Changes in Rainfall Factors in the Context of Hurricane Harvey

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ABSTRACT

This paper uses Hurricane Harvey as a case study to explore factors that affect extreme rainfall. Radar reflectivity analysis at three-hour resolution using raw NOAA data is used to explore the fundamental factors that are affecting extreme rainfall and how these factors, and their changing influence and severity, affect the likelihood of future extreme storms. In particular, geographic and weather timing peculiarities of Hurricane Harvey are discussed, in addition to the factors of urbanization, urban heat islands, abundant aerosols, and the Clausius-Clapeyron relationship with contextualization from literature. Lastly, arguments are made regarding the unbounded nature of extreme rainfall.

KEYWORDS: Hurricane Harvey, Extreme Storms, Rain, Radar, Urban, Hydrometeor Nucleation, Rainfall Bounds.

1 INTRODUCTION

Hurricane Harvey was the second costliest storm in U.S. history (behind Hurricane Katrina), largely due to catastrophic flooding from historic rainfall (Blake and Zelinsky, 2018; Brauer et al., 2020). Emanuel (2017) found the rainfall to be a 2000-year maximum (even using a lower value of 500 mm rather than the 840 mm that was recorded for the storm's accumulation), clearly showing the severity of the precipitation. Global changes, however, will make the likelihood of an event like Harvey from a once in 2000 years to a once in 100 years event by the end of the century, with climate change making the event 3.5 times more likely (Zhang et al., 2018; Emanuel, 2017). Hurricane Harvey started out as a "typical weak August tropical storm" that, initially, actually dissipated over the Caribbean (Blake and Zelinsky, 2018). The storm then reformed and moved northward, rapidly growing into a category 4 hurricane by the time it made landfall near Corpus Christi. After the original tropical storm had dissipated, its remnants remained convectively active. This low-pressure area on around August 23rd exhibited an increase in persistent deep convection, at which time a tropical depression was formed (Blake and Zelinsky, 2018). The storm largely consisted of little shear for wind but with warm water and mid to high layers of moisture.

Making landfall, storms lose energy (Brauer et al., 2020). Upon landfall Hurricane Harvey was weaker; given that most of the storm was often still over the gulf, this fed the entire system. Figure 1 shows the track of the storm, with a large concentration of dots all pivoting around Houston showing the stationary nature of the storm over the city. Harvey generally slowly moved northeastward, though a north and eastward stationary front developed, keeping Harvey planted over the Houston area with heavy precipitation (Brauer et al., 2020; Blake and Zelinsky, 2018). The center of the storm was to the south of Houston (Figure 1), meaning there was little storm weakening from land—it was continuously fed by the gulf. Only by going completely inland over Louisiana and ultimately as far north as Kentucky did Harvey fully dissipate.

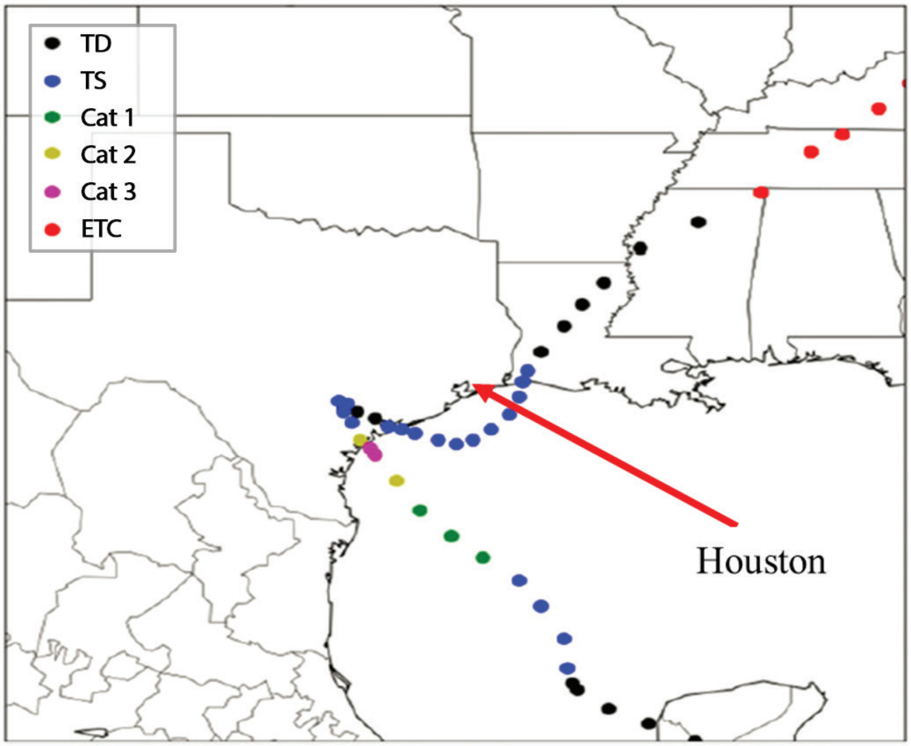

Figure 1. A map based off the HURDAT hurricane database showing the circulation center of Hurricane Harvey in 6 hour increments along with the corresponding storm category characterization. Annotated from Brauer et al., 2020.

2 ANALYSIS

2.1 Three-Hour Resolution Summary of Hurricane Harvey

Using sub-hourly radar analysis of Hurricane Harvey using NOAA data, a three-hour interval summary table (Table 1) was produced to examine the development of the storm and identify possible features of interest at critical points. Overall, this analysis suggests that the largest factors influencing the severity of Hurricane Harvey were its extended stationarity due to larger scale weather and that reflectivity and correspondingly, precipitation, increases over urbanized areas. This helps answer the primary questions addressed here: what fundamental factors are affecting extreme rainfall, how are they changing, and what does this mean for the future?

Date and Time	Description of the Storm	Important Points
August 26, 3 UTC	Landfall as category 4 hurricane near Corpus Christi. Houston is already hit with the outer rain-band.	Time of maximum winds. Surface roughness begins increasing.
August 26, 6 UTC	The eye is completely over land, the outermost band is deformed. Storm winds weaken to category 3.	Weaker winds as the storm moves inland. Based on reflectivity, the strongest rain is southeast of Houston.
August 26, 9 UTC	The storm is mostly overland and has weakened to a category 2 hurricane. Overall, the storm is moving north.	The outermost rain band is largely disrupted; convective rain is hitting north Houston with high reflectivity values around 50 dBZ.
August 26, 12 UTC	The eyewall is beginning to collapse. Slowing winds bring the storm down to a category 1 hurricane.	The outermost two rain bands have merged. Some hail is likely falling though mainly heavy rain. The storm in now moving towards gulf again.
August 26, 15 UTC	The storm has a wind speed around 35 knots, and thus is becoming a tropical storm or weaker for its remaining lifecycle.	It nearly appears as if the storm is splitting into two, with an outer storm of heavy rain and hail and the inner primary core of lighter rain, which is disconnected, meaning the storm is widening.
August 26, 18 UTC	New moister is constantly being brought in from the gulf; high reflectivity values are observed even over water.	Houston itself appears to have a brief respite with heavy rain east of the city. Differential reflectivity values here are low (~1) though very noisy.
August 26, 21 UTC	While the entire region is generally swamped with precipitation (~30 dBZ), small and isolated ultra-high reflectivity hotspots (~50 dBZ) dot the Houston metropolitan area.	Some localized area effects are likely contributing to high rainfall over Houston even as the storm appears to slowly move.
August 27, 0 UTC	The storm has been stationary with little change in the last few hours.	Individual rain bands appear to widen as they approach Houston from the southwest. The intensity appears constant (consisting of heavy rain with hail) but spreading its affected area.
August 27, 3 UTC	The storm moved only slightly northward, but the last highly reflective rain band moved enough to cover eastern Houston.	This may be the last of the major rain bands; the remaining ones closer to the former hurricane eye tend to clump but exhibit lower reflectivity values, suggesting more moderate rain in the future.

August 27, 6 UTC	Very gradual bulk movement takes place eastward towards Houston. Individual rain band reflectivity values tend to increase.	Interestingly, rather than high reflectivity values solely arriving from the southern gulf, values increase from the inland west simply by arriving at the Houston metropolitan area.
August 27, 9 UTC	Individual rain bands are no longer distinguishable. The counterclockwise bulk movement can be discerned through radial velocity, but overall, the storm is stationary.	Reflectivity values at all elevation angles are increased around Houston but lower just a couple miles outside the most developed area. Highest values are directly south. Very high differential reflectivity values around 3 dBZ are over Houston, suggesting a high concentration of smaller rain drops.
August 27, 12 UTC	Significant reflectivity values now form over the gulf (~50 dBZ +), which tend to drift and strength northward.	No particular topographic change appears to play a role, simply by being stationary significant moisture is being funneled from the gulf onto the nearest land: the Houston area.
August 27, 15 UTC	The storm’s cyclonic nature is somewhat disrupted from radial velocity measurements. Highest reflectivity values are northeast of Houston.	Given the geography of Texas, the position of the storm center south of Houston necessitates that precipitation falling closer to Beaumont originally spends more time over the gulf (thus strengthening more).
August 27, 18 UTC	The highest reflectivity values are in eastern Houston, arising from the bulk counterclockwise rotational motion of the storm despite its otherwise stationarity.	So long as the storm center does not move, it appears its behavior will be consistent otherwise.
August 27, 21 UTC	Little change has occurred over the past few hours. “More of the same” seems to be a tendency.	The stretch from Galveston and Houston exhibits the highest reflectivity values, which is also the most heavily urbanized area.
August 28, 0 UTC	Differential reflectivity values have grown extremely high to ~6 dBZ over Houston and Galveston, but standard reflectivity values remain more or less constant.	Hurricane Harvey continues to pound the Houston area; its overall severity appears caused by its stationarity though individual area features appear to create local maximum for precipitation.

Table 1. A detailed analysis of the development of Hurricane Harvey from the time of landfall over 2 days using radar analysis. Comprehensive sub-hourly analysis is summarized into 3-hour increments over 2 days. Examined radar data includes wind field measurements, reflectivity, radial velocity, differential reflectivity, and differential phase shift from level II and level III Houston and Corpus Christi NOAA radar stations on August 26 and 27, 2017. The precipitation size and type classifications found are comparable to those found in literature for these days (Wolff et al., 2020).

2.2 Radar Analysis

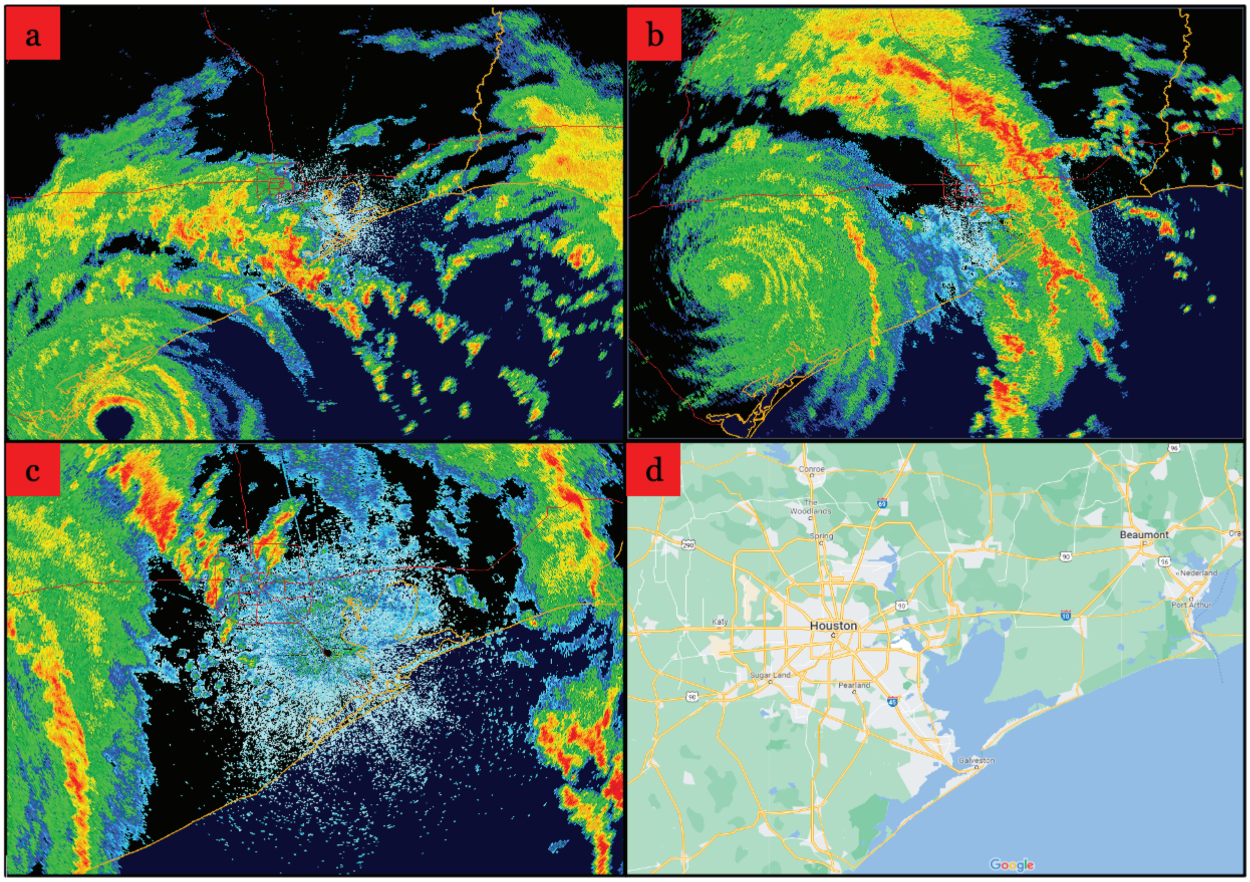

Figure 2. Several images of the Houston area during Hurricane Harvey during critical points all on August 26th, 2017. The same sort of imaging was used to compose Table 1. (a) Reflectivity measurements at 00:05:31 UTC before landfall. The hurricane eye is clearly still over water, but Houston and Corpus Christi are both already experiencing rainfall. (b) Reflectivity measurements at 15:01:26 UTC. This is the point when the winds of the storm have just calmed enough to no longer be classified as a hurricane. The temporary "splitting" nature of bands is visible. (c) Reflectivity measurements 21:01:17 zoomed in to show features near Houston. Individual pockets of high reflectivity like those shown in the northwest tend to pop up around this time as individual "hotspots" near Houston. (d) A Google Maps image showing urban (gray) vs. nonurban (green) areas around Houston. Higher reflectivity values typically match up over the urban areas more for Hurricane Harvey.

The radar analysis demonstrates that the storm's inability to keep moving northward is likely the primary driver of the extreme precipitation, as corroborated by literature. Blake and Zelinsky (2018) noted that Hurricane Harvey's initial northwest motion stopped when the storm became entrained between two light high-pressure steering currents. The bottom one was over the northern Gulf of Mexico, the top one at the mid-tropospheric level from around the four corners region of the U.S. eastward. Nonetheless, besides the stationary nature of the storm due to the larger simultaneously occurring weather patterns, several factors, which have been changing over time, played a role in the severity of precipitation brought by Hurricane Harvey.

3 EXTREME RAINFALL FACTORS

Zhang et. al. (2018) found that increased urbanization not only contributed to more severe flooding, but also directly increased precipitation. Flooding is easier to rationalize: urban areas with asphalt and concrete reduce groundwater infiltration by the rain, increasing the speed and severity of runoff, which increases flooding. However, the direct contribution of urbanization to precipitation is less clear. Through statistically significant modeling analysis, Zhang and colleagues found that the higher surface roughness of urban areas (buildings, as compared to a hypothetical crop field in the same place) increases drag on storm winds, helping create more updraft and cyclonic flow. This brings an increase in low-level convergence and upper-level divergence, which are conditions that help stimulate precipitation (Zhang et al., 2018). These effects are consistent with the radar analysis performed and summarized in Table 1, where ultra-high rainfall reflectivity measurements tend to appear in the most urbanized areas in and around Houston (Figure 2).

Furthermore, local urban surface warming (like the heat island effect) potentially also increases precipitation, as warmer air holds more moisture. However, Zhang and colleagues note that in Houston for Hurricane Harvey, anthropogenic heat played no major role in rainfall. Given that there are physical mechanisms (see following Clausius-Clapeyron equation discussion) that would link the two together though, perhaps in other contexts, urban surface warming plays a larger role. Given the well documented increase in urban heat islands, greater warming would likely only act as positive feedback to increase local precipitation (Sharma et al., 2017). In the case of Hurricane Harvey, a possible explanation for the discrepancy is that the urban area was not a source of moisture and contributed little to transport—the rain was deposited directly over the urban area before having a chance to transport through it. A different geographic configuration, in which the urban heat islands are located in either less rough areas (i.e., very large, but low in height, urbanized areas—like massive parking lots) or areas that otherwise interfere with transport less, would likely lead to a different effect with a large contribution to precipitation. Consequently, as more people increasingly live in urban areas and urban areas grow, precipitation for those people in those areas may increase due to urban surface warming. As a side note, given that convective processes likely give a significant contribution to extreme rainfall, this means that other (nearby, non-urban) areas from which some of the moisture to the urban areas is moving may experience less rainfall simply due to conservation principles. In any case, urban surface warming's effect on rainfall should be investigated further.

Local atmospheric changes also contribute to changes in precipitation. For hydrometeors to form, nucleation seeds are necessary (Beydoun, Polen, and Sullivan, 2016). Urban areas particularly exhibit higher concentrations of aerosols (particulate matter), which are directly emitted from both biogenic and anthropogenic sources. Secondary aerosols are primarily formed through atmospheric reactions between volatile organic compounds (VOCs) and NOx (Ioffe, Isidorov, and Zenkevich, 1977). VOCs are largely produced naturally by vegetation (especially in summer in regions like the southeastern US, which influences Houston) and increasingly, in highly populated areas (also Houston), by consumer products (McDonald et al., 2018). NOx is usually produced through high temperature combustion of fossil fuels (Jacob, 1999). The atmospheric combination of both then leads to the formation of the aerosols, which can act as seeds (with production typically limited by NOx availability in today's cities) (Carter, 1994; Jacob, 1999). Cloud seeding is known to increase precipitation and has been used around the world, including New Mexico, to stimulate rainfall (Battan, 1977; Downing, 2022). Consequently, as unintentional seeding takes place in urban areas due to increased concentrations of aerosols, total precipitation will increase by increasing precipitation efficiency, provided moisture is available. Though Hurricane Harvey likely had a high concentration of sea salt aerosols as nucleation sites, the idea that air pollution played a role in increasing precipitation (including though stimulating convection) has been corroborated by others (Hu et al., 2020). As air standard restrictions around the world become stricter, the effect of “unintentional seeding” should slowly diminish (Koppmann, 2007; Zeng et al., 2019). Nevertheless, urban and industrialized areas today have significantly more free aerosols that may increase precipitation over preindustrial times (Anenberg et al., 2010; Hu et al., 2020).

Lastly, of the changing factors examined here, temperature is perhaps the most clearly connected factor to extreme rainfall. The Clausius-Clapeyron equation clearly relates temperature to moisture:

$$\frac{1}{e_s}\frac{de_s}{dT} = \frac{L_v}{R_v T^2} \tag{1}$$

Where e_s is the saturation vapor pressure of water, T is temperature (in degree kelvin), L_v is the latent heat of vaporization, and R_v is the gas constant for water vapor (Martinkova and Kysely, 2020). Examining just this equation, with more moisture, all other factors held constant, we expect more precipitation (Ye et al., 2014). This is also part of the mechanism that would suggest urban heat islands contribute to increased precipitation. Per degree Celsius increase in temperature, the atmosphere is expected to hold around 6-7% more moisture (Risser and Wehner, 2017). It should be noted however, that there is a difference between simply the moisture holding capacity of the atmosphere and actual rainfall, and the exact relationship is not fully established, but a moister atmosphere leads to more precipitation (Donat et al., 2016). According to the most recent IPCC, global temperatures have increased around 1.2 degrees Celsius since pre-industrial times and are expected to keep increasing, thus increasing atmospheric moisture as well (Ye et al., 2014).

With a heavily urbanized area and an aerosol abundant atmosphere in a warming climate, Houston can be expected to have a higher precipitation than it would being less urbanized, with fewer aerosols, in a cooler environment. However, the average precipitation may not change significantly—it is the intensity of the precipitation that will. This is best demonstrated in Figure 3, where historical data for both average precipitation (fairly constant) and the number of days with more than 3 inches of rain (an “extreme” event, increasing) from 1900 onwards is shown. Figure 4 shows direct high-resolution rain gauge measurements over the Houston area during Hurricane Harvey with areas east or north of significant topographic changes (sea/land and rural/urban) demonstrating the highest rainfalls, in line with the storm’s behavior. Nonetheless, the severity of Hurricane Harvey upon Houston leads to several other important insights.

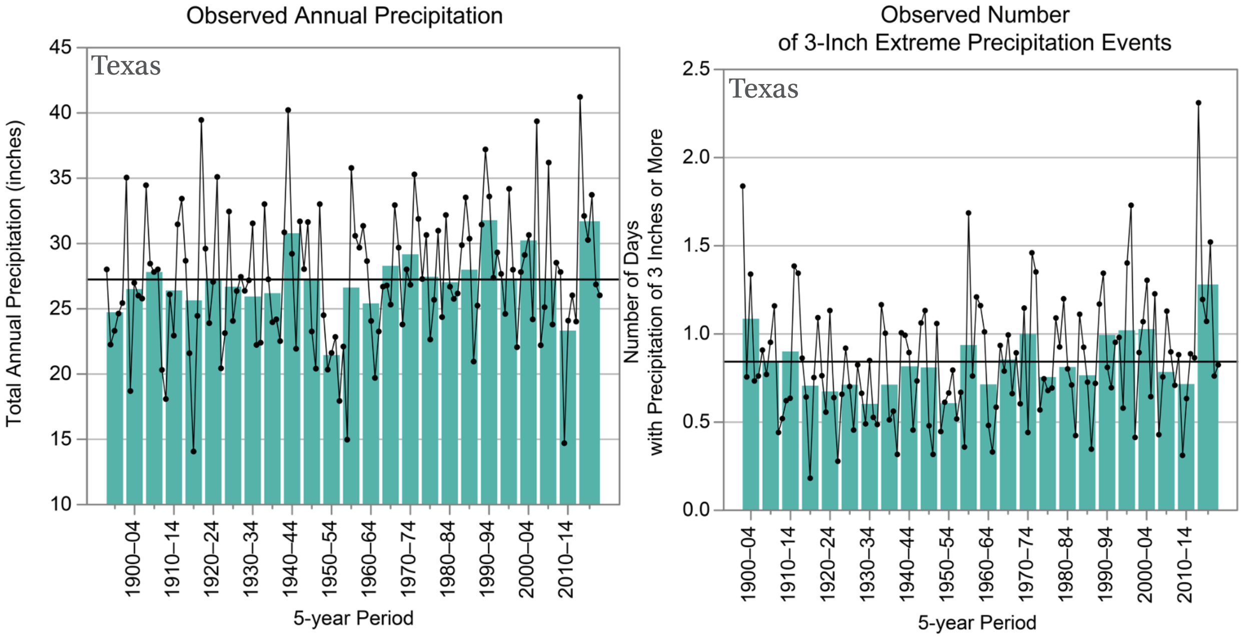

Figure 3. Left: Historical observed annual precipitation in Texas in 5-year increments. Right: Historical observed 3-inch daily rainfall extreme precipitation events in Texas in 5-year increments. During the most recent 2015-2020 period, both the average annual precipitation and the number of extreme events were above average. However, for average annual precipitation, there is no clear increase. Extreme precipitation events generally appear to be increasing, with exceptionary periods. From Runkle et al. (2022).

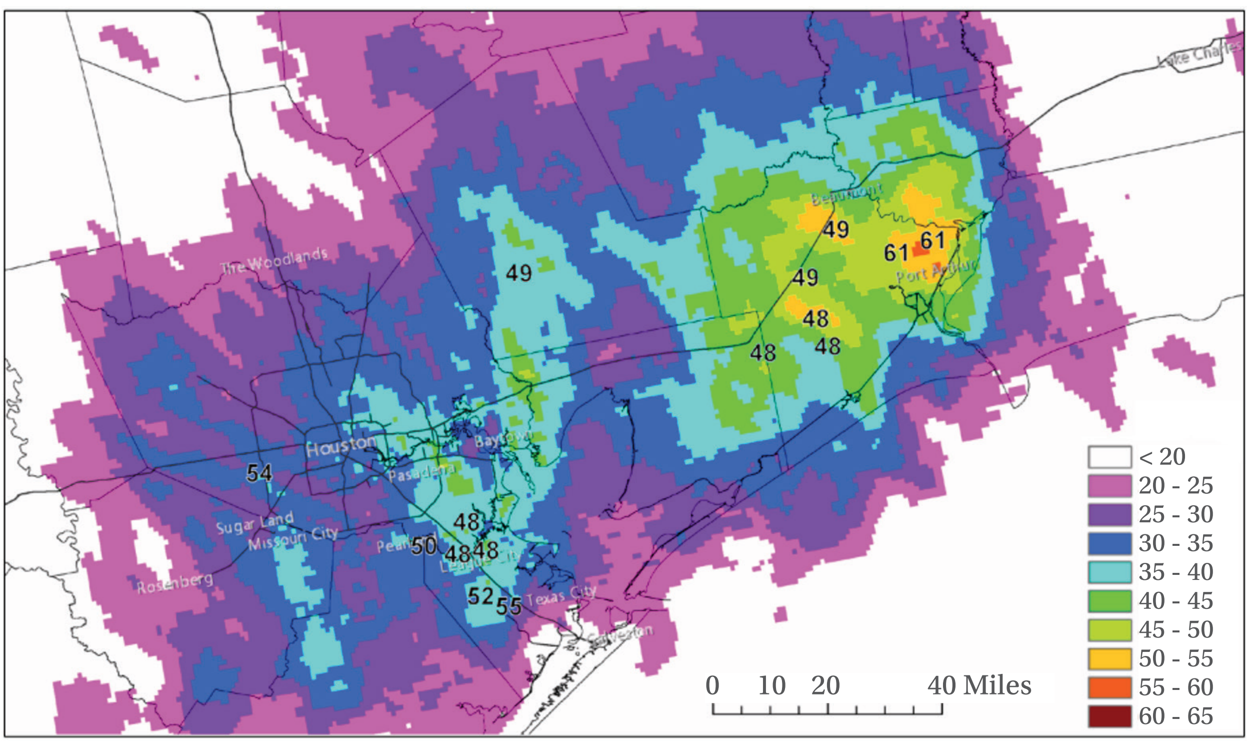

Figure 4. Rain-gauge corrected precipitation estimate for Hurricane Harvey over the Houston area. From Blake and Zelinsky (2018).

Ye and colleagues (2014) define precipitation efficiency to be “the quotient of total precipitation accumulation to the total precipitable water at the surface at the same location within a temporal period” (Brauer et al., 2020). Precipitation efficiencies are typically around 30% for a given column of air (typically due to baroclinic instabilities and deep-layer shear), but if efficiencies are greater than 100% (as was the case for Harvey over Houston from August 26th to 29th), then this provides a possible way to account for dynamic processes and powerful updrafts that lead to extreme precipitation (Brauer et al., 2020). For serious storms, rainfall would then be limited by dynamic processes and the amount of moisture than can be brought in. Brauer and colleagues (2020) found through radar analysis that on August 28th Houston had a precipitation efficiency of around 300%, with a significant concentration of large raindrops being brought in and lofted above the freezing layer of the storm. This would be enabled with an abundant supply of nucleation sites (particulate matter/aerosols), stationarity over the Gulf of Mexico (as opposed to, for example, inland Texas), and a supportive ground roughness (typical urbanization).

4 DISCUSSION

With such high efficiencies, an important follow up question is whether rainfall is bounded; if 100% precipitation efficiency can be easily exceeded then any simple limit is clearly incomplete. Boundness is a critical question for disaster management and design of critical infrastructure, where maximum possible values dictate life-and-death level engineering requirements. Traditionally, strict limits have been set using the previously introduced Clausius-Clapeyron equation—for a given temperature, there is a given amount of water. Hurricane Harvey had over 100% efficiency, meaning that convective processes bringing in moisture are being unaccounted for, in addition to the existing and accounted for precipitation processes not being fully quantified.

If in fact moisture transport is responsible for setting bounds on rainfall, then rainfall must be effectively unbounded, as this is nearly impossible to quantify (though at an extreme, we can set unhelpful bounds such as by considering all the water on the planet, but the objective here is to investigate possible methodological bounds). While the water may need to move at a higher speed and pressure, fundamentally, so long as there exists movable moisture, rainfall can effectively increase without limit. Much like a wave might bring a little water onto the shore, a big wave—going as far as a tsunami—by moving faster and with greater energy, will bring more water. So long as moisture and energy are available to feed a storm and ample nucleation sites exist, precipitation will increase. Statistical analysis supports this notion as well. By analyzing the generalized extreme value distribution for storms in the Houston area from 1950 to 2016, Risser and Wehner (2017) found that the shape parameter is positive, which supports the notion of an unbounded tail—in other words, an unbounded maximum rainfall. It should be noted that the necessitated small sample size with geographic consideration, and limitations in long-term data records of extreme events, do make such purely statistical analyses fundamentally weak without supporting mechanistic explanations.

Literature tends to be in consensus that the severity of storms like Hurricane Harvey is increasing with time (Emanuel, 2017; Brauer et al., 2020; Risser and Wehner, 2017; Zhu, Quiring, and Emanuel, 2013; Zhang et al., 2018). Overall, Hurricane Harvey does not appear to have fundamental physical differences from typical storms despite its precipitation severity. Rather, larger scale weather behavior, together with an increase in rainfall inducing factors, all materialized together in space and time to create the devastation of Hurricane Harvey. Sea surface temperature anomalies in the Gulf of Mexico at the time were actually negative, which likely weakened the storm from its "full potential" (Brauer et al., 2020). Given that rainfall is likely unbounded, as the factors of urbanization, particulate matter/nucleation site abundance, and warming temperatures that all stimulate higher rainfall increase, higher rainfall will increase without bound too. Over time, we should expect more extreme storms with more intense rain. Examining other recent extreme events besides Harvey such as Hurricanes Florence, Ida, and Sandy, among others, and the changing rainfall-inducing factors that played a role in them will help further provide a more general understanding of the changes in extreme rainfall currently taking place to better prepare for the future.

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