Popul Environ (2014) 35:323–339
DOI 10.1007/s11111-014-0209-0

RESEARCH BRIEF

A spatial analysis of population dynamics and climate change in Africa: potential vulnerability hot spots emerge where precipitation declines and demographic pressures coincide

David López-Carr · Narcisa G. Pricope · Juliann E. Aukema · Marta M. Jankowska · Christopher Funk · Gregory Husak · Joel Michaelsen

Published online: 6 March 2014

Abstract We present an integrative measure of exposure and sensitivity components of vulnerability to climatic and demographic change for the African continent in order to identify "hot spots" of high potential population vulnerability. Getis-Ord *Gi** spatial clustering analyses reveal statistically significant locations of spatio-temporal precipitation decline coinciding with high population density and increase. Statistically significant areas are evident, particularly across central, southern, and eastern Africa. The highly populated Lake Victoria basin emerges as a particularly salient hot spot. People located in the regions highlighted in this analysis suffer exceptionally high exposure to negative climate change impacts (as populations increase on lands with decreasing rainfall). Results may help inform further hot spot mapping and related research on demographic vulnerabilities to climate change.

Narcisa G. Pricope—co-lead author.

D. López-Carr (✉) · G. Husak · J. Michaelsen
Department of Geography, University of California Santa Barbara, 1832 Ellison Hall, Santa Barbara, CA 93106-4060, USA
e-mail: carr@geog.ucsb.edu

N. G. Pricope
Department of Geography and Geology, University of North Carolina Wilmington, 102 DeLoach Hall, 601 South College Road, Wilmington, NC 28403-5944, USA

J. E. Aukema
National Center for Ecological Analysis & Synthesis (NCEAS), University of California Santa Barbara, 735 State Street Suite 300, Santa Barbara, CA 93101, USA

M. M. Jankowska
Department of Family and Preventative Medicine, Center for Wireless and Population Health Systems, University of California, San Diego, 9500 Gilman Drive, San Diego, CA 92093, USA

C. Funk
United States Geological Survey, University of California Santa Barbara, 1832 Ellison Hall, Santa Barbara, CA 93106-4060, USA

Results may also inform more suitable geographical targeting of policy interventions across the continent.

Keywords Climate change · Population · Vulnerability · Hazards · Africa · Spatial modeling

Introduction

Despite a burgeoning literature on socioeconomic aspects of vulnerability (e.g., Cutter et al. 2003; Luers 2005; Frank et al. 2011), relatively less research has linked demographics and population dynamics with climate change. Yet understanding population dynamics is critical in order to describe how a given number of people, with their own specific geographical and demographic characteristics, may exacerbate or mitigate climate change or how, conversely, they may be particularly susceptible to climate change impacts (McLeman 2010). Complex relations among population and climate change are often scale and place specific. The focus of this paper is to elucidate this latter point, specifically the question of where and to what degree population dynamics create geographies of vulnerability within the context of climate change.

Specifically, this paper identifies is to identify regions in Africa facing the dual dynamics of increasing spatial and temporal precipitation variability (critical for household subsistence) coupled with initially high and/or increasing population density. We develop an integrative measure of demographic exposure and climate sensitivity components of population vulnerability to climatic change for the African continent in order to identify “hot spots” of potential high vulnerability. Relying on both resilience and natural hazards literatures, we define vulnerability as a function of the sensitivity and adaptive capacity of socioecological systems when exposed to environmental and climatic changes (Turner et al. 2003; Yohe and Tol 2002; Kuriakose et al. 2009).

Building on prior work (López-Carr et al. 2012), we identify these locations by developing and mapping an integrative measure of spatial and temporal changes in precipitation distribution and demographic parameters at continental scales with a spatial resolution of 5 km^2. We do so by integrating demographic distribution data as a function of both total population and children-under-five density, distribution, and change in density, with a 30-year precipitation change analysis for the African continent. We use spatial clustering analyses to identify spatially explicit and statistically significant pockets of change in combined precipitation and population distribution patterns, deemed to be potential vulnerability hot spots. Such an integrated spatio-temporal analysis facilitates a spatial quantification of potential population vulnerability hot spots.

The following section introduces our conceptual framework and background literature for mapping population vulnerability to climate change in Africa. The subsequent section explains the data and analytical methods. Results of cluster and mapping analyses are then presented in the “Results and Discussion” section, followed by a concluding statement on research limitations and significance of the results for policy and future research.

Population vulnerability to climate change in Africa

Scholars have identified a need to increase understanding of coupled physical and social changes in African ecosystems in order to identify vulnerable people and locations as well as potential adaptive strategies in the face of anticipated climate and environmental change impacts (e.g., An and López-Carr 2012; Thornton et al. 2011), but only a small portion of the vulnerability literature to date has explicitly focused on population age, distribution, and location as central exposure elements at a continental scale. The contribution of components of population dynamics—such as growth, migration, urbanization, aging, and household composition—to mitigation and adaptation programs requires further investigation (Stephenson et al. 2010). Given the rapid increase and predominantly rural and youthful population of the African continent, population dynamics play a particularly pertinent role in examining vulnerability to climate change in the region.

The African continent is by most measures the world's most vulnerable region to long-term decreases in rainfall and seasonal rainfall variability (Collier et al. 2008; Hope 2009; Cooper et al. 2008; Verdin et al. 2005; Durack et al. 2012; Haile 2005; Christensen et al. 2007; Fischer et al. 2005). Negative consequences of climate change are anticipated overall for Africa where over 95 % of the farmers subsist on rain-fed land (Muller et al. 2011). By 2050, over half of the currently cropped land in most African nations will fall under climate regimes currently absent within those countries' boundaries (Burke et al. 2009). Knox et al. (2012) estimate reductions of up to 50 % in some of Africa's primary crops, especially maize, wheat, sorghum, and millet. Brown et al. (2011) and Barrios et al. (2010) find that rainfall decline in sub-Saharan Africa during the twentieth century is a partial explanation for the economic situation of these nations, which lags behind that of other nations. Water scarcity is expected to increase in large areas of Africa (Fung et al. 2011), and malaria will move into heavily settled highland environments in eastern Africa (Chaves and Koenraadt 2010). Increasing temperatures have also been suggested to aggravate civil conflict (Burke et al. 2010), while rainfall decline has been linked to rural out-migration to cities in Africa, a trend likely to become exacerbated (Barrios et al. 2006).

Within Africa, the majority rural population remains particularly vulnerable to climate change. While climate dynamics also affect urban populations (Kovats and Akhtar 2008), African rural communities are predicted to be among the globe's most vulnerable to climatic changes (Schlenker and Lobell 2010; Samson et al. 2011; Morand et al. 2012). The level of vulnerability and the adaptive capacity of both individual small farmers and communities are dynamically described by the interactions of culture, existing resource distributions, historical patterns of domination and marginalization, and environment (Eakin and Luers 2006; Brondizio and Moran 2008). Large farms can become more vulnerable to climatic changes, owing to inherent risks in large-scale mono-cropping; yet these farms are more likely to have resources to cope with such changes. Conversely, smallholder farmers face technological limitations, little access to extension services, and market disadvantages that affect coping capacity (Brondizio and Moran 2008).

While all individuals will become increasingly exposed to climate-induced disease pathways in the future, children are particularly vulnerable due to their physiological and cognitive immaturity (sensitivity) and limited ability to change their situation (adaptive capacity) (Shea and The Committee on Environmental Health 2007; Seal and Vasudevan 2011). The World Health Organization asserts that "the major diseases most sensitive to climate change—diarrhea, vector-borne disease such as malaria, and infections associated with under-nutrition—are most serious in children living in poverty" (World Health Organization 2009). Childhood diseases have a lifelong impact, resulting in a higher probability of decreased overall wellness and diminished human capital later in life.

Hot spot mapping of population vulnerability to climate change

Multiscale and multistressor vulnerability assessments of coupled human–environment systems are important for providing policy advice related to climate change, but these tasks remain challenging due to high spatial and temporal variability (Cutter et al. 2003; Antwi-Agyei et al. 2012). Mapping facilitates an exploration of multiple vulnerability stressors simultaneously in a given spatial context, highlighting locations where policy interventions may be crucial (O'Brien et al. 2004; Eakin and Luers 2006; Preston et al. 2011). However, choropleth map boundaries simplify spatial information by connoting threshold distinctions, belying internal heterogeneity in, for example, social vulnerability variables such as gender, race, class, age, and education within bounded spatial units (Cutter et al. 2003; O'Brien et al. 2004).

Mapping the distribution of vulnerability—including exposure, sensitivity, and adaptive capacity—has become a central tool for communicating with policy makers and local stakeholders (Eakin and Luers 2006). Vulnerability hot spots mapping can help policy makers visualize climate change impacts on the landscape to more effectively support risk management and spatial planning (Preston et al. 2011). In the past several years, there has been a notable expansion of efforts to map climate change hot spots. Some have been designed for vulnerable populations, agriculture and food security, and water scarcity, while others have mapped humanitarian crises and conflict (de Sherbinin 2013). Hot spot research to date has largely concentrated on vulnerability identification (Yusuf and Francisco 2009; Gbetibouo and Ringler 2009; Heltberg and Bonch-Osmolovskiy 2011).

Spatial uncertainty is associated with any regional analysis and can be usefully examined and clarified (Preston et al. 2011). While it is relatively straightforward to identify hot spots, it remains a more difficult task to examine vulnerability dynamics associated with a potential coupling between demographic changes and climate changes. The analysis in this paper allows us to identify regions facing the burden of increasing spatial and temporal precipitation variability (conceptualized as exposure) coupled with initially high and/or increasing population density (conceptualized as sensitivity). While calculating a vulnerability index for the continent is beyond the scope of this paper, we aim to identify regions of Africa where dense and rapidly growing human population clusters spatially coincide with observed

climate changes. We argue that locations of long-term decreasing trends in precipitation coupled with high and increasing human population densities represent potential hot spots of population vulnerability to climate changes and inherent food security. We aim to identify hot spots of (a) statistically significant total population and children-under-five density change coupled with (b) statistically significant decreasing trends in precipitation.

Data and methods

In a global analysis of human demography and climate change forecasts, Samson et al. (2011) identified regions of high vulnerability as those where a decline in favorable climate conditions is collocated with high population density and rapid population growth. Most of Africa emerged as highly vulnerable in this assessment. We build on Samson et al.'s work by enhancing the spatial resolution with state-of-the-art climate and population data in mapping an integrative measure of population vulnerability to climatic and demographic change for the African continent and in identifying statistically significant hot spots of high vulnerability for this combined measure.

For precipitation change, we identify regions over the entire continent of Africa where significant changes in rainfall have occurred during the main growing season months within the last 30 years using rainfall data compiled by the Famine Early Warning Systems (FEWS) Network. Assuming some temporal lag between climate change and its impact on humans, we analyze two decades of precipitation change prior to our examination of population change. To measure the population density change, we focus on regions where 2010 human population density is high and significant increases in density from 1990 to 2010 have occurred; additionally, we examine where significant changes in children-under-five densities have occurred from 2000–2010 and are projected for 2015. Our methods involve three consecutive steps as described below. Table 1 presents a comprehensive list of type, source, and temporal/spatial resolutions of the data utilized in the paper.

Analysis of population dynamics

To calculate the population change between 1990 and 2010, we used the Global Rural–Urban Mapping Project (GRUMPv1) 1990 and 2000 population density grids at 30-arc second grid resolution ($\sim$1-km grid) from NASA's Socioeconomic Data and Applications Center (SEDAC). We augment this with the 1-km grid resolution 2010 AfriPop population density map, the most up-to-date and accurate population density dataset in existence for Africa. The GRUMPv1 and AfriPop datasets are based on inherently different methods of aggregating population estimates at administrative levels, hence resulting in functionally different spatial resolutions, which hinder direct population change estimates. In order to arrive at spatial estimates of approximate population change from 1990 to 2010, we combined the two datasets and calculated a standardized pixel-by-pixel distribution of population density for the African continent, using the GRUMP data to weigh the AfriPop 2010

Table 1 Precipitation and population data used at the continental scale

Data	Spatial scale	Temporal scale	Source
Standardized precipitation index (observed rainfall)	5 km; continental scale	1979–2010	FEWS Net CHARM
AfriPop population density	1 km; continental scale	2010	WORLD POP
AfriPop under-five children density	1 km; continental scale	2000, 2005, 2010, 2015	WORLD POP
Global rural and urban mapping project (GRUMPv1) population density	1 km; continental scale	1990, 1995, 2000	SEDAC CIESIN

data by a factor reflecting the proportionate growth from 1990 to 2000 (Pricope et al. 2013). In essence, we divided the GRUMP 2000 data by the GRUMP 1990 data and multiplied the result by the AfriPop 2010 data, thus allowing us to combine the high-resolution 2010 population data with population density changes from 1990 to 2000.

We additionally calculate a percent change distribution map of children-under-five from 2000 to 2015. AfriPop launched the *alpha* version Africa-wide 1-km dataset in 2012; it contains five-yearly time steps of density data for children less than five years of age from 2000, including a projection for 2015. The AfriPop demography data are based on a unique combination of the most recent country-specific census and survey data, satellite imagery, and expert knowledge to map settlements and populations, combined with land cover, infrastructure, and other geospatially referenced ancillary data (Linard et al. 2012; Tatem and Linard 2011).

Analysis of precipitation dynamics

Precipitation changes were measured by coupling available gauge and satellite data using the Climate Hazards Group InfraRed Precipitation with Stations data (CHIRPS) precipitation dataset. CHIRPS is a 0.05° (~ 5-km grid) spatial resolution dataset from 1979 to 2010 available at ftp://chg-ftpout.geog.ucsb.edu/pub/org/chg/products/CHIRPS-latest. CHIRPS blends infrared geostationary satellite observations with in situ station observations to produce monthly grids. For each location, a 1979–2010 time series of main growing season rainfall was produced, based on the 3-month period with the highest climatological 3-month mean rainfall. Time series of these 3-month accumulations was then transformed into standardized precipitation index (SPI) time series. The SPI calculates rainfall anomalies from main growing season monthly precipitation as normalized variables which convey the probabilistic significance of the observed or estimated rainfall in locations where the rainfall regime remains poorly understood (McKee 1993). The CHIRPS SPI dataset for Africa was produced using gamma distributions to parameterize historical

rainfall amounts (Husak et al. 2007). We used the mean growing season monthly SPI data for 1981 to 1998 and 1999 to 2010 to determine the difference between the average growing season precipitation values in the decade prior to the major 1998 El Niño (Galvin et al. 2001) and the ensuing, drier decade. The justification for the 1979–1998 versus 1999–2010 partitioning is based on recent research detailing a substantial shift (Lyon and DeWitt 2012; Funk et al. 2012) in the Indo-Western Pacific circulation after 1998. As a consequence of this circulatory shift, sea surface temperatures (SST) and precipitation in the Indo-Western Pacific (15S–15N, 60–170E) increased dramatically (Lyon and DeWitt 2012; Funk et al. 2012) and may have been linked to the 2011 East African drought that led to widespread famine (Lyon and DeWitt 2012) as well as the increased frequency of drought in East Africa in recent years.[1]

The difference in pixel-by-pixel rainfall estimates between the two time periods (Fig. 2) was then used in a local clustering analysis to determine drying trend hot spots in precipitation.

Analysis of significant hot spots resulting from the spatial coincidence of drying precipitation and population change from 1990 to 2010

Building toward an understanding of vulnerability as the confluence of exposure and sensitivity, we integrated the exposure climate product with a sensitivity component represented by our population density measure and by under-five percent density change from 2000 to 2015. Following our calculations of population density and change measure using the GRUMPv1 and AfriPop products, we applied the Getis-Ord *Gi** local clustering method to locate statistically significant “hot” and “cold” spots in our data (Getis and Ord 1992). Our approach consisted of several steps that were performed similarly on both population data and precipitation data in the following sequential order. First, we began by resampling the population data to match SPI (to a common 5-km grid resolution). Second, we exported both the population change and SPI datasets to point data, reprojected them to a common projection system (Lambert Conformal Conic, WGS 84) and calculated the Global Moran’s I to determine the most appropriate, statistically significant distance band to use in the calculation of hot and cold spots for the *Gi** analysis. Given the inherently different nature of our datasets, we calculated the Global Moran’s I incremental spatial autocorrelation on the 5-km resolution SPI difference precipitation data. The maximum peak distance band occurred at approximately 250 km (Moran’s Index = 0.499990, z-score = 2534.683371, $p = 0.000000$). To determine the most appropriate distance band for our population data, we used a distance

[1] A detailed examination of the latest phase 5 Coupled Model Intercomparison Project (CMIP5) simulations and a suite of climate reanalyses indicate that the coupled models recreate this recent warming. Observations indicate, however, that the 1999–2011 period is associated with an exceptionally strong western-to-central tropical Pacific SST gradient, increased western Pacific sea level heights, and an intensification of the Walker circulation. The interaction between strong gradient events and ENSO enhances the impact of La Niña events in Africa (Williams and Funk 2011; Hoell and Funk 2013) and supports the threshold we used to analyze drying trends in Africa relative to the 1998 event.

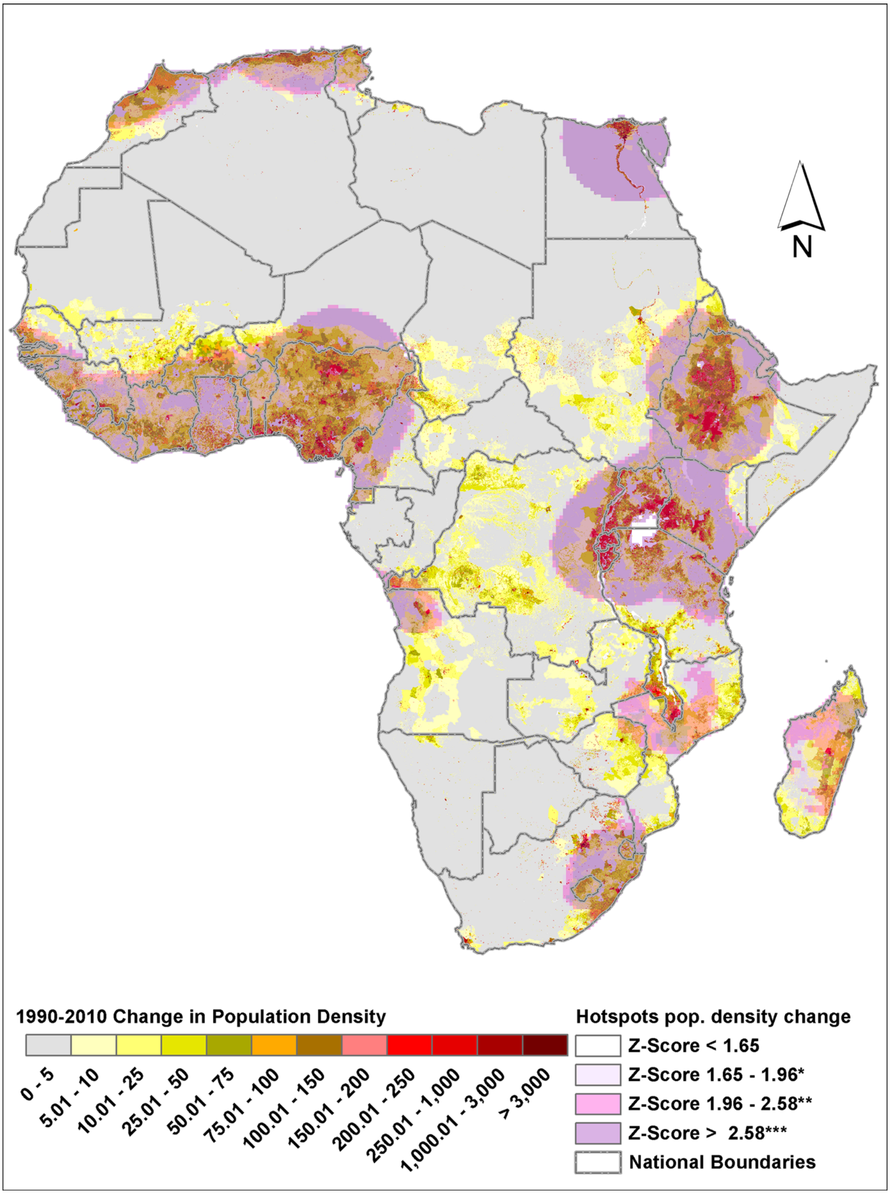

Fig. 1 Areas of overlap between the original GRUMPv1 (1990 and 2000) and AfriPop (2010) combined product that approximates areas of change in population density from 1990 to 2010 and the result of the 250-km fixed-distance band Getis-Ord *Gi** local clustering hot spot analysis on the same dataset (*0.05 significance, **0.01 significance, ***0.001 significance)

band of 250 km derived from the mean area (60,232 km^2) of all enumeration polygons from the most recent Demographic and Health Survey (DHS) dataset for each African country (n = 426 DHS region polygons). DHS enumeration polygons

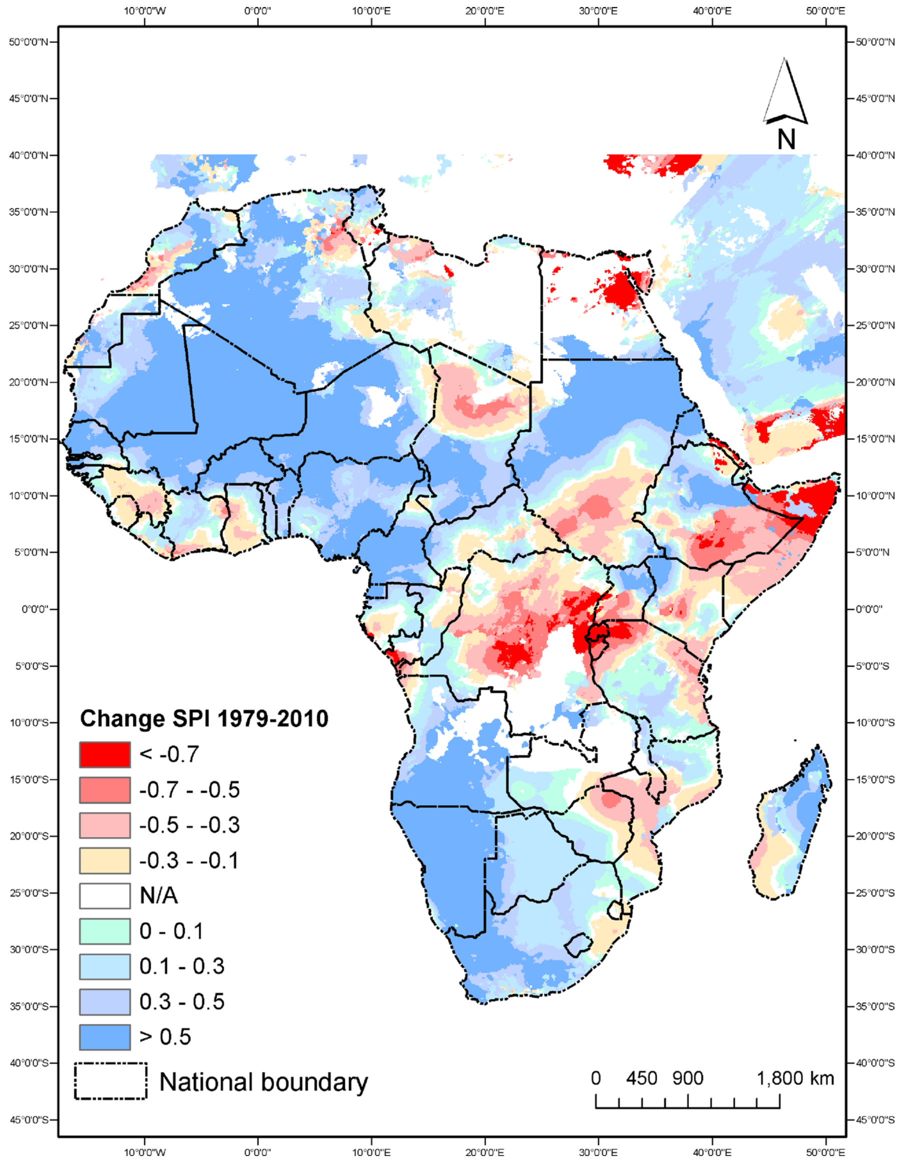

Fig. 2 Change in the standardized precipitation index (SPI) expressed as a difference between the 1979–1998 and the 1999–2010 3-month wet season precipitation

were used to determine a distance band for the population analysis, as these polygons carry meaning for demographic-related patterns and policy outcomes.

Third, we performed local clustering Getis-Ord *Gi** analyses on both datasets using an inverse distance conceptualization of spatial relationships for our SPI analysis and a fixed-distance band for the population change data with the threshold distance bands presented above. We subsequently exported the z-scores,

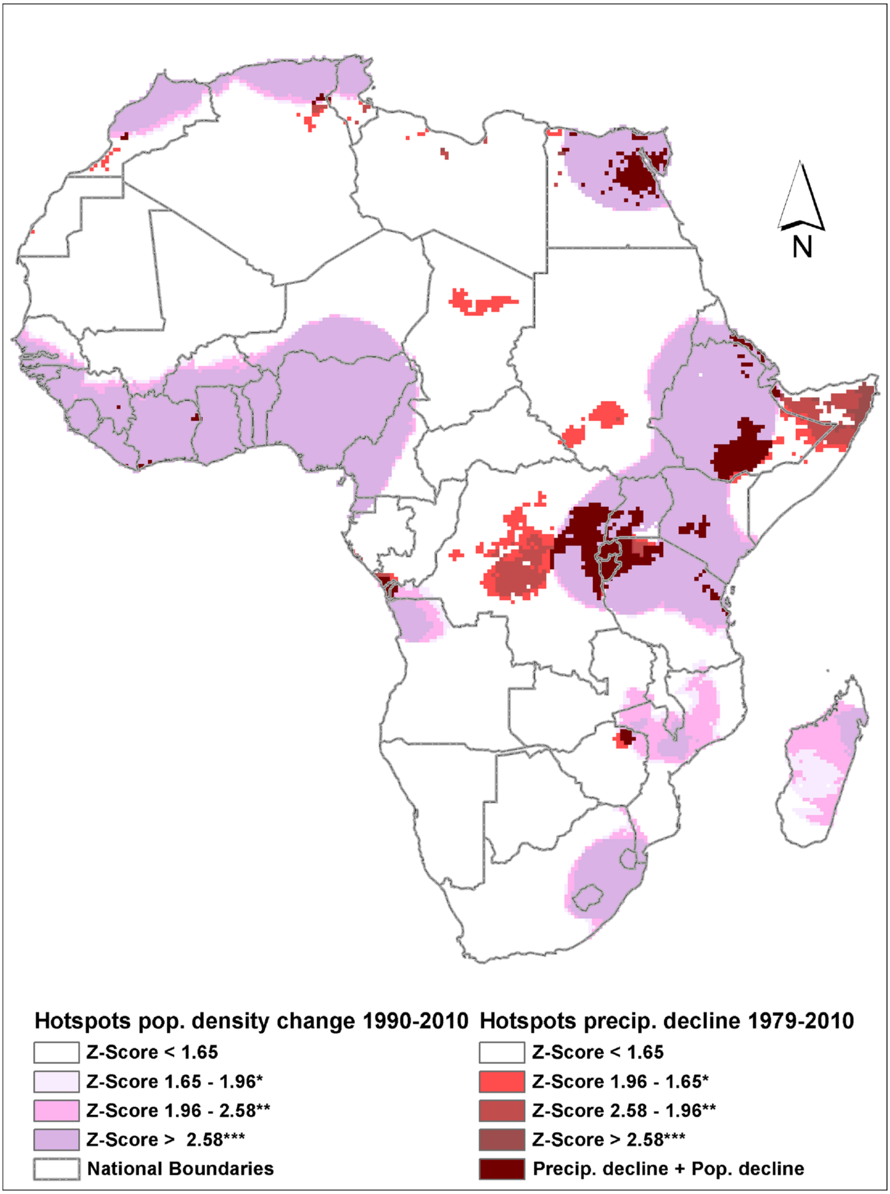

Fig. 3 Areas of overlap between hot spots of population density change calculated using the Getis-Ord *Gi** 250 km local clustering algorithm on the combined GRUMPv1 (1990 and 2000) and AfriPop (2010) datasets and hot spots of precipitation decline as calculated using the Getis-Ord *Gi** 250 km local clustering algorithm on the standardized precipitation index (SPI) dataset for 1979 to 2010 (*0.05 significance, **0.01 significance, ***0.001 significance)

indicating hot or cold spots from the Gi* analysis for both datasets, into raster format. We then performed spatial overlays of the hot spots of population increase in 2010 relative to 1990 with drying precipitation trends for the last thirty years at

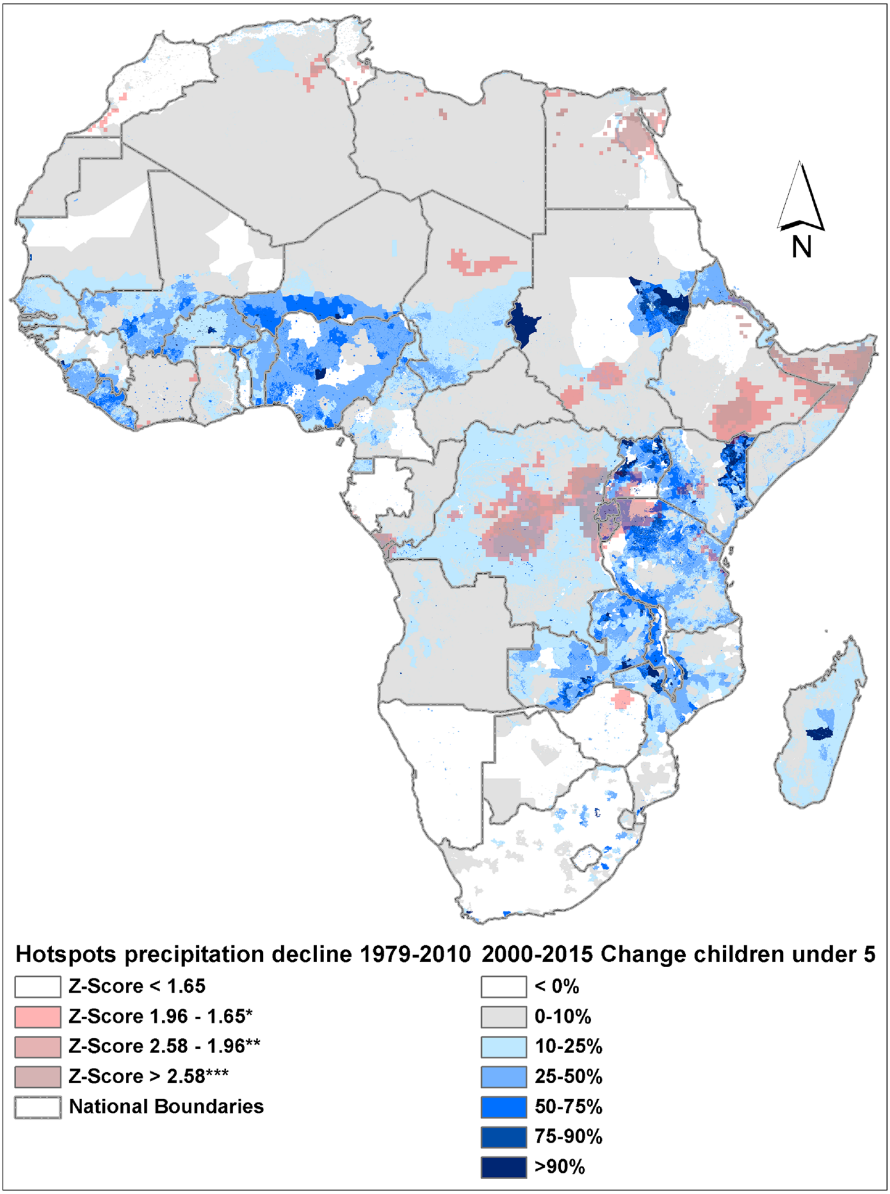

Fig. 4 Areas of overlap between hot spots of precipitation decline as calculated using the Getis-Ord *Gi** 250 km local clustering algorithm on the standardized precipitation index (SPI) dataset for 1979 to 2010 (*0.05 significance, **0.01 significance, ***0.001 significance) and percent changes in the population of children-under-five from 2000 to 2015 (projected)

the continental scale (Fig. 3). Finally, we used the derived precipitation hot spots to create overlays with the percent changes in under-five distribution for the African continent (Fig. 4).

Results and discussion

Hot spots of population change

Figure 1 illustrates the spatial distribution of population density dynamics from 1990 to 2010, based on the combined GRUMPv1 for 1990 and 2000 and AfriPop 2010 population density estimates. The results of the Getis-Ord *Gi** local hot spot analysis are overlain (in purple) as bands radiating out from areas of high population density and change. Regions where population increased by more than 5 people/km^2 in 2010 relative to 1990 are displayed in light yellow tones, while dark red tones connote population increase greater than 3,000 people/km^2. Hot spots of population density dynamics are presented as z-score values in three major categories of significance, ranging from 0.05 (z-scores between 1.65 and 1.96) to 0.001 (z-scores higher than 2.58). The regions of the greatest population dynamism are concentrated mainly along the western African Atlantic coast, from Senegal to Equatorial Guinea and up into southern Niger, and in the east African region of the Ethiopian highlands and Lake Victoria, encompassing Uganda, Rwanda, Burundi, Kenya, and parts of Tanzania. Another significant hot spot of population change is located along the Mediterranean coast of Morocco, Algeria, and Tunisia, as well as across the Nile Delta. Smaller hot spots are observed in the vicinity of the Congo Delta, in the Democratic Republic of Congo (DRC), in northern Angola, in the Lake Malawi basin and in southeastern Africa, in Madagascar, in Mozambique, and in eastern South Africa, including Lesotho and Swaziland.

Hot spots of declining rainfall and population change

A continental map depicting the standardized precipitation index (SPI) change between 1979–1998 and 1998–2010 is presented in Fig. 2. SPI values greater than zero indicate conditions wetter than the median, while negative SPI values indicate drier than median conditions. The magnitude of decline in SPI for Africa during the study period exceeds -0.7, with minimum values of -1.56 in parts of eastern and northern Africa. Typically, in drought analyses, negative SPI values exceeding -1 indicate moderate drying, while values greater than -1.5 indicate a one-in-fifteen-year desiccation event, characteristic of severe drought (Funk et al. 2003). Prolonged drying emerges in several regions including northeastern Egypt, the Eritrean coast, eastern and south-central Ethiopia, throughout the horn region of Somalia, coastal Congo, and much of the inland Democratic Republic of the Congo. Also, salient in the analysis are extensive declines in SPI across Rwanda, Burundi, and northwestern Tanzania. Regions with less significant precipitation decreases over the 32-year period traverse much of central tropical and subtropical Africa, coastal southern Africa (particularly Malawi, Mozambique, South Africa, and Madagascar), and the west and north African coasts (Fig. 2).

Similar to the Getis-Ord *Gi** local demographic clustering analysis results presented in the previous section, in Fig. 3 we overlay three classes of z-scores at different significance intervals. The primary node demonstrating a coinciding decline in precipitation and high population growth and density is the Lake Victoria

basin, from eastern DRC, fully encompassing Rwanda and Burundi, and extending to northern Tanzania and southern Uganda (neighboring areas highlighted in dark red in Fig. 3). Similar hot spots emerge in central Kenya, the agro-pastoralist region of southern Ethiopia, and along the Djibouti and Eritrean coasts. The third highly significant area of climatic–demographic convergence occurs in central and northern Egypt, including the southern tip of the Sinai Peninsula and along the Mediterranean coast, the West African Atlantic coast, and the Congo–Angola littoral. Additional regions in Africa are experiencing declining precipitation trends, highlighted in our hot spot analysis, notably the horn of Somalia and the eastern tip of Ethiopia, central DRC, Chad, South Sudan, and northern Zimbabwe.

Finally, Fig. 4 displays change in total population under 5 years of age between 2000 and 2015 calculated using AfriPop demography data overlaid with the hot spots of observed precipitation declines. A near-doubling in 15 years of children-under-five is observed in pockets of the central African Rift Valley, Darfur, northern Nigeria, and eastern Kenya. The greatest under-five increases occur along the eastern border of Somalia and Kenya, currently home to the world's largest refugee camp (Dadaab), parts of Sudan, Malawi, Zambia, Mozambique, Tanzania, most of Uganda, and large swaths of western Africa. These areas presage continued population momentum over the coming decades, potentially complicating efforts to curb population growth and, thus, the magnitude of population exposure to climate change. These areas do not generally overlap with hot spots of reduced precipitation, except in the Lake Victoria region where currently some of the strongest associations between observed precipitation declines and 1990 to 2010 population density and increase have been recorded.

Boreal spring rains in eastern Kenya, eastern Ethiopia, and southern Somalia have been declining (Funk et al. 2012), and the rapid increase in children-under-five in this area may pose significant food security challenges. In 2010/2011, the combination of a naturally occurring La Niña-related fall drought and an anthropogenically enhanced spring drought resulted in an estimated 258,000 deaths in Somalia. The associated mortality rate for children-under-five in southern and central Somalia was greater than 10 percent, resulting in some 133,000 deaths. In this context, rapid increases in population densities of children-under-five in southeastern Ethiopia and eastern Kenya may indicate a salient spatial confluence of exposure and sensitivity.

Conclusion

In this paper, we identified regions that have experienced significant decreases in precipitation over a recent 30-year period and correlated those drying trends with changes in population density and in populations of children under 5 years of age. Coupled trends of rapidly swelling populations and dramatic drying of agricultural lands converge across some of the most destitute regions on the globe's poorest continent. People located in the regions highlighted in this analysis, particularly central, southern, and eastern Africa, are not only highly exposed to climate change (increased population on land with decreased rainfall), but they are also among the

most socioeconomically marginalized, with extremely low mean annual earnings and generally poor educational and employment possibilities. Specifically, results demonstrate that increasing population in some areas (such as the East African Horn) and a near-doubling of children-under-five between 2000 and 2015 (projected) are observed in areas experiencing significant drying precipitation trends. The highly populated Lake Victoria basin emerges as a salient hot spot in our analysis. This dual population–climate burden is exacerbated in this region by recurrent droughts and flooding associated with increasing rainfall variability and the associated detrimental effects on human health, especially malaria and diarrhea.

The impact of possible changes on rainfall intensity or extreme events adds complexity to the implications of our results. Individuals are not only vulnerable to changes in average rainfall but also, and sometimes more markedly, to the changes in rainfall distribution over the course of a year and changes in rainfall seasonality. Average rainfall levels may change little, but if rain falls only at one time in the seasonal calendar or too late or too early in the agricultural cycle, crops and therefore rural livelihoods may suffer.

By mapping and analyzing spatial and temporal climatic variability in conjunction with demographic density distribution and change, we aim to enhance future understanding of geographical variability in factors predictive of vulnerability to climate change (Meyerson et al. 2007; Samson et al. 2011). Further results based on this continental-scale analysis may provide estimates and locations of future numbers of children vulnerable to climate-change-related morbidity and mortality. These results may contribute to our understanding of local adaptation needs and mitigation mechanisms to current and future environmental change.

Population vulnerability to climate change at local and regional scales is characterized by complex multidimensionality in causes, pathways, and outcomes. As livelihood zones shift due to climate change, one adaptation will increasingly be out-migration, thus increasing population pressures in less vulnerable areas (Barbieri et al. 2010). Despite the need for integrated analyses of policies and impacts of climate-change-related adaptation and mitigation, research has been limited by the disciplinary gap between climate scientists and social scientists (O'Neill and Schweizer 2011). The richness of our integrated data at a continental scale is relatively rare today, but we believe that it represents the future of integrated geographical, climate, environmental, and sociological research. We hope our research may help foster improved spatial analysis in the context of challenging population–climate change dynamics in Africa and other global regions facing similar challenges.

Acknowledgments This work was supported through USGS cooperative agreement #G09AC000001 "Monitoring and Forecasting Climate, Water and Land Use for Food Production in the Developing World," with funding from the NASA Applied Sciences Program, Decisions award #NN10AN26I for "A Land Data Assimilation System for Famine Early Warning," and SERVIR award #NNH12AU22I for "A Long Time-Series Indicator of Agricultural Drought for the Greater Horn of Africa"; USAID Office of Food for Peace, award #AID-FFP-P-10-00002 for "Famine Early Warning Systems Network Support"; and the USGS Land Change Science Program. The work was also partially supported by a National Oceanic and Atmospheric Administration (NOAA) and Climate Scene Investigators (CSI)—Transitions Program Grant: A Global Standardized Precipitation Index Supporting the US Drought Portal and the Famine Early Warning System Network. We would also like to acknowledge Jim Regetz and Alex

Zvoleff for statistical and computing consultation and Shuang Yang for assisting in our hot spot analysis literature review.

References

An, L., & López-Carr, D. (2012). Modeling coupled human-natural systems: Research directions. *Ecological Modeling, 229*, 1–4.

Antwi-Agyei, P., Fraser, E. D. G., Dougill, A. J., Stringer, L. C., & Simelton, E. (2012). Mapping the vulnerability of crop production to drought in ghana using rainfall, yield and socioeconomic data. *Applied Geography, 32*, 324–334. doi:10.1016/j.apgeog.2011.06.010.

Barbieri, A. F., Domingues, E., Queiroz, B. L., Ruiz, R. M., Rigotti, J. I., Carvalho, J. A., et al. (2010). Climate change and population migration in Brazil's Northeast: scenarios for 2025–2050. *Population and Environment, 31*(5), 344–370.

Barrios, S., Bertinelli, L., & Stroble, E. (2006). Climatic change and rural-urban migration: The case of sub-Saharan Africa. *Journal of Urban Economics, 60*(3), 357–371.

Barrios, S., Bertinelli, L., & Stroble, E. (2010). Trends in rainfall and economic growth in Africa: A neglected cause of the African growth tragedy. *Review of Economics and Statistics, 92*(2), 350–366.

Brondizio, E. S., & Moran, E. F. (2008). Human dimensions of climate change: The vulnerability of small farmers in the Amazon. *Philosophical Transactions of the Royal Society B: Biological Sciences, 363*(1498), 1803–1809.

Brown, C., Meeks, R., Huni, K., & Yu, W. (2011). Hydro climate risk to economic growth in sub-Saharan Africa. *Climatic Change, 106*(4), 621–647.

Burke, M. B., Lobell, D. B., & Guarino, L. (2009). Shifts in African crop climates by 2050 and the implications for crop improvement and genetic resources conservation. *Global Environmental Change, 19*(3), 317–325.

Burke, M. B., Miguel, E., Satyanath, S., Dykema, J. A., & Lobell, D. B. (2010). Climate robustly linked to African civil war. PNAS 107(51).

Chaves, L. F., & Koenraadt, C. H. (2010). Climate change and highland malaria: Fresh air for a hot debate. *The Quarterly Review of Biology, 85*(1), 27–55.

Christensen, J. H., Hewitson, A., Busuioc, A., Chen, A., Gao, X., Held, R., Jones, R., Kolli, R. K., Kwon, W. K., & Laprise, R. (2007). Regional climate projections. In Climate change: The physical science basis. Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change, pp 849–940. Cambridge: Cambridge University Press.

Collier, P., Conway, G., & Venables, T. (2008). Climate change and Africa. *Oxford Review of Economic Policy, 24*, 337–353.

Cooper, P., Dimes, J., Rao, K., Shapiro, B., Shiferaw, B., & Twomlow, S. (2008). Coping better with current climatic variability in the rain-fed farming systems of sub-Saharan Africa: An essential first step in adapting to future climate change? *Agriculture, Ecosystems & Environment, 126*, 24–35.

Cutter, S. L., Boruff, B., & Shirley, W. (2003). Social vulnerability to environmental hazards. *Social Science Quarterly, 84*(2), 242–261.

de Sherbinin, A. (2013). Climate change hotspots mapping: What have we learned? *Climatic Change,*. doi:10.1007/s10584-013-0900-7.

Durack, P. J., Wijffels, S. E., & Matear, R. J. (2012). Ocean salinities reveal strong global water cycle intensification during 1950 to 2000. *Science, 336*, 455–458.

Eakin, H., & Luers, A. L. (2006). Assessing the vulnerability of social-environmental systems. *Annual Review of Environment and Resources, 31*, 365–394. doi:10.1146/annurev.energy.30.050504.144352.

Fischer, G., Shah, M., Tubiello, F. N., & Van Velhuizen, H. (2005). Socio-economic and climate change impacts on agriculture: An integrated assessment, 1990–2080. *Philosophical Transactions of the Royal Society B: Biological Sciences, 360*, 2067–2083.

Frank, E., Eakin, H., & López-Carr, D. (2011). Social identity, perception and motivation in adaptation to climate risk in the coffee sector of Chiapas, Mexico. *Global Environmental Change, 21*(1), 66–76.

Fung, F., Lopez, A., & New, M. (2011). Water availability in +2 Centigrade and +4C worlds. Phil. Trans. R. Soc. A 369: 1934 99–116.

Funk, C., Michaelsen, J., & Marshall, M. (2012). Mapping recent decadal climate variations in precipitation and temperature across Eastern Africa and the Sahel, Chapter 14. In: Wardlow, B.,

Anderson, M., Verdin, J. (Eds.), *Remote sensing of drought: Innovative monitoring approaches*. Taylor and Francis, 25 p.

Funk, C., Michaelson, J., Verdin, J., Artan, G., Husak, G., Senay, G., et al. (2003). The collaborative historical African rainfall model: Description and evaluation. *International Journal of Climatology, 23*, 47–66.

Galvin, K. A., Boone, R. B., Smith, N. M., & Lynn, S. J. (2001). Impacts of climate variability on East African pastoralists: Linking social science and remote sensing. *Climate Research, 19*, 161–172.

Gbetibouo, G. A., & Ringler, C. (2009). Mapping South African farming sector vulnerability to climate change and variability in demographic trends and future carbon emissions. *Proceedings of the National Academy of Sciences* (PNAS), 107(41): 17521–17526; doi:10.1088/1748-9326/5/1/014010 (http://iopscience.iop.org/1748-9326/5/1/014010/fulltext/).

Getis, A., & Ord, K. (1992). The analysis of spatial association by use of distance statistics. *Geographical Analysis, 24*, 189–206.

Haile, M. (2005). Weather patterns, food security and humanitarian response in sub-Saharan Africa. *Philosophical Transactions of the Royal Society B: Biological Sciences, 360*, 2169–2182.

Heltberg, R., & Bonch-Osmolovskiy, M. (2011). Mapping vulnerability to climate change. World Bank policy research working paper series, vol 24.

Hoell, A., & Funk, C. (2013). The anomalous circulation associated with the ENSO-related west pacific sea surface temperature gradient. *Climate Dynamics* (in review).

Hope, K. R. (2009). Climate change and poverty in Africa. *International Journal of Sustainable Development and World Ecology, 16*, 451–461.

Husak, G., Michaelsen, Joel, & Funk, Chris. (2007). Use of the gamma distribution to represent monthly rainfall in Africa for drought monitoring applications. *International Journal of Climatology, 27*, 935–944.

Knox, J., Hess, T., Daccache, A., & Wheeler, T. (2012). Climate change impacts on crop productivity in Africa and South Asia. *Environmental Research Letters*, 7(3).

Kovats, S., & Akhtar, R. (2008). Climate, climate change and human health in Asian cities. *Environment and Urbanization, 20*(1), 165–175.

Kuriakose, A., Livia, B., & Bachofen, C. (2009). *Assessing vulnerability and adaptive capacity to climate risks: Methods for investigation at local and national levels*. Washington, DC: World Bank.

Linard, C., Gilbert, M., Snow, R. W., Noor, A. M., & Tatem, A. J. (2012). Population distribution, settlement patterns and accessibility across Africa in 2010. *PLoS ONE, 7*(2), e31743.

López-Carr, D., & Pricope, N. G., Jankowska, M. M., Funk, C., Husak, G., & Michaelson, J. (2012). Mapping population vulnerability to climate change in Africa. Proceedings of the international union for the scientific study of population (IUSSP) international seminar on population dynamics and the human dimensions of climate change. Canberra, Australia.

Luers, A. L. (2005). The surface of vulnerability: An analytical framework for examining environmental change. *Global Environmental Change-Human and Policy Dimensions, 15*, 214–223.

Lyon, B., & DeWitt, D. G. (2012). A recent and abrupt decline in the East African long rains. *Geophysical Research Letters, 39*, 2.

McLeman, R. (2010). Impacts of population change on vulnerability and the capacity to adapt to climate change and variability: A typology based on lessons from “a hard country”. *Population and Environment, 31*(5), 286–316.

Meyerson, F. A. B., Merino, L., & Durand, J. (2007). Migration and environment in the context of globalization. *Frontiers in Ecology and the Environment, 5*, 182–190.

Morand, P., Kodio, A., Andrew, N., Sinaba, F., Lemoalle, J., & Béné, C. (2012). Vulnerability and adaptation of African rural populations to hydro-climate change: experience from fishing communities in the Inner Niger Delta (Mali). *Climatic Change*. doi: 10.1007/s10584-012-0492-7 (http://link.springer.com/article/10.1007/s10584-012-0492-7/fulltext.html).

Muller, C., Cramer, W., Hare, W. L., & Lotze-Campen, H. (2011). Climate change risks for African agriculture. *PNAS, 108*(11), 4313–4315.

O’Brien, K., Leichenko, R., Kelkar, V., Venema, H., Aandahl, G., Tompkins, H., et al. (2004). Mapping vulnerability to multiple stressors: Climate change and globalization in India. *Global Environmental Change, 14*(4), 303–313.

O’Neill, B. C., & Schweizer, V. (2011). Projection and prediction: Mapping the road ahead. *Nature Climate Change, 1*(7), 352–353.

Preston, B. L., Yuen, E. J., & Westaway, R. M. (2011). Putting vulnerability to climate change on the map: A review of approaches, benefits, and risks. *Sustainability Science, 6*(2), 177–202. doi:10.1007/s11625-011-0129-1.

Pricope, N. G., Husak, G., Lopez-Carr, D., Funk, C., & Michaelsen, J. (2013). The climate-population nexus in the East African Horn: Emerging degradation trends in rangeland and pastoral livelihood zone. *Global Environmental Change, 23*, 1525–1541.

Samson, J., Berteaux, D., McGill, B. J., & Humphries, M. M. (2011). Geographic disparities and moral hazards in the predicted impacts of climate change on human populations. *Global Ecology and Biogeography, 20*(4), 532–544.

Schlenker, W., & Lobell, D. B. (2010). Robust negative impacts of climate change on African agriculture. *Environmental Research Letters, 5*, 014010.

Seal, A., & Vasudevan, C. (2011) Climate change and child health. Archives of disease in childhood.

Shea, K. M., & The Committee on Environmental Health. (2007) Global climate change and children's health. *Pediatrics* 120:e1359.

Stephenson, J., Newman, K., & Mayhew, S. (2010). Population dynamics and climate change: What are the links? *Journal of Public Health, 32*(2), 150–156.

Tatem, A., & Linard, C. (2011). Population mapping of poor countries. *Nature, 474*, 36.

Thornton, P. K., Jones, P. G., Ericksen, P. J., & Challinor, A. J. (2011). Agriculture and food systems in sub-Saharan Africa in a 4 C + world. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 369*, 117–136.

Turner, B. L., Kasperson, R. E., Matson, P. A., McCarthy, J. J., Corell, R. W., Christensen, L., et al. (2003). A framework for vulnerability analysis in sustainability science. *Proceedings of the National Academy of Sciences of the United States of America, 100*, 8074–8079.

Verdin, J., Funk, C., Senay, G., & Choularton, R. (2005). Climate science and famine early warning. *Philosophical Transactions of the Royal Society B: Biological Sciences, 360*, 2155.

Williams, P., & Funk, C. (2011). A westward extension of the warm pool leads to a westward extension of the walker circulation, drying eastern Africa. *Climate Dynamics*, V37.11-12, 2417–2435. http://www.springerlink.com/content/u0352236x6n868n2/fulltext.pdf.

Yohe, G., & Tol, R. S. J. (2002). Indicators for social and economic coping capacity—moving toward a working definition of adaptive capacity. *Global Environmental Change-Human and Policy Dimensions, 12*, 25–40.

Yusuf, A. A., & Francisco, H. (2009). Climate change vulnerability mapping for Southeast Asia. Economy and Environment Program for Southeast Asia (EEPSEA), Singapore.