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REVIEW

The effects of season and meteorology on human mortality in tropical climates: a systematic review

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Research in the field of atmospheric science and epidemiology has long recognized the health effects of seasonal and meteorological conditions. However, little scientific knowledge exists to date about the impacts of atmospheric parameters on human mortality in tropical regions. Working within the scope of this systematic review, this investigation conducted a literature search using different databases; original research articles were chosen according to pre-defined inclusion and exclusion criteria. Both seasonal and meteorological effects were considered. The findings suggest that high amounts of rainfall and increasing temperatures cause a seasonal excess in infectious disease mortality and are therefore relevant in regions and populations in which such diseases are prevalent. On the contrary, moderately low and very high temperatures exercise an adverse effect on cardiorespiratory mortality and shape the mortality pattern in areas and sub-groups in which these diseases are dominant. Atmospheric effects were subject to population-specific factors such as age and socio-economic status and differed between urban and rural areas. The consequences of climate change as well as environmental, epidemiological and social change (e.g., emerging non-communicable diseases, ageing of the population, urbanization) suggest a growing relevance of heat-related excess mortality in tropical regions.

Keywords: Meteorological effects, Mortality, Seasonality, Tropical climates

Introduction

The projected consequences of climate change established in recent years have resulted in heightened interest in the effects of atmospheric conditions on human health. To date, the majority of research has focused on industrialized regions of the mid-latitudes (e.g., Europe, North America or Japan). Generally, studies investigating atmospheric effects can be separated into two groups: those assessing seasonal effects (mid- to long-term effects ranging from several weeks to several months) and those assessing the effects of meteorological parameters such as temperature, humidity and precipitation (short- to mid-term effects ranging from a few days to several weeks). Although atmospheric effects are not directly assessed in a seasonality analysis, seasonal mortality variations are primarily thought to be caused by varying meteorological conditions.

Recent studies conducted in temperate climates have revealed higher mortality rates in winter as compared to summer and demonstrated ‘U’ or ‘;V-shaped temperature-mortality curves with increased mortality at both low and high values.[1–3] The exact shape of the seasonal distribution and the magnitude of meteorological effects has shown to be modified by non-atmospheric influences, such as disease prevalence, age structure, cultural and behavioral aspects or socio-economic conditions, resulting in various patterns and dose-response relationships within the same climatic region.[3–7] Nonetheless, geographic region and latitude play a crucial role; Douglas and Rowels[8] demonstrated peak seasonal amplitudes in mid-latitude regions with declining levels towards the equator and the poles. Lastly, seasonality also seems to vary with time and has changed over the period of decades or centuries.[3,9]

Given the dynamic and complex nature of seasonal and meteorological effects on mortality, comprehensive analyses are necessary to design target-oriented health interventions most efficiently. Understanding the relationship between seasonality, meteorology and mortality is particularly important when seeking to control and mitigate the impact of the projected consequences of global warming. Within the scope of this systematic review, we aim at identifying relevant research studies on seasonal and meteorological effects in the tropics, extracting and synthesizing respective information thus elucidating cause and effect chains. A major focus is given to the modifying influence of non-atmospheric conditions, vulnerable subgroups and temporal dynamics allowing an appraisal of future trends and developments.

Methodology

Inclusion and exclusion criteria

A literature search was conducted using the PubMed and BIOSIS databases as well as Web of Science. For the database query, we combined the keyword 'mortality' or 'death' (which needed to be included in the title) with the following terms: 'temperature', 'weather', 'climate', 'cold', 'heat', 'meteorological', 'meteorology', 'atmospheric', 'atmosphere', 'season', 'seasonal' or 'seasonality'. We limited our search to articles written in English, Spanish and French and those relevant to the human species. In the BIOSIS and Web of Science literature search we limited findings to the category 'Public Environmental Occupational Health'. We selected all original research papers dealing with seasonality or meteorological effects on mortality in the tropics. Eco-epidemiological studies based on (sample) vital registration systems or based on hospital statistics were included. Case studies and laboratory results were not included; neither were studies investigating morbidity or studies focusing exclusively on accidental or maternity-related deaths. We considered studies that featured descriptive analyses, time-series analyses, regression modeling, or case-crossover approaches. We did not limit our inclusion criteria to any particular effect (e.g., solely heat effects or a particular time frame); rather, we compiled all research conducted in the regions of interest. The database search conducted in January 2014 returned 4224 hits, of which 98 were selected on the basis of their title and abstract. We excluded 33 articles after the screening of the full text, thus obtaining 65 articles that met the search criteria: 33 studies related to seasonal effects on mortality, 24 to meteorological effects, and eight studies which assessed both (see Figure 1).

Defining and characterizing tropical climates

For the purpose of this review, tropical regions were established on a solar definition, selecting all regions situated between the 23.5° northern and southern latitudes. We also classified regions by a so-called effective climate classification to account for effective climatic conditions. Of all the available methods, perhaps the most commonly used is the Köppen–Geiger classification, which also has recently been applied to climate model predictions[10,11] and is likely to be used in future simulations and models.[12] Köppen[13] constructed five zones based on thermal criteria: between 23.5° north and 23.5° south, the climate types 'A', 'B' and 'C' can be found. The sub-classification (indexed by second and subscript letter) of these zones is based on additional thermal criteria and hydrological factors.[13,14] Type 'A' climates can be considered as classical tropical climates with constantly elevated temperatures and high amounts of precipitation. In close proximity to the equator, type 'A' climates are usually fully humid (A_f). Precipitation decreases when moving north and south towards the 23.5° latitudes, and a type of dry season emerges as regions feel the effect of the subtropical high pressure system (A_w).

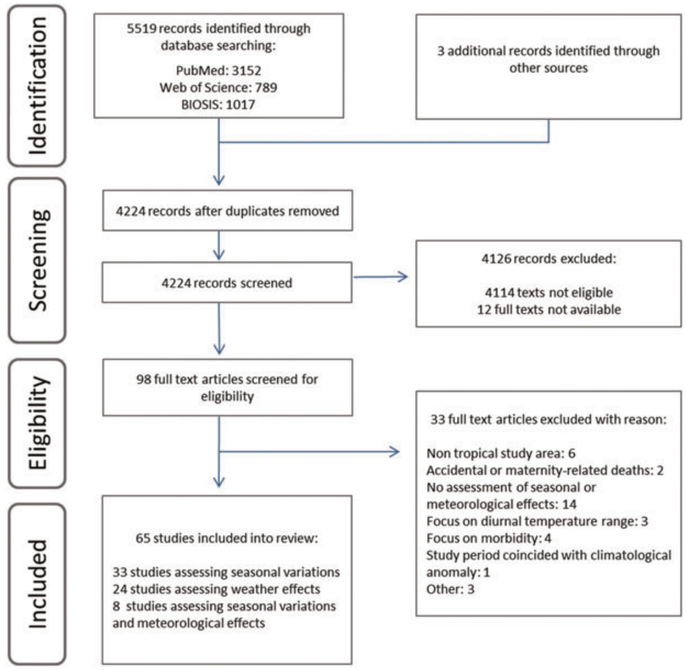

Figure 1. Schematic illustration of the literature search and inclusion/exclusion steps.

Climates become increasingly dryer with the growing influence of this high pressure system, marking the crossover from type 'A' to type 'B' climates (arid climates). In addition to these latitude-dependent climate variations, elevation plays a crucial role. Regions situated at higher altitudes exhibit lower temperatures and are therefore usually classified as having warm temperate type 'C' climate. Furthermore, in geographical regions where the subtropical high pressure system is not well developed 'C' climates follow directly after 'A' climates in poleward direction (see Table 1).

Results

Studies of seasonal effects on mortality

In total, 41 studies investigated seasonal variations in mortality. The regions investigated comprised countries in Africa, Latin America, and Asia. An overview of the spatial distribution of the areas studied is given in Figure 2. The research approaches ranged from descriptions of (monthly) death counts and mortality rates to more sophisticated methodologies such as time series and regression analysis. Several studies stratified samples by cause of death, age, sex or socio-economic status (Table 2 summarizing the results of these 41 studies can be viewed as part of the full-length text).

All-cause and cause-specific seasonality

The vast majority of studies showed a strong association between rainfall and increased mortality. Peaks during the rainy season and at the beginning or end of the rainy season were observed for various regions and climate regimes reaching from type A to type C climates.[15–45] Nevertheless, in several study areas and sub-

Table 1. Köppen-Geiger climate types and classification criteria

Climate Type	Description	Criterion
A	Equatorial climates	$T_{min} \geq +18°C$
A_f	Equatorial rainforest, fully humid	$P_{min} \geq 60$ mm
A_m	Equatorial monsoon	$P_{ann} \geq 25(100 - P_{min})$
A_s	Equatorial savannah with dry summer	$P_{smin} < 60$ mm
A_w	Equatorial savannah with dry winter	$P_{wmin} < 60$ mm
B	Arid climates	$P_{ann} < 10\ P_{th}$
B_S	Steppe climate	$P_{ann} > 5\ P_{th}$
B_W	Desert climate	$P_{ann} \leq 5\ P_{th}$
C	Warm temperate climates	$-3°C < T_{min} < +18°C$
C_s	Warm temperate climate with dry summer	$P_{smin} < P_{wmin}$, $P_{wmax} > 3\ P_{smin}$ and $P_{smin} < 40$ mm
C_w	Warm temperate climate with dry winter	$P_{wmin} < P_{smin}$ and $P_{smax} > 10\ P_{wmin}$
C_f	Warm temperate climate, fully humid neither C_s nor C_w	
D	Snow climates	$T_{min} \leq -3°C$
D_s	Snow climate with dry summer	$P_{smin} < P_{wmin}$, $P_{wmax} > 3\ P_{smin}$ and $P_{smin} < 40$ mm
D_w	Snow climate with dry winter	$P_{wmin} < P_{smin}$ and $P_{smax} > 10\ P_{wmin}$
D_f	Snow climate, fully humid neither D_s nor D_w	
E	Polar climates	$T_{max} < +10°C$
E_T	Tundra climate	$0°C \leq T_{max} < +10°C$
E_F	Frost climate	$T_{max} < 0°C$

P_{ann}: accumulated annual precipitation.
P_{min}: precipitation of the driest month.
P_{smin}, P_{smax}, P_{wmin} and P_{wmax}: lowest and highest monthly precipitation values for the summer and winter half-years on the hemisphere considered.
P_{th}: dryness threshold derived from complex calculation based on temperature and precipitation.
T_{max} and T_{min}: monthly mean temperatures of the warmest and coldest months.

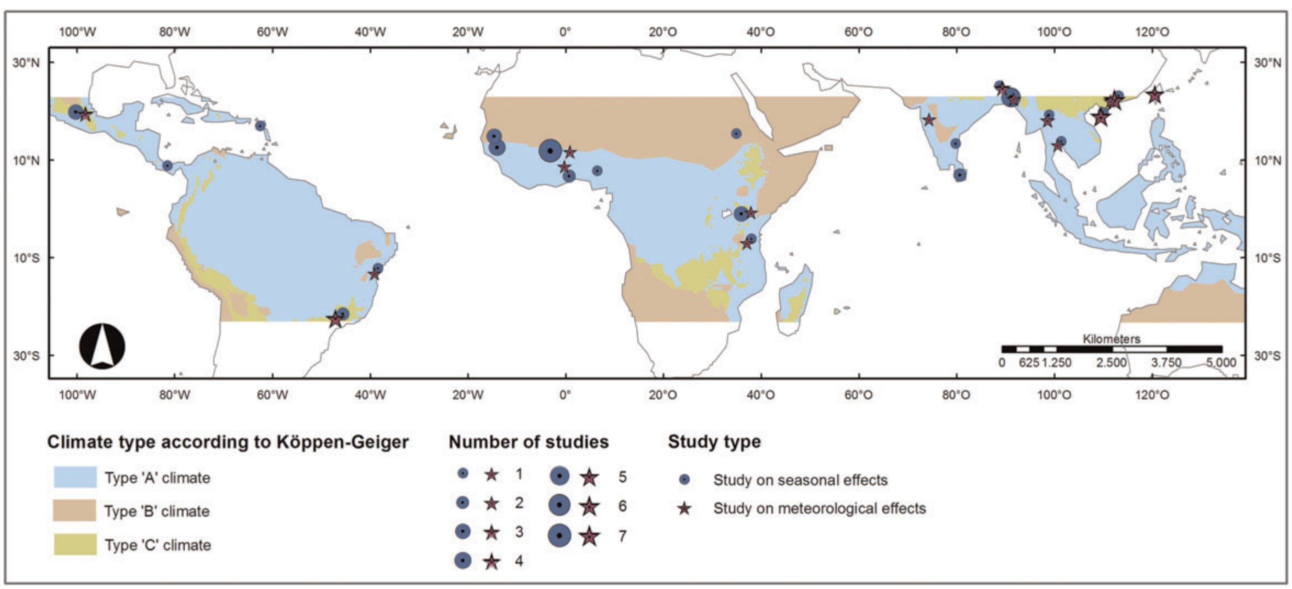

Figure 2. The spatial distribution of studies conducted in the tropics between the 23.5° northern and southern latitudes (shaded area). Data source: Kottek et al.[12]

groups, or for specific causes of death, mortality increased during the dry season. Burkina Faso exhibited a general peak during the dry and hot summer season.[28,45–47] In Senegal, meningitis deaths peaked in the dry and cold season whereas the incidence of deaths from all other causes peaked in the rainy season.[48] Pison[20] found a peak during the rainy season in Senegal which the author attributed to malaria, and another peak during the dry season which was explained by measles outbreak. Fargues and Nassour[49] found a general peak during the dry season for children in Bamako, Mali. In Matlab, Bangladesh, overall mortality peaked during the cold and dry season, whereas, for several sub-categories, such as for fever, dysentery, diarrhoeal deaths, accidents, and tetanus, peaks during the warm and rainy season were observed.[35,36,38] In a nationwide study in Bangladesh, bi- and multimodal distribution were presented for all-cause and cause-specific mortality with a general primary maximum during the cold and dry winter season but evolving secondary summer maxima were observed for several subgroups.[39] In Mexico, peaks in diarrhoeal deaths were associated with both the rainy and the cold and dry season.[15,44] An increase in all-cause and cause-specific mortality during the cold and dry season was observed in Mexico, Brazil, Thailand and China.[50–53]

Age effects and vulnerable subgroups

Age was found to be a determining factor for the shape and the magnitude of seasonal variations.[21,28,30,32,35,36,39,40,44,45] Generally, children and the elderly were more affected by seasonal effects compared to other age groups.[21,39,40,44,46,51,52] Besides, seasonality regimes varied with age groups showing a temporal displacement in the occurrence of maximum and minimum mortality. While a peak in the dry and hot season was observed in Burkina Faso for adults and the elderly,[28,32,45–47,54] a peak at the end of the rainy season was presented by the figures for infants and children.[28,29,32,45] Interestingly, in Burkina Faso, malaria mortality among the elderly peaked during the dry season, although overall malaria mortality generally peaked in the rainy season.[28] Similarly, in Tanzania mortality was associated with the rainy season for children, while a peak was observed during the cold and dry season for youths, adults and the elderly.[30,31] In Bangladesh, mortality mostly peaked during the cold season, however, neonatal and child mortality peaked during summer and the monsoon season.[35–37] Only a few studies assessed the modifications of seasonal or meteorological effects on mortality arising from socio-economic conditions. Muhuri[37] found decreased seasonal variations in a treatment area, in which health interventions were undertaken, compared to a reference area. Moreover, the author found an increased risk in mortality, particularly diarrhoeal mortality, in cases in which the mother had no education. Similarly, Ou et al.[51] found increased winter excess mortality in those with low education. In Bangladesh, summer-related excess mortality was especially observed for urban areas and areas with a high socioeconomic status (SES).[39] The analysis of gender differences yielded conflicting outcomes. While some studies did not observe varying seasonality between sexes,[21,52] Ou et al.[51] found increased winter excess mortality in females in Guangzhou, China whereas in another study conducted in São Paulo it seemed that males were more vulnerable to myocardial infarction in winter.[53]

Temporal changes

Only a few studies analyzed long-term changes in seasonality patterns, with inconsistent outcomes. Decreased seasonality was observed in Gambia after 1985.[21] Similarly, a time series analysis conducted in Costa Rica between 1851 and 1921 showed that mortality had become less seasonal in the later period of analysis (1892–1921).[42] In Senegal, decreasing seasonality was observed in the 1980s compared with the 1960s. However seasonal fluctuations increased in the 1990s.[17] In Bangladesh, the seasonality of neonatal mortality and injury-related deaths declined, but remained pronounced for all other causes of death despite a general decline in mortality between the 1970s and the 1980s.[35,36] Whilst neonatal mortality peaked in the monsoon seasons of 1972–1974, in the 1982–1990 period, it peaked at the beginning of the cold season.[35,36] In Mexico, a shift from summer (in the eighties) to autumn and winter peaks (in the nineties) was observed for diarrhoeal deaths.[15,44]

Studies of meteorological effects on mortality

Thirty-two studies assessed meteorological effects on mortality focusing on Latin America, sub-Saharan Africa and Asia (see Figure 2). Whilst the majority focused on temperature, some studies assessed the influence of rainfall, humidity, wind, solar radiation or diurnal temperature range. Within this review we considered the effects of thermal conditions and precipitation, but did not include other meteorological effects as studies were too few (Table 3 summarizing the results of these studies can be viewed as part of the full-length text).

Thermal effects on all-cause and cause-specific mortality

Temperature exhibited a determining effect on human mortality in the studies reviewed. Generally, the studies presented linear as well as 'U' or 'V'- shaped temperature-mortality curves, with increasing mortality levels at low and high values (Table 3 summarizing the results of these studies can be viewed as part of the full-length text).[22,23,30,32,41,50,55–69] In some regions, such as Mexico and Brazil cold effects outweighed heat effects; this was observed for all-cause as well as cardio-respiratory and other cause mortality.[50,56,59,60] Nonetheless, heat effects above a specific threshold could be found in the majority of study locations.[41,50,55–60,62–66,68,70–76] Studies conducted in sub-Saharan Africa demonstrated a dominance of heat effects. Heat-related mortality was observed in Burkina Faso,[32] Ghana[22] and Kenya[23] while cold-related mortality was not significant. Using monthly average temperature as predictor, a study analyzing temperature effects in a rural area of Tanzania observed an increase in mortality with decreasing temperature, whereas heat effects were not found.[30] In Matlab, a rural area of Bangladesh, Hashizume et al.[57] observed heat- and cold-related mortality with a steep increase above an estimated threshold. Infectious disease mortality increased over the whole range of the temperature distribution.[57] In two other studies from Bangladesh no, or only moderate, heat effects were observed above the 75th temperature percentile while cold effects were comparable with those observed in other studies.[41,61] Two other studies, relying on nationwide data highlighted the existence of very pronounced heat-related mortality for some subgroups.[58,72]

In a study conducted in India, severe heat and cold effects were observed.[65] Similarly, Thailand exhibited cold and heat effects[50,64]; while in Bangkok heat effects were slightly more evolved than cold effects, cold effects clearly dominated in the Northern city of Chiang Mai.[50] Altogether, 15 studies analyzed thermal effects in East Asia (Mainland China, Taiwan and Hong Kong). The effects of temperature[51,52,55,62,63,66,68,69,73–75,77] and heat and cold waves[67,76,78] were the subjects of investigation. Significant associations between the investigated exposure and mortality were observed, demonstrating heat and cold effects, with effect estimates varying among subgroups.

Age effects and vulnerable sub-groups

A total of 21 studies conducted an age-stratified analysis (Table 3 summarizing the results of these studies can be viewed as part of the full-length text). In general, temperature effects were observed for all ages but were particularly pronounced in young age groups and in the elderly.[22,23,30,32,41,51,56,57,60,64–66,68,70–72,77,78] Children were particularly affected in African countries[22,23,32] and South Asia.[41,57,65] Temperature-related mortality in the elderly was mostly observed in studies conducted in Latin America and China[51,56,60,66,68,70,71,77,78] but also studies analyzing data from Bangladesh[57,72] and Thailand[64] reported an increased risk for the elderly. Particularly, cardio-respiratory mortality was subject to thermal influences in higher age groups.[56,60]

Fourteen studies included in this review assessed meteorological effects by gender with some studies revealing no, or no significant, differences and others demonstrating an increased risk for males or for females.[22,23,32,41,51,61,65,69,70,72,73,76,78] Increased risk for heat-related mortality in males was found in Ghana[22] and in Bangladesh.[41,72] Chan et al.[73] reported particularly strong heat effects in males under the age of 74 years while another study presented increased mortality during the 2005 heat wave in Guangzhou for females.[76] Males were more vulnerable to the effects of cold in studies conducted in Guangzhou, Taishan and Hong Kong (China).[73,78] Nonetheless, another study conducted in Hong Kong found significant cold effects in females while those for males were not significant.[69] Severe cold effects in females were similarly observed in Bangladesh.[61]

Gouveia et al.[56] found little modification of temperature effects due to socio-economic factors at an ecological level. However, Bell et al.[70] identified effect modifications due to socio-economic status, using education at the individual level as an indicator in a case-crossover study but findings were inconsistent. The greatest increase in heat-related mortality in São Paulo was found amongst those with no education, but in Mexico City, the greatest increase was observed amongst those with the highest level of education.[70] In Bangladesh strongest heat effects were observed in those living in high SES areas.[72] Wu et al.[67] observed that susceptible and aborigine population was positively related with mortality after heat and cold wave events, whereas medical resources and urbanization exerted a mitigating effect after cold waves. In Guangzhou, low educational status and working in a blue collar occupation were associated with augmented thermal effects.[51,76] Goggins et al.[62] observed particularly strong heat effects in areas classified as hot and low SES in Hong Kong while Xu et al.[69] demonstrated increased cold-vulnerability for those with a higher body mass index.

Rainfall effects on all-cause and cause-specific mortality

Six studies in sub-Saharan Africa and South Asia investigated the effects of rainfall with partly inconsistent outcomes. In Ghana, Kenya and Tanzania a positive association between rainfall and mortality was observed.[22,23,30] In Bangladesh, broken line relationships were found with a decrease in mortality with increasing precipitation and an increase above a threshold.[41,61] In India, Ingole et al.[65] found a negative association up to a one week lag and a negative association for a longer period.

Discussion

This review revealed a complex pattern of varying seasonal and meteorological influences. Evidently, atmospheric effects were shaped by factors such as location, subpopulation, age, socio-economic status and, in particular, by weather and climate. Patterns of decreasing seasonality over time and patterns of re-emerging seasonality were observed. The causes and drivers affecting and modifying seasonal or meteorology-driven fluctuations can be classified as biomedical, pathogen-specific, or socio-behavioral factors.[2,3] Considering these different drivers and chains of effects, we aimed to explain and interpret the findings of the studies included in this review.

The majority of the seasonality studies reported increased mortality during the rainy season. Infectious diseases and regions and strata with high levels of mortality from infectious diseases exhibited mortality peaks during the rainy season.[17–27,30,31,33,40,42–44,48,79] Sub-populations (e.g., infants and children) suffering from a high burden of infectious diseases exhibited the highest levels of mortality during the rainy season, even if the overall pattern showed a peak during the dry season (e.g. Bangladesh, Burkina Faso).[28,29,32,35–37,45] Similarly, studies conducting regression analysis found an increase in mortality with rising amounts of precipitation in Africa and South Asia, but also protective effects were observed (e.g., in South Asia).[22,23,30,41,61,65] The etiology of infectious diseases is rather complex and a number of explanations have been presented for excess mortality during the rainy season. The most common include approaches involving sanitary conditions and hygiene. High amounts of rainfall usually overstrain water supply and sewage systems and stagnant waters at the beginning or end of the rainy season provide a good breeding ground for several disease agents.[80–83] If the rainy season coincides with the hot season as, for example, in Gambia, Senegal, Kenya, Tanzania, Malawi, Bangladesh or Costa Rica,[17,19,21,23,25,26,30,31,33,35,36,39,42,48,79] elevated temperatures might furthermore enhance the replication and survival of disease agents.[84] Respiratory viruses and influenza infections have been observed mainly during the rainy season in Asian, African and South American countries.[85] Moreover, the rainy season represents a time during which the population spends a considerable period indoors, has its lowest annual level of access to food and faces infrastructural limitations, resulting in poor nutrition and diminished access to health care.

While the mortality peak during the rainy season is explained by pathogen-specific causes, biomedical mechanisms could provide a good explanation for the seasonal patterns exhibiting excess mortality during the dry season.[28,29,35,36,39,45–47,50,54] Such biomedical mechanisms refer to changes in the non-specific immune response characterized by reduced phagocyte activity or inflammatory changes in the airways or bronchoconstriction.[86–89] In addition, increased plasma and blood viscosity, elevated red blood cell counts and increased levels of several proteins are all associated with low and high temperatures. Cold can further lead to vasoconstriction, whereas heat induces vasodilation; both mechanisms can strain the cardiovascular system.[90–95]

In Burkina Faso the strongly pronounced level of excess mortality during the hot and dry season might possibly be due to the very high summer temperatures experienced in this 'B' climate (desert climate). Similarly, high temperatures might explain the summer peak in child mortality in Mali.[49] In Bangladesh, Brazil, Mexico and China the dry season coincides with the cold season, and the excess mortality is likely to be cold-related.[35–39,41,50–53] All four regions experience rather low winter temperatures for tropical regions (Brazil, Mexico and China are classified as temperature type 'C'-climates, Bangladesh is a type 'A' to 'C' transition zone). The relevance of low temperatures has also been highlighted by studies conducting regression analysis on temperature effects.[30,41,50–52,55–63,65–69,73,77,78] Winter or cold-related excess mortality might not necessarily be due to absolute low temperatures but rather a relative drop in temperature. A similar conclusion was drawn by Douglas et al.[96] who analyzed the seasonal patterns in Kuwait. Particularly, cardio-respiratory and non-communicable diseases might be highly sensitive towards temperature drops. Apart from low temperature, comorbidity and severity of illness have been underlined as contributors to winter excess mortality.[97] Nonetheless, some authors have also pointed to pathogen-specific causes associated with the dry and cold season. e.g., shigella bacteria or the rotavirus favour rather moderate temperatures.[82,84,98] Although influenza epidemics have generally been linked to the rainy season in tropical regions, the quite low winter temperatures might be related to influenza mortality as observed in temperate or subtropical regions.[3,85,99] Likewise, the lack of dilution of water systems and the increased contamination of ponds and lakes during times of low rainfall might be associated with the low levels of hygiene and increased spreading of pathogens.[80,82] The protective effects of rainfall have, for example, been observed in Bangladesh and India.[41,61,65] Despite the dominance of cold effects, the majority of the studies under review also demonstrated heat effects[22,23,32,41,50,55–59,62–66,68,70–76] with a few studies showing exclusively heat-related increase in mortality.[22,23,32,50] In some study areas such as Bangladesh, Bangkok (Thailand), Taiwan and Hong Kong (China), heat effects outweighed the effects of cold with regard to temperature increase above a threshold.[57,58,62,66,73] As for cold, biomedical drivers might be crucial for heat effects observed at the upper end of the temperature distribution. Especially strong heat effects were found amongst the elderly, for cardio-respiratory mortality and urban areas.[56–58,64,66,70–72,76] This steep increase beyond a breakpoint underlines the disastrous potential of high temperatures as has, for instance, been observed during heat waves in North America and Europe.[100,101]

From this review, few and conflicting findings on the temporal dynamics of the atmosphere-health relationship have been reported. Patterns of persistent and declining and re-emerging seasonality were observed. Generally, this review indicates that a decrease in infectious disease mortality and a rise in the prevalence in non-communicable diseases might result in a shift from excess mortality associated with rainfall to excess mortality associated with thermal conditions. Considering projections pointing at an ongoing rise in non-communicable disease in developing and tropical countries,[102,103] winter and cold-related excess mortality is likely to become increasingly relevant. Nonetheless, there also seems to be evidence that heat-related mortality will increase as vulnerable sub-groups increase and meteorological conditions change. The increase in global temperatures, the strong urbanization processes in many tropical regions,[104,105] the ageing of the population[106–108] and the increase in cardiovascular diseases[102,103] are possible factors leading to the increasing relevance of heat-related mortality.

Authors' contributions: KB designed the outline, conducted the literature search, reviewed and analyzed the relevant literature, and wrote the manuscripts. MK, AS, SB, AK, and WE contributed to the study design, critically reviewed the manuscript and gave assistance in the whole process. ML assisted in the climatological classification and critically reviewed the manuscript. KB is guarantor of the paper.

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