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Research Article

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Overblown? Analyzing Wind Speed in the Hurricane Warning Response System

Keywords

Hurricanes, Saffir-Simpson, warnng response system, recovery, resilience

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Abstract

The role of wind speed in determining the impacts of hurricanes is examined via statistical analysis of Category 2-5 hurricanes that made landfall in the U.S. Atlantic basin coastline, including Puerto Rico's coast, from 1970-2020. The results indicate a positive yet statistically insignificant correlation between wind speed and hurricane deaths, cost of damages and federally obligated recovery aid. Other factors, such as storm surge, rainfall, and inland inundation, may be more strongly correlated with these impacts. The results are contextualized by a wealth of literature pointing to the role of social, political, and economic factors in determining the destructiveness of hurricanes. Finally, alternative indices to the popular Saffir-Simpson hurricane hazard scale – which relies on wind speed – are examined. As climate change advances and hurricanes become increasingly frequent and severe, more comprehensive hazard-rating scales may provide the basis for a more effective warning-response system, ultimately bolstering the resilience of coastal areas.

Introduction

Hurricane Katrina hit New Orleans in 2005 as a Category 3 hurricane, yet the residents had expected a Category 1. A Category 1 unexpectedly became a Category 5 in a matter of hours, then a Category 3 at landfall. New Orleans, a city used to hurricanes, was left unprepared[3]. These categories, found on the Saffir-Simpson Scale, are used to assess hurricane risk in the Western Hemisphere and communicate it to the public. However, when the scale fails to accurately predict or communicate risk, on top of other bureaucratic challenges, the public and authorities are ill-prepared. Katrina marked an important turning point in warning-response research and led to reforms in hurricane preparedness and response[4].

Almost 16 years post-Katrina, hurricane research has never been more relevant. As the climate changes due to a warming atmosphere, storms can hold more water, move more slowly and are becoming more frequent. In other words: storms are becoming increasingly damaging[5]. Since 1980, tropical cyclones in the US have caused $945.9 billion in total damages, averaging $21.5 billion per event.

2017 saw the highest costs ever from hurricanes, largely from Hurricane Harvey which made landfall in Houston, Texas. Additionally, of all weather-related disasters, hurricanes are responsible for the highest number of deaths (6,593 direct deaths since 1980)[6]. Although advancements in meteorology have greatly improved storm forecasting, as hurricanes become more damaging, it is critical that cities can anticipate and build resilience to hurricanes with accurate warning response systems[5]. Thus, the value of relying on wind speed in the Saffir-Simpson Scale comes under question.

Hurricane-related damages, costs, and deaths result primarily from water (rainfall, storm surge, etc.), though wind is the measure by which governments prepare for and respond to hurricanes through the Saffir-Simpson Scale (see Table 1). In fact, 88% of deaths are from water, not wind[7]. Furthermore, scholars such as Robert D. Bullard and Beverley Wright (2009) studied Hurricane Katrina at length and deemed it a "preventable catastrophe", driven by socio-economic factors such as discriminatory policy, poor land-use planning and failure of the warning-response bureau-organization[4,8].

Thus, two questions arise: What role does wind speed play in hurricane risk assessment? Should other factors be considered in this process? By providing a more holistic assessment of the factors driving hurricane damage and deaths, we can better anticipate vulnerabilities, build social and ecological resilience to extreme weather and align policy and financial responses with on-the-ground realities.

To develop this holistic assessment, two primary objectives are observed: [1] examine wind speed as a determinant of hurricane-related deaths, cost of damages and recovery aid for hurricanes that made landfall in the United States and Puerto Rico from 1970 to 2020, and [2] identify other factors, such as storm surge; rainfall; and social, economic, and political factors which may better predict deaths, damages, and recovery aid. The 3-part methodology involves building a database, conducting linear regression analysis, and contextually investigating the qualitative literature. This will facilitate analysis to determine if there are significant changes in deaths, damages, and recovery funding between Saffir-Simpson Categories (i.e. between different wind speeds).

We expect that wind speed as a hurricane categorization limits the effectiveness and resilience of the warning-response system, and hope to contribute to a system more capable of adaptation and emergency management planning.

Table 1. Saffir-Simpson Hurricane Scale[9]

Saffir-Simpson Hurricane Scale Category	Maximum Sustained Wind Speed (kt)	Maximum Sustained Wind Speed (km/h)
Tropical Depression	< 34	< 62
Tropical Storm	35-63	63-118
1	64-82	119-153
2	83-95	154-177
3	96-112	178-208
4	113-136	209-251
5	≥ 137	≥ 252

Methods

Firstly, we constructed a database containing wind speed, deaths, cost of damages, and federal recovery aid from the Atlantic Hurricane Database (NOAA), Historical Hurricane Tracks (NOAA/GIS), U.S. Census Data (GIS, U.S. Census Bureau, various sources), Public Assistance Funded Projects Details (FEMA), and the Emergency Management Events Database (EM-DAT)[10-15]. Our database includes hurricanes that made landfall in the United States (including Puerto Rico) from 1970-2020 at Category 2 or higher. The first step in building the database was to reference the Atlantic Hurricane Database to identify landfall events (marked by system indicator L) of Category 2 or higher and filter for the timeframe 1970-2020. Then, we used the Historical Hurricane Tracks GIS application, overlaid on a U.S. Census map for the decade the hurricane occurred in, to identify the counties (municipalities in Puerto Rico and parishes in Louisiana) intersected by the corresponding hurricane's track on the date of landfall. The U.S. Census data was then used to calculate the intersected counties' average population density.

To ensure data accuracy, hurricanes were divided by the decade in which they made landfall to refer to the corresponding U.S. Census decade. For example, hurricanes that made landfall in 1995-2005 rely on 2000 census data, whereas hurricanes that made landfall in 2005-2015 use 2010 census data. For hurricanes before 1995, there were no GIS maps with population data, so the intersected counties were identified using a map and the county population data were found in U.S. Census reports from 1990, 1980, and 1970.

From the Historical Hurricane Tracks GIS application, we downloaded the NOAA hurricane reports to identify the deaths and damages in the intersected counties or states. In the instances where county-level data were unavailable, NOAA state-wide data were used (county-level data were used 29 times and were unavailable 24 times). Of note is that the hurricane reports greatly differ in format depending on the year, and there is no centralized federal database containing this information. For example, deaths and damages data for the older hurricanes were in scanned reports, making it in some cases difficult to decipher the data.

Furthermore, we used EM-DAT's Consumer Price Index (CPI) to normalize NOAA damages to 2021 dollars. The EM-DAT dataset was built by selecting the categories "Tropical storm" under "Natural" disasters from 1900 to 2021 in the United States and Puerto Rico. The data were downloaded as an Excel document containing the event's name, time, number of deaths, number of injuries; an estimate of the damages; and a Consumer Price Index (CPI) with a base 100 in 2021. Notably, an event is created on EM-DAT if it has 10 or more deaths, 100 or more affected individuals or resulted in an international appeal for assistance. As a result, some events present on NOAA's Atlantic Hurricane Database were not on EM-DAT, restricting the number of observations available for our research. Due to these limitations, NOAA data were used for deaths and damages in the statistical analysis, while EM-DAT's Consumer Price Index was used to normalize the NOAA damages to 2021 dollars.

To identify the amount of federal recovery aid—the grant that the federal government is obligated to pay—we filtered the Public Assistance Funded Projects Details (FEMA) data by hurricane landfall date and intersected counties and summed the "federal share obligated." In instances where the hurricane emergency was not declared on the date of landfall, reports from 1-2 days post-landfall were used. However, the FEMA database extends from 1998 to the present, and data were missing for several hurricanes within that period. Hurricanes where FEMA recovery aid data were unavailable are marked by a period (.) in the database.

Damages and deaths were normalized using the average population density of the nearest decennial census for counties intersected by the hurricane track. They are hence represented in the database as deaths, or damages, per person per square mile. The recovery aid data is presented as a ratio of the obligated federal aid against the total project amount, to demonstrate the proportion of aid paid by the federal government. The total project amount is the total cost of recovery based on FEMA's damage survey.

Once the database was complete, we statistically analyzed it using the Stata application[16]. We conducted three primary statistical analyses regarding: [1] the relationship between hurricane wind speed and deaths as a ratio of population density, [2] hurricane wind speed and damages as a ratio of population density, and [3] hurricane wind speed and recovery funding as a proportion of damages.

For all analyses, we assumed authorities prepared for the maximum sustained wind speed at landfall since hurricanes decay over land[17]. The analysis (linear regression) entailed creating two-way scatter plots of maximum sustained wind speed at landfall and each dependent variable. Then, we added regression lines and overlaid vertical lines demarcating each Saffir-Simpson category. In general, for data where there were significant outliers, we conducted additional analysis, generating graphs and regression lines that excluded the outliers.

Additionally, for damages and deaths, because EM-DAT data had a country-level scope while NOAA data had a county or state-level scope, we could compare the deaths and damages that occurred in counties or states intersected by the hurricane track with country-wide deaths and damages. This comparison revealed that many of the hurricane-related deaths and damages actually occur outside counties intersected by the hurricane track; we analyze this in the Discussion section, though the comparison is outside the main scope of this paper. Furthermore, the EM-DAT database had only 42 data points that could be compared with the NOAA reports.

After conducting statistical analysis with Stata and identifying statistical trends (or lack thereof) between sustained maximum wind speeds and deaths, cost of damages or recovery aid, several patterns in the data warranted further investigation. As a result, we contextualized the data with a qualitative investigation of the literature on hurricanes and their social impacts. While gathering data and processing results, a set of questions arose regarding why some hurricanes of the same category had such different impacts even after accounting for population density and inflation. Such questions are partially answered in the Discussion section. However, further research is needed as this secondary research theme is outside the scope of our primary objectives.

Results

The Data

From 1970 to 2020, there were 53 landfall events at Category 2 or higher in the United States and Puerto Rico for 40 different hurricanes. Hurricane Georges (1998) had the highest number of landfall events (4) at Category 2 or higher, while 31 hurricanes only had one recorded landfall event at Category 2 or higher. In some years, there were 0 Category 2-5 recorded landfall events in the United States and Puerto Rico.

Often, we found that this was because hurricanes made landfall in other countries in the Atlantic Basin, such as Cuba or the Bahamas, and reached the United States only as a tropical depression. There was an average of 2.3 landfall events per year, a median of 2, and a mode of 1. It is noteworthy that observations of four and five landfall events per year only occur post-1996, which may indicate that hurricanes made landfall outside of the U.S. in the past, or point to the increasing frequency of Category 2 and higher hurricanes as the climate warms.

There were only 2 observations in Category 5, 9 in Category 4, and 21 each in Categories 2 and 3. The Category 5 landfall events were Hurricane Andrew (1998), which made landfall at Category 5 in Miami-Dade County, Florida; and Hurricane Michael (2018), which made landfall at Category 5 in Florida and maintained Category 5 wind speeds into Georgia.

The average maximum sustained wind speed at landfall of all observations is 102.55 kt or 189.9 km/h (equivalent to a Category 3), with a standard deviation of 15.40 kt or 28.5 km/h.

Hurricane path/track: We refer to 'best track' in the Historical Hurricane Tracks GIS application, which is a "representation of a tropical cyclone's location and intensity over its lifetime"[1,2].

Landfall: We refer to "the intersection of the surface center of a tropical cyclone with a coastline"[1].

Maximum Sustained Wind Speed at Landfall and NOAA Deaths Normalized

Figure 1 shows a regression plot of wind speed at landfall (x-axis) and normalized NOAA deaths (y-axis). Red lines are thresholds between Saffir-Simpson categories. 53 observations were computed. Among them, 2 are largely outside the 95% confidence interval of the fitted values computed by Stata. Both outliers are Katrina landfall events (11.80 and 6.32). The coefficient of the fitted values' regression line is β=0.0084779.

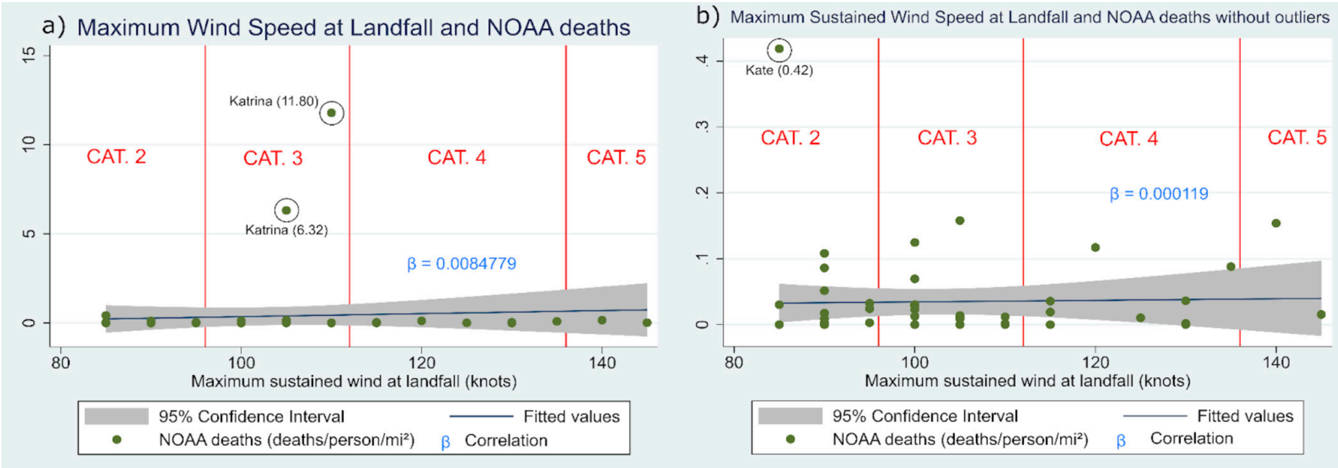

Figure 1. Maximum Sustained Wind Speed at Landfall vs NOAA Deaths Normalized. Figure 1a includes outliers while Figure 1b excludes outliers. The unit of the x-axis is knots, which is commonly used by atmospheric researchers and is equal to 1.852 kilometers per hour. The unit of the y-axis is deaths per average population density of intersected counties. Each point is an observation of a hurricane that made landfall.

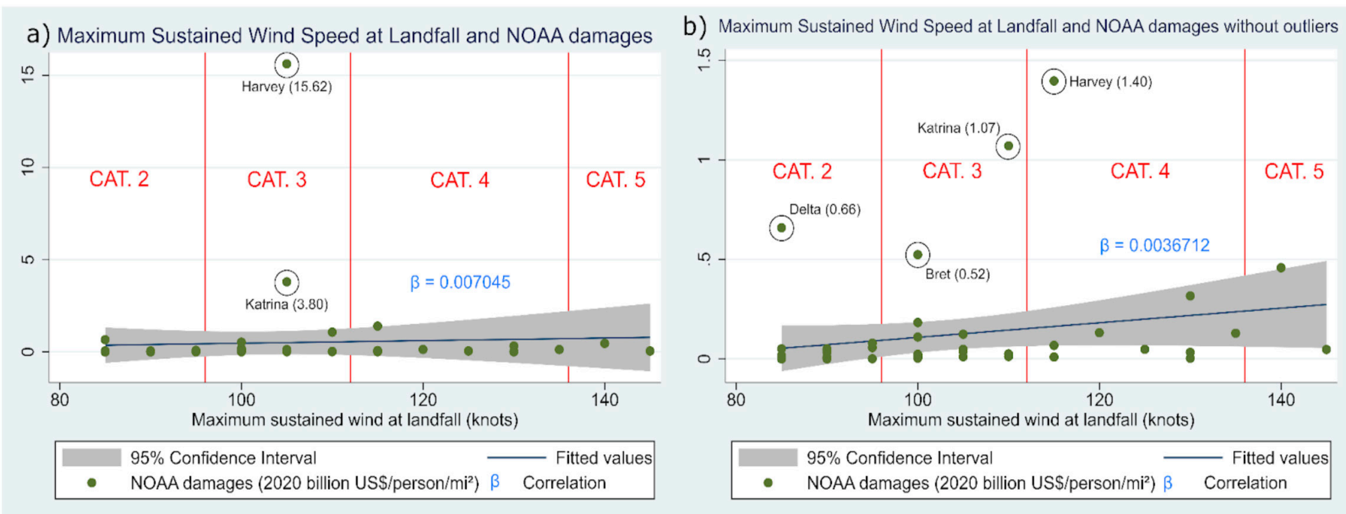

Figure 2. Maximum Sustained Wind Speed at Landfall vs NOAA Damages Normalized. Figure 2a includes outliers while Figure 2b excludes outliers. The unit of the x-axis is the same as in the previous regression plot. For the y-axis, the unit is billions of US dollars per average population density of intersected counties.

To analyze trends, especially between Saffir-Simpson categories, a new graph was computed by removing the two outliers. 21 observations or 41.1% of total observations are outside the 95% confidence interval of fitted values computed by Stata. The top left outlier is from Hurricane Kate (0.42) The coefficient of the fitted values' regression line is β=0.000119.

Maximum Sustained Wind Speed at Landfall and NOAA Damages Normalized

Figure 2 shows a regression plot of Maximum Sustained Wind Speed at Landfall (x-axis) and standardized NOAA Cost of Damages (y-axis). 52 observations were computed. Among them, 1 is an outlier and does not allow the analysis of other observations. 2 other observations seem to be outside the 95% confidence interval on the fitted values computed by Stata. The largest outlier is Hurricane Harvey (15.62), the other being Hurricane Katrina (3.80). The coefficient of the fitted values' regression line is β=0.007045.

A new graph was computed to remove the outliers (Hurricane Harvey and Hurricane Katrina landfall events). In this new graph, 4 hurricanes were above the 95% confidence interval. All were Category 2, 3 or 4 events. Some events were below the 95% confidence interval but closer than the previous 4. The 4 points far above the confidence interval are from left to right, Hurricane Delta (0.66), Hurricane Bret (0.52), Hurricane Katrina (1.07), and Hurricane Harvey (1.40). Interestingly, these outliers are in Category 2-4 hurricanes, with none in Category 5, perhaps suggesting that their lower Category designation caused an underestimation of the risks of the hurricane that resulted in the high damages. The coefficient of the fitted values' regression line is β=0.0036712.

Maximum Sustained Wind Speed at Landfall and FEMA Recovery Aid Normalized

Figure 3 has maximum sustained wind speed at landfall (x-axis) and normalized recovery aid from FEMA (y-axis). 18 observations were computed, all between a ratio of 0.75 and 1.00. At least seven observations are outside the 95% confidence interval of fitted values. There were no extreme outliers, and with only 18 observations, only one graph was generated. The coefficient of the fitted values' regression line is β=0.0000424.

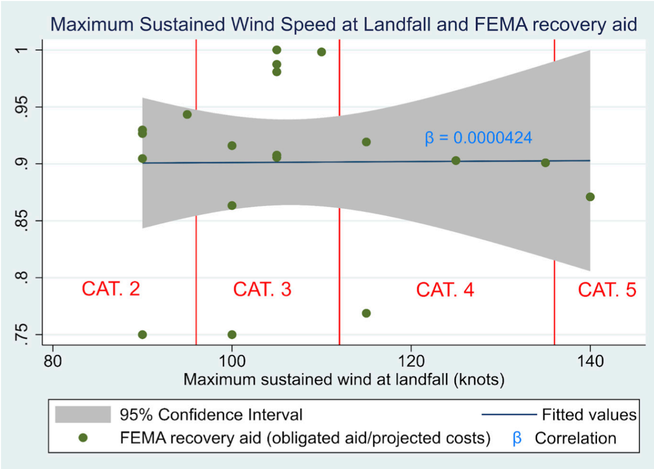

Figure 3. Maximum Sustained Wind Speed at Landfall vs. FEMA Recovery Aid Normalized. The unit of the x-axis is knots while the y-axis is a ratio of federally-obligated aid over the total project amount.

Discussion

Interpreting the Statistics

For each regression, the R-squared values, coefficients, and P values provide insight into the relationship between wind and hurricane outcome variables (see Table 2). The R-squared values suggest that the independent variable (maximum sustained wind speed at landfall) cannot explain the variation in the dependent variables (deaths, cost of damages, recovery aid). For the relationship between wind speed and deaths including outliers, the R-squared of 0.0052 was greater than the R-squared excluding outliers (0.0007). For the relationship between wind speed and cost of damages, the opposite was observed: R-squared for the relationship including outliers (0.0024) was less than the R-squared for the relationship excluding outliers (0.0457). The lower R-squared for the relationship between wind speed and deaths including outliers may point to the fact that in the case of outliers, wind speed variance explains less variance in outcomes than in hurricanes within the 95% confidence interval. The R-squared value for the relationship between wind speed and recovery aid was 0.0001.

Table 2: Regression Output Statistics

Analysis	**Correlation (β)**	**R-Squared**
Deaths (deaths/person/mi²)	0.0084779*	0.0052
Deaths without outliers	0.00012*	0.0007
Damages (2020 billion US$/person/mi²)	0.007045*	0.0024
Damages without outliers	0.0036712**	0.0457
Recovery (obligated aid/projected costs)	0.0000424*	0.0001

Level of significance: $* = 1 \geq p \geq 0.5$, $** = 0.5 > p \geq 0.1$

Low coefficient values (under 0.01) for each variable further suggest that there is a positive but weak correlation between wind speed and deaths and damages. This may in part be explained by the fact that some hurricanes weaken faster than others and thus correlation for wind speed at landfall may be lower than correlation to surface wind speed for all non-landfall counties. However, this analysis used wind speed at landfall to reflect the Saffir-Simpson scale, which is how counties assess hurricane intensity. For recovery aid, the correlation was so small that it can be considered flat (0.00004). P values (all ≥ 0.1) from deaths, damages, and recovery aid analysis suggest that the findings are not statistically significant, indicating strong evidence for the null hypothesis – in this case, that there is little relationship between the variables studied. We suspect that this is in part due to the limited sample size (n = 53), compared to the total number of hurricanes that occurred from 1970-2020. However, this may also suggest that using wind speed as the determining factor for hurricane risk does not reflect the real extent of the correlation between wind speed and hurricane impacts.

Spatial Variation

During data collection, we observed that many of the deaths caused by the hurricanes occurred outside intersected counties or states. This is demonstrated by the large disparity between the NOAA deaths, which are specific to county/state, and the EM-DAT deaths, which are country-wide. The disparity is visible in Fig. 4, which plots EM-DAT deaths against NOAA deaths, with a 1:1 ratio notated by the line x=y. Because EM-DAT has fewer recorded hurricane events than the NOAA database, this comparison has a somewhat smaller sample size than our main analysis, at 42 data points compared to 53.

Many of the external deaths were due to flooding caused by storm surge or heavy rainfall, following the trend that most hurricane deaths are caused by water (i.e. flooding and offshore deaths), in line with previous research which found that 80% of U.S. hurricane deaths occur in non-landfall counties[7,18]. Since the bulk of fatalities occur due to water, the hurricane does not have to directly hit an area for it to cause deaths. Hurricanes cause heavy rainfall across a large area, leading to flooding even if the area is not experiencing high winds, and the wind can kick up waves that reach a long distance to cause storm surges. The National Hurricane Center lists heavy rainfall and inland flooding, storm surge, rip currents, and tornadoes as the primary hazards of hurricanes, along with high winds[19]. While these factors are correlated with wind speed, Irish et al. (2008) demonstrate that for a given Saffir-Simpson intensity, storm surge can vary as much as 30%[20]. Between our results and existing research that shows the role of water in deaths from hurricanes, a hurricane scale that includes rainfall predictions may be more effective for hurricane warning and preparedness systems. Risk-prediction models that account for various hazards, such as wind and rain, storm surge, and freshwater inundation have been proposed by authors such as Baradaranshoraka et al. (2017)[21].

Outliers

Both NOAA deaths and damages had outliers that were two orders of magnitude higher than most other values, notably Hurricane Katrina and Hurricane Harvey. Neither hurricane was a Category 5, making landfall at Category 3 and 4 respectively. The magnitude of differences between the fitted line and observed deaths and damages, particularly in outliers, points to the critical human/social/political influence on storm outcomes. Much literature has analyzed the role of socioeconomic and demographic factors in determining hurricane impact.

For example, Parker et al. (2009) point to the psychological, organizational, and political factors that preconditioned the Katrina catastrophe[4]. Bullard (2007) additionally illustrates the "racial divide in the way the U.S. government responds to natural and man-made disasters, such as hurricanes and floods, and public health threats," and Bullard and Wright (2009) detail "the role of race and place and how unequal protection and unequal treatment make some populations more vulnerable in the rebuilding and recovery process"[8,22]. Addressing the role that social, political, and economic factors play in determining the outcomes of hurricanes will likely become increasingly important as climate change develops, repeating existing patterns of inequality and environmental injustices[23].

Alternative Scales

Although the scope of our research was limited, there is significant qualitative research on the importance of scale in perceiving and communicating hurricane risk[24,25]. Given the likelihood of increasingly frequent 'outlier' events as climate change worsens, a scale that does not correlate strongly to deaths and damages may not be an adequate tool for communicating risk. Kantha (2006, 2013) examines how the Saffir-Simpson Scale "was devised principally to predict the expected intensity of hurricane wind damage to structures," and while it has served this purpose, Kantha proposes a more comprehensive Hurricane Intensity Index used in conjunction with a Hurricane Hazard Index which captures the risk posed by storm surge, to prepare prior to landfall and for relief efforts, respectively[26,27]. Senkbeil and Sheridan (2006), noting that the Saffir-Simpson scale fails to accurately "account for observed impacts over land," also propose a Hurricane Classification System which also accounts for surges[28]. More recently, Rezapour and Baldock (2014) propose a hurricane hazard index that demonstrates a stronger correlation to deaths and damages for recent hurricanes (2003-2012) and includes a rainfall subindex[29], while Klotzbach et al. (2020) propose that indices account for surface pressure as well[30].

Nonetheless, this proliferation of new indices might undermine their acceptance and understanding by target users. Indeed, while the push for research in this area might develop powerful risk assessment tools, public authorities and citizens might become confused about which one to rely on, ultimately undermining hurricane hazard mitigation strategies. Lastly, residents of areas where hurricanes strike are deeply attached to their homes, and the decision to leave in the face of a hurricane is rarely solely a calculation of risk[31]. Future research that controls for how many people evacuate an area rather than total population density may provide deeper insight into the potential risk of hurricanes and success of emergency management planning. Further, while the adoption of a new scale may better capture hurricane risk, policies such as hurricane scales often take years to change, and more immediate strategies to improve the resilience of coastal areas are critical in the meantime.

Conclusion

In addition to accounting for more recent hurricanes, our research aligns with existing literature to conclude that the Saffir-Simpson Scale does not strongly correlate with hurricane impacts, namely the cost of damages incurred, deaths, and recovery aid. Discrepancies in the deaths and damages in counties intersected by hurricanes tracks compared to country-wide deaths and damages point to the importance of factors other than wind speed, such as storm surge or rainfall. Observed outliers further suggest the importance of social, political, and economic factors in determining hurricane impact. Given the likelihood that hurricanes will become more frequent and severe due to climate change, our research highlights the need for more comprehensive hurricane risk calculation and communication to minimize their impacts.

Additionally, our research has identified several areas for future research or action. Notably, the lack of a centralized federal database recording hurricane characteristics, deaths, cost of damages, federally obligated recovery aid, and emergency evacuation reports may present a barrier to future research. Constructing such a database could facilitate a better understanding of hurricanes and in turn improve hurricane preparation and response by federal agencies such as NOAA and FEMA. While we identified discrepancies in deaths and damages that occurred in counties or states intersected by hurricane tracks versus country-wide deaths and damages, another critical area of future research may include comparisons of indirect and direct deaths. For example, Rappaport & Blanchard (2016) found that since 1995, the ratio of indirect deaths to direct has increased from 1:2 to 2:1, partly due to differences in how deaths are categorized, but also potentially due to changes in electricity infrastructure and evacuation procedures[32]. The causes of indirect and direct deaths in intersected counties and counties outside the immediate hurricane track may be an area where research could be life-saving. Finally, while literature has already suggested new indices for evaluating hurricane risk and hazard, further research on combining social, political and economic vulnerability indices with storm surge, rainfall, and inland inundation risk indices will be critical in improving the resilience of coastal areas.

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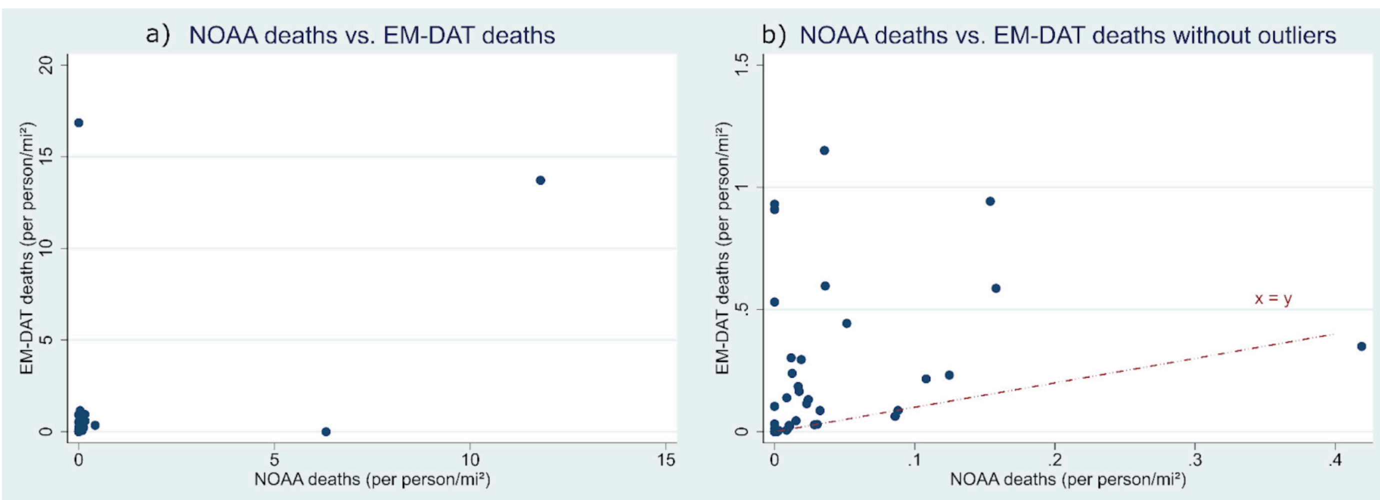

Figure 4. NOAA Deaths vs. EM-DAT Deaths. Figure 4a includes outliers while Figure 4b excludes outliers. The x-axis is NOAA deaths per average population density of intersected counties, and the y-axis is EM-DAT deaths per average population density of intersected counties.

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