Climate change impacts in Sub-Saharan Africa: from physical changes to their social repercussions

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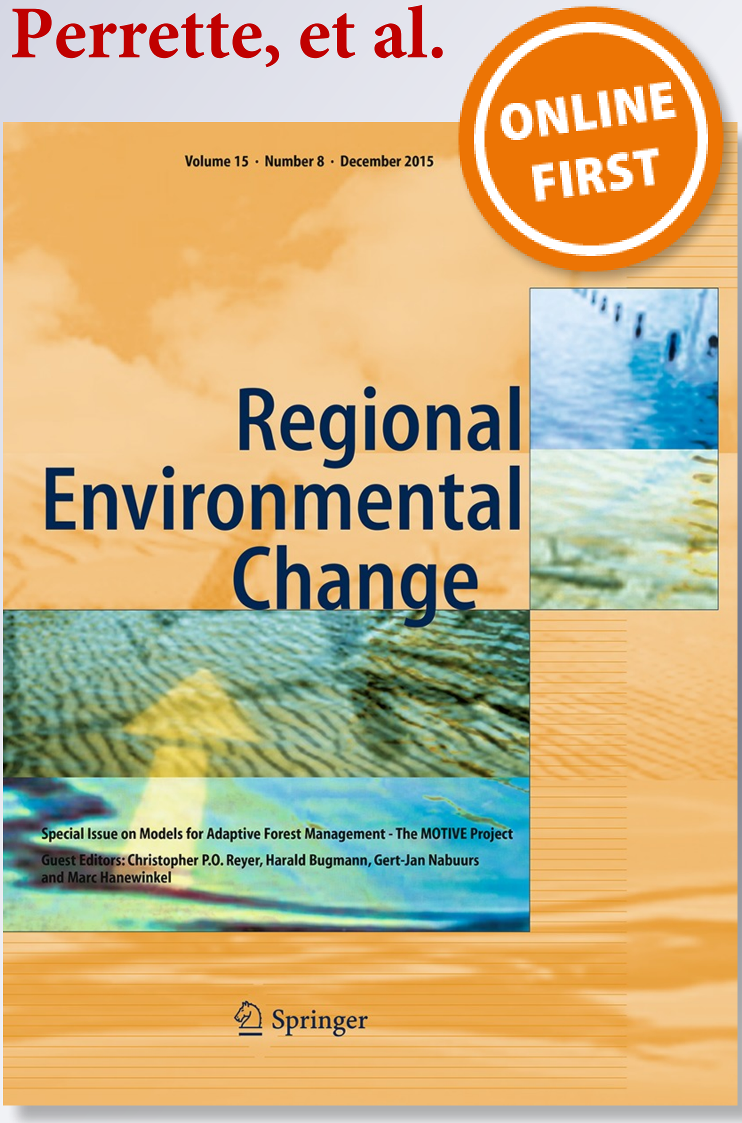

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ORIGINAL ARTICLE

Climate change impacts in Sub-Saharan Africa: from physical changes to their social repercussions

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Abstract The repercussions of climate change will be felt in various ways throughout both natural and human systems in Sub-Saharan Africa. Climate change projections for this region point to a warming trend, particularly in the inland subtropics; frequent occurrence of extreme heat events; increasing aridity; and changes in rainfall—with a particularly pronounced decline in southern Africa and an increase in East Africa. The region could also experience as much as one meter of sea-level rise by the end of this century under a 4 °C warming scenario. Sub-Saharan Africa's already high rates of undernutrition and infectious disease can be expected to increase compared to a scenario without climate change. Particularly vulnerable to these climatic changes are the rainfed agricultural systems on which the livelihoods of a large proportion of the region's population currently depend. As agricultural livelihoods become more precarious, the rate of rural–urban migration may be expected to grow, adding to the already significant urbanization trend in the region. The movement of people into informal settlements may expose them to a variety of risks different but no less serious than those faced in their place of origin, including outbreaks of infectious disease, flash flooding and food price increases. Impacts across sectors are likely to amplify the overall effect but remain little understood.

Keywords Climate change · Impacts · Vulnerability · Sub-Saharan Africa

Introduction

Africa has been identified as one of the parts of the world most vulnerable to the impacts of climate change (IPCC 2014; Niang et al. 2014). Here we present an overview of the impacts of climate change projected for the Sub-Saharan region of the continent. Where possible, we draw attention to how the magnitude of these impacts varies at different levels of warming—particularly those corresponding to 2 and 4 °C above pre-industrial levels. This paper offers a comprehensive understanding of how the repercussions of climate change are felt throughout both natural and human systems.

We combine original data analysis (heat extremes; precipitation; aridity) with probabilistic projections (regional sea-level rise) and a comprehensive literature review (sectoral and human impacts). For the original data analysis, data were obtained from five CMIP5 GCMs for which bias-corrected data were available (Hempel et al. 2013) as selected by Warszawski et al. (2013). Where possible, projections are presented for RCP2.6 and RCP8.5, which are used as scenarios representing 2 and 4 °C warming by 2100, respectively. For a detailed description of methods, please see Schellnhuber et al. (2013). Unless accounted for

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in individual models, projected impacts mostly do not include adaptation.

Social, economic and demographic profile of the Sub-Saharan region

Sub-Saharan Africa is a rapidly developing region of great ecological, climatic and cultural diversity (NASAC 2015). By 2050, its population is projected to approach 2 billion people—a figure which rises to nearly 4 billion by 2100 (UN Department of Economic and Social Affairs 2013). GDP growth increased from 3.7 % in 2012 to 4.7 % in 2013 although recent conflicts in the Central African Republic and South Sudan have led to interruptions to economic activity (World Bank 2013). National poverty rates have been declining in most Sub-Saharan African countries, with the exception of Mozambique, Cote d́Ivoire and Guinea, although Sub-Saharan still has the largest proportion of people living below the poverty line of all world regions (World Bank 2015b). Levels of stunting among children under 5 years of age as a result of chronic hunger are slowly declining but remain high at 39.6 % in 2011 (United Nations Children's Fund, World Health Organization and The World Bank 2012). Around one in four people in Sub-Saharan Africa is undernourished, amounting to a quarter of the world's undernourished people (FAO, IFAD and WFP 2014).

The agriculture sector employs 65 % of Africa's labor force and the sector's output has increased since 2000, mainly due to an expansion of agricultural area (World Bank 2013). Yield potential remains higher than actually achieved, with inadequate water and nutrients being the major limiting factors (Mueller et al. 2012). Agricultural production in Sub-Saharan Africa is particularly vulnerable to the effects of climate change, with rainfed agriculture accounting for approximately 96 % of overall crop production (World Bank 2015a). The production of crops and livestock other than pigs in Sub-Saharan Africa is typically located in semiarid regions (Barrios et al. 2008). In Botswana, for example, pastoral agriculture represents the chief source of livelihood for over 40 % of the nation's residents, with cattle representing an important source of status and well-being for the vast majority of Kalahari residents (Dougill et al. 2010). Relative poverty, which often limits adaptive capacities of the local population and thus increases vulnerability, is generally highest in highland temperate, pastoral and agro-pastoral areas (Faures and Santini 2008).

Higher food prices leading to currency depreciation and conflict and emerging security threats have been identified as a key risk to economic growth in the region (World Bank 2013). Several historical case studies have identified a connection between rainfall extremes and reduced GDP because of reduced agricultural yields. Kenya suffered annual damages of 10–16 % of GDP, not accounting for indirect losses, because of flooding associated with the El Niño in 1997–1998 and the La Niña drought 1998–2000. The majority of flood losses were incurred in the transport sector, and the drought event lead to a 41 % decline in hydropower production and high costs to industrial production and agricultural losses (World Bank 2004). Similarly, historical temperature increases have had substantial negative effects on agricultural value added in developing countries. A 1 °C increase in temperature in developing countries has been found to be associated with 2.66 % lower growth in agricultural output, leading to estimates of economic growth reductions by an average of 1.3 percentage points for each degree of warming (Dell and Jones 2012) and reductions in export growth by 2.0–5.6 percentage points (Jones and Olken 2010).

Regional patterns of climate change

Temperature changes

Projected warming is slightly less strong than that of the global land area, which is a general feature of the Southern Hemisphere. In the low-emission scenario RCP2.6 (representing a 2 °C world), African summer temperatures increase until 2050 at about 1.5 °C above the 1951–1980 baseline and remain at this level until the end of the century. In the high-emission scenario RCP8.5 (representing a 4 °C world), warming continues until the end of the century, with monthly summer temperatures over Sub-Saharan Africa reaching 5 °C above the 1951–1980 baseline by 2100. Geographically, this warming is rather uniformly distributed, although inland regions in the subtropics warm the most (see Figure SOM 1). In subtropical southern Africa, the difference in warming between RCP2.6 and RCP8.5 is especially large. This is likely due to a positive feedback with precipitation: The models project a large decrease in precipitation here (see Fig. 2), limiting the effectiveness of evaporative cooling of the soil.

The normalized warming, indicating how unusual the warming is compared to fluctuations experienced in the past, shows a particularly strong trend in the tropics (Figure SOM 1). The monthly temperature distribution in tropical Africa shifts by more than six standard deviations under a high-emission scenario (RCP8.5), moving this region to a new climatic regime by the end of the twenty-first century. Under a low-emission scenario (RCP2.6), only small regions in western tropical Africa will witness substantial normalized warming of up to about four standard deviations.

Heat extremes

Heat extremes, defined as temperatures 3 and 5 standard deviations above the historical norm [3- and 5-sigma events; see Schellnhuber et al. (2013) for further explanation], increase under both emission scenarios, albeit with large differences between the low- and the high-emission scenarios. By 2100, the multi-model mean of RCP8.5 projects that 75 % of summer months would be hotter than 5-sigma (Figure SOM 2), which is substantially higher than the global average (Coumou and Robinson 2013). During the 2071–2099 period, more than half (∼60 %) of Sub-Saharan African summer months are projected to be hotter than 5-sigma, with especially strong increases in tropical West Africa (∼90 %). Over this period, almost all summer months across Sub-Saharan Africa will be hotter than 3-sigma (Fig. 1). Under RCP8.5, all African regions, especially the tropics, would migrate to a new climatic regime. The precise timing of this shift depends on the exact regional definition and the model used.

Under the low-emission scenario, the bulk of the high-impact heat extremes expected in Sub-Saharan Africa under RCP8.5 would be avoided. Extremes beyond 5-sigma are projected to cover a minor, although non-negligible, share of the surface land area (∼5 %), concentrated over western tropical Africa (Figure SOM 2). In contrast, the less extreme months, beyond 3-sigma, would increase substantially occurring over about 30 % of the Sub-Saharan land area (Figure SOM 2). Thus, even under a low-emission scenario, a substantial increase in heat extremes in the near term is anticipated.

Precipitation changes

A dipole pattern of wetting in tropical East Africa and drying in southern Africa emerges in both seasons and in both emission scenarios, with both increases and decreases of 10–30 % (Fig. 2). Projected precipitation changes based upon the full set of CMIP5 models show the same general patterns, but the magnitude of change (in terms of percentages) is smaller (Collins et al. 2013). This likely reflects only small differences in absolute terms as rainfall over these regions is generally small. Under the low-emission scenario, the models disagree on the direction of change over larger areas. Under the high-emission scenario, the percentage changes become larger everywhere and the models converge in the direction of change. Due to

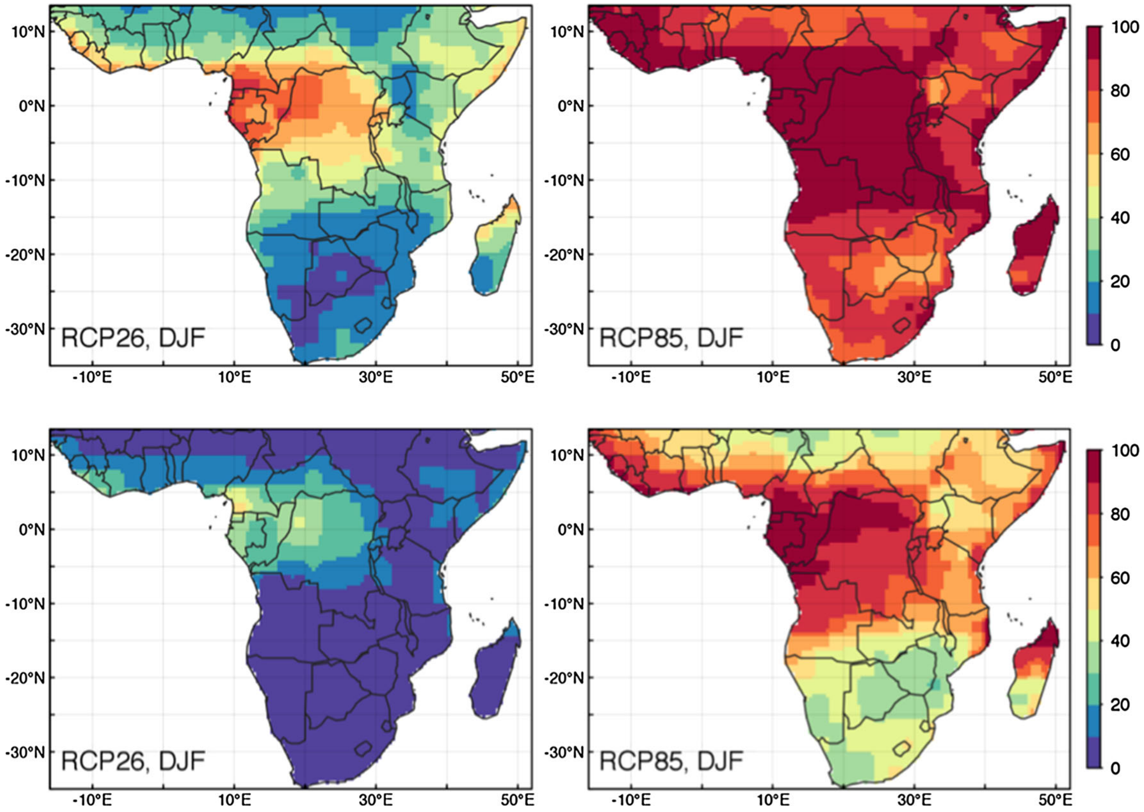


Fig. 1 Multi-model mean of the percentage of austral summer months in the time period 2071–2099 with temperatures greater than 3-sigma (*top row*) and 5-sigma (*bottom row*) for scenario RCP2.6 (*left*) and RCP8.5 (*right*) over Sub-Saharan Africa

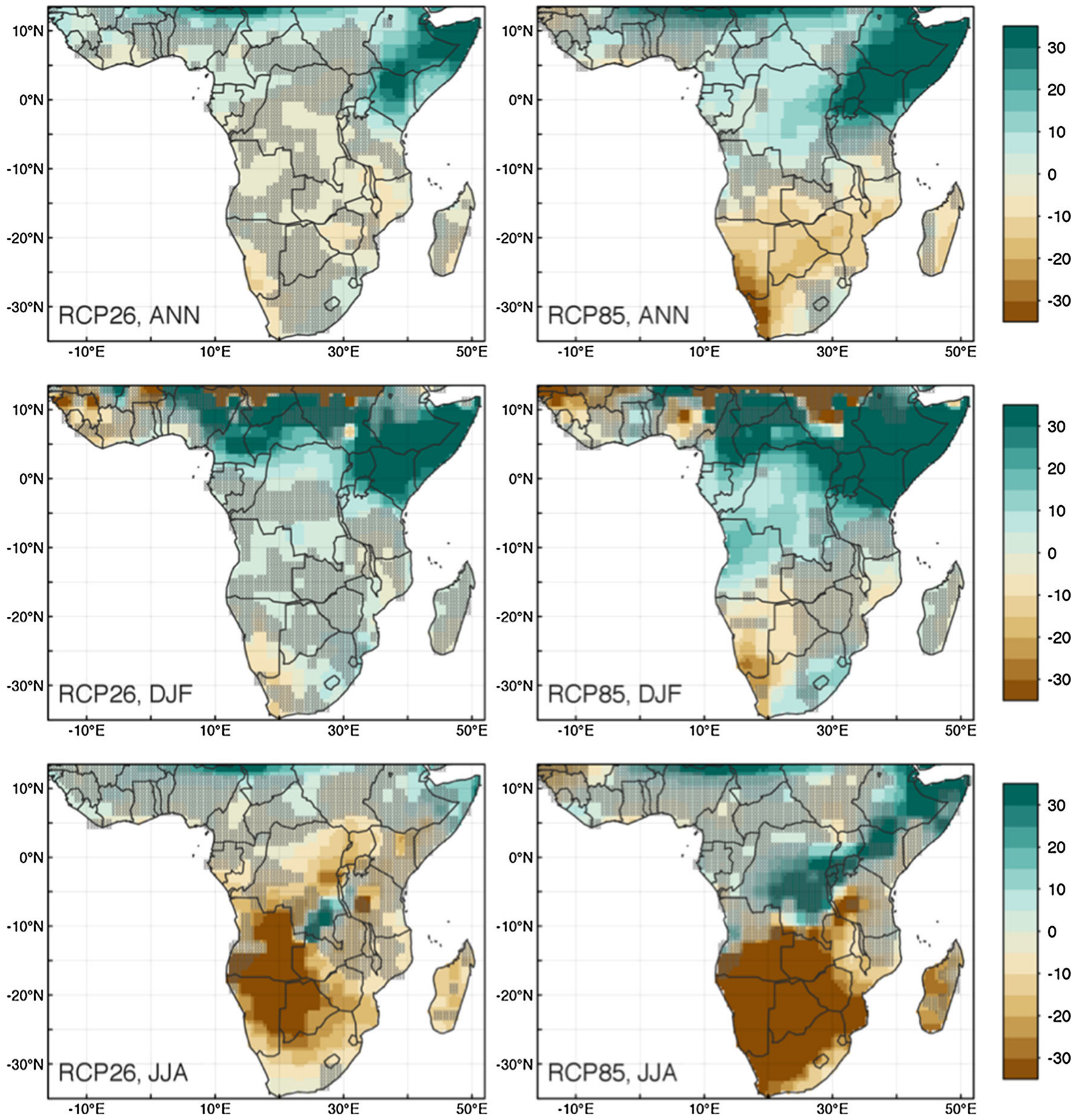


Fig. 2 Multi-model mean of the percentage change in annual (*top*), austral summer (DJF—*middle*) and austral winter (JJA–*bottom*) precipitation for RCP2.6 (*left*) and RCP8.5 (*right*) for Sub-Saharan Africa by 2071–2099 relative to 1951–1980. *Hatched areas* indicate uncertainty regions with two out of five models disagreeing on the direction of change compared to the remaining three models

this stronger signal, model disagreement between areas getting wetter and areas getting drier is limited to south-eastern regions and some regions in tropical western Africa for the months of June, July and August, and to south-eastern regions for the months of December, January and February.

Wetting of the Horn of Africa is also reflected in projected extreme precipitation events based upon the full CMIP5 model ensemble (Sillmann et al. 2013). The high-emission scenario projects an increase in the total amount of annual precipitation on days with at least 1 mm of precipitation (total wet-day precipitation) in tropical eastern Africa by 5–75 %, with the highest increase in the Horn of Africa, although the latter represents a strong relative change over a very dry area (Sillmann et al. 2013). In contrast to global models, regional climate models project no change, or even a drying for East Africa, especially during the long rains (Laprise et al. 2013). Consistently, one regional climate model study projects an increase in the number of dry days over East Africa (Vizy and Cook 2012).

Sillmann et al. (2013) further projected changes of +5 to −15 % in total wet-day precipitation for tropical western Africa with large uncertainties, especially at the monsoon-dependent Guinea coast. Very wet days (that is, the top 5 %) show even stronger increases: by 50–100 % in eastern tropical Africa and by 30–70 % in western tropical Africa. In southern Africa, total wet-day precipitation is projected to decrease by 15–45 % and very wet-day precipitation to increase by around 20–30 % over parts of the region. However, some localized areas along the west coast of southern Africa are expected to see decreases in very wet days (up to 30 %). Here, increases in consecutive dry days coincide with decreases in heavy precipitation days and maximum consecutive five-day precipitation, indicating an intensification of dry conditions. The percentile changes in total wet-day precipitation, as well as in very wet days, are much less pronounced in the low-emission scenario RCP2.6 (Sillmann et al. 2013).

Aridity and Potential Evapotranspiration

The long-term balance between demand and supply is a fundamental determinant of the ecosystems and agricultural systems able to thrive in a certain area. The aridity index (AI) is an indicator which identifies "arid" regions, that is, regions with a structural precipitation deficit (UNEP 1997; Zomer et al. 2008). AI is defined as total annual precipitation divided by potential evapotranspiration. In general, the annual mean of monthly potential evapotranspiration increases under global warming as it is primarily temperature driven. In our analysis, this is observed over all of Sub-Saharan Africa with strong model agreement, except for regions projected to see a strong increase in precipitation [see Figure SOM 2 and Schellnhuber et al. (2013) for a detailed description of methods]. In East Africa and the Sahel region, the multi-model mean shows a small reduction in potential evapotranspiration, albeit with little model agreement. By contrast, a more unambiguous signal emerges for regions projected to get less rainfall (notably southern Africa), where the projections show an enhanced increase in potential evapotranspiration (see Figure SOM 3).

Projected aridity changes show the strongest deterioration toward more arid conditions in southern Africa (Fig. 3). In southwestern Africa, the shift toward more arid conditions due to a decline in rainfall (Fig. 2) is exacerbated by temperature-driven increases in evapotranspiration (see Figure SOM 3). By contrast, the higher aridity index in East Africa is correlated with higher rainfall projected by global climate models, which, however, is uncertain and not reproduced by higher-resolution regional climate models. In addition, note that for Somalia and eastern Ethiopia, the shift implies a large relative shift imposed on a very low aridity index value, which results in AI values still classified as arid or semiarid.

Sea-level rise

Projections of future sea-level rise are not uniform across the world. Sub-Saharan Africa as defined in this paper stretches from 15° north to 35° south. Because of the dominantly tropical location of this region, projections of local sea-level rise along Sub-Saharan coastlines tend to be higher than the global average, by about 10 %.

Sea-level rise for a selection of locations in Sub-Saharan Africa is shown in Fig. 4. For a detailed description of the methods, please see (Schellnhuber et al. 2014). In our projections to 2081–2100, there are no significant differences between the three locations in West Africa (Abidjan, Lomé, Lagos) and Maputo, in southeast Africa. At each of these locations, sea level is projected to rise between 0.4 m and 1.15 m in a 4 °C world, with a median rise of 0.65 m. In a 2 °C world, sea-level rise is expected to be consistently lower, with a range of 0.2–0.7 m and a median rise of 0.4 m. We note that local factors such as land subsidence from natural or human factors, or change in storminess, which may substantially modify sea-level change experienced by the population, are not included in the projections.

Sectoral impacts

Water resources

Rising demand poses substantial threats to water security in Sub-Saharan Africa, and this is exacerbated by climatic changes affecting river runoff, contributing to higher irrigation water demand and posing risks of shallow groundwater contamination due to intense rainfall (MacDonald et al. 2009). The factors increasing water demand include irrigation and hydropower production. Both of these are expected to rise with population and economic growth but are also affected by climatic changes through an increase in evaporative losses (Beck and Bernauer 2011).

The variability of interannual rainfall over most of Africa is high (Janowiak 1988; Hulme et al. 2001). Substantial multi-decadal rainfall variability is particularly pronounced in the Sahel region (Hulme et al. 2001). A period of low rainfall during the 1970s and 1980s compared to the 1900–1970 period caused severe droughts in the region, for example (Mahe et al. 2013; Hulme 2002). Descroix et al. (2009) and Amogu et al. (2010) found decreasing streamflows for rivers in Sudanian areas and increasing discharge for those in the Sahelian regions. Serious flooding has increased in the Niger Basin in the last two decades (Aich et al. 2014a; Amogu et al. 2010), with the risk of flooding increasing with rising temperatures (Aich et al. 2014b; Amogu et al. 2010).

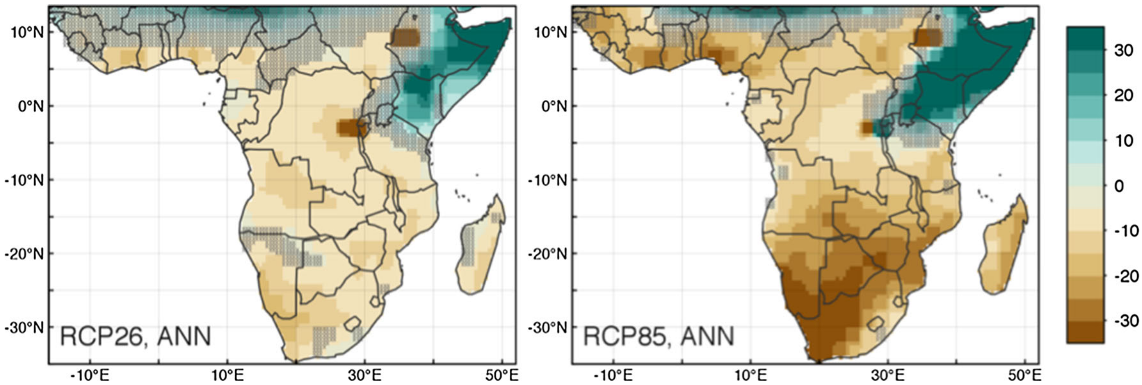
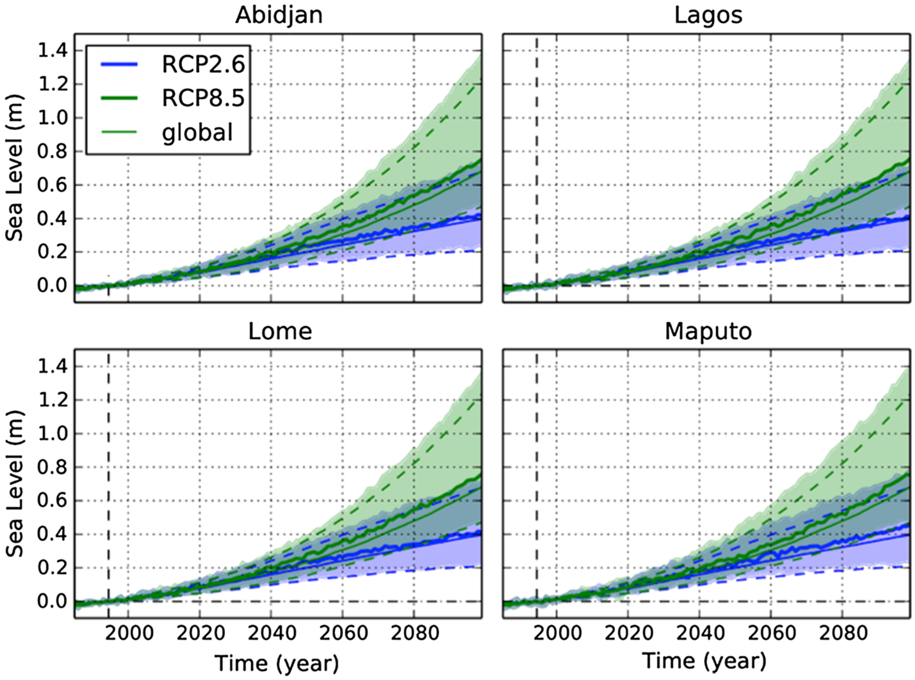


Fig. 3 Multi-model mean of the percentage change in the aridity index in a 2 °C world (*left*) and a 4 °C world (*right*) for Sub-Saharan Africa by 2071–2099 relative to 1951–1980. In non-hatched areas, at least 4/5 (80 %) of models agree. In hatched areas, at least 2/5 (40 %) disagree. Note that a negative change corresponds to a shift to more arid conditions and vice versa

Fig. 4 Local sea-level rise above 1986–2005 mean as a result of global climate change (excluding contribution from pumping groundwater and local land subsidence or uplift from natural or human causes). *Colors* indicate the RCP scenarios (RCP2.6, or 2 °C world: *blue*; RCP8.5, or 4 °C world: *green*), shading indicates the uncertainty range, and *thick lines* indicate median projections. Global sea-level rise is superimposed as *thin* (median) and *dashed lines* (low and high bounds) (color figure online)



In many parts of rural Sub-Saharan Africa, groundwater is the sole source of safe drinking water (MacDonald et al. 2009). Most of Sub-Saharan Africa has generally low permeability and minor aquifers, with some larger aquifer systems located only in the Congo, parts of Angola and southern Nigeria (MacDonald et al. 2012). Groundwater recharge rates have been projected to decline by 30–70 % in the western parts of southern Africa and to increase by around 30 % in some parts of East and southeastern Africa for both 2 and 3 °C warming above pre-industrial levels (Döll 2009). However, these increases may be overestimated, as the increased incidence of heavy rains, which are likely in East Africa (Sillmann et al. 2013), lowers actual groundwater recharge because of infiltration limits which are not considered in Döll (2009). The uncertainties associated with these results are large and relate to climate projections as well as those associated with the hydrological model used and the lack of knowledge about groundwater aquifers (MacDonald et al. 2009). A further uncertainty relates to changes in land use because of agriculture, which responds differently to changes in precipitation compared to natural ecosystems (Taylor et al. 2012). We can be more certain about increases in groundwater extraction in absolute terms resulting from population growth and growing demand particularly in semiarid regions due to projected increases of droughts and an expected expansion of irrigated land (Taylor et al. 2012).

Seasonal water shortages along river basins are expected mostly in the southern parts of East Africa (Niang et al. 2014). Comparing changes in river flow across the Niger, Upper Blue Nile, Oubangui and Limpopo river basins by using the output of the five bias-corrected CMIP5 climate models (Hempel et al. 2013), which also underlie temperature and precipitation projections in this paper, and applying the ecohydrological model SWIM (Krysanova et al. 1998) show highly uncertain results with high disagreement between models (Aich et al. 2014b). However, for the Blue Nile Basin, a consistent increase in mean annual flows and low flows was found for 2 °C warming by mid-century (RCP8.5 in 2020–2049) and 4 °C world (RCP8.5 in 2070–2099) with low flow increases of 10 to 50 %, respectively (Aich et al. 2014b), as well as a robust trend in increasing risk of flooding. High flows are projected to increase by 10–50 % under 2 °C warming by mid-century and 10–150 % in a 4 °C world (Aich et al. 2014b).

For western Kenya (Nyando catchment), a tendency of increasing peak flows for a 3 °C world by mid-century has been projected; mean annual runoff change as well as changes in low flows are rather uncertain (Taye et al. 2011). In a recent model intercomparison by Schewe et al. (2013), an increase in annual discharge of about 50 % in East Africa (especially southern Somalia, Kenya and southern Ethiopia) is projected with more than 80 % model consensus for a warming of 2.7 °C. For South Africa, Schewe et al. (2013) found decreases of 30–50 % for annual runoff in a warming scenario of 2.7 °C by the end of the century. For a warming of about 4.5 °C above pre-industrial levels, even more pronounced decreases in southern Africa of up to 80 % were found (Fung et al. 2011; Arnell et al. 2011).

Projections on future discharge for the Niger Basin in West Africa showed diverging trends between climate models on mean and high flows, depending also on the location in the basin, for a 2 and 4 °C world. Trends in low flows were mostly positive but have to be interpreted with caution (Aich et al. 2014b). Schewe et al. (2013) found decreases in annual runoff of 10–30 % with a strong level of model agreement (60–80 %) for Ghana, Côte D'Ivoire and southern Nigeria in a warming scenario of 2.7 °C above pre-industrial levels. Large uncertainties remain for many regions (e.g., along the coast of Namibia, Angola and central Congo) (Schewe et al. 2013).

Many of those areas that are classified as blue water scarce can at present provide an adequate overall supply of green water to produce a standard diet (Rockström et al. 2009). Projections of green water availability by a single hydrological model show decreases of about 20 % relative to 1971–2000 over most of Africa and increases of about 20 % for Somalia, Ethiopia and Kenya by 2080 with a global mean warming of about 3 °C above pre-industrial levels (Gerten et al. 2011).

Overall projections of impacts of climate change on water resources in Sub-Saharan Africa are associated with large uncertainties. Apart from addressing the lack of observational data, key challenges for assessing climatic risks to water availability relate to their responses to heat waves, seasonal rainfall variability as well as the relationship between land use changes, evapotranspiration and soil moisture at different levels of global warming (Niang et al. 2014).

Agricultural production

The high levels of dependence on precipitation for the viability of Sub-Saharan African agriculture, in combination with observed crop sensitivities to maximum temperatures during the growing season (Asseng et al. 2011; Lobell et al. 2011; Schlenker and Roberts 2009), indicate significant risks to the sector from climate change. The IPCC states with high levels of confidence that the overall effect of climate change on yields of major cereal crops in the African region is very likely to be negative, with strong regional variation (Niang et al. 2014). "Worst-case" projections (5th percentile) indicate losses of 27–32 % for maize, sorghum, millet and groundnut for a warming of about 2 °C above pre-industrial levels by mid-century (Schlenker and Lobell 2010). Using output from 14 CMIP3 GCMs and applying the crop model DSSAT, Thornton et al. (2011) estimate mean yield losses of 24 for maize and 71 % for beans under warming exceeding 4 °C. In a global study using the same bias-corrected climate data from five CMIP5 GCMs (see Hempel et al. 2013) that underlie temperature and precipitation projections in this paper, and seven crop models, Rosenzweig et al. (2014) find yield decreases of >50 % for Maize in the Sahelian region and around 10–20 % in other Sub-Saharan regions if nitrogen stress is considered. Not considering nitrogen stress results in higher model disagreement but still an overall negative trend of 5 to >50 %. Cassava appears to be more resistant to high temperatures and unstable precipitation than cereal crops (Niang et al. 2014). Similarly, multiple-cropping systems appear to reduce the risk of crop failure compared to single-cropping systems (Waha et al. 2012).

A number of adverse effects on crop yields are as yet not represented in modeling studies. High-temperature sensitivity thresholds for important crops such as maize, wheat and sorghum have been observed, with large yield reductions once the threshold is exceeded (Luo 2011). Maize, which is one of the most common crops in Sub-Saharan Africa, has been found to have a particularly high sensitivity to temperatures above 30 °C within the growing season. Each day in the growing season spent at a temperature above 30 °C reduces yields by 1 % compared to optimal, drought-free rainfed conditions (Lobell et al. 2011). The annual average temperature across Sub-Saharan Africa is already above the optimal temperature for wheat during the growing season (Liu et al. 2008), and it is expected to increase further. The sharp declines in crop yields that have been observed beyond certain thresholds are mostly not included in present process-based agricultural models (Rötter et al. 2011).

Moreover, climate extremes can alter the ecology of plant pathogens, and higher soil temperatures can promote fungal growth that kills seedlings (Patz et al. 2008). Such effects are as yet not represented in modeling studies. Similarly, the effect of CO_2 fertilization remains uncertain but important: Depending on crop type and region, assuming positive CO_2 fertilization may even reverse the direction of impacts. However, major crops in West Africa are C4 crops, such as maize, millet and sorghum, which benefits less from higher CO_2 concentration, so that the positive effect may be overestimated (Roudier et al. 2011).

Livestock production in Sub-Saharan Africa is also vulnerable to climate change. Livestock is an important source of food (such as meat and milk and other dairy products), animal products (such as leather), income, or insurance against crop failure (Seo and Mendelsohn 2007). The pastoral systems of the drylands of the Sahel, for example, are highly dependent on natural resources, including pasture, fodder, forest products and water, all of which are directly affected by climate variability (Djoudi et al. 2011). Livestock is vulnerable to drought, particularly where it depends on local biomass production (Masike and Ulrich 2008), with a strong correlation between drought and animal death (Thornton et al. 2009). Available rangeland may be reduced by human influences, including moves toward increased biofuel cultivation, veterinary fencing, increasing competition for land and land degradation (Morton 2012; Sallu et al. 2010). Thorny bush encroachment, for example, is brought about by land degradation (Dougill et al. 2010), as well as rising atmospheric CO_2 concentrations (Higgins and Scheiter 2012).

Savanna ecosystems

Among Sub-Saharan African ecosystems, savanna vegetation has been identified as highly vulnerable to the effects of climate change (Midgley and Thuiller 2011). During the last decades, the encroachment of woody plants has already affected savannas (Buitenwerf et al. 2012; Ward 2005). Woody plants are often unpalatable to domestic livestock (Ward 2005). Observed expansions in tree cover in South Africa have been attributed to increased atmospheric CO_2 concentration or nitrogen deposition (Wigley et al. 2010). In the western Sahel, however, a 20 % decline in tree density and a significant decline in species richness across the Sahel have been observed for the second half of the twentieth century and attributed to changes in temperature and rainfall variability (Gonzalez et al. 2012).

While short-term responses of ecosystems in African biomes are typically driven by water availability and fire regimes, in the longer term African biomes appear highly sensitive to changes in atmospheric CO_2 concentrations (Midgley and Thuiller 2011). A potential shift in competitive advantage from heat-tolerant C4 grasses to C3 trees which better benefit from high CO_2 concentrations produces to the risk of abrupt vegetation shifts at the local level (Higgins and Scheiter 2012). The effect may be further enhanced by a positive feedback loop: Trees are expected to accumulate enough biomass under elevated atmospheric CO_2 concentrations to recover from fires (Kgope et al. 2009), shading out C4 grass production and contributing to lower severity of fires, which further promotes tree growth. High rainfall savannas can be replaced by forests in less than 20–30 years (Bond and Parr 2010). However, forests are also at risk from changes in temperature and precipitation. If extreme weather conditions increase, forests may shrink at the expense of grasses (Bond and Parr 2010). Despite persistent uncertainties pertaining to these mechanisms and thresholds marking tree mortality, increases in extreme droughts and temperatures pose risks of broadscale climate-induced tree mortality (Allen et al. 2010).

Ocean ecosystems

Aquatic ecosystems globally respond sensitively to the effects of climate change (Ndebele-Murisa et al. 2010; Cheung et al. 2010). Consequent risks include the decline in key protein sources and reduced income generation because of decreasing fish catches (Badjeck et al. 2010). Freshwater ecosystems are affected by droughts and associated reductions in nutrient influxes as river inflow is temporarily reduced (Ndebele-Murisa et al. 2010). Furthermore, increasing freshwater demand in urban areas of large river basins may lead to reduced river flows, which may become insufficient to maintain ecological production, meaning that freshwater fish populations may be impacted (McDonald et al. 2011).

Ocean ecosystems respond to altered ocean conditions with changes in primary productivity, species distribution and food web structure (Cheung et al. 2010). Irreversible changes are expected at further warming of 1 °C above present (Pörtner et al. 2014). Theory and empirical studies suggest a shift of ocean ecosystems toward higher latitudes and deeper waters in response to such changes (Cheung et al. 2010). However, there is also an associated risk that some species and even whole ecosystems will be placed at risk of extinction (Drinkwater et al. 2010). Projections for the western African coast—where fish contributes as much as 50 % of animal protein consumed (Lam et al. 2012)—show adverse changes in maximum catch potential of −16 to −5 % for Namibia, −31 to 15 % for Cameroon and Gabon and up to 50 % for the coast of Liberia and Sierra Leone for a warming of 2 °C above pre-industrial levels (Cheung et al. 2010). These projections do not account for changes in ocean acidity or oxygen availability, which are known to negatively impact the performance of marine organisms (Pörtner 2010; Stramma et al. 2008, 2010).

Coastal populations and infrastructure

In the Sub-Saharan African region, the populations of Mozambique and Nigeria are projected to be most affected by sea-level rise in terms of the absolute number of people flooded annually (Hinkel et al. 2011). Assuming 126 cm (64 cm) of global mean sea-level rise above 1995 values by 2100, which corresponds to upper bound (median) estimates in a 4 °C world, and assuming no adaptation, approximately 2 (1) million more people in Mozambique would be exposed to annual flooding than in scenario without sea-level rise, while in Nigeria approximately 3 (2.5) million more people would be flooded annually. In terms of the proportion of the total national population affected by annually flooding, Guinea-Bissau, Mozambique and Gambia are most severely impacted (Hinkel et al. 2011).

Sea-level rise exacerbates the risk of coastal flooding associated with tropical cyclone activity. A medium sea-level rise scenario of 0.3 m by 2050 could see current 1-in-100-year storm surge events in Maputo, Mozambique, for example, occurring once in every 20 years (Neuman et al. 2013). Brecht et al. (2012) also finds Mozambique, along with Madagascar, to be particularly vulnerable in a study of the combined impacts of sea-level rise and cyclonic storm surges. Dasgupta et al. (2011) project Mozambique and Tanzania to be among those countries in the developing world most exposed across several indicators (proportion of total land area, GDP, urban land area, agricultural area and wetland area exposed) to a 10 % intensification of storm surges along with 1-m sea-level rise.

Sea-level rise and storm surges can have significant economic impacts. Damage to port infrastructure in Dar es Salaam, Tanzania, for instance—which handles approximately 95 % of Tanzania's international trade and serves landlocked countries further inland (Kebede and Nicholls 2011)—could have ramifications for the economies of Tanzania and other countries in the region. Most of the tourism facilities of Mombasa, Kenya, are located in coastal zones, where damage is already caused almost every year by extreme weather events (Kebede et al. 2012). Damage to seafront hotel infrastructure has also already been reported in Cotonou, Benin—with this also considered a risk with rising sea levels elsewhere (Hope 2009).

In terms of economic impacts, Mozambique and Guinea-Bissau are projected to experience the highest annual damage costs as a proportion of GDP as a result of coastal flooding, forced migration, salinity intrusion and loss of dry land associated with sea-level rise (Hinkel et al. 2011). According to Dasgupta et al. (2011), the most economically important areas in the region that are prone to storm surges in a scenario of 1-m sea-level rise are located in Mozambique and Tanzania. Abidjan in Cote d'Ivoire is also ranked highly in a global study of the average annual loss as a percentage of GDP caused by coastal flooding in cities, with around 1 % lost annually for 0.4 m of sea-level rise by 2050 taking into account socioeconomic change, subsidence and adaptation in the form of flood defences (Hallegatte et al. 2013).

Human impacts

The sections below outline risks in three areas that have been identified as affected by climate change and which are subject to ongoing research: human health, migration and conflict. It has long been established that climate change is rarely a single driver but tends to be mediated by existing contextual factors to produce repercussions for human life (IPCC 2014). An extensive and growing body of research on the nature and determinants of vulnerability is investigating the role of context (e.g., Birkmann et al. 2013). While this paper is unable to cover this rich scholarship, the following discussion will illustrate some of the ways in which contextual factors shape climate impacts, at the same time that these impacts can coincide and interact with one another to produce combined implications greater than the sum of the first-order impacts.

Human health

Among the direct effects of climate change on human health are fatalities and injuries as a result of extreme weather events or disasters, such as flooding or landslides following heavy rain (McMichael and Lindgren 2011; WHO 2009). Extreme heat events can also have a direct impact on health by causing heat stress. Lengthy exposure to high temperatures can bring about heat cramps, fainting, heat exhaustion, heat stroke and death and compromise outdoor human activities (Smith et al. 2014). Correlations between high ambient temperatures and increased all-cause mortality have been identified in Ghana and Kenya (Azongo et al. 2012; Egondi et al. 2012), with the young and the elderly particularly susceptible. Drought conditions, which can affect the availability and quality of water, have been linked to such illnesses as diarrhea, scabies, conjunctivitis and trachoma (Patz et al. 2008).

Climate change impacts on agriculture are expected to undermine human health by affecting the affordability and availability of nutritious food. While levels of undernutrition are already high across the Sub-Saharan African region, projections indicate that with warming of 1.2–1.7 °C by 2050, the proportion of the population that is undernourished would increase by 25–90 % compared to the present (Lloyd et al. 2011). Undernutrition places people at risk of secondary or indirect health implications by heightening susceptibility to other diseases (World Health Organization 2009; World Bank Group 2010). It can also lead to child stunting, which is associated with reduced cognitive development and poor health into adulthood (Cohen et al. 2008). Projections indicate that the proportion of moderately stunted children in the region would not increase above the 2010 baseline level of 16–22 % in a scenario without climate change, but with 1.2–1.7 °C above pre-industrial values by 2050 could increase by 9 %. The proportion of severely stunted children, which is estimated at 12–20 % in 2010, is projected to decrease by 40 % without climate change and by only 10 % with climate change (Lloyd et al. 2011).

Outbreaks of transmittable diseases, both food- and water- and vector-borne, can occur following extreme weather events such as flooding. Past outbreaks of cholera, which is associated with contaminated water and poor sanitation, have been observed to follow heavy rainfall events combined with elevated temperatures (Tschakert 2007; Luque Fernández et al. 2009; Reyburn et al. 2011). This occurred during the severe flooding in Mozambique in 2000 and again in the province of Cabo Delgado in early 2013 (Star Africa 2013; UNICEF 2013).

Intra-seasonal rainfall variability is a key risk factor for Rift Valley fever, a disease transmitted via mosquito or domestic animals hosting the virus. Outbreaks tend to occur after a long dry spell followed by an intense rainfall event (Caminade et al. 2011). Projections of increased rainfall variability in the Sahel point to a likely increase in the incidence in this region. Northern Senegal and southern Mauritania have been identified as risk hotspots, given the relatively high livestock densities in these areas (Caminade et al. 2011).

The distribution of some vector-borne diseases is expected to shift. For example, malaria appears to already be spreading into the highlands of Ethiopia, Kenya, Rwanda and Burundi, where it previously was not present. In the Sahel, the northern fringe of the malaria epidemic belt is projected to shift southward by 1°–2° with a warming of 1.7 °C by 2031–2050 due to a projected decrease in the number of rainy days in summer (Caminade et al. 2011), potentially leaving fewer people in the northern Sahel exposed to malaria. More recent malaria model intercomparison further indicates a decrease in the length of transmission season for the Sahel (Caminade et al. 2014). Overall, an increase in the risk of malaria is projected for eastern, central and southern Africa; for eastern Africa, estimates of additional people at risk range from around 40–80 million under 2 °C warming and from around 70–170 million under 4 °C warming (Caminade et al. 2014). There is, however, significant uncertainty in anticipating changes in malaria distribution due to the complexity of factors—both climatic and non-climatic—involved, with the relationship between temperature and malaria transmission varying from region to region (Chaves and Koenraadt 2010).

Population movement

Generally, the displacement of people is projected to increase under continued climate change (IPCC 2014). The drivers of migration tend to be complex and also include cultural, economic and political factors as well as non-climatic environmental factors such as desertification (Tacoli 2009). The response to the same type of climatic driver can therefore vary considerably according to local context (Findlay 2011). Sub-Saharan Africa is expected to be particularly affected by migration associated with climate change-related drivers, including sea-level rise and declining or disrupted availability of resources due to shifts in climatic conditions or extreme weather events (Gemenne 2011).

The majority of migration in response to environmental change worldwide occurs within country borders (Tacoli 2009), and much migration is from rural to urban areas. This trend may be exacerbated by the impacts of climate change as they place growing pressure on rural livelihoods (Adamo 2010). Africa's rate of urbanization, already the highest in the world, is expected to increase further, with as much as half the population expected to live in urban areas by 2030 (UN-HABITAT 2010). Patterns of urbanization in Senegal, for example, have been attributed to desertification and drought, which have made nomadic pastoral livelihoods less feasible and less profitable (Hein et al. 2009).

While migration in general can be seen in many cases as an adaptive response to local environmental pressures (Tacoli 2009; Warner 2010; Collier et al. 2008), it can bring with it a whole set of other risks—not only for the migrants but also for the population already residing at their site of relocation. Repercussions can arise from tensions between ethnic groups, political and legal restrictions, and competition for and limitations on access to land

(Tacoli 2009). In general, levels of poverty and unemployment are often high among migrants, particularly among unskilled subsistence farmers who have moved to urban areas (Tacoli 2009). Population movements also have health implications. For example, the spread of malaria into the East African highlands mentioned above is associated with the migration of people from the lowlands to the highlands (Chaves and Koenraadt 2010). Further costs and trade-offs that can result from migration, and in particular forced displacement, include loss of social ties, loss of sense of place and of cultural identity (Barnett and O'Neill 2012).

Conditions in the new place of residence can place people at risk of different environmental risks to those they may have left behind, especially when migrants come to reside in precarious conditions. Many informal settlements worldwide are constructed on steep, unstable hillsides, along the foreshores of former mangrove swamps or tidal flats, or in low-lying flood plains (Douglas et al. 2008). Where adequate sanitation and water drainage infrastructure are lacking, residents must depend on water supplies that can easily become contaminated (Douglas et al. 2008). These and other health risks are often particularly acute in densely populated urban areas. Heat extremes, for example, are felt more in cities due to the urban heat island effect (UN-HABITAT 2010). Further the urban poor are among the most vulnerable to food production shocks that cause jumps in food prices (Ahmed et al. 2009; Hertel et al. 2010).

Conflict

The connection between environmental factors and conflict is contested. Gleditsch (2012) summarizes a suite of recent studies on the relationship between violent conflict and climate change and stresses that there is to date a lack of evidence for such a connection. Other meta-analyses by Hsiang et al. (2013) and Hendrix and Salehyan (2012) suggest that deviation from normal precipitation and mild temperatures increases the risk of conflict. In Africa, (Hsiang and Meng 2014) have investigated and reproduced the disputed finding of (Burke et al. 2009) that the likelihood of civil war is greater in hotter years. The most recent assessment report of the IPCC is the first to posit an indirect causal connection between poverty and economic shocks amplified by climate change and intra-state violence (IPCC 2014).

These analyses add support to the long-standing claim that, on both long and short timescales, depletion of a dwindling supply of, as well as uneven access to, resources has the potential to lead to competition between different groups and heighten the threat of conflict (Hendrix and Glaser 2007). The causal connection also operates in the opposite direction, with conflict often leading to environmental degradation and increasing the vulnerability of populations to a range of climate-generated stressors (Biggs et al. 2004; IPCC 2014). The breakdown of governance due to civil war can also exacerbate poverty and cause ecosystem conservation arrangements to collapse; both of these factors can potentially cause further exploitation of natural resources (Mitchell 2013).

It is clear that how these dynamics play out is complex and not uniform, with the environment figuring as only one of several interrelated drivers of conflict (Kolmannskog, 2010). However, given that unprecedented climatic conditions (Fig. 1) are expected to place severe stress on the availability and distribution of resources, the potential for climate-related violent conflict constitutes a real risk in some circumstances (Barnett and Adger 2007).

Development repercussions

The climatic and sectoral impacts outlined above can combine to further produce complex and not easily predicted consequences for various aspects of human development. Figure 5 integrates projected physical and sectoral impacts across different warming levels.

Any sectoral assessment falls short of providing a comprehensive picture of climate impacts under different warming levels as potential interactions between impacts across sectors are rarely represented. Slow-onset impacts in different sectors may interact and thereby change the overall toll of climate damages. Elliott et al. (2014), for example, find irrigation adaptation limits for agriculture in southern Sub-Saharan Africa due to climate-induced constraints in freshwater availability. Human responses to changes in one sector can also bring about impacts in other sectors. Expansion of agricultural areas to compensate for crop yield declines, for example, can come at the cost of terrestrial carbon sinks and other ecosystem services (Frieler et al. 2015).

Extreme weather events in particular can cause simultaneous damage across sectors, exacerbating the overall effect. From the list of impacts described for Sub-Saharan Africa in this paper, for example extreme events, such as flooding events which are expected to increase, for example, for the Upper Blue Nile River basin, can trigger outbreaks of disease to which people are likely to be more vulnerable under conditions of existing food insecurity. At the same time, tropical cyclones and flooding events can cause severe damage to critical infrastructure, including transport, tourism and healthcare infrastructure. This can be particularly serious if precisely those institutions that are designed to cope with impacts, such as healthcare infrastructure, are themselves placed under additional pressure due to extreme weather events.

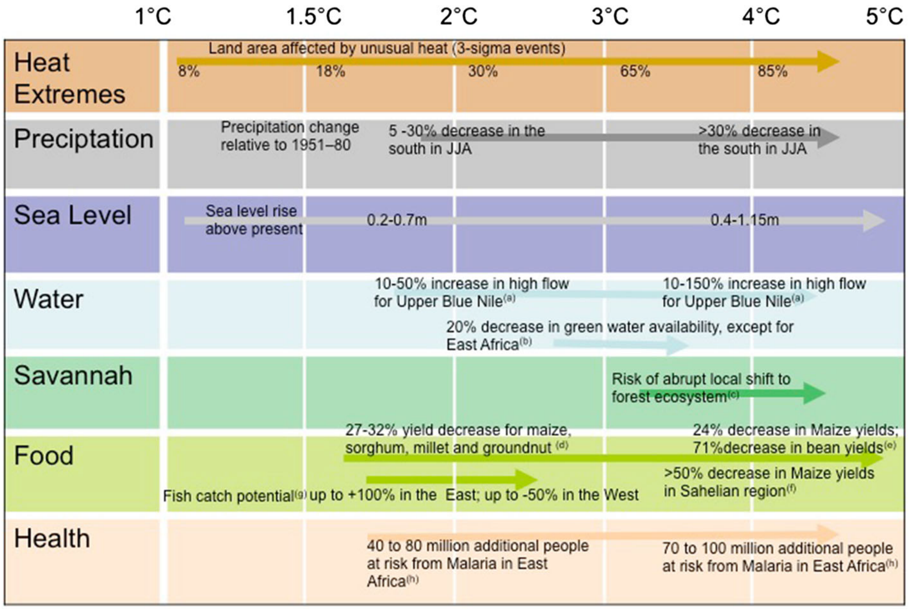


Fig. 5 Climatic changes and impacts across sectors at different levels of warming. Transient warming for heat extremes and precipitation is based on RCP8.5 where impacts in the periods 2009–2039; 2023–2053; 2044–2074 and 2064–2094 are grouped under 1.5, 2, 3 and 4 °C above pre-industrial levels, respectively. Where no references are given, results are based on original data analysis as presented in Schellnhuber et al. (2013), particularly Appendices A.1–3). (a) Aich et al. (2014b); (b) Gerten et al. (2011); (c) Higgins and Scheiter (2012); (d) Schlenker and Lobell (2010); (e) Thornton et al. (2011); (f) Rosenzweig et al. (2014); (g) Cheung et al. (2010); (h) Caminade et al. (2014)

While these examples illustrate how complicated and at times speculate the link of human and biophysical impacts is, some human impacts are more easily traced to the physical and sectoral climate signal. For example, while food security is determined by a number of factors, child malnutrition and stunting have been observed to correlate with periods of inadequate local agricultural yields (Black et al. 2008; Lloyd et al. 2011; UNDP 2007). Other human impacts are more indirectly associated with the effects of climate change. Food security is potentially undermined where food price increases following harvest loss—whether in regions neighboring or distant—disproportionately affect the urban poor (Ahmed et al. 2009; Hertel et al. 2010). Here too a cross-sectoral perspective is required. In certain regions, for example West Africa, projected agricultural yield declines need to be seen in concert with potential decreases in protein intake due to declining fish catch potential. The adverse effects of a projected decrease in fish catch potential by up to 50 % on regional protein intake amount to decreases of 7.6 % for Ghana and 7.0 % for Sierra Leone compared to the amount of protein consumed in 2000 (Lam et al. 2012). The job loss associated with projected declines in catches is estimated at almost 50 % compared to the year 2000 (Lam et al. 2012).

It is beyond the scope of this paper to map out the differential vulnerability of different population groups to climatic impacts or to do justice to the rich literature on multi-dimensional poverty and its effects on vulnerability. However, it becomes clear that a number of factors are affected by climate change that co-determine the level of development: Human health is negatively affected; employment opportunities may dwindle; critical infrastructure is damaged, and tourism revenues are threatened. Often the poor are disproportionately exposed to physical impacts, such as storm surges or more indirect effects such as food price increases.

Conclusion

This paper shows that climatic changes and sectoral climate impacts need to be expected to affect the population of Sub-Saharan Africa in a variety of ways. Changes are not uniform across the region. East Africa is at higher risk of flooding and concurrent health impacts and infrastructure damages. West Africa is projected to experience severe impacts on food production, including through declines in oceanic productivity, with severe risks for food security and negative repercussions for human health and employment. South Africa sees the strongest decrease in precipitation with concurrent risks of drought. Sea-level rise puts at risk a growing number of densely populated coastal cities, whose population is set to increase and may receive yet more in-migration as a result of rural livelihood degradation. The potential interactions and amplifying effects across sectors are not yet reflected in the science. Integrating impacts across sectors and population dynamics remains a major challenge for science and—due to the resulting uncertainties—to adaptation planning and decision making alike.

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