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Review

Climate-sensitive disease outbreaks in the aftermath of extreme climatic events: A scoping review

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SUMMARY

Outbreaks of climate-sensitive infectious diseases (CSID) in the aftermath of extreme climatic events, such as floods, droughts, tropical cyclones, and heatwaves, are of high public health concern. Recent advances in forecasting of extreme climatic events have prompted a growing interest in the development of prediction models to anticipate CSID risk, yet the evidence base linking extreme climate events to CSID outbreaks to date has not been collated and synthesized. This review identifies potential hydrometeorological triggers of outbreaks and highlights gaps in knowledge on the causal chain between extreme events and outbreaks. We found higher evidence and higher agreement on the links between extreme climatic events and water-borne diseases than for vector-borne diseases. In addition, we found a substantial lack of evidence on the links between extreme climatic events and underlying vulnerability and exposure factors. This review helps inform trigger design for CSID prediction models for anticipatory public health action.

INTRODUCTION

Anthropogenic climate change is leading to unprecedented changes in the frequency, intensity, location, timing, and duration of extreme climate events, such as floods, droughts, tropical cyclones, and heatwaves.[1] Extreme climate events are defined by the Intergovernmental Panel on Climate Change (IPCC) as "the occurrence of a weather or climate variable above (below) a threshold value near the upper (lower) end of the range of observed records of the variable."[2] Anthropogenic greenhouse gas emissions are driving global temperature increases. With current mitigations, the Earth's climate is on track to warm 2.7°C above pre-industrial levels by the end of the century,[3] which will have far-reaching impacts on human and planetary health. Indeed, the incidence of some infectious diseases affecting humans is affected by climate, and changes in climate patterns may affect their transmission dynamics. Outbreaks of climate-sensitive infectious diseases (CSIDs) in the aftermath of extreme climatic events are of high public health concern[4] and particularly in lower- and middle-income countries that are highly vulnerable and exposed to climate change, despite having contributed very little to global greenhouse gas emissions.[5–7]

Recent advances in forecasting of the climate and extreme climatic events have prompted a growing interest in the development of prediction models to anticipate CSID risk based on hydrometeorological indicators. These models attempt to quantify the association between precipitation, temperature, and/or humidity and the risk of exceeding an epidemic threshold—a level of disease incidence above which triggers an urgent public health response.[8] Typically, these outbreaks represent an excess of what would normally be expected: a bigger seasonal peak than "routinely anticipated," unseasonal cases of an infectious disease, or the occurrence of an unexpected disease (whether emergent or re-emergent) in a defined community or geographic area.[8] As weather and climate forecasts become more skillful, it becomes possible to act earlier—even before the extreme climatic event has occurred—to try to mitigate or forestall disease outbreaks. This is known as anticipatory action and is a growing field of interest in public health and humanitarian action. Anticipatory actions are "interventions taken in anticipation of a crisis, either before the shock or at least before substantial humanitarian needs have manifested themselves, which are intended to mitigate the impact of the crisis or improve the response."[9] Yet, to date, there has not been a collation of existing evidence linking extreme climatic events to CSID outbreaks, nor a synthesis of which hydrometeorological drivers are most useful to monitor for a given CSID. This review attempts to fill that knowledge gap.

Table 1. Estimated global burden, number of deaths, and DALYs per climate-sensitive infectious disease[10–27]

Disease	Disease type	Estimated burden globally per year (per million)	Estimated number of deaths globally per year (per 10,000)	Estimated number of DALYS per year (per 100,000)
Diarrheal disease	waterborne	unknown in all ages; 1,700+ in under fives[11]	130[12]	790[13]
Dengue	vector-borne	100–400[14,15]	>4[15]	2[13]
Malaria	vector-borne	241[16]	62.7[16]	330[13]
Typhoid	waterborne	14.3[17]	13.6[17]	98[17]
Cholera	waterborne	1.3–4[18]	>10[18]	Unknown
Leptospirosis	zoonotic/waterborne	13[19]	5.9[19]	29[13]
Hepatitis E	waterborne	20[20,21]	4.4[20]	0.12[13]
Hepatitis A	waterborne	>1.5[21]	0.71[22]	2[13]
Leishmaniasis	vector-borne	0.07–1[23]	Uncertain[24]	0.72[13]
Lyme disease	vector-borne	12.3[25]	N/A	N/A
Chikungunya	vector-borne	0.05–0.32[26]	uncertain	1.06[26]
Zika	vector-borne	0.035–0.099[26]	uncertain	0.44[26]
Schistosomiasis	waterborne disease	220[27]	200,000[27]	17–45[28]
Rift Valley fever	vector-borne	not available	not available	not available

In this paper, we review the epidemiological evidence of the risk of CSID outbreaks occurring in the aftermath of broad range of extreme climate events (floods, tropical cyclones, droughts, heatwaves), in order to summarize and appraise the evidence in peer-reviewed studies. CSIDs include, but are not limited to, water-borne (including feco-oral transmission) and vector-borne diseases. Estimated ranges of their global burden, the number of deaths they cause, and estimated disability adjusted life years (DALYs) for which they are responsible are established for some CSIDs, but unknown for others (e.g., cholera DALYs) (see Table 1). These estimates are likely to be below the true burden as many diseases exist in contexts in which surveillance systems are not operating and access to healthcare is limited.

Certain CSIDs have a particularly high global burden in terms of mortality, morbidity, and DALYs. These include diarrheal disease (all-cause, non-cholera), cholera (water-borne disease caused by the *Vibrio cholerae* bacterium, serogroups O1 and O139), typhoid (feco-oral transmission, spread by food or water contaminated with *Salmonella typhi* bacterium), malaria (vector-borne transmission of *Plasmodium* spp. parasites via *Anopheles* spp. mosquitoes), and dengue (vector-borne disease, spread by the bite of an infected *Aedes aegypti* or *Ae. albopictus* mosquitos). These five CSIDs were thus selected as outcomes of interest for this review. The aims of this review are to (1) identify potential hydrometeorological and climatic triggers that are important in driving outbreaks of cholera, diarrheal disease (including typhoid), malaria, and dengue and (2) assess the state of knowledge on how extreme climate events interact with underlying exposure and vulnerability factors. This scoping review followed PRISMA-ScR guidelines to systematically review relevant literature in the extreme climate and climate-sensitive infectious disease fields (see experimental procedures for further details).[28] The term "event" is used throughout to refer to a specific extreme climate event-disease outbreak event, e.g., flooding-cholera, tropical cyclone-diarrheal disease, heatwave-dengue.

KNOWLEDGE ON CSID OUTBREAKS AFTER EXTREME CLIMATE EVENTS

Extreme climate event, disease, country

Of the 90 different events that were identified, the most common extreme climate events reported were floods (38%, n = 34/90) and tropical cyclones (cyclone/hurricane/typhoon) (26%, n = 23/90). Relatively few papers were retrieved for drought (n = 9) or heavy rainfall (n = 10) or heatwaves (n = 5). Nine papers reported on the occurrence of multiple extreme climate events that combined to drive CSID outbreaks. Excluding review papers (i.e., studies that were not primary research), the index used to measure the hydrometeorological variables was provided in 70% (n = 52/74) of events, from the national meteorological services, local weather gauges, Palmer Drought Severity Index (PDSI), National Oceanic and Atmospheric Administration, and National Aeronautics and Space Administration. Extreme climate event definitions were provided in 65% (n = 48/74) of extreme climate-disease outbreak events. Heatwaves were typically defined by their duration and intensity, for example, as two or more (consecutive) days where the daily maximum temperature exceeded the 90th–99th percentile of its historic distribution.[29–31] Extreme rainfall was defined as upper or lower 5%–10% of distribution or by a specific threshold (e.g., above a certain amount of millimeters per day).[32–35] Floods were defined by the presence of floodwater or rivers exceeding the danger levels.[36–41] Tropical cyclones were defined according to the Saffir-Simpson Scale or Beaufort Scale. Droughts were defined by the PDSI[42] and the Standardized Precipitation Index.[43]

Of the 90 events identified, water-borne diseases accounted for 68% (n = 61/90) and vector-borne diseases accounted for 32% (n = 29/90). Most studies focused on diarrheal (non-cholera) outbreaks (48%, n = 43/90), followed by cholera (20%, n = 18/90), dengue (20%, n = 18/90), and malaria (12%, n = 11/90) (see disease-specific sections and data and code availability for full breakdown). As only one paper focused on

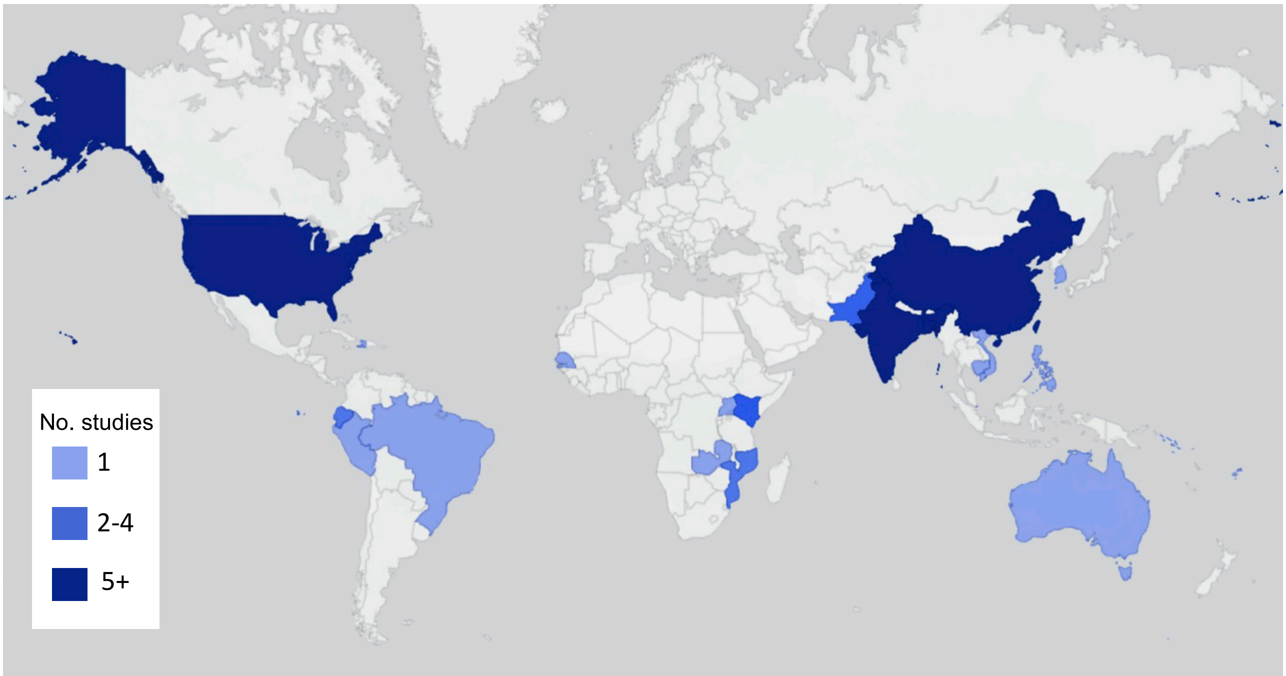

Figure 1. Map of study countries (n = 26) in the retrieved studies
Colors indicate the number of studies per country.

typhoid specifically, typhoid was incorporated into the overall diarrheal diseases analysis.[44]

Studies covered 26 different countries, the US (n = 6) and China (n = 12) had the most studies per country (Figure 1). Over half (53%, n = 14/26) of the countries were low or lower middle income: Sudan and Uganda (low income), Bangladesh, Cambodia, Haiti, India, Kenya, Mozambique, Pakistan, Peru, the Philippines, Senegal, Solomon Islands, and Vietnam (lower middle income).[45] The remaining 12 countries included: Barbados, Ecuador, Fiji (middle income); China, Tuvalu, Brazil (upper middle income); Australia, the US (and specifically Puerto Rico), Singapore, South Korea, Taiwan (high income).[45]

Cholera

We found 17 studies investigating extreme climate events and cholera outbreak risk. However, one paper investigated both droughts and floods and cholera outbreaks and was therefore separated into two separate extreme climate-cholera outbreak events (i.e., drought-cholera event and flood-cholera event).[46] Three studies were categorized as "multiple" as they were systematic reviews investigating multiple water-related disasters,[47,48] or the sequential impacts of drought followed by heavy rain.[49] This resulted in 18 extreme climate-cholera outbreak events (these will be referred to as "events") for analysis (Figure 2).

Studies reported on both suspected and laboratory confirmed cholera cases. Only 39% (n = 7/18) studies provided a clear case definition of a cholera outbreak.[30,46,49–52] For these studies, as per international reporting guidelines, one case of laboratory-confirmed cholera triggered an outbreak declaration and relaxed the case definition. One study reported seasonal cholera outbreaks and used a measure of 2 standard deviations away from previous seasonal peaks to investigate the link with extremely heavy monsoon rainfall.[53]

Cholera outbreaks were reported in 17 of 18 events. One longitudinal register-based ecology study found that cholera outbreaks began during only 1 out of every 14 floods.[46] There was high agreement and high evidence that cholera outbreaks occurred after tropical cyclones.[51,54–59] There was high agreement and medium evidence that sequential extreme climate events, such as droughts followed by heavy rainfall and flooding, were linked with cholera outbreaks.[47–49] Two studies found linkages between drought and cholera outbreaks.[46,52] Rieckmann et al. found that cholera outbreaks can be expected in one out of every three droughts in Sub-Saharan Africa.[46] Three studies reported that cholera outbreaks (or an increase in cases for the study in Senegal) occurred in the aftermath of flooding.[41,50,60]

Suspected cholera cases were reported within a few days to 2 weeks in Haiti and Mozambique following tropical cyclones (Matthew, Idai, and Kenneth).[54,55,57] A study in Senegal that investigated the effects of flooding on the ongoing cholera outbreak found a lag of 23 days between flooding and an increase in cholera cases.[50] A study on heatwaves and endemic cholera found a lag of 2 days.[30]

Descriptions of the extreme climate events were analyzed to understand the possible hydrometeorological triggers influencing cholera outbreak risk. Abrupt and heavy or extreme rainfall (from thunderstorms or tropical cyclones) coupled with extensive flooding was most frequently cited as the trigger for cholera outbreaks (high agreement) (see Figure 3). Higher

Disease	Heavy Rainfall	Tropical Cyclones	Drought	Flooding	Heatwaves	Multiple Events	Total
Cholera	**Low evidence** (N=1) Outbreak [53]	**High agreement, high evidence** (N=7) Outbreak [51, 54–59]	**High agreement, low evidence** (N=2) Outbreak [46,52]	**Medium agreement, medium evidence** (N=4) Outbreak [41,60] [50] noted the floods did not seed the outbreak; outbreaks began during only one out of every 14 floods [46]	**Low evidence** (N=1) Outbreak [30]	**High agreement, medium evidence** (N=3) Including drought followed by heavy rains [49] and two systematic reviews investigating water-related disasters[48, 61]	N=18
Diarrheal Diseases (Non-cholera)	**High agreement, high evidence** (N=5) Outbreak:[32,34,35] But dynamics of dry period followed by rainfall vs wet period followed by rainfall are important[33] and on type of rainfall event[62]	**High agreement, high evidence** (N=10) Outbreak:[44,68,69,71,73-75,80,84,,85]	**High agreement, low evidence** (N=2) Outbreak [63,64]	High agreement, high evidence (N=20) Outbreak [36-39, 62, 66, 70, 71, 76-79, 81-83, 86, 87, 94, 104, 105] [62] found that the relationship between flooding and diarrhea risk appeared to vary by pathogen	**Low evidence** (N=1) Increasing heatwaves days were linked with increased emergency department visits for childhood diarrhea[79]	**High agreement, high evidence** (N=5) [106]looked at EM-DAT data in general for a 'disaster' period [47,67,72,88]were all reviews which covered multiple hazards	N= 43
Malaria	**Low evidence** (N=1) Outbreak[91]	**Low evidence** (N=1) No outbreak[90]	**Low agreement, low evidence** (N=1) [64] found that evidence of associations was mixed	**Medium agreement, medium evidence** (N=8) Outbreaks [38,92, 93, 95] A scoping review reports overall positive linkages between floods and outbreaks [94] No outbreak [78,89]	*No papers retrieved*	*No papers retrieved*	N = 11
Dengue	**High agreement, medium evidence** (N=3) Increased outbreak risk[31,42,43]	**Low agreement, high evidence** (N=5) Outbreak[96,73, 103] No outbreak[90,100]	**High agreement, medium evidence** (N=4) Increased outbreak risk[42,43,64,99]	**Medium agreement, low evidence** (N=2) Unclear impacts of flooding on outbreaks Mixed findings, including decreases and increases[95] Decreased risk (possibly due to vector control activities)[78]	**Medium agreement, medium evidence** (N=3) Outbreak: [31,97] No outbreak[29]	**Low evidence** (N = 1) [98]investigate heavy rainfall, but defined 'flood' periods caveating that this did not necessarily correspond with actual flood waters	N = 18
Total	N=10	N=23	N= 9	N= 34	N=5	N= 9	90

Figure 2. Number of papers identified per climate-sensitive infectious disease and extreme climatic event
Colors indicate the level of agreement. High agreement, green; medium agreement, orange; low agreement, blue. Increasing transparency of the color indicates a lower amount of evidence. Further details on specific cases can be found in the cited works.[29–36,38,40–44,46–102,103,104–106]

temperatures and heat waves were statistically significant in one modeling study, which found that drought was a significant predictor of cholera outbreaks in Africa;[52] while another study reported that heatwaves and rainfall resulted in increased risk.[30]

Interpretations by study authors of how extreme climate events interacted with underlying systemic vulnerability largely focused on weak water and sanitation systems (55%, n = 10/18). For instance, extreme rainfall (associated with storms and resulting in flooding) led to water contamination due to inadequate drainage systems and overflowing latrines.[53,54,57,59] Consequently, increased run-off of water or inundation of water and sanitation infrastructure enabled the transport of pathogens into drinking water sources.[53,58,59,61] Only one study in Bangladesh investigated how extreme climate events interacted with ecological conditions to influence cholera outbreak risk.[30] They found that tree cover surrounding households mitigated the effect of heatwaves on cholera risk.[30] No studies explored the influence land-use change or rural to urban dynamics on outbreak risk.

Four studies reported on the interaction between extreme climate events and socioeconomic status.[46,48,50,52] A study on drought found that higher population numbers and people living in poverty were significantly associated with increased cholera outbreaks.[52] Higher per capita access to fresh water,[52] boiling (reliant on ability to buy fuel), and chlorination of water were cited as protective factors.[48] Sharing sanitation facilities with other households showed higher odds of cholera transmission (OR = 1.82; 95% CI, 1.33–2.51).[48]

Tropical cyclones and floods commonly resulted in widespread population displacement and subsequent crowding in evacuation centers with limited access to safe water and basic sanitation, which were cited as major outbreak risks.[50,54,57–59] Cholera vaccination campaigns were reported following Hurricane Matthew in Haiti[51,54] and Cyclone Idai in Mozambique.[55]

Anticipatory actions to prevent an outbreak were only mentioned in a study in Mozambique, given recent experience with Cyclone Idai and a cholera epidemic.[57] These activities focused on improving surveillance, stockpiling, and social mobilization for prevention. Early response activities were frequently

CSID	Climate/weather trigger	Confidence	References
Cholera	Abrupt and heavy/extreme rainfall, extensive flooding	High agreement, medium evidence	De Magny et al. 2012; Passeto et al. 2018; Sinyange et al 2018; Cann et al 2013
	Higher temperatures/heatwave (one study reported drier conditions being a risk modifier, whilst the other reported rainfall was a significant risk modifier)	Medium agreement, low evidence	Charnley et al. 2021; Wu et al. 2018
Diarrheal diseases	Heavy and extended rainfall (torrential) and flooding	High agreement, high evidence	Ding et al 2013; Chen et al 2012; Thompson et al. 2014; Kim et al. 2013; Deng et al 2015; Jones et al 2016; CDC 1983; Wade et al. 2003; Saulnier et al. 2017
	High temperatures	High agreement, Medium evidence	Kraay et al. 2020; Levy et al. 2016; Mertens et al. 2019; Thompson et al. 2014; Xu et al. 2014
	Heavier and longer duration of flood, than a flash flood	Low evidence	Ding et al 2013
	Excessive rainfall especially when following a dry period or period of low rainfall	High agreement, Medium evidence	Despande et al 2020; Levy et al 2016; Carlton et al. 2014; Mertens et al 2019
Malaria	Amount and duration of heavy rainfall, leading to extensive flooding	High agreement, high evidence	Boyce et al. 2018; Maes et al. 2014; Ding et al. 2014; Okaka et al. 2018; Himeidan et al. 2007
Dengue	Extreme heavy rain	High agreement, medium evidence	Chen et al. 2012; Lowe et al. 2018; Lowe et al. 2021; Cheng et al. 2021
	Above normal temperatures or drought followed by extremely high rainfall, 1-3 months lag time	High agreement, medium evidence	Lowe et al. 2018; Lowe et al. 2021; Cheng et al. 2021
	Drought conditions, especially with increased temperatures	High agreement, medium evidence	Stanke et al 2013; Ayambe et al. 2014; Lowe et al. 2018; Lowe et al. 2021
	Heatwaves delay timing and increase magnitude of dengue outbreaks, up to a point as longer duration of heatwaves (number of heatwave days) may reduce dengue outbreak risk	Medium agreement, medium evidence	Cheng et al 2020; Cheng et al. 2021; Seah et al. 2021

Figure 3. Identified hydrometeorological triggers linked with CSID outbreaks with a corresponding confidence assessment
Green indicates high agreement between studies. Orange indicates medium agreement between studies. The transparency of the color indicates the amount of evidence: the more transparent the color the lower the amount of evidence (number of studies). Light blue indicates that there was only one study, and therefore an agreement qualifier is not provided. For citation details, please see the references list.[29–31,33–36,42,43,50,54,60–62,64,66–73,77,79,80,91–94,97,99,102]

reported, typically involving oral cholera vaccination campaigns, health promotion activities, enhanced surveillance, and water treatment.

Diarrheal diseases

Infectious diarrheal diseases included any reported diarrheal diseases not identified as cholera, such as typhoid, rotavirus, shigella, salmonella, or non-specific. There were 42 studies investigating extreme climate events and diarrheal (non-cholera) outbreak risk, which resulted in 43 events. One systematic review was divided into heavy rainfall-diarrheal diseases and flooding-diarrheal diseases.[62] Case definitions were provided in just under half of the studies (48%, n = 21/43). Comparator/reference groups were explicitly provided in 44% (n = 19/43) of the studies.

There was high agreement and high-medium evidence for the links between diarrheal outbreaks and heavy rainfall, tropical cyclones, and flooding (Figure 2). We retrieved a low number of studies that specifically explored the link between drought and heatwaves and diarrheal diseases (n = 2 and n = 1, respectively). In these studies there was high agreement of a link between drought and diarrheal diseases.[63,64] Similarly, the one paper specifically on heatwaves in China found that increasing heatwaves days were linked with increased emergency department visits for childhood diarrhea.[65]

To better understand climate-diarrhea dynamics, the descriptions of the extreme climate events were analyzed to unpick the possible hydrometeorological triggers influencing diarrheal outbreak risk. Despite the low number of studies focused specifically on heatwaves or drought, several studies reported on temperature. High temperatures were linked with increased diarrheal risk.[34,62,65,66] A previous systematic review found high to medium evidence that warmer temperatures are associated with elevated rates of diarrhea, although the association varies depending on the pathogen (for example, rotavirus was negatively associated with temperature).[67] Increased diarrheal outbreak risk was also linked to heavy and extended periods of rainfall and flooding.[36,66,68–73] Excessive rainfall and high temperatures following a dry period or period of low rainfall were also reported as possible triggers.[33–35,67] Floods with a longer duration in Anhui Province, China, were associated with increased diarrheal cases compared with flash floods, where waters receded relatively quickly.[70] Diarrheal cases were recorded from 2 days to 3 weeks later.[32,33,35,38–40,62,65,68–70,72–79]

Interpretations by study authors of how extreme climate events interacted with underlying systemic vulnerability largely focused on weak water and sanitation systems. Consumption of contaminated water due to flooding, heavy rainfall, and tropical cyclones (specifically Typhoon Haiyan in the Philippines and Typhoon Nari in Taiwan) was hypothesized as the main source of infection in 17 studies, including four previous review papers.[37,47,62,64,67,70–73,76,78,80–82] The disruption of the sewage treatment processes or damage of water pipes (due to flooding in the US),[36,71] extensive structure damage (due to Hurricane Katrina in the US, and Cyclone Tomas in Fiji),[44,74] destruction of household toilets (due to flooding in India)[83] were also provided as explanations for the diarrheal outbreaks. Floodwaters that were highly turbulent, created mud flows, and receded slowly were highly damaging to water infrastructure in China.[70,76]

Displacement of thousands of people was common during floods and tropical cyclones[37,38,44,67,70,72,74,77,80,83–88] and resultant overcrowding in evacuation centers, malnutrition, and inadequate access to water, sanitation and hygiene facilities, and health services was linked with increased diarrheal risk.[88] Lower socioeconomic status was positively associated with increased diarrheal risk in Cambodia[88] and in one study in Bangladesh,[39] but another study in Bangladesh did not find an association with socioeconomic status.[81] Lower socioeconomic status was hypothesized to play a role in a study in Vietnam, but the study lacked socioeconomic data at the household level to investigate this.[66]

Anticipatory actions were not mentioned in diarrheal disease studies. Early response activities were reported in 21% (n = 9/43) of events and included enhanced surveillance, outbreak monitoring, vaccination campaigns health promotion activities, and hyperchlorination of water sources.[36,44,63,77,83,85,86] People's behavior may adapt to previous experience of extreme climate events, in response to the event (e.g., having to clean up after flood waters), or as a result of public health messaging which can influence the outbreak risk.[36,37,64,67]

Malaria

We identified 10 studies investigating extreme climate events and malaria incidence risk in China, Haiti, Kenya, Solomon Islands, Sudan, Uganda, and globally. One study in Kenya reported on two different epidemic periods and therefore these two epidemic events were separated in the analysis.[89] This resulted in 11 events (Figure 2).

Specific outbreak definitions were not provided in any of the studies. Five of the 11 events reported on *P. falciparum* malaria, including in Kenya,[89] Haiti,[90] Sudan,[91] and Uganda.[92] One study in China reported on *P. vivax* malaria.[93] The other five studies did not specify the type of *Plasmodium* species (three were reviews that collated data from many different regions).[38,64,78,93–95] Malaria incidence pre/post extreme climate event, including seasonal averages between years in which there was an extreme event and years in which there was none, was used as a comparator in all the primary research studies.[38,78,89–93]

The evidence for the occurrence of malaria outbreaks following extreme climate events was mixed. There was low evidence for heavy rainfall (n = 1), tropical cyclones (n = 1), and drought (n = 1) and no studies were retrieved for heatwaves. One study on heavy rainfall in Sudan found that heavy rainfall in 1992 and 1998 initiated malaria epidemics.[91] Hurricane Jeanne in Haiti was not linked with an outbreak of malaria during the surveillance period 2–3 months post-hurricane, although three cases of malaria were detected indicating ongoing transmission of malaria.[90] A systematic review found mixed results for the association between drought and malaria outbreaks.[64] Four studies found linkages between floods and outbreaks in China,[38,93] Kenya,[94] and Uganda (a >4-fold increased risk of a positive malaria test in the post-flood period, compared with the pre-flood period, during a typically low transmission season).[92] A positive association between floods and malaria outbreaks was supported by the overall findings of a scoping review.[95] However, two other flood events in Solomon Islands[78] and Kenya[89] were not associated with malaria outbreaks. Both of these studies reported early vector control measures, which are thought to have contributed to preventing outbreaks.[78,89] An analysis of the descriptions of the extreme climate event gave high agreement that the amount and duration of heavy rainfall, leading to extensive flooding, was linked with malaria outbreaks in Uganda, Kenya, China, and Sudan[89,91–94] (see Figure 3). A scoping review found that areas in which malaria transmission is stable or seasonal (i.e., endemic regions) there was more evidence for outbreaks after flooding or heavy rainfall in comparison with areas with low transmission (i.e., non-endemic regions).[95]

The time lag between an extreme climate event and malaria outbreak varied according to the extreme climate event type. Post-flood, cases were reported as beginning to increase from 25 to 27 days in China[38,93] to 2 months in Kenya.[89] The epidemic peak was reached 3 months post-flood in Uganda.[92] A previous scoping review found no obvious temporal lag patterns with flooding events.[95] Time lags between drought and malaria outbreaks were not reported in the scoping review.[64]

Evidence on how extreme climate events interact with underlying vulnerability and exposure factors was scarce for malaria. No studies reported on whether human behavioral change, socioeconomic status, or displacement may have influenced outbreak risk. Four studies hypothesized that extreme rainfall and flooding events (leading to surface water and waterlogging) increased malaria vector breeding habitats, positively influencing vector population size and outbreak risk in Uganda,[92] Kenya,[94] China,[93] and Sudan.[91] Early vector control measures during flooding in Kenya and Solomon Islands were suggested to have contributed to preventing outbreaks.[78,89]

Dengue

We found 15 studies investigating extreme climate events and dengue risk in Barbados, Brazil, China, Haiti, Kenya, Puerto Rico, the Philippines, Singapore, Solomon Islands, Taiwan, Vietnam, as well as globally or regionally (e.g., East Africa). One paper that investigated extreme rainfall and drought in Barbados was divided into two events: extreme rainfall-dengue and drought-dengue.[43] Another paper also investigated extreme rainfall and drought in Brazil and was divided into two events: extreme rainfall-dengue and drought-dengue.[42] A paper investigated extreme rainfall and heatwaves in China and was divided into two events: extreme rainfall-dengue and heatwave-dengue.[31] This resulted in 18 events for further analysis (see Figure 2).

Outbreaks definitions were provided in 56% of the events (n = 10/18).[29,31,42,43,96–98] They were defined by their epidemic threshold, for instance, the average number of cases from previous years being surpassed[29,96,97] by, for example, a measure of +2 standard deviations from seasonal mean[31] or a defined upper quartile of the distribution.[43] Comparisons of dengue incidence pre/post extreme climate event, including seasonal averages between years in which there was an extreme event and years in which there was none, were used to establish if there was higher transmission.

There were mixed results for different extreme climate events and dengue outbreaks. Heavy rainfall and drought events, separately, were linked with outbreaks in Taiwan and East Africa,[64,73,99] and were strongly linked when droughts were followed by extreme rainfall in Brazil and China.[31,42,43] The impact of flooding or heatwaves was less certain. Pluvial floods (i.e., floods due to heavy rainfall) were linked with decreased cases, according to a previous scoping review,[95] and a flooding event in Solomon Islands was linked with decreased dengue cases.[78] Heatwaves appeared to increase the magnitude of dengue outbreaks in China and Vietnam,[31,97] but a subsequent study in Singapore found that a longer duration of heatwaves (number of heatwave days) may reduce dengue outbreak risk in the long term.[29] Study authors reasoned that high temperatures reduce adult lifespan and egg-to-adult survival and thus the overall *Aedes* population, lowering the risk of dengue transmission in the long term.[29]

Dengue outbreaks tended to occur more than a month after the extreme climate event. Specifically, dengue outbreaks were typically reported 1–3 months after extreme rainfall;[31,42,43] 1–4 months after flooding;[95] 1–3 months after heatwaves, and heatwaves may delay the timing of large outbreaks;[31,97] 3–5 months after a drought;[42,43] and more than 2 months after a tropical cyclone.[73]

The impact of extreme climate events on dengue outbreaks was most often linked with climate-induced changes in mosquito ecology or human behavior (n = 13/18 events). Heavy rainfall was reported to both positively and negatively influence the availability of larval and pupal habitats. Extreme torrential rainfall (e.g., associated with tropical cyclones) may result in the destruction of habitats and flushing of larvae and pupae in the immediate aftermath of such an event,[73,95] but heavy rainfall (associated with thunderstorms) could result in increased larval habitats (through rain-filled containers or debris) in the longer term.[42,43,95] High temperatures during heatwaves can have complex effects depending on timescale: they may increase the activity (e.g., biting rate) of mosquitoes leading to high transmission in the short to medium term,[29] and yet may reduce the lifespan and survival of adult mosquito vectors in the medium term but favor the growth of larvae and pupae in the long term.[29,97]

Behavior changes due to an extreme climate event were reported in 44% of events (n = 8/18). This included spending more or less time outside in the daytime and wearing less clothing (e.g., during heatwaves) which would modify exposure to mosquitoes and risk of infection,[29,97,100] and storing water in response to drought conditions which would increase availability of larval habitats[42,43,64,99] and may counteract dengue suppression activities.[64] Vector control measures were reported in the aftermath of floods in the Solomon Islands,[78] of Typhoon Haiyan in the Philippines,[96] and of Hurricane Georges in Puerto Rico.[100]

Rural and urban differences in extreme climate and outbreak risk were noted in three studies.[42,73,98] The risk associated with extremely wet conditions was high in rural areas of Brazil[42] and Kenya.[98] Nosrat et al. postulated that rural areas may absorb excessive rainfall until more stable pools of water are formed, which would favor mosquito breeding.[98] Wet conditions in high population density townships in Taiwan were associated with increased dengue risk.[73] The risk associated with extreme drought was exacerbated in highly urbanized areas in Brazil, possibly linked with gradual changes in water storage practices.[42]

IDENTIFIED PATTERNS AND KNOWLEDGE GAPS

This scoping review builds on previous peer-reviewed studies that focus on the associations between climatic extremes and CSID outbreak risk.[61,62,64,72,95,101,102] We offer further insight on (1) the potential hydrometeorological and climatic triggers of outbreaks and (2) the state of knowledge on how extreme climate events interact with underlying exposure and vulnerability factors. We found higher evidence and higher agreement on the links between extreme climate events and water-borne diseases (cholera and diarrheal diseases) than for vector-borne diseases (malaria and dengue). In addition, we found a substantial lack of evidence on the links between extreme climate events and underlying vulnerability and disease outbreaks.

Increasing climate variability due to climate change will likely influence the timing, frequency, intensity, and location of extreme climate events.[1] Infectious disease transmission and risk depends on complex interactions between the intrinsic disease ecology, environmental and climatic factors, sanitation and water systems, human behavior, population health status, access to health care, and social and economic policies and decisions. There is a growing body of literature on the links between El Niño Southern Oscillation (ENSO)—an interannual climatic phenomena in the Pacific Ocean that affects weather globally and can result in anomalous warm El Niño and cooler La Niña episodes and is associated with an increased intensity of extreme climate events—and CSID outbreaks.[107–109] ENSO events can drive dramatic interannual variation in rainfall, affecting a huge range of systems (e.g., freshwater availability, agricultural productivity, habitat ecology) with implications for public health. When the interacting components of systems are destabilized by extreme climate events (driven by ENSO or anthropogenic climate change in general), the resulting disruptions in healthcare, water supply, or sanitation systems, inability to use protective measures such as bed nets, and crowding due to displacement, can favor disease transmission and increase the risk of potentially devastating outbreaks.[110] Therefore, it is important to identify the potential patterns in climatic *drivers* of outbreaks and the *consequences* of extreme climate events in order to help inform the range of public health actions that will be the most effective in a given setting in either preventing potential outbreaks (ideally) or minimizing the impact by taking appropriate and timely action.

In this review we identified several potential climatic drivers for the different CSIDs that could be used to help direct further in-depth investigation (see Figure 3). Extremely heavy, extended rainfall usually resulting in flooding was identified with high agreement as a common driver in outbreaks of cholera, diarrheal diseases, malaria, and dengue in the reviewed studies. Heavy rainfall and subsequent flooding exacerbate disease risk factors through the destabilization, damage or destruction to the natural and built environment, the displacement of people, and the disruption of critical services (water, sanitation, healthcare). While heavy rainfall and flooding emerged as patterns in this review, previous reviews have cautioned that disease transmission risk is likely to be highly context and flood-event specific.[111,112] There was high agreement that high temperatures were linked with diarrheal diseases and dengue. A previous systematic review found that when temperatures increase, the risk of infectious diarrheal diseases increases.[113] Temperature is also known to influence mosquito survival, host-seeking and feeding behavior, and arboviral replication, with optimal transmission temperatures for dengue virus ranging between 26°C and 29°C.[114,115] The effect of heatwaves on dengue depends on how hot the temperatures reached and the duration of the heatwave.[114] Heatwaves that exceed the optimal transmission temperatures can result in a reduction in dengue viral transmission. Our findings also reveal that it is important to consider the effects of sequential extreme climatic events as risk modifiers for outbreak risk. For instance, there was high to medium agreement that excessive rainfall following a period of abnormally low rainfall or drought was important for outbreaks of cholera, diarrheal diseases, and dengue.[30,31,33–35,42,43,52,67] The design of early warning systems, therefore, needs to consider not only one type of extreme event but ideally the compound effects of interacting and successive extreme climate events.

Geographic representation

There was an under-representation of certain contexts that are highly exposed to extreme climate events. Of the 90 papers retrieved, only 26 different countries were studied. Countries included, such as Mozambique, Puerto Rico, Haiti, and India, frequently rank as highly prone to extreme climate events,[116] as do countries such as the Philippines and Bangladesh. Yet, numerous other countries that are highly vulnerable to climate change (according to the ND-Gain Index and INFORM Severity Index) and report numerous outbreaks, such as the Democratic Republic of the Congo, South Sudan, Nigeria, and Angola,[117] were not represented. Overall, the research effort (the number of papers) was not aligned with the need (in terms of outbreak frequency, exposure to the impacts of climate change and extreme climate events, and population vulnerability of countries). The under-representation of certain geographies has been highlighted as a major knowledge gap in previous studies focused specifically on heatwaves[118] and water-borne diseases.[67] Overcoming this will be important in gaining a better understanding of the complex—and often context-specific—interactions between extreme climate events, outbreaks, and other social and environmental factors.

Types of extreme climate events

There were relatively fewer studies on droughts and heatwaves. For droughts, this may be partially explained by the challenges of establishing when they begin and end.[64] Yet this was not the case for studies on heatwaves, which tended to have robust definitions (for example, based on thresholds of 5% or 1% relative to a reference period lasting for 2 to 3 consecutive days).[29,97] Therefore, it is less evident why there were relatively fewer studies on heatwaves. Instead, it may be challenging to link short- and long-term disease data back to these types of events, in which the underlying climate conditions (whether in a subtropical, tropical, arid, semi-arid, or temperate region) are also extremely important when trying to understand the independent estimates of heatwave effects.[29,119]

Water-borne versus vector-borne diseases

We found more research and higher agreement on the linkages between water-borne disease and extreme climate events, compared with vector-borne diseases. This is concerning as both malaria and dengue are diseases of high public health concern, are globally widespread, and their impact costs billions of dollars a year.[120–123] This may be explained by the following reasons. First, vector life cycles are complex. Mosquitoes—the vectors for both dengue and malaria—are highly sensitive to environmental conditions and have species-specific breeding habitat preferences, climate-mediated mosquito-parasite interactions, and climate tolerances.[114,124] Climate extremes tend to have non-linear impacts and cascading consequences on socio-ecological systems,[125] which makes researching the links at the correct timescale between vector-borne diseases and extreme climate events challenging. Here, we found that there were relatively fewer studies on malaria and there was lower agreement between studies. This may in part be attributable to the substantial number of *Anopheles* species involved in transmitting malaria, each of which has its own particular species traits, including their survival and adaptation strategies in response to extreme climate. The lack of studies linking extreme climate events to malaria outbreaks may also be explained by the presence of interventions. Vector control measures, such as insecticide spraying and the use of bed nets, may mask the

Exposure 'extreme weather'	Outcome 'climate sensitive infectious disease'
Drought Flood* Cyclon* Typhoon* Hurricane* "natural disaster*" Heatwave "extreme heat" "cyclonic storm*"	Dengue Choler* Diarrhea* diarrhoea* malaria* typhoid*

Figure 4. Search terms used to search PubMed, EMBASE, and Medline related to extreme climate events and CSIDs

impact of climate events on outbreaks, making it challenging to disentangle the impact of multiple factors.

Second, there are challenges in setting thresholds for what constitutes a malaria or dengue outbreak, which are likely to be highly context specific. For instance, there will likely be higher and more prolonged seasonal peaks in high transmission contexts and outbreaks are more likely in low transmission contexts.[126] An outbreak of cholera, on the other hand, is widely agreed as being one confirmed case.[127] Specific outbreak definitions were not provided in the malaria studies, and a wide range of thresholds (e.g., +2 standard deviations from seasonal mean, upper quartile of the distribution) were used in the dengue studies.[43,97] Previous studies that used a variety of outbreak thresholds when developing disease prediction models have highlighted the importance of researchers and decision makers working collaboratively to agree on definitions of outbreak thresholds so that model predictions are useful for planning and aligned to the capacity of the public health system to respond to alarm trigger thresholds indicating an imminent outbreak.[43,128]

Interactions with underlying vulnerability and exposure factors

There was very limited scientific evidence on how extreme climate events interacted with underlying vulnerability and exposure factors, beyond suboptimal water and sanitation conditions. In the studies identified there was limited in-depth investigation of how other factors (population demographics, displacement, migration, underlying health status, disruption to health services, and behaviors) modify relationships between extreme climate and outbreaks. One study in Mozambique reported that recent experience with Cyclone Idai and a cholera epidemic improved the early action and response in the event of a subsequent cyclone.[57] Previous experience (of a major outbreak or disaster) can in some cases improve resilience and disaster preparedness.[129] A significant knowledge gap was how extreme climate events, especially long-term droughts or extended heatwaves, affected ecological systems (changing species composition and organization, proximity of humans and animals, agriculture productivity) and how this impacts outbreak risk. As most of the studies focused on one singular event, there was limited information on how recurrent extreme climate events may increase vulnerability and compound outbreak risk.[130]

Limitations

Despite providing an important and timely review of the evidence linking climate events to infectious disease outbreaks, this scoping review has several limitations. First, the existing data available on outbreaks and caseloads are underestimates of the true global burden. The findings of this scoping review are not fully representative of the interconnections between extreme climate events and outbreaks. Public health systems often collapse during and following extreme climate events, making surveillance even harder if strong surveillance systems (including active community-based surveillance) are not already in place, further reducing the estimates of caseloads or likelihood of identifying and recording an outbreak. Second, information from non-English publications and gray literature was not included. However, fewer than 20 studies were excluded for language reasons and this review specifically targeted peer-reviewed publications to assess the extent of scientific evidence. Rich information held in gray literature could be exploited for future studies to bring together data from across diseases and geographies to identify consistent or predictable drivers to inform early warning. Third, most studies reported on positive associations between extreme climate events and outbreaks, with fewer studies reporting negative effects (n = 8). This is strongly suggestive that bias toward publishing non-zero effects is impacting the evidence base. Most studies were retrospective, conducted following a disaster when knowledge of the outbreak existed. In any study of a real-world event, the inherent lack of a counterfactual makes unpicking the drivers and factors that lead to an outcome a challenge. Fourth, many of the studies provided a reference group (e.g., caseloads in pre-event years) but rarely investigated other dynamic contextual factors (e.g., human behavior, or the influence of socioeconomic factors, or other factors impacting disease dynamics, such as high or low levels of population immunity from prior outbreaks) that could have confounded results. These are challenging variables to include, and appropriate data are often lacking.

RECOMMENDATIONS AND OUTLOOK

Based on the knowledge gaps identified in the review, we formulated several key recommendations. First, future studies should focus on low- and middle-income countries in which the impacts of climate change are going to be felt the hardest and where the underlying vulnerability in health systems is the highest. Improved geographic representation of studies, based on vulnerability criteria (e.g., vulnerability to climate change, burden of infectious disease outbreaks), will help to build the evidence base on climate-disease dynamics that can then be leveraged to reduce the health equity gap. Second, further research should focus on understanding the causal chain between climate change, extreme climate events, and disease outbreaks, for both water-borne and vector-borne diseases. For vector-borne diseases specifically, there is a clear need for more integrated research that embraces the complexity inherent in different vector-borne disease systems

Agreement ↑

High agreement (100% studies reporting the same finding) **Low evidence** (2 studies)	**High agreement** (100% studies reporting the same finding) **Medium evidence** (3–4 studies)	**High agreement** (100% studies reporting the same finding) **High evidence** (5+ studies)
Medium agreement is not possible with only 2 studies	**Medium agreement** (>50% but <100% of studies reporting same finding) **Medium evidence** (3–4 studies)	**Medium agreement** (>50% but <100% of studies reporting same finding) **High evidence** (5+ studies)
Low agreement (equal number of studies report different findings) **Low evidence** (2 studies)	**Low agreement** equal number of studies report different findings) **Medium evidence** (3–4 studies)	**Low agreement** equal number of studies report different findings) **High evidence** (5+ studies)
No agreement qualifier given **Low evidence** (1 study)		

Evidence (amount) →

Figure 5. Categorization for the assessment of confidence given in terms of the degree of agreement between identified studies and the amount of evidence (studies) available

Green indicates high agreement between studies. Orange indicates medium agreement between studies. Blue indicates a low agreement between the studies. The transparency of the color indicates the amount of evidence: the more transparent the color the lower the amount of evidence (number of studies). Light gray indicates there was only one study and therefore an agreement qualifier is not provided.

and their specific responses to extreme climate—not only climate variation—across different landscapes. Third, there is need to improve how data on extreme climate events are integrated with disease incidence data, including improved matching of time-scales to identify outbreaks risk in the short (<1 week), medium (1–2 months), and long term (<6 months). Overall, there is a need to significantly improve health information systems in all countries such that they can integrate ecological determinants of health and meteorological data on a timescale that is useful for health decision making. Finally, reporting guidelines should be developed for future studies, which would ensure consistent use of reference/comparison group, clear definitions of extreme climate events and outbreak thresholds, case definitions, quantification of lag periods (this is supported in the recommendations of previous studies[61,67,95]), and underlying vulnerability should be considered.

This review aims to incentivize further research on the key trends and associations between extreme climate events and CSID outbreaks. An understanding of these linkages provides the cornerstones for early warning systems, and is the foundation for the design of operational protocols for anticipatory action. This scoping study provides important knowledge to help design triggers for programs on anticipatory action, such as the forecast-based financing programs of the Red Cross Red Crescent Movement.[131] These programs rely on an Early Action Protocol with a pre-defined trigger (e.g., a certain windspeed or threshold of rainfall), which when reached activates the mobilization of emergency funds for activities aimed at reducing impacts (including negative health outcomes) ahead of the extreme climate event. Findings of this study highlight the importance of considering the temporal dynamics of the extreme event when designing triggers. For instance, the abrupt nature of heavy rainfall, the sequence of a dry period followed by heavy rains, or the duration of heatwaves and floodwaters. The role of extreme climate events in driving CSID outbreaks is highly dependent on the intensity and type of event (flooding, drought, rainfall, heatwave, etc.), the time lag under consideration (immediate aftermath or long-term consequences), and the disease itself. As forecasting of extreme climate events improves in tandem with the predictive ability of disease models, knowing which climate drivers are most useful to monitor will become more straightforward.

In summary, this review enhances the knowledge base on the connection between extreme climate events and climate-sensitive disease outbreak risk and contributes to a number of previous reviews focused on understanding the interconnections between human and planetary health. This review identifies potential hydrometeorological triggers of outbreaks and highlights gaps in knowledge on the causal chain between extreme climate events and disease outbreaks, which can help inform the growing field of anticipatory action and direct future research efforts.

EXPERIMENTAL PROCEDURES

Resource availability

Further information and requests for resources should be directed to lead author, Tilly Alcayna (tilly.alcayna@lshtm.ac.uk).

Materials availability

This study does not report any new materials.

Data and code availability

An excel table of extracted data from the scoping review is available at https://doi.org/10.5281/zenodo.6376135. This review analyzed existing, publicly available data. The papers from which these data were extracted can be found

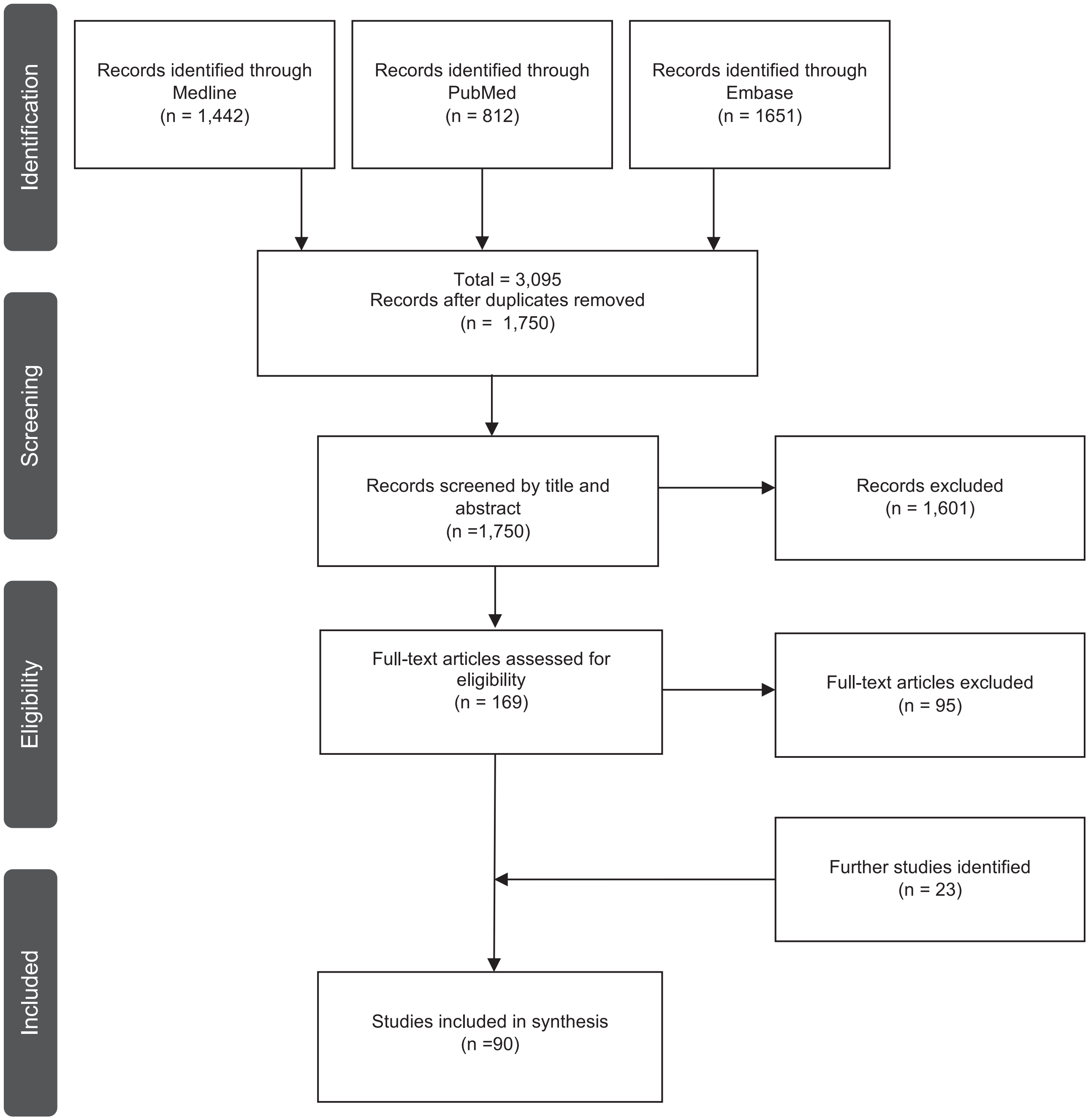

Figure 6. PRISMA-ScR reporting flow chart.

in the reference list and in this provided link. This paper does not report any original code. Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

Search strategy

The PRIMSA-ScR guidelines were followed for this review.[28] Three online databases were searched (PubMed, EMBASE, and Medline) using relevant terms to the exposure "extreme climatic events" and outcome "climate-sensitive infectious diseases" (see Figure 4). The search was completed across November to December 2021. Results were combined and stored using Endnote; duplicates were removed via software and checked manually. Titles and abstracts were screened and irrelevant articles removed. Reference lists were also investigated to identify further studies that had not been identified in the original search strategy. Two reviewers (T.A. and I.F.) screened full texts independently and disagreements were resolved by consensus.

Inclusion and exclusion criteria

The following inclusion criteria were applied: articles must be peer-reviewed, published in English, and investigate the climate-sensitive infectious disease outcomes of an extreme climatic event (drought, flood, heavy rainfall, tropical cyclone, heatwave). Target CSIDs were diarrheal diseases, cholera, typhoid, malaria, and dengue. They were selected as they either featured in the top 3 diseases in terms of estimated burden globally, estimated annual deaths globally, or DALYs. The top 3 estimated burden globally were: diarrheal diseases, dengue, and malaria. The top three diseases in terms of estimated annual deaths were diarrheal disease, malaria, and typhoid; however, as cholera deaths are likely a huge underestimation it was also included. The top three diseases for estimated DALYs were diarrheal diseases, malaria, and typhoid. Review articles were included. There was no limit on publication date or geographic location. Articles were excluded if they did not have an extreme climate-related exposure (e.g., investigated seasonal weather patterns, or monthly anomalies that were not extreme) or if they investigated linkages between extreme climate events and other risk components, such as an increase/decrease in mosquito populations, and did not report on human health outcomes. Conference abstracts, protocols, books or book reviews, studies for which full text articles are not available were also excluded.

Data analysis

Data were extracted for the following variables: title, first author, year of publication, institution in which first author was based, country of the author's institution, country/region studied, extreme climate event, extreme climate event name (tropical cyclones are often named, e.g., Typhoon Haiyan), the index used to measure climate anomaly, extreme climate event definition, text description of extreme climate event, disease, outbreak definition, time period of the study, data source, baseline/reference period, study design, statistics, outcome, outcome quantification, outbreak risk, qualitative description of extreme climate event and outbreak risk, time lag. Outcome was defined as either disease cases or incidence. Thematic findings on vulnerability factors related to socioeconomic status, water and sanitation supply and infrastructure, altered human behavior, altered ecology, land-use, non-water and sanitation infrastructural damage, displacement, anticipatory action, and early response.

To qualitatively develop the key findings, an assessment of confidence in the findings was given in terms of the degree of agreement between identified studies and the amount of evidence (studies) available (IPCC Guidance Note on Uncertainty Language) (see Figure 5). The degree of agreement was categorized as follows: high agreement for all studies (100%) reporting the same finding, medium agreement for >50 to <100% of studies reporting the same finding, low agreement for 50% reporting the same finding. If there were only two studies for a given extreme climate event and climate-sensitive infectious disease (e.g., heavy rainfall and dengue) and they reporting conflicting findings, they were categorized as low agreement. If there was only one study an agreement qualifier was not given. The amount of evidence was categorized as follows: less than three studies (low evidence), three to four studies (medium evidence), five or more studies (high evidence).

Results of PRISMA-scoping review

A total of 90 published articles met the inclusion criteria (see Figure 6). Sixteen of these were review articles (i.e., systematic, scoping, or literature) reporting general linkages between extreme climate events and CSIDs. These were retained for qualitative analysis but were not included in the main quantitative analysis as separating the specific extreme climate-disease dynamics was not straightforward. The remaining 74 papers reported on either single extreme climate-disease outbreak events or multiple extreme climate events and single or multiple diseases outbreaks with clearly separated results and specific findings on the extreme climate-disease dynamics. These were split into specific extreme climate-disease outbreak events (e.g., heavy rainfall-cholera), resulting in 90 different events for analysis of specific trends and research gaps (see Figure 2 and supplemental material).

Most papers (92%, n = 68/74 papers) were retrospective and mainly involved observational studies (case-control, case-crossover, cross-sectional, cohort studies, and interrupted time-series, as well as outbreak investigations). One study reported on near real-time forecasting,[54] one study took advantage of an ongoing randomized control trial study, which was interrupted by an extreme climate event,[49] and four others were prospective studies.[32–34,36] Discounting the review papers, just over half of papers were descriptive only. All were published since 2000, bar one paper from the Centers for Disease Control and Prevention published in 1983.

Explicit reporting on baseline or comparative groups was only provided in 43% (n = 32/74) extreme climate-disease outbreak events, after excluding review papers. When a comparator (sometimes referred to as a "reference period") or baseline was given it was typically either: (1) cases from a similar period in the year(s) directly preceding/flanking the year of the extreme climate event in which normal weather patterns were observed (i.e., a "non extreme climate event period"); (2) a change from average in a longitudinal disease dataset; or (3) caseloads from a neighboring communities who did not experience the extreme climate event (i.e., a "non extreme climate event area").

AUTHORS CONTRIBUTIONS

All authors were involved in defining the search strategy. T.A. and I.F. performed the search and screening of articles. T.A. drafted the article with feedback, input, and guidance from I.F., R.G., L.T., S.F., B.R., and R.L. All authors read and approved the final manuscript

DECLARATION OF INTERESTS

The authors declare no competing interests.

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