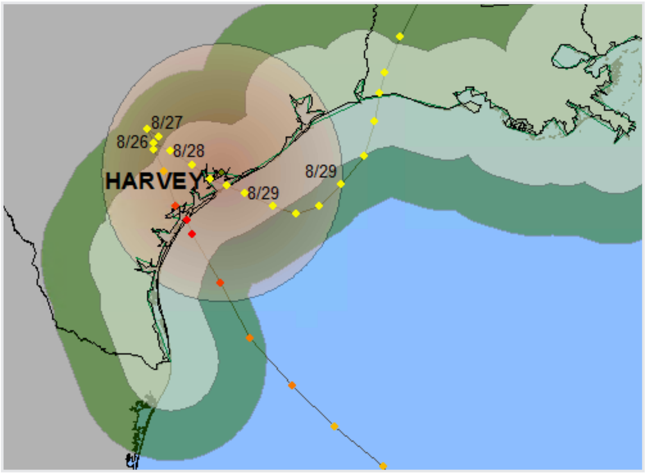
Stalling Hurricanes Wreak Havoc

Were Harvey and Florence Unique or Will More Storms Stall Out?

In 2017 and 2018, Hurricanes Harvey and Florence made landfall on the continental US. Both storms stalled at the time of landfall wreaking havoc through long-duration wind exposure and excessive rainfall. In the following paper TigerRisk discusses what causes storms to stall and the history of stalling storms. Is this a new phenomenon of hurricane behavior or mere coincidence that this occurred in back-to-back years?

A storm is classified as stalling if its forward speed is 6 mph or less for at least 12 consecutive hours. The following references to "stalling" Atlantic tropical cyclones (TC) use the HURDAT2 data set consisting of temporal, spatial and descriptive information of cyclones from 1851 – 2017 [1].

1. The cyclone makes US landfall with at least tropical storm (TS) strength (maximum sustained wind speeds of at least 39 mph).
2. The cyclone stalls inland within 100 miles of the coast or 50 miles out to sea.
3. The cyclone produces wind speeds of 40 mph or more on average during the stall period.



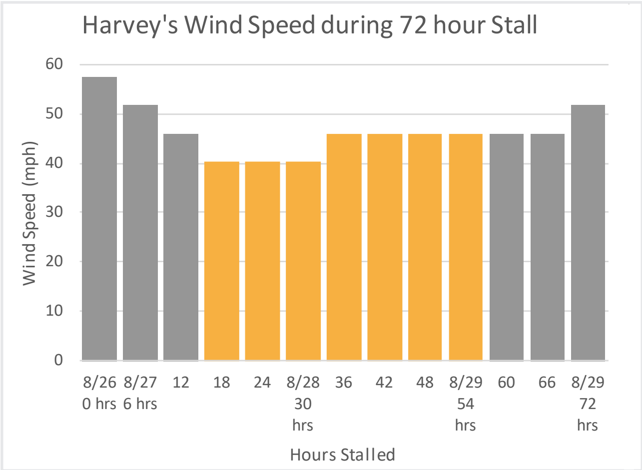


Figure 1: (Left) Hurricane Harvey's (2017) track shown against the 100-mile and the 50-mile coastal buffer shown in dark green and light green respectively. (Right) Harvey's maximum sustained winds during the 72-hour stall period. Gray bars indicate Harvey was within 100 miles of the coast, while yellow bars indicate Harvey was within 50 miles of the coast.

Applying the criteria above to the HURDAT2 data resulted in 37 stalling cyclones from 1851 to 2017, eight of which occurred after 1981 when more accurate satellite data was available, see Table 1 and Table 2. Figure 3 shows the temporal spread of the 37 TCs and illustrates that stalling TCs have occurred in back-to-back years six times in the past.

Time Period	TC with strength ≥ TS	Landfalling TC with strength ≥ TS	Stalling TC with strength ≥ TS	Annual Landfall Frequency	Annual Stall Frequency
1851 - 2017	1,576	454	37	2.72	0.22
1981 - 2017	455	110	8	2.97	0.22

Table 1: Tropical cyclone annual frequency.

Time Period	TS strength	Cat 1 - 2	Cat 3 - 5	TS strength Annual Frequency	Cat 1 - 2 Annual Frequency	Cat 3 - 5 Annual Frequency
1851 - 2017	11	19	7	0.066	0.114	0.042
1981 - 2017	2	5	1	0.054	0.135	0.027

Table 2: Intensity of the landfall occurring closest in time to the stalling event for the 37 TC.

There are many contributing factors causing extreme rainfall from a slow-moving cyclone including duration and storm strength before and during the stall, as well as neighboring atmospheric conditions. For instance, rain rates increase and become more centrally concentrated with TC intensity [8] and naturally, long-duration rain events lead to higher rainfall totals.

Harvey's torrential rains were caused in part by a weak stationary front over the southern United States which combined cool, dry air with Harvey's warm, moist air to create prolonged heavy rains that occurred outside the core where most of a cyclone's heavy rains usually reside [9]. In fact, prior research concludes that there is no way to tell if a TC will coincide with an extreme rainfall event based on a cyclone's attributes such as category, genesis location and minimum central pressure [10].

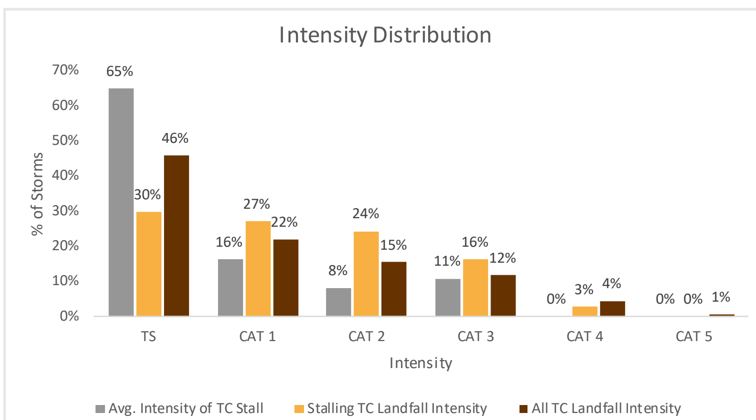


Figure 2: (Gray) Proportion of stalling cyclones stratified by average intensity during a stall occurrence. (Yellow & Brown) Proportion of cyclones stratified by landfall intensity (1851 – 2017).

State Affected	Since 1851	Annual Freq (since 1851)
Florida	10	0.060
Texas	10	0.060
Louisiana	7	0.042
Alabama	4	0.024
North Carolina	3	0.018
Mississippi	2	0.012
Georgia	2	0.012

Table 3: (Top) Geographical breakdown of the 37 TC (Including the fifth TC in 1878 which affected Florida and Georgia during two separate stall occurrences).

Max Rainfall (inches)	Storm	Location
60.58	Harvey 2017	Nederland, TX
48.00	Amelia 1978	Medina, TX
45.20	Easy 1950	Yankeetown, FL
45.00	Claudette 1979	Alvin COOP site, TX
40.68	Allison 2001	Jefferson County, TX
38.46	Georges 1998	Munson, FL
36.71	Danny 1997	Dauphin Island, AL
35.93	Florence 2018	Elizabethtown, NC

Table 4: Historical rainfall totals from tropical cyclones [2].

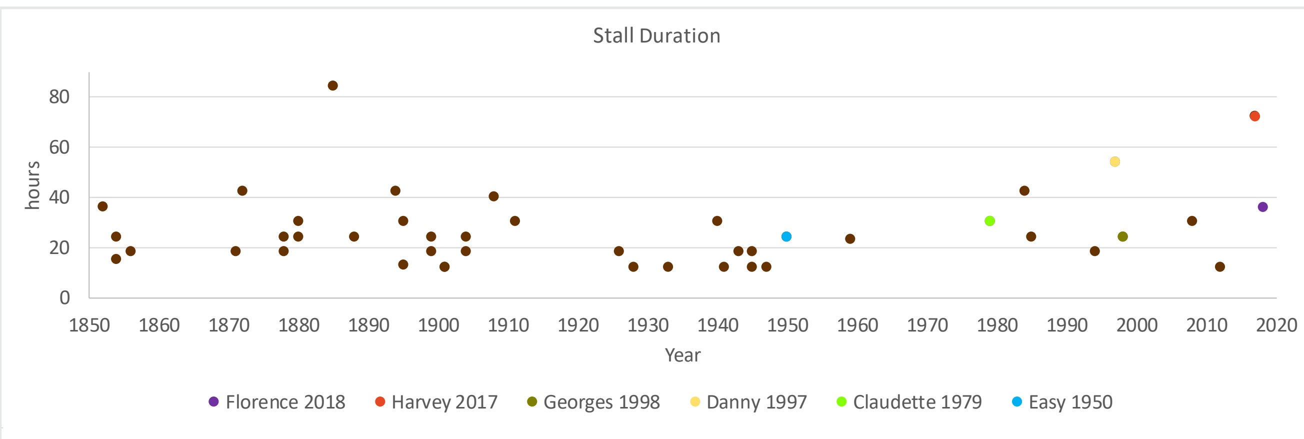


Figure 3: Temporal spread of TC stalls and their duration.

What guides a hurricane's movement?

The path and forward speed of a tropical cyclone depends on many factors such as trade winds, high- and low-pressure systems, jet streams and vertical wind shear. In the Atlantic basin, trade winds steer cyclones from the development area off the coast of Africa westward towards the Caribbean Sea and North American coasts. A cyclone's path is further influenced by the location of the high-pressure system known as the Bermuda High, the Azores High or the subtropical ridge. Typically, cyclones ride the strongest winds of the Bermuda High along the periphery. If the high is positioned to the east, then cyclones are more likely to move northeastward out into the open Atlantic. Tropical cyclones are more likely to track toward Florida, Cuba and the Gulf of Mexico when the high is positioned to the west and extends south, effectively blocking any northeastern movement [3]. In fact, a persistent high-pressure system (ridge) over the eastern United States and the western Atlantic during the 2004 hurricane season, helped steer storms along a more westerly track and in the 2005 season, the ridge was farther south and west than in 2004 which helped steer the storms in the Gulf of Mexico [4] [5], see Figure 4. The primary driver of the ridging along the East Coast in 2005 is believed to be from warming sea surface temperatures in the Pacific causing heat to propagate downstream across North America and into the Atlantic Ocean [6].

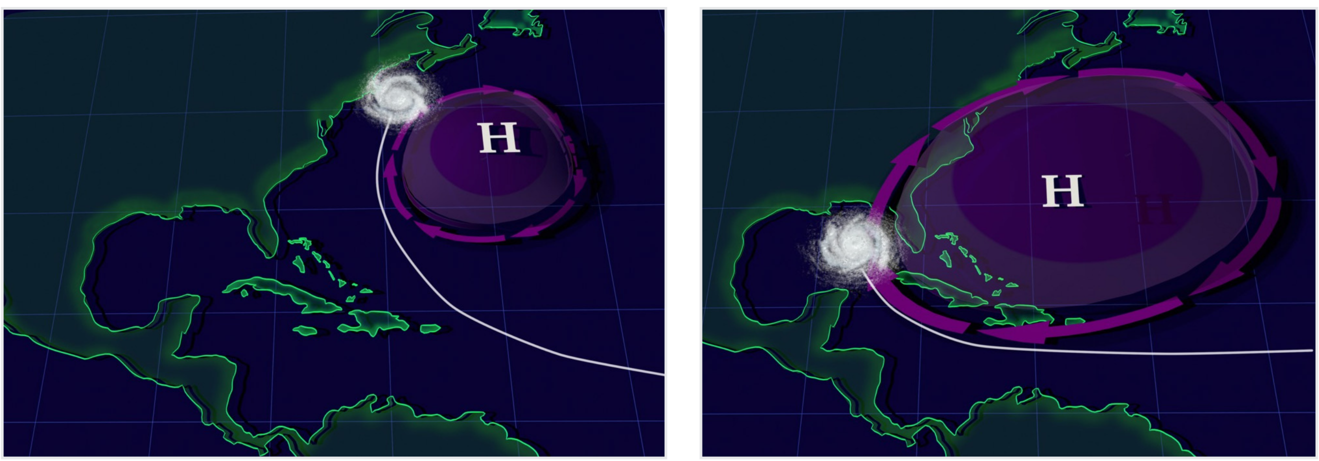


Figure 4: (Left) Easterly position of the Bermuda High. (Right) Position of the Bermuda High during the 2004 and 2005 hurricane season. Image by NASA/Goddard Space Flight Center Conceptual Images Lab via [7].

Many stalling cyclones stall more than once and affect more than one region. The maps in Figure 5 reveal the areas affected by each stall occurrence including stalls that are less than tropical storm strength. We found that some of the stalling cyclones were impeded by neighboring high-pressure systems. Upon Harvey's Texas landfall, the cyclone became embedded in light steering currents that were sandwiched between two high-pressure systems located to the east and west preventing Harvey from advancing farther inland or back out to sea. Florence's (2018) westward movement was blocked by a high-pressure system over eastern North America. Tropical storm Claudette of 1979 was forecasted to remain progressive as it approached Texas, however it was blocked to the north by a ridge causing it to slowly turn westward describing a tight loop where 42 inches of rainfall fell over a 24-hour period in Alvin, Texas.

Tropical storm Allison of 2001 also stalled over Texas, inundating many of the same areas that Harvey flooded such as the Port of Houston which received about 37 inches. Allison's track was like Harvey's in that it moved inland via a northward track due to a subtropical ridge off the southeast. That ridge later weakened and moved further southeast while another ridge developed over New Mexico causing Allison to turn southward back out to sea. Moreover, Allison experienced two distinct stalls separated by 6 hours where the cyclone's forward speed reached 6.35 mph, but together these two stall events lasted about 72 hours, with average maximum sustained winds around 23 mph. Allison is not included in the 37 storms analyzed here because the wind speed during the stall never reached tropical storm strength.

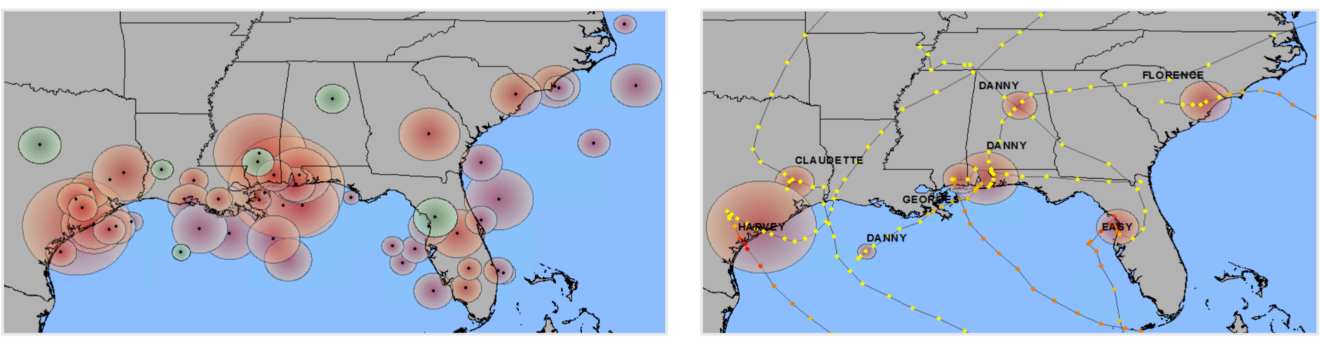


Figure 5: (Left) Black dots represent the centroid of the stall locations. The circles are the minimum size encompassing all locations involved in the stall event, where red and purple circles are at least Tropical storm strength stalls and green circles are less intense. (Right) Historical cyclones that caused extreme rainfall (Hurricane Florence in 2018 is not included in the 37 TC in this study).

The bubble chart in Figure 6 illustrates stall duration and storm strength for each stall occurrence from the 37 cyclones in addition to Hurricane Florence in 2018. Compared to the other cyclones, Harvey's 72-hour stall and category 3 landfall strength are unique among the group. The parameters of the other noteworthy TCs that produced extreme rainfall-- Georges, Danny, Claudette and Easy-- are less extreme, except for Easy's category 2 status during the stall period right off the western coast of Florida near Citrus County. There is only one other storm that stalled longer and with similar intensity to Harvey - the sixth TC in 1885. This storm affected parts of Louisiana, Mississippi, Alabama and Florida during its 84-hour stall, though no records of extreme rainfall could be found. In 1997, Hurricane Danny had the third-longest stall duration of 54 hours which did cause an extreme rainfall event in Alabama when at least 36.71 inches fell on Dauphin Island (Table 4), though the flooding was not widespread [11].

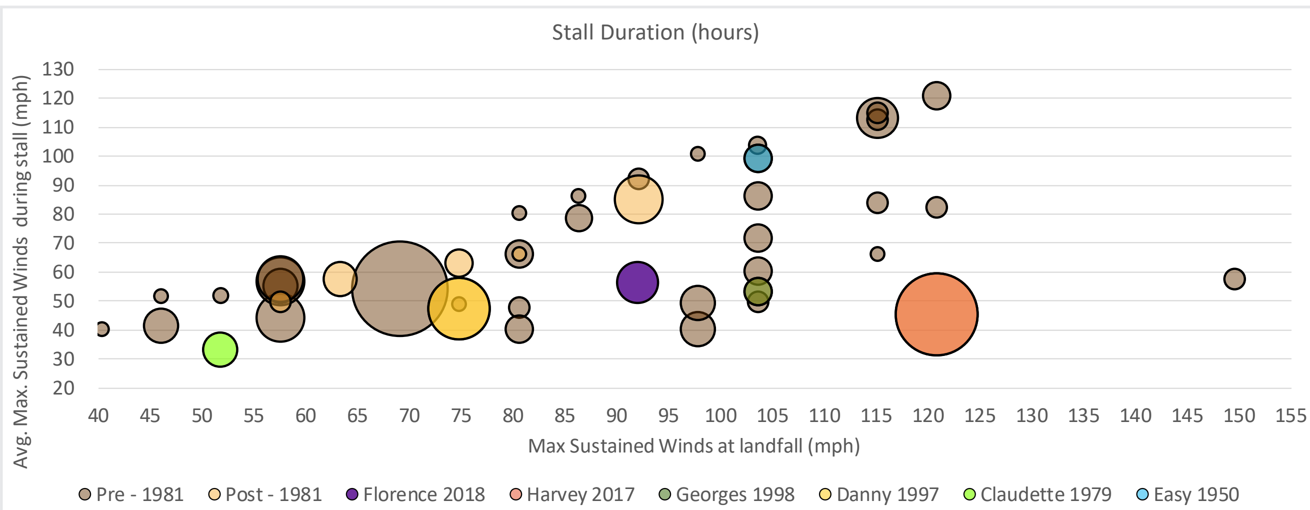


Figure 6: Bubble chart illustrating the maximum sustained winds before and during stalling and the duration of the stall by the size of the bubble.

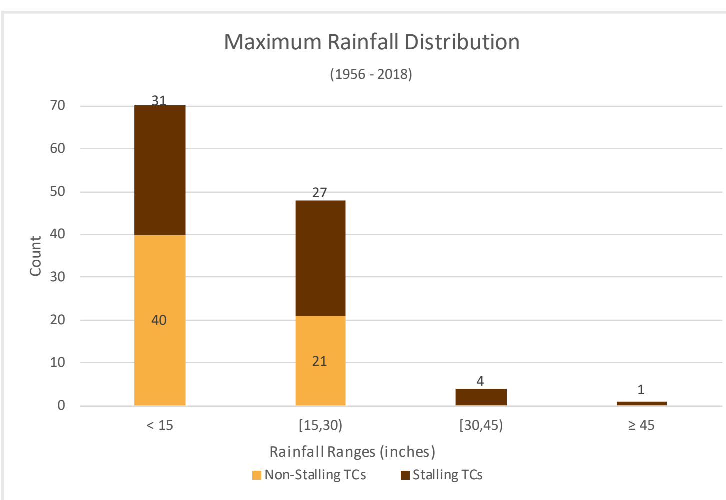


Figure 7: Maximum rainfall distribution from North Atlantic tropical cyclones since 1956, [2].

Using the maximum rainfall data from [2], which lists the highest storm total rainfall amount for North Atlantic tropical cyclones from 1956 – 2018, we find that the median of the maximum rainfall any one location experiences is 13.4 inches and all cyclones that dropped at least 30 inches of rain at a single location have stalled, see Figure 7.

Globally, the forward speed of tropical cyclones decreased 10% from 1949 to 2016, though the magnitude varies by basin, latitude and whether the cyclone is over ocean or land. This slowdown trend has been observed in all basins except for the Northern Indian Ocean. Significant slowing of 16% and 14% are observed in the western Northern Pacific and the southern Hemisphere, around Australia, respectively. Cyclones have also been sluggish over land with a decrease of 21%, 16% and 22% over the western North Pacific, the North Atlantic and the Australian land mass regions, respectively. The causes are debatable, but there is evidence that anthropogenic warming is causing a general weakening of summertime tropical circulation (rising air near the equator, flowing poleward into the subtropics where it descends and flows back toward the equator), and since cyclones are carried within their ambient environmental winds, it is plausible to expect their forward speed to slow with warming as well. Moreover, a warmer atmosphere increases water vapor capacity, leading to increased precipitation rates [12].

Texas and Florida experience the most landfalling tropical storms at 15% and 36% respectively, and so it is not surprising that they also experience more stalls. When compared to their landfall frequency, Texas has been hit by a disproportionately high number of stalling storms, 27%, whereas Florida has been hit by a disproportionately low number, also 27%.

Hurricane Harvey in 2017 was a rare event from the standpoint of landfall strength (stalling storms tend to be category 1 or weaker at landfall), rainfall accumulations (Harvey caused a 1-in-1000-year flood event), and stall duration. Hurricane Florence was more typical with respect to duration and landfall strength, but it occurred over the Carolinas, an area that has experienced only three stalling storms in the past, none of which caused excessive rainfall. It is important to continually examine the past to help understand the events of today and in the future.

From this research we conclude that stalling tropical cyclones are not new and have been accompanied by extreme rainfall in the past. Considering the growing exposure in coastal areas, the risk from stalling hurricanes may be growing even if the frequency is not. More research is required to understand the unique risks posed by these kinds of storms which are sure to reappear in the future.

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