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Individual and Interactive Effects of Floods and Tropical Cyclones on Mortality: A Multicountry Time-Series Analysis

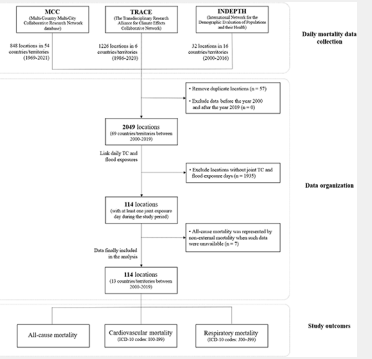
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ABSTRACT: Floods and tropical cyclones (TCs) are two of the most common and costliest climate disasters worldwide, yet a consistent evaluation of their individual and interactive health effects across events and countries remains lacking. We aimed to quantify the individual and joint all-cause and cardiopulmonary mortality risks associated with flood and TC exposure across countries and regions. Daily all-cause, cardiovascular, and respiratory mortality data between Jan 1, 2000, and Dec 31, 2019, were obtained from 2049 locations in 69 countries or territories globally. Historical flood and TC events were sourced from the Dartmouth Flood Observatory and the International Best Track Archive for Climate Stewardship, respectively. For each location, we applied quasi-Poisson regression with distributed lag nonlinear models to estimate cumulative mortality risks over 14, 30, 60, and 180 days following flood-only, TC-only, and joint flood-TC exposures. Location-specific estimates were then pooled using multivariate random effects meta-analysis to derive overall risk patterns. A total of 24.9 million all-cause deaths, 6.9 million cardiovascular deaths, and 3.4 million respiratory deaths from 114 locations with ≥1 joint exposure day were analyzed. Relative to hazard-free days, TC-only exposure days were associated with substantially higher and more prolonged mortality risks than flood-only days. Overall, we observed a 3% (95% confidence interval [CI]: 0−7%) increase in mortality over 60 days following flood-only days, compared to 19% (8−32%) for TC-only days. In the modification analysis of flood effects by TCs (using nonflood days as risk reference), flood days co-occurring with TCs exhibited considerably higher mortality risks than flood days without TCs, particularly for cardiovascular deaths at 30 days following the event (1.9% [95% CI: 0.9−3.0%] versus 0.1% [0.0−0.2%]). However, additive interactions between flood and TC exposures were generally not statistically significant. Strong effect modification was observed for economic development and institutional quality, as locations having lower GDP per capita, government effectiveness, and regulatory quality exhibited particularly elevated mortality risks, especially for mortality related to TC-only exposure days. In the current study, TC-only exposure days were found to be associated with greater short-to-medium-term mortality risks than flood-only days, and floods co-occurring with TCs could exhibit higher mortality risks than flood-only events, particularly from cardiovascular causes. Strengthening economic and institutional capacity and directing targeted postevent clinical support (particularly cardiovascular care) to socioeconomically and institutionally vulnerable locations may help reduce disaster-related deaths, especially after TCs.



INTRODUCTION

Floods and tropical cyclones (TCs) represent two of the most devastating and frequent climate disasters worldwide, accounting for over 70% of all recorded disasters globally.[1,2] On average, over 600 million people worldwide are affected annually by floods and TCs.[3,4] The economic impact of these disasters continues to escalate dramatically, with an average of US$78 million in economic damages daily solely for TCs, and the current decade already amounting to US$460 billion in damages—double the total losses from 1980 to 1999.[5] Given the projected intensification of TCs and floods under a warming climate, these disasters are likely to remain important public health concerns and key drivers of climate-related hazards.[6−8]

Elevated mortality risks associated with floods and TCs have been increasingly well-documented, with emerging evidence in recent years extending from single-event case studies[9−12] to multievent, cross-regional systematic analyses.[13−19] Beyond immediate injuries, recent epidemiological evidence reveals increased mortality risks from noncommunicable diseases,

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including respiratory conditions and cardiovascular diseases, that could persist for weeks following the event.[13,18] As well as direct physical impacts (e.g., drowning, injury), evidence suggests that floods and TCs could also have indirect, prolonged, or delayed adverse effects on human health, potentially resulting from disrupted healthcare services, contaminated water supplies, displacement, and mental health stressors.[1,20] However, the majority of existing epidemiological studies have focused solely on either floods or TCs in isolation, without an integrated and systematic evaluation of their independent, interactive, and joint cause-specific effects, particularly at a multicontinent scale. This gap inhibits our understanding of the health impacts of co-occurring exposures and the underlying mechanisms across diverse disease outcomes, population subgroups, and geographic contexts. Such knowledge is essential for improving evidence-based public health strategies in response to the increasing global co-occurrence of these events under a changing climate.[21−24]

To address these gaps, we integrated a location-specific daily mortality dataset spanning two decades in 69 countries and territories across five continents. On the basis of this best-available and, to our knowledge, the largest mortality dataset, we aimed to quantify the individual and joint mortality risks associated with flood and TC exposures across diverse mortality outcomes, geographic regions, socio-demographic groups, and levels of institutional quality.

METHODS

Data Collection and Organization

We collected daily mortality data in overlapping periods between Jan 1, 2000, and Dec 31, 2019, from 2049 locations in 69 countries or territories globally. Each location represents a small-scale geographic aggregation unit (city, metropolitan area, or small region). The detailed data sources and procedures of data collection and organization were provided in Supplementary Text S1 and Figure 1. Briefly, location-level daily counts of all-cause mortality were obtained from the national and local authorities within each country/territory. Nonexternal cause mortality data were alternatively collected when all-cause mortality was unavailable. Two leading causes of death, cardiovascular and respiratory mortality, were also collected for each location. The cause of death was defined as the primary reason leading to death and coded according to the International Classification of Diseases-10th revision (ICD-10): nonexternal cause mortality data (ICD-10 codes A00−R99), cardiovascular diseases (ICD-10 codes I00−I99), and respiratory diseases (ICD-10 codes J00−J99).

We also obtained global gridded population data at approximately 1 km spatial resolution from LandScan.[25] The population data was calibrated for each country and territory in each year to be consistent with data from the United Nations, as detailed in our previous work.[26] We calculated the total population size and population density, as well as the population-weighted centroid for each location in each year, based on the calibrated grid-specific population data within the geographical boundary of the location. We estimated the Gross Domestic Product (GDP) per capita for each location by dividing the local GDP by the local population.[27] Global gridded, age- and sex-specific population data were obtained from WorldPop to calculate the percentage of the population aged ≥65 years and the percentage of females for each location.[28] Furthermore, we collected two governance indicators (regulatory quality and government effectiveness) from the World Bank to represent the government performance of each location.[29] Both regulatory quality and government effectiveness are country/territory-level indices ranging from −2.5 to 2.5, with higher values indicating better regulatory quality and government effectiveness, respectively. All the above data in 2010 were used to represent the average between 2000 and 2019.[30] Finally, near-surface ambient temperature data was obtained from the ERA-5 land reanalysis dataset to estimate the daily average temperatures for each location.[31]

Flood and TC Exposure Assessment

We obtained flood data from the Dartmouth Flood Observatory (DFO), which is a comprehensive and validated collection of global flood events from satellite observations, news, government, and instrumental sources.[32,33] DFO data include the spatial coverage (i.e., the flooded areas), occurrence date, and duration of each flood event and have been commonly used in previous studies of flood climatology and health risk assessments.[13,34,35] For each location and day, flood exposure was defined as occurring when the population centroid of the location was located within the flooded area.[13]

For TC exposure assessment, we applied an improved wind field model[36] to estimate the historical temporal dynamics of the windspeed associated with TCs. This wind field model has been widely used in previous studies[37−39] and has been detailed in our previous work.[19,40] Briefly, based on the global TC information from the International Best Track Archive for Climate Stewardship (IBTrACS),[41] we used a parametric wind model to generate gridded hourly wind fields (i.e., daily maximum of 1 min sustained wind speeds associated with the TC) for each TC event in IBTrACS with a spatial resolution of 1/12° (∼10 km). For this analysis, we aggregated the data to 0.5° (∼55 km) spatial and daily temporal resolution, matching the local time zones of our collected data. Grid cells with a TC-related maximum sustained wind speed of at least 34 knots (i.e., 17.5 m/s) were considered to be TC-exposed.[17,42] A TC exposure day for each location was defined as any day on which the population centroid was situated within a TC-exposed grid cell.[13,19,43]

Statistical Analysis

We adopted a widely used two-stage analytical framework to model the mortality risks associated with TCs and floods.[13,43−46] To distinguish the individual and combined effects of floods and TCs, we defined our primary exposure (i.e., the variable of interest) in the model as a four-category daily variable for each location: (1) no exposure (reference category: days without floods or TCs), (2) flood-only exposure, (3) TC-only exposure, and (4) joint exposure (days with flood and TC co-occurrence).[47,48] We focused on the locations with at least 1 day of joint exposure during the study period in the analysis to ensure the comparability of the effect estimates across the exposure categories.

In the first stage, we implemented quasi-Poisson regression and distributed lag nonlinear models to quantify the relative risk (RR) of cause-specific mortality associated with flood-only, TC-only, and joint exposures compared to the reference category of none. The quasi-Poisson regression and distributed lag nonlinear model were used to account for possible overdispersed daily mortality counts and the delayed effects of the exposures, respectively. We modeled our primary exposures with a distributed lag term up to 14, 30, 60, and 180 days after the exposure (with a natural cubic spline function of 2 degrees of freedom [dfs][19]) to assess the short-, intermediate-, and longer-term effects. The models were adjusted for natural fluctuations in mortality and effects of temperature. Specifically, we controlled long-term and seasonal trends in the mortality counts by including a cubic B-spline with three degrees of freedom for time and a cyclic cubic B-spline with three equally spaced knots for day of the year, respectively.[13] Within-week temporal patterns were controlled by including a day-of-week dummy variable in the model. Finally, the average of daily mean temperature over 0−21 lag days was included in the model with a natural cubic B-spline with three internal knots (10th, 75th, and 90th percentiles of location-specific temperature distributions) to account for the potential delayed and nonlinear confounding effects.[44] These modeling parameters were informed by previous studies,[13,19] with alternative options explored in sensitivity analyses.

In the second stage, we used multivariate random-effect meta-analysis to pool the location-specific effect estimates. These estimates were pooled at the global and regional level and also by tertiles of GDP per capita, regulatory quality, government effectiveness, population density, the proportion of the population that is aged ≥65 years, and the proportion of the population that is females. Results were presented as the cumulative RR of mortality over specified lag periods following

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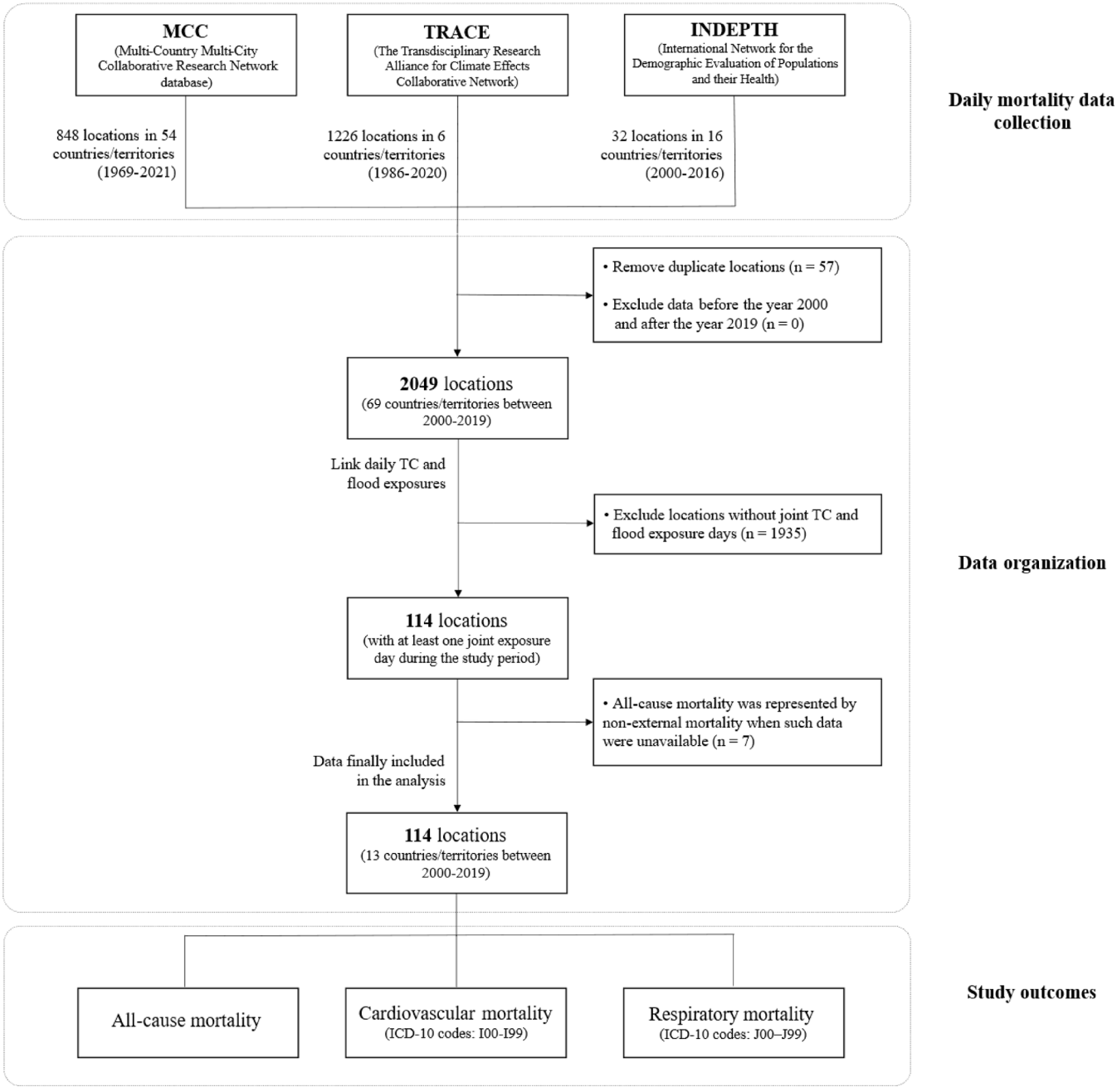


Figure 1. Flowchart of mortality data collection and organization procedures. Abbreviations: ICD, International Classification of Diseases; TC, tropical cyclone.

flood-only, TC-only, and joint exposures, compared to nonexposure days (i.e., neither TC nor flood exposure). The statistical differences in the mortality risks across subgroups were tested using a Wald-type test on the effect estimates across groups.[49] We evaluated the possible additive interaction between flood and TC exposures on mortality using the relative excess risk due to interaction (RERI): $RR_{11}-RR_{01}-RR_{10}+1$, where RR_{10}, RR_{01}, and RR_{11} are the RR of mortality associated with flood-only, TC-only, and joint exposure, respectively. A RERI greater than 0 indicates positive additive (synergistic) interaction, whereas a RERI below 0 indicates negative additive (antagonistic) interaction. To quantify uncertainty in the interaction estimates, we used a Monte Carlo simulation approach with 10,000 iterations. In each iteration, RR estimates were sampled from their respective distributions and used to recalculate the interaction metric. The resulting distributions of the simulated interaction estimates were then used to derive their 95% confidence intervals.

To further investigate how TCs might modify the health effects of floods (i.e., effect modifications by TCs), we conducted secondary analysis by defining our exposure variable of interest as a three-category variable: (1) nonflood days (reference category), (2) flood days without TCs; (3) flood days with TCs. Using the same model adjustment as in the primary analysis, we estimated and compared cause-specific mortality risks associated with flood exposures in the presence or absence of TCs, relative to nonflood days.

Finally, to assess the robustness of our results, we reperformed our analyses by (1) excluding the locations without all-cause mortality data, with nonexternal mortality used as a proxy (n = 7); (2) additionally adjusting for public holiday effects in the models; (3) varying the df (3, 4, 5, or 6) for the splined temperature term to control for the nonlinear effects; (4) using different window lengths (14, 30, 60, or 180 days) for the moving average of temperature to account for the potential delayed confounding effects; (5) using a larger df (3 and 4, compared to 2 in the

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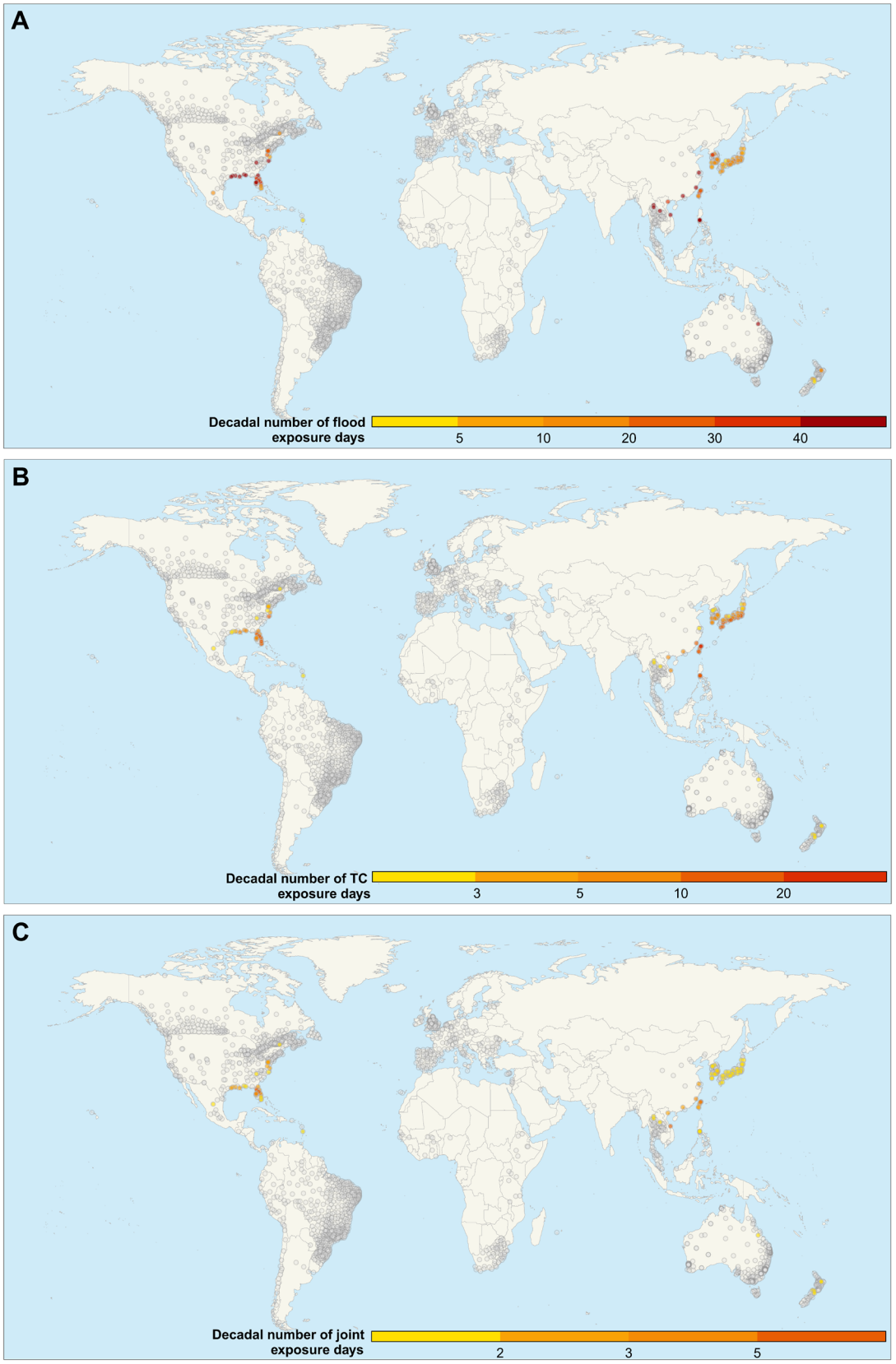


Figure 2. Geographical distributions of the study locations and the decadal number of flood (A), TC (B), and their joint exposure (C) exposure days. Joint exposure days are defined as days when TC and flood exposures occur simultaneously. Gray points indicate locations excluded from the primary analysis due to the lack of joint flood-TC exposure days during the study period. Abbreviations: TC, tropical cyclone.

main model) to model the lag effects of flood and TC exposures; (6) using various df (2, 4, 5, or 6) for the spline function of time to model long-term trends; (7) expanding the analytical sample to include locations with either TC or flood exposure, rather than restricting to

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Table 1. Summary of the Study Periods, Cause-Specific Deaths, and TC and Flood Exposure Days in the 114 Locations across 13 Countries/Territories Included in the Analysis[c]

Country/territory	Study period	No. of locations	Total no. of deaths			Average no. of days (range)		
			All-cause mortality	Cardiovascular mortality	Respiratory mortality	Floods	TCs	Joint events[a]
Australia	2009–2019	1	1,736	489	194	95 (95, 95)	1 (1, 1)	1 (1, 1)
Canada	2000–2015	1	2,374	660	233	17 (17, 17)	1 (1, 1)	1 (1, 1)
China Mainland	2004–2015	3	173,254	65,089	28,831	157 (137, 190)	9 (3, 14)	4 (3, 4)
Japan	2000–2019	36	18,820,448	5,361,971	2,829,371	13 (2, 23)	10 (2, 17)	2 (1, 2)
Martinique, France	2000–2015	1	19,986	NA[b]	NA[b]	5 (5, 5)	2 (2, 2)	1 (1, 1)
Mexico	2000–2019	1	111,064	31,078	9,544	11 (11, 11)	1 (1, 1)	1 (1, 1)
New Zealand	2000–2018	6	28,198	10,419	2,481	10 (2, 18)	2 (1, 2)	2 (1, 2)
Philippines	2006–2019	9	653,556	239,509	97,370	71 (57, 76)	13 (12, 14)	2 (1, 2)
South Korea	2000–2018	16	1,998,060	462,871	144,400	17 (6, 31)	6 (2, 10)	2 (1, 3)
Taiwan	2000–2018	6	1,740,776	373,288	183,139	25 (19, 32)	21 (17, 24)	5 (3, 6)
Thailand	2000–2008	3	84,610	11,059	11,139	440 (366, 477)	2 (2, 2)	2 (2, 2)
United States	2000–2006	29	1,224,044	380,155	111,874	45 (10, 102)	8 (2, 12)	4 (2, 6)
Vietnam	2004–2013	2	8,625	2,215	166	85 (34, 135)	8 (7, 9)	5 (3, 7)
Overall	—	114	24,866,731	6,938,803	3,418,742	44 (2, 477)	9 (1, 24)	3 (1, 7)

[a]Joint event days are defined as days on which TC and flood exposures occur simultaneously. [b]Cardiovascular and respiratory mortality data are unavailable for Martinique, France. [c]Abbreviations: TC, tropical cyclone; and NA, not available.

Table 2. Relative Risks and RERI (with 95% CI) for Exposures to Floods and Tropical Cyclones on All-Cause and Cardiovascular Mortality

	Periods after exposure, RR[a] (95% CI)			
	14 days	30 days	60 days	180 days
All-cause mortality				
None	Reference	Reference	Reference	Reference
Flood	1.02 (1.01, 1.04)	1.04 (1.02, 1.07)	1.03 (1.00, 1.07)	1.02 (0.95, 1.11)
Tropical cyclone	1.07 (1.03, 1.12)	1.14 (1.07, 1.20)	1.19 (1.08, 1.32)	1.29 (0.97, 1.72)
Joint event[b]	1.08 (0.99, 1.16)	1.12 (0.93, 1.35)	1.01 (0.78, 1.30)	1.07 (0.56, 2.06)
RERI[c]	−0.02 (−0.11, 0.08)	−0.06 (−0.27, 0.18)	−0.22 (−0.48, 0.09)	−0.25 (−0.92, 0.76)
Cardiovascular mortality				
None	Reference	Reference	Reference	Reference
Flood	1.03 (1.01, 1.06)	1.05 (1.02, 1.10)	1.00 (0.96, 1.06)	0.92 (0.83, 1.02)
Tropical cyclone	1.05 (0.99, 1.11)	1.18 (1.07, 1.30)	1.26 (1.09, 1.46)	1.69 (1.29, 2.20)
Joint event[b]	1.22 (1.05, 1.42)	1.29 (1.00, 1.67)	1.30 (0.93, 1.80)	3.88 (1.35, 11.13)
RERI[c]	0.14 (−0.05, 0.34)	0.06 (−0.25, 0.44)	0.03 (−0.38, 0.55)	2.27 (−0.31, 9.30)

[a]Cumulative relative risks (RRs) of mortality risks over the lag period compared to unexposed days (i.e., no TC or flood). [b]Joint event days are defined as days when both tropical cyclone and flood exposure occur simultaneously. [c]Relative excess risk due to interaction (RERI) was calculated as $RR_{11}-RR_{01}-RR_{10}+1$, where RR_{11}, RR_{01}, and RR_{10} represented relative risks for concurrent tropical cyclone-flood days, tropical cyclone-only days, and flood-only days, respectively. A RERI greater than 0 indicates a positive additive interaction (synergism), whereas a RERI less than 0 denotes antagonism.

those only experiencing joint TC and flood events; (8) redefining joint exposures using a lagged flood-TC co-occurrence window to account for potential temporal exposure misclassification (i.e., flood days that occurred on the same day as, or within 3 days immediately following, a TC exposure day were considered as TC-induced floods and defined joint exposure days).

All analyses were performed in R software (version 4.1.3),[50] using the R packages d lnm[51] and mixmeta[52] for the first and second stage analyses, respectively.

RESULTS

Descriptive Statistics

We collected daily mortality data from 2,049 locations across 69 countries and territories (Figure 1). The geographical distribution of these locations, as well as their exposure to floods and TCs, is illustrated in Figure 2. Among the 2,049 locations, 114 in 13 countries or territories experienced at least 1 day of joint flood and TC exposure during the study period and were included in subsequent analyses. Table 1 shows a summary of the study periods, number of cause-specific deaths, and TC and flood exposure days of these 114 locations. In total, approximately 24.9 million deaths, 191 TC events, and 155 flood events were included in the analysis.

A wide range of flood and TC exposure levels was observed across locations (Figure 2 and Table 1). Locations in Thailand and mainland China experienced the most frequent flood exposures, averaging more than 100 flood days per decade, whereas locations in Martinique (France) and New Zealand had much lower flood exposure, with fewer than 10 days per decade. For TCs, the highest exposure was observed in Taiwan and the Philippines, with more than 10 TC days per decade, while locations in Australia, Canada, and Mexico had much lower exposure, averaging only about one TC day per decade. There is an overall average of 3 days with joint flood and TC exposure per decade across locations (Figure 2 and Table 1). Cumulatively,

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the all-cause mortality model incorporated a total of 4900 flood-only days, 1123 TC-only days, and 267 joint-exposure days across all 114 locations, with the exact exposure days and sample sizes contributing to each cause-specific model detailed in Table S1.

Short- and Longer-Term Cause-Specific Mortality Risks Following TCs and Floods

For exposure to either TCs or floods alone, increased risks of all-cause mortality were observed for up to 60 days following the exposure day (Table 2). Notably, the RRs associated with TC-only days (relative to days without floods or TCs) were consistently higher than those for flood-only days across all of the time windows. Specifically, the cumulative RR for all-cause mortality over 60 days postexposure was 1.03 (95% CI: 1.00, 1.07) for flood-only days and 1.19 (95% CI: 1.08, 1.32) for TC-only days. For joint exposure to both floods and TCs, elevated all-cause mortality risks were also observed; however, these estimates were accompanied by much greater uncertainty (i.e., wider CI) and did not reach statistical significance. Additionally, the RERI for all-cause mortality was consistently statistically insignificant, providing no evidence of additive interaction between flood and TC exposures (Table 2).

A similar pattern was observed for the cardiovascular mortality. TC-only exposure days were associated with substantially higher risks than flood-only days, particularly at longer lag periods (Table 2). For instance, the cumulative RR for cardiovascular mortality over 60 days after exposure was 1.26 (95% CI: 1.09, 1.46) for TC-only days compared with 1.00 (95% CI: 0.96, 1.06) for flood-only days. While days with joint exposures of floods and TCs were associated with elevated cardiovascular mortality risks, there was insufficient statistical evidence to support the presence of additive effects. There was also no sufficient evidence to detect statistically significant associations between any exposure type (flood only, TC only, or joint) and respiratory mortality (Table S2).

In the secondary analysis of flood effects by TCs (using nonflood days as risk reference), flood days with TCs were associated with higher mortality risks compared to flood days without TCs, particularly for cardiovascular mortality (Figure 3). Elevated cardiovascular mortality risks were observed during the first 60 days following flood exposure days with TCs, and the risks gradually declined over time. In contrast, minimal increases in mortality risks were found for flood days without TCs across all of the mortality outcomes. For example, flood days with TCs were associated with a 1.9% (95% CI: 0.9−3.0%) increase in the cardiovascular mortality at lag day 30 following exposures (relative to the nonflood days), compared with 0.1% (95% CI: 0.0−0.2%) for flood days without TCs (Table S3).

Region-Specific Mortality Risks Associated with TC and Flood Exposures

When examining risks by continent and region, the Asia/Pacific region (particularly Eastern Asia) exhibited the most pronounced and statistically significant increases in all-cause and cardiovascular mortality associated with TC-only exposure days (Table 3). The risks observed for TC-only exposure days (relative to days without floods or TCs) were substantially higher than those associated with flood-only days. For example, the cumulative RR for all-cause mortality in the Asia/Pacific region over the 60 days after exposure was 1.19 (95% CI: 1.08, 1.31) for TC-only exposure days compared to 1.04 (95% CI: 1.00, 1.08) for flood-only days. However, the mortality risks associated with joint flood and TC exposure days, as well as the additive interaction between these exposures, were generally not statistically significant across all continents and regions (Table 3 and Table S4).

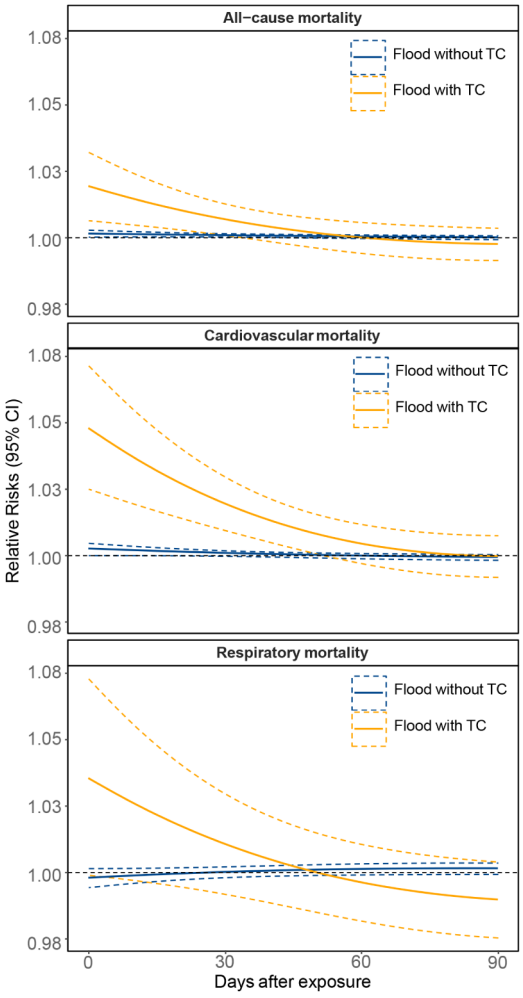


Figure 3. Temporal evolutions of relative risks (with 95% CI) of all-cause, cardiovascular, and respiratory mortality associated with floods and TCs along the 90 days following the exposures. Relative risks were derived from the secondary three-category analytical framework, where the reference group is all nonflood days. Abbreviations: CI, confidence interval; TC, tropical cyclone.

Cause-Specific Mortality Risks by GDP Per Capita and Institutional Quality

GDP per capita demonstrated a clear gradient effect on TC- and flood-related mortality risks, particularly for cardiovascular outcomes (Figure 4 and Figure S2). Higher risks of both all-cause and cardiovascular mortality associated with TC-only exposure days were consistently observed at lower levels of GDP per capita (Figure 4). The risks of all-cause and cardiovascular mortality were higher for TC-only exposure days compared to flood-only days, with this difference being most pronounced in the lowest GDP per capita tertile. A substantially higher risk of cardiovascular mortality was observed among the populations in the lowest GDP per capita tertile for TC-only exposure days (RR: 1.87 [95% 1.41, 2.47], relative to days without floods or TCs) compared to flood-only days (RR: 0.97 [95% 0.89, 1.05]). Joint exposure days of both floods and TCs also exhibited elevated risks at lower GDP levels, while confidence intervals were considerably wider (Figure 4 and Figure S2).

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Table 3. Continent- and Region-Specific Relative Risks (with 95% CI) of All-Cause and Cardiovascular Mortality Associated with Flood and Tropical Cyclone Exposures[e]

Region[a]	RR (95% CI)[b] All-cause mortality	Cardiovascular mortality
America		
None	Reference	Reference
Flood	1.02 (0.90, 1.15)	1.01 (0.90, 1.14)
Tropical cyclone	1.53 (0.75, 3.11)	0.97 (0.50, 1.87)
Joint event	1.01 (0.48, 2.12)	4.54 (0.78, 26.46)
Northern America		
None	Reference	Reference
Flood	1.03 (0.90, 1.17)	1.02 (0.90, 1.15)
Tropical cyclone	1.60 (0.77, 3.32)	0.96 (0.50, 1.84)
Joint event	0.95 (0.45, 2.03)	4.82 (0.77, 30.17)
Central America and the Caribbean		
None	Reference	Reference
Flood	0.83 (0.57, 1.20)	0.92 (0.48, 1.79)
Tropical cyclone	0.37 (0.01, 13.55)	NA[c]
Joint event	NA[c]	NA[c]
Asia/Pacific		
None	Reference	Reference
Flood	1.04 (1.00, 1.08)	1.00 (0.95, 1.06)
Tropical cyclone	1.19 (1.08, 1.31)	1.28 (1.10, 1.48)
Joint event	1.00 (0.76, 1.32)	1.22 (0.87, 1.72)
Eastern Asia		
None	Reference	Reference
Flood	1.09 (1.05, 1.13)[d]	1.05 (0.99, 1.11)
Tropical cyclone	1.19 (1.07, 1.31)[d]	1.21 (1.05, 1.39)
Joint event	0.93 (0.71, 1.22)[d]	1.16 (0.83, 1.64)
Southeastern Asia		
None	Reference	Reference
Flood	0.92 (0.86, 0.98)[d]	0.92 (0.83, 1.02)
Tropical cyclone	1.20 (0.84, 1.71)[d]	2.73 (1.54, 4.83)
Joint event	6.93 (1.74, 27.66)[d]	NA[c]
Australia and New Zealand		
None	Reference	Reference
Flood	1.11 (0.69, 1.79)	1.03 (0.35, 3.08)
Tropical cyclone	NA[c]	NA[c]
Joint event	NA[c]	NA[c]

[a]Regions are defined according to UN Statistics Division (M49) regional groupings. [b]Cumulative RRs of mortality risks over 60 days after exposures. [c]Reliable estimates were unavailable due to nonconvergence of the region- and mortality-specific models. [d]The additive interaction is statistically significant. [e]Abbreviations: CI, confidence interval; NA, not available; and RR, relative risk.

Government effectiveness and regulatory quality exhibited strong modifying effects on mortality risks associated with both TC-only and joint TC-flood exposure days (Figure 4 and Figure S2). The risks of all-cause and cardiovascular mortality were consistently highest and statistically significant at the lowest tertiles of government effectiveness and regulatory quality (Figure 4). The most pronounced disparity in risks among flood-only, TC-only, and joint exposures was observed in populations with the weakest governance indicators. For populations experiencing the lowest levels of government effectiveness and regulatory quality, the highest risks of all-cause and cardiovascular mortality were observed for joint TC-flood exposure days, followed by TC-only days. In contrast, mortality risks associated with flood-only days remained relatively modest across all levels of government effectiveness and regulatory quality.

Cause-Specific Mortality Risks by Demographic Characteristics

Significantly elevated mortality risks associated with TC and flood exposures were observed only in locations with population density in the highest tertile (Figure 4 and Figure S2). At these high-density levels, the greatest risks of cardiovascular mortality were observed for joint exposures, followed by TC-only days and flood-only days. By comparison, mortality risks for any exposure type were generally statistically insignificant across mortality outcomes in medium- and low-density areas.

Less consistent modification effects were observed for age structure and sex compositions across mortality outcomes, though generally higher mortality risks observed for TC-only exposure days compared to flood-only days (Figure 4). TC-only exposure days were associated with significantly higher all-cause and respiratory mortality risks in regions with the highest tertile of the population that is ≥65 years. Conversely, in areas with the lowest tertile of population that is older, TC-only exposure days showed elevated cardiovascular mortality risks, while flood-only days remained nonsignificant. In locations with the highest female proportion, TC-only exposure days demonstrated significantly higher respiratory mortality risks compared to flood-only days. In contrast, areas with the lowest female proportion exhibited elevated cardiovascular mortality risks for TC-only exposure days, with no significant associations for flood-only days.

Sensitivity Analysis

The cause-specific mortality risks associated with TC and flood exposures did not change substantially in a series of sensitivity analyses. Similar results were observed when excluding the locations without all-cause mortality data (Table S5), in models with additional adjustment for public holiday effects (Table S6), in models using different dfs (Table S7) and moving average windows (Table S8) for temperature adjustment, and in models with varying dfs for modeling lag effects (Table S9) and long-term trends (Table S10). Finally, when extending analytical locations by including those with at least one TC or flood exposure day (n = 1696) rather than only those with at least one joint event exposure day (n = 114), we also observed similar results, demonstrating a robust and consistent pattern of greater mortality risks for TC-only exposure days compared to flood-only days (Table S11). Finally, when redefining joint exposures using a 3-day lagged flood-TC co-occurrence window to account for potential temporal exposure misclassification, the results remained consistent with our primary analysis, demonstrating generally similar risk magnitudes and directions of associations (Figure S1).

DISCUSSION

To our knowledge, this study represents the first integrated and comparative analysis of mortality risks associated with floods and TCs. Using a large population-based dataset at a multination scale, we found that TC-only exposure days were associated with higher all-cause, cardiovascular, and respiratory mortality risks than flood-only days, especially in locations with lower GDP per capita and government performance. TCs could modify the flood-related mortality risks; flood days co-occurring with TCs exhibited markedly higher mortality risks than flood days without TCs, particularly for cardiovascular mortality. However, there is insufficient evidence to support the additive interactions

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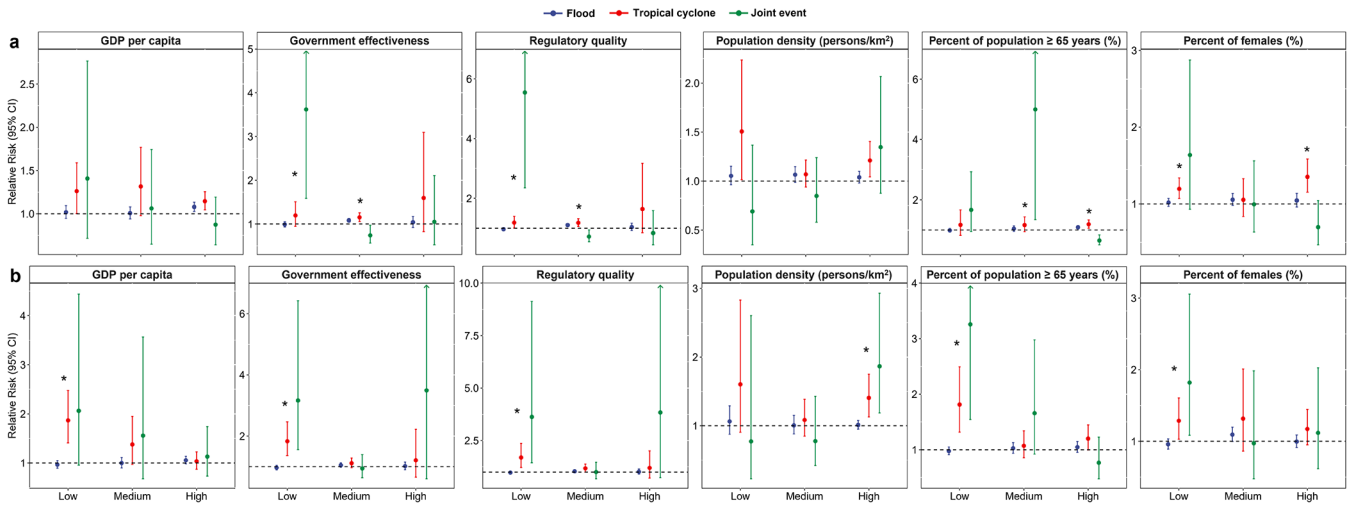


Figure 4. Cumulative relative risks (with 95% CI) of all-cause (a) and cardiovascular mortality (b) associated with floods and tropical cyclones over the 60 days after exposures, by tertiles (low: Q1, medium: Q2, high: Q3) of GDP per capita, government effectiveness, regulatory quality, population density, percentage of population aged ≥65 years, and percentage of females. Relative risks were derived from the primary four-category analytical framework, where the reference group is days without any flood or TC exposure. Abbreviations: CI, confidence interval; GDP, Gross Domestic Product. *P for difference between events was <0.05.

between floods and TCs for all-cause, cardiovascular, or respiratory mortality.

Despite the well-established hazards of floods and TCs, evidence characterizing their individual and combined health effects remains scarce. Existing studies, primarily conducted in the United States and China and typically focused on high-amplitude flood/TC events, have largely examined the health risks associated with either floods or TCs in isolation.[1,20] Despite substantial variations in reported risk magnitudes (attributable to great differences in the analytical methodologies and event characteristics), these studies generally suggested increased mortality risks associated with flood or TC exposure.[1,20] More recent multicountry studies examining a broader range of flood/TC events have provided more conclusive findings on increased all-cause, cardiovascular, and respiratory mortality risks after flood or TC exposures, although these risks varied greatly across regions.[13,18,19,43,53] However, previous research has not systematically distinguished the separate impacts of floods and TCs or explored their potential interactions. Furthermore, direct comparisons of flood- and TC-related mortality risks have been hindered by differences in modeling approaches and hypothetical exposure windows among studies. For example, a multicountry study spanning 761 locations in 35 countries reported a 2.1% (95% CI: 0.6−3.6) increase in mortality over 60 days postflood exposure,[13] whereas another study covering 341 locations in 14 countries found a 6.0% (95% CI: 4−8) increase in mortality during the first 2 weeks following TC exposure.[19] Our findings align with and extend this body of evidence by providing a systematic and integrated analysis of flood and TC exposure. In the main analysis, we observed substantially and consistently higher mortality risks for TC-only exposure days compared to flood-only days across immediate, intermediate, and long-term timeframes (14, 30, 60, and 180 days). This underscores the imperative for hazard-specific preparedness and response strategies that account for both the greater and potentially more prolonged mortality risks following TCs and the higher mortality risks when these hazards cooccur.

In addition to the higher mortality risks posed by TCs compared to floods, our modification analysis indicated that flood days with TCs were associated with substantially higher cardiovascular mortality risks compared to those of flood days without TCs. However, the underlying mechanisms remain largely unclear because of limited evidence and are likely complex, involving multiple interconnected biological, physical, and socioeconomic pathways. This may reflect the particular susceptibility of cardiovascular outcomes to the disruptive effects of compound flood-TC events. The multihazard nature of floods with TCs may cause more disruptions to healthcare systems and local economies, greater population displacement, and heightened psychological stress compared to floods without TCs.[16,54,55] These disruptions could particularly hinder the effective management of chronic diseases that are generally characterized by cardiovascular conditions.[55,56] For example, extensive infrastructure damage associated with concurrent flood-TC events can lead to the disruptions of life-saving cardiovascular medications and severe delays in emergency medical care, which is particularly fatal for time-sensitive cardiovascular emergencies.[57] Furthermore, the psychological stress and intense physical exertion associated with surviving and evacuating from multihazard disasters can act as important triggers of coronary events, particularly among people with preexisting or subclinical cardiovascular diseases.[58] More studies with detailed individual and infrastructural data are warranted to test these hypotheses and elucidate the complex pathways underlying the observed mortality patterns.

Evaluating potential interactions between extreme events pose important statistical challenges. Although RERI was more stable than the synergy index when the estimated effects (i.e., RR) of individual exposures (e.g., flood-only or TC-only days) were close to 1.0, the 95% CIs were still relatively wide and generally did not reach statistical significance. This uncertainty is primarily driven by sparse data bias, as joint flood-TC days are relatively rare (averaging around 3 days per decade per location). This sparsity was further compounded by relatively limited respiratory mortality counts and the use of extended lag periods, which inherently accumulated higher uncertainty over

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time. While we did not find sufficient evidence to support additive interactions between floods and TCs, our findings demonstrated a higher estimated mortality risk following flood days with TCs than following flood-only days, particularly for cardiovascular mortality. These findings suggest that the association between floods and mortality may be modified by the presence of TCs and should be distinguished from additive interaction. This may suggest that while TCs could modify flood-related mortality potentially through their compound hazard nature, there was insufficient statistical evidence that the joint effect exceeded the sum of the individual effects on an additive scale. The elevated mortality risks may therefore reflect an intensification of existing flood-related pathways rather than the emergence of novel synergistic mechanisms.[15,59] Additionally, the relatively limited number of joint flood and TC events could reduce the statistical power and also contribute to the wide CI and lack of statistical significance for the observed additive interactions.

Our findings reveal that locations with lower GDP per capita and weaker government performance experience disproportionately higher mortality risks associated with TC-only exposure days compared with flood-only days. In contrast, demographic factors (i.e., percentage of population aged ≥65 years and percentage of females) exert less consistent and weaker effect modification. These highlight that populations in socioeconomically and institutionally vulnerable locations could bear a disproportionate health burden associated with flood and TC exposures. However, the subgroup findings should be interpreted as associational and hypothesis-generating. These included macro-indicators may reflect broader underlying disparities and are likely proxies for a range of closely related underlying social, economic, and health-system factors. For example, regions with stronger economic resources and more effective governance may be better positioned to invest in disaster preparedness, early warning systems, resilient healthcare infrastructure, and coordinated emergency response capacity.[60−62] While these indicators may not represent direct causal pathways or effect modifiers, they can serve as useful markers for identifying highly susceptible populations that urgently warrant targeted capacity-building in disaster preparedness, particularly to mitigate the identified disproportionate mortality risks associated with TCs.

A key strength of this study is its use of a large sample size with a multinational, high-resolution population-based dataset and the adoption of a unified analytical framework across exposure types, postevent time frames, subpopulations, and geographic regions. This allows us to provide a consistent evaluation and systematic comparisons of the flood- and TC-related mortality risks. Nonetheless, some limitations should be acknowledged. First, we assessed flood and TC exposures at the location level rather than the individual level, assigning the same exposure to all individuals within a given location at a given time. While this is a common practice, given the challenges of obtaining daily individual-level data across countries,[17,63,64] such nondifferential exposure misclassifications may introduce Berkson-type and classical exposure measurement errors. This could inflate the variance of our effect estimates[65] and bias them toward the null,[66,67] indicating that our results are likely conservative. In addition, our exposure definition relied on binary metrics for floods and TCs. While using population-weighted centroids and high-resolution spatial polygons reduced misclassification, this binary approach cannot capture intraevent intensity, such as wind speed intensity or flood depth. Finer stratifications by flood or TC intensity were mathematically unfeasible in our quasi-Poisson models due to the rarity of joint flood-TC events, which would induce sparse data bias and model nonconvergence. Future studies with larger regional event pools are warranted to explore the potential dose−response relationships of these compound disaster characteristics. The direct comparisons of the observed risk magnitudes between floods and TCs also require cautious interpretation. TCs are complex multihazard events that may involve intense winds, heavy rainfall, storm surge, and widespread infrastructure damage. In contrast, floods represent a broader and more heterogeneous exposure category. Therefore, the observed risk differences between flood-only and TC-only days may reflect unmeasured variations in disaster intensity, duration, local surveillance quality, and exposure classification rather than an inherent difference in the danger posed by these hazard types. Our findings should therefore be interpreted as showing that TC-only days were associated with higher estimated mortality risks than flood-only days under specific study settings. Furthermore, our analysis was limited to all-cause and cardiopulmonary deaths due to the unavailability of data on other specific causes of death; consequently, the mortality patterns following floods and TCs cannot be comprehensively captured since other specific causes of death could also be affected. Finally, despite the large sample size, some vulnerable countries (e.g., Bangladesh, Myanmar, and Haiti) were not included due to the data availability.[19] Further work from these regions with limited epidemiological evidence on floods and TCs is needed to complement the evidence provided in this study.[1,20]

CONCLUSION

In the current study, TC-only exposure days were found to be associated with considerably higher mortality risks compared to flood-only days, particularly in regions with a lower GDP per capita and weaker government performance. TC could modify flood-related mortality, with substantially higher associated cardiovascular mortality risks observed for flood days with TCs than those without TCs. No clear evidence of additive effects between the floods and TCs was observed.

APPENDIX A

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■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/EHP.6c00097.

Additional details on mortality data collection and organization, as well as supplementary tables (Tables S1−S11) and figures (Figures S1−S2) as mentioned in the text (PDF)

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Author Contributions

W.H. and Z.Y. contributed equally to this work. Y.G. and S.L. conceptualized and designed the study and contributed to supervision, provision of resources, and funding acquisition. W.H. performed the methodology and analysis, and took the lead in drafting the manuscript. All authors contributed to providing the mortality data and revising the manuscript.

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The funders had no role in study design, data collection, data analysis, data interpretation, and study report.

Notes

The authors declare no competing financial interest.

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