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Mortality risks associated with floods in 761 communities worldwide: time series study

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ABSTRACT

OBJECTIVE

To evaluate lag-response associations and effect modifications of exposure to floods with risks of all cause, cardiovascular, and respiratory mortality on a global scale.

DESIGN

Time series study.

SETTING

761 communities in 35 countries or territories with at least one flood event during the study period.

PARTICIPANTS

Multi-Country Multi-City Collaborative Research Network database, Australian Cause of Death Unit Record File, New Zealand Integrated Data Infrastructure, and the International Network for the Demographic Evaluation of Populations and their Health Network database.

MAIN OUTCOME MEASURES

The main outcome was daily counts of deaths. An estimation for the lag-response association between flood and daily mortality risk was modelled, and the relative risks over the lag period were cumulated to calculate overall effects. Attributable fractions of mortality due to floods were further calculated. A quasi-Poisson model with a distributed lag non-linear function was used to examine how daily death risk was associated with flooded days in each community, and then the community specific associations were pooled using random effects multivariate meta-analyses. Flooded days were defined as days from the start date to the end date of flood events.

RESULTS

A total of 47.6 million all cause deaths, 11.1 million cardiovascular deaths, and 4.9 million respiratory deaths were analysed. Over the 761 communities, mortality risks increased and persisted for up to 60 days (50 days for cardiovascular mortality) after a flooded day. The cumulative relative risks for all cause, cardiovascular, and respiratory mortality were 1.021 (95% confidence interval 1.006 to 1.036), 1.026 (1.005 to 1.047), and 1.049 (1.008 to 1.092), respectively. The associations varied across countries or territories and regions. The flood-mortality associations appeared to be modified by climate type and were stronger in low income countries and in populations with a low human development index or high proportion of older people. In communities impacted by flood, up to 0.10% of all cause deaths, 0.18% of cardiovascular deaths, and 0.41% of respiratory deaths were attributed to floods.

CONCLUSIONS

This study found that the risks of all cause, cardiovascular, and respiratory mortality increased for up to 60 days after exposure to flood and the associations could vary by local climate type, socioeconomic status, and older age.

Introduction

Floods are the most common (43%) natural disasters worldwide and they have extensive adverse impacts on environments, economies, and human health—over the past four decades the number of people affected by, and the number of deaths directly due to, floods has been increasing.¹ An estimated 1.81 billion people (23% of the world's population) are exposed to inundation depths of >0.15 m during 1-in-100-year flood events.² As a result of more frequent extreme precipitation and rising sea levels linked to the change in global climate, flood events are projected to increase in severity, duration, and frequency.³ The health of many of the world's population is at risk from exposure to floods. Traditionally, a surveillance approach is used to estimate deaths attributable to floods, but this method has been shown to systematically underestimate numbers.⁴ The surveillance approach searches death records for specific mentions of links to a flood event and may refer to other documents, including government and media reports, to identify deaths that can be attributed to the flood event.⁵ This approach can well capture deaths caused by direct physical forces of floods or from unintentional causes linked to hazards created by flood events, such as drowning, electrocution, and

WHAT IS ALREADY KNOWN ON THIS TOPIC

Flood events are projected to increase in severity, duration, and frequency as a result of climate change

Deaths from natural causes might increase after flood events, but current evidence is inconsistent

Previous studies had limitations in exposure assessments, sample sizes, geographical areas, and study durations

WHAT THIS STUDY ADDS

The findings of this study suggest that the risks of all cause, cardiovascular, and respiratory mortality reach a peak at around 25 days after exposure to floods and last for up to 60 days

The associations appeared to vary with climate type and were stronger in populations with a low socioeconomic status or a high proportion of older people
In communities impacted by floods, up to 0.10% of all cause deaths, 0.18% of cardiovascular deaths, and 0.41% of respiratory deaths were attributed to floods

hypothermia,⁴ but a substantial number of deaths from natural causes can be overlooked. Such deaths may result from contamination of food and water, exposure to pathogens (fungi, bacteria, and viruses), impaired access to health services, and psychological impairment.⁶⁻⁸

According to our literature review, five studies have assessed associations between floods and non-external or all cause mortality, but the findings were inconsistent.^{4,9-12} One study observed a counterintuitive 10% decline in all cause mortality in the year after the population in England and Wales had been exposed to flood events during 1994-2005,¹² whereas a study of the 1968 “great flood” in Bristol, England, observed a 50% increase in all cause mortality among the exposed population for a similar follow-up period.¹¹ Yet a study of the flood in Beijing, China, in July 2012 found a 34% increased risk of all cause mortality and 37% increased risk of cardiovascular mortality, but no change in risk of death from respiratory diseases.⁴ The other two studies, which investigated the impacts of the 2004 flood in Bangladesh and the 1997 central European flood in the Czech Republic, found no evidence of a flood-mortality association.^{9,10}

The inconsistency in findings between studies might be attributed to methodological differences, small sample sizes, and limited geographical and temporal scopes. To overcome these limitations, a comprehensive global study to inform the improvement of disaster response strategies for governments and health service providers is necessary to reduce avoidable deaths from natural causes, especially in flood prone areas. Using data from a global database, we estimated the associations of exposure to flood with risk of all cause, cardiovascular, and respiratory mortality to quantify the lag-response associations and to identify potential effect modifiers.

Methods

Mortality data

We obtained data on mortality from several sources. Daily mortality data for all causes, cardiovascular diseases (international classification of diseases, 10th

revision (ICD-10) codes I00–I99), and respiratory diseases (J00–J99) were obtained for each city from the Multi-Country Multi-City (MCC) Collaborative Research Network database.^{13,14} Data for each statistical area level 3 were obtained from the Australian Cause of Death Unit Record File, for each territorial authority from the New Zealand integrated data infrastructure,¹⁵ and for each health and demographic surveillance systems sites from the International Network for the Demographic Evaluation of Populations and their Health (INDEPTH) Network database. See the supplementary methods for more details.

Temperature data

Daily mean temperatures were retrieved from monitoring stations for each MCC community. Details of the assessment can be found elsewhere.¹³ For communities in Australia (statistical area level 3), New Zealand (territorial authority), and INDEPTH (health and demographic surveillance systems sites), average daily mean temperatures at the ground level of each community were derived from the ERA5-Land dataset, which provided hourly observations of global ground level temperature at a resolution of $0.1^{\circ} \times 0.1^{\circ}$.¹⁶

Flood exposure

Data on flood events worldwide during 2000-19 were obtained from Dartmouth Flood Observatory.¹⁷ Data in the observatory were extracted from news, government, and instrumental sources and were validated using satellite observations.¹⁸ Previous studies on assessment of exposure to flood globally examined accuracy and reliability of Dartmouth Flood Observatory and found it well represented global major flood events over time, although it might have underrepresented flood events in Africa and South America.¹³ Other catalogues of global flood events, such as the Emergency Event Database, only provide rough locations (eg, flooded states or provinces). Mapping entire states and provinces when an event occurs in a small area or crosses the border results in major misclassifications of exposure. Dartmouth Flood Observatory provides spatial estimates of flooded

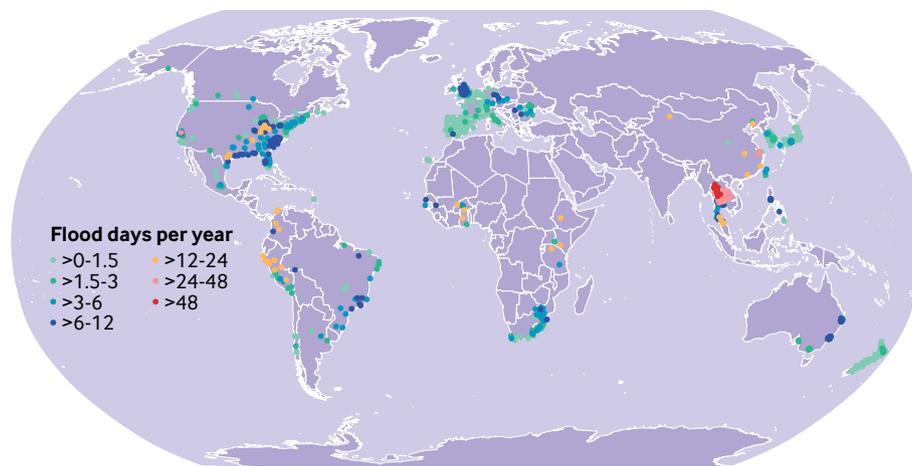


Fig 1 | Annual flood days in 761 communities from 35 countries or territories during study period

areas, enabling users to determine if a community was flooded. In this study, we considered a community to have been flooded if the community centroid was within the flooded areas. Start dates (when floods were officially recognised), end dates (when floods were officially announced to be receding), and severities (large: return period <100 years; extreme: return period \geq 100 years) of flood events were consistently defined across countries or territories and provided by Dartmouth Flood Observatory.¹⁹ For each flooded community (communities in the MCC database, statistical areas level 3 in Australia, territorial authorities in New Zealand, and health and demographic surveillance systems sites in INDEPTH), we defined our exposure, flooded days, as days from the start dates to the end dates of flood events.

Statistical analysis

Two stage analytical approach

To examine the association of exposure to flood with mortality, we adopted a two stage analytical approach^{20 21} using the methods outlined in previous

studies.²²⁻²⁴ In the first stage, a standard quasi-Poisson time series model was used in combination with a distributed lag non-linear model to estimate the exposure-lag-response association of floods with mortality risk over 0-60 lag days (ie, 0-60 days after exposure) for each community. We selected the maximum lag period of 60 days because previous studies and our preliminary results suggested that the impact of large floods on mortality risks lasted for up to eight weeks.^{25 26} A cross basis function was employed through the lag non-linear model to quantify the exposure-lag-response association. Each cross basis was a combination of two functions that defined the conventional exposure-response association and an additional lag-response association. The lag-response association captured the temporal change in risk over a particular period after an exposure.²⁷ Specifically, we modelled the exposure-response association with a strata function (strata: not exposed or exposed) and the lag-response association with a natural cubic B spline with three degrees of freedom.²⁸ We also included a cubic B spline with three degrees of freedom for time to model long term trends (eg, for changes in populations), a cyclic cubic B spline with three equally spaced knots for day of the year to explain the seasonal trend, and a day of the week indicator to control for weekly variations in mortality.²¹ Potential confounding effects introduced by non-optimal temperature were controlled for by including a cross basis function of daily mean temperature over 0-21 lag days, as suggested by previous work.¹³ The supplementary methods provide detailed information on the community specific model. Communities without any flooding days during the study period were excluded before this stage.

In the second stage, we pooled the coefficients and covariance matrixes of the cross basis functions that quantified the community specific associations between floods and mortality risks, using random effects meta-analyses with restricted maximum likelihood estimation to obtain overall lag-response associations. The overall lag-response associations were pooled at global, regional (United Nations geoscheme), and country or territory levels, as well as according to local climate types (Köppen climate classification), demographic characteristics (proportion of older population (\geq 65 years) and population density), socioeconomic status (country's income class (2010 version) and human development index), and population health status (infant mortality rates).²³ The supplementary methods provide details of the sources and assessments of the demographic and socioeconomic variables. For each meta-analysis, we examined heterogeneity using Cochran's Q test and quantified inconsistency using the I^2 statistic.²⁹ For each lag-response association, we calculated a cumulative relative risk over the maximum lag period.³⁰ Sensitivity analyses were performed to examine the robustness of our results (see supplementary methods).

Effect modifications

To identify effect modifications for the flood-mortality association, we used random effects meta-regressions

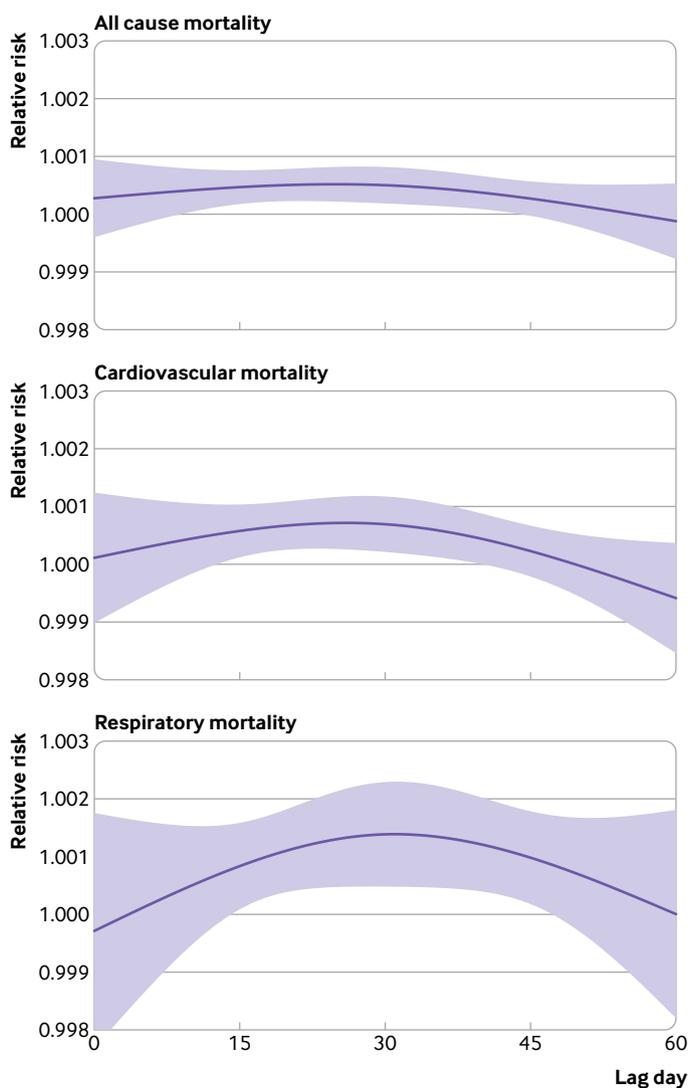


Fig 2 | Relative risks of mortality associated with exposure to floods during lag 0-60 days in 761 communities from 35 countries or territories

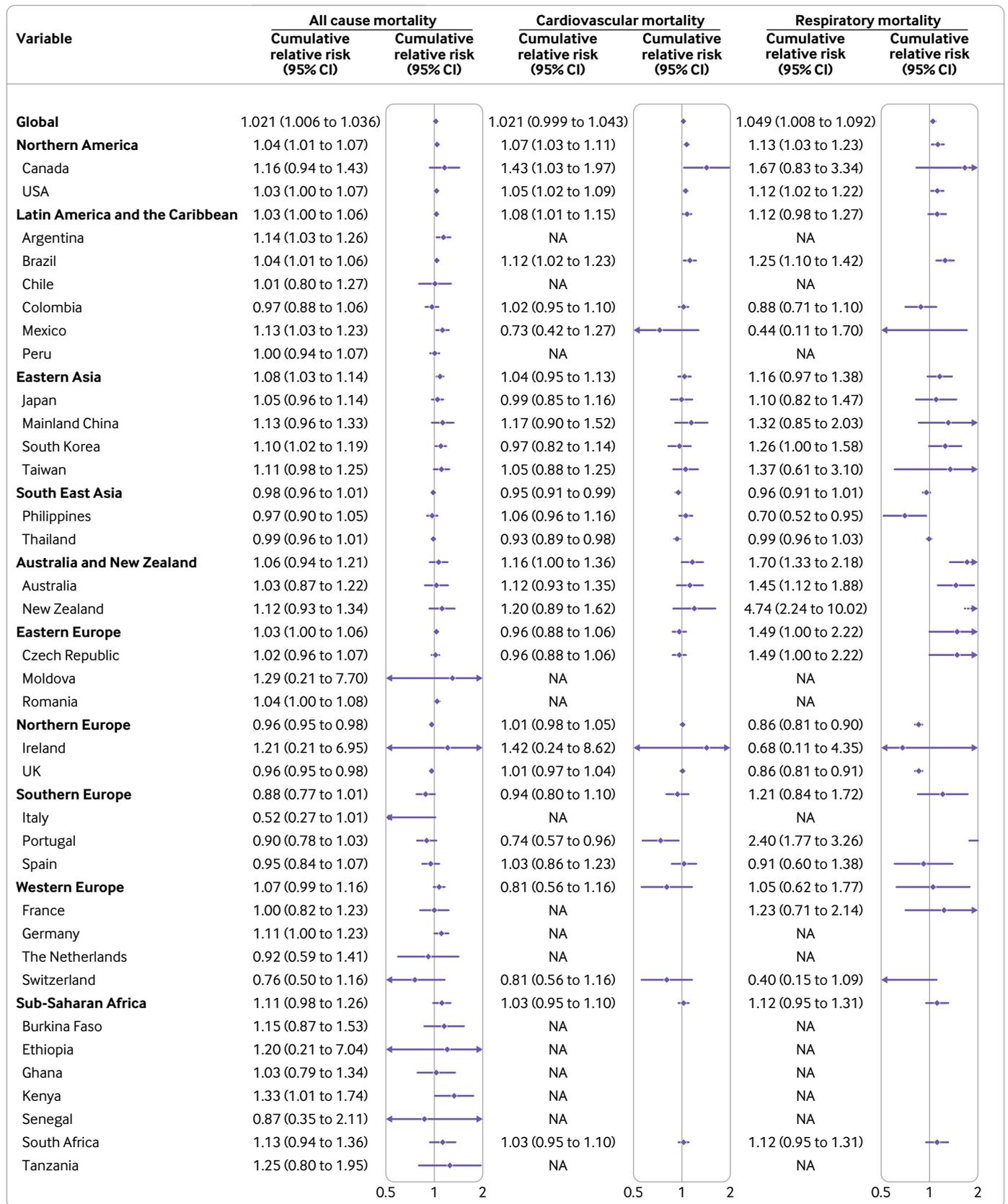


Fig 3 | Cumulative relative risks of all cause, cardiovascular, and respiratory mortality associated with exposure to floods during lag 0-60 days of all locations, and by country or territory and region. CI=confidence interval; NA=not available

with maximum likelihood estimation to compare the cumulative relative risks across different strata of potential modifiers (ie, climate types, demographic characteristics, socioeconomic status, and population

health status) because these estimates were based on different populations. To assess the effect modification by flood severity, we first estimated the effects of different flood severities by modifying the exposure strata function from two strata to three strata (not exposed, exposed to large floods, and exposed to extreme floods) in the first stage. After calculating the cumulative relative risks of different flood severities, we used fixed effect meta-regressions with no statistical adjustment to test whether the effect estimates were modified by flood severity as the estimates were based on the same or overlapping populations.³¹

Attributable fraction

By assuming the mortality risks were the same within each country or territory, we calculated the attributable fraction of deaths due to floods for each country or territory based on the country or territory level associations obtained at the second stage.²⁰ The supplementary methods present the specific method and formulas used.

We used R software (version 4.1.1) to perform all data analyses. The packages *dnm* and *mixmeta* were used to fit the community specific models in the first stage and to perform the meta-analyses in the second stage. Meta-regression was conducted with package *mvmeta*. A two sided P value <0.05 was considered statistically significant.

Patient and public involvement

This study was not funded for public involvement and did not involve patients—it was based on deidentified death registration data, without patient access. As a result, no patients or members of the public were involved in the design, conduct, reporting, or dissemination plans of our research.

Results

After excluding 305 communities without flood days during the study period, 761 communities from 35 countries or territories were included in analyses. Communities with the most flood days per year during the study period were located in the

Table 1 | Cumulative relative risks of mortality associated with exposure to flood during 0-60 days by climate type, socioeconomic status, demographic characteristics, population health status, and flood severity

Variables	All cause mortality		Cardiovascular mortality		Respiratory mortality	
	Cumulative relative risk (95% CI)	P value for difference	Cumulative relative risk (95% CI)	P value for difference	Cumulative relative risk (95% CI)	P value for difference
Climate type						
Tropical	0.99 (0.97 to 1.01)	Ref	0.96 (0.93 to 1.00)	Ref	0.97 (0.92 to 1.02)	Ref
Arid	1.20 (1.06 to 1.34)	0.001	1.03 (0.80 to 1.33)	0.62	1.14 (0.54 to 2.39)	0.67
Temperate	1.02 (1.00 to 1.05)	0.01	1.04 (1.02 to 1.07)	0.001	1.08 (1.03 to 1.15)	0.004
Continental	1.08 (1.01 to 1.15)	0.007	1.12 (0.98 to 1.28)	0.04	1.26 (1.04 to 1.54)	0.01
Polar	0.97 (0.78 to 1.21)	0.91	NA	NA	NA	NA
Income class						
High	1.02 (1.00 to 1.05)	Ref	1.04 (1.01 to 1.07)	Ref	1.09 (1.02 to 1.15)	Ref
Upper middle	1.02 (1.00 to 1.04)	0.92	0.99 (0.96 to 1.03)	0.04	1.06 (1.01 to 1.11)	0.51
Lower middle	0.98 (0.91 to 1.05)	0.24	1.06 (0.96 to 1.16)*	0.73	0.70 (0.52 to 0.95)*	0.006
Low	1.24 (1.05 to 1.45)	0.02	NA	NA	NA	NA
Human development index (quartiles)						
4th: >20.1	1.02 (1.00 to 1.04)	Ref	0.99 (0.96 to 1.03)	Ref	1.03 (0.98 to 1.09)	Ref
3rd: 5.9-20.1	0.97 (0.94 to 1.00)	0.02	1.00 (0.97 to 1.04)	0.69	1.00 (0.90 to 1.10)	0.52
2nd: 1.0-5.9	1.04 (1.01 to 1.07)	0.30	1.06 (1.02 to 1.11)	0.009	1.07 (0.98 to 1.16)	0.52
1st: <1.0	1.08 (1.01 to 1.15)	0.11	1.13 (1.04 to 1.24)	0.006	1.29 (1.13 to 1.48)	0.003
Infant mortality rate (%) (quartiles)						
1st: <0.8	1.04 (1.01 to 1.08)	Ref	1.01 (0.95 to 1.08)	Ref	1.13 (0.98 to 1.30)	Ref
2nd: 0.8-2.8	1.02 (0.96 to 1.07)	0.48	1.05 (0.99 to 1.12)	0.37	1.10 (0.99 to 1.23)	0.80
3rd: 2.8-6.7	1.04 (1.01 to 1.06)	0.89	1.06 (1.02 to 1.10)	0.22	1.12 (1.03 to 1.22)	0.94
4th: >6.7	1.01 (0.99 to 1.03)	0.11	0.99 (0.95 to 1.02)	0.50	1.00 (0.95 to 1.05)	0.11
Proportion of older population (%) (quartiles)						
1st: <9	1.02 (0.99 to 1.05)	Ref	1.00 (0.97 to 1.04)	Ref	1.02 (0.96 to 1.09)	Ref
2nd: 9-13	1.03 (1.00 to 1.06)	0.69	1.05 (1.00 to 1.10)	0.12	1.02 (0.96 to 1.09)	0.97
3rd: 13-16	1.01 (0.99 to 1.04)	0.78	1.03 (0.99 to 1.07)	0.34	1.05 (0.96 to 1.15)	0.59
4th: >16	1.02 (0.98 to 1.06)	0.98	1.01 (0.96 to 1.07)	0.74	1.21 (1.05 to 1.40)	0.03
Population density (per km²) (quartiles)						
1st: <152	1.04 (0.99 to 1.09)	Ref	0.98 (0.93 to 1.05)	Ref	1.11 (1.02 to 1.22)	Ref
2nd: 152-526	1.01 (0.99 to 1.04)	0.34	1.00 (0.96 to 1.04)	0.67	1.02 (0.97 to 1.07)	0.09
3rd: 526-2010	1.03 (1.00 to 1.06)	0.85	1.04 (1.00 to 1.09)	0.13	1.09 (1.00 to 1.20)	0.76
4th: >2010	1.02 (1.00 to 1.04)	0.53	1.04 (1.01 to 1.08)	0.10	1.01 (0.92 to 1.10)	0.12
Flood severity						
Large	1.04 (1.02 to 1.07)	Ref	1.03 (1.01 to 1.06)	Ref	1.06 (1.01 to 1.11)	Ref
Extreme	1.01 (0.98 to 1.04)	0.66	1.02 (0.98 to 1.06)	0.45	1.07 (1.01 to 1.13)	0.91

CI=confidence interval; NA=not available; Ref=reference.

P values for difference for flood severity were estimated by fixed effect meta-regression with no statistical adjustment as these models were based on the same or overlapping populations.

P values for difference for other variables were estimated by random effects meta-regression with maximum likelihood estimation as these models were based on different populations.

*The Philippines is the only lower middle income country with cardiovascular and respiratory data.

Table 2 | Attributable fraction (%) of mortality related to flood in communities impacted by floods, by country or territory

Variable	Attributable fraction (%) (95% CI)		
	All cause mortality	Cardiovascular mortality	Respiratory mortality
Northern America			
Canada	0.049 (−0.021 to 0.117)	0.123 (0.011 to 0.226)	0.159 (−0.057 to 0.336)
USA	0.032 (0.000 to 0.063)	0.051 (0.017 to 0.085)	0.112 (0.022 to 0.198)
Latin America and the Caribbean			
Argentina	0.072 (0.019 to 0.122)	NA	NA
Brazil	0.048 (0.014 to 0.080)	0.178 (0.044 to 0.319)	0.336 (0.159 to 0.519)
Chile	0.002 (−0.077 to 0.080)	NA	NA
Colombia	−0.114 (−0.466 to 0.198)	0.082 (−0.165 to 0.318)	−0.443 (−1.320 to 0.321)
Mexico	0.099 (0.024 to 0.173)	−0.246 (−0.723 to 0.157)	−0.757 (−2.550 to 0.379)
Peru	0.011 (−0.099 to 0.113)	NA	NA
Eastern Asia			
Japan	0.012 (−0.010 to 0.034)	−0.001 (−0.038 to 0.035)	0.026 (−0.049 to 0.099)
Mainland China	0.327 (−0.090 to 0.707)	0.378 (−0.277 to 0.937)	0.792 (−0.539 to 1.830)
South Korea	0.044 (0.008 to 0.079)	−0.016 (−0.097 to 0.058)	0.088 (−0.007 to 0.172)
Taiwan	0.075 (−0.017 to 0.162)	0.033 (−0.093 to 0.151)	0.212 (−0.368 to 0.705)
South East Asia			
Philippines	−0.035 (−0.151 to 0.083)	0.099 (−0.044 to 0.238)	−0.510 (−1.004 to −0.062)
Thailand	−0.105 (−0.306 to 0.088)	−0.537 (−0.906 to −0.182)	−0.043 (−0.350 to 0.254)
Australia and New Zealand			
Australia	0.035 (−0.176 to 0.235)	0.144 (−0.099 to 0.371)	0.412 (0.113 to 0.681)
New Zealand	0.026 (−0.017 to 0.066)	0.041 (−0.028 to 0.108)	0.335 (0.174 to 0.478)
Eastern Europe			
Czech Republic	0.026 (−0.061 to 0.108)	−0.052 (−0.208 to 0.093)	0.593 (−0.011 to 1.118)
Moldova	0.164 (−1.185 to 0.866)	NA	NA
Romania	0.048 (0.001 to 0.093)	NA	NA
Northern Europe			
Ireland	0.084 (−0.844 to 0.756)	0.174 (−0.862 to 0.852)	−0.178 (−1.422 to 0.650)
UK	−0.064 (−0.092 to −0.035)	0.013 (−0.038 to 0.066)	−0.276 (−0.375 to −0.175)
Southern Europe			
Italy	−0.154 (−0.331 to 0.008)	NA	NA
Portugal	−0.030 (−0.071 to 0.009)	−0.093 (−0.174 to −0.021)	0.228 (0.151 to 0.295)
Spain	−0.018 (−0.063 to 0.025)	0.013 (−0.060 to 0.081)	−0.028 (−0.190 to 0.114)
Western Europe			
France	0.000 (−0.041 to 0.041)	NA	0.047 (−0.078 to 0.159)
Germany	0.049 (0.003 to 0.095)	NA	NA
The Netherlands	−0.016 (−0.103 to 0.064)	NA	NA
Switzerland	−0.118 (−0.320 to 0.054)	−0.086 (−0.243 to 0.052)	−0.298 (−0.714 to 0.026)
Sub-Saharan Africa			
Burkina Faso	0.445 (−0.517 to 1.199)	NA	NA
Ethiopia	0.673 (−10.082 to 3.755)	NA	NA
Ghana	0.088 (−0.824 to 0.821)	NA	NA
Kenya	0.674 (−0.021 to 1.240)	NA	NA
Senegal	−0.386 (−4.433 to 1.248)	NA	NA
South Africa	0.064 (−0.036 to 0.156)	0.015 (−0.026 to 0.055)	0.052 (−0.026 to 0.124)
Tanzania	0.495 (−0.585 to 1.263)	NA	NA

CI=confidence interval; NA=not available.

Attributable fractions were calculated using pooled country or territory level risk estimates. See supplementary table S5 for corresponding number of deaths.

areas along the Mississippi in the United States, the Pacific coast of Latin America, Lake Victoria and the Volta in Africa, South East Asia, the coastal areas of mainland China, and the eastern coast of Australia (fig 1). Supplementary table S1 summarises the number of included communities, study period, and income classification, as well as the number of flood events, frequency of flood days, and mortality count during the study period. Supplementary figures S1-S5 show the distributions of climate types, proportions of older people, population densities, human development indices, and infant mortality rates. The median of the study periods was nine (interquartile range: 6-16) years. From 2000 to 2019, 47.6 million all cause deaths (8.5 million causes of death in 142 communities from six countries or territories were

non-external), 11.1 million cardiovascular deaths, and 4.9 million respiratory deaths were included in analyses.

At global level, we found that exposure to flood in the 761 communities was associated with increased risks of all cause, cardiovascular, and respiratory mortality for up to 60 days. The lag-response associations appear as inverted U-shapes (fig 2). The effect of flood on cardiovascular mortality persisted for up to 50 days (cumulative relative risk 1.026, 95% confidence interval 1.005 to 1.047, see supplementary table S3) and on all cause mortality and respiratory mortality for up to 60 days: 1.021 (1.006 to 1.036) and 1.049 (1.008 to 1.092), respectively (fig 3). Sensitivity analyses showed that the estimates were robust (see supplementary tables S3 and S4 and figure S6).

Figure 3 shows the pooled associations at the levels of country or territory and region. Inconsistency of effect estimates was moderate or low ($I^2 < 40\%$) within most countries or territories (see supplementary table S2). Country or territory level cumulative relative risks were >1 for all cause, cardiovascular, and respiratory mortality in 68.7% (24/35), 65.0% (13/20), and 61.9% (13/21) of countries or territories, respectively. However, some cumulative relative risks suggested a reduction in mortality risk after floods, including for all cause mortality in the United Kingdom, cardiovascular mortality in Thailand and Portugal, and respiratory mortality in the Philippines and UK. Inconsistency in relative risks was moderate or low ($I^2 < 40\%$) within all regions except for Latin America and the Caribbean, South East Asia, and Sub-Saharan Africa (see supplementary table S2). Increased risks of mortality ($P < 0.05$) were found in Northern America, Latin America and the Caribbean, Eastern Asia, Australia and New Zealand, and Eastern Europe.

The analyses of effect modification (table 1) showed that the flood-mortality associations were modified by climate type; the association with all cause mortality was stronger in low income countries; the association with cardiovascular and respiratory mortality was stronger in communities with a low human development index; and the association with respiratory mortality was stronger in communities with a high proportion of older people; but little evidence for effect modifications was found by infant mortality rate, population density, and flood severity. The highest attributable fractions (table 2) were observed in Mexico (all cause mortality), Canada and Brazil (cardiovascular mortality), and Brazil, Australia, New Zealand, and Portugal (respiratory mortality).

Discussion

This multi-country study estimated the association between exposure to flood and risks of mortality, quantifying the lag-response effects, exploring the effect modifiers of the associations, and estimating the attributable fraction of mortality due to flood. A dataset covering 35 countries or territories was used, eliminating the major factors leading to inconsistent findings in previous studies. We found that exposure to floods was associated with increased risks of all cause, cardiovascular, and respiratory mortality, although the associations varied across countries or territories and regions. The risks of mortality among populations exposed to floods increased during the subsequent 25 days and returned to normal values around 60 days. The flood-mortality associations were modified by climate type and were stronger in communities with low socioeconomic status or high proportions of older people (≥ 65 years). Among the 35 countries or territories, up to 0.10% of all cause deaths, 0.18% of cardiovascular deaths, and 0.41% of respiratory deaths were attributed to floods in communities impacted by floods.

Comparison with other studies

Only five studies assessed the association of exposure to flood with non-external mortality risk, and findings were inconsistent.^{4-9,12} An explanation for this discrepancy is that the flood-mortality association varies across countries or territories and regions, as observed by our study, and previous studies only focused on a single city or territory. Other potential reasons are limitations in methodology and small sample sizes. The study of the 1968 flood in Bristol, England, only compared the differences in death counts after and before one flood event among flooded households ($n=88$) and among non-flooded households ($n=132$) without considering any potential confounding¹¹; the study of the 1997 flood in central Europe only covered 207 autopsy cases during 1994-97 in a single medical institution in the Czech Republic, and the conclusion was based on comparing the number of cases in 1997 with those in other years.⁹ The reliability of estimates was reduced as a result of the small sample sizes and weaknesses in statistical analyses.³² Although the study of the 2004 flood in Bangladesh included 5280 all cause deaths in non-flooded areas and 2388 in flooded areas, the exposure assessment lacked precision (ie, exposure to flood was ascertained through interviews four years after the flood event).¹⁰ To increase precision, we used a database that collected information from multiple countries or territories and continents, covered deaths from 761 communities during 2000-19, and assessed exposure using a global flood catalogue that had been validated for assessment of exposure to flood.

The study covering all floods in England and Wales during 1994-2005 observed a counterintuitive flood-mortality association, showing a 10% (95% confidence interval 0% to 18%) reduction in risk of all cause mortality in flood areas after flood events.³³ This is consistent with our findings in the UK. Similar counterintuitive associations were also observed in Thailand, Portugal, and the Philippines. Two possible reasons for this are that some people's deaths were not registered at their usual place of residence because of evacuation and that exposure to flood raised the level of attention to personal health and health services. Local death registration systems and disaster response policies should be considered when interpreting flood-mortality associations.

The observed interactions of exposure to flood with climate type, socioeconomic status, and proportion of older population are comparable with those of previous studies. In New Zealand, the association between heavy rainfall and first time paediatric admissions for gastrointestinal infection was the strongest in extremely dry and wet areas, where heavy rainfall could increase surface run-off and mobilise and transport pathogens into the water system, whereas topsoil absorbs rainwater more readily in locations with moderate wetness.³⁴ Another study reported that gross domestic product per capita was negatively correlated with mortality directly as a result of flood at a global level, indicating that socioeconomic development greatly improved urban resilience

and immediate responses to flooding disasters.¹ Previous studies found that the association of tropical cyclones with mortality risk and the impact of floods on incidence of gastrointestinal diseases were the strongest in older populations,^{25 35} suggesting that older people are more vulnerable to the impacts of hydrological natural disasters. No evidence was found for effect modifications related to infant mortality rate, population density, and flood severity. The reasons may be that infant mortality rate mainly captures the health status of infants and children rather than the general population³⁶; population densities did not directly reflect the socioeconomic status or residential environments. Serious floods generally were linked to greater impacts on environments and infrastructures, so not finding stronger associations for such floods is puzzling. It is possible that such floods resulted in more evacuations and supportive facilities, which could prevent hazards to the population.

Clinical and policy implications

The findings of our study have important clinical and policy implications. Healthcare providers should be aware of the increased risks to health after floods, particularly in vulnerable communities and when floods are persistent because of the cumulative effects on health, and they should be prepared for the sudden increased demands of health services to reduce avoidable deaths from natural causes. Public health institutions should monitor the changes in mortality rate in the 25 days after floods to enable prompt interventions. Policy makers should prioritise comprehensive disaster preparedness, early warning and detection systems, and efficient disaster response protocols to reduce the attributable deaths from floods. Adaptation measures in response to climate change, including improvements to infrastructure, land use planning, and flood resilience considerations in healthcare systems are crucial in the context of climate change, which is projected to exacerbate floods globally.³ Attention should be given to communities with a low socioeconomic status or a high proportion of older people. These implications highlight the importance of the collaborations among healthcare providers, policy makers, and stakeholders to minimise the health impacts of floods in flood prone areas.

Limitations of this study

This study has some limitations. Although the mortality database included 35 countries or territories, it did not cover all continents, regions, and countries or territories evenly, especially the MCC database, which mainly covered urban communities. The pooled risk estimates therefore should not be interpreted as highly representative estimates. Besides, as with other studies using data from death registers, misclassifications of exposure would occur if the recorded addresses of residents differed from their actual addresses during flooded periods. For example, as people tend to migrate out of flooded areas, the mortality risks in such areas might have been underestimated. This practice

would not, however, lead to false positive results and might explain the negative associations observed in the UK, Thailand, Portugal, and the Philippines. Moreover, the Dartmouth Flood Observatory dataset primarily covers flood events reported in the news and may underrepresent flood events, especially in Africa and South America.³ This might have resulted in exposure misclassification, with flooded days regarded as non-flooded days. However, this would only bias the associations to none, and the extent of the underrepresentation was small.³ Furthermore, the exposure assessment was at community level rather than individual level because residential addresses were not available. Some participants therefore might not have resided in flooded areas. However, they would still be impacted through impaired access to health services, psychological impairment, and contaminated food and water. Additionally, the effect modifications could be further explored through including more communities in low income countries, considering that our study only included eight communities from four low income countries; through employing datasets with higher spatial resolutions, given that the climatic, socioeconomic status, and population health status variables used in this study were assessed at subnational levels; and through examining other potential modifiers, including factors related to ecological environments and resilience and responses to floods. Lastly, our analyses only captured a part of the health impacts of floods owing to lack of data. We call for future studies to evaluate a wide range of health impacts of floods, such as effects on morbidity (eg, admissions to hospital and emergency department visits).

Conclusions

This study provides epidemiological evidence for associations between floods and mortality risks, based on a quasi-global dataset and standard statistical methods. The increases in risk of mortality were most prominent around 25 days after exposure to floods and lasted for up to 60 days. The associations appeared to be modified by climate type and were strongest in communities with a low socioeconomic status and a high proportion of older people. Policy makers and health professionals should raise awareness of the increased mortality risk after floods to improve disaster response strategies and thereby reduce the number of avoidable deaths.

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The lead authors (YG and SL) affirm that the manuscript is an honest, accurate, and transparent account of the study being reported; that

no important aspects of the study have been omitted; and that any discrepancies from the study as planned (and, if relevant, registered) have been explained.

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- Hu P, Zhang Q, Shi P, Chen B, Fang J. Flood-induced mortality across the globe: Spatiotemporal pattern and influencing factors. *Sci Total Environ* 2018;643:171-82. doi:10.1016/j.scitotenv.2018.06.197.
- Rentschler J, Salhab M, Jafino BA. Flood exposure and poverty in 188 countries. *Nat Commun* 2022;13:3527. doi:10.1038/s41467-022-30727-4.
- Tellman B, Sullivan JA, Kuhn C, et al. Satellite imaging reveals increased proportion of population exposed to floods. *Nature* 2021;596:80-6. doi:10.1038/s41586-021-03695-w.
- Yan M, Wilson A, Peel JL, et al. Community-wide Mortality Rates in Beijing, China, During the July 2012 Flood Compared with Unexposed Periods. *Epidemiology* 2020;31:319-26. doi:10.1097/EDE.0000000000001182.
- Rocha LA, Fromknecht CQ, Redman SD, Brady JE, Hodge SE, Noe RS. Medicolegal Death Scene Investigations After Natural Disaster- and Weather-Related Events: A Review of the Literature. *Acad Forensic Pathol* 2017;7:221-39. doi:10.23907/2017.023.
- Alderman K, Turner LR, Tong S. Floods and human health: a systematic review. *Environ Int* 2012;47:37-47. doi:10.1016/j.envint.2012.06.003.
- Dosa DM, Skarha J, Peterson LJ, et al. Association Between Exposure to Hurricane Irma and Mortality and Hospitalization in Florida Nursing Home Residents. *JAMA Netw Open* 2020;3:e2019460. doi:10.1001/jamanetworkopen.2020.19460.
- Paterson DL, Wright H, Harris PNA. Health Risks of Flood Disasters. *Clin Infect Dis* 2018;67:1450-4. doi:10.1093/cid/ciy227.
- Obrová J, Sovová E, Ivanová K, Táborský M, Loyka S. Effects of the July 1997 floods in the Czech Republic on cardiac mortality. *Disaster Med Public Health Prep* 2014;8:492-6. doi:10.1017/dmp.2014.111.
- Milojevic A, Armstrong B, Hashizume M, et al. Health effects of flooding in rural Bangladesh. *Epidemiology* 2012;23:107-15. doi:10.1097/EDE.0b013e31823ac606.
- Bennet G. Controlled Survey of Effects on Health of Local Community Disaster. Bristol floods 1968. Controlled survey of effects on health of local community disaster. *Br Med J* 1970;3:454-8. doi:10.1136/bmj.3.5720.454.
- Milojevic A, Armstrong B, Kovats S, et al. Long-term effects of flooding on mortality in England and Wales, 1994-2005: controlled interrupted time-series analysis. *Environ Health* 2011;10:11. doi:10.1186/1476-069X-10-11.
- Gasparrini A, Guo Y, Hashizume M, et al. Mortality risk attributable to high and low ambient temperature: a multicountry observational study. *Lancet* 2015;386:369-75. doi:10.1016/S0140-6736(14)62114-0.
- Zhao Q, Guo Y, Ye T, et al. Global, regional, and national burden of mortality associated with non-optimal ambient temperatures from 2000 to 2019: a three-stage modelling study. *Lancet Planet Health* 2021;5:e415-25. doi:10.1016/S2542-5196(21)00081-4.
- Milne BJ, Atkinson J, Blakely T, et al. Data Resource Profile: The New Zealand Integrated Data Infrastructure (IDI). *Int J Epidemiol* 2019;48:677-677e. doi:10.1093/ije/dyz014.
- Muñoz-Sabater J, Dutra E, Agustí-Panareda A, et al. ERA5-Land: a state-of-the-art global reanalysis dataset for land applications. *Earth Syst Sci Data* 2021;13:4349-83. doi:10.5194/essd-13-4349-2021.
- Brakenridge GR. Global Active Archive of Large Flood Events. Dartmouth Flood Observatory. <https://floodobservatory.colorado.edu/> (accessed 18 Jul 2022).
- Carozza DA, Boudreault M. A Global Flood Risk Modeling Framework Built With Climate Models and Machine Learning. *J Adv Model Earth Syst* 2021;13:e2020MS002221. doi:10.1029/2020MS002221.
- Kundzewicz ZW, Pińskwar I, Brakenridge GR. Large floods in Europe, 1985-2009. *Hydrological Sci J* 2013;58:1-7. doi:10.1080/02626667.2012.745082.

- 20 Chen G, Guo Y, Yue X, et al. Mortality risk attributable to wildfire-related PM_{2.5} pollution: a global time series study in 749 locations. *Lancet Planet Health* 2021;5:e579-87. doi:10.1016/S2542-5196(21)00200-X.
- 21 Scortichini M, Schneider Dos Santos R, De' Donato F, et al. Excess mortality during the COVID-19 outbreak in Italy: a two-stage interrupted time-series analysis. *Int J Epidemiol* 2021;49:1909-17. doi:10.1093/ije/dyaa169.
- 22 Bhaskaran K, Gasparrini A, Hajat S, Smeeth L, Armstrong B. Time series regression studies in environmental epidemiology. *Int J Epidemiol* 2013;42:1187-95. doi:10.1093/ije/dyt092.
- 23 Sera F, Gasparrini A. Extended two-stage designs for environmental research. *Environ Health* 2022;21:41. doi:10.1186/s12940-022-00853-z.
- 24 Chen R, Yin P, Wang L, et al. Association between ambient temperature and mortality risk and burden: time series study in 272 main Chinese cities. *BMJ* 2018;363:k4306. doi:10.1136/bmj.k4306.
- 25 Parks RM, Benavides J, Anderson GB, et al. Association of Tropical Cyclones With County-Level Mortality in the US. *JAMA* 2022;327:946-55. doi:10.1001/jama.2022.1682.
- 26 Quist AJL, Fliss MD, Wade TJ, Delamater PL, Richardson DB, Engel LS. Hurricane flooding and acute gastrointestinal illness in North Carolina. *Sci Total Environ* 2022;809:151108. doi:10.1016/j.scitotenv.2021.151108.
- 27 Gasparrini A. Modeling exposure-lag-response associations with distributed lag non-linear models. *Stat Med* 2014;33:881-99. doi:10.1002/sim.5963.
- 28 Gasparrini A, Guo Y, Hashizume M, et al. Mortality risk attributable to high and low ambient temperature: a multicountry observational study. *Lancet* 2015;386:369-75. doi:10.1016/S0140-6736(14)62114-0.
- 29 Gasparrini A, Armstrong B, Kenward MG. Multivariate meta-analysis for non-linear and other multi-parameter associations. *Stat Med* 2012;31:3821-39. doi:10.1002/sim.5471.
- 30 Gasparrini A, Leone M. Attributable risk from distributed lag models. *BMC Med Res Methodol* 2014;14:55. doi:10.1186/1471-2288-14-55.
- 31 Borenstein M, Hedges LV, Higgins JPT, Rothstein HR. A basic introduction to fixed-effect and random-effects models for meta-analysis. *Res Synth Methods* 2010;1:97-111. doi:10.1002/jrsm.12.
- 32 Button KS, Ioannidis JPA, Mokrysz C, et al. Power failure: why small sample size undermines the reliability of neuroscience. *Nat Rev Neurosci* 2013;14:365-76. doi:10.1038/nrn3475.
- 33 Milojevic A, Armstrong B, Kovats S, et al. Long-term effects of flooding on mortality in England and Wales, 1994-2005: controlled interrupted time-series analysis. *Environ Health* 2011;10:11. doi:10.1186/1476-069X-10-11.
- 34 Lai H, Hales S, Woodward A, et al. Effects of heavy rainfall on waterborne disease hospitalizations among young children in wet and dry areas of New Zealand. *Environ Int* 2020;145:106136. doi:10.1016/j.envint.2020.106136.
- 35 Quist AJL, Fliss MD, Wade TJ, Delamater PL, Richardson DB, Engel LS. Hurricane flooding and acute gastrointestinal illness in North Carolina. *Sci Total Environ* 2022;809:151108. doi:10.1016/j.scitotenv.2021.151108.
- 36 Schell CO, Reilly M, Rosling H, Peterson S, Ekström AM. Socioeconomic determinants of infant mortality: a worldwide study of 152 low-, middle-, and high-income countries. *Scand J Public Health* 2007;35:288-97. doi:10.1080/14034940600979171.

Supplementary information: Additional methods, tables S1-S5, figures S1-S6, and references