**Association of tropical cyclones with county-level mortality in the United States**

**Date of revision:** January 25th 2022

*Robbie M Parks, PhD*

Department of Environmental Health Sciences, Mailman School of Public Health, Columbia University, New York, New York, USA

The Earth Institute, Columbia University, New York, New York, USA

*Jaime Benavides, PhD*

Department of Environmental Health Sciences, Mailman School of Public Health, Columbia University, New York, New York, USA

*G Brooke Anderson, PhD*

Department of Environmental & Radiological Health Sciences, Colorado State University, Fort Collins, Colorado, USA

*Rachel C Nethery, PhD*

Department of Biostatistics, T. H. Chan School of Public Health, Harvard University, Boston, Massachusetts, USA

*Ana Navas-Acien, PhD*

The Earth Institute, Columbia University, New York, New York, USA

Department of Environmental Health Sciences, Mailman School of Public Health, Columbia University, New York, New York, USA

*Francesca Dominici, PhD*

Department of Biostatistics, T. H. Chan School of Public Health, Harvard University, Boston, Massachusetts, USA

*Majid Ezzati, FMedSci*

MRC Centre for Environment and Health, School of Public Health, Imperial College London, London, UK

Abdul Latif Jameel Institute for Disease and Emergency Analytics, Imperial College London, London, UK

Regional Institute for Population Studies, University of Ghana, Legon, Ghana

*Marianthi-Anna Kioumourtzoglou, ScD*

Department of Environmental Health Sciences, Mailman School of Public Health, Columbia University, New York, New York, USA

**Corresponding Author:**

Robbie M Parks

Department of Environmental Health Sciences

Columbia University Mailman School of Public Health

722 West 168th Street, #1104, New York, New York, 10032

Email: [robbie.parks@columbia.edu](mailto:robbie.parks@columbia.edu)

Phone: +1 (212) 305-3748

**Word Count:**

Abstract: 410 words

Main Text: 2,999 words

**Key Points**

**Question:** In the United States from 1988–2018, were tropical cyclones associated with increases in county-level cause-specific death rates in subsequent months?

**Findings:** In this retrospective observational analysis that included 33.6 million deaths in 1,206 counties that experienced tropical cyclones from 1988-2018, each additional cyclone day per month was associated with increases in monthly county-level death rates in the month following a cyclone for several causes of death including injuries (3.7%), infectious and parasitic diseases (1.8%), respiratory diseases (1.3%), cardiovascular diseases (1.2%), and neuropsychiatric conditions (1.2%), but not for cancers.

**Meaning:** Among US counties that experienced at least one tropical cyclone from 1988–2018, each additional cyclone day per month was associated with modestly higher death rates in the months following the cyclone for several causes of death.

**Abstract**

**Importance:** Tropical cyclones have a devastating effect on society, but a comprehensive assessment of their association with cause-specific mortality over multiple years of study is lacking.

**Objective:** To comprehensively evaluate the association of county-level tropical cyclone exposure and death rates from various causes in the United States.

**Design, Setting, and Participants:** A retrospective observational study using a Bayesian conditional quasi-Poisson model to examine how tropical cyclones were associated with monthly death rates. Data from 33.6 million deaths in the United States were collected from the National Center for Health Statistics over 31 years (1988–2018)**,** including residents of the 1,206 counties in the United States which experienced at least one tropical cyclone during the study period.

**Exposure:** Tropical cyclone days per county-month, defined as number of days in a month with a sustained maximal wind speed ≥34 knots.

**Main Outcomes and Measures:** Monthly cause-specific county-level death rates by six underlying causes of death: cancers, cardiovascular diseases, infectious and parasitic diseases, injuries, neuropsychiatric conditions, and respiratory diseases. The model yielded information about the association between each additional cyclone day per month and monthly county-level mortality compared with the same county-month in different years, up to six months after tropical cyclones and how these estimated associations varied by age, sex, and social vulnerability. The unit of analysis was county-month.

**Results:** There were 33,619,393 deaths in total (16,691,681 females and 16,927,712 males; 8,587,033 0-64 years and 25,032,360 65+ years) from the six causes recorded in 1,206 US counties. There was a median of 2 tropical cyclone days experienced in total in included US counties.Each additional cyclone day was associated with increased death rates in the month following the cyclone for injuries (3.7%[95%CrI,2.5%–4.9%]; 2.0[95%CrI,1.3,2.7] additional deaths per 1,000,000 for 2018 monthly age-standardized median rate (DPM); 54.3 to 56.3 DPM), infectious and parasitic diseases (1.8%[95%CrI,0.1%–3.6%]; 0.2[95%CrI,0.0,0.4] additional DPM; 11.7 to 11.9 DPM), respiratory diseases (1.3%[95%CrI,0.2%–2.4%]; 0.6[95%CrI,0.1,1.1] additional DPM; 44.9 to 45.5 DPM), cardiovascular diseases (1.2%[95%CrI,0.6%–1.7%]; 1.5[95%CrI,0.8,2.2] additional DPM; 129.6 to 131.1 DPM), neuropsychiatric conditions (1.2%[95%CrI,0.1%–2.4%]; 0.6[95%CrI,0.1,1.2] additional DPM; 52.1 to 52.7 DPM), with no change for cancers (-0.3%[95%CrI,-0.9%–0.3%]; -0.3[95%CrI,-0.9,0.3] additional DPM; 100.4 to 100.1 DPM).

**Conclusions and Relevance:** Among US counties that experienced at least one tropical cyclone from 1988–2018, each additional cyclone day per month was associated with modestly higher death rates in the months following the cyclone for several causes of death, including injuries, infectious and parasitic diseases, cardiovascular diseases, neuropsychiatric conditions, and respiratory diseases.

**Introduction**

In the United States and worldwide, hurricanes and other tropical cyclones have had a devastating effect on society.1–4 Recent tropical cyclone seasons—which have yielded stronger,5 more active,6 andlonger-lasting7 tropical cyclones than previously recorded—indicate that tropical cyclones will remain an important public health concern. States in the Atlantic and Gulf Coasts, most frequently exposed to tropical cyclones, have among the fastest growing populations in the United States and contain nearly half the population of the entire country.8 There is an intense concentration of economic and social activity in these states,9 which have also been particularly vulnerable to damage from climate change.10 While immediate coastal locations are often enclaves of wealth, an outsized proportion of low-income and historically-disadvantaged communities in the United States also reside in tropical cyclone-affected areas.11 Though tropical cyclones have not been selective of the communities they have affected, community characteristics have played an important role in their protection and resilience.12

Tropical cyclones have previously been associated with a wide range of hospital admissions in the US during 1999-2014.4 However, beyond a few case studies, including after Hurricane Maria in 201713 and after Hurricane Sandy in 2012,14 there remains a critical knowledge gap about cause-specific tropical cyclone-related mortality risks; a large-scale, multi-year study is needed to gain further insight and is an essential step in disaster risk reduction.15 This comprehensive study of tropical cyclones affecting the United States over a 31-year period evaluated how tropical cyclones were associated with deaths from major causes up to six months post-cyclone in the United States, and how the associations varied by strength of tropical cyclone, age, sex, and social vulnerability.

**Methods**

This study was approved by the Institutional Review Board at the Columbia Mailman School of Public Health and was classified as exempt from needing to obtain Informed Consent (Protocol IRB-AAAT9710).

*Study population*

Data on deaths by age, sex, cause, and county of residence in counties of the United States that experienced at least one tropical cyclone during 1988–2018 through the National Center for Health Statistics (NCHS) were used, described in the Supplement. A subset of the data from counties that experienced at least one hurricane or at least one gale to violent storm during the study period was used. County-level annual population data from the NCHS bridged-race dataset for 1990–2018 and from the US Census Bureau before 1990 were used. Monthly population counts were calculated through linear interpolation of annual counts, assigning each yearly count to June. County-level data on social vulnerability from the Centers for Disease Control and Prevention (CDC) Social Vulnerability Index (SVI) for 2018 were used, a relative measure of social vulnerability of every US county which incorporates data from the US Census on socioeconomic status; household composition and disability; minority status and language; and housing type and transportation.11 Included counties were divided into SVI tertiles (low vulnerability to high vulnerability, 1 to 3 (eAppendix, eFigures 4-5).

*Exposure*

Data were obtained on tropical cyclones in the United States, indicated by windspeed, and categorized by county and month into all tropical cyclones (≥34 knots), as well as subset of the data including only hurricanes (≥64 knots), described fully in the Supplement.4,16 Data on county-level monthly mean temperature were obtained from Parameter-elevation Regressions on Independent Slopes Model (PRISM).17

*Outcomes*

The underlying cause of death, defined by the World Health Organization (WHO) as the primary disease or injury that initiated the train of events leading directly to death,18 was coded according to the *International Classification of Diseases* (ICD) system (9th revision before 1998 and 10th revision thereafter) and WHO Global Health Estimate cause categories.19

Underlying causes of death were classified into seven categories: cancers, cardiovascular diseases, infectious and parasitic diseases, injuries, neuropsychiatric conditions, respiratory diseases, and an aggregate set of other death causes (eTable 1). The results of all of these categories were reported except other causes of death. The “other causes” category was not included because the diversity of causes it captures led to substantial heterogeneity, and the composition varied greatly by age, sex, county, and time.

*Statistical analysis*

The county-level association between number of days in a month with tropical cyclone exposure and monthly death rates was analyzed by applying a Bayesian formulation of the conditional quasi-Poisson model,20 including unconstrained distributed lag terms up to six months after tropical cyclones. The quasi-Poisson model accounts for potentially overdispersed outcomes. This conditional approach examines contrasts within matched strata (in this case county-months, as described below), similar to a case-crossover study design, thus controlling for confounding bias that could arise by factors varying across strata, such as socioeconomic status (SES), in a computationally efficient way.20 Bayesian inference allows for the full distributional estimation of the parameters of interest, as well as ‘borrowing of information’ across county units.21 Bidirectional matching was made by county and month of the year, only comparing a tropical cyclone-exposed county-month in a particular year to the same county-month in all other included years, thus effectively controlling for any non-time varying factors that varied across counties (such as seasonal hours of daylight) in the analyses, as well as seasonality. Although the conditional formulation adjusts for most sources of confounding by matching each county-month to itself, long-term trends (via a natural spline) and temperature (via a second order random walk term; equivalent to a spline with equally-spaced knots) were also specifically adjusted for. A county-month-specific population offset was included so that changes in death rates were analyzed*.* Unconstrained distributed lag terms for the exposure counts were included,22,23 to quantify the association between each additional day of tropical cyclone exposure in a month and death rates up to six months post-cyclone. Therefore, a tropical cyclone in one particular month would be considered a lagged tropical cyclone in another month for the relevant distributed lag term.22,23 Full details on model terms are described in the Supplement.

Analyses were conducted separately by cause of death and class of tropical cyclone (all tropical cyclones, hurricanes), with further analyses stratified by broad age groups (0-64 and 65+ years), as older adults have been identified as vulnerable to being hospitalized from tropical cyclones,4 finer age groups (0-24 years, 25-44 years, 45-64 years, 65-84 years and 85+ years), sex (female/male), and county-level social vulnerability tertiles (low vulnerability to high vulnerability, 1 to 3), because death rates vary by these characteristics,24–26 as might their associations with tropical cyclones.

The sensitivity of the results to temperature adjustment (i.e., including temperature in the model or not) and limiting the matched control period of tropical cyclone exposure to years in the same 5-year period, in addition to the month and county matching, were assessed*.*

Results are presented as relative (percentage) changes per one day increase in tropical cyclones in a month and as deaths per 1,000,000 for 2018 monthly age-standardized median rate (DPM) by multiplying the relative changes by the median (50th percentile) death rates for 2018 from eTables 2-3. Any reported positive association was based on a positive point estimate with a two-sided 95% credible interval (CrI) which excluded the null, with a negative association the same but with a negative point estimate. Any comparative analyses of effect estimates were obtained by a formal comparative analysis of 1,000 draws from the posterior marginal distribution of each effect estimate; the proportion of draws that was higher than the other set of draws represented the probability that one effect estimate was higher than the one compared to.21 Statistical analyses were conducted using the R Statistical Software, version 3.6.3 (Foundation for Statistical Computing, Vienna, Austria), integrated nested Laplace approximation (INLA) in R-INLA, version 21.03.17, and the ns function from the splines package, version 3.6.3. Study findings should be interpreted as exploratory, due to numerous outcomes and issues related to multiple comparisons. There were no missing data.

**Results**

*Tropical cyclones*

1,206 counties, covering 48.1% of the 2018 population of the United States, experienced at least one tropical cyclone during the 31-year study period (Figure 1, eFigure 1) with a total of 4,978 tropical cyclone county-days in 4,842 county-months (Table 1). For included counties, the total number of tropical cyclone days across all years ranged from 1 to 26, with median of 2 (mean=4.1). Tropical cyclones occurred May-November, with greatest occurrence in September (n=2,188). Tropical cyclones were most frequent in the eastern and southeastern coastal counties. There were 233 hurricane county-days in 228 county-months across 153 counties, including 9.0% of the 2018 population of the United States. The total number of hurricane days across all years ranged from 1 to 5, with a median of 1 (mean=1.5). Hurricanes occurred July-October, with greatest occurrence in September (n=99).

*Deaths*

During 1988–2018, in included counties, there were 38,756,460 deaths (Table 1). For the six studied causes (cancers, cardiovascular diseases, infectious and parasitic diseases, injuries, neuropsychiatric conditions, and respiratory diseases) there were 33,619,393 deaths (86.7% of total deaths in tropical cyclone-exposed counties). 16,691,681 females and 16,927,712 males died from the six studied causes; 81.1% of female and 67.9% of male deaths were among those aged 65+ years (eFigures 2-3).Cardiovascular diseases were the leading cause of death overall (129.6 deaths per 1,000,000 for 2018 monthly age-standardized median rate (DPM)), by sex (98.9 and 157.1 DPM for females and males), for 65+ years (1053.7 DPM) and social vulnerability tertile (109.0, 130.4, and 156.8 DPM for SVIs 1-3) (eTables 2-3). Deaths from injuries were mostly among those aged 0-64 years (59.2% for females and 78.1% for males) and were the leading cause of death for this age group (43.7 DPM).

*Association of tropical cyclones and hurricanes with total death rates*

Highest overall increases were observed in injury-related mortality after tropical cyclones, peaking one month post-cyclone (3.7% [95%CrI,2.5%–4.9%]; 2.0 [95%CrI,1.3,2.7] additional DPM; 54.3 to 56.3 DPM) and the month of a hurricane (33.4% [95%CrI,28.3%–38.8%]; 18.2 [95%CrI,15.4,21.1] additional DPM; 54.5 to 72.7 DPM) (Figure 2, eTable 4).Infectious and parasitic disease death rate increases peaked one month post-cyclone (1.8% [95%CrI,0.1%–3.6%]; 0.2 [95%CrI,0.0, 0.4] additional DPM; 11.7 to 11.9 DPM) and two months post-hurricane (11.4% [95%CrI,4.7%–18.4%]; 1.5 [95%CrI,0.6,2.4] additional DPM; 13.3 to 14.8 DPM). Respiratory disease death rate increases peaked one month post-cyclone (1.3% [95%CrI,0.2%–2.4%]; 0.6 [95%CrI,0.1,1.1] additional DPM; 44.9 to 45.5 DPM), and one month post-hurricane (8.3% [95%CrI,4.0%–12.7%]; 3.6 [95%CrI,1.7,5.5] additional DPM; 43.2 to 46.8 DPM). Cardiovascular disease death rate increases peaked one month post-cyclone (1.2% [95%CrI,0.6%–1.7%]; 1.5 [95%CrI,0.8,2.2] additional DPM; 129.6 to 131.1 DPM) and the month of a hurricane (4.4% [95%CrI,2.3%–6.5%]; 5.7 [95%CrI,3.0,8.5] additional DPM; 130.4 to 136.1 DPM). Neuropsychiatric condition death rate increases peaked one month post-cyclone (1.2% [95%CrI,0.1%–2.4%]; 0.6 [95%CrI,0.1,1.2] additional DPM; 52.1 to 52.7 DPM) and the month of a hurricane (9.9% [95%CrI,5.6%–14.3%]; 5.0 [95%CrI,2.8,7.2] additional DPM; 50.5 to 55.5 DPM). Cancer death rates did not change in the six months after tropical cyclones or hurricanes (e.g., one month post-cyclone, -0.3% [95%CrI,-0.9%–0.3%]; -0.3 [95%CrI,-0.9,0.3] additional DPM; 100.4 to 100.1 DPM).

*Association of tropical cyclones with death rates by age group and sex*

Increases in injury death rates were larger for 65+ years in the first two months after a tropical cyclone (Figure 3, eTable 5) (>99% posterior probability) (e.g., one month post-cyclone, 6.4% [95%CrI,4.2%,8.7%]; 6.2 [95%CrI,4.0,8.4] additional DPM; 96.6 to 102.8 DPM) for 65+ years and 2.7% [95%CrI,1.3%,4.2%]; 1.2 [95%CrI,0.6,1.8] additional DPM; 43.7 to 44.9 DPM) for 0-64 years). The association of hurricanes by broad age group as well as by finer age groupings (eFigures 6-8) was also examined in stratified analyses. For females and males associations were largely consistent and similar (eFigures 9-10), though relative increases in injury death rates in the month of a hurricane were higher for females than for males (>99% posterior probability) (46.5% [95%CrI,37.3%,56.4%]; 13.7 [95%CrI,11.0,16.6] additional DPM; 29.5 to 43.2 DPM) for females and 27.6% [95%CrI,21.9%,33.6%]; 21.0 [95%CrI,16.7,25.6] additional DPM; 76.1 to 97.1 DPM) for males).

*Association of tropical cyclones with death rates by social vulnerability*

For injuries, death rates in the most vulnerable tertile (3) were larger than the least vulnerable tertile (1) one month post-cyclone (5.5% [95%CrI,3.1%,7.8%]; 3.3 [95%CrI1.9,4.8] additional DPM; 60.8 to 64.1 DPM for most vulnerable (3) and 2.6% [95%CrI,0.1%,5.0%]; 1.2 [95%CrI,0.1,2.4] additional DPM; 46.7 to 47.9 DPM for least vulnerable (1); 96% posterior probability that 3rd tertile>1st tertile) (Figure 4, eTable 6). The association of hurricanes by social vulnerability was also examined, with >99% posterior probability that increases in injury death rates in 3rd tertile>1st tertile in the month of a hurricane (eFigure 11). There was a correlation of 0.91 between the first year available of SVI data (2000) to the SVI data used in this analysis (2018) (eFigure 5).

Full results of formal comparisons by posterior draws of model parameters are found in eTables 7-12.

*Sensitivity analyses*

For temperature sensitivity analyses (eFigure 12), there was correlation of R=0.99 and a slope of 1.00 [95%CrI,0.98–1.01] between estimates of associations with (main) and without (sensitivity) temperature in the model. For sensitivity analyses limiting county-month matching to control periods in nearby years (eFigure 13), there was a correlation of R=0.95 and a slope of 0.95 [95%CrI,0.88–1.05] between estimates of associations without (main) and with (sensitivity) the 5-year matching control period restriction. The same conclusions would be drawn from the main and sensitivity analyses.

**Discussion**

Among US counties that experienced at least one tropical cyclone from 1988–2018, each additional cyclone day per month was associated with modestly higher death rates in the months following the cyclone for several causes of death.

There were generally county-level increases in death rates on the month of and months after tropical cyclones when compared to the same months in years without tropical cyclones. Directly-related deaths are caused by the physical forces of tropical cyclones, whereas indirect deaths are caused by unsafe or unhealthy conditions in their aftermath.1 Well-known direct threats to lives include drowning while driving motor vehicles in shallow water, being mortally wounded from flying objects, and electrocution from downed power lines.1,27–29 The observed increases up to six months after tropical cyclones for some outcomes indicates that some associations could be due to indirect pathways, such as cardiovascular failure, medical equipment outage, and disruption of normal care for those already vulnerable.1,28

After a tropical cyclone, injury deaths could result from direct causes, such as drowning,27,30 and indirect causes, such as mortal injuries in clean-up efforts or intentional self-harm from economic hardship after destruction of property.1 Infectious and parasitic diseases may spread from compromised drinking water and sanitation, damage to water pipes and disruption to treatment plants, as well as standing water.1 Cardiovascular disease death increases have been linked to heart attacks and cardiac arrests from physical overexertion,28 as well as increases in stress31 and disruption in treatment of chronic conditions.32. Neuropsychiatric condition deaths from the high prevalence in anxiety-mood disorders were evident after Hurricane Harvey and Hurricane Katrina.30 There was increased risk of dementia diagnosis after natural disasters such as earthquakes and tsunamis in Japan.33 Respiratory disease deaths could be related to disrupted power supplies for breathing aids.34,35 High winds during tropical cyclones may spread dust and other particulates into the air, exacerbating chronic respiratory diseases.36 Residents in low-income and historically disadvantaged communities have been differentially affected after disasters,37 consistent with some findings here of larger relative and absolute increases in death rates in socially vulnerable counties.

Leveraging complete death data from 33.6 million deaths and a curated tropical cyclone dataset over a 31-year period, this study is the first, to our knowledge, comprehensive investigation of the association of tropical cyclones with cause-specific deaths and by age group, sex, and social vulnerability.

**Limitations**

This study has several limitations. First, a potential limitation is exposure misclassification, if decedents’ recorded county of residence differs from the actual location during a tropical cyclone. Exposure misclassification, however, is likely non-differential as it is not expected to be correlated with the outcomes assessed, potentially biasing towards the null.38 Second, the analysis may have been susceptible to confounding. By matching on county-month of tropical cyclone occurrence and using the conditional Poisson model to account for the matching, this design controls for factors varying across counties, as well as month and season, but the possibility of residual confounding by unknown or unmeasured factors cannot be ruled out. Long-term trends, such as temperature and population age composition were also adjusted for, by temperature terms and in age-stratified models, respectively. Any variable would have to covary with both death rates and tropical cyclones in counties and be independent of the variables included in analyses to induce residual confounding*.* Third, wind speed was used as an identifier of hurricanes and tropical cyclones; the causal pathways will include other environmental hazards and should be further explored. Fourth, this study was focused on the continental United States, though devastating effects of hurricanes, such as Hurricane Maria in Puerto Rico, have also been recorded.13 Fifth, the overall association of tropical cyclone exposure with death rates over three decades was examined; however, like any exposure, results may have variations over time, space, and communities, which future work should highlight and examine further, as well as examine excess mortality by specific events. Sixth, the unit of analysis was US county. Counties contain disparities within them, which was not captured by the analysis. Future work may be able to study associations by smaller areal units, e.g., ZIP Code, as appropriate exposure and outcome data become available. Seventh, analysis of social vulnerability used 2018 values for the entire study period; however, rankings of social vulnerability change over time, though there was a high correlation of social vulnerability when comparing first available (2000) and last available (2018) years. Eighth, the data used extended only through 2018, and it is unknown whether the findings of this study reflect more recent cyclone activity and mortality following cyclones.

**Conclusions**

Among US counties that experienced at least one tropical cyclone from 1988–2018, each additional cyclone day per month was associated with modestly higher death rates in the months following the cyclone for several causes of death, including injuries, infectious and parasitic diseases, cardiovascular diseases, neuropsychiatric conditions, and respiratory diseases.

**Acknowledgements**

**Author contributions:** Dr Parks had full access to all the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis.

*Study concept and design:* Parks, Kioumourtzoglou.

*Acquisition, analysis, or interpretation of the data:* Parks, Anderson, Navas-Acien, Ezzati, Kioumourtzoglou.

*Drafting of the manuscript:* Parks, Kioumourtzoglou.

*Critical revision of the manuscript for important intellectual content:* Benavides, Anderson, Nethery, Navas-Acien, Dominici, Ezzati, Kioumourtzoglou.

*Statistical analysis:* Parks, Anderson, Benavides, Nethery, Dominici, Ezzati, Kioumourtzoglou.

*Obtained funding*: Parks, Dominici, Ezzati, Kioumourtzoglou.

*Administrative, technical, or material support:* Parks, Anderson, Ezzati, Kioumourtzoglou.

*Study Supervision*: Kioumourtzoglou.

**Conflict of interest disclosures:** Majid Ezzati reports a charitable grant from AstraZeneca Young Health Programme, and personal fees from Prudential, Scor, and Third Bridge, all outside the submitted work; all other authors declare no competing interests.

**Funding/Support:** Robbie M Parks was supported by the NIEHS K99 ES033742 and the Earth Institute post-doctoral research fellowship at Columbia University. Francesca Dominici was funded by the Climate Change Solutions Fund. Funding was also provided by the National Institute of Environmental Health Sciences (NIEHS) grants R01 ES030616, R01 ES028805, R01 ES028033, R01 MD012769, R01 AG066793, R01 ES029950, R01 AG060232, RF1 AG071024, R21 ES028472, P30 ES009089, and P42 ES010349. Majid Ezzati is funded by the Pathways to Equitable Healthy Cities grant from the Wellcome Trust (209376/Z/17/Z), the UK Medical Research Council (MRC) through the MRC Centre for Environment and Health (MR/S019669/1), and the British Heart Foundation Imperial College Centre for Research Excellence (RE/18/4/34215). Work on the US mortality data is supported by a grant from US Environmental Protection Agency, as part of the Center for Clean Air Climate Solution (assistance agreement no. R835873). This paper has not been formally reviewed by EPA. The views expressed in this document are solely those of authors and do not necessarily reflect those of the Agency. EPA does not endorse any products or commercial services mentioned in this publication.

**Role of the Funder/Sponsor:** The funders had no role in the design and conduct of the study; collection, management, analysis, and interpretation of the data; preparation, review, or approval of the manuscript; and decision to submit the manuscript for publication.

**Code availability:** All code will be publicly available via GitHub.

**References**

1. Shultz JM, Russell J, Espinel Z. Epidemiology of tropical cyclones: The dynamics of disaster, disease, and development. *Epidemiol Rev*. 2005;27(1):21-35. doi:10.1093/epirev/mxi011

2. Peduzzi P, Chatenoux B, Dao H, et al. Global trends in tropical cyclone risk. *Nature Climate Change*. 2012;2(4):289-294.

3. Weinkle J, Landsea C, Collins D, et al. Normalized hurricane damage in the continental United States 1900–2017. *Nat Sustain*. 2018;1(12):808-813. doi:10.1038/s41893-018-0165-2

4. Parks RM, Anderson GB, Nethery RC, Navas-Acien A, Dominici F, Kioumourtzoglou MA. Tropical cyclone exposure is associated with increased hospitalization rates in older adults. *Nature Communications*. 2021;12(1):1-12.

5. Wang S, Toumi R. Recent migration of tropical cyclones toward coasts. *Science*. 2021;371(6528):514-517.

6. National Oceanic and Atmospheric Administration. 2020 Atlantic Hurricane season takes infamous top spot for busiest on record. Published 2020. Accessed November 24, 2020. https://www.noaa.gov/news/2020-atlantic-hurricane-season-takes-infamous-top-spot-for-busiest-on-record

7. Li L, Chakraborty P. Slower decay of landfalling hurricanes in a warming world. *Nature*. 2020;587(7833):230-234. doi:10.1038/s41586-020-2867-7

8. US Census Bureau. Coastal areas. The United States Census Bureau. Published 2020. Accessed May 13, 2021. https://www.census.gov/topics/preparedness/about/coastal-areas.html

9. NOAA. *National Coastal Population Report: Population Trends from 1970 to 2020*.; 2021. Accessed May 13, 2021. https://coast.noaa.gov/digitalcoast/training/population-report.html

10. Hsiang S, Kopp R, Jina A, et al. Estimating economic damage from climate change in the United States. *Science*. 2017;356(6345):1362-1369.

11. Flanagan BE, Hallisey EJ, Adams E, Lavery A. Measuring community vulnerability to natural and anthropogenic hazards: the Centers for Disease Control and Prevention’s Social Vulnerability Index. *Journal of environmental health*. 2018;80(10):34.

12. Bodenreider C, Wright L, Barr O, Xu K, Wilson S. Assessment of social, economic, and geographic vulnerability pre- and post-Hurricane Harvey in Houston, Texas. *Environmental Justice*. 2019;12(4):182-193. doi:10.1089/env.2019.0001

13. Kishore N, Marqués D, Mahmud A, et al. Mortality in Puerto Rico after Hurricane Maria. *New England Journal of Medicine*. 2018;379(2):162-170. doi:10.1056/NEJMsa1803972

14. Kim S, Kulkarni PA, Rajan M, et al. Hurricane Sandy (New Jersey): Mortality rates in the following month and quarter. *American Journal of Public Health*. 2017;107(8):1304-1307.

15. Shultz JM, Galea S. Preparing for the next Harvey, Irma, or Maria — addressing research gaps. *New England Journal of Medicine*. 2017;377(19):1804-1806. doi:10.1056/NEJMp1712854

16. Anderson GB, Ferreri J, Al-Hamdan M, et al. Assessing United States County-Level Exposure for Research on Tropical Cyclones and Human Health. *Environmental health perspectives*. 2020;128(10):107009. doi:10.1289/EHP6976

17. PRISM Climate Group. The PRISM Climate and Weather System - An Introduction. Published online 2013. https://prism.oregonstate.edu/documents/PRISM\_history\_jun2013.pdf

18. World Health Organization. *Medical Certification of Cause of Death: Instructions for Physicians on Use of International Form of Medical Certificate of Cause of Death*. World Health Organization; 1979.

19. Boerma T, Mathers CD. The World Health Organization and global health estimates: improving collaboration and capacity. *BMC medicine*. 2015;13(1):1-4.

20. Armstrong B, Gasparrini A, Tobias A. Conditional Poisson models: a flexible alternative to conditional logistic case cross-over analysis. *BMC Medical Research Methodology*. Published online 2014. doi:10.1186/1471-2288-14-122

21. Gelman A, Carlin JB, Stern HS, Dunson DB, Vehtari A, Rubin DB. *Bayesian Data Analysis, Third Edition*. CRC Press; 2013.

22. Schwartz J. The distributed lag between air pollution and daily deaths. *Epidemiology*. 2000;11(3):320-326.

23. Bobb JF, Obermeyer Z, Wang Y, Dominici F. Cause-specific risk of hospital admission related to extreme heat in older adults. *JAMA*. 2014;312(24):2659-2667.

24. Lozano R, Naghavi M, Foreman K, et al. Global and regional mortality from 235 causes of death for 20 age groups in 1990 and 2010: A systematic analysis for the Global Burden of Disease Study 2010. *The Lancet*. Published online 2012. doi:10.1016/S0140-6736(12)61728-0

25. Parks RM, Bennett JE, Foreman KJ, Toumi R, Ezzati M. National and regional seasonal dynamics of all-cause and cause-specific mortality in the USA from 1980 to 2016. *eLife*. 2018;7. doi:10.7554/eLife.35500

26. Murray CJ, Kulkarni S, Ezzati M. Eight Americas: New perspectives on US health disparities. *American journal of preventive medicine*. 2005;29(5):4-10.

27. Rappaport EN. Fatalities in the United States from Atlantic tropical cyclones: New data and interpretation. *Bull Amer Meteor Soc*. 2014;95(3):341-346. doi:10.1175/BAMS-D-12-00074.1

28. Rappaport EN, Blanchard BW. Fatalities in the United States indirectly associated with Atlantic tropical cyclones. *Bull Amer Meteor Soc*. 2016;97(7):1139-1148. doi:10.1175/BAMS-D-15-00042.1

29. Tellman B, Schank C, Schwarz B, Howe PD, de Sherbinin A. Using Disaster Outcomes to Validate Components of Social Vulnerability to Floods: Flood Deaths and Property Damage across the USA. *Sustainability*. 2020;12(15):6006. doi:10.3390/su12156006

30. Shultz JM, Galea S. Mitigating the mental and physical health consequences of Hurricane Harvey. *Jama*. 2017;318(15):1437-1438.

31. Cruz-Cano R, Mead EL. Causes of excess deaths in Puerto Rico after Hurricane Maria: a time-series estimation. *American journal of public health*. 2019;109(7):1050-1052.

32. Swerdel JN, Janevic TM, Cosgrove NM, Kostis JB, Group MIDAS (MIDAS 24) S. The effect of Hurricane Sandy on cardiovascular events in New Jersey. *Journal of the American Heart Association*. 2014;3(6):e001354.

33. Hikichi H, Aida J, Kondo K, et al. Increased risk of dementia in the aftermath of the 2011 Great East Japan Earthquake and Tsunami. *PNAS*. 2016;113(45):E6911-E6918. doi:10.1073/pnas.1607793113

34. Lane K, Charles-Guzman K, Wheeler K, Abid Z, Graber N, Matte T. Health effects of coastal storms and flooding in urban areas: A review and vulnerability assessment. *Journal of Environmental and Public Health*. 2013;2013:1-13. doi:10.1155/2013/913064

35. Liu H, Davidson RA, Rosowsky DV, Stedinger JR. Negative binomial regression of electric power outages in hurricanes. *Journal of infrastructure systems*. 2005;11(4):258-267.

36. World Meteorological Organization. *Sand and Dust Storms*.; 2017. Accessed November 17, 2021. https://public.wmo.int/en/https%3A//www.wmo.int/sdswas

37. Fothergill A, Peek LA. Poverty and disasters in the United States: A review of recent sociological findings. *Natural Hazards*. 2004;32(1):89-110. doi:10.1023/B:NHAZ.0000026792.76181.d9

38. Carroll RJ, Ruppert D, Stefanski LA, Crainiceanu CM. *Measurement Error in Nonlinear Models: A Modern Perspective*. CRC press; 2006.

**Table 1.** Tropical cyclones from 1988–2018 and their maximal intensities recorded in the United States (in knots), with number of tropical cyclone exposures in the United States and total deaths in included counties per year. Underlined tropical cyclone names were subsequently retired by the World Meteorological Organization because of destruction wreaked in the United States or elsewhere. Tropical cyclone names in grey did not contribute any tropical cyclone exposures in the United States.

|  |  |  |  |
| --- | --- | --- | --- |
| **Year** | **Tropical cyclones (maximal intensity in United States (knots))** | **Tropical cyclone exposures** | **Total deaths in analysis from included counties** |
| 1988 | Alberto (22.8), Beryl (44.8), Chris (34.1), Florence (51.4), Gilbert (33.0), Keith (47.8), AL13 (11.3), AL14 (27.8), AL17 (12.6) | 53 | 1,009,179 |
| 1989 | Allison (45.0), Chantal (59.0), Hugo (94.1), Jerry (60.2) | 244 | 994,218 |
| 1990 | AL01 (16.7), Bertha (11.0), Marco (46.7) | 12 | 993,622 |
| 1991 | Ana (20.0), Bob (75.6), Fabian (22.8), AL12 (30.9) | 100 | 1,002,601 |
| 1992 | AL02 (25.0), Andrew (110.0), Danielle (46.8), Earl (19.2) | 101 | 1,007,167 |
| 1993 | AL01 (9.8), Arlene (31.4), Emily (57.9) | 35 | 1,044,692 |
| 1994 | Alberto (44.4), AL02 (27.0), Beryl (49.4), Gordon (50.5) | 55 | 1,049,668 |
| 1995 | Allison (49.8), Dean (34.4), Erin (72.4), Gabrielle (21.9), Jerry (35.0), Opal (82.9) | 282 | 1,063,748 |
| 1996 | Arthur (25.5), Bertha (81.8), Edouard (34.4), Fran (88.3), Josephine (49.5) | 383 | 1,061,303 |
| 1997 | AL01 (19.0), Ana (12.3), Danny (58.4) | 57 | 1,054,165 |
| 1998 | Bonnie (93.1), Charley (36.5), Earl (64.8), Frances (43.6), Georges (83.3), Hermine (30.6), Mitch (51.5) | 300 | 1,058,349 |
| 1999 | Bret (91.7), Dennis (54.5), AL07 (16), Floyd (75.8), Harvey (44.7), Irene (65.0) | 247 | 1,079,454 |
| 2000 | AL04 (17.8), Beryl (25.5), AL09 (24.4), Gordon (46.8), Helene (39.9), Leslie (29.9) | 35 | 1,083,674 |
| 2001 | Allison (41.3), Barry (51.8), Gabrielle (54.9), Karen (14.6), Michelle (24.6) | 71 | 1,083,045 |
| 2002 | Arthur (20.3), Bertha (31.0), Cristobal (13.4), Edouard (31.3), Fay (45.2), Gustav (36.9), Hanna (42.4), Isidore (50.5), Kyle (34.0), Lili (69.9) | 96 | 1,089,933 |
| 2003 | Bill (45.3), Claudette (66.2), AL07 (21.8), Erika (47.9), Grace (34.7), Henri (28.7), Isabel (81.7) | 227 | 1,087,587 |
| 2004 | Alex (51.7), Bonnie (28.9), Charley (107.3), Frances (87.4), Gaston (59.3), Hermine (32.3), Ivan (85.4), Jeanne (98.1), Matthew (26.2) | 303 | 1,067,225 |
| 2005 | Arlene (43.5), Cindy (54.3), Dennis (87.0), Emily (45.3), Katrina (97.0), Ophelia (54.6), Rita (82.0), Tammy (39.3), Twenty-Two (27.0), Wilma (79.5) | 268 | 1,082,681 |
| 2006 | Alberto (37.2), Beryl (34.3), Chris (9.3), Ernesto (47.0) | 114 | 1,069,021 |
| 2007 | Andrea (21.9), Barry (37.7), Erin (47.7), Gabrielle (42.4), Humberto (67.6), Ten (23.2), Noel (31.0) | 89 | 1,065,336 |
| 2008 | Cristobal (31.7), Dolly (64.3), Edouard (50.6), Fay (58.7), Gustav (87.1), Hanna (55.2), Ike (88.8), Kyle (35.3), Paloma (8.9) | 544 | 1,084,664 |
| 2009 | One (10.4), Claudette (37.8), Ida (30.7) | 6 | 1,068,770 |
| 2010 | Alex (32.0), Two (24.8), Bonnie (30.6), Five (24.9), Earl (31.4), Hermine (51.8), Nicole (19.9), Paula (16.1) | 22 | 1,083,043 |
| 2011 | Bret (18.3), Don (26.6), Emily (14.3), Irene (68.5), Lee (39.9) | 193 | 1,099,280 |
| 2012 | Alberto (25.2), Beryl (51.0), Debby (30.2), Isaac (63.3), Sandy (64.5) | 196 | 1,111,594 |
| 2013 | Andrea (40.5), Dorian (16.0), Karen (16.9) | 81 | 1,135,359 |
| 2014 | Arthur (76.2) | 55 | 1,148,798 |
| 2015 | Ana (38.7), Bill (49.9), Claudette (19.7) | 19 | 1,182,341 |
| 2016 | Bonnie (29.1), Colin (44.9), Eight (16.5), Hermine (63.1), Julia (44.1), Matthew (68.0) | 270 | 1,196,221 |
| 2017 | Cindy (44.1), Emily (37.4), Harvey (103.2), Irma (91.9), Jose (23.9), Nate (60.6), Philippe (8.6) | 166 | 1,226,793 |
| 2018 | Alberto (36.8), Chris (15.7) Florence (79.4), Gordon (57.4), Michael (130.5) | 354 | 1,235,862 |
| Total | | 4,978 | 33,619,393 |

**Figure 1.** Tropical cyclone counts. Number of total tropical cyclone days (≥34 knots) (left; n=4,978) and number of total hurricane days (≥64 knots) (right; n=233) by county for 1988–2018.

**Figure 2.** Percentage change in death rates per one day increase in monthly tropical cyclone or hurricane-only exposure by cause of death, and lag time. Lag time was measured in months after tropical cyclone or hurricane. Dots show the point estimates and whiskers represent 95% credible intervals. Numbers in the top-right of each panel represent overall deaths per 1,000,000 for 2018 monthly age-standardized median rate (DPM) for tropical cyclone- or hurricane-exposed counties. Pneumonia-type deaths were classified as respiratory diseases.

**Figure 3**.Percentage change in death rates per one day increase in monthly tropical cyclone exposure by cause of death, age group (0-64 years, 65+ years), and lag time. Lag time was measured in months after tropical cyclone. Dots show the point estimates and whiskers represent 95% credible intervals. Numbers in the top-right of each panel represent overall and age group-specific deaths per 1,000,000 for 2018 monthly age-standardized median rate (DPM) for tropical cyclone-exposed counties. Pneumonia-type deaths were classified as respiratory diseases.

**Figure 4**. Percentage change in death rates per one day increase in monthly tropical cyclone exposure by cause of death, social vulnerability tertiles, and lag time. The first tertile (blue) represents lowest social vulnerability and the third tertile (red) represents highest social vulnerability. Lag time was measured in months after tropical cyclone. Dots show the point estimates and whiskers represent 95% credible intervals. Numbers in the top-right of each panel represent overall and social vulnerability tertile-specific deaths per 1,000,000 for 2018 monthly age-standardized median rate (DPM) for tropical cyclone-exposed counties. Pneumonia-type deaths were classified as respiratory diseases.