The effect of extreme temperature and precipitation on cause-specific deaths in rural Burkina Faso: a longitudinal study

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Summary

Background Extreme weather is becoming more common due to climate change and threatens human health through climate-sensitive diseases, with very uneven effects around the globe. Low-income, rural populations in the Sahel region of west Africa are projected to be severely affected by climate change. Climate-sensitive disease burdens have been linked to weather conditions in areas of the Sahel, although comprehensive, disease-specific empirical evidence on these relationships is scarce. In this study, we aim to provide an analysis of the associations between weather conditions and cause-specific deaths over a 16-year period in Nouna, Burkina Faso.

Methods In this longitudinal study, we used de-identified, daily cause-of-death data from the Health and Demographic Surveillance System led by the Centre de Recherche en Santé de Nouna (CRSN) in the National Institute of Public Health of Burkina Faso, to assess temporal associations between daily and weekly weather conditions (maximum temperature and total precipitation) and deaths attributed to specific climate-sensitive diseases. We implemented distributed-lag zero-inflated Poisson models for 13 disease-age groups at daily and weekly time lags. We included all deaths from climate-sensitive diseases in the CRSN demographic surveillance area from Jan 1, 2000 to Dec 31, 2015 in the analysis. We report the exposure–response relationships at percentiles representative of the exposure distributions of temperature and precipitation in the study area.

Findings Of 8256 total deaths in the CRSN demographic surveillance area over the observation period, 6185 (74·9%) were caused by climate-sensitive diseases. Deaths from communicable diseases were most common. Heightened risk of death from all climate-sensitive communicable diseases, and malaria (both across all ages and in children younger than 5 years), was associated with 14-day lagged daily maximum temperatures at or above 41·1°C, the 90th percentile of daily maximum temperatures, compared with 36·4°C, the median (all communicable diseases: 41·9°C relative risk [RR] 1·38 [95% CI 1·08–1·77], 42·8°C 1·57 [1·13–2·18]; malaria all ages: 41·1°C 1·47 [1·05–2·05], 41·9°C 1·78 [1·21–2·61], 42·8°C 2·35 [1·37–4·03]; malaria younger than 5 years: 41·9°C 1·67 [1·02–2·73]). Heightened risk of death from communicable diseases was also associated with 14-day lagged total daily precipitation at or below 0·1 cm, the 49th percentile of total daily precipitation, compared with 1·4 cm, the median (all communicable diseases: 0·0 cm 1·04 [1·02–1·07], 0·1 cm 1·01 [1·006–1·02]; malaria all ages: 0·0 cm 1·04 [1·01–1·08], 0·1 cm 1·02 [1·00–1·03]; malaria younger than 5 years: 0·0 cm 1·05 [1·01–1·10], 0·1 cm 1·02 [1·00–1·04]). The only significant association with a non-communicable disease outcome was a heightened risk of death from climate-sensitive cardiovascular diseases in individuals aged 65 years and older associated with 7-day lagged daily maximum temperatures at or above 41·9°C (41·9°C 2·25 [1·06–4·81], 42·8°C 3·68 [1·46–9·25]). Over 8 cumulative weeks, we found that the risk of death from communicable diseases was heightened at all ages from temperatures at or above 41·1°C (41·1°C 1·23 [1·05–1·43], 41·9°C 1·30 [1·08–1·56], 42·8°C 1·35 [1·09–1·66]) and risk of death from malaria was heightened by precipitation at or above 45·3 cm (all ages: 45·3 cm 1·68 [1·31–2·14], 61·6 cm 1·72 [1·27–2·31], 87·7 cm 1·72 [1·16–2·55]; children younger than 5 years: 45·3 cm 1·81 [1·36–2·41], 61·6 cm 1·82 [1·29–2·56], 87·7 cm 1·93 [1·24–3·00]).

Interpretation Our results indicate a high burden of death related to extreme weather in the Sahel region of west Africa. This burden is likely to increase with climate change. Climate preparedness programmes—such as extreme weather alerts, passive cooling architecture, and rainwater drainage—should be tested and implemented to prevent deaths from climate-sensitive diseases in vulnerable communities in Burkina Faso and the wider Sahel region.

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Research in context

Evidence before this study

We searched the Google Scholar database on July 16, 2022, using the search terms "climate-sensitive diseases", "extreme temperature", "precipitation", "climate change", "sahel", "cause-specific death", and "time-series". We read and considered peer-reviewed articles and reviews that centred on analysing the effects of temperature and precipitation on health outcomes in human populations globally, but with a specific focus on populations in west Africa. We searched for articles published from the inception of the database to July 1, 2021, written in English. We found papers on rural Burkina Faso covering the effects of weather variables on all-cause mortality, years of life lost due to malaria, and years of life lost due to cardiovascular diseases. All of these studies were confined to calendar time periods of observation shorter than 10 years. A positive relationship was shown between weather variables and each of these outcomes.

Added value of this study

Our study assesses the relationship between daily maximum temperature, total precipitation, and deaths from 13 climate-sensitive disease-age groups in a complete population of 106 611 people living in a geographically contiguous community in the Sahel. To date, studies in the Sahel region have not looked at both climate-sensitive communicable and non-communicable causes of death in the same community. With an observation period of 16 years, our study is also, to our knowledge, the longest-running longitudinal study to date. Thus, we can determine more fine-scale and robust relationships than any of the previous studies. Our results establish specific relationships between acute exposure to weather factors and risk of death using the comprehensive individual-level longitudinal data from the Nouna Health and Demographic Surveillance System. We found strong associations between extreme weather conditions (high temperature and low precipitation), and risk of death from malaria 14 days later (particularly in children), and from cardiovascular disease 1 week later in adults aged 65 years and older. Complex, lagged associations emerged between extreme weather conditions and risk of death from communicable diseases.

Implications of all the available evidence

We showed that extreme heat and low precipitation are associated with excess risk of death from particular climate-sensitive communicable and non-communicable diseases. These findings support existing evidence and highlight emerging potential health risks posed by the effects of climate change to populations in the Sahel and similar regions globally. The results of this study provide motivation for the expansion of routine data systems to monitor climate effects on health, and for developing and implementing climate preparedness programmes for vulnerable communities in the Sahel region.

Introduction

Extreme weather is becoming more common due to climate change and threatens human health unevenly across the globe. Climate change affects both temperature and precipitation by making extreme highs (eg, heatwaves and flooding) and extreme lows (eg, coldwaves and droughts) more common. Evidence on the relationships between extreme weather and disease burdens has led to the conception of so-called climate-sensitive diseases,[1] which span both communicable and non-communicable domains.[2,3] Among the deadliest climate-sensitive diseases are malaria, diarrhoeal diseases, and non-communicable diseases of the respiratory and cardiovascular systems.[1,4,5] As the climate continues to change, the distribution and intensity of these diseases are expected to shift.[6]

West African countries are expected to be strongly adversely affected by climate change.[6] Rural populations in west Africa are particularly vulnerable to the health effects of climate change, because they commonly lack the resources to adapt to weather extremes and already suffer from a high burden of communicable diseases and rising incidence of non-communicable diseases.[7,8] Temperature in west Africa has increased by 0·5–1·0°C since 1980 and this trend is now accelerating.[9] The Sahel is experiencing less frequent but more extreme rainfall since the late 1960s.[10] Rural communities in the Sahel are most vulnerable to these changes because they need rainfall for crop growth and good harvests.[11,12] These dynamics have consequences for population health. For example, rural communities in Nigeria have shifted to unhealthier diets due to unfavourable farming conditions and increased access to processed foods.[13] These nutritional transitions have been associated with increased prevalence of non-communicable diseases in west Africa.[14,15] Infectious diseases, such as malaria, are also sensitive to changes in precipitation and temperature, which probably lead to changing disease burdens and patterns in the Sahel.[16] Although there are several plausible mechanisms connecting temperature and precipitation and climate-sensitive diseases, few empirical studies exist that quantify these relationships in communities in the Sahel.[15–19]

Previous analyses have focused on the effects of temperature and precipitation on the distribution and intensity of specific climate-sensitive diseases.[20–22] However, few studies have analysed the relationship between temperature, precipitation, and deaths from these climate-sensitive diseases.[15,18] Burkina Faso is one country that remains understudied. The Health and Demographic Surveillance System (HDSS) in the rural, agrarian community of Nouna, Burkina Faso regularly collects individual-level data on cause of death and detailed data on weather conditions.[23] In this study, we aim to use these

data to analyse the effects of temperature and precipitation on cause-specific deaths from climate-sensitive diseases.

Methods

Study site

The Centre de Recherche en Santé de Nouna leads an HDSS, which routinely collects vital event data (ie, births, cause-specific deaths, marriages, immigration, and emigration) on a dynamic cohort of all individuals who live in a geographically contiguous area within the Nouna region of Burkina Faso.[23] In this observational study of longitudinal data, the demographic surveillance area was 1775 km² with a population of 106 611 people living in 14 300 households in 58 villages in 2015 (figure 1). The most common occupation of the people living in the catchment area was subsistence farming. The catchment area had one weather station during the study period and is characterised by a Sahel climate with a mean annual rainfall of 800 mm. The temperature peaks in April during the dry season, with a daily average of 37·2°C, which drops to 20°C during the coldest months. The humid rainy season typically lasts from June to September. This study was exempt from ethics review, because we used only de-identified data in the analyses.

Exposure variables

The primary exposures in this analysis were daily maximum temperature (highest temperature in a 24-hr window, °C), total precipitation (total precipitation in a 24-hr window, cm), weekly maximum temperature (highest temperature in a 7-day window, °C), and weekly total precipitation (total precipitation in a 7-day window, °C; appendix p 1). Although precipitation data were complete, maximum temperature data from the Nouna Weather Station were not complete (>50% missing), so we obtained hourly mean and maximum temperature data from the National Climatic Data Centre for the Dédougou Weather Station (12·4° N, 3·4° W, 53 km from the centroid of Nouna, Burkina Faso) from Jan 1, 2000, to Dec 31, 2015. Only 20% of the maximum temperature data were missing from the Dédougou dataset. We imputed missing data by averaging 15 consecutive days of temperature on either side of a missing temperature value to create a 30-day moving average. We used missing value imputation by weighted moving average, using the na_ma function in the imputeTS package in R software. No imputation was necessary for total precipitation.

To confirm imputed data would not bias results, we conducted Pearson's correlation analysis comparing maximum temperature data from the Nouna Weather Station, the Dédougou Weather Station, and the satellite-derived ERA5-Reanalysis dataset.[24] Over the study period of 5844 days, 2432 days (42%) of maximum temperature from Nouna were available for comparison. Following imputation, data on maximum temperature in Dédougou, Nouna, and ERA5 Reanalysis exhibited strong correlations (appendix p 2). We are thus confident that the Dédougou Weather Station data is a valid proxy measure for weather conditions in Nouna.

Outcome variable

We obtained 16 years of de-identified, daily cause-of-death data from the Nouna HDSS facilitated by the Centre de Recherche en Santé de Nouna.[23] Our dataset included all registered deaths between Jan 1, 2000, and Dec 31, 2015. Mortality data comprised age at death (calculated as number of days between date of death and date of birth), sex, cause of death coded according to the International Classification of Diseases (ICD-10), and cause of death determined by verbal autopsy.[25] For deaths that were not assigned an ICD-10 code, we selected the ICD-10 code that corresponded to the verbal autopsy data.

We broke ICD-10 codes down by climate sensitivity and the Global Burden of Disease (GBD) cause-specific categories of communicable diseases, non-communicable diseases, and injuries (appendix pp 2–3). Our categorisation of diseases as climate-sensitive followed the categorisation used by Watts and colleagues[1] (appendix pp 2–4). We further analysed additional disease groupings and individual diseases, to test the robustness of our findings. To account for variation in response to our exposures across age groups, we divided deaths from cardiovascular diseases into two categories (individuals younger than 65 years and those 65 years and older), and deaths from malaria into three categories (individuals younger than 5 years, between 5 years and 64 years, and 65 years and older).

Statistical analysis

See Online for appendix

We used distributed-lag zero-inflated Poisson models to regress cause-specific deaths on maximum temperature and total precipitation. To assess the relationship between exposures and outcomes of interest, this approach models zeros under a logistic distribution and cases under a Poisson distribution. Communicable diseases were modelled against temperature, at daily lags (varying from 1 day to 28 days) and weekly lags (varying from 1 week to 8 weeks), whereas non-communicable diseases were modelled at daily lags (varying from 1 day to 14 days). In all models, we applied a natural cubic spline with five degrees of freedom per year to control for long-term trends and seasonality in mortality, temperature, and precipitation. We chose maximum lag values for each disease based on sensitivity analyses (appendix pp 5–6) and review of biologically relevant periods of effect for the temperature and precipitation levels observed in Nouna, Burkina Faso.[15,16,18,26] As the baseline comparison, we chose the median of maximum daily temperatures (36·4°C) and the median of daily total precipitation (0·14 cm) over the observation period.

To assess the effects of maximum temperature on cause-specific deaths, we modelled the exposure–response curve as a natural cubic spline with knots at the tenth, 50th, and

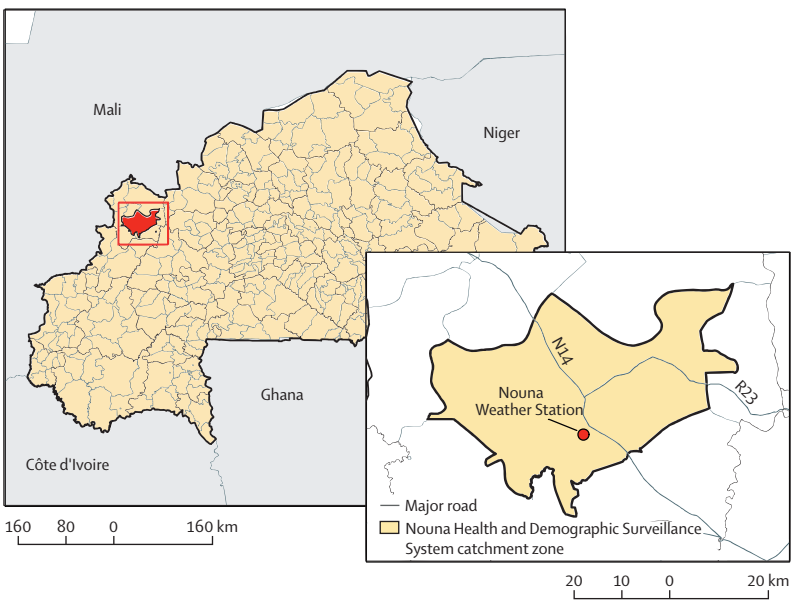


Figure 1: **The demographic surveillance area of the Nouna Health and Demographic Surveillance System**

90th percentiles. We modelled the lag response as a natural cubic spline with two degrees of freedom. To assess the effects of total precipitation on cause-specific deaths, we modelled the exposure–response curve as a natural cubic spline with knots at the 75th, 90th, 95th, and 99th percentiles.

In our models, we included an indicator for years with disease-specific policies (2013 and 2014 malaria control policies; appendix [p 11]), and indicators for day of the week and day of the month, heaping effects of death dates apparent in the data. We filtered the results of our analyses by statistical significance and reported model results at temperature and precipitation values that are representative of the distributions of each exposure. Specifically, we report exposure–response relationships for daily and weekly maximum temperature at 38·9°C (75th percentile), 41·1°C (90th percentile), 41·9°C (95th percentile), and 42·8°C (99th percentile) with reference to 36·4°C (the median); cold effects as 28·3°C (first percentile), 30·6°C (fifth percentile), 31·3°C (tenth percentile), and 33·3°C (25th percentile) with reference to 36·4°C. We report daily total precipitation at 0·0 cm (40th percentile), 0·1 cm (49th percentile), 2·8 cm (75th percentile), 3·8 cm (80th percentile), 6·9 cm (90th percentile), 10 cm (95th percentile), and 18·3 cm (99th percentile). Finally, we report weekly total precipitation at 0·0 cm (30th percentile), 0·5 cm (40th percentile), 3·6 cm (50th percentile), 9·0 cm (60th percentile), 17·5 cm (70th percentile), 28·6 cm (80th percentile), 45·3 cm (90th percentile), 61·6 cm (95th percentile), and 87·7 cm (99th percentile).

We conducted several sensitivity analyses to test the robustness of altering model choices for daily lagged models (appendix pp 5–6), using mean temperature instead of maximum temperature as the primary exposure, extending the degrees of freedom for the lag response between two and six degrees of freedom, varying the control for season and time trend ranging between four and ten degrees of freedom, and extending the lag period to 28 days for all exposures with a 7-day and 14-day lag to assess if deaths were related to weather conditions on a longer time scale. We used Akaike information criteria values to guide model selection. We used the dlnm package (version 2.2.3) in R software to estimate the distributed-lag zero-inflated Poisson models in our study.

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

Maximum daily temperatures in the Nouna demographic surveillance area over the study period ranged from 23·8°C to 47·2°C, with a mean of 36·1°C (SD 3·6°C). On average across the study period, March until May had the highest mean temperatures spanning 39·4–40·6°C, which coincided with low rainfall (average daily precipitation 0·1–1·7 cm). The least hot months were July until September, with mean temperatures spanning 31·4–33·0°C. These months occured during the rainy season in which daily precipitation averaged 3·6–8·1 cm. Our dataset showed that 10·6% (624 of 5843 days) of days reached temperatures of 41·1°C or higher, and 10·1% (585 of 5843 days) of days had a total precipitation of 7·1 cm or higher. Of these 624 extreme heat days, 418 days had less than 0·16 cm of precipitation.

Over 16 years, 8256 deaths were recorded, 6185 of which were from climate-sensitive diseases (figure 2). Of these deaths, 83·9% (5192 of 6185 deaths) were from communicable diseases, whereas 13·2% (814 of 6185 deaths) were attributed to non-communicable diseases and 2·9% (179 of 6185) to injuries. Slightly more of these deaths occurred in men (52·1% [3219 of 6185 deaths]) than in women (47·9% [2966 of 6185 deaths]; appendix p 4). Data on ethnicity were unavailable in the dataset. We found that 16 observations had neither a cause of death nor an ICD-10 code and were thus excluded from the final analysis. Those deaths that could be analysed by specific cause included malaria (ICD-10 codes B50–B54; n=2852), intestinal infectious diseases (ICD-10 codes A00–A09; n=1038), bacterial diseases (ICD-10 codes A37–A39; n=342), respiratory diseases including asthma (ICD-10 codes J00–J99; n=811), malnutrition (ICD-10 codes E40–E46; n=219), and cardiovascular diseases (ICD-10 codes I00–I99; n=571). We further classified the ICD-10 codes as either communicable diseases, non-communicable diseases, or injuries, using the GBD definitions of these categories.

Daily maximum temperature was associated with the risk of death across varied temperatures and disease-age

groupings (figures 3, 4). Heightened risk of death from communicable diseases was associated with 14-day lagged daily maximum temperatures of 28·3°C, the first percentile (relative risk [RR] 1·55 [95% CI 1·02–2·36]), 41·9°C, the 95th percentile (1·38 [1·08–1·77]), and 42·8°C, the 99th percentile (1·57 [1·14–2·18]), relative to 36·4°C, the median. We found that malaria deaths across all ages showed significant reductions in cumulative 14-day risk at daily maximum temperatures of 33·3°C, the 25th percentile (RR 0·78 [95% CI 0·63–0·96]) as compared with 36·4°C. Malaria mortality also increased significantly over 14 cumulative days at daily maximum temperatures of 41·1°C, the 90th percentile (RR 1·47 [95% CI 1·05–2·05]), 41·9°C (1·78 [1·21–2·61]), and 42·8°C (2·35 [1·37–4·03]), relative to 36·4°C. The trend we detected is largely driven by deaths in individuals younger than 5 years (2113 [70·3%] of all malaria cases). Among this age group, significant heightened cumulative 14-day risk of death occurred at daily maximum temperatures of 41·9°C (RR 1·67 [95% CI 1·02–2·73]) compared with 36·4°C. Furthermore, at lag 0 to 4 days, we found that deaths from all communicable diseases and malaria at all ages (except 65 years and older—which was probably due to the small sample size in this age group) displayed an inverse U-shaped relationship between temperature and cause-specific deaths. This relationship reversed at the beginning of lag day 6 and a U-shaped relationship became more apparent through lag day 14.

Total daily precipitation showed significant associations with the RR of death from communicable diseases, malaria at all ages, and malaria in individuals younger than 5 years (figures 3, 5). At 0 cm, the 30th percentile, and 0·1 cm, the 40th percentile, of the 14-day lagged total precipitation, all three groups showed heightened cumulative RR compared with 0·14 cm, the median (communicable diseases: 0·0 cm RR 1·04 [95% CI 1·02–1·07], 0·1 cm RR 1·02 [1·01–1·03]; malaria all ages: 0·0 cm RR 1·04 [1·01–1·08], 0·1 cm RR 1·02 [1·00–1·03]; malaria younger than 5 years: 0·0 cm RR 1·05 [1·01–1·10]), 0·1 cm RR 1·02 [1·003–1·04]). We found that higher precipitation at 2·8 cm, the 75th percentile, and 3·8 cm, the 80th percentile, were associated with a 0·58 (95% CI 0·42–0·79) and 0·55 (0·39–0·77) lower cumulative RR of death from communicable diseases. Malaria at all ages and in individuals younger than 5 years exhibited a similar trend in which the cumulative RR of death was reduced at 14-day lags of 2·8 cm (malaria all ages: RR 0·55 [95% CI 0·36–0·83]; malaria younger than 5 years: 0·48 [0·29–0·80]), 3·8 cm, the 90th percentile, (malaria all ages: 0·49 [0·31–0·76]; malaria younger than 5 years: RR 0·41 [0·24–0·70]), and 6·9 cm, the 95th percentile, (malaria all ages: 0·56 [0·32–0·97]; malaria younger than 5 years: 0·41 [0·21–0·80], relative to the median). The relationship between precipitation and deaths from all communicable diseases and malaria at all ages was consistent across lag 0 to 8 days. The risk of death due to these causes increased when precipitation was between 10 cm and 30 cm. At lags 10–14 days, this relationship reversed and the risk of death due to these causes reduced when precipitation was between 15 cm and 35 cm.

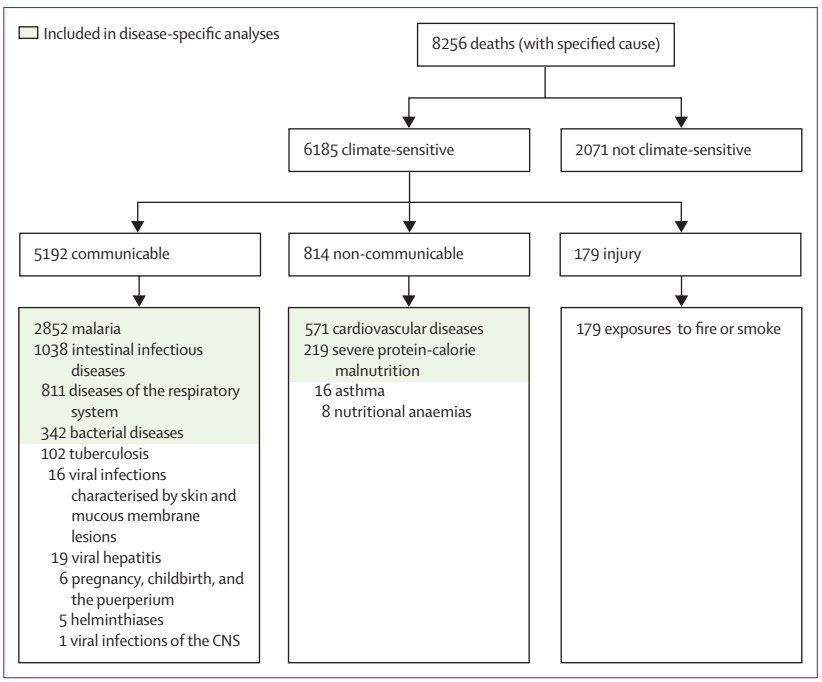


Figure 2: **Causes of deaths in the Nouna Health and Demographic Surveillance System over the study period**

Three statistically insignificant relationships are noteworthy. First, malaria risk in the 5–64 years and 65 years and older age groups was not associated with any changes in temperature or precipitation. Second, at extremely low and extremely high temperatures, we detected heightened cumulative 14-day RR of death from intestinal diseases. Third, at higher temperatures, we found a heightened 28-day RR of death from bacterial diseases.

Weekly maximum temperature and total precipitation at cumulative lags of 8 weeks were significantly associated with several disease and age groups (figure 3). We found that cumulative 8-week risk of death from communicable diseases was positively associated with weekly maximum temperatures of 33·3°C, the 25th percentile (RR 1·23 [95% CI 1·03–1·48]), 41·1°C, the 90th percentile (1·23 [1·05–1·43]), 41·9°C, the 95th percentile (1·30 [1·08–1·56]), and 42·8°C, the 95th percentile (1·35 [1·09–1·66]) compared with 36·4°C, the median. This relationship held true for malaria at all ages at 33·3°C, the 25th percentile (RR 1·33 [95% CI 1·03–1·71]) compared with 36·4°C.

Some disease-age groupings exhibited significant positive relations at specific lag and temperature combinations (appendix p 9). Notably, risk of death from malaria in individuals aged 5–64 years and bacterial diseases increased at 1-week to 3-week lags at 42·8°C maximum temperature compared with 36·4°C. No effect estimates beyond lag 6 weeks were statistically significant.

Cumulative 8-week risk of death from communicable diseases was positively associated with total weekly

Short-term daily lags

		Cumulative 14-day lag																					
		Communicable disease			Malaria (all)			Malaria (aged <5 years)			Malaria (aged 5–64 years)			Malaria (aged ≥65 years)			Intestinal disease			Bacterial disease		
		RR	LCI	UCI	RR	LCI	UCI	RR	LCI	UCI	RR	LCI	UCI	RR	LCI	UCI	RR	LCI	UCI	RR	LCI	UCI
Maximum daily temp (°C)	28·3	**1·55**	1·02	2·36	1·19	0·68	2·05	1·02	0·53	1·96	0·96	0·22	4·24	1·52	0·37	6·32	1·51	0·57	3·97	0·92	0·07	12·85
	30·6	1·00	0·80	1·26	0·78	0·56	1·07	0·76	0·52	1·13	0·70	0·30	1·65	0·95	0·44	2·05	1·15	0·7	1·89	0·85	0·27	2·70
	31·3	0·93	0·74	1·17	0·74	0·54	1·01	0·74	0·50	1·09	0·69	0·29	1·61	0·88	0·41	1·91	1·08	0·65	1·78	0·85	0·26	2·73
	33·3	0·89	0·76	1·04	**0·78**	0·63	0·96	0·79	0·61	1·02	0·75	0·42	1·36	0·86	0·50	1·47	0·95	0·66	1·36	0·87	0·36	2·12
	38·9	1·09	0·94	1·28	1·13	0·90	1·42	1·18	0·89	1·55	1·18	0·66	2·11	1·05	0·61	1·80	1·37	0·96	1·95	1·21	0·54	2·71
	41·1	1·26	1·00	1·58	**1·47**	1·05	2·05	1·46	0·97	2·21	1·63	0·68	3·89	1·10	0·50	2·38	1·6	0·95	2·69	1·5	0·46	4·87
	41·9	**1·38**	1·08	1·77	**1·78**	1·21	2·61	**1·67**	1·02	2·73	2·02	0·79	5·15	1·14	0·49	2·65	1·57	0·9	2·75	1·65	0·5	5·52
	42·8	**1·57**	1·14	2·18	**2·35**	1·37	4·03	2·02	0·98	4·14	2·76	0·83	9·13	1·22	0·39	3·78	1·46	0·7	3·03	1·87	0·43	8·08
		RR	LCI	UCI	RR	LCI	UCI	RR	LCI	UCI	RR	LCI	UCI	RR	LCI	UCI	RR	LCI	UCI	RR	LCI	UCI
Total daily precipitation (cm)	0·0	**1·04**	1·02	1·07	**1·04**	1·01	1·08	**1·05**	1·01	1·10	1·00	0·92	1·10	1·06	0·96	1·16	1·03	0·97	1·09	1·12	0·95	1·32
	0·1	**1·02**	1·01	1·03	**1·02**	1·00	1·03	**1·02**	1·00	1·04	1·00	0·97	1·04	1·02	0·99	1·06	1·01	0·99	1·03	1·04	0·98	1·11
	2·8	**0·58**	0·42	0·79	**0·55**	0·36	0·83	**0·48**	0·29	0·80	0·97	0·32	2·96	0·49	0·17	1·47	0·67	0·32	1·39	0·48	0·07	3·18
	3·8	0·55	0·39	0·77	**0·49**	0·31	0·76	**0·41**	0·24	0·70	1·01	0·31	3·34	0·45	0·14	1·46	0·61	0·28	1·35	1·12	0·14	9·03
	6·9	0·75	0·48	1·18	**0·56**	0·32	0·98	**0·41**	0·21	0·80	1·61	0·34	7·70	0·74	0·16	3·37	0·68	0·23	1·99	9·44	0·26	342·09
	10·0	1·18	0·74	1·88	1·03	0·57	1·86	0·67	0·34	1·34	4·23	0·83	21·59	2·50	0·44	14·11	1·20	0·37	3·82	0·03	0·00	1·36
	18·3	0·70	0·31	1·55	0·80	0·29	2·23	0·59	0·19	1·88	1·04	0·05	22·99	0·28	0·01	8·43	0·75	0·10	5·59	28·67	0·02	52702·95

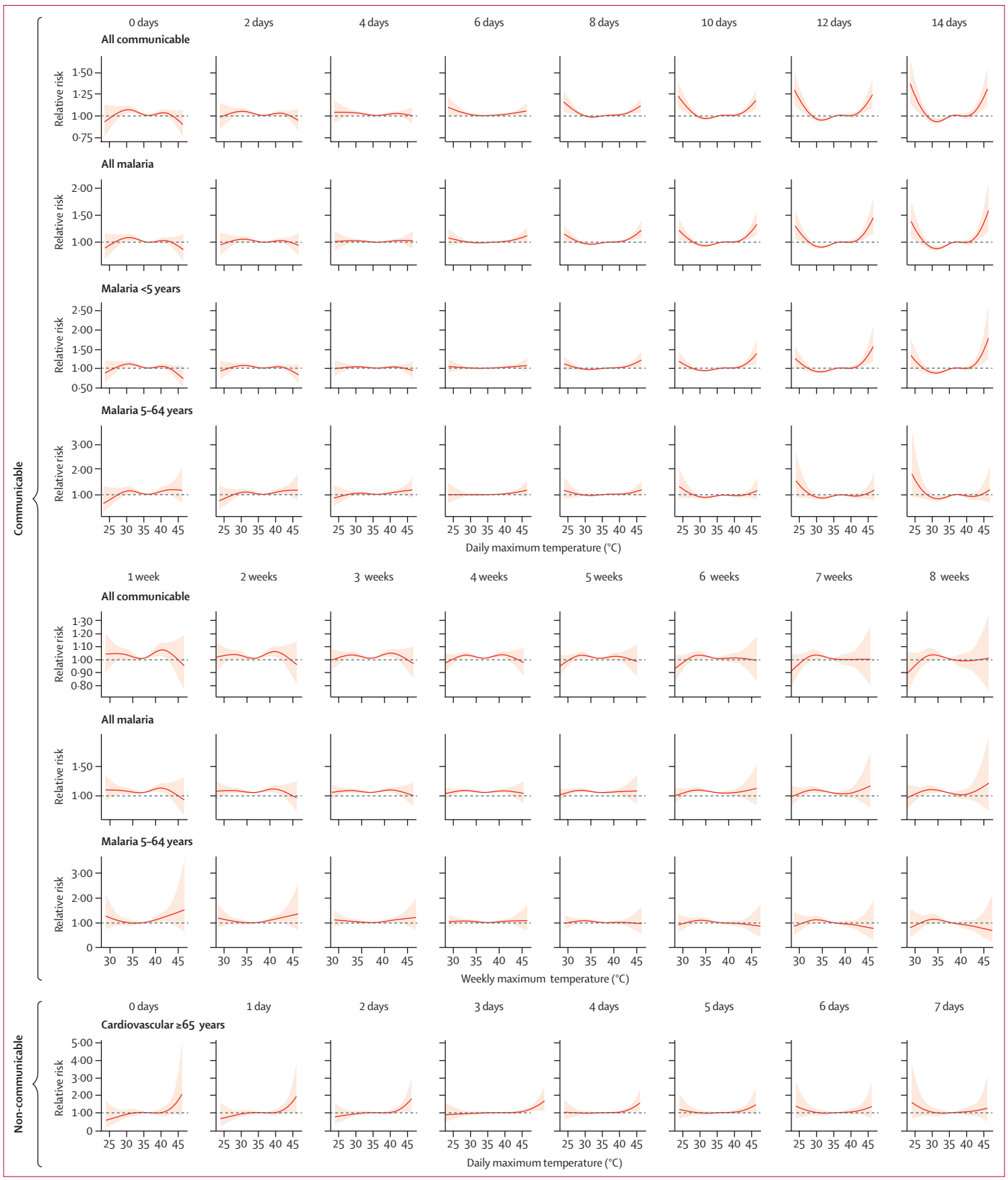
Long-term weekly lags

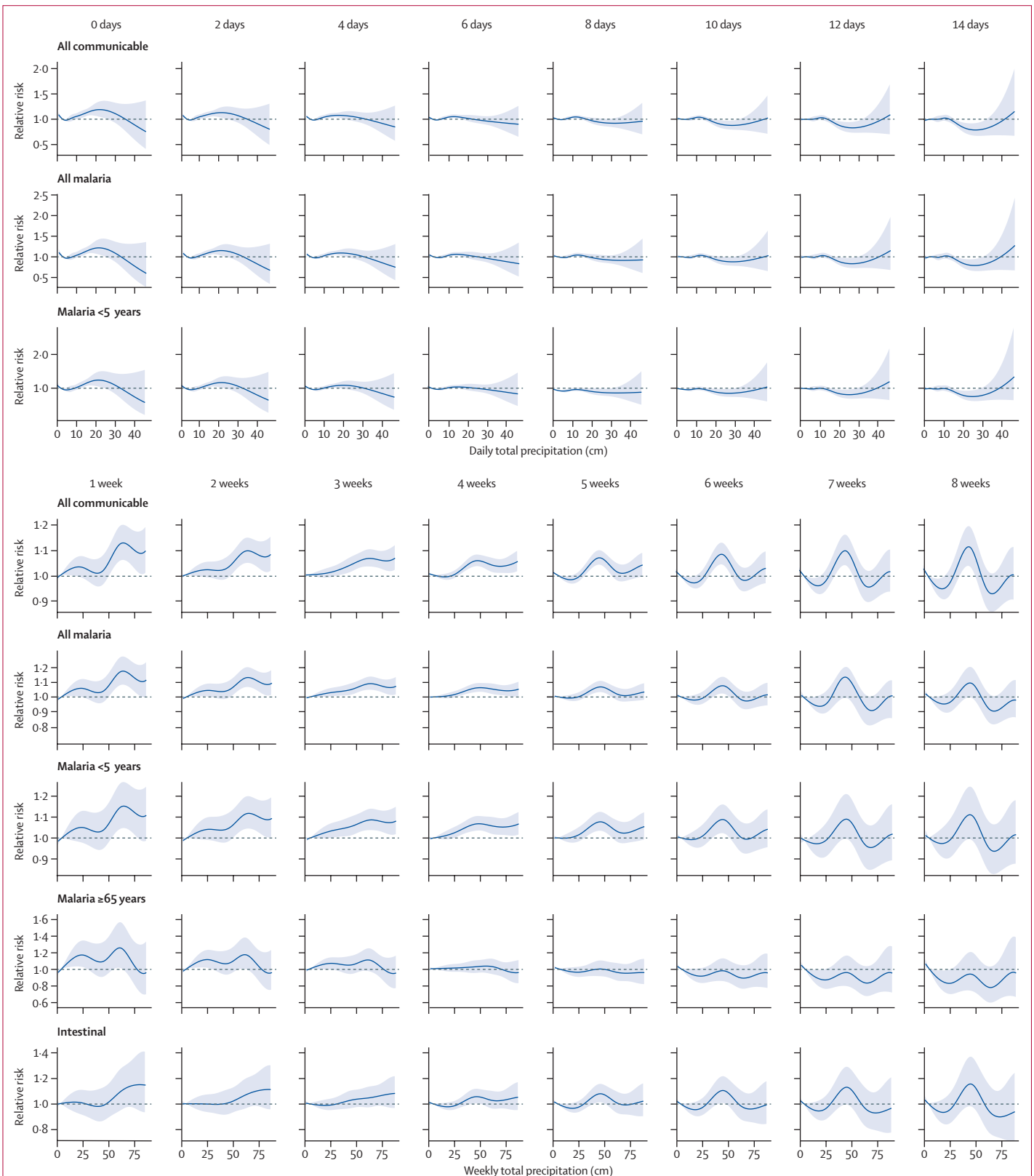
		Cumulative 8-week lag																					
		Communicable disease			Malaria (all)			Malaria (aged <5 years)			Malaria (aged 5–64 years)			Malaria (aged ≥65 years)			Intestinal disease			Bacterial disease		
		RR	LCI	UCI	RR	LCI	UCI	RR	LCI	UCI	RR	LCI	UCI	RR	LCI	UCI	RR	LCI	UCI	RR	LCI	UCI
Maximum weekly temp (°C)	28·3	0·73	0·41	1·30	0·87	0·40	1·91	0·98	0·40	2·42	1·38	0·17	11·01	0·13	0·01	1·28	0·66	0·17	2·67	1·30	0·09	19·72
	30·6	1·01	0·77	1·33	1·15	0·79	1·68	1·19	0·77	1·84	1·62	0·61	4·33	0·42	0·14	1·24	0·87	0·45	1·67	0·68	0·19	2·48
	31·3	1·10	0·88	1·37	1·23	0·90	1·67	1·24	0·87	1·77	1·67	0·77	3·65	0·57	0·25	1·33	0·93	0·56	1·55	0·58	0·21	1·60
	33·3	**1·23**	1·03	1·48	**1·33**	1·03	1·71	1·29	0·95	1·75	1·62	0·85	3·06	1·08	0·57	2·03	1·06	0·71	1·58	0·48	0·23	1·02
	38·9	1·03	0·99	1·08	1·03	0·96	1·09	1·02	0·94	1·10	1·03	0·88	1·21	0·94	0·79	1·11	1·00	0·92	1·10	1·09	0·95	1·26
	41·1	**1·23**	1·05	1·43	1·22	0·97	1·53	1·17	0·89	1·55	1·32	0·77	2·27	0·97	0·55	1·70	1·04	0·76	1·44	1·12	0·67	1·86
	41·9	**1·30**	1·08	1·56	1·30	0·99	1·70	1·24	0·89	1·72	1·46	0·78	2·75	1·04	0·55	1·95	1·05	0·72	1·54	1·15	0·63	2·11
	42·8	**1·35**	1·09	1·66	1·36	0·98	1·89	1·28	0·86	1·91	1·60	0·77	3·33	1·17	0·56	2·43	1·05	0·68	1·62	1·25	0·64	2·44
		RR	LCI	UCI	RR	LCI	UCI	RR	LCI	UCI	RR	LCI	UCI	RR	LCI	UCI	RR	LCI	UCI	RR	LCI	UCI
Total weekly precipitation (cm)	0·0	1·03	0·99	1·07	0·98	0·93	1·03	0·96	0·90	1·02	1·08	0·94	1·23	0·98	0·87	1·12	1·09	1·00	1·19	1·09	0·93	1·27
	0·5	1·02	0·99	1·06	0·98	0·94	1·03	0·96	0·91	1·02	1·07	0·95	1·19	0·99	0·88	1·10	1·08	1·00	1·17	1·08	0·94	1·23
	3·6	0·99	0·99	1·00	1·00	0·99	1·00	1·00	0·99	1·00	0·99	1·00	1·00	1·00	0·99	1·00	1·00	1·00	1·00	1·00	1·00	1·00
	9·0	0·97	0·92	1·02	1·03	0·96	1·11	1·07	0·98	1·17	0·90	0·75	1·09	1·02	0·86	1·22	0·89	0·78	1·00	0·90	0·72	1·12
	17·5	0·96	0·86	1·08	1·11	0·95	1·29	1·19	0·99	1·44	0·83	0·56	1·23	1·06	0·73	1·53	0·81	0·62	1·05	0·86	0·55	1·35
	28·6	1·12	0·98	1·29	**1·29**	1·07	1·55	**1·41**	1·13	1·78	0·93	0·57	1·51	1·08	0·69	1·69	0·96	0·70	1·33	1·23	0·68	2·23
	45·3	**1·62**	1·33	1·97	**1·68**	1·31	2·14	**1·81**	1·36	2·41	1·38	0·68	2·81	1·18	0·60	2·33	1·61	0·99	2·62	2·46	0·85	7·07
	61·6	**1·50**	1·18	1·91	**1·72**	1·27	2·31	**1·82**	1·29	2·56	1·24	0·53	2·92	1·31	0·56	3·02	1·26	0·69	2·29	1·04	0·22	4·85
	87·7	**1·69**	1·20	2·37	**1·72**	1·16	2·55	**1·93**	1·24	3·00	1·47	0·42	5·23	0·65	0·18	2·43	1·57	0·62	3·96	0·71	0·06	8·00

Figure 3: **Weather conditions and risk of death from communicable diseases**
The figure shows relative risk (RR) and 95% CI bounds for cause-specific deaths from communicable diseases, for lags based on sensitivity analysis and the literature. Bolded and coloured RRs show significant relationships. Orange and red colours indicate significant harmful associations, green colours indicate significant protective associations, and yellow colours indicate significant but small associations. LCI=lower confidence interval. UCI=upper confidence interval.

precipitation of 45·3 cm, the 80th percentile (RR 1·62 [95% CI 1·33–1·97]), 61·6 cm, the 90th percentile (1·50 [1·18–1·91), and 87·7 cm, the 99th percentile (1·69 [1·20–2·37]) compared with 3·6 cm, the median. Similarly, cumulative 8-week risk of death from malaria at all ages, and malaria in children younger than 5 years was positively associated with a total weekly precipitation of 28·6 cm, the 70th percentile (all ages: RR 1·29 [95% CI 1·07–1·55]; younger than 5 years: 1·41 [1·13–1·78]), 45·3 cm (all ages: 1·68 [1·31–2·14]; younger than 5 years: 1·81 [1·36–2·41]), 61·6 cm (all ages: 1·72 [1·27–2·31]; younger than 5 years: 1·82 [1·29–2·56]), and 87·7 cm (all ages: 1·72 [1·16–2·55]; younger than 5 years: 1·9 [1·24–3·00]) compared with 3·6 cm.

Figure 4: **Relative risk of different cause of death associated with daily and weekly maximum temperature across different lag times.** Estimates are shown as red lines, 95% CIs shown as red ribbons, and boxes indicate estimates with significant associations. The figure shows only those causes of death for which we found significant associations with temperature. Effect estimates are shown across the full distribution of each exposure.


Communicable
0 days
2 days
4 days
6 days
8 days
10 days
12 days
14 days
All communicable
Relative risk
1·50
1·25
1·00
0·75
All malaria
2·00
1·50
1·00
Malaria <5 years
2·50
2·00
1·50
1·00
0·50
Malaria 5–64 years
3·00
2·00
1·00
25 30 35 40 45
Daily maximum temperature (°C)
1 week
2 weeks
3 weeks
4 weeks
5 weeks
6 weeks
7 weeks
8 weeks
All communicable
1·30
1·20
1·10
1·00
0·90
0·80
All malaria
1·50
1·00
Malaria 5–64 years
3·00
2·00
1·00
0
30 35 40 45
Weekly maximum temperature (°C)
Non-communicable
0 days
1 day
2 days
3 days
4 days
5 days
6 days
7 days
Cardiovascular ≥65 years
5·00
4·00
3·00
2·00
1·00
0
25 30 35 40 45
Daily maximum temperature (°C)


0 days
2 days
4 days
6 days
8 days
10 days
12 days
14 days
All communicable
All malaria
Malaria <5 years
Relative risk
Daily total precipitation (cm)
1 week
2 weeks
3 weeks
4 weeks
5 weeks
6 weeks
7 weeks
8 weeks
All communicable
All malaria
Malaria <5 years
Malaria ≥65 years
Intestinal
Relative risk
Weekly total precipitation (cm)

Some disease-age groupings exhibited significant positive relations at specific lag and precipitation combinations (appendix p 10). At short lags of 1–3 weeks, low values of weekly precipitation were associated with heightened risk of death from all communicable disease, malaria at all ages, and malaria in individuals aged 65 years and older. At precipitation values from 9·03 cm, the 60th percentile, to 17·49 cm, the 70th percentile, this relationship reversed among these groups such that longer lags were associated with a protective effect on deaths from these causes, whereas shorter lags were associated with heightened risk of death. Weekly precipitation at levels higher than 28·6 cm were associated with heightened risk of death from all communicable diseases, malaria at all ages, malaria in children younger than 5 years, and malaria in individuals aged 65 years and older at 1-week to 8-week lags. Finally, we observed heightened risk of death from intestinal diseases at 4-week to 6-week lags from weekly precipitation of 0 cm, the 30th percentile, and 0·45 cm, the 40th percentile, and at 5-week to 6-week lags with weekly precipitation values of 45·3 cm, and a protective effect of 5-week lag at weekly precipitation of 9·0 cm.

Fewer associations were significant among non-communicable diseases groupings (figures 4, 6) compared with communicable diseases. At temperatures in the 95th and 99th percentile, or respectively at 41·9°C and 42·8°C, cardiovascular disease deaths among individuals aged 65 years and older showed significant positive associations. Cardiovascular disease deaths in individuals aged 65 years and older were associated with heightened cumulative 7-day risk at daily maximum temperatures of 41·9°C (RR 2·25 [95% CI 1·06–4·81]) and 42·8°C (3·68 [1·46–9·25]) compared with 36·4°C. These effects were most apparent 2 days and 4 days after exposure (figure 4). Deaths from non-communicable diseases were not significantly associated with precipitation at any percentile.

Discussion

We analysed the temporal associations between weather conditions and 13 distinct categories of deaths attributed to climate-sensitive diseases at daily and weekly lags. We used daily data over a 16-year period from rural Burkina Faso. To our knowledge, this is the most detailed and comprehensive study analysing patterns of deaths due to climate-sensitive diseases spanning both communicable and non-communicable domains in the Sahel region. We show significant associations between 14-day lagged temperatures and precipitation with the risk of dying from malaria. This relationship was particularly strong among children younger than 5 years. Furthermore, higher temperatures and precipitation were associated with heightened risk of death from malaria at an 8-week cumulative lag. Extremely high temperatures were associated with increased risk of death from cardiovascular diseases in individuals aged 65 years and older over a 7-day cumulative lag. Our study highlights relationships between deaths due to specific causes, temperature, and precipitation in rural Burkina Faso and identifies the age groups that are particularly vulnerable as the region continues to experience dramatic shifts in climate.[27,28]

Overall, our findings are consistent with—and expand—existing knowledge on weather–health associations in the Sahel. Communicable disease-related deaths in our study are mostly attributed to malaria infections. Using HDSS data from Kenya, Sewe and colleagues[16] showed that deaths from malaria in children younger than 5 years were positively associated with high weekly average temperatures (≥25°C) with lags of 9–16 weeks.[16] This previous study combined malaria and anaemia deaths, and as malaria infection temporally precedes anaemia, the lag times between exposure and mortality could be longer. To build on this analysis,[16] we investigated lags at shorter time scales, with implications for both disease surveillance and human and vector biology. The significant U-shaped relationship between 8–14 day lagged minimum and maximum temperatures (minimum temperatures in Burkina Faso can reach <10°C) and deaths due to malaria might be caused by children's weak thermoregulatory capabilities at extreme temperatures, leading to excess mortality.[28,29] At lag 1–14 days, children are likely to have active malaria infections, and extreme hot and cold temperatures could acutely increase deaths from malaria[29] in children, particularly in low-income, rural contexts, in which households and medical centres cannot control the indoor climate. Our results also showed a heightened risk of death from malaria at 8–14 day lagged daily precipitation of 0·01 cm or less, which could coincide with prolonged exposure to higher temperatures and drought periods further inhibiting thermoregulation. Exposure to precipitation and temperature at or near the median at short-term lags of 1–2 weeks was protective against death from malaria, which might be explained by moderate and stable weather patterns reducing either malaria transmission or the risk of dying from malaria infection.

Significant relationships between longer, weekly lagged temperatures and precipitation with risk of death from malaria could be due to altered disease transmission intensity. *Anopheles* mosquitoes, which transmit malaria, have been shown to increase in abundance during hotter, drier periods after heavy, episodic rain when breeding habitats are stable.[30] However, consistent exposure to low or high precipitation can deprive *Anopheles* of the breeding habitat required for proliferation.[31] Our results can be explained by such

Figure 5: **Relative risk of different causes of death associated with total daily and weekly precipitation across different lag times.** Estimates are shown as blue lines, 95% CIs shown as blue ribbons, and boxes indicate estimates with significant associations. The figure shows only those causes of death for which we found significant associations with precipitation. Effect estimates are shown across the full distribution of each exposure.

	Non-communicable diseases																	
	Cumulative 7-day lag															Cumulative 28-day lag		
	NCDs			Cardiovascular diseases			Cardiovascular diseases (<65 years)			Cardiovascular diseases (≥65 years)			Respiratory diseases			Malnutrition		
Maximum daily temperature (°C)	RR	LCI	UCI	RR	LCI	UCI	RR	LCI	UCI	RR	LCI	UCI	RR	LCI	UCI	RR	LCI	UCI
28·3	1·29	0·65	2·56	1·04	0·46	2·33	1·58	0·52	4·86	0·71	0·22	2·29	1·29	0·60	2·80	0·92	0·07	12·85
30·6	1·07	0·70	1·63	0·84	0·50	1·41	0·90	0·41	1·95	0·77	0·38	1·54	1·03	0·66	1·63	0·85	0·27	2·70
31·3	1·04	0·69	1·57	0·83	0·49	1·38	0·84	0·39	1·79	0·80	0·40	1·57	1·00	0·64	1·56	0·85	0·26	2·73
33·3	1·03	0·78	1·35	0·90	0·64	1·26	0·87	0·53	1·44	0·90	0·57	1·42	0·99	0·74	1·34	0·87	0·36	2·12
38·9	0·84	0·63	1·12	0·86	0·60	1·22	0·72	0·43	1·22	1·04	0·64	1·68	0·85	0·63	1·14	1·21	0·54	2·71
41·1	0·88	0·57	1·36	0·99	0·58	1·70	0·63	0·29	1·37	1·61	0·78	3·31	0·83	0·53	1·28	1·50	0·46	4·87
41·9	1·00	0·63	1·59	1·23	0·70	2·17	0·68	0·30	1·56	**2·25**	1·06	4·81	0·88	0·56	1·38	1·65	0·50	5·52
42·8	1·24	0·70	2·19	1·74	0·87	3·48	0·82	0·29	2·33	**3·68**	1·46	9·25	0·99	0·56	1·73	1·87	0·43	8·08
Total daily precipitation (cm)	RR	LCI	UCI	RR	LCI	UCI	RR	LCI	UCI	RR	LCI	UCI	RR	LCI	UCI	RR	LCI	UCI
0·0	0·96	0·90	1·02	0·97	0·90	1·04	0·94	0·84	1·05	0·99	0·89	1·09	1·05	0·98	1·13	1·00	0·84	1·18
0·1	0·98	0·96	1·01	0·99	0·96	1·02	0·98	0·94	1·02	1·00	0·96	1·03	1·02	0·99	1·05	1·00	0·94	1·07
2·8	1·63	0·79	3·35	1·52	0·63	3·71	1·78	0·47	6·74	1·36	0·42	4·46	0·64	0·28	1·43	0·83	0·12	5·76
3·8	1·56	0·73	3·33	1·54	0·60	3·96	1·42	0·34	5·94	1·71	0·49	5·96	0·83	0·35	1·95	0·62	0·08	4·71
6·9	1·10	0·39	3·10	1·30	0·37	4·60	0·62	0·09	4·25	2·70	0·51	14·28	2·50	0·74	8·39	0·33	0·01	8·11
10·0	1·80	0·62	5·27	1·68	0·46	6·15	3·19	0·45	22·92	1·19	0·21	6·86	1·02	0·27	3·93	1·58	0·04	58·22
18·3	2·61	0·39	17·35	4·40	0·45	42·88	3·83	0·10	141·22	4·86	0·26	90·58	0·29	0·03	3·43	10·28	0·01	9273·53

Figure 6: **Weather conditions and risk of death from non-communicable diseases**
The figure shows relative risk (RR) and 95% CI bounds for cause-specific deaths from non-communicable diseases, for lags based on sensitivity analysis and the literature. Bolded and coloured RRs show significant relationships. Orange and red colours indicate harmful associations. LCI=lower confidence interval. NCDs=non-communicable diseases. UCI=upper confidence interval.

vector dynamics: at lags of 5–8 weeks, precipitation in the middle of the distribution increases risk of death from malaria, whereas this effect reverses at extreme precipitation. Furthermore, at lag 4–5 weeks, exposure to median temperatures was associated with heightened risk of death from malaria at all ages. A previous simulation study predicted that climate change, particularly an increase in mean temperature and a reduction in total rainfall, is unlikely to increase the malaria burden in the Sahel.[32] Our empirical results support these findings: malaria deaths are not associated with temperatures above 41°C in rural Burkina Faso.

We showed heightened risk of death from acute cardiovascular diseases over a cumulative 7-day lag period after extremely high daily temperatures (>40°C). Exposure to acute extreme heat is a well-established risk factor for death related to cardiovascular diseases, because it increases blood pressure and causes dehydration and electrolyte imbalances.[33] Before our analysis, a study using data from the Nouna HDSS dataset showed that extreme temperatures were associated with deaths from non-communicable diseases in general.[15] Here, we find that deaths from cardiovascular diseases explain this relationship. Many communities in the Sahel are experiencing an epidemiological transition from infectious to non-communicable diseases, in part because the local diets increasingly include refined carbohydrates and highly processed foods.[34-36] Extremely hot days increase in frequency in Burkina Faso and the wider Sahel region, and deaths due to non-communicable diseases, particularly cardiovascular diseases, are likely to become more common.

Our results have at least two important implications for policies in the Sahel region. First, we have shown the importance of using regularly collected climate data in a rural, Sahelian community. Similar data and analyses in additional communities in the region could be used as early warning systems for deaths from climate-sensitive diseases. In 2010, Thomson and colleagues[37] called for improved climate data collection in African countries to fight climate-sensitive diseases, and urged for increased funding, collaboration, and data integration between meteorological and public health institutions. Since then, international institutions including the United Nations Environmental Programme have launched public health initiatives in climate-vulnerable regions of Africa with a focus on climate response.[38,39] Despite these initiatives, collaborations on climate change between meteorological institutions and public health agencies are rare.[40] Heatwave and drought alert systems are a good starting point for such collaborations. An initiative financed by the Adaptation Fund under the World Meteorological Organisation and the West Africa Regional Water Partnership aims to establish such systems. This initiative aims to strengthen the institutional and technical capacity of National Meteorological and Hydrological Services to mitigate climate change-related disaster risk and implement climate change adaptation. The activities under the above initiatives

could be used in the future to develop early warning systems alerting policy makers to the places and periods at high risk of deaths from climate-sensitive diseases. Specifically, with the introduction and roll out of the RTS,S/AS01 malaria vaccine, such early warning systems could inform the geographical targeting and timing of large vaccination campaigns before anticipated spikes in malaria deaths.

Second, as the Sahel climate continues to become harsher, with higher temperatures and more extreme rainfall,[41] understanding differences in climate-disease dynamics among Sahelian countries will become increasingly important. This region, which encompasses parts of Senegal, Mauritania, Mali, Burkina Faso, Niger, Nigeria, Chad, and Sudan, is host to a population of more than 135 million people and is characterised by a delayed demographic transition with a young age structure and high fertility.[42–44] While climate and climate trajectories across the Sahel are broadly similar,[41] countries and communities in the region differ widely, for instance in urbanisation and threats to national security. Further studies should be conducted in communities in the Sahel that are different to Nouna to elucidate differences in climate-disease dynamics and to more accurately tailor response policies to local circumstances.[45,46]

Our study has several limitations. First, it is confined to one community and the specific relationships between weather conditions and cause-specific deaths we have measured might not generalise well to other Sahelian areas. Second, despite having 16 years of comprehensive data, our sample size was too small to assess all climate-sensitive disease deaths. Third, verbal autopsy data for cause of death might not always be accurate, especially in cases of comorbidities. Although verbal autopsy data is typically quite complete, a few deaths might not be documented, in particular when people who live alone die. Fourth, our weather data were geographically separated from individual homes where deaths occurred, which could lead to some imprecision in the assignment of weather conditions to a death. Finally, the weather data were limited to temperature and precipitation and we were thus not able to estimate the relationships between other weather conditions, such as humidity and wind speed, with death.

Our study determines temporal associations between two weather conditions—temperature and precipitation—and causes of death in a rural, subsistence-farming, climate-vulnerable community of Burkina Faso. We detected significant relationships between both extremely high temperature and extremely low precipitation, and risk of death from malaria over 14 cumulative days, particularly in children younger than 5 years. We also showed a heightened risk of death from malaria at all ages, and particularly in children younger than 5 years over 8 cumulative weeks of exposure to both moderately high temperature and moderately high precipitation. Furthermore, we determined a significant positive association between 7-day risk of death from cardiovascular diseases and extremely high temperature in individuals aged 65 years and older. Our results could help develop climate preparedness programmes and early warning systems in climate-vulnerable communities such as Nouna, Burkina Faso. In one community, we show the insights that can be gained by using regularly collected climate and health data. The strong relationships between weather conditions and cause-specific deaths we find in this study should motivate governmental programmes that measure similar data at national levels and prepare vulnerable communities in the Sahel region for the changing risks of death due to climate change.

Contributors

NJA, AB, and MOS conceived the study and designed and conducted the analyses. NJA wrote the first draft of the manuscript with input from AB. NJA prepared the figures. All authors contributed to revising the manuscript. All authors have accessed and verified the data used in the study, and AB was responsible for the decision to submit the manuscript.

Declaration of interests

We declare no competing interests.

Data sharing

The data used for this study cannot be shared due to ethical restrictions.

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