FSE
STANFORD

Center on Food Security and the Environment

Stanford Symposium Series on Global Food Policy and
Food Security in the 21st Century

Climate Change and Agricultural Adaptation

David B. Lobell

Assistant Professor of Environmental Earth System Science, FSE Center Fellow,
Stanford University

December 8, 2011

Acknowledgements: This paper serves as background to the sixth presentation in a symposium series on Global Food Policy and Food Security hosted by the Center on Food Security and Environment at Stanford University, and supported by the Bill and Melinda Gates Foundation. I would like to thank Wally Falcon and Michela Biasutti for comments on an earlier version of this manuscript.

The Center on Food Security and the Environment (FSE) is a joint center between Stanford's Freeman Spogli Institute for International Studies (FSI) and Stanford Woods Institute for the Environment.

Abstract

Food policy makers are increasingly faced with the question of how to adapt to climate change. The increased attention on climate adaptation is partly related to the fact that greenhouse gas emissions and climate change show little sign of slowing, partly because of prospects for large sums of money devoted to adaptation, and partly because of well publicized recent weather events that have affected agricultural regions and rattled global food markets. A common and reasonable reaction from the food policy and agricultural community has been to argue that climate variations have always been a challenge to agriculture, and that climate change just makes addressing these variations more important. A logical conclusion from this perspective is to emphasize activities that help build resilience to unpredictable weather events, as well as to focus on the types of weather variables that exhibit a lot of year-to-year variability and cause the bulk of farmers' concerns in current climate.

However reasonable as a starting point, this perspective is misguided and risks taking a challenging problem and making it even harder. Anthropogenic global warming (AGW) is fundamentally different from the natural variations driven by internal dynamics in the climate system. Indeed, predicting the course of climate change is less like predicting the weather next week than it is like predicting that summer will be warmer than winter. Progress in climate science has shown that the most indelible hallmarks of AGW will be increased occurrence and severity of high temperature and heavy rainfall extremes in all regions, and increased frequency and severity of drought in sub-tropical regions. Changes in the timing and amount of seasonal rainfall also appear likely in some regions, but at a much smaller pace relative to natural variability. In all of these cases, predictions from climate science are most robust at broader spatial scales, with considerable uncertainty in predicting changes for any single country.

Meanwhile, progress in crop science has shown that most crops show fairly rapid declines in productivity as temperatures rise above critical thresholds, with as much as 10 percent yield loss for +1°C of warming in some locations. Both sub-Saharan Africa and South Asia appear particularly prone to productivity losses from climate change, in part because major staples in these regions are often already grown well above their optimum temperature.

Approaches to climate adaptation should recognize these realities, and should not equate anticipating climate changes with the considerably harder task of predicting next year's weather. Predicting and building resilience to climate variability still remain important goals for agricultural development, but adaptation efforts should balance these activities with those focused more on the specific threats presented by climate change. Heat tolerant crop varieties and strategies to deal with heavy rainfall provide two examples of important needs. Similarly, balance is needed between the local-scale efforts that attract most of adaptation investment currently, and regional and global networks to develop needed technologies. Given the greater certainty of climate changes at broader scales, as well as the positive track record of international networks for crop breeding, investments in these global systems are very likely to deliver substantial adaptation benefits. Finally, given the downward pressures that climate change will exert on smallholder farm productivity in sub-Saharan Africa, and the critical role productivity gains play in catalyzing an escape from poverty, speeding the pace of investment in African agriculture can also be viewed as a good bet for climate adaptation.

Climate Change and Agricultural Adaptation

Introduction

In the summer of 2011, a prolonged drought in the Horn of Africa contributed to widespread hunger in Somalia, with tens of thousands of deaths and many more refugees. For the first time since 1992, the United Nations issued a formal declaration of famine in Somalia on July 20, 2011.[1] Meanwhile, across the world, and at the other end of the development spectrum, the Corn Belt of the United States experienced a massive heat wave in July 2011, during the critical flowering phase of maize. Subsequent yields were well below trend line, helping to prop up an already high world price of maize.

In the eyes of some, these two recent stories exemplify the threats that climate change poses to food security: conditions for crop growth in subsistence areas deteriorate from bad to worse, leading to massive food insecurity and migration; conditions in high production areas deteriorate by enough to raise world prices, harming food importers; and efforts to cope with the changes are not enough to avoid the suffering of millions.

The two examples also raise many questions that characterize the difficulty of adapting to climate change: were the droughts in Eastern Africa related to global warming or simply natural variability? Is climate really the main culprit, or is focusing on political institutions and overall development the best long-run approach for coping with climate disasters? And will the private sector in the United States rapidly develop new heat tolerant seeds, or are major investments in public research and development needed to avoid global impacts of climate change?

Many food security experts are now more interested in climate change than ever before, as evidenced by the presence of climate in the short list of topics addressed by this policy series. This interest is partly a response to weather events in recent years - including droughts in China in 2010-2011, in Australia in 2007-2008, and heat waves in Russia in 2010 - but also to at least two additional factors. First, there is widespread recognition that international efforts to reduce greenhouse gas emissions have stalled, for various political and economic reasons, and that even if agreements are quickly reached to pursue aggressive emission targets, there is enough inertia in energy infrastructure and the climate system to ensure further warming for the next few decades. In fact, climate projections that assume slow versus rapid changes in emissions begin to diverge only after 2050. Until then, the Earth is essentially locked into further climate change as a result of past actions.[2]

Another important reason for renewed interest is the prospect, and indeed the beginning, of large flows of money into climate adaptation.[3] It is conceivable, although by no means guaranteed, that tens of billions of dollars per year will be available for adaptation efforts in developing countries by 2020. Only a small fraction of this money is likely to be directed at agriculture, but nonetheless the sums could add substantially to other sources of investment in food security.

---

[1] The UN formally defines a famine as more than 20 percent of households facing extreme food shortages, a crude mortality rate of more than 2 people per 10,000 per day, and malnutrition rates of above 30 percent.

[2] Barring the possibility of geo-engineering schemes that attempt to rapidly cool Earth, for example, by blocking sunlight with aerosols or giant mirrors into space.

[3] For a current summary of funds, see www.climatefundsupdate.org.

How, then, can these adaptation resources be most effectively used? Although large, the amount of money will continue to be a small fraction of estimated needs[4], forcing tough decisions on selecting priorities for investment. The premise of this paper is that sound science should be an important part of these decisions, and therefore that policy makers should understand the key aspects of the science.[5] Rather than attempt a review of a vast and growing literature, I seek to outline a handful of lessons that those working in food security and climate should know, and to suggest some implications of the science for policy design.

Climate change versus climate variability

Weather has always been a concern to farmers and herders. Every year brings a different combination of temperature, rainfall, cloudiness, and various other factors that affect agriculture. This inter-annual variability results from the simple fact that the Earth is a spinning sphere of land and (mostly) water, with sunlight unevenly distributed across the world. As energy and water moves around the Earth's atmosphere and oceans, many patterns of natural variability emerge. A well-known example is the El Niño Southern Oscillation, driven by changes in the tropical Pacific that then propagate throughout the world.

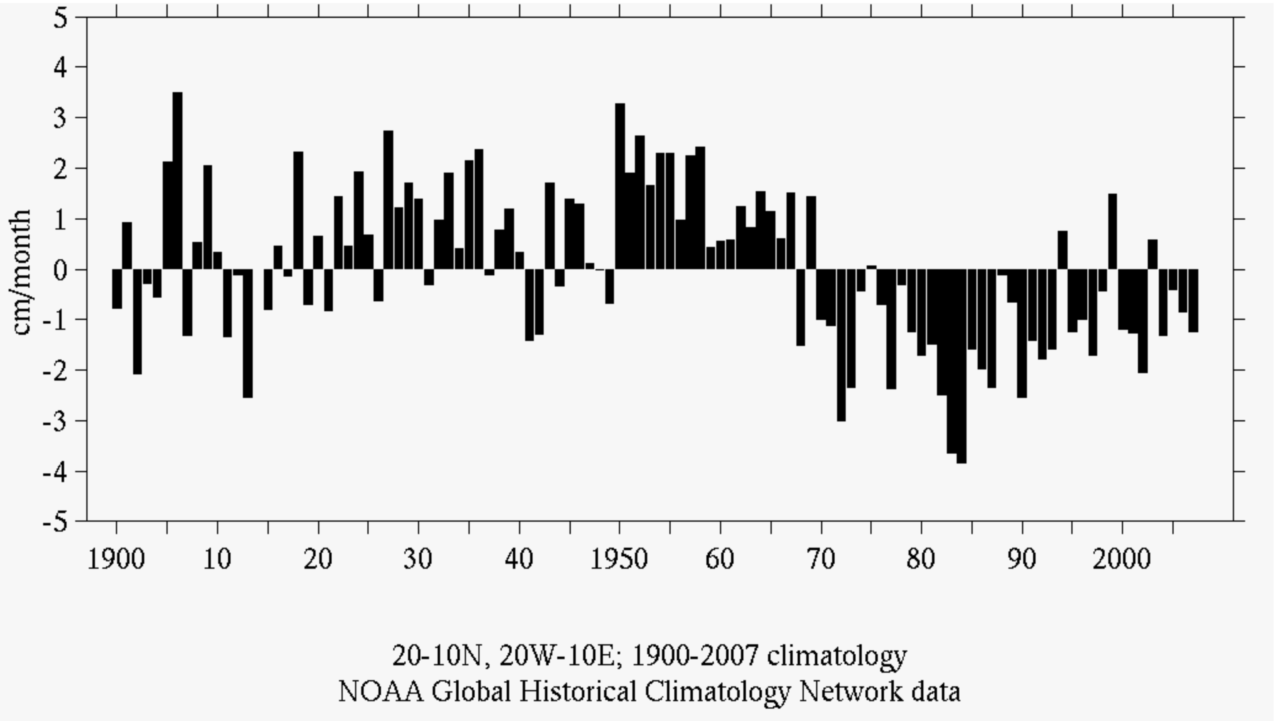
Just as no two years are the same, decades can also differ significantly because of natural variability of the climate system. For example, Figure 1 shows rainfall in the Sahel region over the 20th century. Some decades are very wet, such as the 1920s or 1950s, and some are very dry, such as the 1970s and 1980s. Although some of this variability is due to changes in external factors, such as aerosol concentrations, most of the variability is simply the result of internal dynamics in the climate system (Giannini et al. 2003).

---

[4] The World Bank recently estimated a need of $75 billion USD per year by 2030 to adapt to a 2°C warmer world.

[5] In focusing on adaptation, I recognize that adaptation may not be the only goal of adaptation finance, and in some cases it may not even be the main objective. Often these funds are viewed simply as a way of transferring wealth to those who are least responsible for global warming but bear much of the impacts, or as an incentive to participate in broader agreements on mitigation commitments.

Figure 1. JJASO-mean Sahel precipitation anomalies 1900-2007



Source: JISAO 2011. A century of growing season rainfall in the Sahel region.

Climate change is distinct from climate variability. The former term describes changes that occur because of human activities, especially the emissions of greenhouse gases, whereas climate variability refers to changes that result from internal dynamics of the climate system, independent of any external forcing. At first glance, the distinction between climate change and variability[6] may seem arbitrary and unhelpful. After all, no one is exposed to only climate variability or only climate change, but to the combination of the two. If the weather is changing in a farmer's field, why does the cause of this change matter when deciding how to respond?

However, the distinction is very important for anyone seeking to understand adaptation to climate change, for two main reasons. First, the processes underlying climate change are very different than those behind natural variability. In the former case, accumulation of greenhouse gases in the atmosphere traps outgoing heat, leading to an increase in the overall energy of the climate system. Natural variability occurs because of internal dynamics in the climate system, which are fed by gradients in solar radiation and ocean circulation. As a result of different underlying processes, one should expect different weather variables to be affected.

For example, internal natural variability leads to large fluctuations in rainfall from year to year in many locations, as illustrated for the Sahel in Figure 1. But natural variability in temperature is quite low throughout the tropics, with the warmest and coolest years often differing by less than 2°C. In contrast, global warming has its strongest effect on temperatures, with often much smaller effects on rainfall than natural variability.

---

[6] In climate science, the distinction between climate change and variability is also often referred to as "forced" vs. "unforced" climate response.

Thus, confusing climate variability and change runs the risk of focusing on the wrong aspects of weather when designing adaptation strategies. For instance, if climate change is perceived as simply amplifying variability (a common view among many farmers and agricultural scientists), then there will be a tendency to overemphasize the importance of rainfall.

A second important reason for distinguishing change from variability is the risk of overreacting to short-term trends driven by natural variability. Returning to Figure 1, if an observer in the mid-1950s assumed that the rainfall trend since 1920 was mostly the result of anthropogenic climate change, then he or she would reasonably have argued for adaptations to permanently wetter conditions, only to be confounded when rainfall declined for the next few decades. For this reason, climate scientists expend great efforts to understand the potential magnitude of trends driven by natural variability in order to be able to identify when trends are truly out of bounds. The recent drying in Eastern Africa, for instance, still appears within the range of natural variability. Devoting a lot of adaptation resources to coping with this rainfall trend might therefore be misguided, especially since it would pull resources away from other trends that are much more certain to continue.

With this general background on the meaning of climate change, and why it is distinct from climate variability, I now turn to a discussion of the current state of climate science.

What is known about climate change?

Scientific understanding of climate change has made great progress in the past few decades, both in terms of explaining the recent past and in providing a clearer picture of the next few decades. There are still clearly many uncertainties and shortcomings in the ability to predict the future, but there are also many near-certainties that are often underappreciated by the public. In fact, one of the disservices of the politically-motivated "debate" about whether humans are causing climate change is that policy makers and the public often underestimate how much climate science can say about the future.

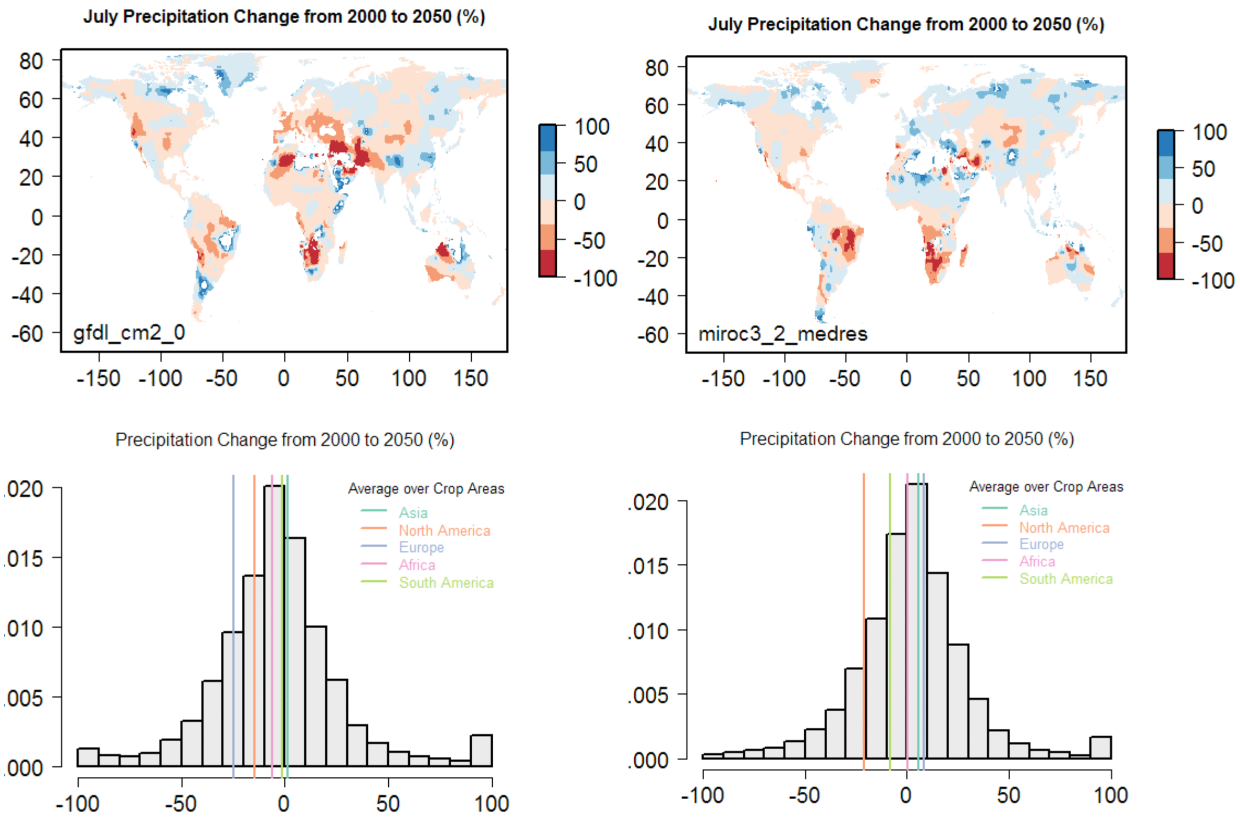
Here I provide a brief review of the aspects of climate science that I find most relevant to the future of food security, with an emphasis on areas where the science is most firm. Although a detailed discussion of how climate science arrives at a consensus view is beyond the scope of this paper, an important general point is that multiple lines of evidence are typically required for consensus. For example, a projected increase in heavy rainfall events is considered very likely because the basic physics underlying that change are fairly well understood (Allen and Ingram 2002; O'Gorman and Schneider 2009), many independent climate models repeatedly simulate an increase in heavy rainfall (Tebaldi et al. 2006), increases in heavy rainfall have already been observed in many regions (Alexander et al. 2006), and the magnitude and pattern of these changes are consistent with model predictions (Min et al. 2011). Any of these alone, without the others, would not result in consensus.

The critical importance of scale

For any specific climate variable of interest (such as those discussed below) one can consider changes at a range of spatial scales, from an individual field or village to an average for the entire globe. It is difficult to overemphasize the importance of making scale explicit in any analysis of climate change impacts, because the overall magnitude and uncertainty of any climate change will be scale dependent. Statements such as “rainfall changes are too uncertain” or “we don’t know enough to design good adaptation strategies” fail to make the scale distinction. Three factors in particular contribute to the scale dependence of climate projections.

1. *Spatial differences in projected changes*. The simple fact that projected changes are not uniform across space means that averages over larger areas will tend to be less extreme than averages over small areas. For example, Figure 2 shows projected changes in July rainfall by 2050 for two different climate models. Both models show some individual grid cells (roughly 50km x 50km near the equator) with large percent increases, and other areas with large decreases. For several individual cells or even countries (e.g., Kenya), there are large differences between the two models. However, if one considers averages over broader regions, such as continents, the magnitudes of change and the differences between the models become smaller. The bottom panel of Figure 2 shows a histogram of changes for all cells, along with averages over the crop areas in each continent. Both models indicate less rainfall for crop areas in North America and slightly more rainfall for Asia. Although important differences still exist at the continental scale (e.g., for Europe), there are no longer any changes greater than 30 percent in absolute value, whereas this value was commonly exceeded for individual cells. Thus, the main point is that magnitudes and uncertainties change with scale.

Figure 2. Projected changes in July rainfall by 2050 for two climate models



Note: (Top) Projections of precipitation change (%) by 2050 for two climate models, as an illustration of the spatial variations present in projections. (Bottom) The corresponding histograms of values in the top figures (shown in gray bars) along with lines showing the change in average rainfall over large cropping regions. Changes tend to be much more muted over large areas because of the spatial heterogeneity.

2. *Natural variability is larger at smaller scales*. A second important factor is that natural variability is more muted over large spatial scales. The ratio of signal (in this case the climate change) to noise (natural variability) therefore tends to be higher at broad scales, even if the signal itself becomes more muted. One example of this fact is that global temperature increases have been much easier to detect and link to greenhouse gas emissions than changes over individual countries.

3. *Many climate forcings differ across space*. Greenhouse gases such as carbon dioxide or methane are well-mixed in the atmosphere, meaning that they diffuse from the source of emission and eventually spread throughout the atmosphere. Other types of human activities that affect climate, however, are much more local in scope. A primary example of a local forcing is emission of microscopic sulfate particles (aerosols) from power plants, which can strongly affect climate by altering the amount of sunlight reflected back to space. However, these particles typically fall out of the sky after a day or two, so they only affect the climate in the vicinity of the emissions. Another example is conversion of

forests into agriculture, which can also affect local climate but has little effect in remote regions. These local effects will continue to be important in some regions, but not others. In general, as one considers broader scales the importance of these local factors will diminish, making it somewhat easier to predict the future course of climate.

All of these factors point to the fact that climate predictions at broader scales are generally more reliable than predictions at finer scales. In contrast, many of the adaptation needs are at local scales, and some go so far as to claim that "all adaptation is local" (Kostel 2009). The tension in scale between what the adaptation community demands and what climate science can provide is a topic to which I will return to below. First I turn to a brief discussion of trends in climate variables most relevant to food security.

Observed and projected climate changes

Underlying any prediction of climate change are a couple of basic physical principles, both of which have been known for more than 100 years. First, gases such as carbon dioxide (CO2), methane (CH4), and nitrous oxide (N2O) absorb outgoing radiation emitted from the Earth's surface and re-emit part of it back towards the surface, much like a blanket keeps warm air from escaping. Raising the concentration of these greenhouse gases therefore leads to an increase in energy within the Earth's atmosphere, reflected in an increase in global temperatures (i.e. the greenhouse effect). Second, the amount of water vapor that air can hold increases exponentially with air temperature, so that a world with higher average temperature will tend to have more water vapor (itself a greenhouse gas). These and other physical principals form the core of general circulation models (GCMs), which are used to project future changes in climate.

As mentioned, output from GCMs are frequently tested against observations, as well as compared to other models, and confidence is highest in those aspects of GCMs that agree with historical trends. This logic leads to a question commonly asked by agricultural scientists of whether it would be simpler and just as reasonable to take simple linear extrapolations of recent trends in order to predict climate changes over the next few decades. This approach is especially attractive to those who do not wish to rely on models they neither understand nor trust. The simple answer is no, although again the answer depends partly on scale. For sub-continental regions, it is likely that some or even all of the historical trends are driven by natural variability or by regional climate forcings like aerosol, which may not continue into the future. Thus the emphasis in the climate community on using output from physics-based models.

As a rule of thumb, however, it is difficult to imagine any large changes over the next few decades that have not already shown signs of changing. Similarly, there are few cases of variables that have been changing fast at global scales but are not expected to change greatly in the future.[7] Indeed, many of the predictions of climate models are consistent with observed changes, particularly at global scales. At finer scales, the main disagreements between models

---

[7] An exception is diurnal temperature range (DTR = the difference between day and night temperatures). For many years night temperature rose faster than day temperature, and this was especially true in Asia since 1950. However, these changes were mainly due to changes in aerosols and the DTR has not changed much since 1980 (Wild 2009). Despite this, many agricultural scientists persist in thinking that night temperatures will go up faster than day temperatures.

and data are traceable to forcings such as aerosols or land use that existed in reality but not in the model, or to natural variability.

Table 1 provides a summary of key expected and observed changes. The most ubiquitous feature of climate change is an increase in global mean temperatures (GMT) (hence the name “global warming”). Models project an average increase of 0.2°C per decade in GMT. Warming in agricultural areas is expected to be faster than GMT, because the global mean includes the 75 percent of Earth’s surface that are oceans, which warm more slowly than land because of constant upwelling of deeper, cooler waters.

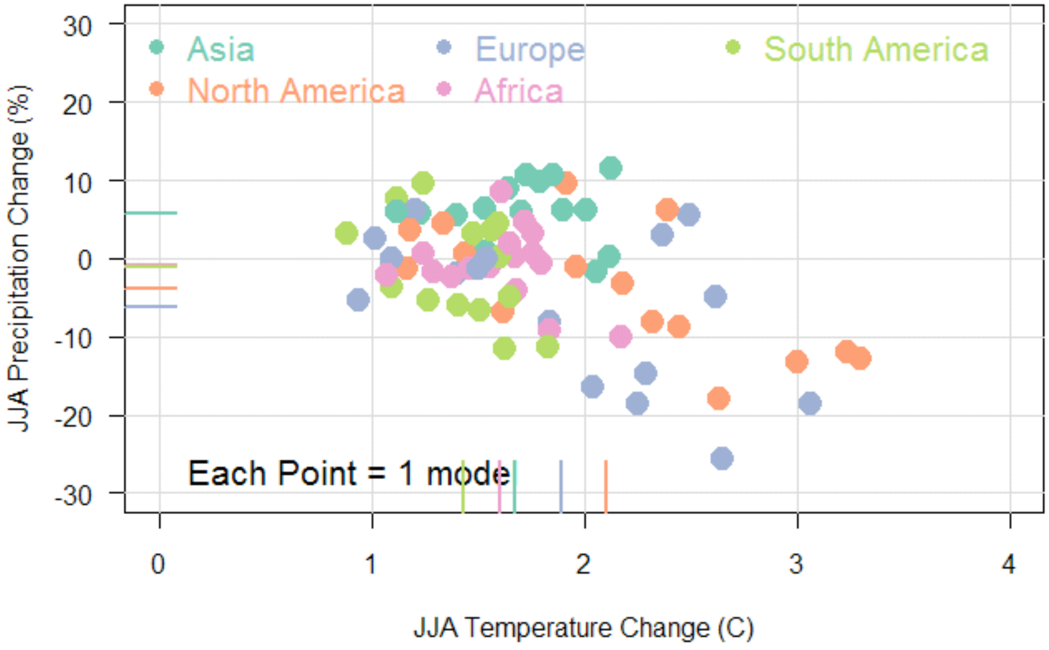
Table 1. Summary of projected and observed changes in key climate variable (T = temperature, P = precipitation)

Climate aspect	Projected Changes to 2050	Observed Changes as of 2011	References
Average growing season T	• +0.2° C per decade increase in global mean temperature • +0.3-0.4° C per decade increases for most cropping regions (Fig. 2)	• Warming in most major cropping regions, with exceptions of North America and South Africa	(IPCC 2007; Lobell et al. 2011b)
T extremes	• Decline in frost occurrence • Increase in occurrence of very hot days and nights.	• Decline in frost occurrence • Increase in occurrence of very hot days and nights.	(Alexander et al. 2006; New et al. 2006; Tebaldi et al. 2006; Kharin et al. 2007; Zwiers et al. 2011)
Average growing season P	• Potential changes as much as 10 percent in some regions, but expected changes fairly small	• Some regions with positive rainfall trends in past 30 years, some with negative. Nothing outside of natural variability	(IPCC 2007; Lobell et al. 2011b)
P extremes	• Increased fraction of rain falling in heavy events • Increased magnitude of heavy rains	• Increased heavy rainfall in many regions • Increased magnitude of heavy rains	(Alexander et al. 2006; New et al. 2006; Tebaldi et al. 2006; Kharin et al. 2007; Min et al. 2011)
Start and length of rainy season	• Delay in start of rainy season in	• Lack of scientific literature	(Biasutti and Sobel 2009; Seth et al. 2011)

	monsoon areas (e.g., Sahel) by up to 7 days by 2100		
Soil moisture / drought	• Increases in frequency and spatial extent of droughts in most regions • Trends not likely to be detectable (compared to natural variability) for a few more decades	• No detectable trends outside of natural variability	(Wang 2005; Sheffield and Wood 2008b; Sheffield and Wood 2008a)
Year-to-year variability	• Potential increases, particularly for T variability in interior of continents • Still considerable model disagreement	• Lack of scientific literature	(Räisänen 2002; Giorgi and Bi 2005)

Figure 3 shows expected June-August temperature changes averaged over crop areas in each continent, with warming rates ranging from 0.2-0.6 °C per decade depending on model and continent.

Figure 3. T and P changes (2050 minus 2000) June-August for 16 climate models averaged over crop area by continent

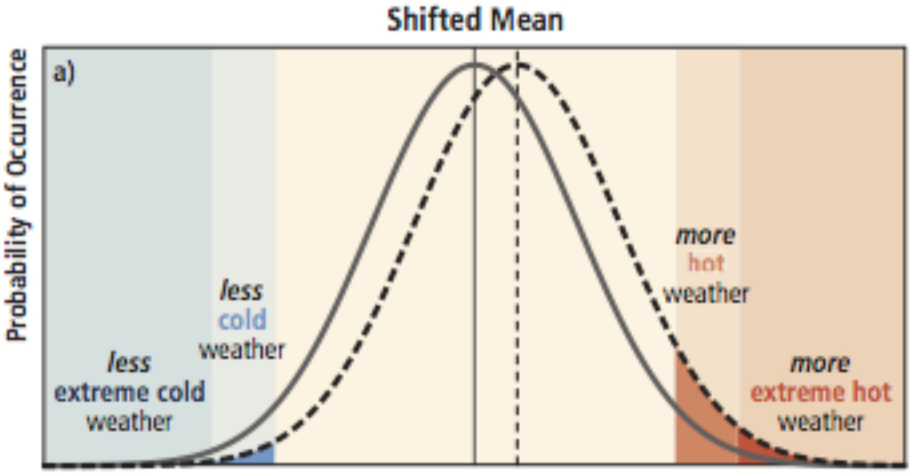


Note: Crop regions warm by a projected 1-3°C for 50 years, or .2-.6 per decade. This is considerably faster than the rate of GMT increase.

Consistent with these projections, an increase of roughly 0.7°C GMT has already been seen since 1950, and most agricultural areas have warmed more quickly. For example, in many cropping regions the growing seasons have warmed by more than 1°C since 1980 (Lobell et al. 2011b). Climate models are consistently able to reproduce these trends globally and in individual regions. In fact, models can only reproduce the trends if the increase in greenhouse gas concentrations are specified, indicating that the trends are not plausibly the result of natural variability alone (IPCC 2007).

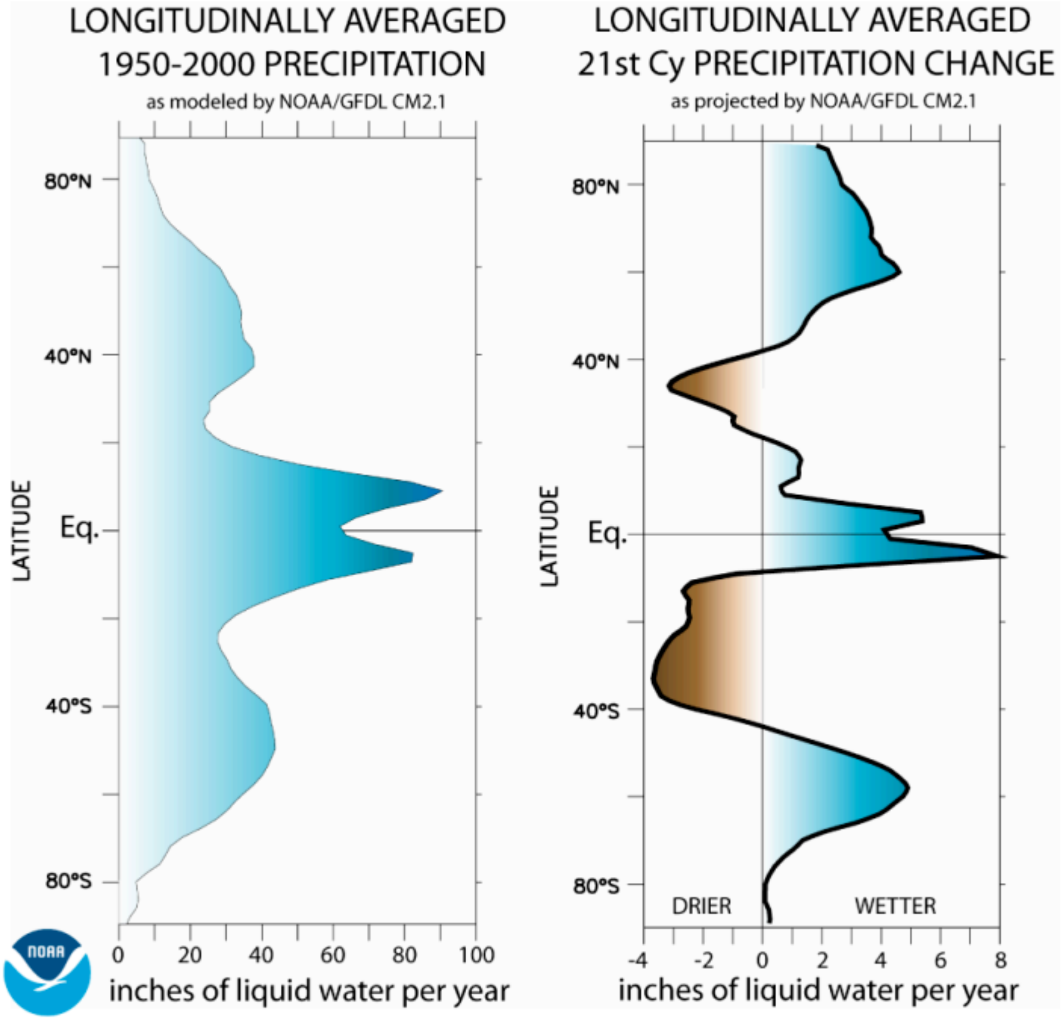
Along with mean temperature increases, models agree in projecting several other relevant changes: (i) a reduction in the occurrence of extremely cold days or extremely cold nights (i.e. frost); (ii) an increase in the occurrence of extremely warm days and nights; (iii) an increase in the occurrence of heavy precipitation events; and (iv) an increase in the frequency and severity of droughts in subtropical regions. The first two can be understood as a direct consequence of the rise in mean temperatures, which shifts the temperature distribution toward historical warm extremes and away from historical cold extremes (Figure 4). The latter two changes, in heavy rains and drought, can be understood as the consequence of an increase in water fluxes within the atmosphere, which causes dry areas and seasons to be even drier, and wet areas and seasons to be wetter (Figure 5).

Figure 4. Effects of a simple shift of the entire distribution toward a warmer climate



Source: IPCC 2012. An increase in mean temperature leads to more hot extremes and less cold extremes, where extreme is defined based on the frequency of occurrence in historical data.

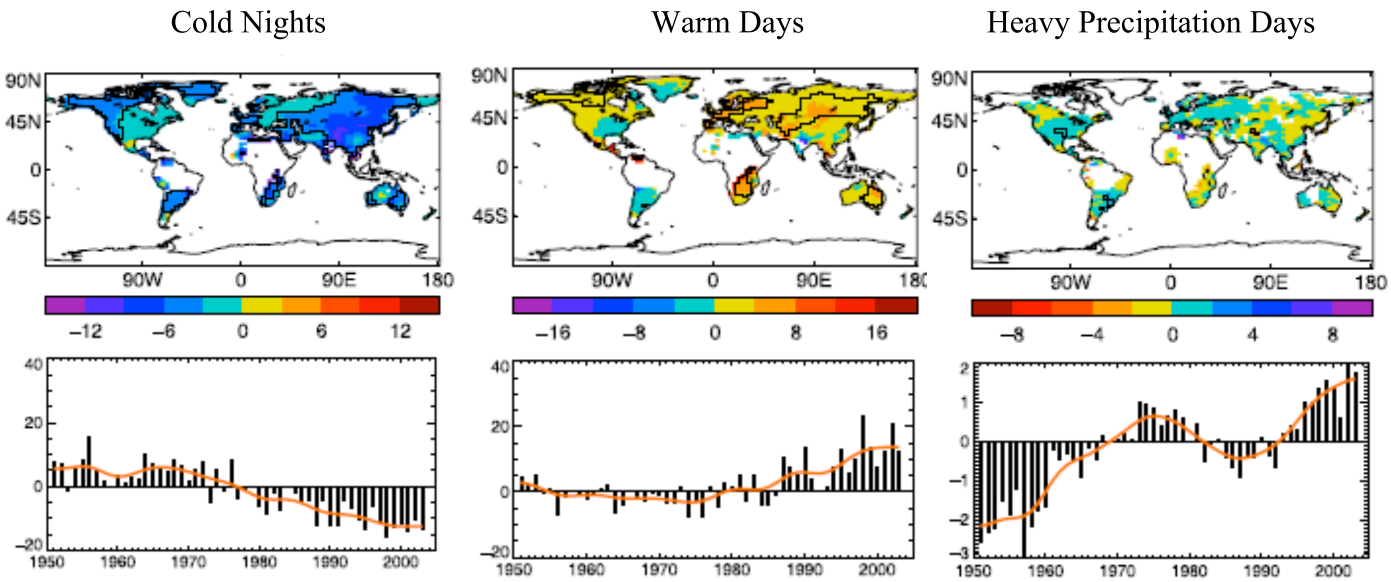
Figure 5. Intensification of the hydrological cycle in the Geophysical Fluid Dynamics Laboratory (GFDL) climate model



Source: GFDL 2012. (a) Average annual precipitation by latitude; (b) change in average precipitation by latitude by 2100. Dry areas (where rainfall is less than evaporation) in the sub-tropics tend to get drier and wet areas tend to get wetter.

As with GMT, the above changes are not only predicted for the future but have already been observed in many regions. For example, Figure 6 displays observed trends in measures of cold extremes, warm extremes, and heavy rainfall events for 1951-2003 throughout the world (Alexander et al. 2006). In most locations, cold nights (defined as the 10th percentile of night temperatures for 1961-1990) are less common, warm days are more common, and rainfall events over 10mm/day are more common. The availability of data is insufficient throughout most of Africa to discern trends, although more detailed studies of Africa indicate a similar picture. For example, extremely warm days (defined as the 95th percentile of historical values) were nearly twice as frequent in Southern and West Africa by 2000 compared to 1961 (New et al. 2006).

Figure 6. Observed trends in global measures of cold extremes, warm extremes, and heavy rainfall events for 1951-2003



Source: Alexander et al. 2006. Maps of trends (in days per decade, top) and annual global time series of anomalies relative to 1961-1990 mean (bottom) for cold nights (10th percentile of Tmin for 1961-1990), warm days (90th percentile of Tmax) and heavy precipitation days (days with more than 10mm precipitation).

The magnitude and speed of all of these changes are unprecedented on a global scale, and even in individual countries the changes are likely to produce unprecedented weather in the next few decades. A good example is the case of very hot days. The hottest single day over a 20 year period, for instance, is expected to be on average 1.7°C warmer by mid-century than in 1980-2000 (Kharin et al. 2007). At first glance this change may seem unremarkable, but consider that what had been the warmest single day in 1980-2000 would occur on average every 1.5 years. In the tropics, where year-to-year variability tends to be lower than in temperate systems, this historical “extreme” would be expected every single year by 2050. Similarly, throughout the tropics the majority of growing seasons by mid-century are expected to be warmer than any growing season experienced in the 20th century (Battisti and Naylor 2009).

In addition to temperature, rainfall is of obvious relevance to agriculture. The increased frequency of heavy rainfall events has already been mentioned, but beyond that the picture gets murkier. Global precipitation is expected to increase, but in many regions the changes in average precipitation disagree in sign from model to model. Figure 3 presents precipitation changes for June-August averaged over crop regions in each continent, illustrating that in each region one can find models that show increases or decreases in precipitation. A related point, but one less emphasized by many, is that very few models show absolute changes of more than 10 percent (or 2 percent per decade) in any region, with the exception of some projections for European and North American crop areas. Observed trends in average growing season rainfall since 1980 similarly show relatively small changes (Lobell et al. 2011b), with the number of countries with positive trends roughly equal to the number with negative trends. Thus, it is unlikely that changes in average rainfall are likely to be a major feature of climate change (although year-to-year changes in rainfall will undoubtedly remain important).

However, total rainfall per se is not of concern to agriculture, but rather the availability of moisture for plant growth. Moisture depends on the balance between inputs of rainfall into soils and losses from evaporation and plant transpiration. Given that more rainfall will fall in heavy events, the fraction of rainfall entering soil is likely to decrease because heavy events tend to produce more runoff into rivers (leading to floods in extreme cases). Higher temperatures will also mean faster rates of evaporation. Taken together, these two factors explain why most models indicate reductions of soil moisture and increased occurrence and spatial extent of drought, particularly in currently dry areas (Sheffield and Wood 2008b). However, these trends tend to emerge more slowly than the temperature trends, with significant changes reached relative to natural variability reached only by 2050.

Throughout the tropics, the length of the rainy season is a major concern. More specifically, the onset of the rainy season is important since it is closely linked to the length of the rainy season (the end of the season is typically less variable from year to year) (Sivakumar 1988). Most climate models indicate a delay in rainy season onset in many monsoonal systems, such as the Sahel (Biasutti and Sobel 2009; Seth et al. 2011), as well as in Indonesia (Naylor et al. 2007). A likely reason for this delay is the melting of sea ice, which affects the seasonality of temperatures in the Northern Hemisphere (water responds more slowly to seasonal changes in sunlight than ice) (Biasutti and Sobel 2009). Although models consistently show a delay, it is important to note that this delay will likely be less than one day per decade in the Sahel. Moreover, a trend toward later onset has not yet been noted in the published literature, perhaps because the signal is small relative to natural variability.

In addition to rainfall, much of the world relies on irrigation to supply soil moisture. Irrigation is less important in sub-Saharan Africa, where it comprises less than 5 percent of cereal area, but in Latin America and Asia irrigation is very common and often dependent on meltwater from upstream glaciers. In Asia, all major rivers begin in the Tibetan plateau and adjacent mountains, where warming is expected to accelerate melting. In the next couple of decades, this melting will likely contribute to greater streamflow as the glaciers melt, but by 2050 the net streamflow from glaciers is expected to decline (Immerzeel et al. 2010). Regional increases in precipitation may partially offset this loss of meltwater, but net water availability is expected to decline significantly in basins that depend heavily on glaciers. In particular, the Indus and Brahmaputra basins in India will likely be the most affected, while the Ganges, Yellow, and Yangtze basins are much less dependent on glaciers. A similar story exists in Latin America, where Andean glaciers are already receding and increased streamflow has been observed in several rivers (Vuille et al. 2008). One particular concern with glacier melting is that the temporary increases in streamflow will encourage expansion of irrigation and settlements, which only increases the vulnerability to the eventual decline in flows once the glaciers shrink or disappear.

Finally, many agricultural scientists and policy makers are often under the impression that climate change will cause year-to-year variability in weather to increase. However, there are not very clear patterns of changes in inter-annual variability, either in models or observations (Meehl et al. 2007). In many regions, rainfall variability is expected to rise, whereas temperature variability is likely to go up in regions that experience drying (because soil moisture is one buffer against temperature fluctuations). But there are few universal statements that one can make about changes in variability. As mentioned, hot extremes and heavy rainfall will become more common, but more extremes is not the same thing as more variability. The latter implies, for example, that highs will get higher and lows will get lower, whereas observations and models indicate that cold extremes will get less frequent.

Implications for food security

What do these changes in climate imply for food security? There are arguably two main avenues of impacts on food security in any location: impacts on local productivity of agriculture, and impacts on global productivity that affect local prices. The relative importance of these two pathways will obviously depend on location. North Africa, for instance, is highly reliant on food imports and likely more sensitive to global changes, whereas much of sub-Saharan Africa remains largely subsistent. Although both local and global productivity will continue to play important roles in shaping food security, the increasing connectedness of agricultural markets and the urbanization of poverty means that global aspects will be increasingly important in 20 or 30 years. Discussions of climate change impacts often address only local to regional changes, and therefore miss an important dimension of the problem.

Although effects on agricultural productivity are the focus of this discussion, it is worth noting that other pathways may also emerge as important. Non-agricultural sectors of the economy can depend on weather in surprising ways. Total economic output in Central America and the Caribbean, for example, is negatively correlated with annual temperatures, with a 1°C increase in mean temperature lowering GDP by roughly 3 percent (Hsiang 2010). Interestingly, this effect is driven not by agriculture but by the effect of very hot days on productivity of labor in sectors such as retail and restaurants. Losses in overall economic performance for warm years has also been detected in Africa as well as poor countries in other regions (Dell et al. 2008; Dell et al. 2009), although richer countries show no effect (presumably because of air conditioning). Thus, warming can be expected to affect productivity in a range of activities that either affect food supply chains (including processing and distribution of food) or the ability of poor people to generate incomes for purchasing food. There is also some evidence that warming increases the risk of conflict (Burke et al. 2009; Hsiang et al. 2011), which is a major impediment to food security (World Bank 2011).

Productivity impacts within Africa and South Asia

As stated by several speakers in this series, improving on-farm productivity is one of, if not the most, effective ways to improve food security. Among other things, higher farm productivity improves farmer income, raises local food availability and lowers prices, improves farmers' assets and ability to invest, and frees up labor to pursue education or employment in off-farm activities. Anything that slows (or reverses) productivity growth therefore stands as an important threat to food security.

Given that food insecurity is most prevalent in sub-Saharan Africa and South Asia, this section discusses only these two regions. In both regions, work has focused mainly on the staple crops (e.g., maize and sorghum in Africa, wheat and rice in South Asia), and so for brevity and lack of ample science, the discussion will omit "minor" crops as well as non-crop sources of food and food security, including livestock and fish.

There have been three main approaches to understanding impacts of climate change on crops. First, greenhouse or field experiments under manipulated environments, such as elevated CO2 or temperature, provide a direct measure of plant responses. Second, crop simulation models have been developed from these types of experiments and used to predict responses under a wider range of conditions. Third, statistical approaches have combined historical weather data with harvest data (either from fields, states, or entire countries) to define a statistical relationship between weather inputs and crop outputs. Each of these approaches has strengths and weaknesses, the details of which are beyond the scope of this paper. As with the discussion of climate above, the scientific confidence is greatest when all three methods converge on the same view. Among the main lessons from these studies are the following:

1. Higher CO2 raises yields in crops with a C3 photosynthetic pathway (e.g., rice, wheat). In C4 crops common in tropical areas (e.g., maize, sorghum, millet), the response is much more muted and only observable in drier settings, because CO2 helps to improve water use efficiency. Crop response appears to be limited, in part, by the ability of grains to use additional carbohydrates without equal supply of other nutrients. Thus, responses are typically greatest in well-fertilized conditions, and for non-grain crops that require less nutrients per carbohydrate. In particular, root crops like potatoes and cassava show responses that are double those for rice and wheat, and that far exceed maize.

2. Even slight warming tends to reduce yields throughout the tropics, because most crops are already growing beyond their optimum temperatures. Figure 7 shows the current yields of four crops relevant to the discussion for each country in the world compared to the average T for the growing season in its current area within the country. Although many factors contribute to differences between countries (for instance, cooler countries tend to be richer and apply more fertilizer), it is clear that each crop exhibits a negative relationship with T beyond a certain point. For wheat, this point is roughly 15°C, for maize roughly 20°C, and for rice and sorghum closer to 25°C.[8]

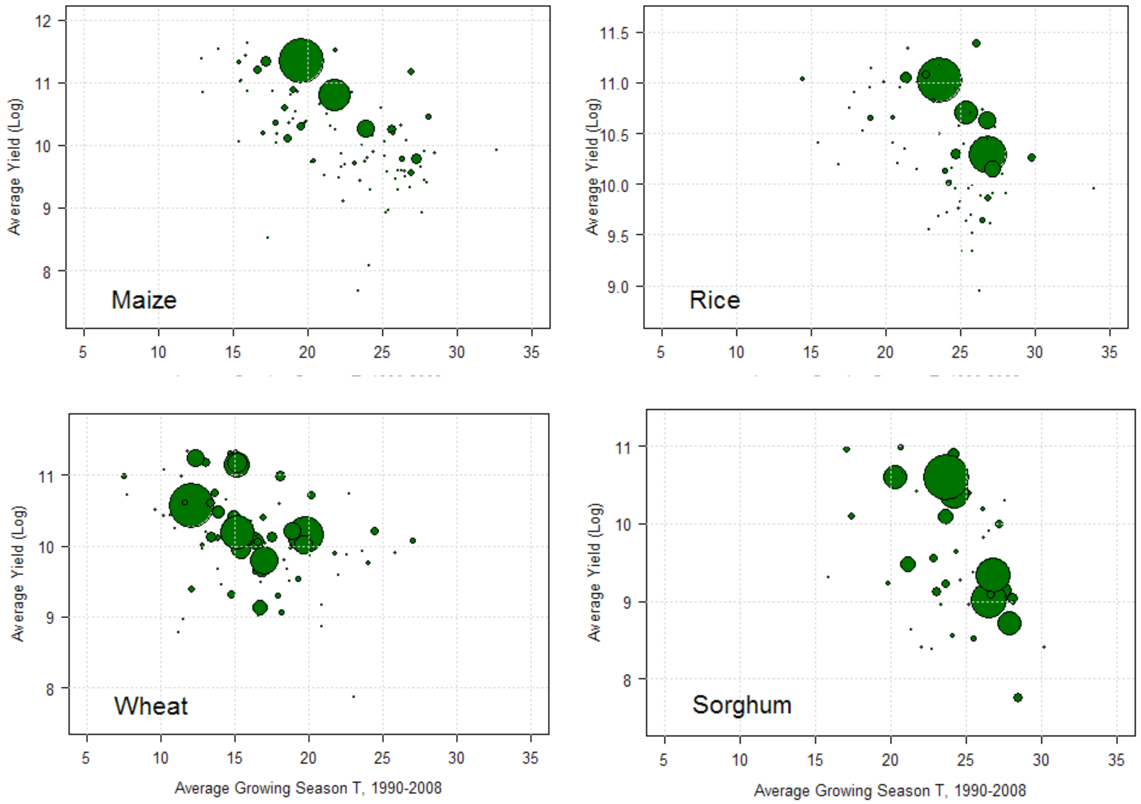
   For 1°C of warming, yield losses in the tropics vary from a few percent for crops that are currently growing near their optimum, to as much as 10 percent or more for crops growing well beyond their optimum. The reasons for yield loss are multiple[9] and vary by crop. For example, rice appears particularly sensitive to warming at nighttime, and actually benefits from daytime warming until T is hot enough to damage pollen (~35°C) (Welch et al. 2010). Maize is particularly sensitive to hot daytime temperatures, with rapid losses when T exceeds 30°C (Schlenker and Roberts 2009; Lobell et al. 2011a).

---

[8] Although this analysis is simplistic it agrees well with optimum temperatures derived from other studies.

[9] The main mechanisms include shortening of the crop season, increased respiration rates, reduced photosynthesis rates, damage to cells at high T, and increased evaporation rates.

Figure 7. Scatterplots of average national yields and growing season temperature for four major crops



Source: Lobell et al. 2011b. Size of dots is scaled to total production of country.

3. Both the effects of high CO2 and T depend on fertilizer and irrigation practices (see Table 2). A main reason that CO2 benefits yields is that it helps cope with dry conditions, and this benefit is mainly forfeited under irrigation. As mentioned, CO2 responses also tend to be higher for well-fertilized crops.

   The presence of irrigation helps crops to handle high T, both because of cooling the microclimate and providing water for crop transpiration. For example, sensitivity to high T was 1.7 times higher in maize trials grown under intentional water stress than in well watered conditions (Lobell et al. 2011a). Similar effects have been noted for wheat and rice in India (Lal et al. 1998). Nitrogen, in contrast, tends to increase the yield difference between favorable and unfavorable weather conditions, and therefore increases overall sensitivity to T. For example, yield sensitivities to T are higher in South Africa (high fertilizer rates) than in neighboring Botswana (low fertilizer rates) (Schlenker and Lobell 2010).

Table 2. The effects of irrigation or fertilizer on crop sensitivities to CO2 and T

	Irrigated	Well-Fertilized
Capacity to benefit from high CO_2	↓	↑
Capacity to cope with high T	↑	↓

Note: CO2 is more beneficial for well-fertilized crops, whereas high T is most damaging to well-fertilized and rainfed crops.

Admittedly, the above is a rather short list of key lessons from crop studies, and there are many aspects scientists would like to know better. What are the effects of heavy rains on crop productivity? How is nutritional quality of crops affected by climate change and CO2 increases? How do biotic pressures like disease and pests change with climate? Will the delay in rainy season onset mentioned earlier be fast enough to rival the challenges presented by warming? The science continues to progress on these questions, but no consensus has yet emerged.

Projections of future impacts generally indicate a net downward pressure on yields from changes in T, P, and CO2 within Africa and South Asia. Exceptions include rice in Asia, which will benefit from higher CO2 over the next few decades more than it will be harmed by higher T. In addition, high elevation areas that tend to be cooler, such as in parts of Eastern Africa will tend to cope well with warming. East Africa is also expected to see increased rainfall, although this projection is a topic of ongoing debate (Shongwe et al. 2010; Williams and Funk 2011).

At the continental scale, staples yields in Africa have been projected to decline without adaptation by 22 percent for maize[10], 17 percent for sorghum and millet, 18 percent for groundnut, and 8 percent for cassava by 2055 relative to 1980 (Schlenker and Lobell 2010). These numbers do not include CO2 fertilization effects, which would be substantially positive for groundnut and cassava. Other studies find similar results at the continental or country scale (Nelson et al. 2009; Thornton et al. 2009; Lobell et al. 2011a; Roudier et al. 2011), with many also evaluating impacts within countries. Of course, national or continental averages mask considerable variations, and there will be some parts that gain from climate change, such as the high-elevation areas in East Africa mentioned before. Some authors emphasize this heterogeneity as reason to focus adaptation entirely at finer scales (Thornton et al. 2009), since different places face different threats and opportunities. However, it is also at these scales that differences between climate scenarios and crop models are largest, a point to which I will return later.

---

[10] It is worth recalling that average temperatures in Africa are expected to rise by ~0.3°C per decade. Also mentioned is that 1°C of warming tends to reduce yields by up to 10 percent in the tropics. Thus, the numbers stated for impacts (roughly 3 percent loss per decade for maize) are consistent with this view.

In South Asia, most work has focused on rice and wheat, the two key staples, although some projections exist for sorghum, mustard, and sugarcane among other crops (Boomiraj et al. 2010; Knox et al. 2011). Growing conditions for both rice and wheat are hot relative to most regions of the world, and declines are expected even for moderate warming (Lal et al. 1998; Lobell et al. 2008). Because both wheat and rice are C3 crops, elevated CO2 should impart significant yield benefits over the next few decades. To some extent, however, these gains will be counteracted by a large and increasing loss of yield from high ozone levels (Van Dingenen et al. 2009).

Overall, without effective adaptation the productivity impacts of climate change are likely to be more severe in Africa and South Asia than in any other region (Lobell et al. 2008). In Africa, damages result from a combination of very low rates of irrigation (less than 5 percent of staple crop area), high prevalence of C4 crops that do not benefit from CO2, and high dependence on maize which is already grown above its optimal temperatures in many parts. In South Asia, climate change is challenging because it is already very hot, and because food security is very dependent on wheat, which is highly sensitive to warming in this region.

Global productivity and price impacts

For both producers and consumers, food prices are an important concern. Although local markets can be insulated from fluctuations in global prices (see chapter by P. Timmer), the latter are increasingly relevant to the food insecure. For example, sub-Saharan Africa now imports 42 percent of total rice consumption and 63 percent of wheat (Naylor and Falcon 2010). Even if one is interested only in climate change impacts on food security in Africa or South Asia, an analyst's imperative is now to consider impacts across the world.

Having already discussed that Africa and South Asia are the most threatened by climate change, it stands to reason that global impacts on production will, on average, be smaller than in these regions. Indeed, the Intergovernmental Panel on Climate Change (IPCC) concluded in 2007 that benefits from higher CO2 and warming at high latitudes were likely to more than compensate for losses in lower latitudes (Easterling et al. 2007):

> "Higher output associated with a moderate increase in the GMT likely results in a small decline in real world food (cereals) prices, while GMT changes in the range of 5.5°C or more could lead to a pronounced increase in food prices of, on average, 30 percent."

Embedded within this statement are at least two important assumptions that may paint an overly optimistic view. First, all of the global price studies used in the IPCC assumed some level of on-farm adaptation, such as adoption of new varieties or expansion of irrigation. Second, recent evidence from field experiments suggests that most modeling studies have used overly optimistic CO2 fertilization effects (Long et al. 2006; Ainsworth et al. 2008). Thus, a more accurate statement may be "Given effective adaptation efforts, small increases in GMT likely result in small changes (positive or negative) in world food prices"

Policy makers, of course, must contend not only with expected changes but also with the range of possibilities. Studies since the IPCC point to the possibility of larger price increases, for instance 20-30 percent average increases for major cereals by 2050 (Nelson et al. 2009), or in a pessimistic scenario of rapid climate change and little adaptation, as much as 30 percent increase for 1°C of additional warming (Hertel et al. 2010). Conversely, optimistic scenarios of high CO2 effects and low warming effects result in significant price declines for the next few decades.

Policy makers must also worry about increased volatility of prices, in addition to changes in average prices (reference Timmer Chapter). Studies of climate impacts on price volatility are just emerging, but there is some basis to expect global prices to become more volatile. Specifically, as the risks of intense heat waves and heavy rainfall events rise, so do the chance of sharp production shortfalls in important producers. In the US, for instance, projections indicate on average that maize production will increase its coefficient of variation by ~40 percent by mid-century (Urban et al. 2011).

Most studies of climate change continue to frame the issue in terms of anticipating future impacts (e.g., impacts by 2050). An emphasis on the future is understandable, since the goal is to take actions now to prevent future losses. However, this framing risks overlooking an important fact discussed above: that significant climate changes, such as warming and increased heavy rainfall, have already been observed in most cropping regions.

The same models used to project future impacts can also be used to assess impacts of past change. In a recent study, we evaluated the impacts on various crops at the national scale and for total global production (Lobell et al. 2011b). Table 3 presents estimates of the impacts on global yields, and compares them to overall yield progress. Although yields of all four crops have improved by 50-60 percent since 1980, maize and wheat yields have been held back by warming.

Table 3. Global average yield increases for major crops and estimated impacts of climate trends for 1980-2008

	Yield in 1980	Yield in 2008	Yield Increase	Impact of T and P trends	Ratio of climate impact to yield increase
	(ton/ha)	(ton/ha)	(ton/ha)	(ton/ha)	fraction
Maize	3.1	5.0	1.9	-0.19	-0.10
Rice	2.9	4.3	1.4	0.01	0.01
Wheat	2.0	3.0	1.0	-0.16	-0.16
Soybean	1.6	2.5	0.8	-0.04	-0.05

Source: Lobell et al. 2011b. All crops except maize have benefitted by ~3 percent from CO2 trends over the period.

This retrospective analysis highlights two important points. First, the challenges to agricultural productivity are already upon us. There are therefore immediate benefits to adapting, and policy makers should not view climate adaptation as simply preparing for the distance future.

Second, there are clear differences between crops. Wheat and maize appear particularly hurt so far, which results from the fact that several major producers of each are already warmer than the optimum T for yields (Figure 7). At the global scale, these are also among the crops for which demand is rising most quickly (Table 4). For example, demand for rice, whose production is relatively unhurt by warming, is leveling off on a per capita basis, whereas per capita consumption of wheat and maize, which are most sensitive to warming, continue to increase (FAO 2006).

Table 4. The coincidence between crops with strong demand growth and sensitivity to warming

Crop	Highest favorable growing season T (see Figure 7)	Climate Related Yield Losses (1980-2008) (as % of 2008 yield)	Projected Demand Increase (%), 2030 vs. 1998*
Wheat	15	-5.4	67
Maize	20	-3.7	98**
Rice	25	0.3	40
Sorghum	25	-0.6	98**

Note: Tastes appear to be getting more temperate while climate gets more tropical. * Based on projections in (Bruinsma 2003). ** Projected increase for coarse grains, which includes maize and sorghum.

There is therefore an interesting dynamic playing out at the global scale. As poorer countries develop, they demand more of crops typically consumed in more developed, temperate countries. At the same time, conditions for crop growth continue to get more tropical (i.e. warmer), giving a comparative advantage to those crops for which demand is slowing (rice, sorghum, cassava). Thus, the ongoing shift in diets can be viewed as a “mal-adaptation” to climate change.

Beyond 2050

The above discussions of climate change and impacts on food security have emphasized changes over the next few decades, given that food policy rarely looks beyond this time period. However, it should be noted that emissions today affect climate well beyond 2050, given the long lifetime of CO2 in the atmosphere. Unregulated emissions could plausibly lead to 4°C of GMT increase as early as 2060 (Betts et al. 2011), and to much greater warming by 2100 or beyond. The adaptation challenges presented by this magnitude of climate change would be enormous, and impacts even with adaptation would likely be severe. Efforts to adapt to the inevitable climate changes over the next few decades should therefore not be perceived as reducing the need to limit emissions.

Implications for food policy

Two dilemmas in adaptation

Recommendations for adapting agriculture to climate change are typically of two types, which appear to stem from two different views on the meaning of adaptation. On the one hand are what I will call the "welfare improvers", who define adaptation as anything that restores welfare to what it would have been without climate change. For example, the International Food Policy Research Institute (IFPRI) suggests an additional $7 billion USD per year to help agriculture adapt to climate change (Nelson et al. 2009), with much of this going to building roads or general agricultural research. Similarly, in an effort to measure the costs of adapting to climate extremes, the World Bank poses the question (World Bank 2010a):

> "As climate change increases potential vulnerability to extreme weather events, how many additional young women would have to be educated to neutralize this increased vulnerability? And how much would it cost?"

Thus, the goal is to compensate for welfare losses, not to avoid the impacts of the extremes. To be fair, the World Bank is also emphasizing "climate-smart" development: for instance, cities should not be developed in areas prone to future flooding, and should be built with adequate drainage.

On the other hand are what I will term the "impact avoiders", who view adaptation as an action that adjusts explicitly to the change in climate. For example, the IPCC defines adaptation as:

> "Adaptation is the adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities."

Both views of adaptation have some merit, but both also have some weaknesses. The welfare improvers are correct to point out that adjusting to the new climate, for instance by improving drought tolerance of seeds, may not be the most cost-effective way to improve productivity or food security. Better to build up overall welfare levels, they would say, which will improve resilience for any shock, including those related to climate. At the same time, the welfare improver perspective can be a convenient stance for those who do not understand the specifics of the climate risks, or who are simply advocating for more resources for their existing activities.

The impact avoiders can reasonably say that there are unique activities associated with adjusting to climate that are not covered by traditional development activities. At the same time, a narrow focus on avoiding impacts could arguably result in worse food security outcomes than a broader strategy.

In theory, the welfare approach appears superior – who can argue against using resources most efficiently? In practice, however, the welfare improver strategy can result in simply "more of the same," with progress that is potentially too slow to deal with impending climate impacts. The impact avoider strategy forces us to identify new goals, which may well prove to have faster and higher payoffs. It may well be a lot cheaper, for instance, to develop heat tolerant seeds than to improve welfare by an equivalent amount using a broader approach. Thus, a balanced approach, where some fraction of adaptation funds is set aside for impact avoidance activities, appears appropriate. This view is similar to the World Bank's perspective that "development may need to be done differently, with much greater emphasis on climate and weather risk" (World Bank 2010b).

A second dilemma that pervades discussion of adaptation concerns scale. As repeatedly noted above, the science tends to be most uncertain at the finest spatial scales. For instance, the global incidence of both droughts and floods are very likely to rise, but one cannot say with any certainty whether drought will become more frequent in Arusha, Tanzania. There is similarly little doubt that crops around the world will be increasingly exposed to severe heat, but it is conceivable that some locations will avoid this fate if, say, regional land use changes or aerosol emissions modify local climate.

However, policy makers are typically and justifiably concerned with their part of the world. They want to know what will happen in their province or country, and if the answer is too uncertain, they will reasonably resort to strategies that build overall resilience.

The current structure for adaptation funding also reinforces the emphasis on adaptation at local scales. To qualify for funding, each country must develop its own national adaptation program of action (NAPA), which in turn is often developed from stakeholder meetings at the subnational level. One result of this is that each country prioritizes plans that are tractable at a local scale of implementation. Another consequence is poor coordination among neighboring countries, such as in the case of central and eastern Africa (Nzuma et al. 2010). This lack of coordination is troubling given the important role of regional and global networks in key areas such as developing water resources (Denton 2010) and new crop varieties (Alene et al. 2009).

A brief survey of existing strategies

With these general dilemmas as background, it is helpful to look at specific strategies that have been put forth by various people. All have some merit, but each misses some important aspects of the challenge:

1. *Focus on variability*. Several authors have rightly pointed out that climate risks already incur large costs to developing world farmers, and they suggest society focuses on these risks as an "essential first step" to climate adaptation (Washington et al. 2006; Cooper et al. 2008). A focus on dealing with these current risks is attractive because farmers may be more eager to participate when they see immediate benefits, and because the institutions required to cope with variability (e.g., seasonal forecasting capabilities, better farmer extension services) will also be needed to deal with longer-term changes. An added benefit could be that dealing with variability will register higher on national priorities than climate change, and therefore may capture more domestic resources. The emphasis in this approach is on the need for, and current lack of, capacity to deal with weather-related risks. The shortfall, however, relates to the important differences between climate variability and change. A focus on variability will inevitably emphasize dealing with variations in rainfall amounts and timing. Yet it is very likely that rainfall amounts and timing will be changed only slightly in 20 or 30 years, whereas incidence of extreme heat or heavy rain events will have increased. A focus on variability thus risks missing those aspects of weather that are changing fastest.

2. *Focus on mitigation*. Others have emphasized the importance of accelerating climate mitigation activities in agriculture, such as activities that increase soil carbon (e.g., Lal 2004) or reduce methane emissions from crop and livestock systems. They argue that the potential to sequester carbon in agricultural soils is high, and therefore that carbon payments for these activities will provide an important source of revenue if and when carbon markets become solidified. Thus, they view investments in setting up certified carbon projects as a good use of initial adaptation funds, since it will spark a much larger and continuous source of revenue for poor farmers than adaptation funding would provide. Moreover, more soil carbon will improve soil quality and resilience to periods of drought or heat.

   Three main problems hamper this approach in my view. First, the science on potential sequestration in agricultural soils is far from clear, and it may be much less than what some advocates claim (Baker et al. 2007). Second, the logistics of monitoring actions and making payments to millions of poor farmers are potentially prohibitive, or at least too cumbersome to attract private investment from carbon creditors. Third, improving soil quality is surely helpful for dealing with climate change, but again the magnitude of this benefit relative to other measures, such as improving seeds or access to irrigation, is unclear.

1. *Get out of agriculture*. An interesting combination of both the welfare improver and impact avoider are those who advocate simply transitioning as many people as possible out of agriculture (Collier et al. 2008). The logic here is that if conditions for agriculture are deteriorating, better to invest in other sectors of the economy and subsidize movement away from agriculture. Of course, "getting out of agriculture" could be considered the overall goal of development (Timmer 1988). But as emphasized in other talks in this series, agricultural labor and GDP shares decline only after agricultural productivity improves. The best way to speed the structural transformation away from agriculture is to invest more, not less, in agricultural productivity. In addition, even if skipping the development of domestic agriculture could work as a poverty-reducing strategy, it would leave a country very dependent on food imports. Many countries will be understandably reluctant to rely too much on imports, especially if climate change and other factors stand to increase the volatility of market prices.

Summary and recommendations

Climate change has emerged as a preeminent challenge for society in the 21st century, not least because it threatens the productivity of agriculture in many regions of the world. This challenge, combined with the fact that climate related funds are likely to comprise a sizable fraction of development assistance, means that food policy makers should strive to achieve a basic literacy in climate science and its implications for food security. The following list summarizes some of the main scientific lessons discussed in this chapter.

- There is a key distinction between natural variability, which is inherent in an unforced climate system, and climate change, which results from external forcing of the system. A farmer experiences the combination of variability and change, but separating the two is important for understanding future risks.

- Climate projection uncertainties are largest for local scales, because natural variability is higher at these scales, local climate forcings like aerosols become more important, and projected changes tend to average out over larger regions.
- The most significant aspects of climate change relative to historical variability will be increased occurrence of hot days, warm nights, and heavy rainfall events. Individual days or seasons that were once considered extreme will be increasingly common.
- One consequence of higher temperatures and heavier rainfalls will be less available moisture for plant growth in many places, with drought becoming more common. Rainfall seasons will tend to shorten in many regions, although most changes will be from natural variability and not climate change.
- Significant warming has already been observed since 1980 for most agricultural regions. The increase in global mean temperatures of 0.2 °C decade $^{-1}$ belies significantly faster changes in cropped regions, given that land warms faster than the oceans. Changes in average rainfall have been modest and in nearly every region can be explained solely by natural variability.
- Warming is productivity-reducing in most agricultural areas, because of a range of plant physiological responses. Effects of extremely hot days (i.e. with peak temperatures greater than 30°C) appear especially important for many crops. Impacts of heat tend to be lower in irrigated fields, and in poorly fertilized fields where nutrient constraints dominate. Efforts to increase rainwater harvesting and irrigation are thus critical to adaptation, whereas efforts to increase fertilizer rates should be coupled with other measures to reduce sensitivity to heat.
- Average global prices are unlikely to change significantly because of climate change in the next few decades. However, sub-Saharan Africa and South Asia are likely to experience damages that exceed those in the rest of the world.
- One plausible outcome from climate change is increased year-to-year variability of global or local production. However, limited research has addressed this topic to date.
- Dietary trends are likely to increase demand for the crops that are most affected by climate change. Among the major crops, maize and wheat appear most vulnerable, and most impacted by changes that have already occurred. Rice is less affected by climate change, but also experiencing smaller increases in demand. In effect, diets appear to be shifting toward temperate tastes while climate is getting more tropical.

The appropriate policies for climate adaptation will depend on how these scientific factors intersect with various economic and political considerations. The range of viewpoints discussed in this chapter reflects how little we know about what actually works, because serious efforts at implementing adaptation efforts are only beginning. As with any area of food policy, it will be important to critically evaluate ongoing activities to identify and learn from successes and failures. Although the details of any strategy will depend on the context, three general questions seem especially useful for policy makers to ask themselves, and are often missing from the current debate:

1. *Is there a suitable balance between addressing climate variability and climate change?* Significant gains in farmer welfare and institutional capacity can be made by improving management of current, short-term climate risks. However, climate change means that some risks which are relatively small now will be much higher in 20-30 years. Given lags in developing and implementing new technologies, resources need to be devoted now to these growing risks. For example, adaptation should address extremely hot days (such as through improved seeds or irrigation schemes) and heavy rains (such as with break dams, erosion controls, and rainwater harvesting), even if these factors are not perceived as a major source of current year-to-year variability.

2. *Is there a suitable balance between investing in local (national and sub-national) scales and broader (regional to global) scales?* There are many political and practical reasons that adaptation has focused primarily on national or sub-national scales. However, there are several unambiguous and threatening trends at the global scale which can easily get masked by climate uncertainties at sub-national scales. The need for heat, drought, and flood tolerant crops is unambiguous, for example, but no individual country will definitely need all three. In addition, regional and global coordination is critical for some types of adaptation, such as breeding new varieties, conserving genetic resources, and coordinating water management.

3. *Is there a sufficient acceleration of existing activities to improve food security, in light of the future risks of large productivity losses?* As discussed throughout this lecture series, improvements in productivity can lead to a virtuous cycle of reductions in poverty and food insecurity. Once higher levels of productivity have been reached, a farmer or village becomes more resilient to weather shocks. Yet the pressures caused by climate change are already apparent, and will only grow with time. The best preparation for the coming storm may be to get as far along in agricultural development as possible while productivity improvements are still within grasp.

Overall, policy makers should resist the common tendency to take the hard and complex challenge of climate adaptation and make it even harder and more complicated. Much confusion and uncertainty results, for instance, when one focuses on the scales and variables for which climate changes are small relative to natural variability, and for which climate models produce uncertain projections. A greater emphasis on the key aspects of climate change, such as extreme heat and heavier rainfall, and on the most predictable scales, namely regional to global, will help to ensure that efforts to adapt are successful.

References

Ainsworth, E.A., A.D.B. Leakey, D.R. Ort, and S.P. Long. 2008. FACE-ing the facts: inconsistencies and interdependence among field, chamber and modeling studies of elevated CO2 impacts on crop yield and food supply. *New Phytologist* 179(1): 5-9.

Alene, A.D., M. Abebe, S.O. Ajala, B. Badu-Apraku, A.S. Olanrewaju, V.M. Manyong, and A. Ndiaye. 2009. The economic and poverty impacts of maize research in West and Central Africa. *Agricultural Economics* 40(5): 535-550.

Alexander, L.V., X. Zhang, T.C. Peterson, J. Caesar, B. Gleason, A. Klein Tank, M. Haylock, D. Collins, B. Trewin, F. Rahimzadeh, A. Tagipour, P. Ambenje, K. Rupa Kumar, J. Revadekar, G. Griffiths, L. Vincent, D.B. Stephenson, J. Burn, E. Aguilar, M. Brunet, M. Taylor, M. New, P. Zhai, M. Rusticucci, and J.L. Vazquez-Aguierre. 2006. Global observed changes in daily climate extremes of temperature and precipitation. *Journal of Geophysical Research* 111: D05109, doi:10.1029/2005JD006290.

Allen, M.R. and W.J. Ingram. 2002. Constraints on future changes in climate and the hydrologic cycle. *Nature* 419(6903): 224-232.

Baker, J.M., T.E. Ochsner, R.T. Venterea, and T.J. Griffis. 2007. Tillage and soil carbon sequestration--What do we really know? *Agriculture, Ecosystems & Environment* 118(1-4): 1-5.

Battisti, D. and R.L. Naylor. 2009. Historical warnings of future food insecurity with unprecedented seasonal heat. *Science* 323(5911): 240.

Betts, R.A., M. Collins, D.L. Hemming, C.D. Jones, J.A. Lowe, and M.G. Sanderson. 2011. When could global warming reach 4°C? *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 369(1934): 67-84.

Biasutti, M. and A.H. Sobel. 2009. Delayed Sahel rainfall and global seasonal cycle in a warmer climate. *Geophysical Research Letters* 36(23): L23707.

Boomiraj, K., B. Chakrabarti, P.K. Aggarwal, R. Choudhary, and S. Chander. 2010. Assessing the vulnerability of Indian mustard to climate change. *Agriculture, Ecosystems & Environment* 138(3-4): 265-273.

Bruinsma, J. (Editor). 2003. *World agriculture: Towards 2015/2030: an FAO perspective*. Rome, Italy: Earthscan.

Burke, M.B., E. Miguel, S. Satyanath, J.A. Dykema, and D.B. Lobell. 2009. Warming increases the risk of civil war in Africa. *Proceedings of the National Academy of Sciences* 106(49): 20670.

Collier, P., G. Conway, and T. Venables. 2008. Climate change and Africa. *Oxford Review of Economic Policy* 24(2): 337.

Cooper, P.J.M., J. Dimes, K.P.C. Rao, B. Shapiro, B. Shiferaw, and S. Twomlow. 2008. Coping better with current climatic variability in the rain-fed farming systems of sub-Saharan Africa: An essential first step in adapting to future climate change? *Agriculture, Ecosystems & Environment* 126(1-2): 24-35.

Dell, M., B. Jones, and B. Olken. 2008. Climate change and economic growth: evidence from the last half century. *NBER Working Paper*.

Dell, M., B. Jones, and B. Olken. 2009. Temperature and income: reconciling new cross-sectional and panel estimates. *NBER Working Paper*.

Denton, F. 2010. Financing adaptation in Least Developed Countries in West Africa: is finance the real deal? *Climate Policy* 10(6): 655-671.

Easterling, W., P. Aggarwal, P. Batima, K. Brander, J. Bruinsma, L. Erda, M. Howden, A. Kirilenko, J. Morton, P. Pingali, J.F. Soussana, and F. Tubiello. 2007. Food, fibre, and forest products. Chapter 5, pp.273-313 in M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J.v.d. Linden and C.E. Hanson, eds., *Climate change 2007: Impacts, adaptation and vulnerability.* Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

FAO. 2006. *World agriculture towards 2030/2050*. Rome, Italy: Food and Agricultural Organization of the United Nations Interim Report, 78 pp.

Geophysical Fluid Dynamics Laboratory (GFDL). 2012. www.gfdl.noaa.gov/will-the-wet-get-wetter-and-the-dry-drier.

Giannini, A., R. Saravanan, and P. Chang. 2003. Oceanic forcing of Sahel rainfall on interannual to interdecadal time scales. *Science* 302(5647): 1027.

Giorgi, F. and X. Bi. 2005. Regional changes in surface climate interannual variability for the 21st century from ensembles of global model simulations. *Geophysical Research Letters* 32(13): L13701.

Hertel, T.W., M.B. Burke, and D.B. Lobell. 2010. The poverty implications of climate-induced crop yield changes by 2030. *Global Environmental Change* 20(4): 577-585.

Hsiang, S.M.. 2010. Temperatures and cyclones strongly associated with economic production in the Caribbean and Central America. *Proceedings of the National Academy of Sciences* 107(35): 15367.

Hsiang, S.M., K.C. Meng, and M.A. Cane. 2011. Civil conflicts are associated with the global climate. *Nature* 476(7361): 438-441.

Immerzeel, W.W., L.P.H van Beek, and M.F.P Bierkens. 2010. Climate change will affect the Asian water towers. *Science* 328(5984): 1382-1385.

IPCC. 2007. Summary for policymakers. *Climate change 2007: The physical science basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.). Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

IPCC. 2012. Summary for policymakers. *Managing the risks of extreme events and disasters to advance climate change adaptation*. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen,

M. Tignor, and P.M. Midgley (eds.). Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Joint Institute for the Study of the Atmosphere and Ocean (JISAO). 2011. http://jisao.washington.edu/data/sahel/

Kharin, V.V., F.W. Zwiers, X. Zhang, and G.C. Hegerl. 2007. Changes in temperature and precipitation extremes in the IPCC ensemble of global coupled model simulations. *Journal of Climate* 20(8): 1419-1444.

Knox, J., T. Hess, A. Daccache, and M.P. Ortola. 2011. What are the projected impacts of climate change on food crop productivity in Africa and S Asia? DFID Systematic Review Final Report.

Kostel, K.. 2009. The language of change. *Nature Reports Climate Change* doi:10.1038/climate.2009.10.

Lal, M., K.K. Singh, L.S. Rathore, G. Srinivasan, and S.A. Saseendran. 1998. Vulnerability of rice and wheat yields in NW India to future changes in climate. *Agricultural and Forest Meteorology* 89(2): 101-114.

Lal, R.. 2004. Soil carbon sequestration impacts on global climate change and food security. *Science* 304(5677): 1623-1627.

Lobell, D.B., M. Banziger, C. Magorokosho, and B. Vivek. 2011a. Nonlinear heat effects on African maize as evidenced by historical yield trials. *Nature Climate Change* 1(1): 42-45.

Lobell, D.B., M.B. Burke, C. Tebaldi, M.D. Mastrandrea, W.P. Falcon, and R.L. Naylor. 2008. Prioritizing climate change adaptation needs for food security in 2030. *Science* 319(5863): 607-610.

Lobell, D.B., W.S. Schlenker, and J. Costa-Roberts. 2011b. Climate trends and global crop production since 1980. *Science* 333(6042): 616-620.

Long, S.P., E.A. Ainsworth, A.D.B. Leakey, J. Nosberger, and D.R. Ort. 2006. Food for thought: lower-than-expected crop yield stimulation with rising CO2 concentrations. *Science* 312(5782): 1918-1921.

Meehl, G.A., T.F. Stocker, W. D. Collins, P. Friedlingstein, A.T. Gaye, J.M Gregory, A. Kitoh, R. Knutti, J.M. Murphy, A. Noda, S.C.B. Raper, I.G. Watterson, A.J. Weaver, Z.-C. Zhao. 2007. Global climate projections. In *Climate change 2007: The physical science basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.). Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Hegerl. 2011. Human contribution to more-intense precipitation extremes. *Nature* 470(7334): 378-381.

Naylor, R.L., D.S. Battisti, D.J. Vimont, W.P. Falcon, and M.B. Burke. 2007. Assessing risks of climate variability and climate change for Indonesian rice agriculture. *Proceedings of the National Academy of Sciences* 104(19): 7752.

Naylor, R.L. and W.P. Falcon. 2010. Food security in an era of economic volatility. *Population and Development Review* 36(4): 693-723.

Nelson, G.C., M.W. Rosegrant, J. Koo, R. Robertson, T. Sulser, T. Zhu, C. Ringler, S. Msangi, A. Palazzo, M. Batka, M. Magalhaes, R. Valmonte-Santos, M. Ewing, and D. Lee. 2009. *Climate change: Impact on agriculture and costs of adaptation*. Washington, D.C.: International Food Policy Research Institute.

New, M., B. Hewitson, D. B. Stephenson, A. Tsiga, A. Kruger, A. Manhique, B. Gomez, C.A.S. Coelho, D.N. Masisi, E. Kululanga, E. Mbambalala, F. Adesina, H. Saleh, J. Kanyanga, J. Adosi, L. Bulane, L. Fortunata, M.L. Mdoka, and R. Lajoie. 2006. Evidence of trends in daily climate extremes over Southern and West Africa. *Journal of Geophysical Research* 111.

Nzuma, J.M., M. Waithaka, R.M. Mulwa, M. Kyotalimye, and G. Nelson. 2010. *Strategies for adapting to climate change in rural Sub-Saharan Africa.* IFPRI discussion papers.

O'Gorman, P.A. and T. Schneider. 2009. The physical basis for increases in precipitation extremes in simulations of 21st-century climate change. *Proceedings of the National Academy of Sciences* 106(35): 14773.

Räisänen, J.. 2002. CO2-induced changes in interannual temperature and precipitation variability in 19 CMIP2 experiments. *Journal of Climate* 15(17): 2395-2411.

Roudier, P., B. Sultan, P. Quirion, and A. Berg. 2011. The impact of future climate change on West African crop yields: What does the recent literature say? *Global Environmental Change* 21(3): 1073-1083.

Schlenker, W. and D.B. Lobell. 2010. Robust negative impacts of climate change on African agriculture. *Environmental Research Letters* 5(1) 014010.

Schlenker, W. and M.J. Roberts. 2009. Nonlinear temperature effects indicate severe damages to U.S. crop yields under climate change. *Proceedings of the National Academy of Sciences* 106(37): 15594-15598.

Seth, A., S.A. Rauscher, M. Rojas, A. Giannini, and S.J. Camargo. 2011. Enhanced spring convective barrier for monsoons in a warmer world? *Climatic Change* 104(2): 403-414.

Sheffield, J. and E.F. Wood. 2008a. Global trends and variability in soil moisture and drought characteristics, 1950-2000, from observation-driven simulations of the terrestrial hydrologic cycle. *Journal of Climate* 21(3): 432-458.

Sheffield, J. and E.F. Wood. 2008b. Projected changes in drought occurrence under future global warming from multi-model, multi-scenario, IPCC AR4 simulations. *Climate Dynamics* 31(1): 79-105.

Shongwe, M.E., G.J. van Oldenborgh, B. van den Hurk, and M. van Aalst. 2010. Projected changes in mean and extreme precipitation in Africa under global warming. Part II: East Africa*.* *Journal of Climate* 24(14): 3718-3733.

Sivakumar, M.. 1988. Predicting rainy season potential from the onset of rains in Southern Sahelian and Sudanian climatic zones of West Africa. *Agricultural and Forest Meteorology* 42(4): 295-305.

Tebaldi, C., K. Hayhoe, J.M. Arblaster, and G.A. Meehl. 2006. Going to the extremes. *Climatic Change* 79(3): 185-211.

Thornton, P.K., P.G. Jones, G. Alagarswamy, and J. Andresen. 2009. Spatial variation of crop yield response to climate change in East Africa. *Global Environmental Change* 19(1): 54-65.

Timmer, C.P.. 1988. The agricultural transformation. *Handbook of development economics* 1(Part II): 276-331.

Urban, D., M.J. Roberts, W.S. Schlenker, and D.B. Lobell. Projected temperature changes indicate significant increase in interannual variability of U.S. maize yields. *Climatic Change Letters*, in press.

Van Dingenen, R., F.J. Dentener, F. Raes, M.C. Krol, L. Emberson, and J. Cofala. 2009. The global impact of ozone on agricultural crop yields under current and future air quality legislation. *Atmospheric Environment* 43(3): 604-618.

Vuille, M., B. Francou, P. Wagnon, I. Juen, G. Kaser, B.G. Mark, and R.S. Bradley. 2008. Climate change and tropical Andean glaciers: Past, present and future. *Earth-Science Reviews* 89(3-4): 79-96.

Wang, G.. 2005. Agricultural drought in a future climate: results from 15 global climate models participating in the IPCC 4th assessment. *Climate Dynamics* 25(7 - 8): 739-753.

Washington, R., M. Harrison, D. Conway, E. Black, A. Challinor, D. Grimes, R. Jones, A. Morse, G. Kay, and M. Todd. 2006. African climate change: Taking the shorter route. *Bulletin of the American Meteorological Society* 87(10): 1355-1366.

Welch, J.R., J.R. Vincent, M. Auffhammer, P.F. Moya, A. Dobermann, and D. Dawe. 2010. Rice yields in tropical/subtropical Asia exhibit large but opposing sensitivities to minimum and maximum temperatures. *Proceedings of the National Academy of Sciences* 107(33): 14562.

Wild, M.. 2009. Global dimming and brightening: A review. *Journal of Geophysical Research* 114(21): D00D16.

Williams, A.P. and C. Funk. 2011. A westward extension of the warm pool leads to a westward extension of the Walker circulation, drying eastern Africa. *Climate Dynamics* 37(11): 2417-2435.

World Bank. 2010a. *Economics of adaptation to climate change*. Synthesis Report. Washington, D.C., 136 pp.

World Bank, 2010b. *The World development report 2010: Development and climate change*. Washington, D.C.

World Bank, 2011. *The World development report 2011: Conflict, security, and development*. Washington, D.C.

Zwiers, F.W., X. Zhang, and Y. Feng. 2011. Anthropogenic influence on long return period daily temperature extremes at regional scales. *Journal of Climate* 24(3): 881-892.

Core literature on climate change and agricultural adaptation

Alexander, L.V., X. Zhang, T.C. Peterson, J. Caesar, B. Gleason, A. Klein Tank, M. Haylock, D. Collins, B. Trewin, F. Rahimzadeh, A. Tagipour, P. Ambenje, K. Rupa Kumar, J. Revadekar, G. Griffiths, L. Vincent, D.B. Stephenson, J. Burn, E. Aguilar, M. Brunet, M. Taylor, M. New, P. Zhai, M. Rusticucci, and J.L. Vazquez-Aguierre. 2006. Global observed changes in daily climate extremes of temperature and precipitation. *Journal of Geophysical Research* 111: D05109, doi:10.1029/2005JD006290.

This study synthesized observed changes in various measures of extreme climate over different periods in the past century. The results demonstrated clear increases in the occurrence of hot days, warm nights, and the fraction of rainfall falling in heavy events. The paper also provided clear descriptions of how these data are obtained and processed, and how to assess whether trends are significantly outside the range of natural variability.

Cooper, P.J.M., J. Dimes, K.P.C. Rao, B. Shapiro, B. Shiferaw, and S. Twomlow. 2008. Coping better with current climatic variability in the rain-fed farming systems of sub-Saharan Africa: An essential first step in adapting to future climate change? *Agriculture, Ecosystems & Environment* 126(1-2): 24-35.

Similar to the Washington et al. paper (see below), this study provided some more concrete examples of how much climate variability currently constrains agriculture in sub-Saharan Africa, for example, by providing a disincentive to invest in productivity-enhancing technologies like fertilizer. As with the other paper, it made a few important arguments, but glossed over the fact that challenges posed by climate change are often quite different from those posed by climate variability.

Easterling, W., P. Aggarwal, P. Batima, K. Brander, J. Bruinsma, L. Erda, M. Howden, A. Kirilenko, J. Morton, P. Pingali, J.F. Soussana, and F. Tubiello. 2007. Food, fibre, and forest products. Chapter 5, pp.273-313 in M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J.v.d. Linden and C.E. Hanson, eds., *Climate change 2007: Impacts, adaptation and vulnerability.* Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

The most recent IPCC chapter on climate change impacts on food production, this assessment presented a good summary of the state of science as of 2007. Among its arguable shortcomings are that it downplayed the recent evidence that early studies and many models overstated the benefits of elevated CO2, and that it presented model projections of changes in world prices without making clear the fairly strong assumptions of successful adaptation in these models.

Immerzeel, W.W., L.P.H van Beek, and M.F.P Bierkens. 2010. Climate change will affect the Asian water towers. *Science* 328(5984): 1382-1385.

This paper presents a modeling study of changes in streamflow in the five major river basins fed by the Himalayas: Indus, Ganges, Brahmaputra, Yangtze, and Yellow rivers. As the Himalayas melt, an eventual decline in meltwater delivered downstream is likely, but the importance of meltwater varies a lot by basin. The Indus and Brahmaputra are the most susceptible basins to declining surface water resources, and the authors estimated the decline in water flows threaten the food security of roughly 30 million people in each basin.

Lobell, D.B., M.B. Burke, C. Tebaldi, M.D. Mastrandrea, W.P. Falcon, and R.L. Naylor. 2008. Prioritizing climate change adaptation needs for food security in 2030. *Science* 319(5863): 607-610.

This article attempts to identify which cases, among all possible crops and regions of concern to food security, for which climate change represents the greatest threat of local food production. The study developed datasets on historical weather experienced by crops in each country since 1961, and paired this with national crop production data in statistical models of crop response to weather. Projections from multiple climate models were then used to project impacts to 2030. The study emphasized Southern Africa and South Asia as two regions of greatest risk.

Lobell, D. and M. Burke. 2009. Climate change and food security: Adapting agriculture to a warmer world. Springer Verlag.

This book outlines the major issues and approaches for assessing the impacts of climate change on food security. Intended as a textbook for a graduate or upper-level undergraduate class, emphasis is placed on clear descriptions of different methods to evaluate crop and farmer responses to climate changes.

Lobell, D.B., W.S. Schlenker, and J. Costa-Roberts. 2011b. Climate trends and global crop production since 1980. *Science* 333(6042): 616-620.

This study estimated changes in weather conditions experienced by major crops over the past 30 years. Historical data were used both to map trends in temperature and precipitation, as well as to develop statistical models of yield responses to weather. Results indicated that many regions have seen significant declines in yields of wheat and maize because of warming, with roughly 5 percent impact on global production. Rice and soybean yields were affected in some regions, but on balance global effects were insignificant. Effects of rainfall were essentially zero at the global scale for all crops, emphasizing the relative importance of adapting to warming. The study made clear that climate change impacts are of concern not only for the future, but already represent a significant drag on global productivity growth for maize and wheat.

Schlenker, W. and D.B. Lobell. 2010. Robust negative impacts of climate change on African agriculture. *Environmental Research Letters* 5(1) 014010.

This paper presented an analysis of crop responses to weather in Africa, using national reported data to build various statistical models. These models were then combined with climate projections to estimate impacts by mid-century in the absence of effective adaptation. The study estimated expected impacts by 2050 relative to 1980 of −22, −17, −17, −18, and −8 percent for maize, sorghum, millet, groundnut, and cassava, respectively. In all cases except cassava, there is a 95 percent probability that damages exceed 7 percent, and a 5 percent probability that they exceed 27 percent.

Schlenker, W. and M.J. Roberts. 2009. Nonlinear temperature effects indicate severe damages to U.S. crop yields under climate change. ***Proceedings of the National Academy of Sciences*** **106(37): 15594-15598.**

This study helped to establish the critical role that extreme temperatures play in crop yields. Using extensive, county-level datasets on maize, soybean, and cotton production in the United States, the authors estimated the yield impact of time spent at each degree interval experienced during the growing season. They showed that yields exhibit a sudden decline in productivity when temperatures exceed roughly 29 °C. This study also helped to dispel a common notion that agriculture in developed countries is not very vulnerable to warming of a couple degrees.

Sheffield, J. and E.F. Wood. 2008b. Projected changes in drought occurrence under future global warming from multi-model, multi-scenario, IPCC AR4 simulations. ***Climate Dynamics*** **31(1): 79-105.**

This article is a lengthy but interesting study of model projections of drought changes throughout the 21st century. The study described how such projections are made, and shows that climate models do a reasonable job at reproducing historical frequency of droughts. The study also highlighted that projections of drought frequency and intensity exhibit a monotonic increase in most regions and globally, but that the trends are not likely to result in significant shifts away from historical probabilities for at least a few more decades.

Tebaldi, C., J.M. Arblaster, and R. Knutti. 2011. Mapping model agreement on future climate projections. ***Geophysical Research Letters*** **38(23): L23701.**

This recent paper is a clear description of how common representations of climate projections tend to overstate the uncertainties surrounding rainfall projections. In particular, disagreement across climate models in the direction of change is usually used as a measure of uncertainty. This paper showed that in most cases where models do not agree on sign of change, it is because they are all projecting changes that are close to zero and not statistically significant. The authors propose first describing agreement in terms of whether a model shows a statistically significant trend, and then secondarily in the direction of change. Very few places have some models showing significant increases with other models showing significant decreases. This agrees well with agricultural impact studies that downplay the role of precipitation changes.

Washington, R., M. Harrison, D. Conway, E. Black, A. Challinor, D. Grimes, R. Jones, A. Morse, G. Kay, and M. Todd. 2006. African climate change: Taking the shorter route. ***Bulletin of the American Meteorological Society*** **87(10): 1355-1366.**

An early and cogent argument that the best approach to climate adaptation is to focus on coping with climate variability. The primary argument is that climate variability presents a more immediate concern to farmers and policy makers and is more likely to capture their attention. They authors also argued that capacity for monitoring weather and providing advice to farmers is so limited in Africa, that until these capacities are built up there will be little hope for adapting to climate change. Success in coping with climate variability will also go a long way towards coping with climate change in the authors' opinion.

World Bank. 2010b. World Development Report 2010: Development and Climate Change. Washington, D.C.

This volume included several valuable chapters, including one that provides a uniquely concise and clear summary of climate science, and another that details estimates of the cost of climate adaptations. Not surprisingly the report emphasizes the need for development to reduce poverty around the world, but concludes that “economic growth alone is unlikely to be fast or equitable enough to counter threats from climate change, particularly if it remains carbon intensive and accelerates global warming.“ The overall conclusion that development needs to become “climate smart” and the call to “act now”, “act together”, and “act differently” are very consistent with the recommendations in this chapter.