Hurricanes

Global Warming Science

https://courses.seas.harvard.edu/climate/eli/Courses/EPS101/
Hurricane Irma, 2017

https://www.youtube.com/watch?v=KVciUq72gpk
Hurricane Harvey, 2017

https://www.houstonchronicle.com/local/hc-investigations/harvey/one-year-later/
Hurricane Harvey, 2017

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

Humans Are Making Hurricanes Worse. Here’s How.

By John Schwartz

Sept. 19, 2018

When hurricane Florence struck the Carolinas last week, humanity played a role in the destruction.

Human intervention is making natural disasters unnaturally harmful, both in causes and effects, and the number of ways our own influence is making things worse, taken together, is sobering.

On a global scale, we are bolstering the destructive potential of hurricanes and other extreme weather events by driving climate change. At the local level, we remain reluctant to deal with the problems of our own making, building and rebuilding in risky areas even as we avoid the policies and investment that would help mitigate the threats.

Kim Cobb, a climate scientist at the Georgia Institute of Technology, said that people tended to think of climate change as an abstract problem with only technocratic solutions. But it is getting more concrete all the time, and requires real-life action in response.

“This year has shown us that climate change is a present-day threat to the safety and livelihoods of communities across America,” she said. “Some communities are tackling these issues head on, but some have their heads in the sand.”
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 (“power dissipation index”)
Are hurricanes getting stronger?

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

![Graph showing annual unscaled PDI vs SST over years]

- $r^2$ 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
Are Hurricanes getting more frequent?

Number of Atlantic hurricanes per year

(data from Vecchi & Knutson 2011)
Workshop: (1c,d): Calculate the correlation between SST and “hurricane strength” (PDI)

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

**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
How a Hurricane Is Born | The Science of Superstorms | BBC
Hurricanes development

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

How a Hurricane Is Born | The Science of Superstorms | BBC
Hurricanes form in tropical regions where the ocean is at least 80 degrees Fahrenheit. These waters evaporate, creating warm, moist air—which acts as fuel for the storm.

The warm, moist air rises high into the atmosphere where it begins to cool. Water vapor condenses back into liquid droplets and forms big, stormy anvil-shaped clouds.

Many hurricanes in the U.S. are caused by winds blowing across the Atlantic Ocean from Africa, which cause more water to evaporate into the atmosphere.

https://www.youtube.com/watch?v=wPDolrGUrEc
Hurricanes development

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

As warm air rises, the winds begin blowing in a circle. The spiraling winds gather a cluster of clouds.

Thankfully, the GOES-R series of weather satellites take a scan of the U.S. every five minutes, keeping an eye on conditions that might cause a hurricane. This helps meteorologists deliver early warnings and keep people safe.

Once the spinning winds reach 74 miles per hour, the storm has officially become a hurricane. These storms can be 10 miles high and over 1000 miles across!

If a hurricane hits land, it runs out of warm, moist air and begins to slow down, but it can still cause lots of damage (especially from flooding).

Find out more about Earth's weather at scijinks.gov
# Hurricanes categories

## Categories of hurricane

<table>
<thead>
<tr>
<th></th>
<th>Category 1</th>
<th>Category 2</th>
<th>Category 3</th>
<th>Category 4</th>
<th>Category 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind</td>
<td>74-95mph</td>
<td>96-110mph</td>
<td>111-130mph</td>
<td>131-155mph</td>
<td>Over 155mph</td>
</tr>
<tr>
<td>Storm surge</td>
<td>4-5ft</td>
<td>6-8ft</td>
<td>9-12ft</td>
<td>13-16ft</td>
<td>Over 18ft</td>
</tr>
</tbody>
</table>

- **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

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

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:

\[ D = C_D \rho_{air} V_s^2 \times V_s = C_D \rho_{air} V_s^3 \frac{J}{s \ m^2} \]

**Source=Sink:** \( D = G \)
Potential intensity (K. Emanuel)

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

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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

\[ q^*(T) = 1577 \cdot 10^3 e^{-\frac{5415}{T}} \]

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

Carnot Cycle

Photo from https://www.voltiacenower.com/Biographies/CarnotBio.htm

http://galileoandeinstein.phys.virginia.edu/more_stuff/flashlets/carnot.htm
Converting heat to Kinetic energy: Carnot Heat Engine

Carnot Cycle

Heat Flowing from Cool Gas

Programmed by Wan Ching Hui

http://galileoandeinstein.phys.virginia.edu/more_stuff/flashlets/carnot.htm
Hurricane as a Carnot Engine (K. Emanuel)

Entropy reminder:
To understand the calculation of the efficiency, we need to consider the Carnot cycle, and that requires a reminder of what entropy is. When a small amount of heat $dQ$ is gained or lost by a system at a temperature $T$, the entropy gain/loss is defined to be $dQ/T$. To see why entropy typically increases in thermodynamic processes, consider a container with fluid, divided into two equal parts with temperatures $T_H > T_C$. Removing the divider, temperature will eventually be homogenized to $(T_H + T_C)/2$. During the process, the infinitesimal change in entropy due to the transfer of an infinitesimal amount of heat $dQ > 0$ between the two systems leads to a gain of $dQ$ for the cold system and a loss of $dQ$ for the hot system (gain of $dQ$), thus the entropy change is $dS = dQ/T_H + dQ/T_C = dQ/T_H > 0$, so the increase in entropy is because temperature flows from the hot reservoir to the cold one.

Carnot cycle:
See the three first pages from Wikipedia article, including a description of the four steps in the cycle, and the calculation of the efficiency. See also online animation.

Figure 1: A hurricane as a heat engine (Figure from Emanuel, 1991).

Hurricane as a Carnot cycle: (Figure 1, from Emanuel, 1991). Stage (1) of the Carnot cycle, of isothermal expansion, is equivalent to the process in a hurricane by which when air acquires heat (in the form of moisture from evaporation) as it flows along the surface toward the center of the storm, at a temperature $T_H$. (2) The adiabatic expansion occurs in a hurricane east of the core southwest, doing work on the environment. (3) The isothermal compression stage involves the release of heat by the hurricane to the environment (via radiation), while mixing out of the convective plumes at the top of the hurricane. (4) Isothermal compression and radiative cooling.

Wind Shear
Wind shear: what is it? effect on Hurricanes

https://cliffmass.blogspot.com/2017/05/wind-shear-when-atmospheric-seems-to-be.html
Wind shear: what is it? effect on Hurricanes

https://cliffrmass.blogspot.com/2017/05/wind-shear-when-atmospheric-seems-to-be.html

https://weatherstreet.com/weatherquestions/What_is_wind_shear.htm
**Wind shear: what is it? effect on Hurricanes**

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.
“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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Wind shear: what’s affecting it?

Vertical wind profile in the western tropical Atlantic

- Tropopause (16 km)

- More easterly winds
- More westerly winds

- Fewer tropical cyclones (El Niño)
- More tropical cyclones (La Niña)

NOAA climate.gov
Wind shear: what’s affecting it?

Vertical wind profile in the western tropical Atlantic

Tropopause (16 km)

Fewer tropical cyclones (El Niño)

More tropical cyclones (La Niña)

NOAA climate.gov

Observed Sea Surface Temperature Anomaly (°C)

7-day average centered on 17 September 1997

Climate Prediction Center/NCEP/NWS
During El Niño events, a strong wind shear over the Atlantic reduces the number of named storms and Hurricanes.

[Diagram showing wind shear and tropical cyclone frequency during El Niño and La Niña events.

 NOAA climate.gov

[Map showing observed sea surface temperature anomaly in the Atlantic.

 NOAA Climate Prediction Center/NCEP/NWS

http://www2010.atmos.uiuc.edu/(Gh)/guides/mtr/hurr/enso.rxml

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Wind shear: what’s affecting it?

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

<table>
<thead>
<tr>
<th></th>
<th>Atlantic</th>
<th>Eastern Pacific</th>
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<tbody>
<tr>
<td>Average</td>
<td>9.4</td>
<td>16.7</td>
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<tr>
<td>El Niño Avg.</td>
<td>7.1</td>
<td>17.6</td>
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<tr>
<td>Named storms</td>
<td>5.8</td>
<td>9.8</td>
</tr>
<tr>
<td>Hurricanes</td>
<td>4.0</td>
<td>10.0</td>
</tr>
<tr>
<td>Intense Hurricanes</td>
<td>2.5</td>
<td>4.8</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>5.5</td>
</tr>
</tbody>
</table>
Wind shear: how does El Nino affect it?


“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](http://www.noaa.gov)
Wind shear: how does El Niño affect it?


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Hadley cell

SST anomalies (°C) during 1997 El Niño

NOAA climate.gov
(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, \(U = \text{zonal wind}, V = \text{meridional}\). (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

30% increase by 2100...?
Global Warming Science 101, Hurricanes, Eli Tziperman

Hurricane strength (thick) & Atlantic SST (thin)

Will Hurricanes get stronger?

(Swanson 2008)

(Elsner et al. 2006) highlight such suppression of Atlantic TC intensities by remote factors, as they show that in the Atlantic basin global mean temperature acts as a negative predictor of TC intensity when the local impact of MDR SST is removed. Indeed, the fact that global tropical SST trends might have a smaller effect on tropical cyclone intensities than regional fluctuations in MDR SST relative to that global mean was explicitly recognized by Emanuel (2005). Given this state of affairs, it is vital to understand whether local or nonlocal influences dominate TC intensities in the North Atlantic hurricane basin. The degree of localization examined here shades from totally local control, where SST anomalies within the Atlantic MDR dominate observed fluctuations in TC intensity, to nonlocal control, where fluctuations in TC intensity depend solely upon the MDR SST relative to the tropical mean SST. Note that nonlocal control defined in this manner will be more or less independent of global warming, as it depends upon the relative regional distribution of SST anomalies rather than a basin-independent increase in SST.

Within this context, we show that Atlantic TC intensities are nonlocal in the sense that intensity fluctuations and storm numbers depend much more sensitively on MDR SST anomalies relative to the tropical mean than on the MDR SST anomalies themselves. The implication of this behavior is that Atlantic TCs are intrinsically nonlocal, and specifically that the increase in Atlantic TC intensities since roughly 1980 cannot be attributed to a global increase in SST.

2. SST and Hurricane Intensity Fluctuations

We examine TC winds for the period 1950–2006 in the North Atlantic basin based upon Tropical Prediction Center best track reanalysis, with intensity corrections for the pre-1975 part of the record following Emanuel (2005). The SST (Swanson 2008)
Will Hurricanes get stronger?

→ Hurricanes strengthen dramatically in a global warming scenario

(Swanson 2008)

(Vecchi et al 2008)
Will Hurricanes get stronger?

Hurricane strength (thick) & Atlantic SST (thin)

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

→ Hurricanes strengthen dramatically in a global warming scenario

Based on Absolute SST

- Annual observed PDI (1946-2007)
- Five-year observed PDI (1946-2007)
- Five-year PDI based on observed absolute SST (1946-2007); \( r = 0.79 \)

Statistical 5-year PDI downscaling of global climate models (1946-2100)

- Individual model
- Average of 24 models

Power dissipation index anomaly (10^6 m^2 s^-1)

(Vecchi et al 2008)
Will Hurricanes get stronger?

Hurricanes strengthen dramatically in a global warming scenario

→ Hurricanes do not strengthen in a global warming scenario

**Hurricane strength (thick) & Atlantic SST (thin)**

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

(Swanson 2008)

(Vecchi et al 2008)
Will Hurricanes get stronger?

- Hurricanes strengthen dramatically in a global warming scenario
- Hurricanes do not strengthen in a global warming scenario
- Regressions cannot tell if Hurricanes will get stronger in a warm future

**Hurricane strength (thick) & Atlantic SST (thin)**

(Swanson 2008)

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

(Vecchi et al 2008)
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 Callaghan and Power (2011) and 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.
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.
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), following Kossin et al 2020

Left: annual data
Right: 3-year averages

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

• Maximum possible hurricane amplitude (potential intensity) may be estimated from its energy balance (evaporation vs surface frictional dissipation) and is controlled by the SST.

• 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 may have been detected, but the signal is still not large.

• The frequency of hurricanes did not change so far, we do not have a good way of projecting future changes.
The End