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Climate variability and vulnerability to climate change: a review

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Research Review

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Climate variability and vulnerability to climate change: a review

Abstract

The focus of the great majority of climate change impact studies is on changes in mean climate. In terms of climate model output, these changes are more robust than changes in climate variability. By concentrating on changes in climate means, the full impacts of climate change on biological and human systems are probably being seriously underestimated. Here we briefly review the possible impacts of changes in climate variability and the frequency of extreme events on biological and food systems, with a focus on the developing world. We present new analysis that tentatively links increases in climate variability with increasing food insecurity in the future. We consider the ways in which people deal with climate variability and extremes and how they may adapt in the future. Key knowledge and data gaps are highlighted. These include the timing and interactions of different climatic stresses on plant growth and development, particularly at higher temperatures, and the impacts on crops, livestock and farming systems of changes in climate variability and extreme events on pest-weed-disease complexes. We highlight the need to reframe research questions in such a way that they can provide decision makers throughout the food system with actionable answers, and the need for investment in climate and environmental monitoring. Improved understanding of the full range of impacts of climate change on biological and food systems is a critical step in being able to address effectively

the effects of climate variability and extreme events on human vulnerability and food security, particularly in agriculturally-based developing countries facing the challenge of having to feed rapidly growing populations in the coming decades.

Introduction

Climate change has many elements, affecting biological and human systems in different ways. The considerable spatial heterogeneity of climate change impacts has been widely studied; global average temperature increases mask considerable differences in temperature rise between land and sea and between high latitudes and low; precipitation increases are very likely in high latitudes, while decreases are likely in most of the tropics and subtropical land regions (IPCC, 2007). It is widely projected that as the planet warms, climate and weather variability will increase. Changes in the frequency and severity of extreme climate events and in the variability of weather patterns will have significant consequences for human and natural systems. Increasing frequencies of heat stress, drought and flooding events are projected for the rest of this century, and these are expected to have many adverse effects over and above the impacts due to changes in mean variables alone (IPCC, 2012).

In this review, we consider the possible impacts of changes in climate variability on biological and food systems, with a focus on the tropical and subtropical developing world, where the deleterious impacts of anthropogenic climate change are generally projected to be greatest. These less developed regions of the world already face an enormous food security challenge, with human populations rising unabated throughout the present century (UNDESA, 2013). We start with a short consideration of the global importance and costs of climate variability and extreme events. We then briefly review some of the major impacts of climate variability and extremes on biological and agricultural systems at a range of scales, and on human health and nutrition. We then present some new analysis that seeks to link increases in climate variability with increasing food insecurity in the future, before considering the ways in which people deal with climate variability and extremes and how they may adapt in the coming decades. We conclude with a discussion of research gaps in relation to both the biophysical and the socio-economic arenas and what needs to be done to better understand the impacts of climate variability on human vulnerability and food security, ultimately to increase the capacity of farmers in the tropics and subtropics to address climate variability and extreme events.

Climate change, climate variability and extreme events

Climate change is inevitably resulting in changes in climate variability and in the frequency, intensity, spatial extent, duration, and timing of extreme weather and climate events (IPCC, 2012). Changes in climate variability and extremes can be visualised in relation to changes in probability distributions, shown in Figure 1 (IPCC, 2012). The top panel shows a shift of the entire distribution towards a warmer climate (a change in the mean), a situation in which more hot (and record hot) weather would be expected, along with less cold (and record cold) weather. The middle panel shows a change in the probability distribution of temperature that preserves the mean value but involves an increase in the variance of the distribution: on average, the temperature is the same, but in the future there would be more hot and cold (and record hot and cold) weather. The bottom panel shows the situation in which the temperature probability distribution preserves its mean, but the variability evolves through a change in asymmetry towards the hotter part of the distribution; here we would see near constant cold (and record cold) weather, but increases in hot (and record hot weather).

Climate variability already has substantial impacts on biological systems and on the smallholders, communities and countries which depend on them. The importance of rainfall variability at the national level, for example, is illustrated in Figure 2, which shows the relationship between annual rainfall variability and changes in the gross domestic product and agricultural gross domestic product for three countries of sub-Saharan Africa. In Figure 2, interannual rainfall variability is expressed as the 12-month Weighted Anomaly of Standardized Precipitation (WASP), calculated from overlapping multi-month sums of standardized precipitation anomalies weighted according to the fraction of mean annual precipitation at the given time of year (from the data library of the International Research Institute for Climate and Society, iridl.ldeo.columbia.edu). This kind of close relationship is likely to be found for many tropical countries that depend heavily on agriculture as an engine for economic development.

Changes in extremes have been observed since 1950, and there is evidence that some of these changes are a result of anthropogenic influences, although attribution of single extreme events to these influences remains challenging (IPCC, 2012). Global aridity has increased substantially since the 1970s due to recent drying over Africa, southern Europe, East and South Asia, and eastern Australia – the percentage of global land (between 60 °S and 75 °N) defined as dry areas has increased from 17% in the 1950s to about 27% in the 2000s (Dai, 2011). There is considerable uncertainty regarding projected changes in extremes to the end of the current century, and confidence in projecting changes in the direction and magnitude of climate extremes is generally low, although as the IPCC (2012) points out, low confidence in projections of changes in extremes does not mean that such changes are necessarily unlikely. Similarly, given current limits of understanding of the underlying processes regarding climate in many regions, it may be that low-probability, high-impact changes in extremes will occur.

A partial summary of observed changes in some extremes, their attribution, and their future projection, is shown in Table 1, extracted from Table 3.1 in IPCC (2012).

A summary analysis of the numbers of people affected by environmentally-related disasters is given in Raleigh and Jordan (2010) based on data compiled by the Centre for Research on the Epidemiology of Disasters (CRED, 2008). A disaster is entered into the CRED database if at least one of the following criteria is fulfilled: 10 or more people reported killed, 100 or more people reported affected, a declaration of a state of emergency, and a call issued for international assistance. An aggregated summary of these data is shown in Table 2. Chronic environmental hazards such as drought are not the most common, but they do affect the most people, with impacts on an average across all years of 10 per cent of a country's population (in low-income states, this increases to 13 per cent of a country's population). Raleigh and Jordan (2010) note that only in the case of drought is a significant proportion of a state affected. Floods tend to be more localised (for obvious reasons), but may still affect millions of people. The total number of disaster events in each region since 1970 is particularly noteworthy; and since 2000, the average number of events per year is running at more than 380 (Raleigh and Jordan, 2010).

There is a considerable literature on the economic costs of climate variability and extremes. Globally, annual damage from large weather and climate events increased eight-fold between the 1960s and the 1990s; between 1980 and 2004, the costs of extreme weather events amounted to US$ 1.4 trillion (Mills, 2005). Since 1980, annual costs have ranged from a few US$ billion to above US$ 200 billion (in 2010 dollars) for 2005, the year of Hurricane Katrina (IPCC, 2012). While there is considerable regional variation, the relative economic burden of climate extremes as a proportion of GDP is substantially higher in developing countries than it is in developed countries – up to 8% in the most extreme cases. A strong upward trend in overall losses due to climate extremes is indicated since 1980 (Munich Re, 2011), although how these will play out during the course of the current century is highly uncertain; and as yet there is no evidence to link this trend to anthropogenic climate change (Bouwer, 2011). Extreme events may have considerable impacts on sectors that have close links with climate, such as water, agriculture and food security, forestry, health, and tourism, and concomitantly in countries whose economies depend more heavily on such sectors (IPCC, 2012).

Impacts of climate variability and extremes

Biological systems

Warmer climates will generally accelerate the growth and development of plants, but overly cool or hot weather will also affect productivity. Earlier flowering and maturity of several crops have been documented in recent decades, often associated with higher temperatures (Craufurd & Wheeler, 2009). Increases in maximum temperatures (as climate or weather) can lead to severe yield reductions and reproductive failure in many crops. In maize, each degree day spent above 30 °C can reduce yield by 1.7% under drought conditions (Lobell et al., 2011). Impacts of temperature extremes may also be felt at night, with rice yields reduced by 90% with night temperatures of 32 compared with 27 °C (Mohammed and Tarpley, 2009). In contrast to the effects of temperature and photoperiod at optimum and suboptimum temperatures, crop response to temperature and photoperiod at supraoptimal temperatures is not well understood (Craufurd and Wheeler, 2009).

Climate variability and extreme events can also be important for yield quality. Protein content of wheat grain has been shown to respond to changes in the mean and variability of temperature and rainfall (Porter and Semenov, 2005); specifically, high-temperature extremes during grain-filling can affect the protein content of wheat grain (Hurkman et al., 2009).

At aggregated level as well as at the plot level, rainfall variability is a principal cause of interannual yield variability. For example, Hlavinka et al. (2009) found a statistically significant correlation between a monthly drought index and district-level yields in the Czech Republic for several winter- and spring-sown crops, each of which has a different sensitivity to drought. Both intra- and inter-seasonal changes in temperature and precipitation have been shown to influence cereal yields in Tanzania (Rowhani et al., 2011). The increases in rainfall variability expected in the future will have substantial impacts on primary productivity and on the ecosystem provisioning services provided by forests and agroforestry systems. Despite the uncertainty surrounding the precise changes, climate variability needs to be taken into account. For example, the impacts of climate change to the middle of this century on crop yields in parts of East Africa may be under-estimated by between 4 and 27%, depending on the crop, if only changes in climatic means are taken into account and climate variability is ignored (Rowhani et al., 2011).

Changes in temperature and rainfall patterns and amounts will combine to bring about shifts in the onset and length of growing seasons in the future. Projected changes in length of the growing period for Africa to the 2090s were estimated by Thornton et al. (2011) for an ensemble of 14 GCMs. A large proportion of the cropping and rangeland area of sub-Saharan Africa is projected to see a decrease in growing season length, and most of Africa in the southern latitudes may see losses of at least 20 per cent. At the same time, the probability of season failure is projected to increase for all of sub-Saharan Africa, except for central Africa; in southern Africa, nearly all rain-fed agriculture below latitude 15°S is likely to fail one year out of two (Thornton et al., 2011). The robustness of these estimates, in terms of intra-model variability, is particularly low in the Sahel region and in parts of south-western Africa, however (Thornton et al., 2011). In terms of timing of growing season onset, Crespo et al. (2011) demonstrate that it may be possible to adapt to projected climate shifts to at least the 2050s in maize production systems in parts of southern Africa by changing planting dates.

In situations where changes in climate and climate variability may be larger, more fundamental changes may occur, particularly if critical thresholds in temperature and/or rainfall are reached (Gornall et al., 2010). Changes in the nature and timing of the growing season may induce smallholders to grow shorter-duration and/or more heat- and drought-tolerant varieties and crops, for example.

Most domesticated livestock species have comfort zones between 10 and 30 °C; at temperatures below this, maintenance requirements for food may increase by up to 50%, and at temperatures above this, animals reduce their feed intake 3–5% per additional degree of temperature (NRC, 1981). In many livestock systems, changes in temperature and rainfall and rainfall variability affect feed quantity most directly. Droughts and extreme rainfall variability can trigger periods of severe feed scarcity, especially in dryland areas, which can have devastating effects on livestock populations. In the recent past, the pastoral lands of East Africa have experienced droughts about one year in five, and even under these conditions it is generally possible to maintain relatively constant cattle herd sizes; but increases in drought frequency from one year in five to one year in three would set herd sizes on a rapid and unrecoverable decline (Thornton and Herrero, 2009). In Kenya, some 1.8 million extra cattle could be lost by 2030 because of increased drought frequency, the value of the lost animals and production foregone amounting to US$ 630 million (Ericksen et al., 2012).

Craine et al. (2012) found that in a temperate grassland, the effects of drought and high temperatures decline over the season, to the point where climate variability may have minimal impact later in the growing season. Key ecosystem processes are seasonally sensitive to climate variability, and increased understanding of plant productivity will need to recognise that the timing of climate variability may be just as important as its magnitude (Craine et al., 2012). In both temperate and tropical grasslands, species composition is a key determinant of livestock productivity. As temperature, rainfall patterns and CO_2 levels change, so will the composition of mixed grasslands change. Small climatic changes may affect the dynamics and balance of different grasslands species, and these may result in changes in livestock productivity (IPCC, 2007). The overall effects of changes in temperature and rainfall and their variability on species composition and grassland quality, however, are still far from clear, and remain to be elucidated (IPCC, 2007).

Droughts in grasslands can also be a predisposing factor for fire occurrence in many regions (IPCC, 2012), and intensified droughts could exacerbate the problem. There is some evidence that recent years have already seen an increase in grassland fire disasters in parts of China and tropical Asia. In the future, wildfires may be 60 per cent more frequent in much of South America for a temperature increase of 3°C, and in parts of Australia, the frequency of very high and extreme fire danger days could rise by up to 70 percent by 2050 (IPCC, 2012).

Mixed crop-livestock systems are prevalent in much of the developing world (Herrero et al., 2010), and climate change and changing climate variability in the future may affect the relationship between crops and livestock in the landscape in many places. In places that will become increasingly marginal for crop production, livestock may provide an alternative to cropping. Such transitions could occur in up to 3% of the total area of Africa, largely as a result of increases in the probability of season failure in the drier mixed crop-livestock systems of the continent; these are projected to increase from the current rate of approximately one year in 5 to one year in 4 or 3, depending on the combination of emissions scenario and climate model used (Jones and Thornton, 2009).

Changes in climate variability and in the frequency of extreme events may have substantial impacts on the prevalence and distribution of pests, weeds, and crop and livestock diseases. For example, in the past, combinations of drought followed by high rainfall have led to wide-spread outbreaks of diseases such as Rift Valley fever and bluetongue in East Africa and of African horse sickness in South Africa (Baylis and Githeko, 2006). Future increases in the frequency of extreme weather events could allow the expansion of Rift Valley fever northwards into Europe, for example (Martin et al., 2008). In general, the effects of future changes in climate variability on pests, weeds and diseases are not well understood (Gornall et al., 2010).

Evidence of vegetation shifts resulting from increasingly frequent extreme climatic events is still comparatively rare, although what there is supports the existence of stabilizing processes which tend to minimize and counteract the effects of these events, reinforcing community resilience (Lloret et al., 2012). Better understanding of these stabilizing processes and the community inertia that is frequently observed in vegetation under extreme events, are crucial for the establishment of sound management strategies that can improve ecosystem resilience under climate change (Lloret et al., 2012).

Globally, the negative effects of climate change on freshwater systems, in terms of changes in quantity and distribution, are expected to outweigh the benefits of overall increases in global precipitation due to a warming planet; several parts of the tropics and subtropics, including parts of Central-West Asia, North Africa, Asia and North America, are likely to be particularly affected by reduced freshwater availability (Rosegrant et al., 2009). It is expected that more than half the world's population will live in countries with severe water constraints by 2050 (Rockström et al., 2009).

Climate models project increased aridity during the current century over most of Africa, southern Europe and the Middle East, most of the Americas, Australia, and Southeast Asia. There is considerable uncertainty in such results, but the projections are alarming because a very large population may be severely affected in the coming decades. At the same time, precipitation may become more intense but less frequent (i.e., longer dry spells). This has the potential to increase flash floods and runoff, and as a result increase soil erosion, diminish soil moisture, and increase the risk of agricultural drought (Dai, 2011), as well as increasing the potential for crop losses due to flooding and affecting the dynamics of livestock diseases and their vectors, for example.

Food systems, health and nutrition

There is little literature on the effects of climate variability and extreme climatic events on food systems as opposed to food production. Out of nearly 600 pages in the SREX report (IPCC, 2012), for example, there is only one page on the impacts of climate extremes on food systems and food security.

At the local level, Codjoe and Owusu (2011) studied communities in Ghana and showed how extreme climatic events affect rural food production, transportation, processing and storage. Food security in this region could be enhanced by increasing farm-based storage facilities; improving the transportation system, especially feeder roads that link food production areas and major markets; providing farmers with early warning systems; extending credit to farmers; and the use of supplementary irrigation. Some cultural practices, particularly those that prohibit the consumption of certain foods, may reduce the resilience of some individuals and ethnic groups to food system disruptions.

Climate variability has both direct and indirect impacts on human health. Extreme heat affects health, especially among the elderly (McMichael et al., 2006). Other direct impacts are largely expressed through the interaction of infectious and vector-borne diseases with temperature and precipitation. Malaria, dengue and cholera, for example, are all highly affected by changes in seasonal distribution of precipitation, including changes in flood and drought patterns (Costello et al., 2009; McMichael and Kovats, 2000). Although changes in malaria vectors will occur due to the gradual increase in temperature, the incidence of disease is also quite sensitive to changes in precipitation. If changes in climate variability lead to changes in spatial and temporal variation in vegetation and water distribution, we could see more epidemics as the vector moves to new areas (McMichael et al., 2006). Both malaria and dengue fever have associations with La Niña and El Niño cycles (McMichael et al., 2006). Human displacement from extreme events, especially floods, could become more frequent with an increase in climate variability. This also often has negative consequences for human health, not least because of crowded conditions with poor sanitation. Diarrhoeal disease is regularly a problem in such situations (Haines et al., 2006). Additionally, as inadequate access to health services is already a leading cause of poor health in developing countries, displacement and infrastructure damage from extreme events, especially floods, can exacerbate this (although people also often move in response to prolonged drought). If water scarcity increases, this also has an impact on sanitation and health outcomes if clean water is less available (Few, 2007).

Nutrition is correlated with positive health outcomes, and both adequate amount of calories as well as sufficient nutritional diversity and proteins are important. As outlined above, overall availability of food shows some correlation with climate variability. A recent study by Lloyd et al. (2011) builds upon previous work of Nelson (2009) to show clearly that climate change and increased climate variability, through their impact on food production, will have a negative impact on the prevalence of undernutrition, increasing severe stunting by 62% in South Asia and 55% in East and southern Africa by the 2050s. Although nutrition is determined not only by food availability but also access to food as well as nutritional and child care practices, there are almost no studies on these other aspects of nutrition determinants (Tirado et al., 2010).

Some more detailed work has been done at national level. For example, a dynamic economy-wide model of Bangladesh has been used to estimate economic damages from historical climate variability and future anthropogenic climate change. Using a combination of historical yield variability and ten climate projections, future anthropogenic climate change damages are estimated to reduce national rice production in Bangladesh by about 9 percent to mid-century, and most of these losses are attributed in the analysis to flooding damage and climate variability (Thurlow et al., 2011). Another example is the work of Ahmed et al. (2011), who used a modelling approach to estimate how changes in climate variability might affect crop yields and thence poverty rates in Tanzania to the early 2030s. They found that future climate scenarios with the largest increases in climate volatility rendered Tanzanians increasingly vulnerable to poverty through its impact on the production of staple grains.

At the global level, one of the few studies so far to model climate shocks and their impacts on commodity prices in different regions is Willenbockel (2012). Results are indicative only but interesting nevertheless. For example, a drought in North America in 2030 of a similar scale to the historical drought of 1988 would have a dramatic temporary impact on world market export prices for maize and a strong impact on world market price for wheat. These impacts would feed through to domestic consumer prices, with particularly profound effects in parts of sub-Saharan Africa. For instance, Nigeria depends almost entirely on imports of wheat, and under such a scenario the average domestic price for wheat in the country would spike by 50% above the baseline 2030 price, with potentially substantial impacts on households. The treatment of the impacts of climate variability as opposed to the impacts of slow-onset climate change in global economic models is a heavily under-researched area, particularly how harvest failures in one continent may influence food security outcomes in others.

How may changes in climate variability and extremes affect food security in the future?

Human populations are vulnerable to the impacts of climate change largely because of the socio-economic and political context in which they live. Thus vulnerability to climate change is highly differentiated (O'Brien et al., 2007) across geography, income levels, type of livelihood, and governance arrangements, amongst other things. Human vulnerability can be evaluated in terms of a range of different outcomes such as food security or household income. Thus areas vulnerable to disasters are not necessarily the same as those whose food availability is likely to be negatively affected by changes in climate variability. A major challenge in viewing human vulnerability as the result of multiple and dynamic factors is the need to take a synthetic approach to translate the sectoral impacts of changes in climate and climate variability into consequences for people. Food security is a particularly important developmental outcome that is highly vulnerable to climate change. This vulnerability is a product of climate change impacts on biological systems, affecting food availability, as well as economic and social impacts that affect food utilization, access to food and the stability of food security (Ericksen, 2008).

As noted above, there is only limited information on the potential impacts of climate variability on food availability at broad scales such as national and regional. For economies that are agriculturally based, Figure 2 suggests that rainfall variability can have substantial effects on agricultural growth at the national level, although that relationship will be modified by many other factors. Links from climate variability to poverty indicators are also not that straightforward to demonstrate. We undertook some new analysis using recent global datasets to try to throw some light on the possible links between climate variability and food security. Herrero et al. (2013) recently generated maps showing global kilocalorie production per capita from edible animal products, including milk and meat from ruminant species (bovines, sheep and goats) and meat and eggs from monogastric species (pigs and poultry). To estimate total kilocalorie production from crops, we used data on crop yields and harvested areas from the Spatial Production Allocation Model (SPAM) of You et al. (2012). SPAM contains data for the year 2000, and includes 14 food crops or crop groups: banana and plantain, barley, beans, cassava, groundnut, maize, millet, other pulses such as chickpea, cowpeas, pigeon peas, and lentils), potato, rice, sorghum, soybean, sweet potato and yam, and wheat. We calculated the total food production from these 14 crops and crop groups using calorie contents as given in FAO (2001). The SPAM dataset matches FAOSTAT country totals for 2000, and details crops grown in three types of system (irrigated, rainfed commercial and rainfed subsistence). Multiple cropping is also taken into account. We then calculated total kilocalorie production from both livestock and the 14 crops at a resolution of 5 arc-minutes (gridcells of side about 9 km at the equator). Each gridcell was then stratified on the basis of rainfall variability. To do this, we utilised a weather generator, MarkSim, and methods outlined in Jones and Thornton (2013) to estimate the coefficient of variation (CV) of annual rainfall for the globe, from 100 years of generated daily rainfall data. We estimated the human population in each stratum (CIESIN, 2005a). To relate climate variability to some proxy of food insecurity, we used the subnational data set of CIESIN (2005b) on the proportion of children under 5 who are underweight for their age, and again estimated the average proportion for each stratum. The human population and children underweight datasets are both for the year 2000. Results are shown in Table 3, split between developing and developed countries. Here we defined the developing countries as those in the Americas between Mexico in the north and Brazil, Paraguay, Bolivia and Peru in the south, all of Africa, and in Asia up to 45 °N excluding Japan. The remainder we classified as developed countries.

Several points can be made about Table 3. First, some 5.4 billion people, or just under 90 per cent of the global population in 2000, live in places that produce at least some crop and livestock calories. On the basis of this analysis, the 14 crops or crop groups account for 70 per cent of all calories produced and livestock 30 per cent (note that several important crops that provide calories for human nutrition are not included here, including sugar and oil crops). Second, it is noteworthy that developing countries (as defined above) account for 78 per cent of the people but only 40 per cent of the calories available; conversely, the temperate regions account for 22 per cent of the people and 60 per cent of the calories produced. Third, the relationship between rainfall variability and the average prevalence of underweight children seems not to be straightforward: in the developed regions, the value of the food insecurity proxy increases as rainfall variability increases, whereas in developing countries, it increases up to a rainfall CV of 30 per cent and then falls slightly for further increases in rainfall CV. A possible explanation for this is that the higher CV regions, most food is brought in via imports or food aid, for example. Fourth, nearly eight times as many people live in areas of high rainfall variability (with a CV of 30 per cent or more) in the developing countries as they do in the developed countries (407 million compared with 54 million); yet these areas of high rainfall variability in developing countries account for only 3 per cent of all the calories produced, and they also tend to be areas with relatively high child malnutrition. Clearly, many such areas may be targets for the provision of food aid and social safety nets.

We can show that increased rainfall variability will affect agricultural growth and economic development in certain types of countries (Figure 2). The analysis presented above is highly simplified, as there are many other factors and drivers that will interact in complex ways, but there may also be impacts of increased rainfall variability on food security as shown by a proxy such as the prevalence of child malnutrition (Table 3). In the absence of information concerning the nature of increases in rainfall variability in the coming decades, one question that might be asked is, how sensitive are the data in Table 3 to shifts in rainfall variability? To test this, we made several changes across the board to rainfall CV and then re-stratified the data. Results are shown in Figure 3, in terms of population by rainfall CV, for the developing world and the developed world, for "current" conditions and for situations with decreased (-1 per cent) and increased (+1 per cent and +2 percent) rainfall variability . While the likelihood of such changes is essentially unknown, a +2 percentage point increase in annual rainfall CV leads to increases in the population living in areas of high rainfall variability (CV> 30%) in developing countries of more than 230 million to 643 million people (58 per cent), while in the developed countries the number more than doubles from 54 to 112 million.

It is not just rainfall that increases variability in yield. The temperature-related processes reviewed in Section 3.1 also contribute to this. Few climate change impact studies report changes in CV; analysis of those that do shows that increases in CV of more than 50% may not be uncommon from the 2040s onwards (Challinor et al., 2014a).

Even though simplified and with a high degree of uncertainty, our analysis helps to substantiate the hypothesis of an increase in child malnutrition rates in both developed and developing countries in the future as a result of variability changes, all other things being equal. These increases could be particularly large in sub-Saharan Africa as a result of high population growth rates and relatively large areas with high rainfall variability. Sub-Saharan Africa is already by far the largest recipient of food aid: average annual shipments amount to about 2 per cent of all food consumed. Under many scenarios, the number of food-insecure people in sub-Saharan Africa by 2020 is still likely to be at least 500 million (USDA, 2010), and this is a challenge that will clearly not be made any easier by increases in rainfall and temperature variability.

Responses of vulnerable people

Most of the literature and analysis discussed above relates to how climate variability will affect exposure or sensitivity of biological and food systems, and hence food security outcomes. However, the most important element of reducing vulnerability is to enhance the adaptive capacity of people, at various levels of decision-making from the individual up to the national and regional. Institutions play a key role in enabling such adaptation. Increases in variability, which are largely unpredictable in the short and long term, will force institutions (defined loosely as social patterns including organizations) to be more proactive and flexible, qualities that are difficult to foster (Gupta et al., 2012). This applies not only to the national level; for example, Ncube et al. (2012) discuss the example of local government infrastructure in South Africa to provide basic commodities such as water and energy. They found a strong relationship between water and energy demand and rainfall variability, and concluded that local governments will increasingly need to be proactive in planning for adaptation to climate change, because of its influence on their operations and budgets (Ncube et al., 2012).

By focusing on how climate variability might change, we are trying to better characterize what climate change means for vulnerability - a better answer to the question "Vulnerability to what" (Misselhorn et al., 2010). Uncertainty or lack of predictability is considered a real hindrance to planning for adaptation. However, if for example we can explore how sensitive food availability in a given location is to a range of increases in precipitation variation, or what the limits of current institutional arrangements are for dealing with the consequences of increased frequency of extreme events, we can get a clearer definition of the development problem that climate change might exacerbate. This better prepares communities and governments to develop robust adaptation strategies in spite of uncertainty about the precise impacts of climate change.

What might vulnerable people who are partially or wholly dependent on natural resources for their livelihoods do in response to substantially increased climate variability? There is already a considerable literature on the ways in which resilience of agricultural production systems may be increased in the face of climate change, particular under the "climate-smart agriculture" rubric (e.g. FAO, 2010; Thornton et al., 2013). Options range from increasing the efficiency of crop and livestock systems via various components such as soil and nutrient management, water harvesting and retention, improving ecosystem management and biodiversity, diversification of on-farm activities, use of weather forecasts and early warning systems, and methods for managing risk such as index-based insurance and risk transfer products (Barnett et al., 2008). In relation to options for the drylands, the literature is not particularly sanguine. As many have pointed out, particularly in more marginal areas, farmers have already been substantially changing their practices. For example, farmers in northern Burkina Faso have adopted many techniques intended to increase crop yield and reduce yield variability (Barbier et al., 2009). The drivers of these shifts are not climate variability but growing land scarcity and new market opportunities. While improved water harvesting and storage techniques may be able to reduce farmers' dependence on rainfall, they are not likely to be sufficient to significantly reduce vulnerability to drought (Barbier et al., 2009). Institutional change may be critical in enhancing resilience in dryland pastoral systems. In the Kalahari, land privatization policies have increased the vulnerability of poorer communal pastoralists, but increasing access to markets and improving the ability of these farmers to operate in a market economy could reduce their vulnerability (Dougill et al., 2010). At the same time, alternatives that make sense from the perspective of current economic risk or land scarcity, such as the use of higher-yielding crop varieties or improved animal breeds, may not be robust choices for dealing with climate change if they do not outperform local varieties under highly variable conditions (see, for example, Rodríguez et al., 2011). This underpins the importance of crop varieties with increased tolerance to heat and drought stress for managing future climatic variability (Hellin et al., 2012).

There are several ways in which the stability of food systems can be strengthened. These include governments investing in smallholder agricultural production, particularly in downstream activities such as storage, trace, processing and retailing; implementing and scaling up options that help producers to be more resilient to climate volatility, such as the now widespread use of smallholder crop insurance schemes in India and certain other countries; and establishing safety net programmes for the most vulnerable households, such as has been implemented successfully in Ethiopia (Lipper, 2011). Insurance may be an increasingly important way to help smallholders become more resilient, in view of the impacts of climate change on yield variance and the resulting demand for effective risk-reducing measures. Using a microeconomic farm model, Antón et al. (2012) found that area yield and weather index insurance are robust policy options across different scenarios, and are generally cheaper than individual yield insurance. They also found that ex post indemnity payments can be effective in dealing with extreme systemic risk situation and are similarly robust across different scenarios, even with frequent occurrence of extreme events, although they can be costly to implement (Antón et al., 2012).

One recurring thread in recent discussions concerning responses to increasing climate variability is the role of indigenous knowledge. Agro-pastoralists in dryland Kenya (and probably in many other places too) rely on indigenous indicators of rainfall variability and use them as a framework within which to position and interpret meteorological forecasts (Rao et al., 2011); at the same time, few are able to adapt their practices because of a general lack of adaptive capacity (Speranza et al., 2010). Integrating different types of knowledge and bringing different stakeholder groups together pose significant challenges, however, and considerable innovation in participatory action research will be needed (Ziervogel and Opere, 2010). But there would seem to be a rich area of research in investigating the reliability and validity of indigenous knowledge concerning climate variability, and seeing how it can be better integrated into formal monitoring systems to enhance its acceptability, thereby increasing smallholders' resilience to climate variability.

For some communities in marginal areas, climate may decreasingly be the primary concern. Nielsen and Reenberg (2010) present results from northern Burkina Faso that indicate that villagers there are "beyond climate": current livelihood strategies are increasingly independent of climate. There as elsewhere, people have engaged in livelihood diversification in attempts to ameliorate the negative impacts of climate variability on agriculture. At some stage, tipping points are reached such that transformative adaptation alternatives may be the only viable options that remain. There are many examples of such changes to livelihood systems, such as substitution of one crop or livestock species for another. In many parts of sub-Saharan Africa, a highly spatially distributed mode of living is prevalent, and clearly it can be a highly effective way of dealing with change and variability. This is intriguingly mirrored in developed-country situations also, in Australian farming households over the last few years that have seen crippling, multi-year drought followed by record flooding, for example. Many such households are developing more spatially distributed modes of farming and living, whereby multiple priorities and pressures can be accommodated by moving between widely distributed farm businesses, employment and children's activities (Rickards, 2012). Endurance and accommodating change may be widely valued, but others would challenge this world view and emphasise innovation and the conscious creation of innovative alternatives (Rickards, 2012; O'Brien, 2012). Many people may have no choice, and chronic or sudden-onset environmental disasters related to climate change may force large-scale migration; however, this is not expected to be common in the next two decades (Raleigh and Jordan, 2010).

Conclusions: refining the research agenda

Most of the climate change impacts work carried out to date either ignores or downplays variability. On the one hand, this is somewhat understandable. Regarding expected changes in rainfall and temperature variability in the future, there is high uncertainty: IPCC (2012) provides no assessment of projected changes in extremes at spatial scales smaller than for large regions. Indeed, the prognosis for robust quantification in the foreseeable future of changes in weather and climate variability over short temporal and high spatial scales is rather gloomy (Ramirez et al., 2013). But on the other hand, we already know a reasonable amount about how current levels of climate variability have considerable impacts on biological systems and health. While we cannot let limited predictive capability constrain adaptive responses, it does suggest that we will need to become increasingly creative to arrive at actionable answers in response to questions from a wide range of decision makers concerning the appropriate adaptation of biological and food systems. One example of a suitable framework is the combination of impact and capacity approaches (broadly, top down and bottom up, respectively) to adaptation planning; there is considerable potential in this and other problem-orientated approaches for producing robust knowledge and actions in the face of uncertainty (Vermeulen et al., 2013). This is not without its challenges, however: recent assessments indicate an increased probability of future tipping events, in part because of positive feedbacks in the climate system (e.g., Cory et al., 2013), and the corresponding impacts are estimated to be large, making them significant risks (Lenton, 2011). Below, we briefly discuss five areas that warrant considerable attention if we are to address these challenges.

First, there are still important knowledge and data gaps in our understanding of the effects of climate variability and extreme events on biological systems. With regard to crops, Craufurd and Wheeler (2009) identified several areas, including the need for more information on crop development and temperature by photoperiod interactions at the higher end of the temperature scale. There are key knowledge gaps with regard to the ways in which climate variability and extreme events may exacerbate multiple stresses for animals and plants, and how these stresses may interact and combine. There are also important knowledge gaps regarding the impacts of climate variability and extreme events on the prevalence, incidence and severity of crop and livestock diseases, and on key agricultural pests and weeds and how their prevalence may change.

Second, there are substantial limitations in our impact models, at all scales. This certainly applies to models of crops and livestock and on the effects of variability on the quantity and quality of crop and livestock production. Identification of synergies between global, regional and local studies is a promising avenue for improvement (Challinor et al., 2014b). Much work is needed on extending the applicability of current crop and livestock models to the higher-temperature and more variable climates projected as increasingly likely under higher greenhouse gas emission scenarios. Equally importantly, such gaps exist in relation to models of farming systems and the ways in which biophysical and socio-economic drivers of change combine in particular situations (Challinor et al., 2009), and information concerning the way in which climate variability and climate extremes may affect thresholds and tipping points among different farm enterprises in relation to different household objectives is largely missing. Gaps also exist concerning the appropriate incorporation of risk and dynamics in farming system models. For smallholders, higher risks usually imply more costs, directly or indirectly, and so there is a need to link risk to decision making profiles of farmers and their attitudes to investments and technology adoption. Some work has been done on this (see, for example, Willock et al., 1999; Solano et al., 2000), but more in-depth studies on this topic are needed, because increasing adoption rates of key practices under risk is a significant challenge, and targeting options to risk management profiles is essential. At the national and global scales, more sophisticated output is needed from global and regional economic models concerning welfare gains and losses arising from different policy action, and how changes in welfare from gradual climate change and climate shocks are differentially distributed among different groups in society, such as producers and urban poor, and men and women (Skoufias et al., 2011).

Third, there is a great need to improve the monitoring of local conditions, not only to provide data and information for improving our understanding and our models, but also to guide effective adaptation (for example, through downscaling climate model output to local situations) and to provide information for yield early-warning systems and locally-appropriate indices for weather-based crop and livestock insurance schemes. The situation for climate and weather data monitoring in many developing countries is poor and deteriorating. There is considerable research activity in combining satellite and land-based information to produce long-term, high-resolution weather data sets (for example, Maidment et al., 2013). Such hybrid datasets have considerable potential to ease the weather data problem in some countries, but they are not a replacement for land-based weather measurement, however, and considerable investment will be needed to improve climate and weather monitoring. Improved monitoring of local food systems (in relation to food production and accessibility, for example) and of the environment (in relation to local crop and rangeland conditions, for example) are also needed to provide readily actionable information. The tradition of monitoring and surveillance for disease outbreaks within the health community, to allow for better early warning and anticipatory response in relation to food systems, is a promising model, although it can be costly.

Fourth, enhancing food security for the 9.5 billion people projected by 2050, more than 86% of whom will be living in the less developed countries (UNDESA, 2013), will mean adapting biological and food systems to the increasingly variable climate and to increasingly frequent extreme events, which in turn will entail considerably enhanced understanding of the complex system of production, logistics, utilization of the produce, and the socioeconomic structure of communities (IPCC, 2012). This strongly supports the notion of viewing adaptation and vulnerability reduction not as discrete events but as processes through time, from the shorter term to the longer term. The impacts of climate variability and extreme events are often most acutely experienced at the local level (IPCC, 2012), and they also usually occur over short time scales. At local and short temporal scales, the uncertainties associated with their prediction may be at their largest. Food security, health and nutritional outcomes are all the product of multiple interacting stressors, not just climate patterns. This could be one of the reasons the disaster relief community and the agricultural research for development community have not talked much together – the former has a "variability" orientation, the latter a "changing means" orientation. There are exceptions – for example, the story of weather forecasts for emergency aid provision in West Africa in 2008 (Tall et al., 2012) – but there do not seem to be many to date. There are surely synergies to be explored between these two communities of practice, particularly given rapid developments in the field of seamless prediction of weather and climate (Brown et al., 2012; Meehl et al., 2013). In time, seamless prediction may provide a bridge between the shorter term (days, weeks, season) and the longer term (years, decades) and between risk management and adaptation planning. Using models to express uncertainty as the time intervals in which key changes are expected, rather than focussing on a particular time and expressing uncertainty in other ways, may help forge stronger links between prediction and adaptation (Vermeulen et al., 2013). The effectiveness of the links between different spatial and temporal scales will depend on enhanced understanding, models and monitoring of the impacts of climate change and climate variability on both biological and socio-economic systems and the ways in which they interact within and across scales. Enhancing food security in the less developed countries in the coming decades will need balanced, integrated approaches that encompass changes in variability and extreme events as well as changes in means in quantifying impacts on, and identifying appropriate adaptation of, biological and human systems.

Finally, greater and more effective communication is needed between scientists and decision makers, and between natural and social scientists. Currently, climate information is severely underutilised in supporting decision making, which Weaver et al. (2013) partially attribute to a failure to incorporate learning from the decision and social sciences into climate-related decision support. There is a great deal that can be done on the co-generation of information and its communication in appropriate ways, and in engaging meaningfully with decision makers at local and national policy levels, for example. Participatory scenario development may be one useful tool for facilitating some of these processes (Vervoort et al., 2014), in addition to much stronger links between biological and communications scientists. In general, the top-down and bottom-up approaches identified above rarely meet in the form of integrated analyses. Given what is known about vulnerability to climate, what foci should environmental scientists have? Changes in variability are often more important for communities than changes in mean quantities; yet the focus of modelling studies is often on the latter. The ongoing focus on quantifying uncertainty in impacts studies is important if we are to avoid errors; however, these analyses can be targeted more clearly at adaptation

(Challinor et al., 2013; Vermeulen et al., 2013). Systematic intercomparison of impacts studies, with coordinated cycles of model improvement and projection, are useful in reducing uncertainty and synthesising knowledge (Challinor et al., 2014b). Observational data to constrain models at a range of scales are central to these endeavours.

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Figure captions

Figure 1. The effect of changes in temperature distribution on extremes. Different changes of temperature distributions between present and future climate and their effects on extreme values of the distributions: (a) Effects of a simple shift of the entire distribution towards a warmer climate; (b) effects of an increase in temperature variability with no shift of the mean; (c) effects of an altered shape of the distribution, in this example a change in asymmetry towards the hotter part of the distribution. From IPCC (2012).

Figure 2. The relationship between rainfall variability expressed as the 12-month Weighted Anomaly of Standardized Precipitation (WASP) and growth in GDP and agricultural GDP in three countries in sub-Saharan Africa: (a) Ethiopia, (b) Niger, (c) Mozambique. Data sources: World Bank, data.worldbank.org/indicator and the IRI data library, iridl.ldeo.columbia.edu/.

Figure 3. The differential impacts of across-the-board changes in rainfall CV of -1%, +1% and +2% on population distribution by rainfall variability in developing (a) and developed (b) countries.

Table 1. Summary of observed and projected changes of five extremes at a global scale (taken from Table 3.1 in IPCC, 2012).

Variable / phenomenon	Observed changes since 1950	Attribution of observed changes	Projected changes up to 2100
Temperature	Very likely[1] decrease in number of unusually cold days and nights. Very likely increase in number of unusually warm days and nights. Medium confidence in increase in length or number of warm spells or heat waves in many regions. Low or medium confidence in trends in temperature extremes in some subregions due either to lack of observations or varying signal within subregions.	Likely anthropogenic influence on trends in warm/cold days/nights globally. No attribution of trends at a regional scale with a few exceptions.	Virtually certain decrease in frequency and magnitude of unusually cold days and nights. Virtually certain increase in frequency and magnitude of unusually warm days and nights. Very likely increase in length, frequency, and/or intensity of warm spells or heat waves over most land area.
Precipitation	Likely statistically significant increases in the number of heavy precipitation events in more regions than those with statistically significant decreases, but strong regional and subregional variations in the trends.	Medium confidence that anthro-pogenic influences have contributed to intensification of extreme precipitation at the global scale	Likely increase in frequency of heavy precipitation events or increase in proportion of total rainfall from heavy falls over many areas of the globe, in particular in the high latitudes and tropical regions, and in winter in the northern mid-latitudes.
El Niño and other modes of variability	Medium confidence in past trends toward more frequent central equatorial Pacific El Niño-Southern Oscillation (ENSO) events. Insufficient evidence for more specific statements on ENSO trends.	Anthropogenic influence on trends in North Atlantic Oscillation (NAO) is about as likely as not. No attribution of changes in ENSO.	Low confidence in projections of changes in behaviour of ENSO and other modes of variability because of insufficient agreement of model projections.
Droughts	Medium confidence that some regions of the world have experienced more intense and longer droughts, in particular in southern Europe and West Africa, but opposite trends also exist.	Medium confidence that anthro-pogenic influence has contributed to some observed changes in drought patterns. Low confidence in attribution of changes in drought at the level of single regions due to inconsistent or	Medium confidence in projected increase in duration and intensity of droughts in some regions of the world, including southern Europe and the Mediterranean region, central Europe, central North America, Central America and Mexico, northeast Brazil, and southern Africa. Overall low confidence elsewhere because of insufficient agreement of

		insufficient evidence.	projections.
Floods	Limited to medium evidence available to assess climate-driven observed changes in the magnitude and frequency of floods at regional scale. There is low agreement in this evidence, and so low confidence at the global scale regarding even the sign of these changes. High confidence in trend toward earlier occurrence of spring peak river flows in snowmelt- and glacier-fed rivers.	Low confidence that anthropogenic warming has affected the magnitude or frequency of floods. Medium to high confidence in anthropogenic influence on changes in some components of the water cycle (precipitation, snowmelt) affecting floods.	Low confidence in global projections of changes in flood magnitude and frequency because of insufficient evidence. Medium confidence that projected increases in heavy precipitation would contribute to rain-generated local flooding in some catchments or regions. Very likely earlier spring peak flows in snowmelt- and glacier-fed rivers.

1. Likelihood assessment: virtually certain, 99-100%; very likely, 90-100%; likely, 66-100%; more likely than not, 50-100%; about as likely as not, 33-66%; unlikely, 0-33%; very unlikely, 0-10%; and exceptionally unlikely, 0-1%

Table 2. Population affected by selected disasters (aggregated from Raleigh and Jordan, 2010).

Region	**Number of disasters** [1]	**Population affected in 2007 (1000s)**					
		Droughts (5%) [2]	Extreme temperatures (5%)	Floods (45%)	Landslides (7%)	Waves, surges (<1%)	Windstorms (37%)
Americas	1,850	2,264	133	385	10	3	5,224
Africa	928	5,104	333	310	4	28	205
Asia	3,045	43,812	209	9,193	73	369	1,796
Europe	928	1,023	18	88	4	<1	104
Oceania	387	1,206	920	27	2	6	72

1. Number of disaster entries in the Emergency Events Database (EM-DAT), www.emdat.be, for the period 1970-2007.

2. Figures in parentheses show the relative frequency of occurrence of each disaster type in the entire database.

Table 3. Proportion of total calorie availability per person per day from livestock products and from 14 food crops in developing and developed countries, by rainfall variability class.

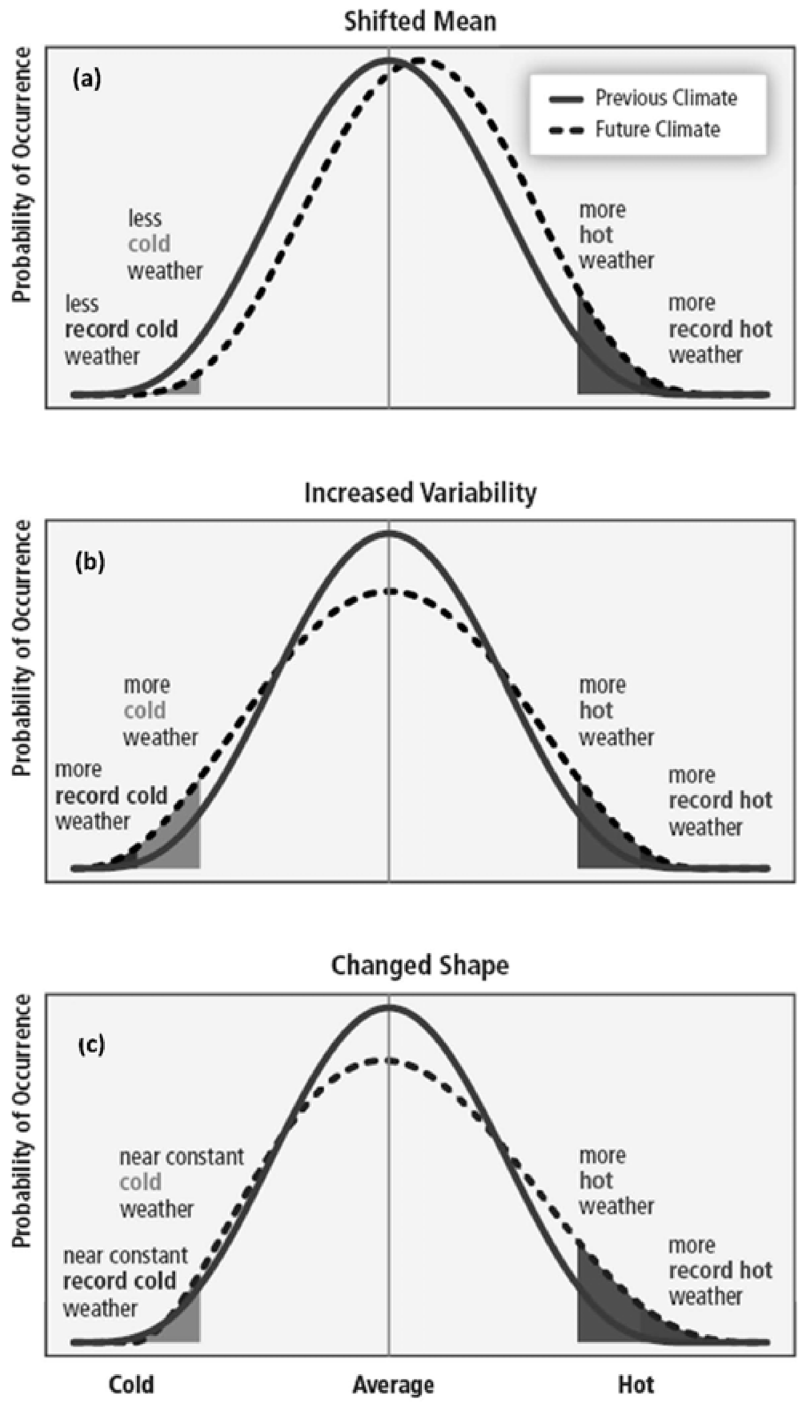
A Developing countries[1]

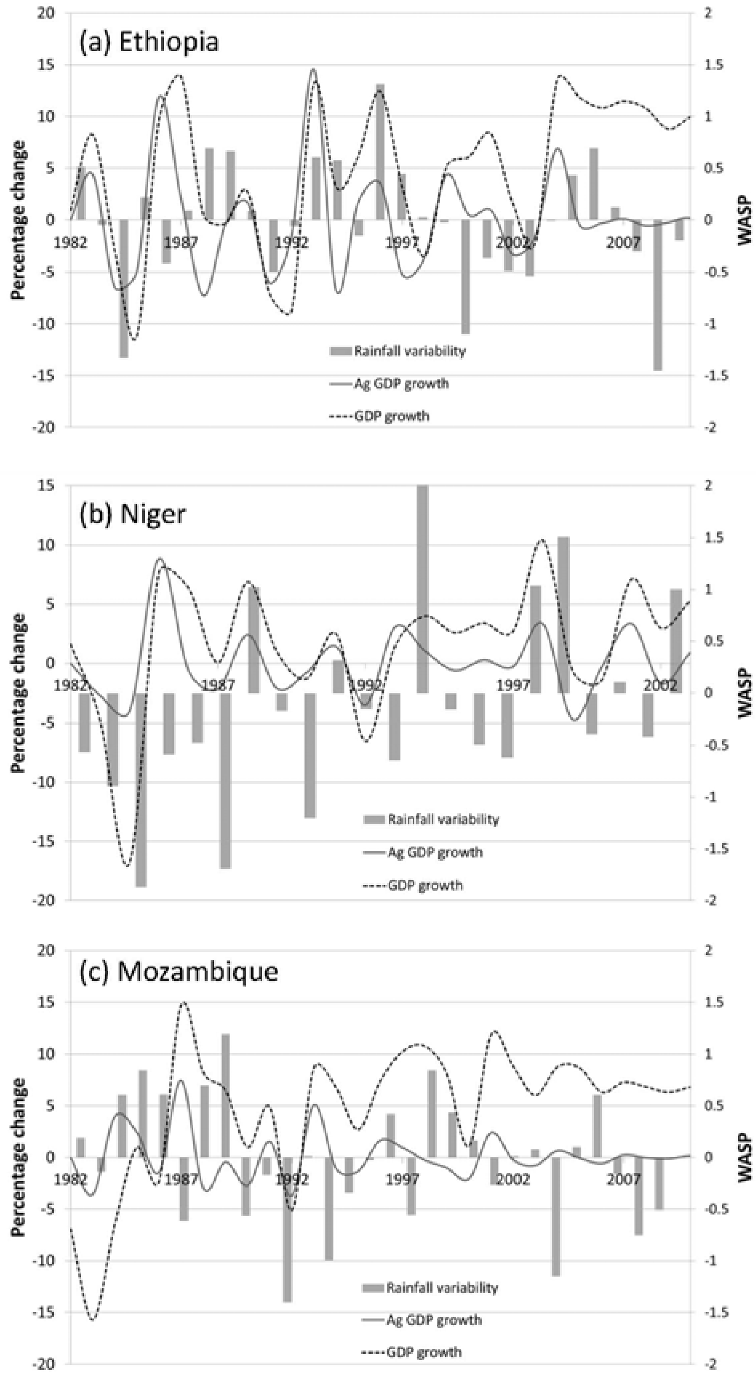
CV[2] of annual rainfall (%)	Mean annual Rainfall[2] (mm)	Human population[3] (million)	Children Underweight[4] (%)	Proportion of calories from 14 Crops[5] (%)	Proportion of calories from livestock[6] (%)
<15%	2739	211	16	1.8	0.2
15-20%	1738	1,318	17	10.3	0.6
20-25%	1118	1,498	20	7.7	11.4
25-30%	657	808	22	3.0	2.9
30-35%	428	242	20	0.7	0.1
>35%	226	165	19	1.1	0.1
Total		**4,241**		**24.6**	**15.2**

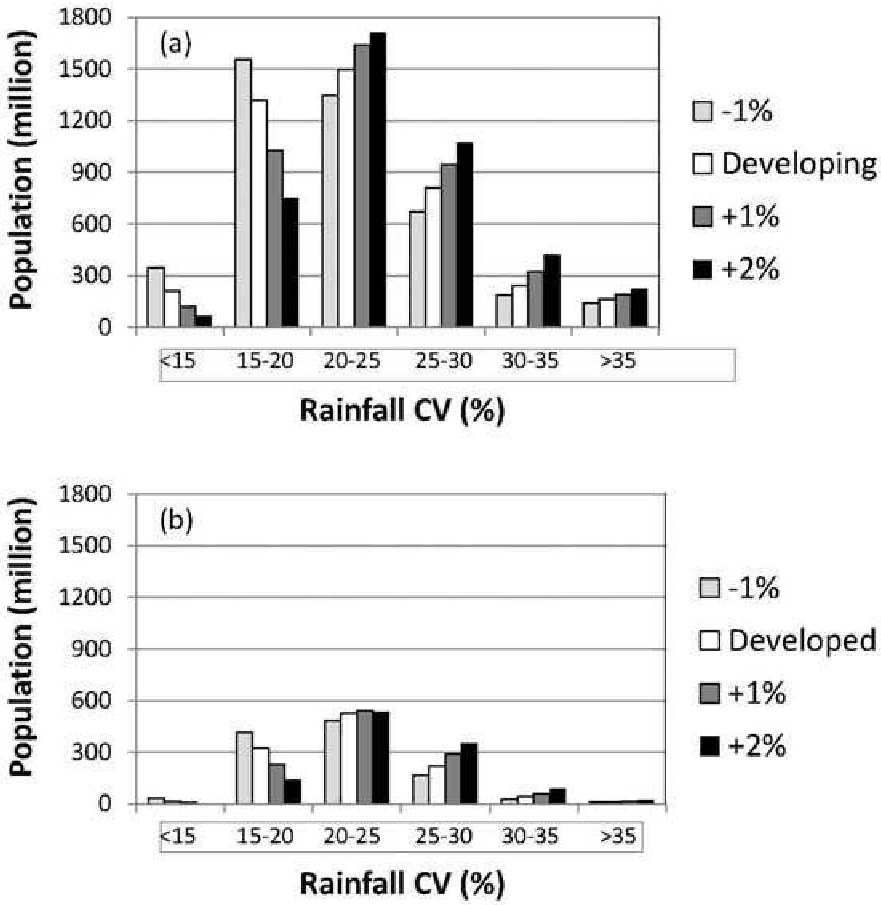
B Developed countries[1]

CV[2] of annual rainfall (%)	Mean annual rainfall[2] (mm)	Human population[3] (million)	Children Underweight[4] (%)	Proportion of calories from 14 Crops[5] (%)	Proportion of calories from livestock[6] (%)
<15%	1938	17	<1	0.1	0.1
15-20%	1094	323	<1	4.6	7.0
20-25%	662	527	2	17.0	2.6
25-30%	469	221	2	18.3	3.4
30-35%	355	42	3	4.7	1.4
>35%	230	12	5	0.5	0.6
Total		**1,142**		**45.2**	**15.1**

1. "Developing countries" defined here as the countries of the Americas between Mexico in the north and Brazil, Paraguay, Bolivia and Peru in the south, all of Africa, and Asia up to 45 °N excluding Japan. "Developed countries" comprise the remainder.
2. Mean rainfall and coefficient of variation of annual rainfall estimates simulated using methods in Jones and Thornton (2013).
3. From Gridded Population of the World Version 3 (CIESIN, 2005a).
4. Global Subnational Prevalence of Child Malnutrition v1, online at beta.sedac.ciesin.columbia.edu/data/set/povmap-global-subnational-prevalence-child-malnutrition
5. Yields and harvested areas from Spatial Production Allocation Model (SPAM) 2000 (You et al., 2012). Crops included: banana and plantain, barley, beans, cassava, groundnut, maize, millet, other pulses, potato, rice, sorghum, soybean, sweet potato and yam, wheat.
6. From Herrero et al. (2013).


Shifted Mean
(a)
Previous Climate
Future Climate
Probability of Occurrence
less
cold
weather
less
record cold
weather
more
hot
weather
more
record hot
weather
Increased Variability
(b)
Probability of Occurrence
more
cold
weather
more
record cold
weather
more
hot
weather
more
record hot
weather
Changed Shape
(c)
Probability of Occurrence
near constant
cold
weather
near constant
record cold
weather
more
hot
weather
more
record hot
weather
Cold
Average
Hot


(a) Ethiopia
Percentage change
WASP
Rainfall variability
Ag GDP growth
GDP growth
(b) Niger
(c) Mozambique
1982
1987
1992
1997
2002
2007


(a)
Population (million)
1800
1500
1200
900
600
300
0
<15
15-20
20-25
25-30
30-35
>35
Rainfall CV (%)
-1%
Developing
+1%
+2%
(b)
Population (million)
1800
1500
1200
900
600
300
0
<15
15-20
20-25
25-30
30-35
>35
Rainfall CV (%)
-1%
Developed
+1%
+2%