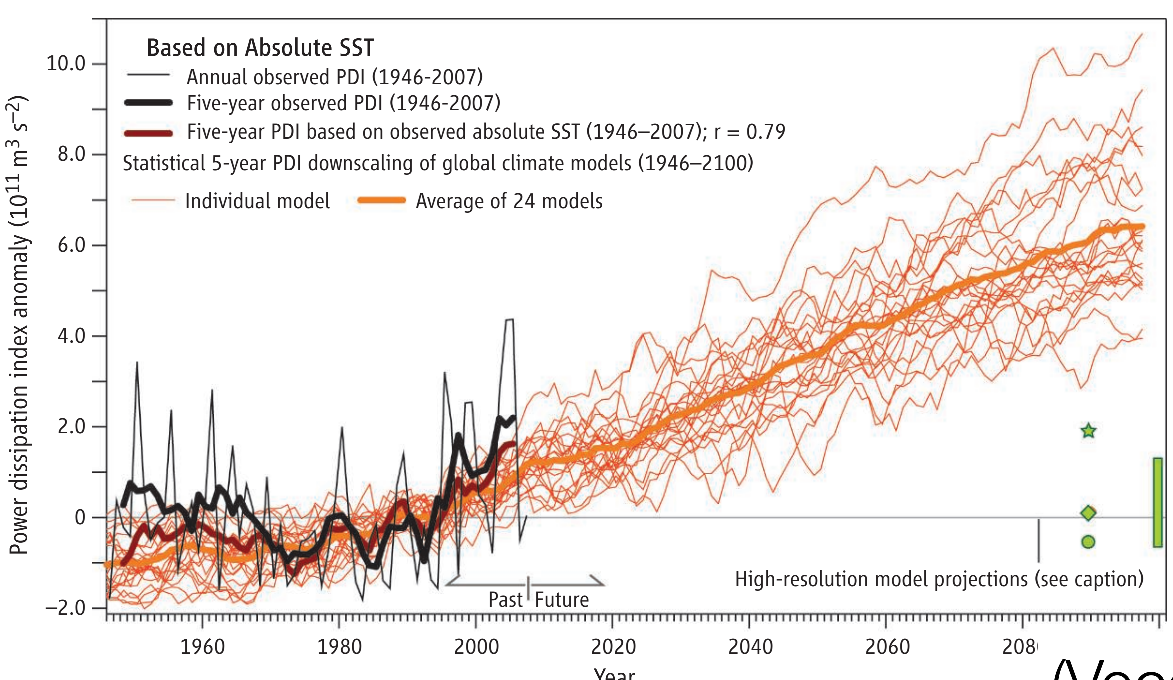


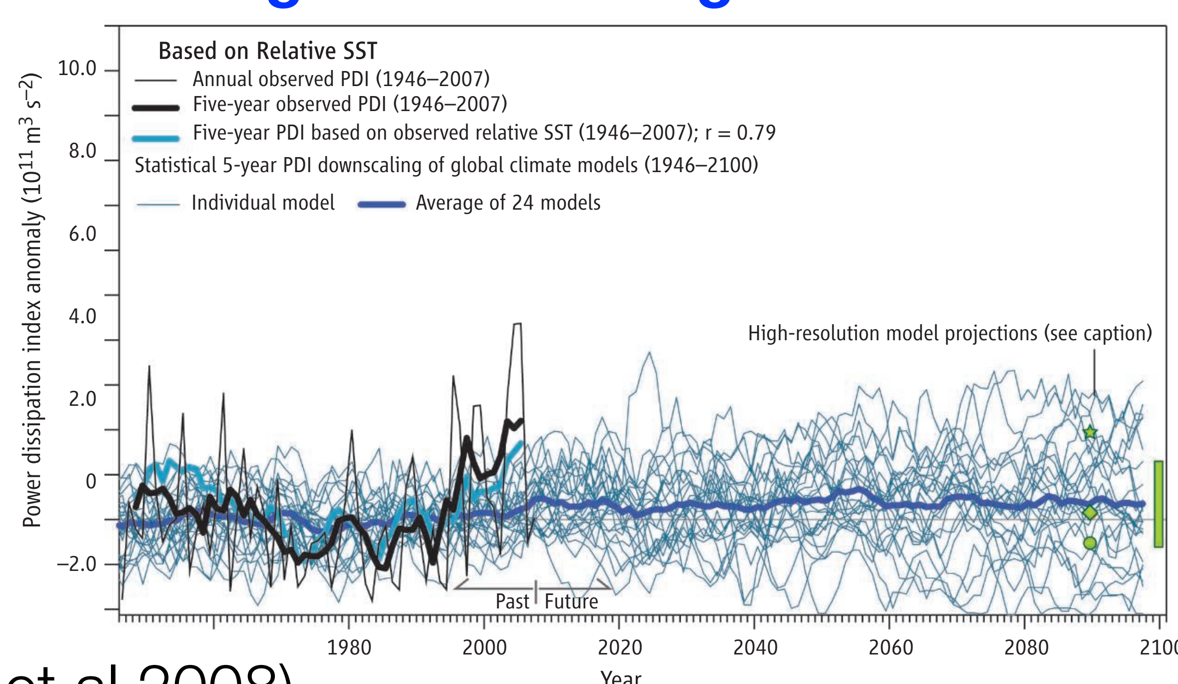
(Swanson 2008)



➔ Hurricanes strengthen dramatically in a global warming scenario

➔ Hurricanes do not strengthen in a global warming scenario

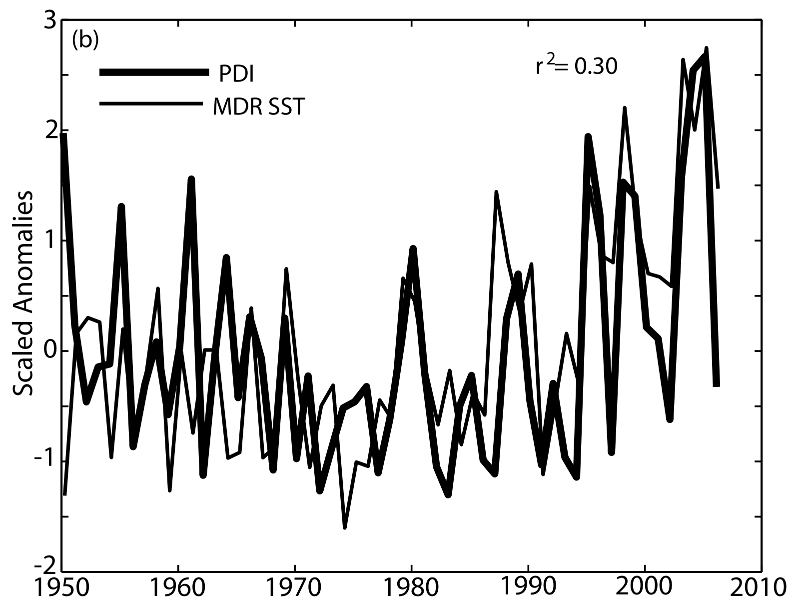




(Vecchi et al 2008)

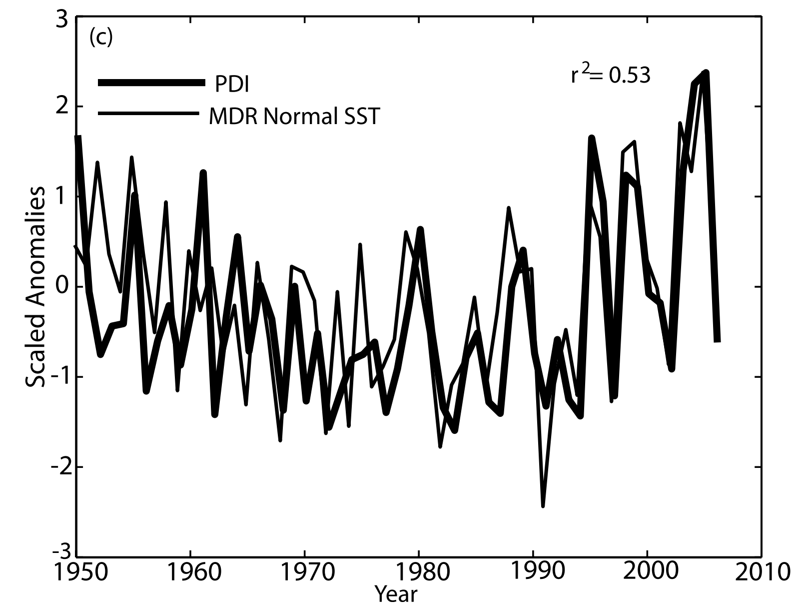
Will Hurricanes get stronger? A statistical approach

Hurricane strength (thick) & Atlantic SST (thin)

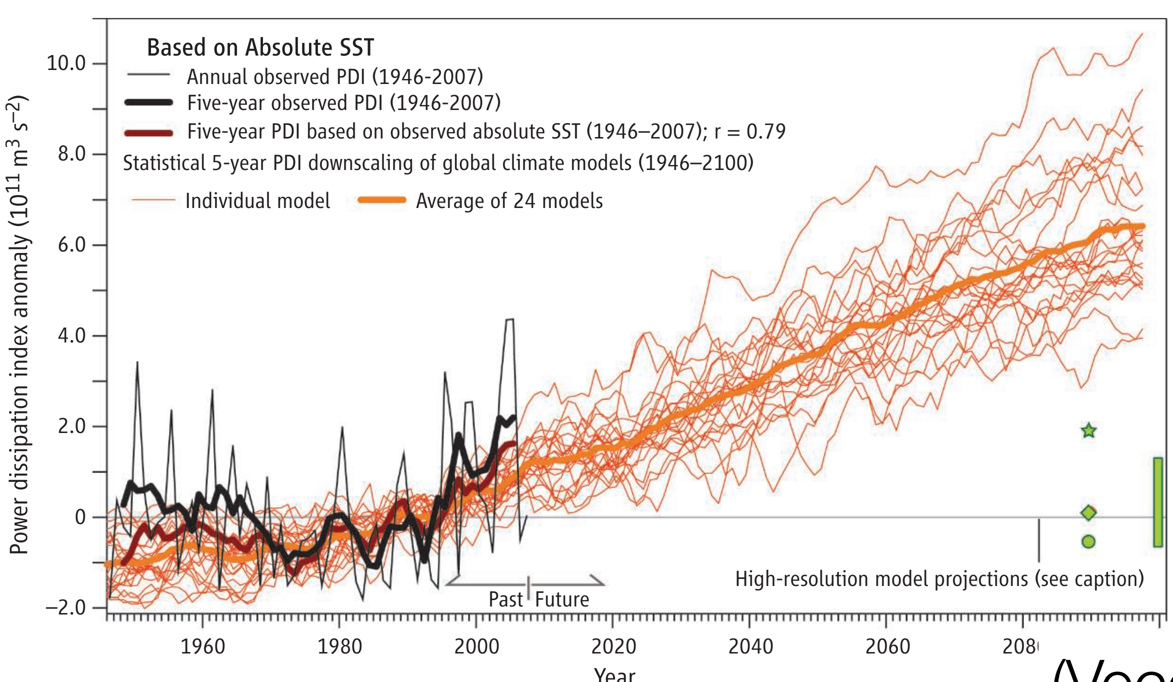


(Swanson 2008)

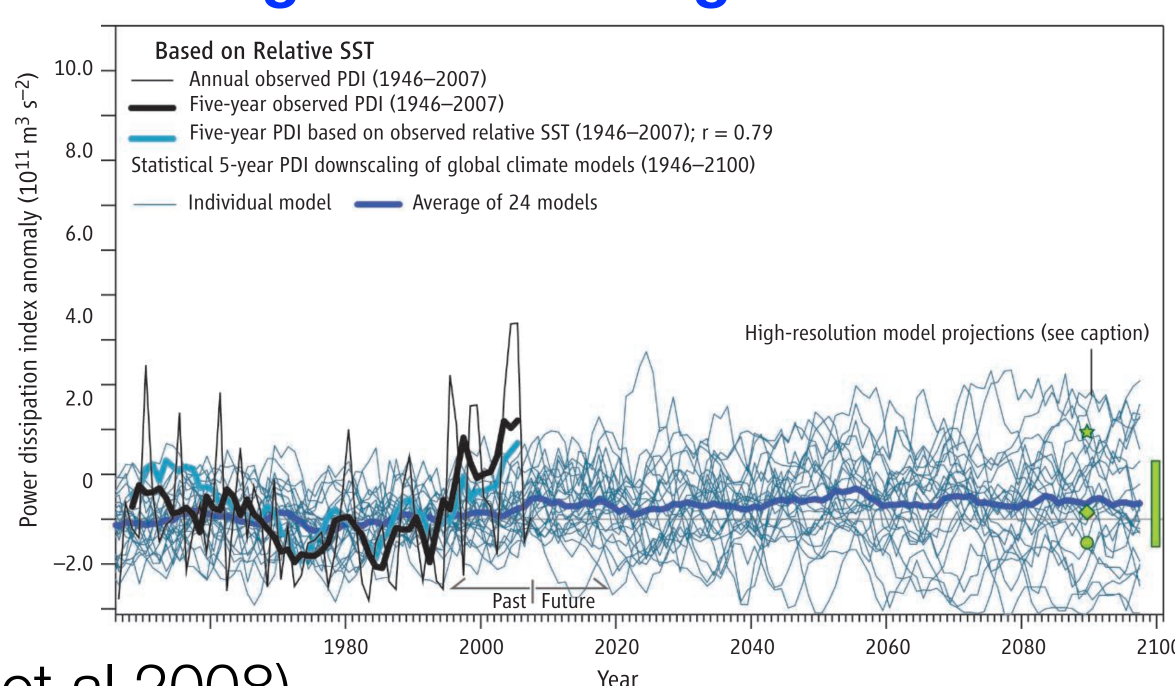
Hurricanes (thick), & Atlantic minus tropical SST (thin)



➔ Hurricanes strengthen dramatically in a global warming scenario



➔ Hurricanes do not strengthen in a global warming scenario

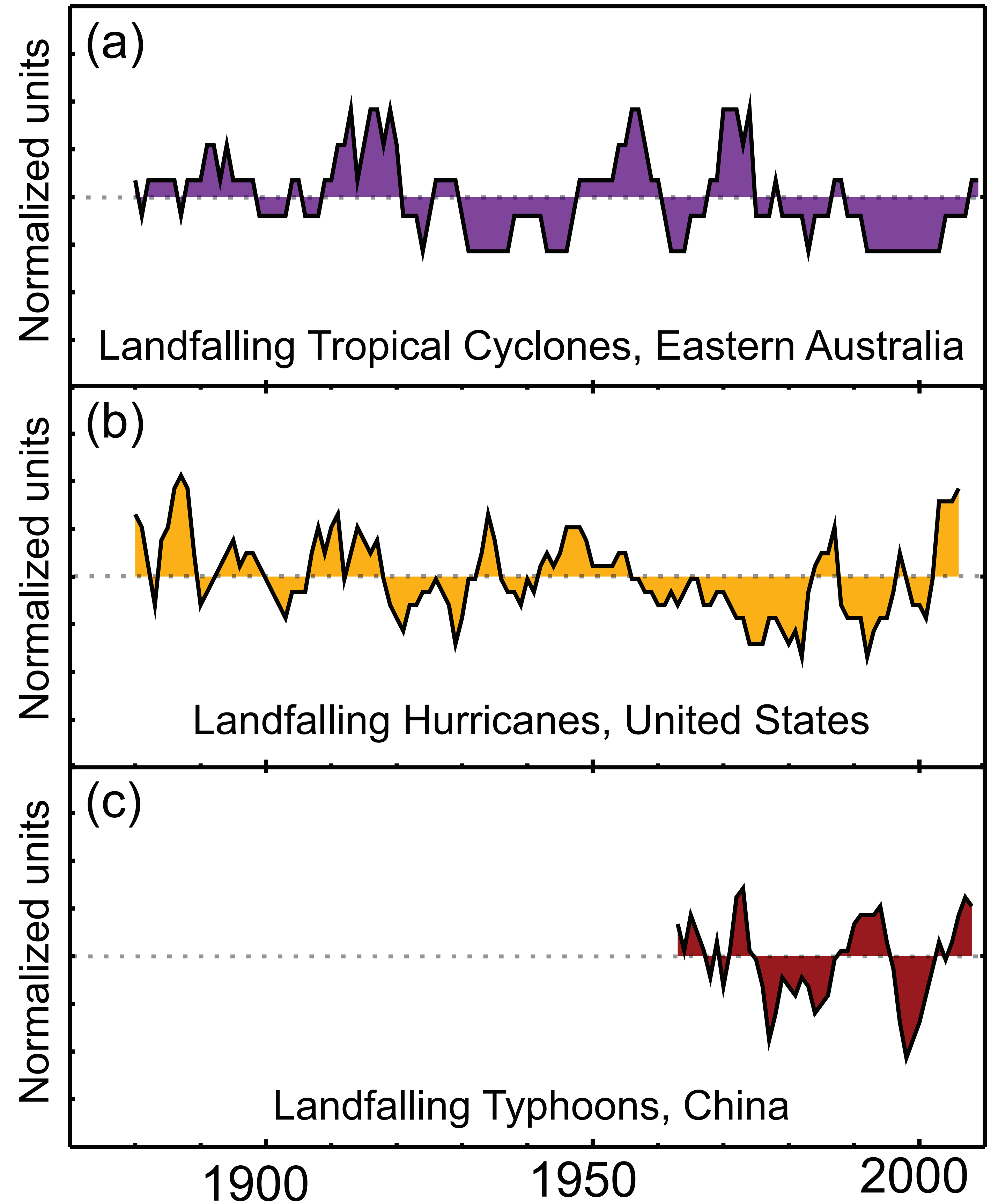


(Vecchi et al 2008)

➨ Regressions cannot tell if Hurricanes will get stronger in a warm future

Are Hurricanes already getting stronger/ more frequent?

Figure 2.34 | Normalized 5-year running means of the number of (a) adjusted land falling eastern Australian tropical cyclones (adapted from Callaghan and Power (2011) and updated to include 2010//2011 season) and (b) unadjusted land falling U.S. hurricanes (adapted from Vecchi and Knutson (2011) and (c) land-falling typhoons in China (adapted from CMA, 2011). Vertical axis ticks represent one standard deviation, with all series normalized to unit standard deviation after a 5-year running mean was applied.



IPCC AR5 2013

Are Hurricanes already getting stronger/ more frequent?

11.7.1.2 Observed Trends

Identifying past trends in TC metrics remains a challenge due to the heterogeneous character of the instrumental data, ('best-track' data, Schreck et al., 2014). There is low confidence in most reported long-term (multi-decadal to centennial) trends in TC frequency & intensity metrics due to changes in technology used to collect the data.

Best-track data of hurricanes that have impacted the USA since 1900 is reliable, & shows no trend in the frequency of USA landfall events (Knutson et al., 2019).

…a significant increase is found in the fraction of global Category 3–5 TC instances (6-hourly intensity during each TC) to all Category 1–5 instances (Kossin et al., 2020).

In summary, there is mounting evidence that a variety of TC characteristics have changed over various time periods. It is likely that the global proportion of Category 3–5 tropical cyclone instances & the frequency of rapid intensification events have increased globally over the past 40 years. It is very likely that the average location where TCs reach their peak wind intensity has migrated poleward in the western North Pacific Ocean since the 1940s. It is likely that TC translation speed has slowed over the USA since 1900.

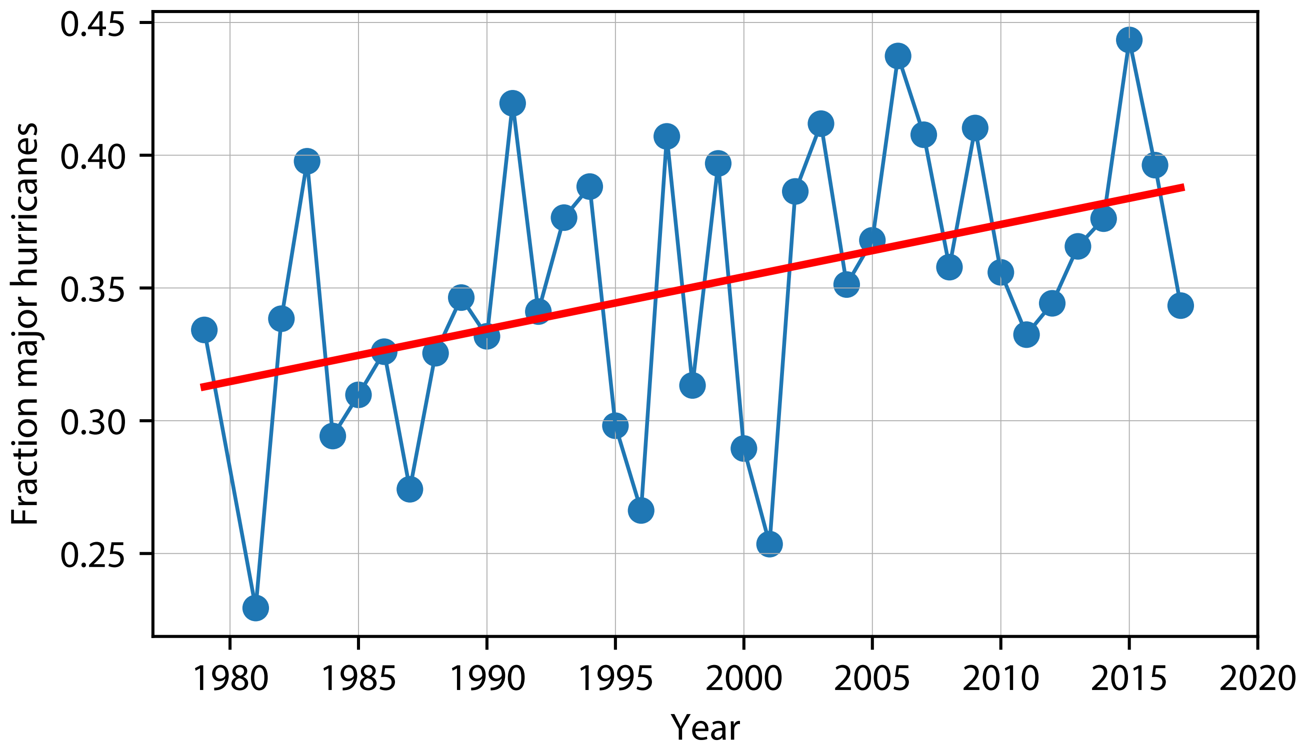
IPCC AR6 2022

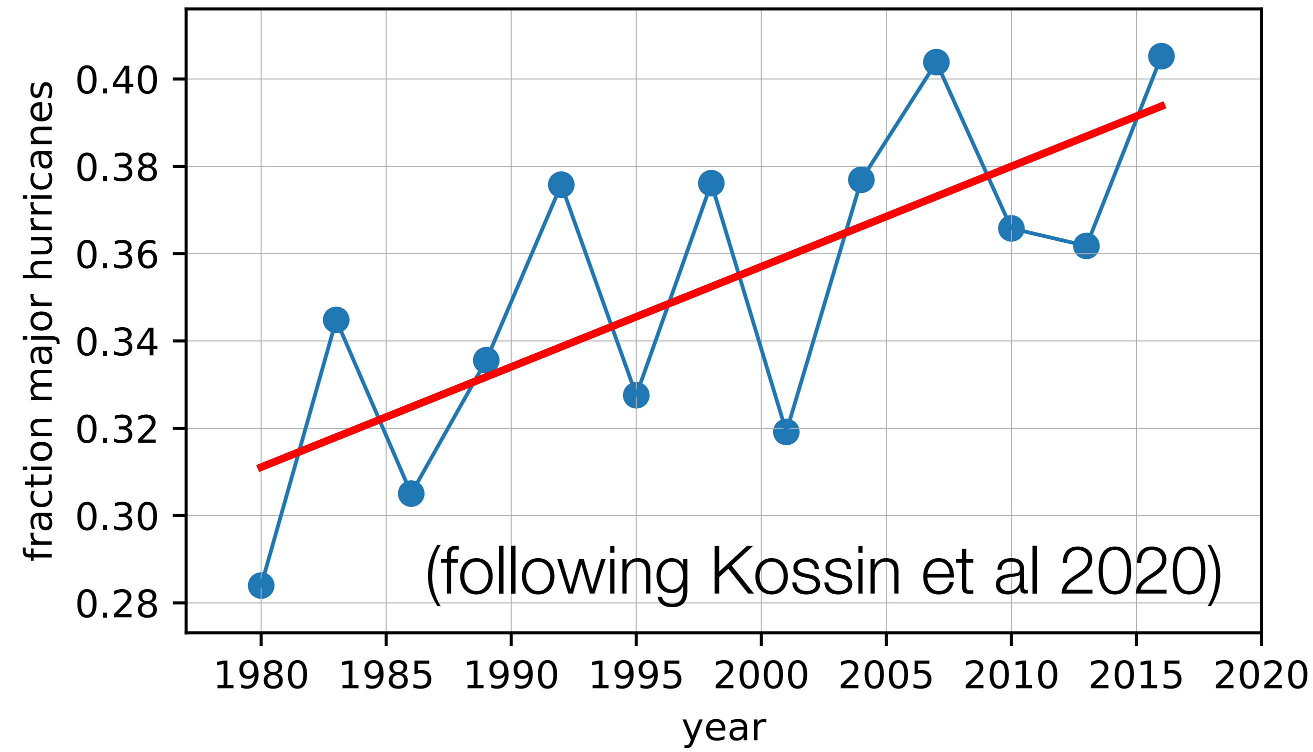
Workshop #3
Leave for homework

Detecting ACC in hurricane intensity: Calculate the fraction of major hurricanes every year and plot it as a function of time. Repeat after averaging in bins of three years. Calculate and plot a linear fit with and without the binning, and calculate the r^2 in each case. Discuss your results.

Detecting ACC in hurricane intensity

Fraction of major hurricanes instances (6 hourly winds in categories 3–5 out of 1–5),



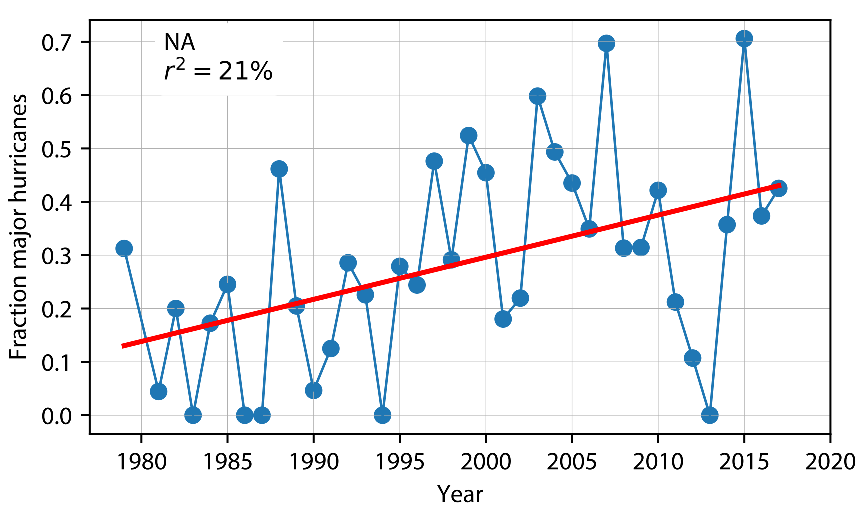


Left: annual data

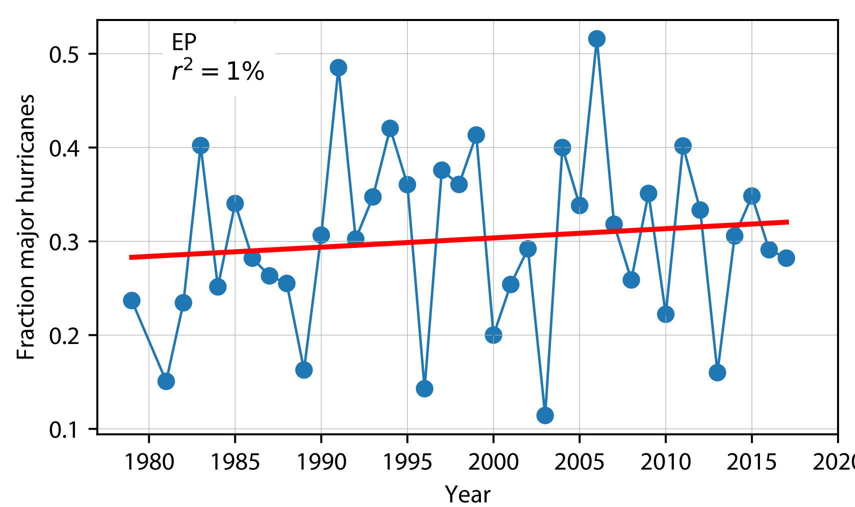
($r^2 = 0.18$; trend significant according to p-value)

Right: 3-year averages

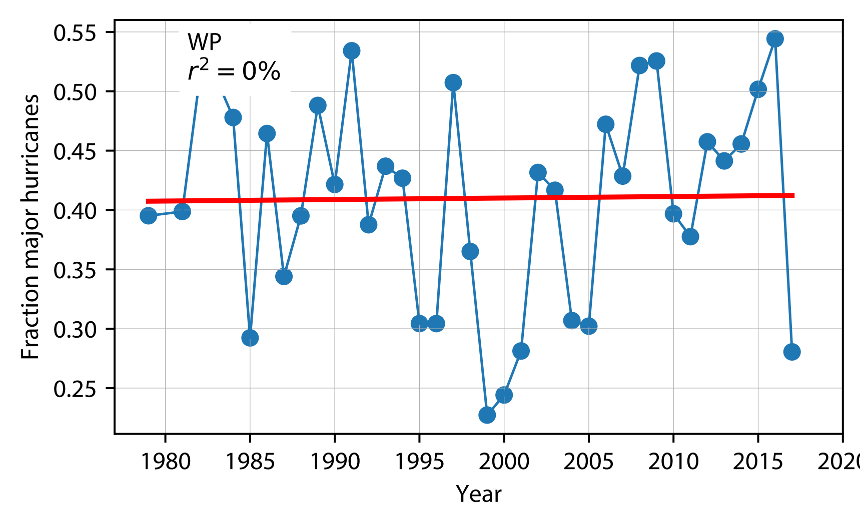
North Atlantic



East Pacific



West Pacific



Conclusions

- The maximum possible hurricane amplitude (potential intensity) may be estimated from its energy balance (evaporation vs surface frictional dissipation) and is expected to increase exponentially with the SST.
- The actual amplitude depends on wind shear and is, therefore, affected by ENSO and other factors.
- An increase in the fraction of major hurricanes so far has been detected, but the signal is still not large and year-to-year variations are very large.
- The frequency of hurricanes has not changed so far; we do not have a good way of projecting future frequency changes.

The End