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Social Inequalities in Climate Change-Attributed Impacts of Hurricane Harvey

Abstract

Climate change is already increasing the severity of extreme weather events such as with rainfall during hurricanes. But no research to date investigates if, and to what extent, there are social inequalities in current climate change-attributed flood impacts. Here, we use climate change attribution science paired with hydrological flood models to estimate climate change-attributed flood depths and damages during Hurricane Harvey in Harris County, Texas. We then combine this information with detailed land-parcel and census tract socio-economic data to describe the socio-spatial characteristics of these climate change-induced impacts. Our findings show that 30 to 50% of the flooded properties would not have flooded without climate change. These climate change-attributed impacts were particularly felt in Latinx neighborhoods, and especially so in Latinx neighborhoods that were low-income and among those located outside of FEMA's 100-year floodplain (and therefore less likely to be insured). An important implication is the need to focus on pressing climate justice challenges that not only concern future climate change-induced risks, but are already affecting vulnerable populations disproportionately now.

JEL-Codes: Q540.

Keywords: Hurricane Harvey, attribution, climate change, poverty, flood insurance.

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Significance Statement

Climate change is increasing rainfall during extreme weather events like hurricanes. But we have a limited understanding of what social groups experienced added impacts because of these climate change-induced effects. Applying scientific advances that estimate what amount of flooding could be contributed to climate change during Hurricane Harvey, we find that 30% to 50% of flood impacts would not have occurred without climate change. Latinx neighborhoods, especially those that are low-income and among areas outside of FEMA's 100-year floodplains, experienced disproportionately high levels of climate change-attributed flooding. Our results showcase the importance on investigating climate justice not only for future scenarios but in observable impacts in our present time.

Classification

Social Sciences

Key Words

Climate Change; Flooding; Climate Justice

Introduction

Climate change can increase the intensity of extreme weather events such as the amount of rainfall associated with tropical storms and cyclones. Climate change can therefore increase the impact of these events and may do so in unequal ways. Indeed, research has already separately identified unequal social vulnerabilities in flood risks regardless of climate change (Collins et al. 2019; Maantay and Maroko 2009; Tate et al. 2021; Walker and Burningham 2011), and increasing flood risks from climate change (Davenport, Burke, and Diffenbaugh 2021; Elliott 2020; NYU Furman Center 2017; Wing et al. 2018). But, not much has been done to connect these two insights. Specifically, climate change's precise role in shaping unequal social impacts now is not yet well-understood (Elliott 2020). This is our focus here, where we combine extreme weather event attribution (to climatic change) research together with spatial quantitative social research to offer a way forward.

This type of event attribution seeks to determine how the meteorological and environmental characteristics for specific extreme weather events that have already occurred were shaped by anthropogenic changes to the climate (Davenport, Burke, and Diffenbaugh 2021; Frame et al. 2020; Risser and Wehner 2017; Sebastian et al. 2019; van Oldenborgh et al. 2017; Wang et al. 2018; Wehner, Zarzycki, and Patricola 2019). As such, it seeks to shed light on how climate change has affected both the likelihood and the intensity of these events. A new strand of this work now melds extreme weather event attribution with hydrological models to estimate the spatial imprint of these events' impacts (Strauss et al. 2021; Wehner and Sampson 2021).

While this growing work on attribution disentangles climate change's role in extreme weather hazards, no research to date analyzes if and to what extent these societal impacts of the increasing hazard link to pre-existing social inequalities. Here, we build on social science work identifying inequalities in disaster impacts that invokes oft-cited, but little-tested hypotheses about increasingly severe and frequent disasters because of climate change. For the first time, we empirically assess the increased severity of disaster impacts because of climate change. We conduct this analysis for a major flooding event with a specific focus on the distribution of these climate-change-attributed impacts across different social groups. To do so, we synthesize data on climate change attribution, hydrological flood models, hazard maps, and socio-spatial characteristics of neighborhoods and land parcels in Harris County, Texas during Hurricane Harvey in 2017.

We first use the increases in flood depths from Hurricane Harvey attributed to anthropogenic global warming (Wehner and Sampson 2021) to examine the extent to which flooding of residential buildings could be attributed to climate change. Then, using multi-variate econometric regression models, we assess what social and demographic factors are associated with these climate change-induced impacts, thereby carrying out the first analysis of inequalities in climate change attributed impacts of extreme weather events. Our analysis is based on a census of approximately 1.1 million residential land parcels nested within 795 census tracts (i.e., neighborhoods) in Harris County, Texas - the largest county of the Houston metropolitan area that was among the hardest-hit areas by Hurricane Harvey (Chakraborty, Collins, and Grineski 2019; Flores et al. 2020; Smiley 2020).

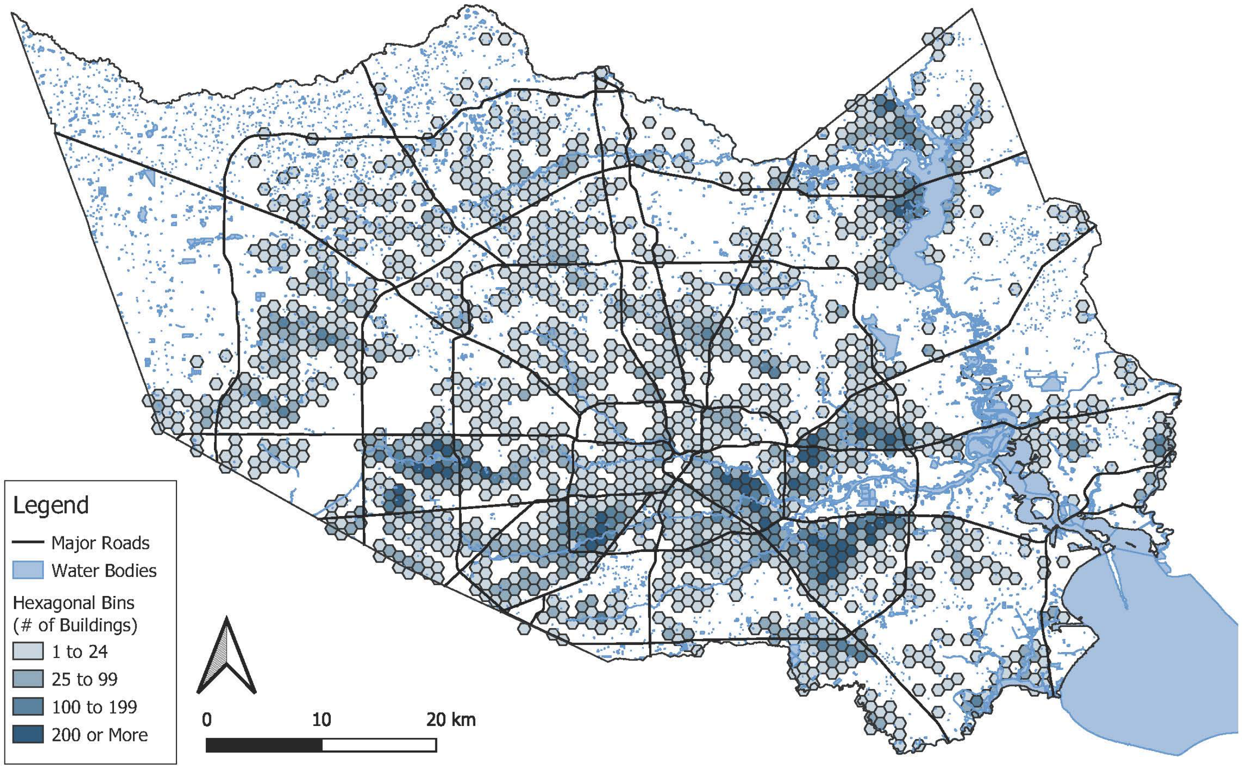
Results

Climate Change-Induced Impacts in Hurricane Harvey

To determine the relative share of flood impacts during Hurricane Harvey that could be attributed to climate change, we calculated climate change-attributed depths and damages using scenarios that compare the flooding that actually occurred to scenarios of flooding with less precipitation (i.e., flooding without climate change). Previous research examined seven possible scenarios of 7%, 8%, 13%, 19%, 20%, 24%, and 38% of precipitation during the storm that could be attributed to climate change, depending on the methodology used (Wehner and Sampson 2021). We calculate the climate change-attributed portion of depths and damages by subtracting flooding data from the scenarios with less precipitation from the baseline flood that occurred. Here, we present results for the two 'best estimates'; a lower scenario of 20% less precipitation without climate change (the 'best estimate' from Wang et al. 2018), and a higher one of 38% less precipitation (the 'best small-region estimate' from Risser and Wehner, 2017). Results for the other five scenarios are presented in the Supporting Information. We only determine a building to be flooded if it had at least 20 cm of flooding as this is a baseline figure typically associated with the threshold of a home (see Methods). Results are shown for residential parcels, as commercial buildings are more variable in their structural vulnerabilities and their financial value, making the modelling of damage considerably more difficult.

Our analysis shows that 9.5 percent of parcels (approximately 106,000 parcels) had buildings that flooded during Hurricane Harvey. For all seven climate change attribution scenarios we consider, almost every flooded building (>99%) experienced at least some flooding attributed to climate change. These depths varied: the median increased flood depths attributed to climate change was 22 cm in the (20%) lower climate change attribution scenario, and 27 cm in the (38%) higher scenario. Figure 1 shows a map of areas that experienced these climate change-attributed flood impacts.

Figure 1: Map of Climate Change-Attributed Flooding (38% Scenario) in Harris County, Texas during Hurricane Harvey



These climate change-attributed flood depths often made the difference between flooding a building and not flooding the same building at all. We assess this by examining parcels where the flooding of the buildings would have dropped below the 20 cm threshold without the climate change-attributed flooding. In the higher scenario (38% of precipitation is attributable to climate change), 49.7% of the buildings that were flooded would have been flooded anyway, but 50.3% flooded only because of climate change; i.e., they would not have been flooded during the hurricane had there been no anthropogenic climate change to generate increased rainfall during the storm. Since Harris County is large, this corresponds to an estimated 53,642 parcels that would not have been flooded without climate change. For the lower 'best estimate' (20%), the comparable figure is almost a third – i.e., 31.8% of the flooded houses would not have flooded without climate change. Even in the most conservative scenario we test – only 7% of the precipitation is associated with climate change – 12.7% of the flooded residential buildings would not have flooded without that small assumed increase in precipitation associated with climate change.

With this approach, we also calculate the property damages wrought by these climate change-attributed flood depths using information on buildings from the National Structure Inventory (see Methods). Our modelled estimate of the baseline flood damage to residential properties, including flooding both attributed and not-attributed to climate change, is US$ 6.42 billion in Harris County. We estimate the climate change-attributed portion of these damages to be approximately $2.39 billion (37.2%) of total damages in the lower scenario, or $3.71 billion (57.7%) in the higher climate-change scenario. These sums include both the damage to buildings that were flooded purely because of climate change, and the additional damage that buildings that would have flooded anyway incurred because of higher flood depth that was caused by climate change.

Factors Associated with Climate Change-Attributed Impacts in Hurricane Harvey

Given the sizeable impacts of climate change on residential flooding from Hurricane Harvey, we next conduct a series of analyses assessing what social and demographic characteristics of neighborhoods and land parcels are associated with these climate change-attributed impacts. We analyze neighborhood-level variables including the racial composition and median household income of the census tracts including potentially noteworthy moderating (interacting) relationships between racial composition and income. We also examine parcel-level variables including the parcel's appraised value, whether it is a single-family residential home, and whether the parcel has a building located in FEMA's 100-year floodplain.

Our first set of analyses assess how these social and demographic characteristics relate to two dependent variables attributed to climate change: (1) flood depths (in cm for houses where flooding was > 20 cm); and (2) flood damages (the estimated amount of damage to residential buildings in US dollars). The multivariate regressions use a Tobit specification, as a Tobit regression is appropriate for a left-censored variable where there are a large number of 0 cases (because many parcels did not have climate change-attributed flood depths). Table 1 shows these results for the 20% and 38% scenario.

We identify five primary findings from these analyses that held across the different scenarios and for both depths and damages. First, parcels in neighborhoods with more Latinx residents had higher climate change-attributed impacts when compared to their share in the population of the county. Figure 2 provides a schematic for these racial disparities in flood depths for the 38% scenario. Figure 3 shows these disparities for damages, with the per capita damages for a Latinx person from climate change-attributed flooding estimated at approximately $1,800; although this estimate is only narrowly higher than that for whites, it should be kept in the context that home values are higher in white neighborhoods, and therefore this disparity per unit of home value would be greater (Bhutta et al. 2020; Howell and Korver-Glenn 2021).

Second, parcels in neighborhoods with higher incomes had higher climate change-attributed impacts across scenarios. Third, in neighborhoods with more Latinx residents, the impact of income is reversed. In these neighborhoods, a greater impact was observed in the lower-income neighborhoods. This finding helps to clarify the previous two: While greater incomes may be linked to more climate change-induced impacts, the opposite is the case in Latinx neighborhoods. Fourth, the parcel-level variable comparing single-family residential parcels to all others showed that single-family residential parcels tended to experience greater flood impacts associated with climate change. Fifth, residential parcels in FEMA's 100-year floodplain were more likely to have climate change-attributed impacts.

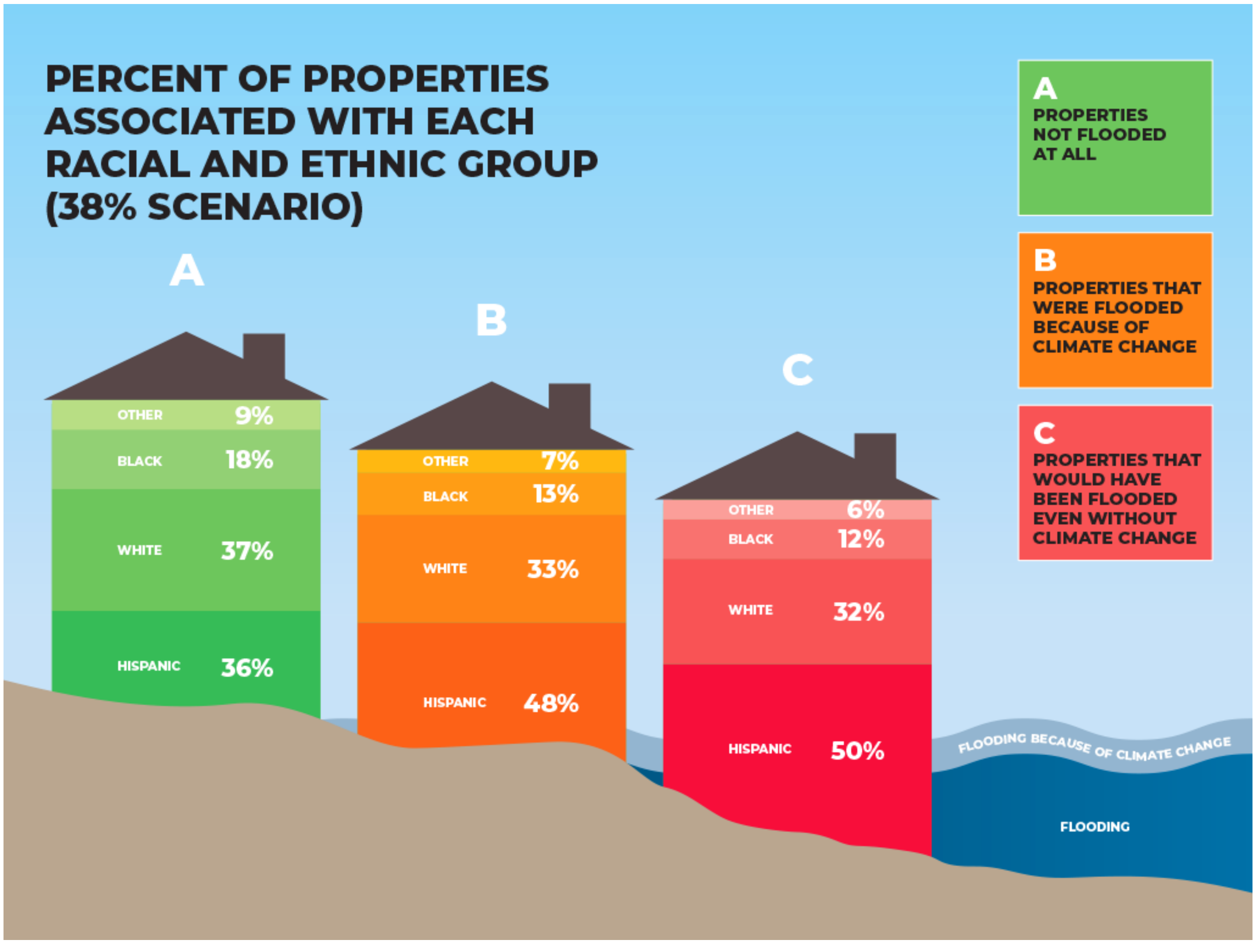


Figure 2: Percent of Properties Associated with each Racial and Ethnic Group (38% Scenario). Note: Group A included 1,003,453 properties, group B 53,672 properties, and group C 52,437. properties.

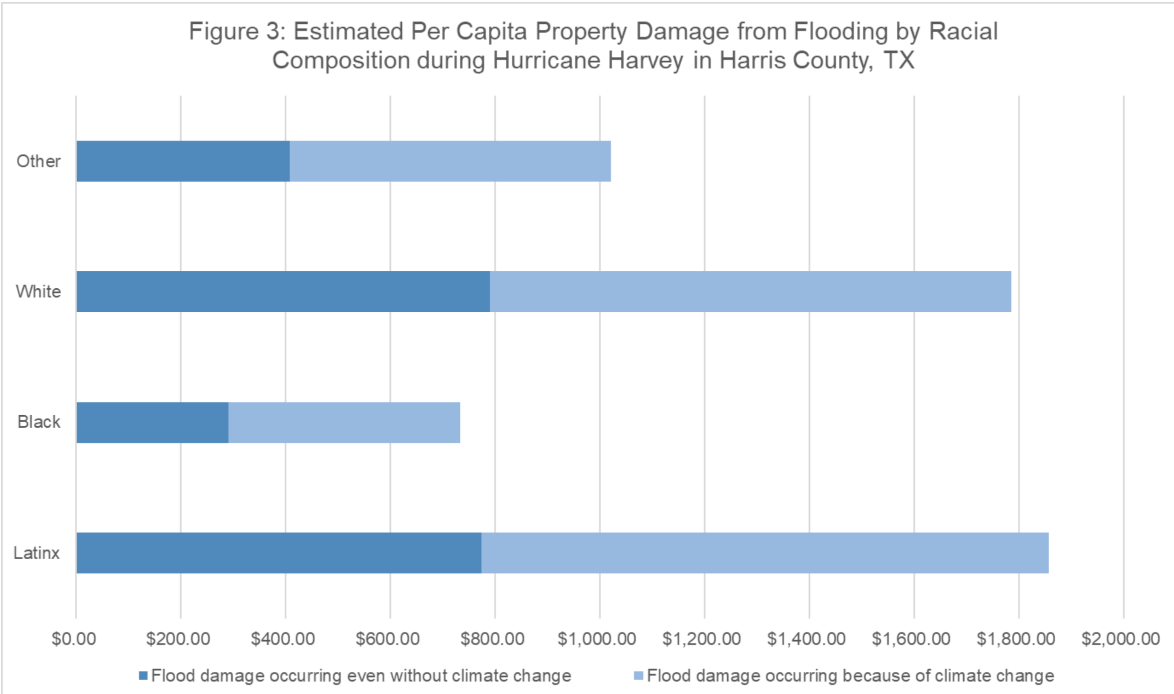


Figure 3: Estimated Per Capita Property Damage from Flooding by Racial Composition

In addition to these primary findings, results were less consistent. For climate change-attributed damages but not climate change-attributed depths, we found evidence of a curvilinear (convex) effect for appraised value of the parcel, but effect sizes were relatively small. Finally, we did not find statistically significant relationships for census tracts with a high proportion of non-Hispanic blacks or non-Hispanic of other race, including for moderating relationships with income.

Factors Associated with Flooding Only Because of Climate Change-Attributed Impacts

In a second set of analyses, we ask what social and demographic characteristics are linked to parcels that would not have flooded without climate change. In this case, we transform our flood depths and flood damages variables into binary outcomes that denote whether a parcel's buildings would not have flooded or did not flood at all. Here, parcels that would have flooded even without climate change-attributed precipitation are excluded; i.e., we conceptualize the sample as all parcels that would not have had flooded buildings if not for climate change. Table 2 shows the results of binary logistic regression analyses with the same set of independent variables as in the previous set of analyses.

Findings from these analyses largely mirror those for climate change-attributed flood depths and damages, thereby providing robust support for the overall findings. Most central to this study's focus on climate justice, we find that Latinx neighborhoods, especially low-income Latinx neighborhoods, had significantly greater odds of flooding (compared to other types of neighborhoods) only because of the added climate change-induced precipitation. This finding held for both depths and damages and across each of the climate change-attribution scenarios. Figure 4 graphs these findings with predicted probabilities by estimating the percentage of climate change-only flooded properties at different levels of percent Latinx residents and median household income. As an example, the estimates show that for a high Latinx, low-income (90% Latino, $25,000 median income) neighborhood, we would estimate that approximately 13% of parcels in the 38% scenario (and 8% in the 20% scenario) would not have flooded if not for climate change.

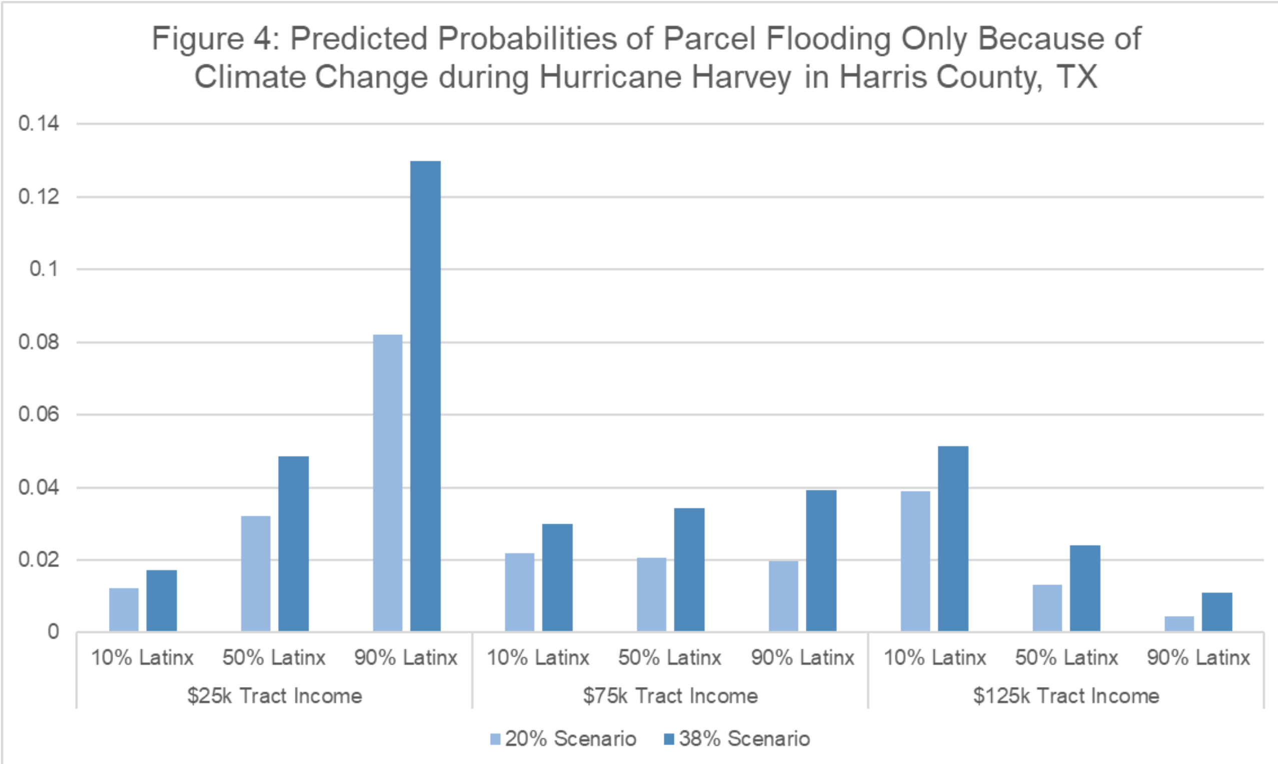


Figure 4: Predicted Probabilities of Parcel Flooding Only Because of Climate Change during Hurricane Harvey in Harris County, TX

Three additional findings in these binary logistic regression models are similar to the Tobit regression model findings. First, a parcel's location in a neighborhood with a higher median income is associated with higher odds of that parcel flooding only because of climate change. While this finding suggests greater risk for households living in neighborhoods that are more economically well-off, it is also in juxtaposition to the opposite effect for income that is found in Latinx neighborhoods. Second, single-family residential parcels had greater odds of crossing the flooding threshold of 20 cm because of climate change-induced impacts. Third, parcels located inside the FEMA 100-year floodplain had greater odds of climate change-attributed flooding.

Factors Associated with Climate Change-Attributed Flooding Inside and Outside of Floodplains

In a third set of analyses, we ask how findings about social inequalities in climate change-attributed impacts are linked to location in FEMA-delineated 100-year floodplains, which we use as an important proxy for whether a residence is likely to be covered by flood insurance. We use this proxy because any property within the 100-year flood zone is required to purchase flood insurance from the National Flood Insurance Program to be eligible for a mortgage from a federal agency (CRS, 2021). Our data show large impacts outside of the 100-year floodplains: 75.7% of parcels with flooding are located outside of these floodplains, an impact that totals $4.9 billion in estimated damages. The climate change-attributed portion of flood damages tends to be higher outside of the floodplains (38.4% of total damages in the lower scenario and 59.4% in the higher scenario) than inside of the floodplains (33.2% of total damages in the lower scenario and 52.2% in the higher scenario). Coupling these climate change-attributed impacts with floodplain location, we estimate that between 29% and 45% of all damages (totalling $1.8 to $2.9 billion) occurred outside of the floodplain (and were therefore likely to have been uninsured) *and* occurred because of climate change.

We find evidence for social inequalities in these impacts outside of the floodplain, but less so inside the floodplain. We re-analyzed the Tobit regression models and binary logistic regression models described in the two previous sections to account for a moderating relationship between floodplain location and census tract-level racial composition and median income variables; the regression results are found in the Supporting Information. Similar to previous models, we find that location within the floodplain is associated with greater climate change-attributed impacts even though the majority of impacted parcels were outside of the floodplains. Among parcels outside of the floodplains, the findings show that climate change-attributed flooding is more likely as the proportion of Latinx residents in a census tract is higher.

Previous findings relating to income, proportion Latinx, and the moderating effect between these two variables holds in these models. Using predicted probabilities from these models, we estimate for the 38% scenario that a census tract that is 90% Latinx would have more than twice as many parcels (5.2%) that would not have flooded without climate change compared to a census tract that is 10% Latinx (2.1%) in the areas outside of 100-year floodplains. In Figure 5, we estimate that approximately 52% of properties outside of the floodplain flooded because of climate change are Latinx householders compared to 38% inside of the floodplain.

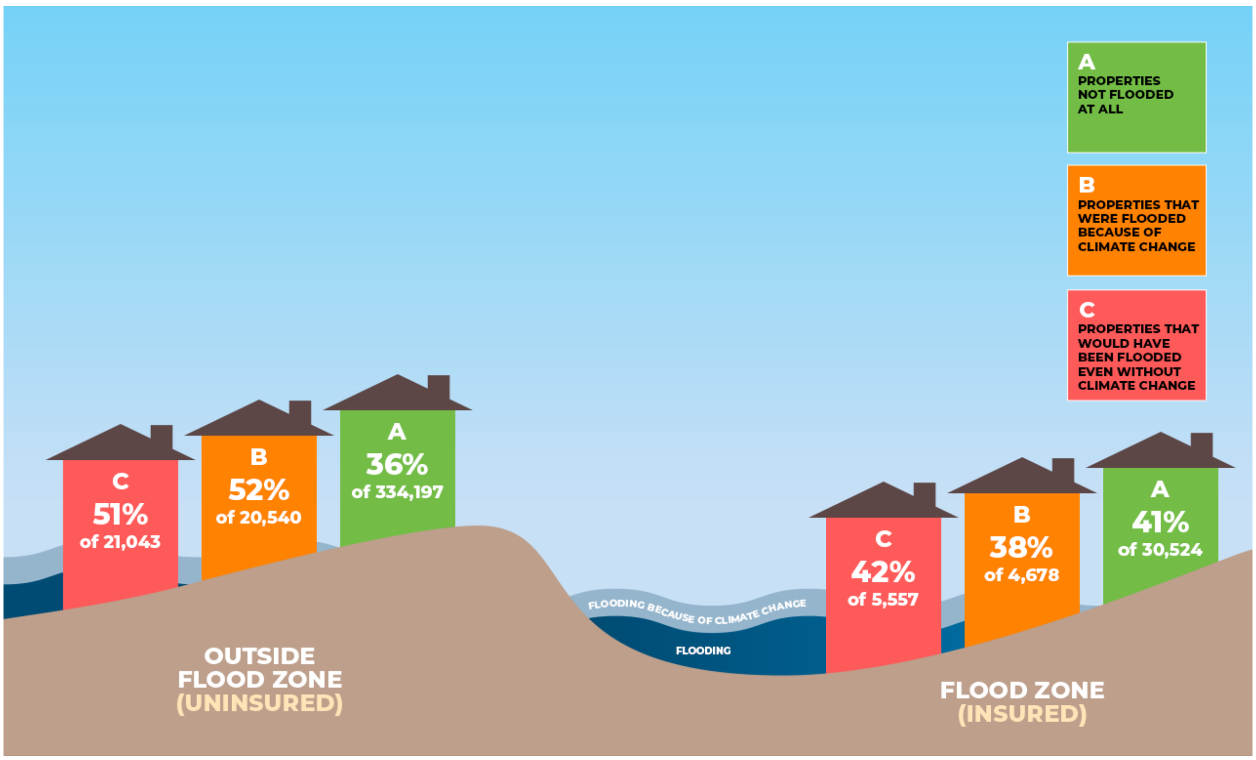


Figure 5: Percent of Latinx Properties Inside and Outside of Floodplains Flooded Because of Climate Change (38% Scenario).

Taken together, these findings suggest that there are more pronounced racial inequalities in climate change-attributed impacts in flooding outside of FEMA's 100-year floodplains; Latinx neighborhoods experience greater impacts. Thus, the racial inequalities we find in the damage are further exacerbated during the disaster recovery process. Floodplain location is a key predictor of whether a homeowner has purchased flood insurance. Insured homeowners are more likely to have the resources to pay for reconstruction and recovery, so a house located outside the floodplain is less likely to have that access to reconstruction funding (Cannon et al. 2020; Kousky 2018; Owen and Noy 2019; Shao et al. 2017).

Discussion

Drawing on flood impacts from Hurricane Harvey in Harris County, Texas, our analysis finds strong evidence for social inequalities in climate change-attributed impacts. Most notably, parcels in Latinx neighborhoods disproportionately experienced these higher levels of flooding compared to other neighborhoods. Within Latinx neighborhoods, parcels located in low-income neighborhoods were even more likely to experience these impacts, and, among parcels located outside of the FEMA floodplain, Latinx neighborhoods were also more likely to experience impacts. All of these suggest that low-income Latinx homeowners were more likely to be exposed to climate change-attributed flooding in Hurricane Harvey, at the same time that Latinx householders were also less likely to be insured against this flooding. These findings are in contrast to our findings for median household income which show that more economically well-off neighborhoods experienced greater impacts.

These patterns were evident across all seven climate change scenarios we examined and for the various damage measures we tracked: for flood depths, for flood damages, and for whether the flooding would have occurred with climate change-attributed increase in flood depths.

Our study is the first of its kind to assess contemporaneous social inequalities in climate change-attributed impacts from increased rainfall from extreme weather events. As such, our findings offer a window not only into the climate justice challenges that cities and towns may face in the future, but the challenges facing these communities right now. The world has warmed by more than 1 degree Celsius already (IPCC, 2021). The common frame of analyzing how climate change might have inequitable social impacts in the future is important but incomplete. We believe an equally important line of inquiry should focus on how climate change is having unequal social impacts in our present time. Already, this theme is emergent in research on topics like climate migration (Beine et al. 2021; Kaczan and Orgill-Meyer 2020; McLeman 2018). We believe that social science analysis of climate change-attribution impacts of extreme weather events can further substantiate the major (and inequitable) impacts climate change is having in our world today.

The specific climate justice challenges are animated by residential segregation (by race and income) in the United States and along other lines of social differentiation around the world. Our findings suggest that this socio-spatial inequality is linked to increasing impacts from climate change. Following this, one important implication of our work is that climate change could exacerbate social inequalities in the wake of the storm if hard-hit areas are majority minority areas, and especially if they are low-income or otherwise socio-economically vulnerable.

Our focus here is on the social inequalities in damages caused by Hurricane Harvey. Inequalities also persist after the damage has been incurred, during the process of recovery (Noy and duPont, 2018). The recovery of lower-income and/or minority communities is typically slower and less complete or successful. Research has shown, for instance, that lower income households are less likely to be insured, or get lower compensation from their insurer, *ceteris paribus* (Cannon et al. 2020; Kousky, 2018; Kousky et al., 2020; Owen and Noy, 2019; Shao et al. 2017). Indeed, insurance is often essential for a fast recovery (Nguyen and Noy, 2020). Our finding that among land parcels outside of the floodplains Latinx neighborhoods disproportionately experienced climate change-induced impacts suggests that these differentials in flood insurance could further expand inequalities in disaster recovery.

Parallel to this, an additional thread to examine is how neighborhood economic characteristics like median income relate to climate change-induced impacts. It may be the case that higher income areas are closer to water bodies as these are perceived as desirable amenities (Collins, Grineski and Chakraborty 2018; Grineski et al. 2015). In a place like Harris County, these findings can be partly interpreted through this lens, as proximity to water bodies can pattern on affluence in some areas (such as along recreational trails on the city's many bayous) but have the opposite effect in others (such as with low-income Latinx neighborhoods near the Houston Ship Channel which hosts a large number of petrochemical facilities) (Grineski et al. 2015; see also Emerson and Smiley 2018).

Increasing attention must be paid not only to both climate change mitigation and to climate change adaptation to lessen these impacts, but also to upending the baseline social inequalities that sustain socio-spatial differentiation in the first place. If and to what extent social inequalities in climate change-attributed impacts may hold across places and across other types of extreme weather events, however, is a critical question for future research. Understanding the climate change justice challenges for other places and other hazards is essential not only for building the climate justice-focused multidisciplinary research synthesis outlined here, but also to documenting and attenuating the inequalities in climate change-attributed impacts in marginalized communities worldwide.

Materials and Methods

1. Data

The empirical analysis we undertake in this study is based on combining information from geo-spatial data from five different sources.

First, data on climate change-attributed flooding comes from Wehner and Sampson's (2021) climate change-attribution hydrological models. To determine the effect of climate change on this baseline flood, seven scenarios of the percentage increase in precipitation based on peer reviewed research were used to calculate the spatial extent of flooding: 7% (the lowest precipitation change attribution level as set by the Clausius-Clapeyron scaling as noted by Risser and Wehner 2017); 8% (the lower bound of Van Oldenbough et al. 2017); 13% (the lower bound of Wang et al. 2018); 19% (the likely lower bound of the small region of Risser and Wehner 2017 and the upper bound of Van Oldenborgh et al. 2017); 20% (best estimate by Wang et al. 2018); 24% (best estimate of the large region by Risser and Wehner 2017), and 38% (the best estimate of the small region by Risser and Wehner 2017 and the upper bound of the estimate by Wang et al. 2018). The full hydrological model used to construct the data we utilize here is described in Wing et al. (2019).

Second, building data is sourced from the National Structure Inventory (NSI) of the U.S. Army Corps of Engineers, and representing every structure in Harris County as a point. The NSI was constructed by combining information from many datasets – including Census data, Microsoft building footprints, CoreLogic parcels, and ESRI business layers – to produce the most accurate possible inventory for assessing natural hazard risk (USACE, 2021). The data includes information on occupancy type and replacement value in order to link them to depth-damage functions and assess their flood vulnerability. Since it is composed from proprietary data, this dataset is not publicly available. Further details can be found in USACE (2021).

Third, parcel-level data is obtained from the 2016 Harris County Appraisal District (HCAD) database. Harris County is the central county of the Houston metropolitan area. These data include more than 1.4 million parcels and are updated annually. Our study focuses only on the 1.1 million parcels which include residential property. Building data is merged with the parcel data using a spatial join in GIS software. Among residential parcels that had flooded buildings, 7.7% (8,822 parcels) had multiple buildings flooded. In these cases, the depths of flooded buildings were averaged, and the damages were summed for the overall parcel.

Fourth, census-tract level data is from the five-year pooled estimates from the 2012-2016 American Community Survey (ACS). The pooled five-year estimates are used to improve the reliability of the survey. Census tracts are units commonly used in socio-economic geo-spatial research to denote neighborhoods and have approximately 4,000 residents. We obtain social and demographic data from the ACS on 798 census tracts in Harris County. Three census tracts had missing values on median income, but these three tracts have only 11 parcels between them; these parcels are dropped from the study sample.

Fifth, data on FEMA-delineated floodplains is obtained for the 100-year floodplain from 2017. This area signifies places that would experience flood inundation in a flood event that has a 1% chance of occurring in a given year. Data was obtained from the Urban Data Platform of Rice University's Kinder Institute for Urban Research (FEMA 2019).

2. Measurements and Calculations

The flood maps generated with the first dataset were intersected with data on the residential buildings in Harris County from the second dataset. Depths were calculated only for above 20 cm, a common threshold used to denote if the flooding would cross the threshold of the structure and provides a conservative method, so as to not over-estimate flood impacts (Wehner and Sampson 2021). Damages were calculated using depth-damage relationships specific to the occupancy type of the NSI structure. The mean damage was calculated for each structure using the non-linear damage functions (in flood depths) constructed from National Flood Insurance claims data described in Wing et al. (2020).

Climate change-attributed depths and damages are calculated using the baseline flood scenarios described above. For each scenario, both the flooding depth and damages are subtracted from the baseline (the actual flooding that occurred) to determine the amount of flooding (in terms of depth or of damages) that could be attributed to climate change. Each scenario produces two variables from these calculations: flood depths (with depths below 20 cm set to 0; see above) and damages to buildings.

A second set of variables is then generated indicating if the parcel's buildings did or did not flood during Hurricane Harvey because of climate change. If a parcel had $0 flood damage or depths below 20 cm in a given counterfactual scenario but had flood damages or depths in the baseline (actual) scenario, then the parcel was assigned a value of 1 to denote that it flooded only because of the presence of climate change-attributed precipitation. Cases that did not flood at all were coded as 0, and cases that would have flooded regardless of climate change-attributed flood depths or damages are assigned as 'anyway flooded' and are excluded from the analysis that focuses only on parcels that would not have flooded with a no climate change scenario.

Census tract-level variables include racial composition and median income. Racial composition is measured by three variables: (1) proportion Hispanic or Latinx, (2) proportion non-Hispanic black, and (3) proportion non-Hispanic, non-black, and non-white (i.e., American

Indian or Alaska Native, Asian, two or more races, or another race). Proportion non-Hispanic white is the reference group with which we compare the other ethnic/racial composition measures.

Median income is measured as the median income of households in the census tract in the previous 12 months and is measured in 2016 inflation-adjusted US dollars. Median income is divided by 10,000 to improve the interpretability of regression coefficients. Additionally, to test for potential intersections between race and class, we employ moderating effects with interaction terms between median income and each of the three racial composition variables.

We use three parcel-level variables. First, 'appraised value' is the full value of the parcel including the parcel's building, land, agricultural value and any value of extra features. This variable is also divided by 10,000 to improve interpretability of regression coefficients. In the estimated econometric models, a squared term for appraised value is included as some previous research indicates evidence for a non-linear (concave) wealth effect (wealth here is proxied by the appraised value of the parcel). Second, a binary variable denoting whether the parcel is a single-family residential parcel (values = 0) or other (values = 1). Single-family residential homes include mobile homes and half duplex parcels. Other residential parcels include apartment-style condominiums, two-family homes, three-family homes, and multi-family homes. Third, we measure floodplain location with a binary variable denoting if a building in the parcel is located in the FEMA 100-year floodplain by conducting an intersect in GIS software between the FEMA 100-year floodplain and all buildings in Harris County, Texas. One limitation of this measurement approach is that some buildings may have modifications to the structure (such as elevating a home) that would not be accounted for in these data, and therefore could be misclassified as subject to 100-year flood risks.

3. Analytical and Estimation Strategy

We first present descriptive statistics about depths and damages relating to climate change-attributed flooding during Hurricane Harvey. All findings are presented at the parcel-level.

We next estimate the following equation:

$$Y_{ic}^{scn} = \alpha + \beta^1 X_c + \beta^2 V_{ic} + \varepsilon_i \qquad (1)$$

With Y_i^{scn} denoting either the depth of flooding attributed to climate change in parcel *i* and in census tract *c,* or the amount of damage attributed to climate change from this flooding (calculated using the damage functions described above). Each one of these is estimated for each climate change scenario (*scn:* from 7% to 38% less precipitation without climate change). X_c is the vector of variables denoting the composition of the census track in which the parcel is located (the ethnic composition variables and the median income. V_{ic} is a vector of measures associated with each specific parcel (the appraised value of the parcel, and whether it is a single-family home). In some specifications, we also interact some of the X_c and V_{ic} variables. The β coefficients denote the association of these measures with the climate change attributable impact on these properties.

Since both dependent variables (attributable depth and damage) are censored on the left at zero, we estimate these with a Tobit regression models (the results are reported in the Article and Supporting Information). The error term (ε_i) is assumed to be independently and identically distributed, but there still might be a census tract effect that we cannot model (since we include the X_c in our estimations). We therefore cluster the standard errors at the census tract (*c*) level to account for any unmeasured similarity that these within-tract parcels may have compared to parcels elsewhere in the county.

In addition to these Tobit regression models as specified in Equation (1), we also estimated a binary logistic regression models predicting whether the parcel flooded because of climate change (or would have otherwise not been flooded).

$$FL_i^{scn} = \frac{e^{\alpha+\beta^1 X_c+\beta^2 V_i+\varepsilon_i}}{1+e^{\alpha+\beta^1 X_c+\beta^2 V_i+\varepsilon_i}} \qquad (2)$$

In this case, the dependent variable (FL_i^{scn}) is a binary indictor (=1) noting that the property had flood depth of >20cm and had also less than that for the scenario (*scn*) being assessed. Parcels that always had flood depth <20cm in both the scenario being assessed and the actual flood are the default category (=0). Parcels that had depths >20cm in both scenarios are excluded from this analysis to focus only on parcels that would not have flooded in the no climate change scenarios. We use similarly clustered standard errors at census tracts as in the Tobit regression model (Eq. 1). The odds ratios estimated from the logit estimation are presented in the tables of results. In estimating Eq. 2, the sample is smaller than Eq. 1 since properties that would have anyway been flooded, even without the additional precipitation attributed to climate change, are excluded. A such, the sample includes 793 to 795 census tracts as in some scenarios a few census tracts no longer had any valid observations (i.e., all parcels had flood depths/damages even with the reduced modelled precipitation).

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Table 1: Tobit Regression of Climate Change-Attributed Depths for Hurricane Harvey in Harris County, Texas

	(1) Depths: 20% Scenario	(2) Depths: 38% Scenario	(3) Damages: 20% Scenario	(4) Damages: 38% Scenario
Multi-Family Homes or Apartments	-0.291***	-0.463***	-27724.079***	-42267.246***
	(0.039)	(0.063)	(3953.080)	(6081.003)
Appraised Value (in 10,000s)	0.000*	0.000*	72.680***	109.444***
	(0.000)	(0.000)	(12.752)	(18.842)
Appraised Value (in 10,000s)*Appraised Value (in 10,000s)	-0.000	-0.000	-0.007**	-0.011**
	(0.000)	(0.000)	(0.002)	(0.003)
FEMA 100-Year Floodplain=1	0.306***	0.494***	39900.343***	60788.816***
	(0.028)	(0.044)	(4222.727)	(6393.245)
Prop. Latinx	1.015***	1.621***	118987.255***	180335.276***
	(0.188)	(0.307)	(22286.491)	(34055.327)
Prop. Black	-0.282	-0.463	-28799.836	-43155.784
	(0.284)	(0.458)	(33305.369)	(50992.562)
Prop. Other Race	-0.404	-0.652	-56280.221	-86906.804
	(0.526)	(0.846)	(61452.031)	(93840.227)
Median Income (in 10,000s)	0.045*	0.071*	4787.458*	7194.510*
	(0.018)	(0.029)	(1971.194)	(3023.936)
Prop. Black*Median Income (in 10,000s)	-0.004	-0.007	377.388	284.704
	(0.069)	(0.111)	(8161.173)	(12470.227)
Prop. Latinx*Median Income (in 10,000s)	-0.141**	-0.225**	-15552.854**	-23121.674**
	(0.049)	(0.078)	(5512.672)	(8458.605)
Prop. Other Race*Median Income (in 10,000s)	-0.081	-0.130	-7764.190	-11346.686
	(0.080)	(0.129)	(8775.159)	(13391.266)
Constant	-0.937***	-1.496***	-121392.740***	-184142.558***
	(0.137)	(0.222)	(17412.944)	(26476.091)
Observations	1109531	1109531	1109531	1109531

Standard errors in parentheses
Standard errors clustered within census tracts
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 2: Logistic Regression of Climate Change-Attributed Depths for Hurricane Harvey in Harris County, Texas

	(1) Depths: 20% Scenario	(2) Depths: 38% Scenario	(3) Damages: 20% Scenario	(4) Damages: 38% Scenario
Multi-Family Homes or Apartments	0.280***	0.271***	0.302***	0.293***
	(0.046)	(0.041)	(0.049)	(0.043)
Appraised Value (in 10,000s)	1.001	1.001	1.001*	1.001*
	(0.000)	(0.000)	(0.000)	(0.000)
Appraised Value (in 10,000s)*Appraised Value (in 10,000s)	1.000	1.000	1.000	1.000
	(0.000)	(0.000)	(0.000)	(0.000)
FEMA 100-Year Floodplain=1	3.261***	3.554***	3.259***	3.551***
	(0.398)	(0.449)	(0.398)	(0.449)
Prop. Latinx	43.937***	46.559***	43.089***	45.486***
	(28.418)	(30.871)	(27.895)	(30.175)
Prop. Black	0.276	0.366	0.273	0.358
	(0.329)	(0.468)	(0.326)	(0.459)
Prop. Other Race	0.131	0.213	0.122	0.202
	(0.235)	(0.419)	(0.219)	(0.398)
Median Income (in 10,000s)	1.172***	1.181**	1.168**	1.177**
	(0.055)	(0.063)	(0.055)	(0.063)
Prop. Black*Median Income (in 10,000s)	1.162	1.068	1.165	1.073
	(0.324)	(0.331)	(0.325)	(0.333)
Prop. Latinx*Median Income (in 10,000s)	0.593**	0.628*	0.596**	0.631*
	(0.105)	(0.118)	(0.106)	(0.119)
Prop. Other Race*Median Income (in 10,000s)	0.836	0.795	0.844	0.802
	(0.184)	(0.196)	(0.186)	(0.197)
Observations	1037346	1057088	1036839	1056625

Exponentiated coefficients; Standard errors in parentheses.
Standard errors clustered within census tracts
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$