Hurricane Harvey 2017

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Climate science at a glance

- Sea level rise, combined with coastal storms, has increased the risk of erosion, storm-surge damage, and flooding for coastal communities, especially along the Gulf of Mexico.[1]
- Global warming is increasing water vapor in the air, which in turn is fueling extreme rainfall, increasing the threat of flooding driven by hurricanes.[2]
- From 1963 to 2012, 88 percent of storm-related fatalities occurred in water-related incidents; storm surge caused 49 percent and freshwater floods due to heavy rainfall caused 27 percent.[3]
- Harvey intensified rapidly in the Gulf of Mexico, aided by sea surface temperatures up to 2.7 - 7.2°F (1.5 - 4°C) above average relative to the temperature average from 1961-1990.[4]
- Increasing surface land and ocean temperatures are increasing the potential energy available to passing storms.[5]
- Harvey's rapid intensification is consistent with the observed trend toward rapidly intensifying tropical cyclones, particularly in the North Atlantic and Caribbean.[6][7]

Storm surge inundates coastlines on rising seas

Hurricanes now ride atop elevated sea levels contributing to storm surge and flooding, the leading cause of hurricane storm damage and fatalities. During Harvey, a storm tide level of 7.0 feet above Mean Sea Level (MSL) was observed at Port Lavaca, Texas - the highest storm surge in that location since Hurricane Carla in 1961.[8] In Galveston, flooded riverwater going out to the Gulf Coast collided with a roughly three-foot storm surge, producing a total water surge of about nine feet.[9]

Sea levels are now 8 inches higher due to sea level rise, [1] an increase that drives flooding much further inland along low-lying areas such as much of the Gulf of Mexico coastline. A small vertical increase in sea level can translate into a very large increase in horizontal reach by storm surge depending upon local topography. For example, sea level rise extended the reach of Hurricane Sandy by 27 square miles, affecting 83,000 additional individuals living in New Jersey and New York City[10] and adding over $2 billion in storm damage.[11] Aided by sea level rise, Hurricane Matthew set several storm tide records during its approach to the eastern sea board.

NOAA reports that so-called "nuisance flooding," e.g. coastal flooding during king tides, has already increased 300 to 925 percent due to sea level rise to date.[12]

Global warming loads hurricanes with more rainfall, increasing the threat of flooding

Parts of southeast Houston received over two feet of rain in 24 hours during the storm. [13] As of 7 am CDT on August 27th, the Weather Service office in Houston was reporting a 24-hour rainfall total of 24.1 inches.[14] Bush Continental Airport broke its record for wettest calendar day by over five inches, receiving 16.07 inches of rain on August 27th, and Hobby Airport set a new two-day rainfall record with 23.06 inches August 26th-27th, surpassing its previous record by nearly eight inches.[13] As of 12 pm on the 27th, the storm had dropped total of 9 trillion gallons of water on the greater Houston area and southeast Texas.[15] That's the volume equivalent of a giant cube that's

two miles long, two miles wide, and two miles high.[15] Consequently, most Houston-area rivers and bayous rose to record levels.[14] Multiple feet of water accumulated on interstates. Rainfall totals were so high the National Weather Service had to update the color charts on their graphics to effectively map the event.[16]

Numerous rainfall records were set during Harvey, including the following:

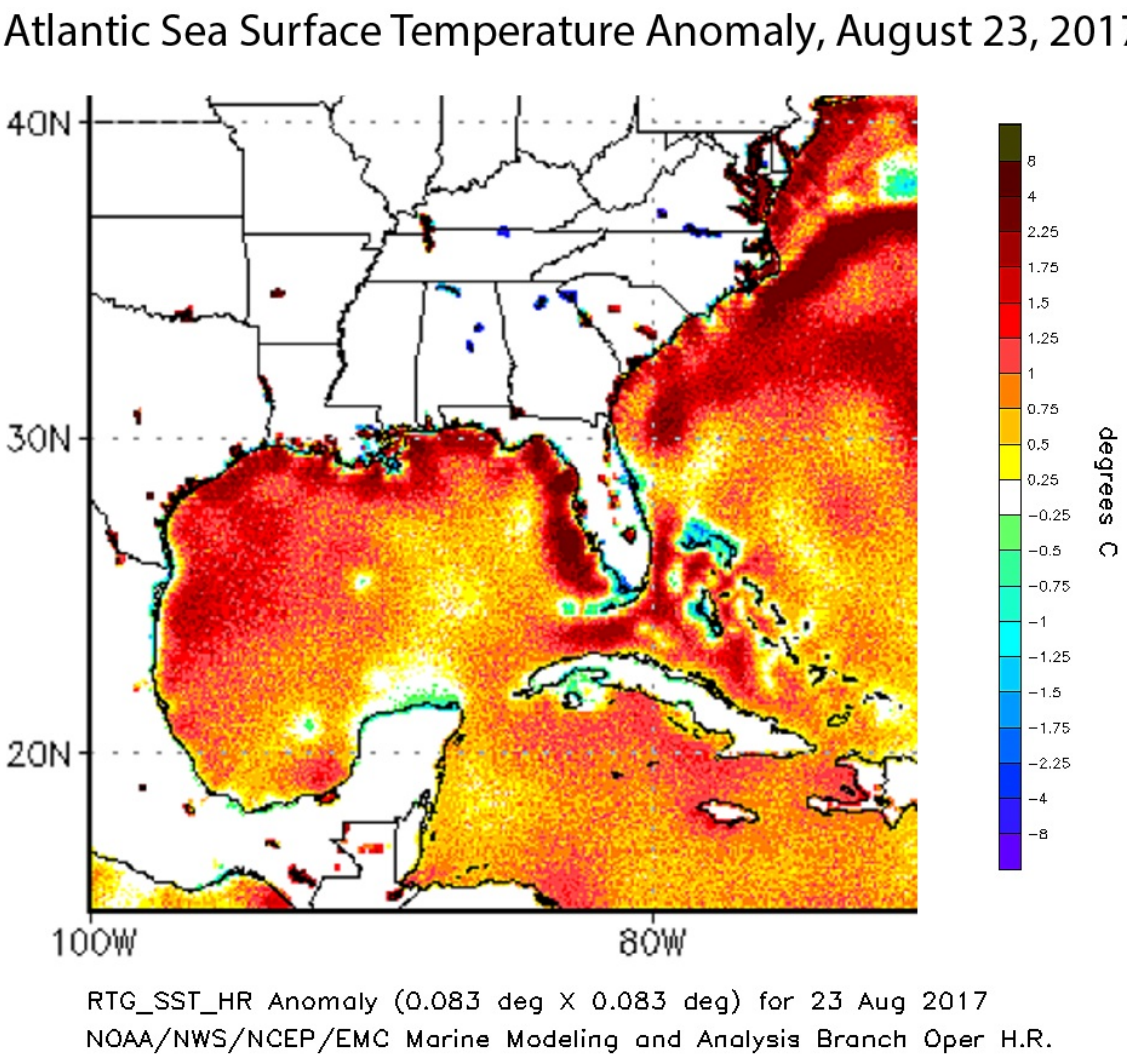
- Houston is experiencing its third '500-year' flood in 3 years.[17]
- Many areas of Southeast Texas have received rain that is expected to come around only once every 1,000 years (or having a 0.1 percent probability of occurrence), according to the Space Science and Engineering Center at the University of Wisconsin at Madison.[18]
- A rain gauge in Mont Belvieu, about 40 miles east of Houston, had registered 50.4 inches of rain through midday Tuesday. This total exceeds the previous record of 48 inches set during tropical cyclone Amelia in Medina, Texas in 1978.[18]

Climate change is increasing rainfall during hurricanes.[19]

It increases the rate at which ocean water evaporates into the air and the amount of water vapor the air can hold when fully saturated. As the amount of water in the air increases, this causes more precipitation from all storms, which significantly amplifies extreme precipitation and flooding risk.[2]

Increasing rainfall rates is one of the more confident predictions of the effects of future climate change on hurricanes.[20]

Harvey intensified rapidly in the Gulf of Mexico, where waters were up to 2.7 - 7.2°F (1.5 - 4°C) above average



Upon entering the warm waters of the Gulf of Mexico, Harvey intensified from a disorganized, fragmented system into a strong Tropical Storm, finally making landfall as a Category 4 hurricane around 9:45 pm on August 25 (with wind speeds of 130 mph).[21]

Harvey's rapid intensification from a tropical depression to an 85-mile-per-hour hurricane in less than 24 hours was due to favorable conditions—warm water and low wind shear—in the Gulf of Mexico, where sea surface temperatures were up to 2.7 - 7.2°F (1.5 - 4°C) above the 1961-1990 average.[4][22]

On the morning of August 25, Harvey passed over especially warm waters for over 6 hours, and the extra energy allowed Harvey's central pressure to fall 15 mb in just two hours, from 967 mb to 952 mb.[23]

Sea surface temperature has been consistently higher during the past three decades than at any other time since reliable observations began in 1880.[24]

Hurricanes are fueled by available heat. Warming seas are increasing the potential energy available to passing storms, effectively increasing the power ceiling or speed limit for these cyclones.[20] This trend is strongest in the Atlantic, where rising ocean temperatures correlate closely to an increase in Atlantic tropical cyclone strength.[25] However, other factors, such as wind shear and the global pattern of regional sea surface temperatures, also play controlling roles. The balance of these factors is not fully known.[26]

Intense wind speed is only one of three major drivers of hurricane impacts, and

Harvey has them all

A hurricane's category is a measure of wind speed, but that is just one of the three major hazards caused by hurricanes, the other two being rainfall and storm surge. According to Texas State Climatologist John Nielsen-Gammon, hurricanes usually come with storm surge and *either* extreme winds *or* extreme rains.[27]

> *[Harvey] has the dual threat of both being very intense at landfall and producing widespread flooding at the same time." — John Nielsen-Gammon[27]*

Hurricane Harvey had intense wind and rain because unique wind patterns prevented the storm from moving quickly out of the region.[27]

Climate change links to stalling weather systems

Rainfall totals were so high in the Houston area in large part because Harvey stalled over southeast Texas, where it was able to feed on warm waters in the Gulf of Mexico. Waves in the jet stream can stall in place (instead of moving eastward), leading to blocking and persistent weather patterns that fuel the intensity and duration of rainfall events.

A study from March 2017 found that climate change is altering large-scale weather patterns, such as the jet stream.[28] These changes can dramatically amplify extreme weather events, such as extreme rainfall, during the summer.[28]

> *The kind of stalled weather pattern that is drenching Houston is precisely the sort of pattern we expect because of climate change." — Michael Mann, climatologist and director of the Earth System Science Center at Pennsylvania State University[29]*

> *I agree with Mike [Mann] that the weak steering currents over the south-central US coincident with Harvey are consistent with our expectations for a warmer world, which of course includes effects of a very warm Arctic." — Jennifer Francis, a climate scientist at Rutgers University and leading expert on climate change jet stream impacts[29]*

More tentative, is a general slowdown of atmospheric summer circulation in the mid-latitudes. [30][31] This is a consequence of the disproportionally strong warming in the Arctic; it can make weather systems move less and stay longer in a given location – which can significantly enhance the impacts of rainfall extremes, just like we're sadly witnessing in Houston.[31]