Global short-term mortality risk and burden associated with tropical cyclones from 1980 to 2019: a multi-country time-series study

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Summary

Background The global spatiotemporal pattern of mortality risk and burden attributable to tropical cyclones is unclear. We aimed to evaluate the global short-term mortality risk and burden associated with tropical cyclones from 1980 to 2019.

Methods The wind speed associated with cyclones from 1980 to 2019 was estimated globally through a parametric wind field model at a grid resolution of 0·5°×0·5°. A total of 341 locations with daily mortality and temperature data from 14 countries that experienced at least one tropical cyclone day (a day with maximum sustained wind speed associated with cyclones ≥17·5 m/s) during the study period were included. A conditional quasi-Poisson regression with distributed lag non-linear model was applied to assess the tropical cyclone–mortality association. A meta-regression model was fitted to evaluate potential contributing factors and estimate grid cell-specific tropical cyclone effects.

Findings Tropical cyclone exposure was associated with an overall 6% (95% CI 4–8) increase in mortality in the first 2 weeks following exposure. Globally, an estimate of 97 430 excess deaths (95% empirical CI [eCI] 71 651–126 438) per decade were observed over the 2 weeks following exposure to tropical cyclones, accounting for 20·7 (95% eCI 15·2–26·9) excess deaths per 100 000 residents (excess death rate) and 3·3 (95% eCI 2·4–4·3) excess deaths per 1000 deaths (excess death ratio) over 1980–2019. The mortality burden exhibited substantial temporal and spatial variation. East Asia and south Asia had the highest number of excess deaths during 1980–2019: 28 744 (95% eCI 16 863–42 188) and 27 267 (21 157–34 058) excess deaths per decade, respectively. In contrast, the regions with the highest excess death ratios and rates were southeast Asia and Latin America and the Caribbean. From 1980–99 to 2000–19, marked increases in tropical cyclone-related excess death numbers were observed globally, especially for Latin America and the Caribbean and south Asia. Grid cell-level and country-level results revealed further heterogeneous spatiotemporal patterns such as the high and increasing tropical cyclone-related mortality burden in Caribbean countries or regions.

Interpretation Globally, short-term exposure to tropical cyclones was associated with a significant mortality burden, with highly heterogeneous spatiotemporal patterns. In-depth exploration of tropical cyclone epidemiology for those countries and regions estimated to have the highest and increasing tropical cyclone-related mortality burdens is urgently needed to help inform the development of targeted actions against the increasing adverse health impacts of tropical cyclones under a changing climate.

Funding Australian Research Council and Australian National Health and Medical Research Council.

Lancet Planet Health 2023; 7: e694–705

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Introduction

The frequency and intensity of weather-related disasters have been increasing worldwide over the past century.[1] Tropical cyclones, including hurricanes, typhoons, and tropical storms, have been one of the most frequent meteorological disasters, accounting for a large proportion of the damages and fatalities caused by natural disasters.[1,2] It is estimated that tropical cyclones have affected more than 629 million people globally since the beginning of the 20th century.[3] Furthermore, the impacts of tropical cyclones are likely to worsen due to the increasing number of tropical cyclone landfalls and population vulnerability under a changing climate.[4–7] Understanding and quantifying the national, regional, and global spatiotemporal distributions of the tropical cyclone-related health effects has important implications for disaster planning and resource allocation.

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Research in context

Evidence before this study

We searched MEDLINE, Embase, Web of Science, Scopus, and PubMed for studies published up to Jan 30, 2023, using a combination of search terms related to cyclones: “cyclon*”, “hurricane*”, “typhoon*”, “tropical storm*”; and mortality: “mortalit*”, “death*”, “hospital*”, “admission*”, “injur*”. We found no studies that had examined the effect of tropical cyclones on mortality at a global scale. Previous reports mostly quantified the health risks associated with a single cyclone event or several cyclone events within a limited region and period. Additionally, the studies were greatly heterogeneous, using different study settings, study periods, cyclone characteristics, exposure definitions, and modelling approaches, hindering the ability to generalise results.

Added value of this study

To the best of our knowledge, this is the first global study to comprehensively quantify the spatiotemporal pattern of mortality risk and burden associated with tropical cyclones, using a high spatial resolution of 0·5° × 0·5° (approximately 55 km × 55 km at the equator) over an extended time period (1980–2019). We found that tropical cyclone exposure was associated with an overall 6% (95% CI 4–8) increased risk of mortality, over the 2 weeks following exposure. Globally, 97 430 (95% empirical CI 71 651–126 438) excess deaths per decade were associated with short-term exposure to tropical cyclones, accounting for 20·7 excess deaths per 100 000 residents and 3·3 per 1000 deaths over 1980–2019. East Asia and south Asia were the regions with the highest tropical cyclone-related excess deaths. Southeast Asia and Latin America and the Caribbean were the regions with the highest excess death ratios and rates. Temporal trends of increasing mortality burdens associated with tropical cyclones were observed globally, especially for Latin America and the Caribbean and south Asia, but not for Oceania. Further extremely unequal tropical cyclone-related mortality burden was observed at the country level.

Implications of all the available evidence

The scientific evidence regarding the global spatiotemporal pattern of tropical cyclone-related mortality risks and burdens presented in this study can help better understand the health impact of tropical cyclones. The results highlight the urgency and need for evidence on the epidemiology of tropical cyclones for those countries and regions with high and increasing tropical cyclone-related mortality burdens. The anticipated increase in tropical cyclones under a changing climate further increases the need to develop targeted actions and adaptive strategies to respond to the tropical cyclone-related health hazards in the most affected countries and regions.

Emerging evidence suggests that tropical cyclones are associated with an increased risk of adverse health outcomes such as hospitalisations and mortality.[8–13] However, previous epidemiological studies on tropical cyclone-related mortality were national or regional (mostly from the USA), and largely focused on a single tropical cyclone event (eg, Hurricane Katrina, Hurricane Sandy).[12] The differences in the characteristics of tropical cyclone events, study periods, modelling approaches, and population backgrounds among the studies and the potential publication bias (eg, limited evidence from low-income countries and areas with relatively low frequency of tropical cyclones) could result in difficulty in estimating the overall global mortality risk associated with tropical cyclones. To date, the relevant burden of mortality attributable to tropical cyclones has not been well quantified across countries and regions. There is an overall knowledge gap in consistently quantifying the global, regional, and national mortality risks and burdens associated with tropical cyclone exposure over a long timeframe.

The Multi-Country Multi-City (MCC) Collaborative Research Network was developed in 2014 to systematically assess the mortality risk associated with environmental factors across countries and regions using a unified methodology.[14] The most updated MCC network has expanded to 45 countries or territories. These countries or territories account for 46·4% of the world’s population.[15] The MCC dataset is therefore well placed to help solve the interstudy differences in modelling, parameterisation, and results interpretation, and provide a representative health risk assessment. Within the framework of an integrated global dataset based on the MCC network, this study aimed to quantify the global mortality risks and burdens associated with tropical cyclones and estimate their global and regional spatiotemporal patterns over long timeframes. A global view of the tropical cyclone-associated mortality burden could help to inform a better understanding of the health implications of tropical cyclones and assist with developing guidelines for intergovernmental strategies to mitigate the adverse health impacts of tropical cyclones.

Methods

Data source

Mortality data were obtained from an integrated global dataset based on the most updated MCC Collaborative Research Network, an international multi-community network that collects and updates daily time-series data on mortality and weather conditions from multiple locations. The details of the MCC network have been described in our previous work.[15,16] Briefly, the integrated dataset covers 1630 locations from 45 countries or territories. Out of the 1630 locations in the dataset, 341 locations from 14 countries or territories experienced at least one tropical cyclone during the study period and were thus included in the final analysis (two countries in North America, three in Latin America and the Caribbean, six in Asia, one in Europe, and two in Oceania; appendix p 2). The included 341 locations account for 39·2% of the total population of the grid cells (with the world divided into a 0·5° by 0·5° gridded map) ever exposed to tropical cyclones worldwide. For each location, daily counts of all-cause mortality were collected, and were represented by non-external causes of mortality (International Classification of Diseases [ICD], 9th Revision codes 0–799 or ICD-10 codes A0–R99) when such data were unavailable (11 [3%] of 341 locations did not have all-cause mortality; non-external causes of mortality were used to represent all-cause mortality).[15,16]

To account for the potential heterogeneity of cyclone effects across countries and estimate the associated mortality burden, we obtained a series of country-level predictors from more than 200 countries that have been shown to be strongly associated with cyclone-related deaths.[17,18] Annual country-specific gross domestic product (GDP) per capita (US$), population density (people per km^2), annual gender ratio (female percentage of the total population), and mortality rate from 1960 to 2019 were collected from the World Bank. Annual country-level median population age data were obtained from the UN Population Division[19] for the period 1950–2020. Annual gridded population and GDP per 10 years between 1980 and 2100 at a spatial resolution of 0·5° × 0·5° were also collected from the Global Carbon Project, which was estimated by ensemble machine learning technique and models and exhibited higher validity (R^2 values ranged from 0·81 to 0·84).[20] The population and GDP for each location in each year were calculated as the sum of the population and GDP of the grid cells covered by that location, respectively, which were then aggregated to calculate the country-level GDP per capita and population density for study locations. Any years with missing data between 1980 and 2019 were interpolated using a spline function of available values from other years.

Exposure assessment

The historical temporal dynamics of the global wind speed associated with cyclones were estimated using the improved wind field model by Holland.[21] The methodological details have been described in our previous study.[22] A good agreement was shown in the validation analysis of reported wind fields in the regional dataset (Pearson correlation of r=0·86). Briefly, we first obtained historical information of cyclones including position (ie, centre latitude and longitude coordinates), central pressure, radius, and maximum sustained wind speed from the International Best Track Archive for Climate Stewardship (IBTrACS; a collection of best track data of tropical cyclones from sources worldwide).[23] The above variables served as inputs for the Holland (2008) wind field model as implemented within the CLIMADA Python package, an open-source impact modelling framework available on GitHub.[24] We generated the daily wind profile (ie, the grid cell-level daily maximum of 1-minute sustained wind speeds associated with the cyclone) for each cyclone event in IBTrACS from Jan 1, 1980, to Dec 31, 2019, at a spatial resolution of 0·5° × 0·5° (about 55 km × 55 km at the equator). Cyclone events that had undergone extratropical transition before making landfall were excluded due to the different hybrid system and physical characteristics from tropical cyclones. For each location, we defined our primary exposure, the binary indicator of tropical cyclone exposure day, as a day with maximum sustained wind speed associated with tropical cyclones reaching or exceeding 17·5 m/s (34 knots, 63 km/h, 39 mph; gale-force wind on the Beaufort scale) for the grid cell of the location.[9,25] To further explore potential exposure–response relationships regarding the effect of different cyclone intensities on mortality, two secondary threshold exposures were defined. The first defined tropical cyclone exposure using two maximum sustained wind speed thresholds: 22·5 m/s and 27·5 m/s. The second defined cyclone exposure as a three-category variable: unexposed, gale to violent storm wind exposure (peak daily sustained wind 17·5–32·9 m/s), and hurricane (peak daily sustained wind ≥32·9 m/s).[9]

Statistical analysis

Given that tropical cyclone exposure is relatively rare, in the first stage of our analyses, we followed the methodology used in a previous study.[9] We matched on location and Julian day of the year to control for non-time-varying factors and seasonality. A conditional quasi-Poisson regression with distributed lag non-linear model (DLNM), which accounted for potential overdispersion of mortality, was applied to assess the mortality risk associated with tropical cyclone exposure, according to the following equation:

$$\begin{aligned}
&\mathrm{Log}[E(Y_{it})]=\mathrm{cb}(\mathrm{Exposure}_{it},\ \mathrm{lag}=7,\ \mathrm{dflag}=2)\\
&+\mathrm{cb}(\mathrm{Temperature}_{it},\ \mathrm{dfvar}=4,\ \mathrm{lag}=10,\ \mathrm{dflag}=2)\\
&+\mathrm{DOW}+\mathrm{ns}(\mathrm{year},\ \mathrm{df}=3)+\log(\mathrm{Population}_{it})+\mathrm{intercept}
\end{aligned}$$

where $E(Y_{it})$ represents the estimated number of deaths on day t in location i, and cb() represents the cross-basis function in DLNM through which we accounted for the delayed and non-linear effect and the delayed effect of exposures (eg, tropical cyclones and temperature) on mortality.[26] We chose a maximum lag of 2 weeks with a natural cubic spline (ns) with 2 degrees of freedom (df) in the log scale (plus an intercept) for lag effect (dflag) to quantify short-term impacts on mortality.[9] Based on our previous work, the delayed and non-linear effect of temperature was controlled with an ns of 4 df for predictor (dfvar) and a maximum lag of 10 days with an ns of 2 dflag in the log scale;[27] the within-week variations and time trends were controlled by including the dummy variable

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See **Online** for appendix

For the **World Bank** see https://data.worldbank.org/

For **CLIMADA** see https://github.com/CLIMADA-project/climada_python

of the day-of-the-week (DOW) and year with an ns of 3 df, respectively.[9] To account for the variation in mortality due to changes in population size, we included the offset term of the log of population size, for each location and year—ie, log(Population$_{iy}$). The matching factor of location and year was controlled in the model with the eliminate argument in the gnm function in R statistical software.

In the main model, we assessed the cumulative relative risk (RR) of all-cause mortality associated with tropical cyclone exposure over lags of 0–14 days. Secondary analyses included the estimation of the independent mortality effects of cyclones, using the two secondary threshold exposure definitions. For sensitivity analyses, we examined our selection of maximum lag day by extending the maximum lag to 21 days and visualising the overall and regional lag pattern of tropical cyclone-related mortality risk. Furthermore, to check the robustness of the estimated effects, we also reperformed the analysis by excluding the locations without all-cause mortality data or by respecifying the model: (1) controlling the year with 2 and 4 df, respectively; (2) setting the dflag for tropical cyclone or temperature as 3 and 4, respectively; (3) setting a maximum lag of 14 days for the confounding effect of temperature; (4) controlling the temperature with 3 and 5 df, respectively.

In the second stage, to further explore the heterogeneity of effects and potential contributing factors across countries, we used meta-regression models and included continent indicator, GDP per capita, population density, gender ratio, and median population age as meta-predictors. The meta-regression model was first fitted without any predictor to assess the overall heterogeneity of tropical cyclone-related mortality risk across countries. Univariate meta-regression models were then performed, including one predictor at a time, to assess the contribution of each predictor to the heterogeneity. Finally, a multivariate meta-regression model was fitted with all predictors to assess the combined contribution of all predictors to the heterogeneity of the effects. French overseas territories were excluded in this stage due to the lack of these data. Residual heterogeneity was tested and then quantified by the Cochran Q test and I^2 statistic.

Finally, in the third stage, we divided the world into a 0·5° by 0·5° gridded map and estimated the excess deaths for each grid cell to quantify the global and regional mortality burden associated with tropical cyclones from 1980 to 2019. Specifically, for each grid cell (i) in each year (t), the daily average excess deaths (ED) in the 2 weeks following the expected number of tropical cyclone exposures over a year were calculated as the estimated excess risks multiplied by the average daily mortality, according to the following equation:[28]

$$ED_{it}=(RR_{it}-1)\times N_{it}\times\left(\frac{D_{it}}{365}\right)$$

where RR_{it} is the cumulative RR of mortality in the 2 weeks after tropical cyclone exposure for the country in year t where grid cell i is located; N_{it} is the number of tropical cyclone exposure days for grid cell i in year t; and D_{it} is the estimated annual death count for each year t and grid cell i. RR_{it} is estimated by using the fitted multivariate meta-regression model in the second stage and the five country-level predictors of the country in year t where grid cell i is located. D_{it} was calculated based on the annual mortality rate of the country in which the grid cell was located and the population counts in the grid cell.[15] $D_{it}/365$ is the estimated daily average death count for grid cell i in year t. Yearly counts at grid cell level were summed by country and region to calculate global, regional, and country-specific decadal excess deaths. The regions were grouped according to the UN Statistics Division (M49).[29] To quantify the uncertainty in estimating excess deaths, Monte Carlo simulations (1000 samples) were used to calculate the empirical confidence intervals (eCIs).[16] In addition, the ratio between excess deaths and all deaths of a year (ie, excess deaths per 1000 deaths [the excess death ratio]) and the excess deaths per 100 000 residents (the excess death rate) were also calculated among the tropical cyclone-exposed grid cells. The temporal changes in tropical cyclone-related mortality burdens were explored and presented as decadal changes in excess deaths, excess death ratio, and excess death rate by continent and region, between 1980 and 2019.

All data organisation and analyses were conducted in R software, version 4.0.3. The models were specified using the gnm and crossbasis function, from the gnm and dlnm packages, respectively.[30,31] Meta-regression was conducted using the mvmeta function, from the mvmeta package.[32]

Role of the funding source

The funders of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the report.

Results

A summary of the individual study periods and numbers of locations, deaths, and tropical cyclone exposure days of the included 14 countries is shown in the appendix (p 2). The spatial distribution and average number of tropical cyclone exposure days per decade of the 341 locations during the overall study period is shown in figure 1A. In total, 33·7 million all-cause deaths for these 341 locations during the study period were included in the analyses. Each location contributed an average of 19·6 years (SD 9·5) of data. A total of 1748 tropical cyclone events that made landfall between Jan 1, 1980, and Dec 31, 2019, were included in the analysis. The number of tropical cyclone exposure days per decade varied substantially by study location, ranging from 1 to 28, with a mean of 5 days (SD 5). Tropical cyclones were most frequently (≥14 days per decade) observed for countries such as China, Japan, and the Philippines.

Figure 1B indicates the number of tropical cyclone exposure days per decade, estimated at the global 0·5° × 0·5° resolution grid cell level. Between Jan 1, 1980, and Dec 31, 2019, the average number of tropical cyclone exposure days per decade for all tropical cyclone-exposed grid cells globally was 3 days (SD 3, range 1–35; figure 1B and appendix p 3). Southeast Asia and east Asia had the most frequent tropical cyclone exposure, with 4 (range 1–35) and 4 (range 1–28) days per decade, respectively (appendix p 3). There was no marked trend in global average tropical cyclone exposure days, with a mean change of –0·06 days per decade (SD 1·01, range –7·20 to 5·10) from 1980 to 2019 (appendix p 3). The highest rate of tropical cyclone exposure increase was observed for south Asia (0·74 days per decade [SD 1·31, range –3·00 to 5·10]) and the strongest rate of decrease was observed for southeast Asia (–0·82 days per decade [SD 1·34, range –7·20 to 1·70]; appendix p 3).

The overall and regional lag patterns in the RR for tropical cyclone exposure indicate a persistently elevated risk of mortality following the day of tropical cyclone exposure (appendix p 9). When viewed on a regional scale, excess mortality risk for most regions peaked at 3–4 days following tropical cyclone exposure, before declining rapidly and disappearing around 11–12 days post-exposure. Overall, tropical cyclone-related mortality risk decreased as the number of lag days increased and was minimal 14 days after tropical cyclone exposure. Globally, tropical cyclone exposure was consistently associated with increased mortality risk (table 1). Specifically, tropical cyclone exposure was associated with a 6% (95% CI 4–8) increase in mortality in the 2 weeks after exposure. When the secondary analysis was conducted using the alternative two-category and three-category cyclone metrics, cyclones of higher maximum sustained wind speed consistently exhibited stronger mortality risk. Further sensitivity analysis by excluding the locations without all-cause mortality data or by respecifying the model showed similar estimates, with a robust, monotonically increasing exposure–response relationship between maximum sustained wind speed and mortality risk being observed (appendix pp 4, 10).

The heterogeneity of RR of mortality associated with tropical cyclones across countries is shown in the appendix (p 5). Also shown is a comparison of statistics from the random effect meta-analyses (no meta-predictor), random effect univariate meta-regression model, and multivariate meta-regression model with all meta-predictors (ie, full model). High heterogeneity in effect estimates of tropical cyclones on mortality across countries was observed (I^2=88·6%). The five meta-predictors—continent indicator, GDP per capita, median population age, population density, and gender ratio—all significantly modified the tropical cyclone–mortality association. Two predictors—continent indicator and GDP per capita—accounted for much higher proportions of heterogeneity compared with other meta-predictors. The residual heterogeneity was low after all predictors were included as meta-predictors (I^2=28·1%).

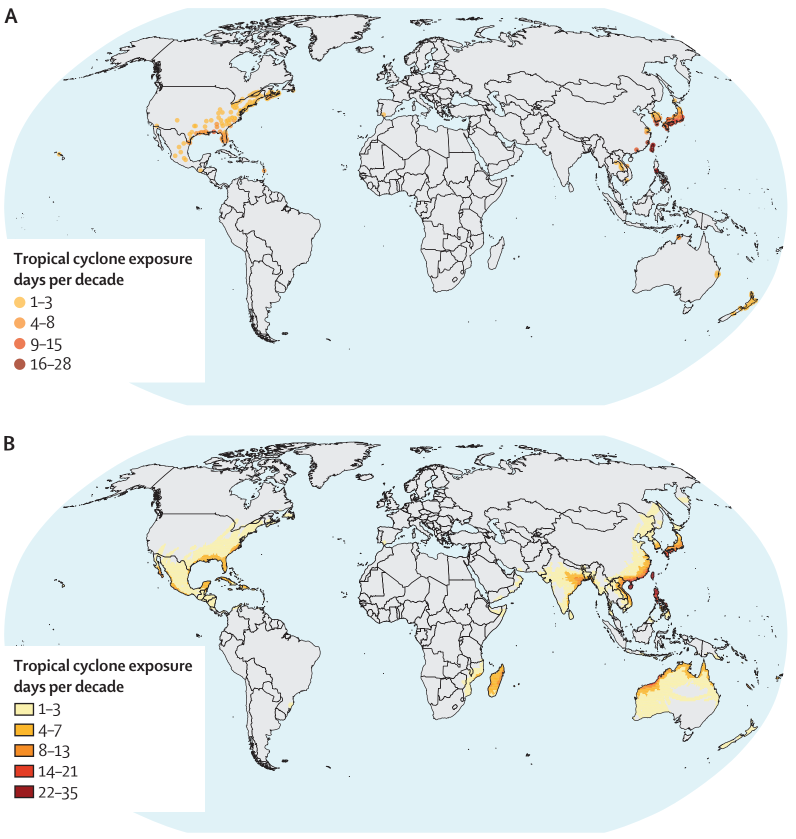


Figure 1: **Average number of tropical cyclone exposure days per decade for the study locations (A) and estimated average number of tropical cyclone exposure days per decade at the global 0·5° × 0·5° resolution grid cell level from 1980 to 2019 (B)**

	Threshold*, m/s	All-cause mortality, RR (95% CI)
Two-category		
Tropical cyclone	≥17·5	1·06 (1·04–1·08)
Tropical cyclone†	≥22·5	1·06 (1·04–1·09)
Tropical cyclone‡	≥27·5	1·09 (1·05–1·12)
Three-category		
Unexposed	<17·5	Ref
Gale to violent storm	17·5–32·8	1·07 (1·03–1·11)
Hurricane	≥32·9	1·20 (1·11–1·31)

RR=relative risk. *Defined by the maximum wind speed (m/s) of peak sustained winds. †Alternative threshold 1. ‡Alternative threshold 2.

Table 1: **Global cumulative relative risks of mortality associated with different tropical cyclone metrics over lags of 0–14 days**

Globally, 97 430 excess deaths (95% eCI 71 651–126 438) were attributable to tropical cyclone exposure per decade, from 1980 to 2019, equivalent to 20·7 (15·2–26·9) excess deaths per 100 000 residents (table 2). There were 86 477 (62 030–114 415) excess deaths per decade between 1980 and 1999, and 108 383 (77 098–144 121) excess deaths

	Excess deaths per decade (95% eCI)*				Excess deaths per 100 000 residents (95% eCI)*†			
	1980–99	2000–19	Overall	Decadal change, %	1980–99	2000–19	Overall	Decadal change, %
Global‡	86 477 (62 030 to 114 415)	108 383 (77 098 to 144 121)	97 430 (71 651 to 126 438)	12·7% (3·9 to 22·8)	10·7 (7·9 to 14·5)	10·3 (7·3 to 13·7)	20·7 (15·2 to 26·9)	–1·9% (–8·8 to 6·1)
Americas	14 075 (10 845 to 17 887)	18 991 (14 452 to 24 302)	16 533 (12 996 to 20 596)	17·5% (9·6 to 26·4)	13·1 (10·1 to 16·6)	14·0 (10·6 to 17·9)	27·1 (21·3 to 33·8)	3·5% (–2·8 to 10·6)
North America	3832 (2620 to 5257)	4341 (3220 to 5592)	4087 (3023 to 5289)	6·6% (–1·2 to 16·1)	6·8 (4·7 to 9·4)	6·5 (4·8 to 8·3)	13·3 (9·8 to 17·2)	–2·9% (–9·4 to 5·0)
Latin America and the Caribbean	10 243 (7918 to 13 068)	14 651 (10 827 to 19 345)	12 447 (9625 to 15 805)	21·5% (12·5 to 31·6)	19·8 (15·3 to 25·2)	21·3 (15·8 to 28·2)	41·3 (31·9 to 52·4)	4·0% (–2·8 to 11·6)
Asia	72 230 (48 545 to 99 609)	89 340 (59 601 to 124 371)	80 785 (56 495 to 108 518)	11·8% (1·9 to 23·7)	10·3 (6·9 to 14·2)	10·1 (6·7 to 14·0)	20·3 (14·2 to 27·3)	–0·9% (–8·8 to 8·4)
Southeast Asia	24 031 (13 996 to 36 572)	25 507 (16 588 to 37 518)	24 769 (16 052 to 35 733)	3·1% (–7·1 to 16·1)	35·7 (20·8 to 54·3)	29·3 (19·1 to 43·2)	64·2 (41·6 to 92·6)	–8·9% (–16·8 to 1·2)
South Asia	22 708 (15 836 to 30 566)	31 825 (25 273 to 39 067)	27 267 (21 157 to 34 058)	20·1% (11·5 to 30·5)	7·7 (5·4 to 10·4)	7·9 (6·3 to 9·7)	15·6 (12·1 to 19·5)	1·1% (–5·2 to 8·7)
East Asia	25 491 (16 391 to 35 533)	31 996 (15 031 to 51 838)	28 744 (16 863 to 42 188)	12·8% (–1·2 to 28·8)	7·5 (4·8 to 10·4)	8·1 (3·8 to 13·1)	15·6 (9·2 to 22·9)	4·2% (–7·9 to 18·0)
Oceania	171 (113 to 242)	51 (26 to 80)	111 (73 to 155)	–35·1% (–38·2 to –31·5)	5·0 (3·3 to 7·0)	1·1 (0·6 to 1·7)	5·5 (3·6 to 7·7)	–38·8% (–41·2 to –36·1)
Australia and New Zealand	164 (116 to 219)	40 (23 to 60)	102 (73 to 136)	–37·7% (–39·9 to –35·1)	6·8 (4·8 to 9·0)	1·3 (0·8 to 1·9)	7·4 (5·3 to 9·8)	–40·3% (–42·1 to –38·4)
Other regions in Oceania	8 (–9 to 30)	11 (0 to 23)	9 (–3 to 25)	19·7% (–47·2 to 28·0)	0·7 (–0·9 to 2·9)	0·7 (0·0 to 1·5)	1·4 (–0·5 to 4·0)	–2·3% (–48·1 to 3·3)

eCI=empirical confidence interval. *The eCIs were calculated by use of Monte Carlo simulations (1000 samples) to quantify the uncertainty. †Among the tropical cyclone-exposed grid cells. ‡Africa, Europe, west Asia, and central Asia were excluded due to the absence of tropical cyclone exposure or deaths.

***Table 2:* Excess deaths per decade and excess deaths per 100 000 residents (with 95% eCIs) associated with tropical cyclone exposures between 1980 and 2019 and the decadal percentage change by continent and region**

per decade between 2000 and 2019 (decadal change 12·7% [95% eCI 3·9–22·8]). East Asia and south Asia had the highest number of excess deaths among all regions, with 28 744 (16 863–42 188) and 27 267 (21 157–34 058) excess deaths per decade during 1980–2019, respectively. The highest regional excess death rates were observed for southeast Asia (64·2 [41·6–92·6]) and Latin America and the Caribbean (41·3 [31·9–52·4]). The greatest increases in excess deaths were observed for Latin America and the Caribbean and south Asia (decadal percentage change 21·5% [12·5–31·6] and 20·1% [11·5–30·5], respectively) from 1980–99 to 2000–19, with no sufficient evidence to detect a trend in excess death rates. Globally, an estimated 3·3 (95% eCI 2·4–4·3) excess deaths per 1000 deaths were associated with tropical cyclones from 1980 to 2019 (appendix p 6). A similar pattern was observed in the excess death ratio, with Latin America and the Caribbean and southeast Asia exhibiting the highest excess death ratios, followed by North America. Increasing trends in tropical cyclone-related excess death ratios were also found for Latin America and the Caribbean, but not for other regions.

A finer overview with gridded excess deaths, excess deaths ratios, and excess death rates associated with tropical cyclones and their decadal changes is provided in figure 2. Finer geographical disparity was observed within regions. Most of the grid cells with a high density of excess deaths were located in heavily populated areas in Latin America and the Caribbean, western coastal areas of southeast Asia, and eastern coastal areas of east Asia and North America. An increasing trend was observed for coastal grid cells surrounding Bay of Bengal, most grid cells in the Caribbean, Taiwan, and South Korea, and eastern coastal grid cells in southeast Asia and Japan, whereas a decreasing trend was observed for western coastal grid cells in Latin America, the southeast coast of China, and the southern coast of India (figure 2A, B). High excess death rates and ratios were observed for most grid cells in central America and the Caribbean and coastal grid cells in North America and Asia (figure 2C, E). Similar patterns of increasing excess death ratios and rates were observed for most grid cells in the Caribbean, the coastal areas of southeast Asia, and northeast India, and a decreasing trend was observed for eastern coastal regions of southeast China (figure 2D, F).

Lists of the top ten countries ranked by tropical cyclone-related overall excess deaths per decade and excess death rate over 1980–2019 were highly diverse (figure 3). China, Bangladesh, and Myanmar (Burma) were the top three countries with a considerably higher number of excess deaths, relative to other countries, with over 10 000 excess deaths per decade associated with tropical cyclone exposure from 1980 to 2019 for each country (figure 3A). However, after controlling for population size, the three countries with highest excess death rate were Haiti, Myanmar (Burma), and Cuba, with a considerably higher

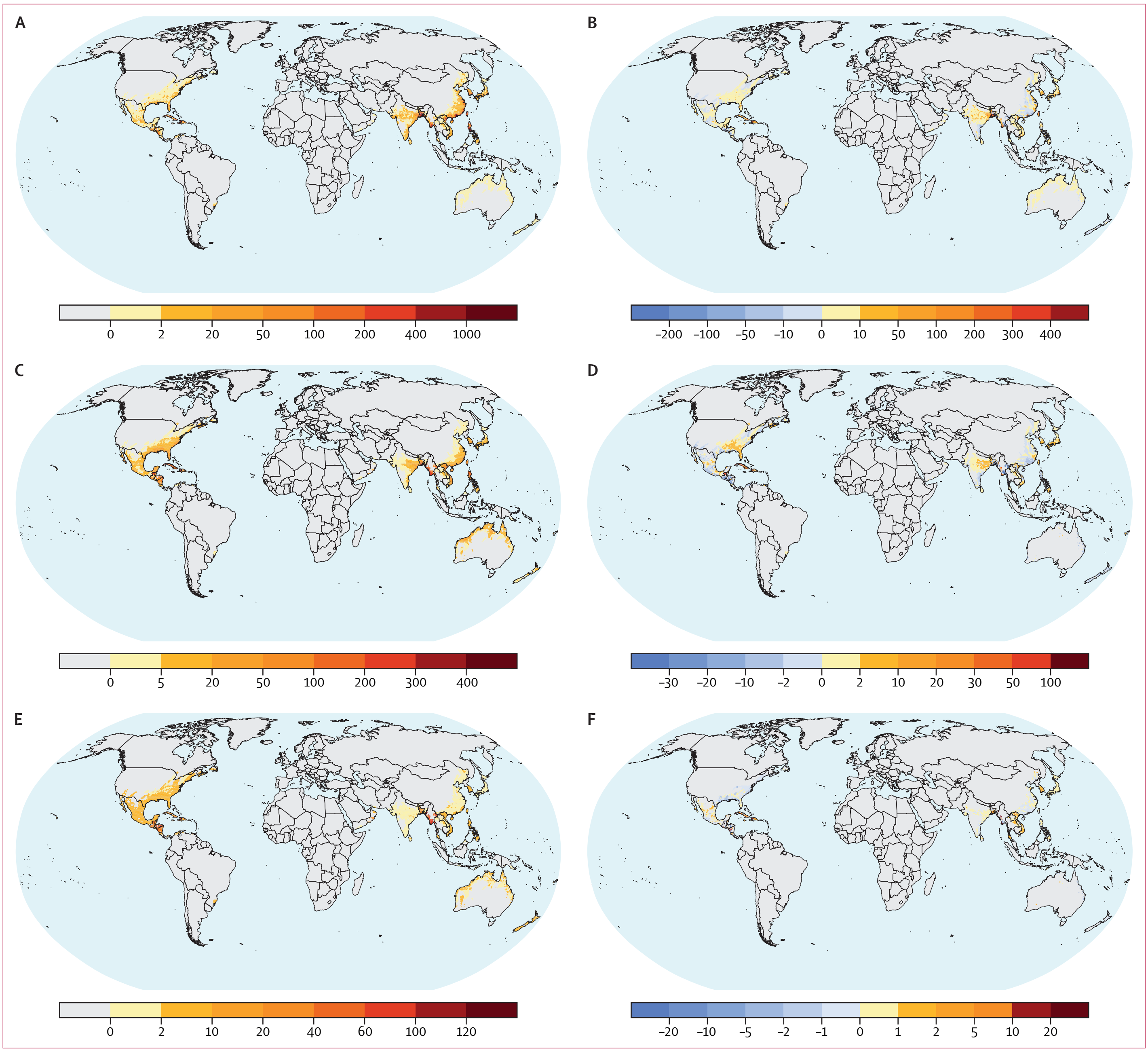
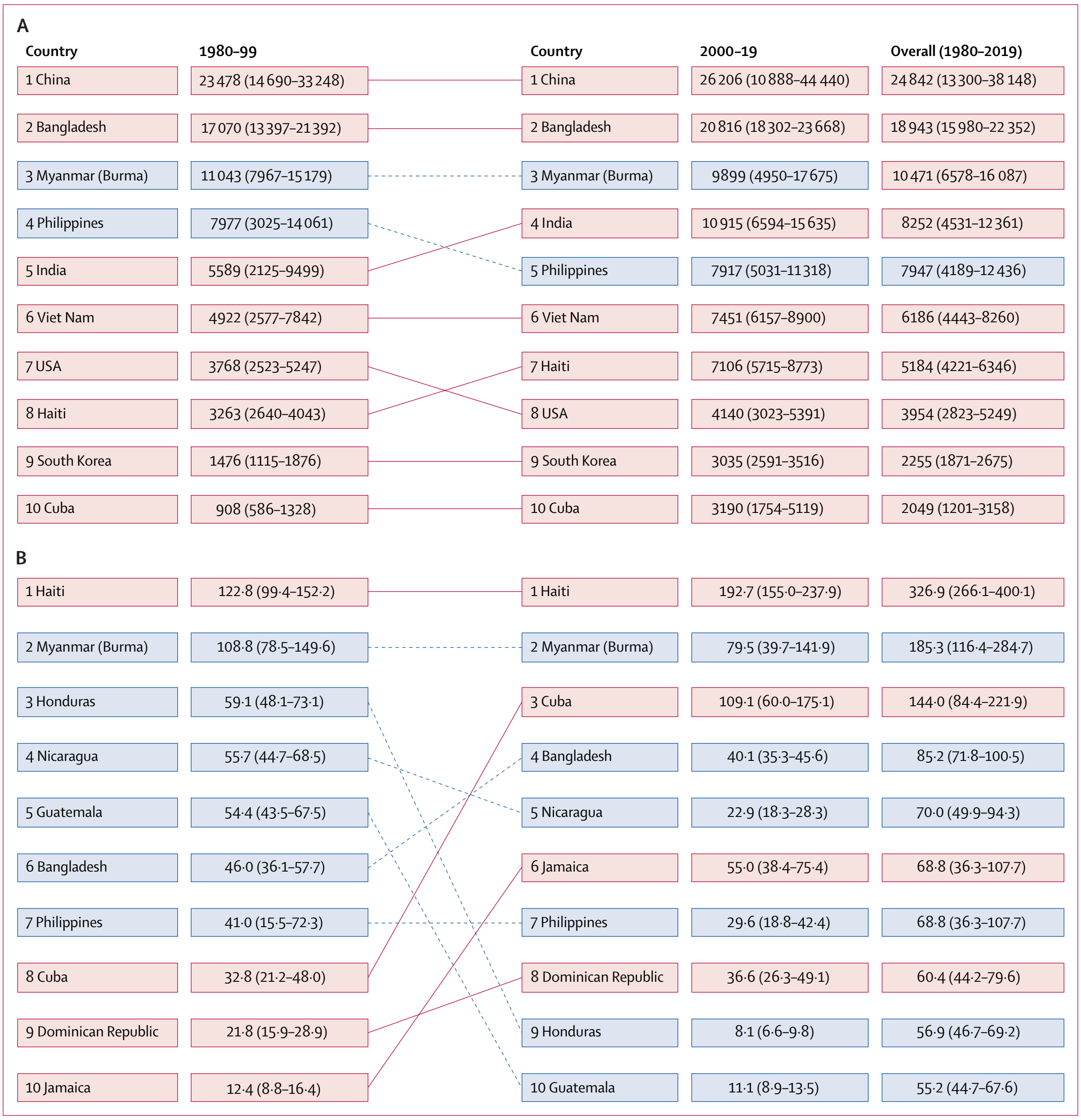


Figure 2: **Gridded estimated excess deaths per decade (A), decadal change in excess deaths (B), excess death rate per 100 000 residents (C), decadal change in excess death rate (D), excess death ratio per 1000 deaths (E), and decadal change in excess death ratio (F) attributable to tropical cyclone exposure from 1980 to 2019, at a spatial resolution of 0·5° × 0·5°**
Numbers in panels B, D, and F represent absolute changes per decade (absolute change in number of excess deaths, in number of excess deaths per 100 000 residents, and in number of excess deaths per 1000 deaths, per decade).

excess death rate of over 100 excess deaths per 100 000 residents associated with tropical cyclones over 1980–2019 compared with other countries (figure 3B). Additionally, significant increasing trends in the number of excess deaths were observed for India, Viet Nam, Haiti, South Korea, and Cuba, with Haiti and Cuba also exhibiting a significant increase in excess death rates. A similar pattern to excess death rates was found for excess death ratios, with Myanmar (Burma), Honduras, Nicaragua, and Haiti exhibiting substantially higher excess death ratios and Haiti showing a marked increase (appendix p 7). Lower-middle-income and upper-middle-income countries, as defined by the World Bank, were the main contributors to the global tropical cyclone-related mortality burden (appendix p 8). After controlling the tropical cyclone frequency (ie, tropical cyclone



A

Country	1980–99	Country	2000–19	Overall (1980–2019)
1 China	23 478 (14 690–33 248)	1 China	26 206 (10 888–44 440)	24 842 (13 300–38 148)
2 Bangladesh	17 070 (13 397–21 392)	2 Bangladesh	20 816 (18 302–23 668)	18 943 (15 980–22 352)
3 Myanmar (Burma)	11 043 (7967–15 179)	3 Myanmar (Burma)	9899 (4950–17 675)	10 471 (6578–16 087)
4 Philippines	7977 (3025–14 061)	4 India	10 915 (6594–15 635)	8252 (4531–12 361)
5 India	5589 (2125–9499)	5 Philippines	7917 (5031–11 318)	7947 (4189–12 436)
6 Viet Nam	4922 (2577–7842)	6 Viet Nam	7451 (6157–8900)	6186 (4443–8260)
7 USA	3768 (2523–5247)	7 Haiti	7106 (5715–8773)	5184 (4221–6346)
8 Haiti	3263 (2640–4043)	8 USA	4140 (3023–5391)	3954 (2823–5249)
9 South Korea	1476 (1115–1876)	9 South Korea	3035 (2591–3516)	2255 (1871–2675)
10 Cuba	908 (586–1328)	10 Cuba	3190 (1754–5119)	2049 (1201–3158)

B

Country	1980–99	Country	2000–19	Overall (1980–2019)
1 Haiti	122·8 (99·4–152·2)	1 Haiti	192·7 (155·0–237·9)	326·9 (266·1–400·1)
2 Myanmar (Burma)	108·8 (78·5–149·6)	2 Myanmar (Burma)	79·5 (39·7–141·9)	185·3 (116·4–284·7)
3 Honduras	59·1 (48·1–73·1)	3 Cuba	109·1 (60·0–175·1)	144·0 (84·4–221·9)
4 Nicaragua	55·7 (44·7–68·5)	4 Bangladesh	40·1 (35·3–45·6)	85·2 (71·8–100·5)
5 Guatemala	54·4 (43·5–67·5)	5 Nicaragua	22·9 (18·3–28·3)	70·0 (49·9–94·3)
6 Bangladesh	46·0 (36·1–57·7)	6 Jamaica	55·0 (38·4–75·4)	68·8 (36·3–107·7)
7 Philippines	41·0 (15·5–72·3)	7 Philippines	29·6 (18·8–42·4)	68·8 (36·3–107·7)
8 Cuba	32·8 (21·2–48·0)	8 Dominican Republic	36·6 (26·3–49·1)	60·4 (44·2–79·6)
9 Dominican Republic	21·8 (15·9–28·9)	9 Honduras	8·1 (6·6–9·8)	56·9 (46·7–69·2)
10 Jamaica	12·4 (8·8–16·4)	10 Guatemala	11·1 (8·9–13·5)	55·2 (44·7–67·6)

Figure 3: **Leading ten countries for excess deaths per decade (A) and excess deaths per 100 000 residents (B) among the tropical cyclone-exposed grid cells between 1980 and 2019**

The red colour indicates potential increasing trends and the blue colour indicates potential decreasing trends.

exposure days), the highest number of tropical cyclone-related excess deaths was observed in countries with lower-middle and upper-middle incomes (appendix p 8). As tropical cyclone frequency increased, the country-level excess deaths per tropical cyclone exposure day first increased and then decreased slightly (appendix p 11).

Discussion

We estimated the global short-term mortality risk associated with tropical cyclone exposure, and quantified the global spatial and temporal pattern of short-term mortality burden at a spatial resolution of 0·5° × 0·5° from 1980 to 2019. We observed an overall 6% elevated mortality risk associated with tropical cyclone exposure, as well as a robust exposure–response relationship indicating a greater mortality risk associated with cyclones defined using higher maximum sustained wind speeds. An estimated 97 430 deaths per decade were associated with tropical cyclones over 1980–2019, accounting for 20·7 excess deaths per 100 000 residents. Asia contributed most to the global tropical cyclone-related excess deaths. The highest tropical cyclone-related mortality burdens (ie, excess death rate and ratio) were observed in southeast Asia and Latin America and the Caribbean. Global excess deaths numbers have been increasing from 1980–99 to 2000–19, especially for Latin America and the Caribbean and south Asia. Consistent and marked increases in excess death ratios were also observed in Latin America and the Caribbean. Further heterogeneous patterns of tropical cyclone-related mortality burden were observed at the country level.

Our findings of the adverse associations of tropical cyclone exposure with mortality were consistent with previous evidence, while the estimated elevated mortality risks varied greatly in terms of magnitude.[33–35] Previous studies were mainly restricted to a single study area or country, or a particular tropical cyclone event.[12] For example, two studies examined the excess mortality due to Hurricane Maria in Puerto Rico, and reported increases of 22% and 62% in premature deaths after the hurricane.[33,34] Another cohort study from nursing homes in Florida found an 18% (95% CI 8–29) higher risk of mortality for elderly people who experienced Hurricane Irma compared with those unexposed.[35] In this multi-country study, we observed an overall 6% (95% CI 4–8) increase in mortality in the 2 weeks following tropical cyclone exposure based on a matched study design with control days (ie, unexposed days) defined both before and after the tropical cyclone exposure.[9,10,36] In comparison, most previous studies derived the relative mortality risk using pre-post comparisons or unexposed neighbouring areas as controls.[33,34,37–39] This might lead to residual confounding by either temporal trends or spatial gradients in the mortality risk.[36] Additionally, tropical cyclones vary substantially in terms of their frequency, intensity, and related hazards geographically. Such variability was reflected in our current study, which found that greater mortality risks were associated with tropical cyclones of higher intensity, and found high heterogeneity in the country-specific estimates. The high heterogeneity of risk estimates across previous studies could be attributable to differences in modelling approaches, study period, tropical cyclone events characteristics, or exposure definitions. Findings from any single area or country, or a particular tropical cyclone event, might not be generalisable to other regions, cyclones, populations, or time periods.

To our knowledge, this study is the first to quantify the spatial and temporal variation of short-term tropical cyclone-related mortality burden at a global scale. A study based on country-level health data estimated the mortality burden associated with hurricanes in 16 small, low-income countries from 1958 to 2011.[40] They found an estimate of 25·93 (95% CI 13·30–38·55) deaths per 100 000 people associated with high-amplitude storms for nations with low GDP per capita, which is higher than our overall global estimate. Such differences are not unexpected, given they only considered tropical cyclones with high intensities (ie, 149 hurricane events of at least category 4 on the Saffir-Simpson scale [maximum sustained wind speed ≥58 m/s]) and nations with higher vulnerability (eg, low GDP per capita), while we included 1822 tropical cyclone events (including hurricanes) globally from 1980 to 2019 in our mortality burden estimation. More regional estimations have been done by previous studies and further inconsistencies exist.[33–35,41,42] For example, eight studies assessed the excess mortality in Puerto Rico after Hurricane Maria,[33,34,43–48] but varied greatly in the estimated number of excess deaths (point estimates of all-cause excess mortality ranged from 514 to 4645). The difference in model settings (eg, control selection, modelling approaches), exposure window, definitions, and study period contributed to the heterogeneity across studies and hindered the comparability and combination of the results.

Our study quantified the short-term tropical cyclone-related mortality burden at 0·5° × 0·5° resolution grid cell level and found that the majority of the excess deaths occurred in Asia, especially in southeast and south Asia. Excess deaths were largely concentrated in the high-density coastal cities of these regions. To account for the impact of population size and total deaths, we further calculated the excess death rate (per 100 000 residents) and the excess death ratio (per 1000 deaths). A considerably higher tropical cyclone-related mortality burden (ie, high death ratio and rate) was still observed for southeast Asia. This result highlights the daunting task facing southeast Asian countries, such as Myanmar and Bangladesh, to reduce the adverse effects of tropical cyclones on the health of local populations and the enormous challenges tropical cyclone poses to their health-care systems. Latin America and the Caribbean also had high tropical cyclone-related excess death ratios and rates. This could be attributable to the high vulnerability of these regions to natural disasters (eg, relatively low GDP per capita and high population density). A high-resolution analysis also revealed high tropical cyclone-related excess deaths and excess death rates at the population level along the eastern coastline of Asia and the island nations in the Pacific and Caribbean. However, very little evidence on tropical cyclone epidemiology was available from these regions or countries. Additionally, the limited study locations from these regions in the current MCC network could also reduce the accuracy of our results for these regions or countries. Epidemiological studies from these regions and countries, especially studies that incorporate multiple tropical cyclones, are highly warranted in the future to verify our findings.

We also explored the temporal change in tropical cyclone-related mortality burden from 1980 to 2019 and observed disparate geographical variations. A marked increase in tropical cyclone-related mortality was observed globally from 1980–99 to 2000–19, especially for Latin America and the Caribbean and south Asia. Similarly, one study using disaster-induced deaths from the Emergency Disasters Database found that flood-induced mortality increased worldwide from 1975 to 2016, which was closely related to tropical cyclones for parts of the countries along the western coast of the oceans (eg, central America and the Caribbean, south Asia, and east Asia).[13] Further country-specific and grid cell-level temporal change revealed consistently and considerably increased tropical cyclone-related excess deaths and excess death ratios and rates for countries or regions in the Caribbean and southeast Asia. These countries and regions would benefit from attention to the adverse effects of tropical cyclones when developing future disaster response and health promotion strategies. Given the anticipated increase in tropical cyclone intensity and the new regions that will be exposed to tropical cyclones due to climate change,[49] the global mortality burden associated with tropical cyclone exposure is expected to increase, although there might be large variations across regions and countries.

This study had multiple strengths. To the best of our knowledge, it is the first and largest global investigation of the mortality risk and burden of tropical cyclones. Compared with previous studies confined to country or region level, we provided a finer and global overview and consistent assessment of tropical cyclone-related mortality burden with high resolution (0·5° × 0·5°). The 40-year study period, from 1980 to 2019, enabled temporal trends in tropical cyclone-related mortality burdens to be assessed. Importantly, the study used advanced statistical modelling techniques to accurately estimate the mortality burden associated with tropical cyclone exposure. This included the use of five significant tropical cyclone–mortality association modifiers, to account for the spatiotemporal heterogeneity in population characteristics and development. The model was developed based on 1748 recorded tropical cyclone events and the extensive MCC dataset (accounting for 39·2% of the total population in the grid cells ever exposed to tropical cyclones), which were characterised by different climates, socioeconomics, demographics, and levels of infrastructure and public health service development. This large sample size and the representativeness of the data help to ensure the high quality of our findings at the global level.

Several assumptions and limitations should also be acknowledged. The possibility of residual confounding cannot be excluded. However, the matched design used would help to mitigate this risk, as it controlled for factors that co-vary with mortality rates and tropical cyclone exposure within locations.[9] The tropical cyclone mortality risks in each country and year were estimated based on five country-level meta-predictors, the underlying assumption being that the meta-predictors could explain the spatiotemporal variation of the country-level tropical cyclone-related mortality risks. It is possible this assumption could introduce uncertainty in the results, especially for the regions or countries with no or limited study locations (eg, China, Myanmar, Bangladesh). As noted above, future studies on tropical cyclone epidemiology from these areas are warranted to complement and verify our findings. Longer-term mortality risks of tropical cyclones, such as those from chronic disease exacerbation or mental health disorders associated with property losses (eg, stress, depression), might not be fully measured by our analysis, as they could manifest more than 2 weeks after tropical cyclone exposure. Therefore, the estimated excess deaths in this study might represent only part of the tropical cyclone-attributable mortality burden (ie, short-term elevated mortality risk and burden). Population displacements after tropical cyclones might affect our estimates of excess death rate and ratio; we could not account for these displacements due to a lack of information for each location after each tropical cyclone. However, as only a small number of tropical cyclone exposure events were high-amplitude hurricanes (cyclones with a Saffir-Simpson category of 4 or 5), the likelihood of large-scale population dislocation would have been limited, especially in the short term.[50,51] Therefore, the impact of population displacements on our results might be modest. Country-level estimates were used due to the rarity of tropical cyclones and the paucity of grid cell-specific predictors, which would have led to large uncertainties in grid cell-level effect estimates. This might have led to some overestimation or underestimation at a finer geographic scale; however, this assumption should not substantially change our findings at the national or large regional level.[15] Surface conditions play an important role in the speed and direction of surface winds. Here, we used the improved wind field model by Holland (2008)[21] which has been successfully applied in other studies.[18,52,53] In this model an attenuation factor, given as the ratio between the distance to centre and the radius of maximum winds, was incorporated to resemble surface friction effects. The wind field model does not explicitly account for surface friction and the resulting reduction in the wind speed,[54] nor does it incorporate the motion-induced asymmetries at the surface, that can increase proportionally with the translation speed.[55] After landfall, the tropical cyclone wind field can become highly noisy due to interaction with complex land surfaces, and it is challenging to account for this uncertainty when assessing the exposure–response relationship of maximum sustained wind speed with health outcomes.[56] However, the impact of neglecting inhomogeneous wind conditions over land on the results of this study should be modest because the study focuses on a binary tropical cyclone exposure variable (ie, exposed *vs* unexposed). Finally, the data were not randomly selected based on the total number of tropical cyclone-exposed locations in each country, which reduced the accuracy of our estimates for those countries and regions with relatively limited data (eg, China and other tropical cyclone-exposed regions of sub-Saharan Africa) and prevented us from estimating the tropical cyclone-related mortality risk and burden in these areas. Therefore, the mortality burden for these areas and subsequent global totals might have been underestimated.

This issue warrants further exploration and should be lessened in the future as the MCC network expands.

In summary, tropical cyclones are associated with an increased short-term mortality risk globally. Tropical cyclones with higher maximum sustained wind speeds consistently demonstrated greater mortality risks. A significant burden of mortality was attributable to short-term exposure to tropical cyclones from 1980 to 2019, which exhibits complex spatiotemporal patterns globally. Targeted actions and in-depth explorations of tropical cyclone epidemiology in countries with high and increasing tropical cyclone-related mortality burdens are particularly needed to respond to the increasing adverse health impacts of tropical cyclones, especially under a changing climate.

Contributors

YG, AG, MH, and BA set up the collaborative network. YG and SL designed the study. YG, WH, and RX developed the statistical methods. WH took the lead in manuscript drafting and results interpreting. All authors provided the data and contributed to interpreting the results and revising the manuscript. YG, SL, and WH accessed and verified the data. All authors had full access to all the data in the study and had final responsibility for the decision to submit for publication.

Declaration of interests

We declare no competing interests.

Data sharing

All data used in our study were obtained from the Multi-Country Multi-City (MCC) Collaborative Research Network under a data sharing agreement and cannot be made publicly available. Researchers can refer to MCC participants, who are listed as co-authors of this Article, for information on accessing the data for each country.

Acknowledgments

This work was supported by the Australian Research Council (DP210102076) and the Australian National Health and Medical Research Council (GNT2000581). WH and RX were supported by China Scholarship Council funds (numbers 202006380055 and 201806010405). YG was supported by a Career Development Fellowship (GNT1163693) and Leader Fellowship (GNT2008813) of the Australian National Health and Medical Research Council. SL was supported by an Emerging Leader Fellowship of the Australian National Health and Medical Research Council (GNT2009866). TV received funding from the German Federal Ministry of Education and Research (BMBF) under the research project QUIDIC (01LP1907A), and through the CHIPS project, part of AXIS, an ERA-NET initiated by JPI Climate, and funded by FORMAS (Sweden), Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)/Bundesministerium für Bildung und Forschung (German Ministry of Education and Research) (grant number 01LS1904A), Agencia Estatal de Investigación (Spanish State Research Agency), and Agence Nationale de la Recherche (French National Agency for Research) with co-funding by the EU (grant number 776608). JM was supported by a fellowship of Fundação para a Ciência e a Tecnlogia (SFRH/BPD/115112/2016). AG was supported by the UK Medical Research Council (grant ID MR/R013349/1), the UK Natural Environment Research Council (grant ID NE/R009384/1), and the EU's Horizon 2020 project, Exhaustion (grant ID 820655). AT was supported by MCIN/AEI/10.13039/501100011033 (grant CEX2018-000794-S).

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