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Permalink

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Journal

Climatic Change, 166(1-2)

ISSN

0165-0009

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Publication Date

2021-05-01


DOI

10.1007/s10584-021-03114-z

Peer reviewed



Attributable human-induced changes in the magnitude of flooding in the Houston, Texas region during Hurricane Harvey

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Received: 2 October 2020 / Accepted: 26 April 2021 / Published online: 19 May 2021

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Abstract

The human influence on precipitation during tropical cyclones due to the global warming is now well documented in the literature. Several studies have found increases in Hurricane Harvey's total precipitation over the Greater Houston area ranging from the Clausius-Clapeyron limit of 7% to as much as 38% locally. Here we use a hydraulic model to translate these attribution statements about precipitation to statements about the resultant flooding and associated damages. We find that while the attributable increase in the total volume of flood waters is the same as the attributable increase in precipitation, the attributable increase in the total area of the flood is less. However, we also find that in the most heavily flooded parts of Houston, the local attributable increases in flood area and volume are substantially larger than the increase in total precipitation. The results of this storyline attribution analysis of the Houston flood area are used to make an intuitive best estimate of the cost of Hurricane Harvey attributable to anthropogenic global warming as thirteen billion US dollars.

Keywords Hurricane Harvey · Flooding · Global warming · Economic cost of climate change

1 Introduction

At an estimated cost of 85–125 billion USD (<https://coast.noaa.gov/states/fast-facts/hurricane-costs.html>), Hurricane Harvey is the 2nd most expensive US tropical cyclone after adjustment for inflation. Damages were principally due to freshwater inland flooding resulting from the copious amounts of precipitation endured during the storm's extended stall over the greater Houston, Texas region from 26 to 31 August 2017. According to a report by the Harris County

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Flood Control District, over 154,000 structures and 600,000 cars were flooded with 37,000 people relocated to shelters (Abbot et al. 2018). Furthermore, although well forecasted, most of the 70+ direct deaths were due to drowning in deep floodwaters (Halverson 2018; Jonkman et al. 2018). Soon after the event, a number of rapid attribution studies were published finding that the effects of anthropogenic global warming on the storm's precipitation totals were significant (Emanuel 2017; Risser and Wehner 2017; van Oldenborgh et al. 2017; Wang et al. 2018). The latter three of these studies concluded that estimated lower bound on the anthropogenic increase in precipitation over the entire area was at least in accordance with Clausius-Clapeyron (C-C)-scaled increases (6–7%/C) of saturation specific humidity from the ~1C of attributable warming in the Gulf of Mexico (Stone et al. 2019). However, best estimates of the effect of this warming on Harvey's precipitation in these studies were considerably larger (up to 24%). Trenberth et al. (2018) also concluded that record high ocean heat content, partly attributable to human consumption of fossil fuels, led to increased evaporation and hence precipitation. Kossin (2018) recently found that the translational speeds of North Pacific and North Atlantic tropical cyclones have significantly slowed since 1949. However, whether this slowdown is attributable to global warming is presently unknown, and Harvey's stall was indeed a rare and very different phenomena. Finally, Patricola and Wehner (2018) recently found that while the expected anthropogenically induced increases in tropical cyclone maximum winds speeds may not have yet emerged, a human influence on precipitation has likely emerged in the most intense tropical cyclones. They also found locally super Clausius-Clapeyron scaling in the heaviest precipitation regions of some storms due to storm structural changes. This provides a plausible physical explanation for the magnitude of these best estimate Harvey attribution statements as the greater Houston area had the misfortune of being in that part of the storm.

However, changes in flood properties may not be linearly proportional to changes in extreme precipitation due to the complexities of the local hydrological properties. This study uses the previously published estimates of Harvey's attributable precipitation increase due to global warming as a forcing factor to a series of hydraulic model simulations to more directly investigate the anthropogenic influence on the Harvey flood. The hydraulic simulations in this study are undertaken using the Fathom-US large-scale hydraulic modeling framework. The 30-m resolution US variant of the hydraulic modeling framework employed here is described by Wing et al. (2017), with the US variant itself being a development of the original global hydraulic model framework of Sampson et al. (2015). The model is able to represent both fluvial (riverine), pluvial (rainfall), and surge (coastal) flood hazards by generating (or being provided with) appropriate boundary conditions before solving simplified forms of the Saint-Venant shallow water equations over a regular 2D grid to simulate the flow of water across the land surface (Bates et al. 2010). The model explicitly represents both floodplain and in-channel flows using a subgrid method based on the principles outlined by Neal et al. (2012)).

The US-variant of the model has been extensively validated against the entire FEMA flood hazard catalog for the conterminous USA, demonstrating its ability to approach the accuracy of traditional local scale flood models (Wing et al. 2017). The specifics of the model setup deployed here for the Hurricane Harvey scenario simulations, and a detailed assessment of model performance relative to observations, are fully presented in Wing et al. (2019)). In summary, Wing et al. (2019) show the baseline simulation to describe the observed flooding of the greater Houston area well, with 78% of the observed wet pixels correctly identified as flooded, and only 17% of observed dry pixels are incorrectly identified as flooded. Overall, the ratio of type I to type II errors is 1.42, indicating that the hydraulic model tends to slight

overprediction of flooding. Furthermore, the simulated high-water marks are on average about 1 m lower than observed (itself with an estimated confidence interval of ± 0.5 m). For context, these errors compare favorably to the NOAA NWM-HAND model (Arctur 2018), which correctly identified only 46% of wet pixels while identifying 16% of observed dry pixels as wet to yield a large negative error bias of 0.31 under the same conditions (Wing et al. 2019). The extensively validated nature of the underlying model physics, coupled with the previously published validation of this particular model configuration against observations in the aftermath of Hurricane Harvey, demonstrates this model to be an appropriate tool with which to explore the sensitivity of the Greater Houston area flooding to perturbations in precipitation.

The design of our numerical experiments is straightforward. As a baseline flood, the hydraulic model is forced by observed 5-day accumulated precipitation estimates (26–30 August inclusive) obtained from the NOAA National Weather Service Advanced Hydrologic Prediction Service (<https://water.weather.gov/precip/about.php>). The effect of climate change on the Harvey flood is then explored by uniformly reducing the observed precipitation by a factor inversely proportional to the published attribution statements on precipitation magnitude. For instance, Risser and Wehner (2017) wrote that their best estimate was that climate change increased the total accumulated precipitation across the region by 24%. The simulated non-anthropogenic flood associated with this attribution statement is obtained by reducing the observed precipitation used to drive the hydraulic model by a factor of $1/1.24 = 0.81$. We explore the sensitivity of Harvey flood statistics to a range of precipitation totals spanning $2/3$ to twice the observed amount. A set of attribution statements about the simulated Harvey flood properties on 31 August 2017 can be then be made from those simulations corresponding to the published Harvey precipitation attribution statements.

Baseline river flows were set to 50% of bankfull discharge, and initial soil conditions were dry at the start of each simulation. Given the overwhelmingly extreme nature of Hurricane Harvey precipitation, model sensitivity to antecedent conditions such as soil saturation is minimal as soil infiltration capacity is almost immediately exceeded due to the very high rainfall intensities and total rainfall volumes. The antecedent conditions are kept the same for every simulated scenario. Of course, under climate change, it may be the case that the probability of wetter or drier antecedent conditions will change; however, there are so many degrees of freedom to antecedent conditions that they are currently beyond the scope of experiment within this study.

This type of extreme event attribution study is often termed a “storyline” approach (Shepherd 2016) as only a portion of the relevant factors is investigated. In addition to precipitation increases from climate change, other anthropogenic influences such as urbanization (Zhang et al. 2018; Sebastian et al. 2019) and land subsidence (Miller and Shirzaei 2019) are important factors in assessing overall flood risk. As a result, the attribution statements in this study are high conditional on only the climate change aspects of the total change in flood risk (Wehner et al. 2019). There are a few other studies completing the chain of attribution from extreme precipitation to flooding to financial losses. Kay et al. (2018) examined the change in flood risk in Great Britain during the winter of 2013/2014 by driving a nationwide hydrological model by very large ensembles of a regional climate model under realistic conditions and a variety of counterfactual conditions with the effects of anthropogenic climate change removed. Earlier, Schaller et al. (2016) used the same set of regional model simulations to drive a hydrological model of the Thames river catchment rather than the entirety of Great Britain. These analyses, as is the Frame et al. (2020) analysis of Hurricane Harvey attributable economic costs, used the change in probability and the associated

fractional attributable risk of the flood properties of these events to estimate the damages resulting from the human interference in the climate system. The present study differs in that it uses a hydraulic model and perturbations to observed precipitation to estimate the detailed geographical changes in flood area and associated economic costs. All of these studies find that the attributable changes in flood damages depend greatly on the assumptions made about how much anthropogenic climate change has affected the precipitation responsible for the flood.

2 Large-scale results

Figure 1 shows the simulated floodwater volume and area as a function of rainfall with each axis normalized by the amounts in the experiment driven by observed precipitation. The left panel of Fig. 1 reveals that the total volume of floodwater (blue line) across the flooded region corresponds to the precipitation amount throughout the range of values explored with a nearly 1:1 relationship. This close correspondence is a result of two circumstances. First, precipitation rates in these simulations are very large causing the soil to be completely saturated very early in the storm. Second, due to the flat Houston topography, the floodplain drains to the sea relatively slowly compared to these large precipitation rates.

Flood area is more complex because it describes the distribution of the floodwater volume around the domain. The right panel of Fig. 1 shows that the total area flooded (blue line) to a depth greater than 20 cm as function of normalized precipitation is sub-linear due to the non-uniform topography of the Greater Houston area and the mix of fluvial and pluvial flooding. Note that we choose to exclude flood depths less than 20 cm as this is the typical threshold at which damages start to occur for residences (UK Environment Agency 2019).

Table 1 summarizes large-scale attribution statements about flooding corresponding to the previously published attribution statements about Hurricane Harvey precipitation. Corresponding to Fig. 1, the attributable increase in floodwater volume is nearly equal to the attributable increase in storm total precipitation, while the attributable increase in flood area at depths greater than 20 cm is somewhat less.

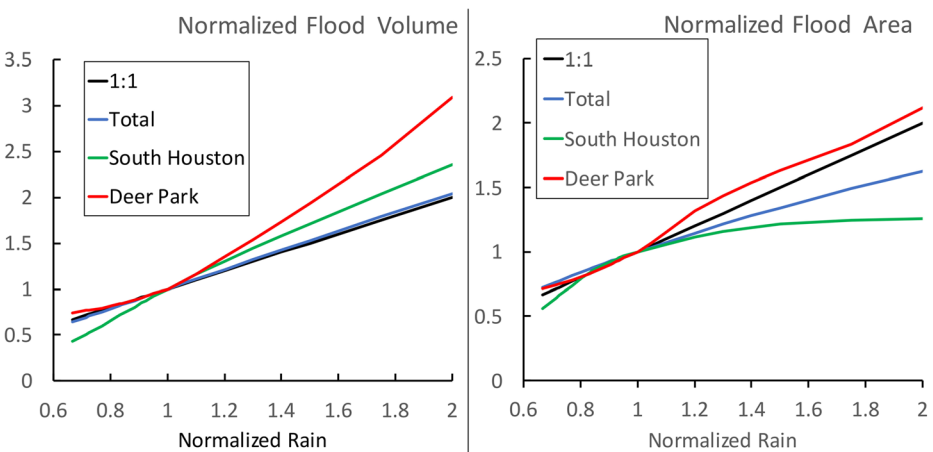


Fig. 1 Hurricane Harvey floodwater normalized volume (left) and normalized area (right) as a function of normalized precipitation over the entire greater Houston area (blue), the South Houston neighborhood (green), and the Deer Park neighborhood (red). A 1:1 line is shown in black for reference

Table 1 Attributable large-scale flood area and volume increases associated with published precipitation magnitude attribution statements (units: volume = 10⁶ m³; area = km²). RW Risser and Wehner 2017, VO van Oldenborgh et al. 2017, W Wang et al. 2018

Source	Attributable precipitation increase	Rainfall coefficient	Attributable flood					
			Greater Houston		South Houston & Pasadena		Deer Park	
			Vol.	Area	Vol.	Area	Vol.	Area
RW Best estimate (small region); W upper bound	38%	0.72	39%	29%	87%	52%	25%	31%
RW Best estimate large region) W best estimate	24%	0.81	25%	18%	48%	25%	18%	21%
RW likely lower bound (small region); VO upper bound	19%	0.84	19%	14%	36%	18%	15%	18%
W lower bound	13%	0.88	13%	10%	23%	11%	11%	12%
VO lower bound	8%	0.93	8%	6%	14%	6%	7%	7%
RW likely lower bound; large region	7%	0.93	7%	5%	12%	5%	6%	6%
actual	0%	1.00	0%	0%	0%	0%	0%	0%

3 Flooding at local scales

While the large-scale flood characteristics are of academic interest and perhaps useful for assessing aggregated damages, the increase in risk at very fine local scales is of a more practical use in assessing the causes of damages to individual homes or neighborhoods. Despite the relative flatness of the Houston region, complexities of the drainage topography are significant enough that the effect of climate change on the flood varies considerably at such fine scales. Some neighborhoods would be flooded even in the absence of climate change, while others remain dry even if the precipitation was to be significantly increased from the actual amounts, as should be expected if a similar storm were to occur in a future warmer climate. To illustrate this, we consider three cases, the actual flood, the lowest attributable precipitation change as dictated by Clausius-Clapeyron scaling (7%), and the highest attributable precipitation change of 38% (Risser and Wehner 2017; Wang et al. 2018) for two different neighborhoods.

3.1 South Houston and Pasadena

The South Houston and Pasadena neighborhoods were among the most severely impacted with 8920 structures flooded (Lindner and Fitzgerald 2018). Figure 2 shows hydraulic model simulations in these neighborhoods of the actual flood (Fig. 2a) and counterfactual floods under the best-case scenario of the 7% Clausius-Clapeyron (C-C) scaling of precipitation with temperature (Fig. 2b) and a worst-case climate change scenario where precipitation was increased by 38% by climate change (Fig. 2c). This most extreme case best illustrates the sensitivity of the flood properties but is not necessarily the best estimate of the human effect on the flood. The amounts of flooding attributable to human influences are the difference of the perturbed rainfall simulations from the observed rainfall simulation and is shown in Fig. 2d for the C-C scaling case and in Fig. 2e for the worst-case scenario considered. In both cases, the depth of additional flooding is fairly uniform in the interior of the inundated region.

This neighborhood contains substantial drainage where floodwater tends to accumulate. Hence, the volume of flood water increases at a greater rate than rainfall in our set of simulations, and the slope of the green line in the left panel of Fig. 1 is greater than unity. Also as a result of this relatively complicated topography compared to the entire domain, the dependence of South Houston flood area on rainfall amount is more nonlinear than Greater Houston. The columns labeled “South Houston” in Table 1 reveal that attribution statements about the flooding in these low-lying neighborhoods (the entire area shown in Fig. 2) are substantially larger than for the entire region. Consistent with Fig. 1, the degree of human influence on the flood in this neighborhood increases at a superlinear rate with the human influence on Harvey’s total precipitation. Comparison of Fig. 2b to Fig. 2a reveals that the anthropogenic increase in the areal extent of the flood due only to Clausius-Clapeyron scaling is rather minor and confined to the perimeter of the flooded area although some of the deeper parts of the flood are made noticeably deeper. However, in the worst-case scenario, large swaths of flooded regions, particularly between the two branches of the Sims Bayou in the center of Fig. 2c, would not be flooded without climate change.

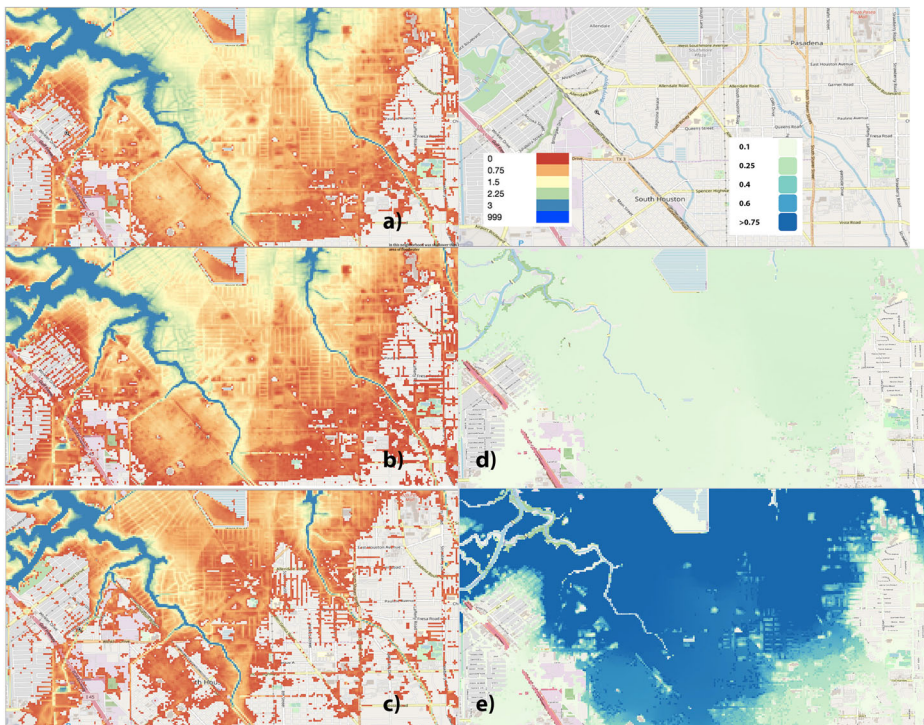


Fig. 2 Simulation of the actual and counterfactual flood in the South Houston and Pasadena neighborhoods. **a** The actual flood that was. **b** The counterfactual flood that might have been in the absence of climate change if human activities increased Harvey storm total precipitation by 7%. **c** Same as **b** except precipitation increased by 38%. **d** Attributable flooding if human activities increased Harvey storm total precipitation by 7%. **e** Same as **d** except precipitation increased by 38%. Rainbow scale is for panels **a**, **b**, and **c**. Blue scale is for panels **d** and **e**. Units: meters. 999 denotes areas of permanent water

3.2 Deer Park

Although the Deer Park neighborhood is just to the east of South Houston and Pasadena, flood damage was considerably less with 820 flooded houses. Figure 3 shows the hydraulic model simulations in this neighborhood under the same precipitation change scenarios as in Fig. 2. The flatter terrain in this neighborhood resulted in shallower floodwater than in South Houston and Pasadena (Fig. 3a–c). The attributable additional floodwater is also less in this neighborhood (Fig. 3d,e). The columns labeled “Deer Park” in Table 1 reveal that attribution statements for this less impacted neighborhood are similar in magnitude to those for the entire region. Figure 1 also shows that for rainfall amounts less than observed, the flood volume and area scale at similar rates in Deer Park (red line) as they do for the Greater Houston area (blue line). However, for rainfall amounts greater than observed, the neighborhood is more severely flooded, and the scaling of flood volume and area with rainfall amounts exceeds that of the larger region. Again, at the lower bound of C-C scaling for the anthropogenic precipitation increase, the change in flooding is minor. Even for the uppermost bound of precipitation increase, the change in flooding is largest towards the northern part of the neighborhood where the flooding is deepest. Outside of that part of the region, the effect of climate change on flooding in this neighborhood was minimal.

4 Economic costs

In addition to the loss of life, Hurricane Harvey was among the most financially expensive weather disasters in US history. Estimates range from US\$85Bn according to the reinsurance estimates (<https://www.munichre.com/topics-online/en/climate-change-and-natural-disasters/natural-disasters/storms/hurricane-harvey-2017.html>) to US\$95Bn from the Centre for Research on the Epidemiology of Disasters database of disaster damages (EMDAT www.emdat.be) to as high as US\$125Bn according to NOAA (<https://www.ncdc.noaa.gov/billions/events.pdf>). A recent paper (Frame et al. 2020) attributed the climate change portion to be 3/4 of the actual total cost. As a conservative cost estimate, they used the average of the reinsurance and EMDAT values, US\$90Bn, which we also use for sake of comparison. The Frame et al. (2020) cost estimate was based on a probabilistic attribution framework and posited that the fractional attributable risk (FAR) is equivalent to the fraction of the total cost of the storm due to climate change. The FAR is defined from the ratio of probabilities of an event both with and without climate change by the following formula

$$FAR = 1 - P_0/P_1 = 1 - 1/PR$$

$$PR = P_1/P_0$$

where P_1 is the estimated probability of the simulated actual event and P_0 is estimated probability of the simulated event without climate change and ranges from 0 (no human influence) to 1 (entirely caused by humans). Alternatively, the so-called risk or probability ratio (PR), ranging from 1 to infinity, provides a more direct measure of the change in risk due to climate change.

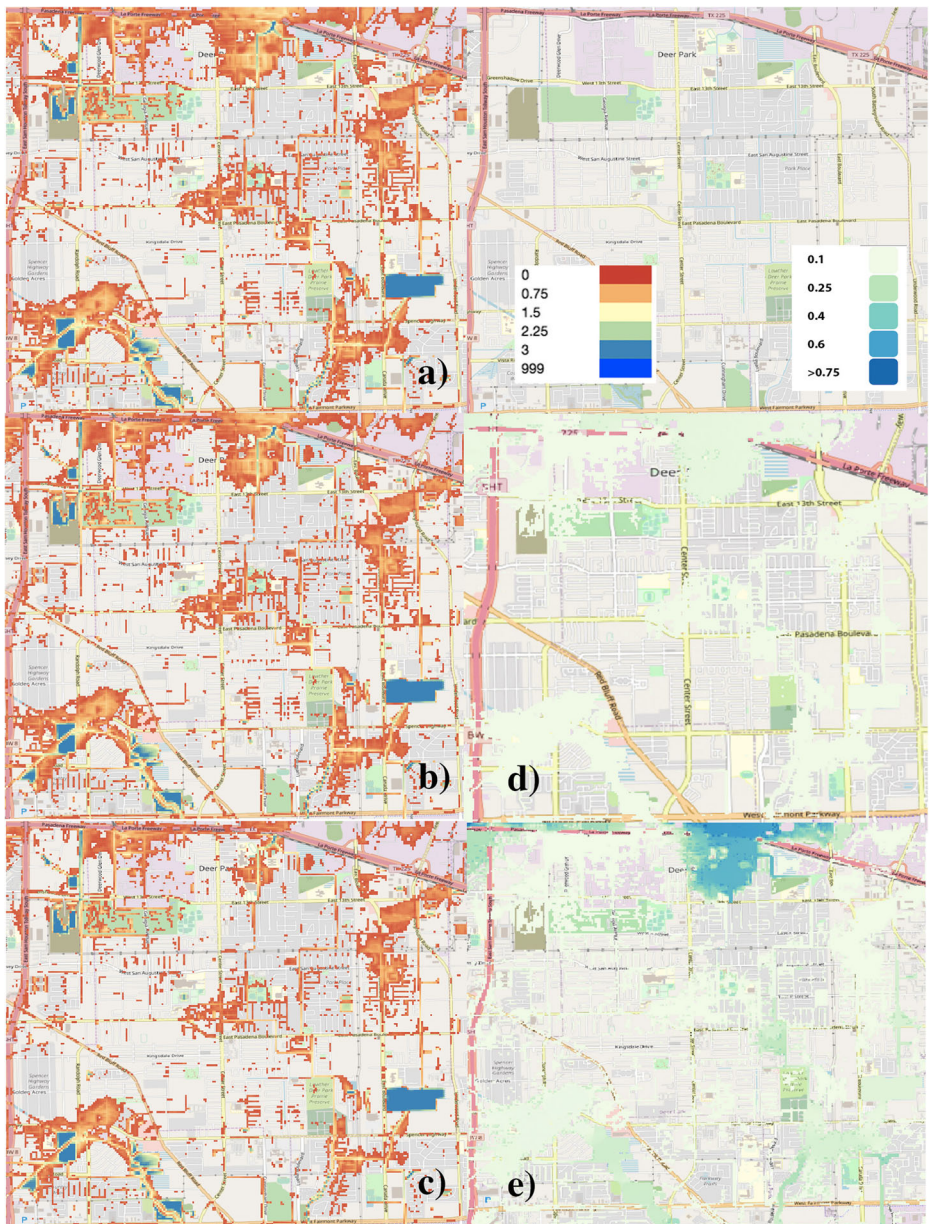


Fig. 3 Simulation of the actual and counterfactual flood in the Deer Park neighborhood. **a** The actual flood that was. **b** The counterfactual flood that might have been in the absence of climate change if human activities increased Harvey storm total precipitation by 7%. **c** Same as **b** except precipitation increased by 38%. **d** Attributable flooding if human activities increased Harvey storm total precipitation by 7%. **e** Same as **d** except precipitation increased by 38%. Rainbow scale is for panels a, b, and c. Blue scale is for panels d and e. Units: meters. 999 denotes areas of permanent water

This usage of FAR to estimate the fractional attributable cost was based on a similar analysis quantifying the number of fatalities during the 2003 European heat wave due to

climate change (Mitchell et al. 2016). Frame et al. (2020) constructed a FAR best estimate of 0.75 by averaging the best estimates of the so-called risk or probability ratio (RR) from the two papers that provided them (Risser and Wehner 2017; van Oldenborgh et al. 2017).

The mechanistic flooding attribution statements of this study presents an alternative and more intuitive approach to quantifying costs, either economic or mortality, due to climate change subject to the conditions of the storylines. The damages suffered during Hurricane Harvey were largely direct consequences of flooding of structures and motor vehicles (Abbot et al. 2018). With the simplifying assumption that structures and motor vehicles were uniformly distributed in value throughout the flooded area, then the additional number of them damaged by climate change is the same as the attributable increase in flood area from climate change. We also assume that damages are not highly dependent on the depth or duration of the flood. These assumptions could be removed by careful application of real estate value upon flood maps enabled by our line of analysis.

Table 2 summarizes the differences between the Frame et al. (2020) probabilistic cost estimates and the mechanistic storyline cost estimates for each case considered by the three available Harvey precipitation attribution studies. We note that the economic costs using our attributable flood area estimates are much less than that obtained by using FAR estimates. Best estimates from the FAR approach are US\$67Bn, while from the flood area approach are US\$14bn. The equivalence between mechanistic and probabilistic framing of the human influence on individual extreme events is quite clear (Otto et al. 2012; Easterling et al. 2016). However, the discrepancy in cost estimates between using FAR or the attributable area magnitude change would suggest otherwise.

So which is the correct interpretation of the costs of climate change? We note that the attributable magnitude change, whether it be in area flooded in a low compared to high precipitation storm or the number deaths in a cooler compared to a warmer heat wave as in Mitchell et al. (2016), is an intuitive and direct interpretation of cost increases. It also could permit incorporating information about the non-uniform distribution of real estate values, flood

Table 2 Cost estimates of Hurricane Harvey attributable to climate change presuming an actual total cost of US\$90Bn using mechanistic and probabilistic attribution statements from previous publications. RW Risser and Wehner 2017, VO van Oldenborgh et al. 2017, W Wang et al. 2018

Source	Greater Houston attributable flood area increase	Mechanistic attributable cost	PR/ probability ratio (P_1/P_0)	Fractional attributable risk: FAR	Probabilistic attributable cost
Best estimate as defined by Frame et al.	14%	US\$13Bn	4	0.75	US\$67Bn
RW Best estimate (small region); W upper bound	29%	US\$26Bn	8	0.88	US\$79Bn
RW Best estimate large region)	18%	US\$16Bn	5	0.80	US\$72Bn
W best estimate	15%	US\$14Bn	—	—	—
RW likely lower bound (small region	14%	US\$13Bn	3.5	0.71	US\$64Bn
VO upper bound	14%	US\$13Bn	5	0.80	US\$72Bn
W lower bound	10%	US\$9Bn	—	—	—
VO lower bound	6%	US\$5Bn	1.5	0.33	US\$30Bn
RW likely lower bound; large region	5%	US\$5Bn	1.7	0.41	US\$37Bn

depth, and flood duration. On the other hand, FAR is just that, the fractional attributable risk of an event of a given magnitude, which in the Hurricane Harvey case is a loss of US\$90Bn. A FAR value of 0.75 is equivalent to a PR of 4, leading to the statement: “The probability of a US\$90Bn hurricane loss in Texas was quadrupled due to climate change.”

Frame et al. (2020) obtained their best estimate that the chances of Harvey precipitation was quadrupled by averaging the probability ratios (Table 2) of the Risser and Wehner (2017) large region best estimate with the average of the two van Oldenborgh et al. (2017) bounds. Performing the same calculation on the corresponding attributable precipitation estimates from Table 2 yields a best estimate of a 19% attributable precipitation increase. This precipitation increase results in a 14% increase in attributable flood area from our hydraulic simulations. Using this method of obtaining a best estimate from multiple publications leads to the following statement: “Our best estimate is that climate change increased the cost of Hurricane Harvey by about 14% or US\$13Bn”. Wang et al. (2018) did not publish a probability ratio; thus Frame et al. (2020) could not use their results in their cost estimate. However, their best estimate of the attributable precipitation change is coincidentally 19% so the magnitude of our cost estimate is not affected by its inclusion.

We stress that our cost estimate attribution statement of US\$13Bn is entirely consistent with the attribution statement about quadrupling of the risk of a US\$90Bn hurricane loss as explained by Otto et al. (2012). And as noted in Frame et al. (2020), even this lower cost estimate is high enough to be inconsistent with macroeconomic estimates of the cost of climate change. But our mechanistic cost estimate is much lower than the probabilistic cost estimate of Frame et al. (2020) with very different policy implications. It is unlikely that accounting for heterogeneities in real estate values, flood depth and flood duration will increase this mechanistic cost estimate enough to accommodate this difference demonstrating the importance of attribution methodologies. We hope that our arguments here lead to a best practices discussion in the wider detection and attribution community as to how to better communicate the costs of climate change.

5 Conclusions

The extent of Hurricane Harvey’s freshwater flood that is attributable to anthropogenic global warming can be quantified and to first order depends on how much of the storm total precipitation over land is similarly attributable. Three previous independent studies provide a range of this human influence on precipitation ranging from the thermodynamically constrained Clausius-Clapeyron results of about a 7% increase to substantially higher increases of 3 to 4 times this amount. A one-degree attributable warming of the Gulf of Mexico surface waters suggests that available moisture for Harvey would be increased by global warming by only about 7% as the Gulf is the source of the storm’s moisture. However, a recent dynamical modeling analysis of 15 different tropical cyclones revealed that while precipitation over the entire duration and spatial extent of such storms may be similarly constrained, locally the anthropogenic precipitation increase can be much larger (Patricola and Wehner 2018). Hence the larger than C-C scaling estimates in the three Harvey precipitation attribution studies are credible.

Human-induced percent changes in intense tropical cyclone precipitation have been shown to be significantly non-uniform (Risser and Wehner 2017; Patricola and Wehner 2018), and this may be important in quantifying changes in flooding. However, in this study, we simply perturbed

precipitation uniformly in the hydraulic model being constrained by the information available from the three precipitation studies. This simplification is a reasonable first effort as flooding is an integrative effect influenced both by local and non-local precipitation over a wide area.

Figures 2c and 3c show the flood extent presuming a 38% attributable increase in total precipitation during Hurricane Harvey and should be interpreted as an upper bound. Figures 2b and 3b show the flood extent presuming the lower bound of Clausius-Clapeyron-scaled precipitation increases (7%). Best estimates in the range of 19–24% on the attributable increase in precipitation are more defensible as are the associated flood increases of Table 1 and the flood data provided in the [Supplement](#).

Over the entire flooded region, we find that the total volume of water in Harvey's flood is close to a 1:1 relationship with the total amount of precipitation during the storm. As the region is very flat, drainage to the Gulf of Mexico is slow compared to the rate at which precipitation fell. However, the topography is complex enough that the total flood area scales at less than one to one with total precipitation amount.

Attributable increases in local flooding are considerably complicated by local topography. We find that in the more severely flooded parts of the region, the human influence on both flood volume and area is larger than over the entire region and can scale superlinearly with precipitation amount. In shallower parts of the flood, the human influence is less pronounced. This should not be surprising as in general; the areas most prone to flooding are likely to be areas into or through which water from a wider surrounding catchment area is funneled. This "concentrating" effect means that any change in rainfall over the wider area will inevitably be amplified in terms of absolute water volume in such areas.

The quantitative estimates of the attributable anthropogenic contribution to flooding and damages provided by this study should be considered unique to Hurricane Harvey. Indeed, the human influence on precipitation during other tropical storms varies (Patricola and Wehner 2018; Reed et al. 2020, 2021). Furthermore, the mix of freshwater flooding (from precipitation) and saltwater flooding (from storm surge) depends on many factors, including coastal bathymetry, windspeed direction, and distance from the coast as exemplified by the damages of Hurricanes Sandy and Florence. Nonetheless, much of the US Gulf Coast is similar to the Greater Houston area both in flatness of the local topography and exposure to the risk of intense tropical cyclones. The methods presented here, including the hydraulic flood model, are widely applicable to inform estimates of the human influence on flood properties and associated damages of recent storms as well as the risk posed by the effect of global warming on storms yet to come.

Assessing the human influence on Harvey's flood for every neighborhood in the greater Houston area is outside of the scope of this paper. However, in order to aid such detailed analysis, output data for each of the attribution results in Table 1 are described in the [online supplement](#) and publically available at <https://portal.nersc.gov/cascade/Harvey/> along with instructions to visualize it with freely available software. Even casual browsing of these datasets reveals that many neighborhoods and homes would have been flooded in the absence of climate change even if the human influence on precipitation is very large. Likewise, some neighborhoods, especially those hardest hit, suffered significantly increased damages due human interference in the climate system.

Flood maps produced by these datasets, combined with local knowledge of the structure type, density, and value, can provide intuitive estimates of the human and financial costs due to climate change during Hurricane Harvey subject to the conditions, caveats, and assumptions of the original precipitation attribution statements.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s10584-021-03114-z>.

Acknowledgements This research was partially supported by the Director, Office of Science, Office of Biological, and Environmental Research of the US Department of Energy under Contract No. DE340AC02-05CH11231 under the ICoM SFA project. This document was prepared as an account of work sponsored by the US Government. While this document is believed to contain correct information, neither the US Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the US Government or any agency thereof or the Regents of the University of California.

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