Exploring the link between climate variability and mortality in Sub-Saharan Africa

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Abstract: High mortality rates in Sub-Saharan Africa (SSA) persist, delaying achievement of the sustainable development goals (SDGs)[1]. We investigated whether climate variability contributed to elevated mortality in rural Kenya, Mali, and Malawi during 2008/2009[2]. We linked high-resolution climate information to nationally representative census data from the Terra Populus data extraction system using multilevel negative binomial models to estimate the association between household-level mortality and climate variability from a long-term climate normal period (1961–1990). Results revealed cold snaps increased mortality in Kenya but reduced mortality in Mali and Malawi. Excessive precipitation and droughts were associated with increased mortality in Kenya and Malawi. Adverse climatic conditions increased mortality in regions with high HIV/AIDS prevalence, but reduced mortality in areas with high malaria prevalence. Programs for reducing climate-related mortality through early warning systems, agricultural extension services, and improved access to health infrastructure will help more fully realise the SDGs of mortality reduction for SSA.

Keywords: climate variability; environment; mortality; Sub-Saharan Africa; SSA; Terra Populus.

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1 Introduction

Mortality reduction constitutes one of the key components of the Sustainable Development Goals (SDGs) (UN DESA[3], 2018), formerly the Millennium Development Goals (MDGs) (UN DESA, 2016). Although good progress has been made to reduce global mortality rates, the goals have not been fully realised (UN DESA, 2018). Particularly, in Sub-Saharan Africa (SSA), mortality rates are still high (UN DESA, 2018). Numerous projects have targeted various causes of high mortality rates in SSA including malnutrition (Lartey, 2008), vector-borne diseases such as malaria (Murray et al., 2012), and sexually transmitted diseases such as HIV/AIDS (Zaba et al., 2013).

However, little attention has been given to climate variability as a potential cause of excess mortality rates in SSA.

Adverse climate impacts include increases in the frequency and severity of phenomena such as heat waves, cold snaps, droughts, floods, and storms (IPCC, 2013; Kirtman et al., 2013). Gradual climate processes, such as desertification and sea-level rise (Church et al., 2013; IPCC, 2013), may undermine farm productivity, income generation, and employment options, leading to livelihood insecurity, malnutrition and increases in morbidity and mortality (Adger et al., 2005). Sudden onset events (e.g., storms, floods, wildfires) more directly impact people through the destruction of houses and crops and may strongly increase the death counts in an affected area (Guha-Sapir et al., 2015; Visser et al., 2014). Poor households in rural areas, in particular, lack the technological means (e.g., irrigation systems) to adapt to such adverse changes (Speranza et al., 2008). In this way, climate-related deaths may add to the already high mortality rates in SSA countries (Brooks et al., 2005).

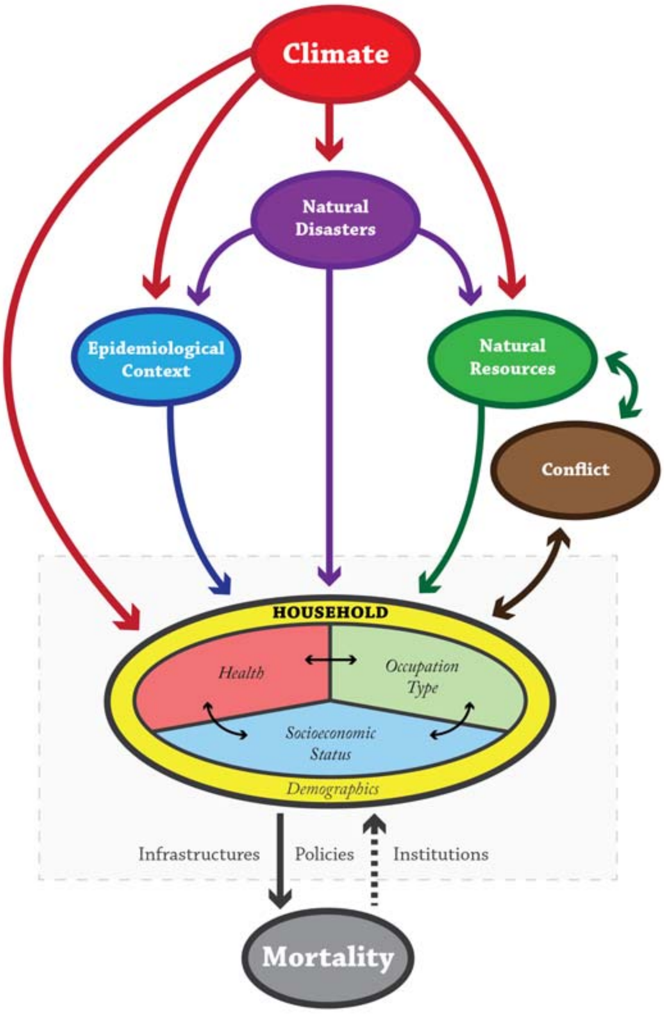
While the impact of climate on mortality has been studied in detail for high- and middle-income nations (Gosling et al., 2009b; McMichael et al., 2008), little is known about this relationship for poor SSA countries (Smith et al., 2014). The few existing studies suffer from a lack of national generalisability (e.g., Diboulo et al., 2012) and are often focused on a single climatic event such as a drought (De Waal, 1989; Ezra and Kiros, 2000; Kidane, 1989). A more thorough investigation of the climate-mortality relationship for SSA is important given existing high levels of mortality (UN DESA, 2018) and projected increases in frequency and magnitude of adverse climate events due to global warming (IPCC, 2013; Seneviratne et al., 2012). Furthermore, based on epidemiological and socioeconomic evidence, the link between climate variability and mortality is complex and manifests through multiple pathways (Patz et al., 2005; Zhou et al., 2004) linking factors within and outside a household, worsening already adverse conditions in SSA countries. Therefore, a thorough investigation of the climate-mortality link in SSA requires a hierarchical modelling structure, analysing data at the household level, while incorporating the impact of factors affecting the link operating both inside and outside the household, which has not been researched before and is the subject of our study.

In this study, we employed a demographic approach and linked high-resolution climate information to nationally representative census data obtained via the novel Terra Populus (TerraPop) data extraction system. Using multilevel negative binomial models, we investigated whether climate variability (heat waves, cold snaps, droughts, and excessive precipitation) from a long-term climate normal period (1961–1990) is associated with increases in household-level all-cause mortality rates. We focused our analysis on rural Kenya, Mali, and Malawi, as poor SSA countries for which no prior research has investigated the climate-mortality relationship. In addition, we examined whether climate effects on mortality are stronger in vulnerable regions characterised by high malaria and HIV/AIDS levels. Our analysis incorporated the multiple factors and pathways inherent in the climate-mortality link through the derivation and application of a climate-mortality framework, discussed in the next section. Our results contribute knowledge regarding the impact of climate on mortality, which will enable policy makers to design effective programs to reduce mortality in SSA in an effort to more fully realise the SDGs.

2 The climate mortality framework

Climate may impact mortality rates through various direct and indirect pathways, including links through natural disasters, access to natural resources, conflicts and the epidemiological context. Climate impacts manifest largely as climate variability, which can be attributed largely to anthropogenic climate change (IPCC, 2013). Our empirical analysis is conceptually grounded in the climate mortality framework (CMF) (Figure 1).

Figure 1 Climate mortality (CM) framework describing various direct and indirect causal pathways connecting climate factors and mortality (see online version for colours)



Note: Stylised representation of the connection between climate and mortality with focus on the most important pathways.

At the core of the CMF framework lies the household (yellow circle) as the social unit most important for livelihoods and well-being in developing countries (Ellis, 2000). The household has a unique demographic composition (e.g., age, gender, marital status) that influences the likelihood of climate-related mortality. For example, a heat-related death is more likely in a household that is largely composed of elderly people (Fouillet et al., 2008). Other household features that may influence the likelihood of a climate-related death include the overall health conditions of the household members, their occupations, and the general socioeconomic status. Household members weakened through acute or chronic diseases are more likely to die under climate stress (McMichael et al., 2006). Similarly, certain occupations differentially expose household members to adverse weather conditions, particularly when employed in manual occupations outdoors (Smith et al., 2014). Socioeconomic status also has a large influence on the vulnerability of households to climate shocks (Haines et al., 2006). For instance, studies show that floods have stronger negative effects on poor compared to richer households (Brouwer et al., 2007). The death of a household member, in turn, will influence the household unit (dotted feedback loop). The loss of the primary breadwinner may increase poverty, impact the demographic composition, employment situation, health, and well-being of other members (Hunter et al., 2007).

Climate may affect the household directly through various health impacts (e.g., heat stroke) (McMichael et al., 2006), or indirectly through natural disasters, natural resource availability, and changes in the epidemiological context. The Intergovernmental Panel on Climate Change (IPCC) predicts that climate change will increase both the frequency and intensity of natural disasters such as floods, cyclones, and extreme temperature events (IPCC, 2013; Seneviratne et al., 2012). Such events directly affect household mortality when members drown in floods, die of heat stroke, or become buried under debris when housing structures collapse in storms (Haines et al., 2006). Such events can also indirectly affect mortality through a spread in disease. For example, diarrheal diseases transmitted through contact with contaminated water sources tend to increase after flood events (Brouwer et al., 2007; Haines et al., 2006).

In rural areas of developing countries, households depend heavily on natural resources (e.g., water, firewood, agricultural outputs) for sustenance and income generation (Davis et al., 2007). When climate change and variability undermines access to natural resources and adversely impacts agricultural productivity (Schlenker and Lobell, 2010), households' livelihoods will degrade with problematic impacts for health and mortality. For example, droughts may damage crops, leading to famines and starvation (Seal and Bailey, 2013). Climate-related food insecurity and under-nutrition constitutes the largest contributor to climate change mortality (Patz et al., 2005). Indirectly, declining access to natural resources may increase risky sexual behaviour as an alternative livelihood strategy, leading to higher rates of HIV/AIDS infection and mortality (Hunter et al., 2011b).

Through changes in the supply of natural resources and disagreement over their allocation, climate change and variability may increase the incidence of violent conflicts (Burke et al., 2009; Hsiang et al., 2013). For example, droughts caused conflicts over disappearing pasture and receding waterholes between farmers and herders in Darfur, Sudan (UNEP, 2007). Armed conflicts and political instability cause injuries and death and often negatively affect health services (Daw et al., 2015).

Moreover, climate has the potential to influence disease transmission by altering the environmental conditions in favour of certain vector populations (Githeko et al., 2000). In the African continent, malaria constitutes the most problematic vector-borne disease, leading to a large number of deaths each year (WHO, 2015). While an increase in temperature may allow the disease to expand to higher altitudes and lengthen the transmission season, drier conditions may depress the spread of malaria (Ermert et al., 2013).

Finally, it is important to recognise that households are located in a region-specific socio-political context (grey box) characterised by infrastructures, policies, and institutions that will influence the likelihood of experiencing a climate-related death (cf., Ramin and McMichael, 2009). For example, early warning systems may help to prepare for heat waves and reduce heat-related excess mortality (Fouillet et al., 2008). Similarly, climate impacts on mortality will be mediated by the availability and access to established health infrastructures (Githeko et al., 2000). We incorporate the climate-mortality framework in our empirical analysis to ensure our results reflect the multiple pathways through which the climate-mortality link operates, particularly for rural households in SSA countries.

3 Prior research on climate and mortality

3.1 Temperature effects

The relationship between temperature and mortality is often described as U- or V-shaped with an increase in mortality below and above a region-specific optimum temperature (Bennett et al., 2014; Honda et al., 2014). This pattern has been confirmed for rural Burkina Faso, with the strongest effects of temperature on mortality for young children (Diboulo et al., 2012). Heat waves, in particular, tend to increase excess mortality (Bambrick et al., 2008; Basu and Samet, 2002; Gosling et al., 2009a), with mortality outcomes strongly dependent on intensity and duration of the temperature extremes (Anderson and Bell, 2009, 2011). Heat related deaths often occur as a result of heat exhaustion and heat stroke (increase in core body temperature over 40.6°C) (Hajat et al., 2010). Similarly, a decline below the optimum temperature is associated with an increase in deaths (McMichael et al., 2008). Cold-temperature related deaths are associated with hypothermia (drop in core body temperature below 35°C), and increases in respiratory and cardiovascular diseases (Ebi and Mills, 2013). Although no study has investigated the effect of cold snaps on mortality for Africa, there is evidence that cold temperatures do increase mortality in warmer regions due to geographically varying levels of acclimatisation (Healy, 2003; Montero et al., 2010; The Eurowinter Group, 1997). Overall, hot temperatures appear to have stronger impacts on mortality than cold temperatures (Kalkstein and Greene, 1997; Yu et al., 2012). Some evidence indicates that heat-related mortality will increase as a result of global warming in future decades (Bennett et al., 2014; Honda et al., 2014), although some of the increase may be offset by a concomitant decline in cold-related mortality (Davis et al., 2004; Ebi and Mills, 2013).

3.2 Precipitation effects

Droughts and floods affect large numbers of people in SSA (Guha-Sapir et al., 2015), and have been associated with increased mortality (Ezra and Kiros, 2000; Fundter et al., 2008). The impact of decreased rainfall and droughts on mortality is indirect and moderated through changes in access to natural resources (e.g., clean drinking water), agricultural productivity, food security, and changes in the epidemiological environment (Benson and Clay, 1998; De Waal, 1989; Mortimore and Adams, 2001). Droughts have been associated with increases in mortality rates in several countries of SSA through these pathways (De Waal, 1989; Ezra and Kiros, 2000; Kidane, 1989; UN, 2011).

While droughts result in negative health outcomes, increases in rainfall and precipitation may also pose health risks. A significant association between an increase in rainfall and mortality was observed for rural Burkina Faso with strongest effects on the elderly (Diboulo et al., 2012). Often adverse effects of an increase in rainfall emerge in response to flood events with longer-term impacts on morbidity and mortality (Alderman et al., 2012; Milojevic et al., 2012). For example, mortality rates have been found to increase by up to 50% in the first year post flood (Bennet, 1970). In addition to drowning (Fundter et al., 2008; Haines et al., 2006), floods often lead to contamination of drinking water, the spread of waterborne diarrheal diseases (Ramin and McMichael, 2009), and vector-borne diseases such as malaria (Ahern et al., 2005). Climate change will increase the frequency and intensity of droughts and rainfall events in the near future (IPCC, 2013) and it is therefore anticipated that associated mortality will increase (Smith et al., 2014).

The risk of climate-related mortality is unevenly distributed among the population, with many similarities in the risk factors for temperature and precipitation events. In general, children and the elderly, those with underlying medical conditions, and the poor are most at risk of temperature-related (Basu and Samet, 2002; Ebi and Mills, 2013) and precipitation-related (Alderman et al., 2012; Ezra and Kiros, 2000) mortality. Rural households that depend on agricultural production and natural resources, with limited access to technological infrastructure (e.g., air-conditioning, irrigation), are most sensitive to environmental impacts (Burney et al., 2013), and will experience the greatest effects of climate impacts on health and mortality (WHO, 2009).

Most studies on the relationship between climate and mortality focus on urban areas of middle- and high-income countries (Gosling et al., 2009a; McMichael et al., 2008; Smith et al., 2014). The limited research that exists for SSA comes from specialised surveys, usually of a few villages (e.g., Diboulo et al., 2012; Kidane, 1989), preventing national generalisations. The measures employed are frequently limited to a single short-term climate event such as a drought (e.g., Ezra and Kiros, 2000). This study is an attempt to improve on some of these shortcomings with the following objectives in mind:

1 investigate the climate-mortality relationship for rural areas in Kenya, Mali and Malawi, as SSA countries for which no prior research exists

2 employ a demographic approach using census data to allow for national generalisability of the observed patterns

3 examine the climate-mortality relationship using an improved set of climate variability measures (heat waves, cold snaps, droughts, and excessive precipitation) constructed relative to a 30-year long-term climate normal period

4 explore whether the climate-mortality relationship varies with the epidemiological context of HIV/AIDS prevalence and malaria infection rates.

4 Data and case

4.1 Data

We make use of the new TerraPop data extraction system (MPC, 2013), publicly available at https://data.terrapop.org/, to obtain the core data for our study of climate and mortality. TerraPop combines census-based microdata with raster and area-level data (Kugler et al., 2015). Census data for Kenya (2009), Mali (2009), and Malawi (2008) are available through TerraPop and originate from IPUMS-International (MPC, 2015; Ruggles et al., 2003). These countries were selected because:

1 the census rounds fall in approximately the same time period (2008–2009)

2 the census questionnaires asked about household-level mortality

3 the countries' geographic location reflects varying climatic zones across SSA

4 important epidemiological information on HIV/AIDS and malaria prevalence could be obtained.

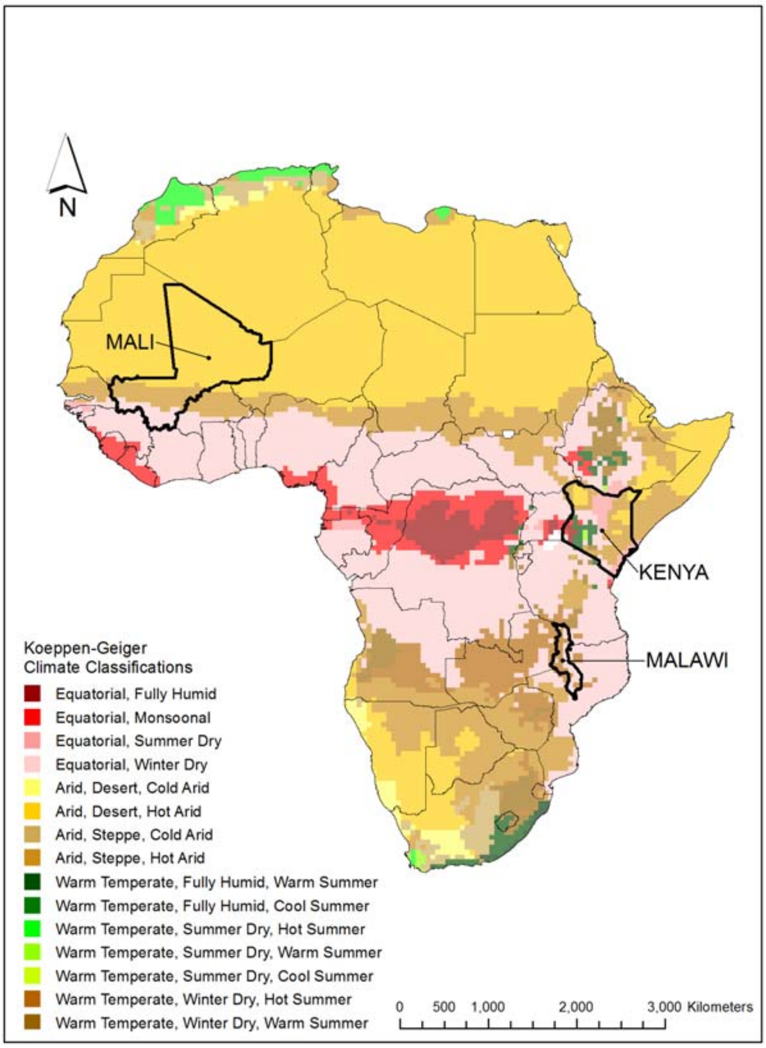
TerraPop also provides spatial boundary files for second-level administrative units (Kenya: district, n = 127; Mali: circle, n = 46; Malawi: traditional authority: n = 171). Using a geographical information system (GIS), we constructed a set of district-level measures such as natural resource access, natural disaster frequency, and conflict occurrence from various publicly available sources and attached this information to the TerraPop data extract as outlined in detail below. In this research, we focused on rural areas, based on the assumption that climate variability will have the strongest effects on rural populations heavily dependent on primary sector activities with little technological means to guard against adverse climate effects (Nawrotzki et al., 2015).

4.2 Case

SSA provides a unique regional setting for the study of the climate-mortality relationship. Kenya, Mali and Malawi are among the poorest countries of the world, ranking 147, 174, and 176, respectively, out of 185 on the human development index (UNDP, 2014). Most households in rural areas of SSA depend on agricultural production for sustenance and income generation (CIA, 2014; Speranza et al., 2008). Agricultural production is largely rain-fed with only 1.69% (Kenya), 3.68% (Mali), and 1.65% (Malawi) of the farmland irrigated (FAO, 2015). Many households rely on natural resources such as forests in Malawi (Fisher, 2004) and small-scale mining in Mali (Hilson and Garforth, 2012) to supplement income from farming. Heavy dependence on agriculture and natural resources combined with low levels of development and technological infrastructure makes households in SSA vulnerable to the impacts of climate variability and change (Cooper et al., 2008; Niang et al., 2014).

The vulnerability of households in SSA is related, in part, to the socio-political context. Weak governments, high levels of corruption, widespread poverty and inequality contribute to the frequent emergence of violent conflicts (Blattman and Miguel, 2010), which often erupt over access to scarce natural resources (Humphreys, 2005; Mwangi, 2006). Climate variability and change can influence natural resource access and productivity (e.g., water, crop) and have been suggested as the underlying drivers of many conflicts (Hsiang et al., 2013; O'Loughlin et al., 2012). As an added strain, SSA suffers from high levels of malaria and HIV/AIDS infection, which are among the leading causes of death in this region (Lozano et al., 2012). The confluence of poverty, weak institutions, and a unique epidemiological context contribute to overall poor health conditions and high mortality rates in SSA (Jamison et al., 2006), as illustrated in our representation of the climate-mortality framework.

Figure 2 Geographical location and climatic zones of the three study countries (Kenya, Mali, and Malawi) (see online version for colours)



Note: Koeppen-Geiger classifications of main climatic zones.

Source: Kottek et al. (2006)

Kenya, Mali, and Malawi span various climatic zones, allowing insights into the relationship between climate and mortality under different climatic conditions (Figure 2). Kenya shows the largest variation in climatic zones, ranging from arid steppe near the coast to equatorial and temperate climates around Mount Kenya in the central west. In contrast, large regions of northern Mali are characterised as desert climate, transitioning to arid steppe and equatorial climate in the south. Much of Malawi is classified as arid steppe with some eastern regions bordering Lake Malawi displaying an equatorial climate.

Over the past decades, average temperatures across SSA have risen significantly, with the strongest increase in most recent years (Collins, 2011; Nicholson, 2001). These historical patterns foreshadow future changes of rising temperatures and increases in the frequency and magnitude of heat waves (Niang et al., 2014; Seneviratne et al., 2012). Precipitation changes over the past decades differed by region, with a trend of drying and increased aridity in Sahelian West Africa but little change in equatorial East Africa (Hulme et al., 2001). Future projections of rainfall are uncertain with a likely increase in variability leading to more flood and drought events but little change in average precipitation (Anyah and Qiu, 2012; Burke and Brown, 2008; Niang et al., 2014).

5 Measures and methods

5.1 Variable construction

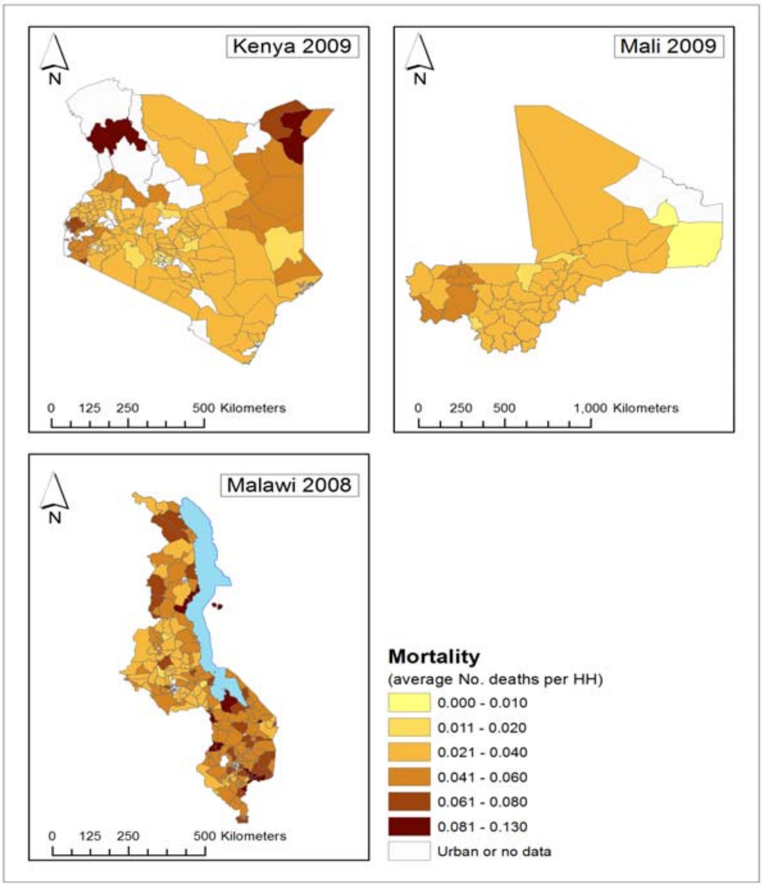
5.1.1 Outcome variable

As part of the census form, households were asked to report the number of deaths experienced in the past year leading up to the census month. As such, the unit of analysis in our study was the household and we used the household-level count of deaths as the outcome variable in our models. Unfortunately, our deaths measure lacks the necessary detail to differentiate between season-specific (e.g., winter vs. summer), cause-specific, or age-specific (e.g., deaths among elderly) mortality, as is sometimes done in epidemiological studies (Bennett et al., 2014; Fouillet et al., 2008). As an important advantage, our outcome measure permits generalisations to the entire population across seasons. In Kenya, the highest mortality rates emerged in the northeast, while in Mali higher mortality rates were reported for districts in the southwest (Figure 3). Malawi showed a mixed pattern with somewhat higher mortality rates for southern districts.

5.1.2 Primary predictor variables

We used gridded high-resolution data of monthly temperature and precipitation, managed and released by the climate research unit (CRU) of the University of East Anglia (Harris et al., 2014). The CRU time series data (CRU-TS) is frequently used in climatological research (Koutsouris et al., 2015) and provides the most reliable climate information for Africa (Zhang et al., 2013). TerraPop computes district averages from the gridded CRU-TS climate data and permits attaching this information to the census microdata (Kugler et al., 2015).

Figure 3 Average number of deaths per household by district for Kenya, Mali, and Malawi during 2008/09 (see online version for colours)



Due to the importance of climate variability for mortality outcomes (Gosling et al., 2009a), we constructed a set of climate measures reflecting threshold-based variation from long-term average conditions. Our temperature measures indicate whether the maximum temperature in a given month was one standard deviation (SD) above (heat waves), or whether the minimum temperature was one SD below (cold snaps) the 30-year ‘climate normal’ period (1961–1990) (Arguez and Vose, 2011). The precipitation measures capture whether precipitation during a given month was one SD below (droughts) or above (excessive precipitation) the long-term average. As heat waves and droughts may occur jointly (Diffenbaugh et al., 2015) with synergetic effects for mortality, the climate impact index indicates months during which the one SD temperature and precipitation thresholds were jointly surpassed. The SD-based relative threshold accounts for the fact that the impact of climate on mortality varies by geographical location due to different levels of acclimatisation of the local population (Basu and Samet, 2002; Gosling et al., 2009b). We then computed the percentage of months during the two years prior to the census date that the threshold was surpassed. The two-year window was chosen to capture both immediate and lagged climate effects on deaths that occurred during the year prior to the census date. Table 1 provides summary statistics for all variables employed in the present analysis.

Table 1 Descriptive statistics of variables employed in the analysis of the climate-mortality relationship for Kenya, Mali, and Malawi

	Unit	*Min*	*Max*	*SD*	*Sample mean*		
					Kenya	*Mali*	*Malawi*
Outcome variable							
Deaths in HH	Count	0	6	0.23	0.03	0.03	0.05
Household controls							
Children in HH	Count	0	73	1.99	2.11	2.96	2.15
Elderly in HH	Count	0	9	0.48	0.20	0.21	0.19
Female head	1|0	0	1	0.45	0.35	0.13	0.29
Head married	1|0	0	1	0.39	0.79	0.91	0.78
Primary educated	%	0	100	30.76	39.55	6.31	15.31
Employed in HH	%	0	100	31.30	55.54	41.97	38.58
Int'l. migrant in HH	1|0	0	1	0.12	0.01	0.01	0.03
Energy access	Scale	0	2	0.39	0.15	0.16	0.05
District controls							
HIV prevalence	%	0	42.11	7.19	5.22	1.34	8.83
Malaria incidence	%	0.92	68.89	19.89	8.47	38.93	39.92
Conflict	1|0	0	1	0.31	0.27	0.07	0.01
NDVI	Scale	0.08	0.53	0.09	0.34	0.29	0.42
Primary crops	sqm/10 ha	0	0.7	0.10	0.08	0.05	0.08
Urban land	%	0	2.82	0.29	0.12	0.05	0.06
Climate measures							
Heat wave	%	8.33	75	17.71	59.19	33.79	25.39
Cold snap	%	0	25	4.57	2.43	7.34	4.39
Drought	%	0	37.5	11.43	15.98	3.44	6.58
Excessive precipitation	%	0	29.17	5.57	10.10	13.04	9.70
Climate impact index	%	6.25	54.17	12.85	37.58	18.61	15.98
Sample size							
Households	Count				445,674	166,791	238,271
Districts	Count				127	46	171

Notes: Values for min, max, and SD refer to the complete sample. Climate measures operate at the district level.

5.1.3 Control variables

Mortality is influenced by various historical, social, demographic, and environmental factors, operating at the household and district levels (Rogers et al., 2005). To capture differences in age distribution, we constructed two measures that reflect the number of children (age 0–14) and elderly (age 65+) within the household. To account for gender differences in social standing that may have impacts on health and mortality; a dummy variable indicated whether the household head was female. A dummy variable captured whether the household head was married (coded 1) or divorced/widowed/never married (coded 0), as an indicator of access to extended kin networks and support systems. To account for differences in human capital, we constructed a set of variables measuring the percentage of household members with at least primary education and the percentage of household members employed. The quality of energy access (0 = no electricity or purchased fuel; 1 = either electricity or purchased fuel; 2 = both electricity and purchased fuel) was included to capture differences in wealth and access to health protective amenities (e.g., refrigerators) that may influence mortality rates. A dummy variable measured whether a household member was sent to an international destination during the past five years (migrant household = 1), as an indicator of socioeconomic status with possible implications for mortality outcomes.

At the district level, we accounted for the epidemiological context by computing measures of malaria incidence and HIV/AIDS prevalence. We obtained high-resolution (5 × 5 km) data on malaria incidences from the Malaria Atlas Project (Bhatt et al., 2015) and used district-level boundary files obtained via TerraPop to compute the average percentage of people infected during the census year in each district.

To obtain estimates of HIV/AIDS prevalence we made use of demographic and health surveys (DHS), as extensive and reliable sources of nationally representative household surveys that are widely used for health and demographic analyses in developing countries (Brown et al., 2014). DHS data comprise the primary source for sub-national estimates of HIV/AIDS prevalence rates (Larmarange and Bendaud, 2014). DHS surveys are fielded during specific years, and we made use of DHS phase V for the year 2008 for Kenya (DHS, 2010), year 2006 for Mali (DHS, 2007), and year 2010 for Malawi (DHS, 2011). Information on the geographical location of cluster points (villages in which households reside) enabled us to compute the percentage of females (age 15–49) in each district that tested positive for HIV/AIDS.

Three measures capture different types of land cover and land use that might influence mortality rates: access to natural resources, agricultural productivity, and urban infrastructure. We obtained gridded information on the normalised difference vegetation index (NDVI) derived from remotely sensed images of the MODIS satellite (Carroll et al., 2004) to approximate access to natural resources. We computed the average greenness value for growing season months during the three-year period prior to the census rounds 2007–09 (cf., Vrieling et al., 2013). Because agricultural dependence may increase climate vulnerability, we included a measure of the district area (sqm/10 ha) where primary crops were harvested, constructed by the global landscape initiative (GLI) (Monfreda et al., 2008) and available through TerraPop. The primary crops in our study countries are tea in Kenya, rubber in Mali, and tobacco in Malawi (CIA, 2014). To account for access to urban infrastructure such as health care facilities and various resources that may impact mortality rates, we made use of the MODIS urban extent classification (Schneider et al., 2009), available through TerraPop, and computed the percentage of urban land within each district.

Finally, we accounted for armed conflicts and natural disasters as potential sources of mortality. Using geocoded data from the armed conflict location and event data project (ACLED) (Raleigh et al., 2010), we constructed a measure indicating whether a conflict was observed in a given district during the census year. To account for natural disasters, we obtained georeferenced data on earthquakes (USGS, 2015) and cyclones (UNEP, 2015), but no occurrence of these two types of natural disasters were recorded for our study countries during the observation period.

5.2 Statistical modelling

Poisson models constitute the simplest form of generalised linear models (GLMs) used for count data (Hoffmann, 2004). Poisson GLMs are based on the assumption that the conditional mean equals the conditional variance, known as equidispersion (Allison and Waterman, 2002; Cameron and Trivedi, 2013). In the presence of a large number of zeros as well as extra-Poisson noise stemming from unobserved heterogeneity, this assumption is frequently violated. Model-based tests (Harrison, 2014) revealed that our data are slightly overdispersed. Overdispersion can bias standard errors and lead to false inferences (Zuur et al., 2009). Negative binomial models constitute a generalisation of the conventional Poisson models and relax the equidispersion assumption through the inclusion of a dispersion parameter (α), which allows the conditional variance to be a multiple of the conditional mean (Allison, 2009; Cameron and Trivedi, 2013). For this study, we employed negative binomial models to predict the count of deaths within a given household. Negative binomial models have frequently been employed to study the determinants of deaths (Johnston et al., 2009; Preston et al., 2010; Rasella et al., 2013). However, due to the clustered nature of our data, we employed random-effects, multilevel version of the negative binomial models (Bolker et al., 2009; Harrison, 2014) as formally described in equation (1).

$$\eta_{ij} = \log_e\left(\frac{\mu_{ij}}{\varphi}\right)$$

$$\eta_{ij} = \beta_0 + \beta_1\left(clim_j\right) + \sum_{n=2}^{k}\beta_n\left(x_{nz}\right) + v_j \tag{1}$$

The negative binomial model uses a natural logarithmic link to guarantee that the set of independent variables linearly produces η_{ij} (Hoffmann, 2004). The symbol μ_{ij} represents the expected counts of deaths for a household *i* located in district *j*. To model the rate of deaths (in contrast to raw counts), we included an offset (φ) as the log of the number of household members at risk of mortality. The parameter β_0 constitutes the conventional intercept, while the parameter β_1 reflects the effect of a given climate predictor ($clim_j$) on the death rate. The climate measures operate at the district level as indicated by the subscript *j*. Because of high correlation, the climate measures were included one at a time in the models. All models control for the effects $\beta_{2\text{–}k}$ of a large number of socio-demographic and spatial control variables ($x_{2\text{–}k}$), which can operate both at the household and district level as indicated by the generic subscript *z*. The random effects parameter (v_j) accounts for the clustering of households within districts, varying numbers of households within areas, as well as heteroscedastic error terms (Luke, 2004).

All models were fit using the *lme4* package (Bates, 2010; Bates et al., 2014) within the 'R' statistical environment version 3.2 (RCoreTeam, 2015). For improved speed and convergence properties we adjusted the model settings (integer scalar settings *nAGQ* = 0) so that the fixed effects and random effects coefficients were optimised (optimiser = 'bobyqa') in the penalised iteratively reweighted least squares step (Bates et al., 2014).

6 Results and discussion

6.1 Base model

In the first step of our analysis, we built a multivariate base model to account for various non-climatic influences on mortality (Table 2). Low values on the variance inflation factor (VIF < 1.9) suggested that multi-collinearity did not influence the estimates. The results showed that household factors are considerably more influential than district factors in determining mortality outcomes.

Table 2 Multilevel negative binomial base models predicting log mortality rates for rural households in Kenya, Mali, and Malawi during 2008/09

	Kenya			*Mali*			*Malawi*		
	b	*Sig.*	*p*	*b*	*Sig.*	*p*	*b*	*Sig.*	*p*
Household controls									
Intercept	–4.06	***	0.00	–4.91	***	0.00	–4.34	***	0.00
Children in HH	–0.19	***	0.00	–0.08	***	0.00	–0.19	***	0.00
Elderly in HH	0.29	***	0.00	0.10	***	0.00	0.21	***	0.00
Female head	0.41	***	0.00	0.03		0.54	0.22	***	0.00
Head married	–0.50	***	0.00	–0.55	***	0.00	–0.50	***	0.00
Primary educated[a]	–0.05	***	0.00	–0.04	**	0.00	–0.02	***	0.00
Employed in HH[a]	0.03	***	0.00	0.01		0.18	0.03	***	0.00
Int'l. migrant in HH	0.06		0.59	1.08	***	0.00	0.72	***	0.00
Energy access	–0.21	***	0.00	–0.19	***	0.00	–0.11	*	0.02
District controls									
HIV prevalence[a]	0.14	***	0.00	0.11		0.59	0.21	***	0.00
Malaria incidence[a]	0.08	***	0.00	0.03		0.18	0.01		0.76
Conflict	–0.04		0.48	–0.01		0.91	0.04		0.91
NDVI	–1.15	***	0.00	0.79	*	0.01	0.79		0.09
Primary crops	0.46		0.07	0.06		0.83	–0.90	***	0.00
Urban land	0.04		0.63	–0.49		0.28	–0.10		0.29
Model statistics									
Random intercept	0.053			0.027			0.069		
Dispersion parameter	0.11			0.2			0.174		
BIC	123,415			44,199			93,869		
N (households)	445,674			166,791			238,271		
N (districts)	127			46			171		

Note: [a]Coefficients reflect an incremental change of 10 units;
$*p < 0.05$; $**p < 0.01$; $***p < 0.001$.

Overall, Table 2 reveals many similarities in the determinants of mortality across our study countries. The risk of death generally increases with age (Rogers et al., 2005), reflected by a decline in the expected mortality rates for young households with larger numbers of children, while mortality rates increase for households largely comprised of older members. Mortality is higher in households headed by females, which may be attributed to gendered access to resources (Chant, 2003; Hyder et al., 2005). We also observed lower mortality rates in households with married heads of household. A marriage may extend a household's access to social and kin networks on which households may draw in times of crises (Abu et al., 2014). Similarly, education had a protective effect, with households with larger proportions of primary educated members being less likely to experience excess mortality, in line with prior studies (Ezra and Kiros, 2000). Surprisingly, households with more members employed showed higher mortality rates, likely related to employment in manual occupations being associated with an elevated risk of injury and death (WHO, 2009). In contrast, access to high quality energy sources (e.g., electricity) was associated with lower expected death rates, perhaps because electricity can be used to power appliances such as refrigerators or stoves, contributing to a healthier lifestyle, and may serve as a proxy indicator for socioeconomic status (Kebede et al., 2010). Households that had sent a member elsewhere were more likely to experience a death. Migration of a household member may indicate low socioeconomic status and the need to access alternative income sources, associated with higher mortality rates in prior research (Ezra and Kiros, 2000).

mThere are also some notable differences in the magnitude of these household-level effects between the study countries. The presence of children in households decreases the chance of death while the presence of more elderly members increases the chance of death in all three countries, but these effects are significantly lower in Mali compared to Kenya and Malawi, even though the average presence of elderly and child members are comparable between the countries (see Table 1). We hypothesise that this is the result of Mali being the most resource poor of the three countries[4], where these additional effects fail to make a difference to the existing rate of mortality. Data on average levels of employment and education and percentage of urban land from Table 1 and a larger location attribute in the desert (see Figure 1) agree with this hypothesis on the interplay of lower education and socioeconomic status and lack of access to amenities. Similarly, the presence of a female head increases mortality in all three countries probably due to gendered access to resources, but the effect is lowest in Mali as well as insignificant. Apart from the above reasons, we find from Table 1 that Mali has the lowest percentage of households with female heads compared to the other countries (the value of the variable itself is too low to have an impact), which again is a sign of lower education and socioeconomic status indicating a potential vicious circle maintaining adverse conditions. The relative value of the explanatory variable in question is also important for the slight difference in a married head reducing the chance of death in Mali compared to the other countries as Mali has the highest percentage of married heads. The location of Mali away from amenities could potentially reinforce this effect as having a cooperative household is more important for more efficient use of limited resources. Malawi has a similar effect from the lowest impact to death from a lack of access to energy sources (as Table 1 shows). The relatively hotter and more humid climate would potentially reinforce this effect by increasing the demand for energy in a market with limited supply. The effect of education lowers the chance of mortality in all countries but the effect is largest in Kenya, presumably owing to the effect of urbanisation, which not only increases access to education (as is apparent from Table 1), but also to healthcare, transportation, and social awareness (Njoh, 2003; Dye, 2008). Employment leads to higher mortality potentially due to largely manual occupations, as we have noted before, but the impact is insignificant in Mali potentially also due to the country having lower resource access than the others and significantly lower employment opportunities to start with (as seen from Table 1). For the same reason, Mali and Malawi are more likely to send migrants to other countries and therefore more likely to experience a death from an employment-related cause compared to Kenya.

At the district level, HIV/AIDS rates were significantly related with higher mortality rates in Kenya and Malawi (Nyandiko et al., 2006; UNAIDS, 2013). In Kenya, higher malaria incidence rates were also associated with higher mortality, a relationship supported by epidemiological research (Smith et al., 2001; Snow and Marsh, 2002). A substantially higher population density (see Table 1) can reinforce incidences of HIV (Buvé et al., 2002) as well as vector borne diseases such as malaria (Donnelly et al., 2005), which supports the contrasting results on mortality from these diseases in Kenya and Malawi, compared to Mali. Vegetation coverage as indicated by NDVI was associated with higher mortality rates in Mali but lower mortality rates in Kenya. While natural resources may be used for food and income generation in times of crises (Hunter et al., 2011a; Shackleton and Shackleton, 2006), the greenness of an area may also reflect the remoteness of a location with limited access to hospitals and sanitation infrastructure (Dussault and Franceschini, 2006; Pullan et al., 2014), producing these contrasting results. Finally, our measure for agricultural dependence suggests lower mortality in Malawi for regions with substantial crop production, perhaps related to more stable income options in these regions (Dorward and Chirwa, 2011; Peters, 2006).

6.2 Climate effects

In the next step of the analysis, we add one climate measure at a time to the fully adjusted multilevel base model and report the results in Table 3.

Table 3 Multilevel negative binomial models predicting changes in log mortality rates in response to climate variability for rural households in Kenya, Mali, and Malawi during 2008/09

	Kenya			*Mali*			*Malawi*		
	b	*Sig.*	*p*	*b*	*Sig.*	*p*	*b*	*Sig.*	*p*
Heat wave	0.03		0.18	0.03		0.32	–0.04		0.58
Cold snap	0.40	***	0.00	–0.12	**	0.01	–0.14	*	0.03
Drought	0.05		0.06	–0.01		0.97	0.08	*	0.01
Excessive precipitation	0.10	*	0.03	–0.05		0.28	0.10		0.14
Climate impact index	0.06		0.07	0.05		0.37	0.11		0.05

Notes: Coefficients reflect an incremental change of 10 units; each coefficient was estimated for a separate model, controlling for all variables listed in Table 2; *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

While heat waves tend to increase mortality in countries such as France (Fouillet et al., 2008) and the USA (Gosling et al., 2009a), we found no significant relationship between the number of heat-wave months and household mortality rates in Kenya, Mali, and Malawi. This difference might be attributed to dissimilarities in region-specific acclimatisation and sensitivity to elevated temperatures in northern and southern countries (cf., Basu and Samet, 2002). In contrast, the occurrence of low temperature extremes (cold snaps) showed a significant relationship with mortality for all study countries but with contrasting directionality. For Kenya, an increase in cold snaps was significantly associated with higher mortality rates, while in Mali and Malawi cold snaps were associated with lower mortality rates. Periods of cold temperatures have been found to increase mortality in several southern European countries (Healy, 2003; Montero et al., 2010). Cold waves lead to excess mortality often through an increase in respiratory and cardiovascular diseases (Ebi and Mills, 2013). Our findings suggest a similar relationship for Kenya. In contrast, cold snaps seem to have positive health effects in Mali and Malawi, associated with lower mortality. This difference may be explained with reference to geography and the general climatic conditions. Kenya's topography includes mountainous regions (Mount Kenya, Mount Elgon, etc.), resulting in a varied climate with temperatures that drop locally to 7.86°C, while the minimum monthly temperature in largely flat regions of Mali (19.96°C) and Malawi (13.24°C) remain much higher. In the hot, arid climate of Mali and Malawi, our measure of cold snaps reflect the occurrence of months with moderately cooler temperatures close to the optimum, preventing the rise above thresholds dangerous for human health (McMichael et al., 2008).

In Malawi, droughts significantly increased mortality, in line with research from Ethiopia (Ezra and Kiros, 2000; Kidane, 1989). Droughts often exacerbate an already precarious food insecurity situation and may lead to famine, malnutrition, and starvation (Speranza et al., 2008; UN, 2011).

For Kenya, an increase in excessive precipitation also increases mortality, in line with observations for Burkina Faso (Diboulo et al., 2012). Excessive precipitation may lead to flooding and associated deaths by drowning (Alderman et al., 2012). More indirectly, mortality may increase after flooding through factors such as the destruction of food supplies and resulting famines (UNDP, 2007), increases in malaria incidences (Ahern et al., 2005), or spreading of diarrheal illnesses such as cholera (Ramin and McMichael, 2009).

6.3 Interaction effects

In SSA, malaria and HIV/AIDS are among the leading causes of death (Lozano et al., 2012). To investigate whether the epidemiological context influences the likelihood of experiencing a climate-related death, we employed interaction models (Table 4, Figure 4). Significant interactions emerged only for Kenya as the focus of the following results exposition. Insignificant interactions for Mali and Malawi suggest that climate effects emerged independent of the epidemiological context for these countries.

The interactions between climate and HIV/AIDS prevalence show a positive directionality, meaning that climate related increases in mortality are strongest in regions with high HIV/AIDS prevalence rates. For example, Figure 4 panel A illustrates essentially no effect of droughts on mortality rates in regions with low HIV/AIDS prevalence (20% ile). However, in areas with considerable burden of HIV/AIDS infection (80% ile), droughts strongly increase mortality. In line with prior research (Basu and Samet, 2002), the results suggest that climate stress is particularly problematic for already vulnerable populations and may synergistically interact with weakened health and nutrition status of affected households (Ramin and McMichael, 2009).

Table 4 Interaction between climate and the epidemiological context in predicting log mortality rates for rural households in Kenya, 2009

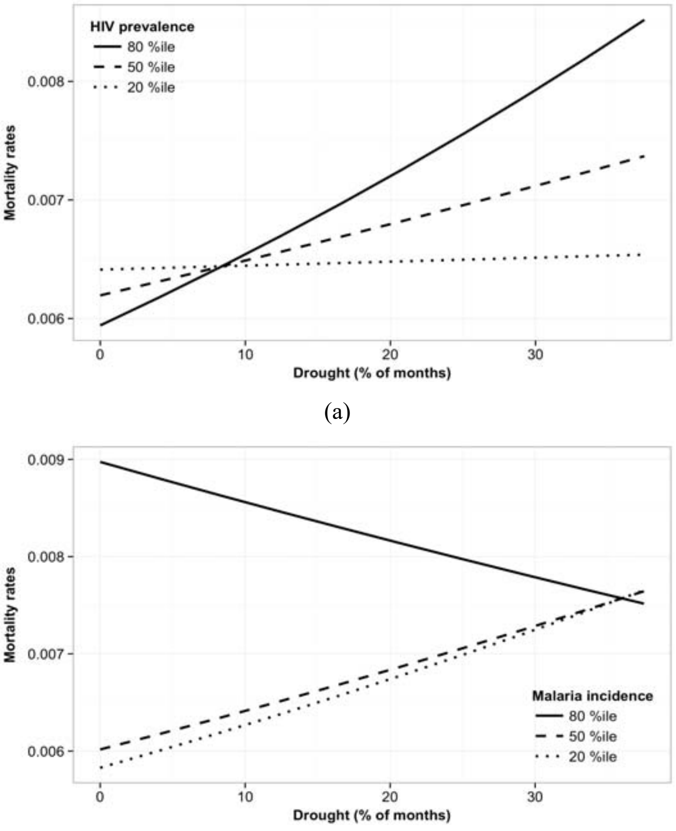
	Clim			*Epi*			*Clim* × *Epi*		
	b	*Sig.*	*p*	*b*	*Sig.*	*p*	*b*	*Sig.*	*p*
HIV prevalence									
Heat wave	0.05		0.06	0.10	*	0.01	0.06		0.16
Cold snap	0.47	***	0.00	0.13	***	0.00	0.29		0.09
Drought	0.06	*	0.02	0.09	*	0.02	0.09	**	0.00
Excessive precipitation	0.17	***	0.00	0.03		0.46	0.21	**	0.00
Climate impact index	0.08	*	0.01	0.08	*	0.04	0.10	**	0.01
Malaria incidence									
Heat wave	–0.03		0.35	0.18	***	0.00	–0.15	*	0.01
Cold snap	–0.03		0.86	0.18	***	0.00	–0.77	***	0.00
Drought	0.00		0.97	0.17	***	0.00	–0.09	*	0.02
Excessive precipitation	0.11	*	0.05	0.05		0.25	0.02		0.78
Climate impact index	–0.03		0.41	0.24	***	0.00	–0.19	**	0.00

Notes: Coefficients reflect an incremental change of 10 units; *Clim* = climate effects, *Epi* = epidemiological context, *Clim* × *Epi* = interaction between climate and epidemiological context; each row represents a fully adjusted multi-level model (Table 2) of which only the coefficients involved in the interaction are shown; variables were centred.
*p < 0.05; **p < 0.01; ***p < 0.001.

In contrast, significant interaction effects between climate and malaria are primarily negative. This directionality indicates that adverse climate conditions tend to decrease mortality in areas with high malaria infection rates. Figure 4 panel B shows that in areas of low (20% ile) or moderate (50% ile) malaria infection rates, an increase in drought months increased mortality. However, in areas with high levels of malaria infection (80% ile), the relationship became inverted and an increase in drought months led to a decline in mortality. Similar effects emerged for temperature extremes, for which both an increase in heat waves and an increase in cold spells tended to reduce mortality in areas of high malaria burden. Both the malaria vector (anopheles mosquito) and pathogen (plasmodium parasite) have a narrow range of optimum growing and transmission conditions. When temperature extremes surpass the upper or lower limits, transmission is reduced (Lunde et al., 2013; Paaijmans et al., 2010). The anopheles vector requires small, temporary, water bodies as breeding grounds (Mwangangi et al., 2007), which multiply with rainfalls. While more precipitation leads to an increase in malaria incidences (Kelly-Hope et al., 2009; Zhou et al., 2010), drought conditions decrease the mosquito population (Kent et al., 2007), leading to a decline in malaria mortality rates.

These results suggest that climate and non-climatic factors could work independently or collectively to affect mortality, based on existing conditions of disease prevalence, topography, and population density in the region.

Figure 4 Interaction between droughts and epidemiological variables predicting mortality rates in Kenya, 2009, (a) panel A: HIV prevalence (b) panel B: malaria incidence



(a)

(b)

7 Conclusions

Prior studies have investigated the climate-mortality relationship for a small selection of villages in Burkina Faso (Diboulo et al., 2012), Ethiopia (Ezra and Kiros, 2000; Kidane, 1989), and Sudan (De Waal, 1989). Building on this initial work, our study employed nationally representative census data for Kenya, Mali, and Malawi, as three SSA countries that have not been studied so far. As additional strength, our study used measures of climate variability (heat waves, cold snaps, droughts, excessive precipitation) relative to a long-term climate normal period (1961–1990) instead of focusing on short-term climate impacts as done in earlier studies (e.g., Diboulo et al., 2012; Kidane, 1989). A better understanding of the climate-mortality relationship is particularly important for SSA countries, which have the highest mortality rates in the world (UN DESA, 2018) and will experience increases in climate variability in future decades as a result of global warming (IPCC, 2013; Seneviratne et al., 2012).

Our results, derived from multilevel negative binomial models, that incorporate the climate-mortality framework in Figure 1, revealed that an increase in cold snaps was associated with higher mortality in Kenya but led to a decline in mortality in Mali and Malawi. The contrasting directionality for cold snaps is likely due to different baseline climatic conditions in the study countries as clarified in the discussion section. We also observed an increase in mortality in districts that experienced more frequent excessive precipitation (flooding) in Kenya and more frequent droughts in Malawi. Interaction models revealed that adverse climatic conditions strongly increased mortality in districts with high HIV/AIDS prevalence, suggesting higher climate vulnerability in the presence of HIV/AIDS. In contrast, adverse climatic conditions reduced mortality rates in districts in which malaria infections were high, likely due to unfavourable breeding conditions for the anopheles vector.

The discussion section clarified the nuances of these results in detail leading to the key lessons learned for the climate-mortality link in SSA for our study: climate variability affects mortality through multiple pathways both within and outside the household and may not always increase mortality. A key pathway is the epidemiological context, which we studied through the prevalence of two major diseases afflicting SSA countries: HIV and malaria. We found that climate-variability could affect mortality differently based on regional characteristics including the epidemiological context, where climate-related deaths could be worsened in areas with high incidences of HIV and be reduced in areas with high incidences of malaria from different reasons such as weakened socioeconomic status in case of HIV prevalence or potential reduction in the transmission of the anopheles vector in case of malaria prevalence. In areas with lower population density and higher climatic variation, climate related deaths are more likely to operate independent of the epidemiological context. These lessons learned from our results could help apply welfare programs in a more targeted and cost-effective way in SSA countries.

Although carefully conducted, this study has a number of limitations. First, our study was restricted to the use of census data. While census data has the benefit of national representativeness and provides useful information on demographic features, it lacks information on health status, income, or distance to hospitals, which may influence the probability of experiencing a death. In addition, temporal mismatches between the census dates and the DHS survey years result in some uncertainty in the HIV/AIDS prevalence measure. In the absence of better data, we assume that the DHS data provide reasonably good approximations of the local conditions. Finally, our quantitative analysis is limited in its ability to investigate causal pathways and reasons for cross-country differences. Future research may employ qualitative methods to better understand the underlying mechanisms leading to contrasting directionality for cold snaps.

Based on the key lessons learned above, our study has important policy implications. In general, our results demonstrate that household-level mortality is sensitive to climate variability. This sensitivity may be attributed to a lack of infrastructure and high levels of poverty that prevent the use of technology to neutralise climatic impacts (Ramin and McMichael, 2009). However, climate variability does not always increase mortality. Within certain regional contexts such as in Mali and Malawi, periods of cooler temperatures may be beneficial. Similarly, climatic variability may have protective effects in areas of high malaria burden, as observed for Kenya. These potential reasons for reduced mortality from climate variability are supported by our results and clarified in the discussion section.

Aside from these exceptions, we find evidence of a number of harmful climatic effects on household mortality. To more fully achieve the SDGs of a reduction in mortality rates across SSA (UN DESA, 2018), future social welfare programs would benefit from an explicit consideration of climate-related health impacts. In Kenya, this includes better protection against the impacts of cold snaps and excessive precipitation/flooding. Program features may include the establishment of early warning systems for floods and temperature extremes (Montero et al., 2010; Smith et al., 2014). Because cold snaps and floods may raise mortality rates through the spreading of infectious diseases, better access to public health services may help buffer climate-related health impacts (Healy, 2003; Smith et al., 2014). Preference for the expansion of health services should be given to districts with high rates of HIV/AIDS infection, since our results show that households in these areas are particularly vulnerable to climatic stress.

In Malawi, programs aimed at building livelihood resilience may reduce drought sensitivity. This may include assistance for livelihood diversification through non-agricultural employment, improved access to agricultural extension services, distribution of drought resistant crop varieties, and installation of irrigation systems (Burney et al., 2013; Speranza et al., 2008). Adding a climate lens to policies and programs aimed at reducing mortality in SSA will go a long way towards more fully achieving the SDGs.

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Notes

1 The sustainable development goals (SDGs) are an extension and reorganisation of the millennium development goals (MDGs), a global development initiative undertaken by the United Nations during 2000–2015. In 2015, the MDGs ended and were replaced by the SDGs, which included the main objectives of the MDGs –https://www.un.org/sustainabledevelopment/development-agenda/.

2 More than 60% of the population in the study countries (Kenya: 75%, Malawi: 84%, and Mali: 62%) were living in rural areas in 2013, World Bank, based on UNEP data, 2018 – http://data.worldbank.org/indicator/SP.RUR.TOTL.ZS.

3 United Nationals Department of Economic and Social Affairs – https://www.un.org/development/desa/en/.

4 https://en.wikipedia.org/wiki/List_of_African_countries_by_Human_Development_Index.