Paper:
Challinor, AJ (2009) *Towards the development of adaptation options using climate and crop yield forecasting at seasonal to multi-decadal timescales.* Environmental Science and Policy, 12 (4). 453 - 465.

http://dx.doi.org/10.1016/j.envsci.2008.09.008

Towards the development of adaptation options using climate and crop yield forecasting at seasonal to multi-decadal timescales

Andrew Challinor
Institute for Climate and Atmospheric Science,
School of Earth and Environment,
The University of Leeds,
Leeds LS2 9JT.
a.j.challinor@leeds.ac.uk
Tel. +44 (0)113 3433194

Abstract

In order for climate forecasting to be used in developing adaptation options, the forecasts should be able to affect decisions made by stakeholders in a manner that improves outcomes. The implications of this requirement for forecasting are presented under five headings: relevance, reliability, stakeholder engagement, holism and accuracy. These characteristics are elucidated through a particular focus on the use of ensemble climate and crop simulations. Resulting recommendations, inclusing comments on mainstreaming and seamlessness, are described using the concepts of quality and value.

Adaptation options can be developed using climate forecasts on a range of timescales, from days to decades. Two cases are presented and discussed, using the five identified characteristics: (i) options based on large-area seasonal crop yield forecasting are discussed, and (ii) genotypic adaptation based on long-term climate change projections is examined. For the latter, novel analyses of existing large-area groundnut simulations are used to assess the magnitude and spatial extent of the impact of changes in the mean and variability of temperature, rainfall and humidity. The genotypic properties required to ameliorate negative impacts are then assessed and compared to observations. The processes examined act on most annual crops, making the method, and to some extent the results, broadly relevant.

Keywords:
GECAFS, climate forecasting, crop model, adaptation, crop germplasm

1. Introduction

Environmental change often demands that individuals and society modify their use of the environment. This process of adaptation occurs at a range of spatial and temporal scales. It involves decisions made by a range of agents, from individuals through to governments, each with diverse objectives (see e.g. Challinor et al., 2007a). In examining adaptation to climate change across a range of scales, Adger et al. (2005) identify three mechanisms: altering (human) exposure to climate change, reducing sensitivity to climate change (sometimes called 'climate proofing'), and increasing the resilience of the system. The first of these applies to social systems, and includes hazard preparedness and mitigation activities. In the case of food security, the second mechanism applies to ecological systems, and includes the breeding and use of crop germplasm that tolerates heat and water stress. It also includes crop management measures such as, for example, the choice of planting date and application of fertiliser and/or pesticide. The third mechanism, increasing resilience, applies principally to social systems, and includes crop insurance schemes and increases in imports in response to food shortages. The food commodity price increases during 2007/2008, ongoing at the time of writing, are indicative that global food systems are not resilient to the range of stresses they are currently subject to (see section 2iii).

Climate forecasts can be a useful part of the decision-making process for adaptation of food systems to environmental change. Indeed, there is an ongoing shift in the focus of climate change assessments from quantification of impacts towards the study of adaptation. This is driven both by policy, which increasingly recognises that – despite mitigation efforts – climate change is inevitable, and by the development of the science of impacts to the point where human and biophysical adaption can be accounted for. This shift presents a challenge to climate science: models must not only be accurate representations of the climate system, they must be able to inform decision-makers. In order for climate forecasting to be used in developing adaptation options, the forecasts should be able to affect decisions made by stakeholders in a manner that improves outcomes. This requirement implies a number of characteristics (see also Patt and Gwata, 2002; Hansen, 2002):

i. The forecast should be relevant: there should be at least one identifiable decision that can be made in response to the forecast. The variables, spatial scale and lead time of the forecast should therefore be appropriate to the decision. A climate impacts simulation model, such as a model of crop growth and development, can be used with climate simulations, to further tailor the climate information to the needs of the stakeholder. The condition of relevance has implications for the spatial resolution of the climate and impacts models used.

ii. The forecasts should be reliable: the uncertainty associated with a forecast should be known to some degree of accuracy. Unreliable forecasts are likely to result in incorrect assessment and management of risk. Even where a forecast is reliable, a positive outcome may not result in every case, but may only emerge over time. The condition of reliability has implications for the sampling of ensembles of climate and climate impacts, as well as the manner in which they are interpreted.

iii. A holistic, systems approach should be taken, so that all the factors affecting the decision are accounted for. Many of these factors will be uncertain, and their interactions will produce further uncertainty; this further underlines the importance of reliability. The condition of holism implies a need for knowledge and research from more than one discipline, so that multiple stresses can be accounted for.

iv. For the practice of adaptation, and arguably for adaptation research, stakeholder engagement is critical. The decision-maker needs to not only have access to the forecasts, but also see the benefit of using the forecasts. The condition of stakeholder engagement can constrain adaptation options: if insurmountable barriers to access or use exist, this condition may rule out some of the target decisions.

v. The forecasts should be of the highest possible accuracy. This is a desirable, rather than strictly necessary condition, which seeks to gain the maximum benefit from the forecast. The condition of accuracy has implications for the manner in which impacts models are calibrated and used.

This study examines the use of climate and crop models to inform the adaptation of food production systems to climate variability and change. First, the characteristics above are illustrated in more detail, using discussion based principally on linked crop and climate models (section 2). These characteristics are then used to examine how existing crop modelling studies might inform adaptation at seasonal (section 3) and multi-decadal (section 4) timescales. These two timescales have different characteristics: in probabilistic seasonal weather forecasting, the initial state of the atmosphere is a principal source of uncertainty. In climate projections, initial conditions do not significantly affect model output, and model structure (i.e.

choice of parameterisation of terrestrial, atmospheric and oceanic processes) and forcing (i.e. the uncertainty in emissions) dominate.

Recognition that analyses of long-term climate change are insufficient for informing decisions is central to the concept of adaptation used in this study. A broad definition of adaptation, which includes strategies to cope with climate variability, is therefore adopted in this study. This is a particularly useful approach given that climate change implies changes – usually increases – in climate variability. Similarly, a broad definition of forecasting is used that includes projections based on scenarios of greenhouse gas emissions.

2. Informing adaptation decisions using forecast models

i. Relevance of forecasts to adaptation decisions

Efforts within the climate modelling community are beginning to focus around the concept of seamless prediction, which seeks to improve the consistency and continuity of medium- and long-range information (WCRP, 2008). This concept arose from the awareness that atmospheric processes do not categorise timescales in the way that prediction systems, and the weather and climate research communities, do. Hence there has been a call to more seamless prediction methods. This call also extends to the way in which forecasts are presented to users: since the categorisation of timescales arises from the scientific community, and not from the users, it is perceived by the climate modelling community as a potential barrier to the use of forecasts.

The forecast community, then, is seeking to create more relevant forecasts. However, forecast relevance arises not just from the manner of its presentation, but from an awareness of the decision-making process. Therefore, in order to assess the relevance of a forecasting system, a climate-dependant decision needs to be identified. This process could begin with the decision and be followed with assessment of the relevance of forecasts to that decision (e.g. Meinke et al., 2006). The needs of decision makers are highly diverse, both geographically and within communities. Hence studies of decision support for food systems in different regions are likely to differ in their conclusions (e.g. Gadgil et al., 2002; Hansen, 2005). One way of ensuring relevance is to extract generalities from specific case studies, as is done in agent-based modelling (Bharwani et al., 2005). However, these models often remain strongly site-specific. An alternative starting point, presented in this study, asks what decisions can be affected by a particular forecasting system. By being rooted in the science of climate change and of its impacts, this study is in the tradition of applied climate science. This is growing field, with increasing outreach towards assessment of climate impacts (Challinor et al., 2008a; Huntingford et al., 2005) and human vulnerability (Cox and Stephenson, 2007; Challinor et al., 2007a).

Adaptation decisions occur on a range of temporal and spatial scales, from the crop management choices of smallholder agriculturalists, to the policy decisions made by governments and regional authorities. As a result, adaptation options can be developed using climate forecasts across a range of timescales, from days to decades. However, the spatial resolution of regional and global climate models may not be appropriate for crop management decisions, since it is rarely less than tens of kilometres. Downscaling techniques exist that, in addition to providing local-scale climate information, can be used to provide inputs to detailed process-based crop models (e.g. Southworth et al., 2002). These models can be used to inform farm-scale decisions, since they produce results that depend upon the specific crop variety, soils and management practices used. Potential sources of error when using this method include over-parameterisation (e.g. Cox et al., 2006; see also section v), where the complexity of the model results in a large number of unconstrained parameters, and non-stationarity in the downscaling relationships (e.g. Challinor et al., 2005a), which can introduce discrepancies between observed and downscaled weather.

Where adaptation can be based on forecast information at larger spatial scales, a large-area crop model, which uses climate model output directly, may be used. Large area crop models are particularly well-suited for use with climate model data, since they avoid errors due to downscaling. These models may be empirical (e.g. Iglesias et al., 2000) or processed based. An example of the latter is presented in figure 1, which shows observed and simulated yields over a 2.5^o by 2.5^o area. Empirical methods can introduce significant errors through the linearisation of the equations for crop yield (Challinor et al., 2006) and/or the use of monthly data, which cannot account for sub-seasonal variability in weather. This can be illustrated by noting that two years in figure 1 with different yields (44% lower in 1981 than in 1975), have the same total rainfall (39cm). A principal reason for this is the different sub-seasonal rainfall distributions, with 1981 producing higher runoff and drainage, and less water availability during pod-fill (see Challinor et al., 2004). Subgrid heterogeneity can sometimes result in inaccuracy when using large-area crop models (Baron et al., 2005;

Hansen and Jones, 2000). Despite this, process-based large-area models have shown promising results in current climates (Osborne et al., 2007; Chee-Kiat, 2006; Challinor et al., 2005a, c). Furthermore, as computer power increases, allowing finer resolution of climate and improved climate simulation skill, large-area modelling becomes increasingly relevant to the scale of crop production.

Whilst they are the focus of the current discussion, impacts models are not a prerequisite for forecast relevance (see e.g. Hellmuth et al., 2007; Patt et al., 2005). Different approaches may be appropriate in different settings. Crop models may be particularly useful where cropping systems are highly managed (see e.g. Ferreyra et al., 2001; Meinke et al., 2001) or where monitoring and forecasting systems are combined (see e.g. Rijks et al., 2003).

ii. Reliability of forecasts

Unless a forecast is reliable as well as relevant, it may lead to detrimental adaptation decisions. For seasonal forecasts, reliability is a well-defined formal concept: forecasts stating an 80% chance of less than 10cm of rain are perfectly reliable if 80% of them are followed by less than 10cm of rain. Thus a number of forecasts, and observations, are required in order to assess reliability. The probabilistic nature of seasonal forecasts also demands careful definition of a successful adaptation decision: whilst positive outcomes should emerge over time (i.e. on average), any one decision could be detrimental. In the example above, a detrimental decision may occur one in five times such a forecast is given, since the most likely outcome (low rainfall) does not occur. In contrast to seasonal timescales, the reliability of climate change forecasts is impossible to verify, since there is only one realisation of climate. Here we can require, more generally, that the quantification of uncertainty should result in projected ranges, and possibly probabilities, that accurately reflect reality.

The increasing availability of climate ensembles on seasonal to multi-decadal timescales is resulting in their increased use with crop models (Challinor et al., 2005b, c; Marletto et al., 2007). The requirement of reliability demands that ensemble size should not be artificially reduced by sub-sampling (WCRP, 2008), particularly where such sub-sampling may omit important non-linearities (e.g. Stainforth et al., 2007; see also the analysis of rainfall and yield above). Efforts should also be made to ensure that the probabilities derived from the ensembles are accurate. This may mean some pre- or post- processing (see e.g. Rougier and Sexton 2007). Also, uncertainty in crop simulation should be accounted for if unfounded confidence is to be avoided. This is commonly achieved through random sampling of uncertainty using a range of crops, locations, models, or scenarios. This method leads to a range of results being produced from a range of studies, so that any subsequent synthesis must deal with 'conflict-based uncertainty' (Patt, 2007). The method of Challinor and Wheeler (2008a), links parameter perturbations to observations, and is a more objective method of quantifying uncertainty.

iii. A holistic approach to adaptation research

Even where a forecast is both relevant to adaptation and reliable, detrimental decisions may be made if account is not taken of the non-climatic aspects of the decision. Farmers base decisions on more than just climate; issues such as insecure land tenure affect farmers' ability to engage in sustainable agriculture (Fraser, 2004). Hence economic and institutional factors influence adaptability (Fraser, 2007) and these factors may undermine the way farmers use even accurate and relevant climate information. In reviewing the linkages between climate change and food security, Gregory et al. (2005) assess the implications of the dynamic interactions between and within the biophysical and human food system environments. These environments vary geographically, as therefore does the local capacity to adapt and the importance of climate change as a threat to food security (see also Diffenbaugh et al., 2007).

It is widely recognised (Financial Times, 24th February 2008; New Statesman, 21st April, 2008) that the drivers of food commodity price increases during 2007/2008 include rising demand, both due to increasing population and dietary trends in developing countries; falling supply, due in part to the negative impact of climatic extremes change on yield; and market mechanisms, including investment and speculation, rising agricultural input prices and the implications of increased demand for biofuels. Food security is clearly, therefore, a challenge that requires problem-based, rather than discipline-based, interdisciplinarity (see Robinson, 2007). Studies exist that bring together a range of researchers and disciplines to examine food systems under environmental change (e.g. Challinor et al., 2007a; Huntingford et al., 2005); further focussed integration, through focussed science meetings and increased collaboration, should be encouraged. Methodologies are required that are capable of integrating the main food system processes (e.g. Schmidhuber and Tubiello, 2007; Tubiello et al., 2007) and suggesting adaptation options that take account of the full range of stresses (see Morton, 2007; Howden et al., 2007). Where important processes are omitted from modelling studies, false certainty may result, with precision being mistaken for accuracy. This is also true where uncertainties are omitted from the analysis.

The quantification of uncertainty is made particularly important by the nature of the relationship between precision and relevance to food security. This relationship is shown in figure 2, which illustrates that as predictions become increasingly relevant, the precision associated with them tends to fall (so long as we require that the predictions are accurate). In particular, a fundamental limit exists: any derived impact cannot be known with greater precision than its cause. Spatial scale is also important in determining the relationship between relevance and precision: climate science has demonstrated a robust link between greenhouse gas emissions and change in global mean temperature; however the link with regional climate is less robust (e.g. Randall et al., 2007).

The second link in figure 2, between climate and yield, has also been the subject of much research, as described in sections 2i and 2ii. Crop modelling uncertainties can be as significant as those arising from climate (Challinor et al., 2005b). Despite this, in the study of Challinor et al. (2008b), where observations were used to constrain the response of crops to climate change (in this case a doubling of CO_2), uncertainty in crop response was not a major component of total uncertainty at the regional-scale. In contrast, the uncertainty associated with the third link in figure 2, between yield and food systems, is likely to be harder to quantify. Only for a very simple food system – where, for example, yield is the key variable and it is determined principally by climate – is it possible to have precise and accurate forecasts with a high degree of relevance to food security. Indeed, as analyses become increasingly relevant to food security, there can be an increasing need for qualitative, as opposed to quantitative, descriptions, so that precision and accuracy themselves become difficult to define.

The complexity of food systems creates additional difficulties in assessing the success of adaptation decisions. Decisions may have multiple positive and/or negative outcomes, and there may be multiple perspectives on these outcomes. In addition to food, agroecosystems have a range of direct (e.g. feed, medicinal products) and indirect (e.g. landscape amenities, environmental services) benefits; adaptation actions should include efforts to enhance these multiple benefits (IAASTD, 2008). One important class of negative outcomes is where adaptation results in increased greenhouse gas emissions. Agricultural methane and nitrous oxide are significant greenhouse gases, with emissions projected to continue to rise for a number of decades (Gregory et al., 2005). Also, agriculture is responsible for a significant fraction of deforestation (see e.g. Tubiello et al., 2007). This fraction is likely to increase with increased cultivation of biofuels, thus potentially creating a long term carbon debt (Righelato and Spracklen, 2007). Clearly, then, a holistic approach to adaptation involves more than accounting for multiple stresses: it demands that multiple perspectives and multiple outcomes are also included. This may include work to integrate local and formal agricultural knowledge (IAASTD, 2008).

iv. Stakeholder engagement and access to forecasts

Climate information, including any derivatives such as crop yield projections, needs to be actionable, in the sense elucidated by Meinke et al. (2006). The forecast should not only be relevant, reliable and in appropriate context, it needs to be perceived as such by the stakeholders: it should be salient, credible and legitimate (see also Patt and Gwata, 2002). Identifying the stakeholders – those who make the adaptation decisions – is therefore a critical aspect of developing adaptation options using forecast systems. Furthermore, the requirements of relevance and of holism imply the need for stakeholder involvement in the knowledge exchange process: who better to know what information is relevant, and how to take a holistic approach, than the decision-maker? Furthermore, stakeholder participation encourages the use of forecasts, increasing uptake by a factor of five in at least one case (Patt et al., 2005; see also Hellmuth et al., 2007).

The diversity of stakeholders means that a range of approaches to stakeholder engagement is needed (see Brown et al., 2001 for one method); it also implies a diversity of needs. Individual subsistence farmers are likely to be interested in local-scale forecasts at relatively short lead-times, whereas planning agencies such as government departments or the World Bank are likely to (also) be interested in regional or national assessments over longer timescales (years to decades). Decisions that could be informed by targeted climate forecasting range from crop choice and the scheduling of planting or harvest to longer-term policy decisions regarding land use (Stone and Meinke, 2005).

Given the diversity of adaptation decisions, it seems pertinent to ask were in the food system forecasts can be put to use. Since climate affects a range of decisions, one answer to this question is simply ‘everywhere.’

Thus there are many points at which climate knowledge needs to be integrated into decision-making structures. This process is often referred to as mainstreaming of climate information. Where can this process of mainstreaming be most effective? To answer this requires theoretical analyses of the complete food system. Arguably, adaptation decisions based on model analyses should where possible be at those points where precision is highest (see figure 2), so long as a positive impact on the food system is predicted. At the very least model uncertainty should be quantified, so that decisions are based on accurate information (see section 2iii).

For mainstreaming to be effective, there must be practical knowledge exchange routes in addition to theoretical analyses (IRI, 2006; Johnston et al., 2007; Patt et al., 2007). Access to knowledge and information is crucial to the ability of farmers to adapt to climate variability and change (Phillips, 2003; Challinor et al., 2007a; Washington et al., 2006). Without stakeholder access, forecasts cannot affect decisions. This issue is particularly important on the seasonal timescale, where information is more regionally specific and where the timescale for action is short. Methods to address the problem of access include organisations that are designed specifically to use forecasts (see e.g. Orlove and Tosteson, 1999) and drought insurance (Diaz Nieto et al., 2006),.

v. Accuracy of forecasts

In order for the quality of information for decision-making to be as high as possible, the accuracy of the forecasts should be as high as possible. Together with the conditions outlined above, this should result in the best possible decision being made, given the state-of-the-art at the time. Skill in the simulation of crop and climate forecasts, as well as any associated estimates of uncertainty, depends on the choice of model (Challinor et al., 2007a). The way in which the model is calibrated will also affect skill and uncertainty estimates. These choices are therefore likely to strongly influence the estimate of total uncertainty. Models should therefore be chosen and calibrated carefully.

The complexity of the impacts model, and its associated spatial scale, are important determinants of the calibration method and of estimates of uncertainty (see Challinor and Wheeler, 2008a, b). Mechanistic modelling necessarily involves a reduction of real-world processes to a set of fallible rules. Over-simplification in modelling will result in a lack of representation of some processes that strongly influence output variables. Over-complexity may result in a large number of unconstrained parameters, increasing the risk of reproducing observations without correctly representing the processes involved. When such a model is run in a new environment (such as a new location, or under climate change), the errors may be large. A model should therefore be sufficiently complex to capture the response of the system to the environment whilst minimising the number of parameters that cannot be estimated directly from data (Sinclair and Seligman, 2000). Where possible, calibration should be performed by using observations of more than one environmental variable. For a crop model this could mean calibration using leaf area index in addition to yield (e.g. Jones and Barnes, 2001). Internal consistency checks should also be performed, to ensure that the simulations are realistic. For example, crop model performance can be assessed in terms of radiation use efficiency and specific leaf area (see e.g. Challinor et al., 2004).

3. Seasonal forecasting of crop yield

As suggested above, seasonal weather and crop forecasting systems may provide a means of adapting to climate change. One such system is that of Challinor et al. (2003), who described a methodology for combining climate model output with a crop model. The methodology, which was developed through a series of subsequent publications, comprised the following stages:

i. Analysis of the relationship between weather and climate, in order to determine the appropriate spatial scale for modelling (Challinor et al., 2003).

ii. Design of a crop model, the General Large-Area Model for annual crops (GLAM), to operate at the chosen spatial scale (Challinor et al., 2004).

iii. Evaluation of the crop model using observed weather data and reanalysis data, and assessment of internal consistency (Challinor et al., 2004, 2005a; see also figure 1).

iv. Testing of the system in hindcast (i.e. retrospective forecast) mode.

This last stage, carried out by Challinor et al. (2005c), used GLAM to test the predictability of crop yield in western India using a multi-climate-model ensemble. Despite significant climate model error, both the ensemble mean and the spread were skilful when compared to simulations with reanalysis data and climatological forecasts. In particular, the study demonstrated accurate (see section 2v) seasonal hindcasts of yield: crop failure was simulated with greater skill than a random forecast based on climatology. The system has also demonstrated some reliability (see section 2ii), although more hindcasts are needed for robust tests of this characteristic.

The forecasting system outlined above has the potential, through its simulation of crop yield, to add value to seasonal forecasts (see WCRP, 2008), increase their relevance (see section 2i) and affect decisions during the season. Where relevance is not severely limited by the large spatial scale of the output, climate risk may be minimised through appropriate management and choice of crops. An existing example of a risk management system in Australia is described by Stone and Meinke (2005): the relationship between potential yield and the phase of the Southern Oscillation Index can be used to demonstrate likely yields to farmers, allowing them to adjust inputs to achieve optimal yields, and/or forecast final yields or crop quality for marketing purposes. Like the analysis of Stone and Meinke (2005), the system of Challinor et al. (2005c) produces probabilistic output, thus supporting a risk management approach and facilitating 'discussion support' (see e.g. Hansen, 2005). The GLAM model incorporates a limited range of management mechanisms; holism (see section 2iii) would require input from other aspects of the decision-making process. This may be best achieved through combination of the modelling approach with descriptive approaches (Hansen, 2002).

A second application of large-area crop yield forecasting to adaptation is in the planning of food aid through the identification of vulnerable areas (ERFARM, 2008). Forecasts could be updated throughout the season using satellite estimates of rainfall, as has been carried out with GLAM by Chee-Kiat (2006). Furthermore, the system could be supplemented by drought and flood monitoring techniques (e.g. Verdin et al., 2005). Responses to such forecasts at the household, governmental and international levels could take similar forms to those described by Haile (2005) for food insecurity caused by drought. However, forecasts are not a panacea and care is needed to foster realistic expectations of outcomes and to ensure that longer-term planning does not suffer as a result of a focus on seasonal timescales (Broad and Agrawala, 2000). Nonetheless, there is evidence that climate forecasts can form part of early warning systems that are sufficiently holistic, and have sufficient stakeholder engagement, to be beneficial (e.g. Erkineh, 2007). The role of crop modelling within such systems would depend on the particular setting (see section 2i).

A third application of large-area yield forecasting could be through crop insurance schemes. Such schemes are prone to three related problems: moral hazard, whereby the very fact of being insured gives the policy owner no incentive to avoid crop failure; asymmetrical information, whereby the farmer knows more about the likelihood of crop failure than the insured; and adverse selection, whereby farmers who know their crops to be at low risk opt out of the system, leaving only the high-risk farmers. Reliable probabilities of crop failure would clearly be relevant to any endeavour aimed at reducing asymmetry in information, thus helping micro-finance schemes to be sustainable in the long term. Further discussion on crop insurance schemes can be found in Diaz Nieto et al., (2006).

The first of the above applications is particularly subject to previously-identified constraints on the use of seasonal forecasts (e.g. Patt and Gwata, 2002). One advantage of the second and third applications is that they naturally lend themselves to larger scales, where barriers to access of information may be less than at smaller scales. In all three cases there are barriers to the implementation of decisions based on forecasts. Appropriate organisations to carry out and act on the forecasts are required, as are resources such as food aid. There is evidence that institutional learning regarding forecast used can lead to beneficial results (e.g. Orlove and Tosteson, 1999).

4. Simulating genotypic adaptation to climate change

Adaptation to climate change will require more than incremental adjustments made on seasonal timescales. This section examines some of the decisions that will be needed for adaptation to longer-term climate change. It deals with projections, rather than predictions, since outcomes at multi-decadal lead times are contingent on a range of factors (see section 1). The discussion centres around the choice of crop variety and how this relates to climate. As with the above section on seasonal forecasting, the concepts elucidated in section 2 are used to examine the potential of longer-term projections to affect decisions.

Accurate and reliable projections

The concepts of accuracy and reliability are, in the case of climate change projections, strongly linked. Reliable yield projections will only result from quantification of uncertainty, something that is enabled by ensemble crop and climate methods (see section 2ii). Accuracy can only be assessed using observations, making the task of forecast evaluation increasingly difficult as lead time increases (since fewer and fewer observations are available for comparison with model output). However, whilst accuracy at one timescale does not guarantee accuracy at another, proven seasonal forecast skill can build confidence in longer term projections. In the case of large-area modelling, the ability to simulate current yields (section 3) has built confidence in simulations of the response of crops to climate change. However, this alone is insufficient, since new limitations may act on crop yield under climate change. These limitations are set by the action of fundamental processes. They imply that accuracy under climate change can only be assessed through comparison of simulations and measurements under controlled environments that create the conditions likely to occur naturally under climate change.

A number of these processes have been examined in the large-area context: reduction in transpiration efficiency due to decreased atmospheric humidity (e.g. Challinor and Wheeler, 2008b); interactions between water stress and elevated CO_2 (Challinor and Wheeler, 2008a); and changes in crop duration in response to mean temperature change (e.g. Challinor et al., 2007b). However, only for a few have direct quantitative comparisons been made: heat stress due to temperature threshold exceedance during anthesis (Challinor et al., 2005d); interactions between water stress and elevated CO_2 (Challinor and Wheeler, 2008a). By examining the response of more than one type of crop variety, studies such as these also inform genotypic adaptation to climate change. For example, Challinor et al. (2007b) found that, at least for one climate change scenario, groundnut yield across most of India is significantly affected by changes in the mean and/or variability of temperature, and that partial adaptation to these changes is possible, by changing the cultivated crop variety.

Increasing the relevance of modelling studies

Whilst the studies mentioned above assess the potential for genotypic adaptation, they do so in a somewhat limited way. Some of them are for only one location, some do not account for uncertainty; and some stop short of comparing the projected genotypic requirements with those found in existing germplasm. Clearly more comprehensive assessments are needed if these projections of genotypic potential are to be relevant to decision-making. To this end, a new assessment, which builds upon previous work, is presented in the Appendix. Figure 3 shows the results, by showing the fraction of the total area under groundnut cultivation that is adversely affected by an approximate doubling of CO_2. Two sets of bars are presented, one based on a common current crop variety and one based on genotypic properties that are less sensitive to the biophysical process in question (except for the case of water stress – adaptation to increases in water stress was not considered). The shading of the bars indicates the magnitude of the impact on yield, whilst the height of the bar indicated the extent of the area affected. For all biophysical processes for which an estimate could be made, both the extent and magnitude of the impact on yield are significantly reduced under adaptation. However, due to insufficiently precise field data on observed responses, an estimate could not be made for the capacity to adapt to increases in mean temperature. For all other biophysical processes, the properties of the adapted crop are contained within existing germplasm. This analysis therefore demonstrates that there is significant potential for adaptation of groundnut cultivation to climate change in India.

Examples of decisions that can be based, at least in part, on studies of genetic adaptation to climate change include: efforts to preserve existing crop varieties in the face of genetic erosion (e.g. the Global Crop Diversity Trust: http://www.croptrust.org); whether or not specific breeding or genetic modification is required for use under future climates; and the need for increased resources to ensure improved access to existing seed. A range of policy decisions regarding land use can also be informed by studies of genotypic adaptation. Consider, for example, a policy aiming to ensure that future demand for food is met. This policy may seek to encourage the use of land for food crops if demand is predicted to exceed supply. In at least one study (Balmford et al., 2005), plausible variation in mean yield was found to be as important as population or per capita consumption in determining the change in cropped area needed to meet future demand (to 2050). Hence such a policy would need to predict likely yields, something that depends on the crop variety grown.

Holism and accuracy

Accuracy requires holism; without including all relevant processes (see section 2iv) and accounting for uncertainty (section 2ii) predictions may be precise, but they will not be accurate (figure 2; section 2iii). Furthermore, accurate crop yield projections require not only on the accurate simulation of individual processes, but also the accurate simulation of the combined influence of these processes. For example, the interaction between genotypic responses to the mean and variability of temperature can determine whether yield increases or decreases under climate change (Challinor et al., 2007b). Demonstrating the potential for adaptation to individual processes is clearly not the same as demonstrating the existence of varieties that contain all of the required properties. Thus, the limitations of the analysis behind figure 3 become apparent, particularly since the properties required of a variety go beyond the biophysical properties examined here. They may include, for example, decreased sensitivity to biotic stresses (likely pests or diseases), nutrient requirements, flood tolerance or crop quality standards. In particular, crop varieties that are less susceptible to biotic stresses may be more susceptible to abiotic stresses, particularly when varieties are selected for high yield.

A second limitation of the analysis presented above stems from a broader consideration of holism: even where a variety with the required properties exists, farmers may not have access to it. Access to seed depends on a broad range of factors, including seed patent ownership, household income, transport infrastructure, access to local markets, and macro- and micro- economics, which determine seed price. Access to seed also depends on the existence of the seed. The need for increased production and the resultant focus on high-yielding varieties, together with the globalisation of trade, has reduced the number of crop varieties cultivated by farmers (a phenomenon referred to as 'genetic erosion'; see e.g. Gepts, 2006). Thus for some crops, food production can be dominated by a small number of varieties that are well-adapted to the current range of seasonal climates. These crops may not perform well under climates outside the current range of variability. Genetic erosion therefore presents a threat to adaptive capacity. It is therefore important to maintain crop biodiversity.

Increasing holism and stakeholder engagement

Food security is dependent on demand, making population growth, changing food preferences and the economics of food production key aspects of the food system. Many integrated studies of food production under climate change (e.g. Parry et al., 2004; see also Schmidhuber and Tubiello, 2007) rely on a single trade model and treat crop growth and development empirically. These methods take a holistic approach to food systems; however, they rarely quantify model uncertainty adequately and they are prone to inaccuracies in simulating crop growth (see section 2i). When integrating a range of processes in this way, choice of the appropriate level of model complexity is particularly important (section 2v).

Whilst steps are being taken towards a more holistic approach to food systems research, there is still some way to go. The analysis of genotypic adaptation presented here, for example, does not attach any probabilities to the scenario produced. Without this information it is difficult to make adaptation decisions, since the likelihood of the scenario is unknown. A sense of the reliability of the scenario can be gained by qualitative comparison with other studies. For example, Challinor and Wheeler (2008b) discuss in more detail the likelihood of an intensification of the monsoon, as is found in the scenario used in the current study. More quantitative assessments of reliability can be carried out using ensembles. Challinor et al. (2008b) used an ensemble of over 180,000 simulations, where both climate and crop model parameters were varied. That study, which focussed on a single grid cell in India, found that despite the inherent uncertainties, the germplasm exists for adaptation of groundnut cultivation to changes in mean temperature.

A holistic approach to adaptation demands more than only the quantification of biophysical uncertainty – the full range of processes, as discussed above, need to be understood and included. A key challenge is to assess the feasibility of adaptation strategies is at the community level, where agricultural systems can be highly complex and location-specific (see e.g. Morton, 2007). This inevitably implies stakeholder engagement (section 2iv) and understanding of local socio-economic processes. The potential for genotypic adaptation presented in this paper, for example, has been determined using biophysical analyses; this does not address the efficacy of on-farm adaptation based on these results. Even for the relatively narrow goal of meeting a given demand for food under a given change in climate, there are a range of adaptation options: a change of variety, a change of crop, an increase in cropped area, increased imports or regional transport of food. Each of these will have a range of different associated impacts on the broader food system and its components. One way to assess the likely efficacy of adaptation options is to examine historical responses to environmental change (Fraser, 2007).

5. Conclusions

There is evidence that farmers can respond creatively and adaptively to environmental change; however, to continue to do so under climate change, they will need governments to create institutional and macro-economic conditions that support and facilitate adaptation (Challinor et al., 2007a). Modelling studies can contribute to policy by providing the science to underpin strategic decisions. By focusing on specific issues, they can also contribute directly to shorter-term adaptation decisions and frameworks (section 2iv). This latter process can be facilitated by agricultural research centres and government extension workers. In all cases, it is important to communicate the level of uncertainty – or robustness – associated with projections.

Many decisions regarding crop cultivation are made on timescales of weeks to months. Thus, increasing the capacity to deal with current climate variability presents a way to adapt to longer-term changes in climate variability (see Washington et al., 2006). This component of adaptation, discussed in section 3, is made particularly important by the expected trend towards increasing extremes of climate. In the longer term, it is therefore important to support adaptation by maintaining the capacity to deal with increased climate variability. Similarly, studies of long-term climate change should, in addition to the impact of mean changes, include the impact of climate variability. This was the approach taken in the current study (figure 3), where existing varietal properties of groundnut were assessed in relation to the likely abiotic stresses associated with climate change in India. The analysis showed that more precise estimates of adaptive capacity could be based upon more precise assessments of the range of responses in existing germplasm to mean temperature increases. More broadly, this method demonstrates how climate and crop prediction can be linked to the adaptive capacity contained in existing germplasm. The method can be used in other regions, with other crops, and using ensembles in order to quantify uncertainty. Where existing varieties are not able to provide sufficient adaptation, such analyses can inform the development of new crop varieties. However, this method cannot result in specific recommendations regarding the choice of crop varieties. Non-linear interactions between genotype and environment make any such recommendations a complex and geographically-specific endeavour. The method presented here merely identifies those biophysical properties that are likely to be required of crop varieties grown under future climates.

This study has demonstrated the potential for modelling studies to inform adaptation and highlighted the characteristics of any such endeavour and their inter-relatedness. As a result, it is possible to make some broader observations and recommendations on the use of crop and climate modelling in informing adaptation. Using the language of WCRP (2008) and Challinor et al. (2008a), these fall into two categories: quality and value.

Value: increasing the relevance of forecasts through stakeholder engagement

Whilst there are computational limits on the spatial resolution of simulations, resolution should be chosen according to stakeholders needs wherever possible. Similarly, the lead time should be matched to the needs of the stakeholder. Decadal timescales have been identified, through the concept of seamless forecasting (section 2i), as being a gap in the continuum of forecast products (e.g. Troccoli and Palmer, 2007). Such systems may be able to capture the emergent climate change signal (Cox and Stephenson 2007). It is essential that stakeholders are involved from the beginning in the development of decadal forecasting systems, in order to ensure that maximum value is obtained from them. Additionally, value in forecasts across the range of timescales can be increased through targeted efforts to mainstream climate information (section 2iv). These efforts should be informed by a holistic view of food systems, since this will enable the identification of the most climate-sensitive points in the system. This is particularly important given that the combination of stochasticity in climate and in external influences such as prices can make economic value inherently probabilistic (Letson et al., 2005).

In addition to spatial scale and lead time, the value of a crop forecast depends on the crop in question. Crops other than the major staples are highly important for livelihoods across the tropics. Lobell et al. (2008) studied a range of crops, and highlighted, for example, a threat to food security under near-term (2030) climate change posed by groundnut cultivation in South Asia. The complexity and regional variation of cultivation systems such as these means that adaptation strategies should be developed and assessed at the community level. Maximum societal benefit may be achieved by a combination of 'top-down' modelling approaches to adaptation, such as the current study, and 'bottom-up' approaches, such as discussion support (e.g. Hansen, 2005). Perhaps, then, the principal focus of seamless forecasting should not be on seamlessness across timescales, but rather on the links that stretch between the developers (research scientists), the providers (practitioners), and the users. It is through this dialogue, which is underpinned by modelling, that understanding will be fostered and adaptation opportunities will emerge. It can be argued that model complexity and uncertainty, in addition to being relevant to quality (see below) are relevant factors in determining the value of models for policy (Shackley et al., 1998).

Quality: methods to maximise accuracy and reliability

The twin aims of accuracy and reliability determine forecast skill. Accuracy should be maximised, whilst unwarranted precision should be avoided in order to ensure reliability. Section 2v showed that in order to maximise accuracy, impacts models should be carefully calibrated and have an appropriate level of complexity. The requirement of holism makes this even more important, since the complexity of food systems is likely to lead to the inclusion of an increasing number of drivers and processes in food systems models. Efforts to assess the socio-economic aspects of food systems on large spatial scales (e.g. Fraser, 2006; Diffenbaugh et al., 2007) will form a key element of emerging methodologies. Only through such holistic approaches to food systems research can we gain the understanding needed to inform food security policies.

Reliable projections can only be achieved where food system models assess and communicate uncertainty candidly (National Research Council, 2006). Where possible, therefore, a range of models and parameter values should be used. This approach is common in climate change research, where a number of climate models are used (e.g. Randall et al 2007) and where perturbed-parameter simulations are carried out (e.g. Murphy et al., 2004). More diversity, and more attention to robustness, is needed in modelling food systems (section 4). Ensemble approaches should be used where possible, and the full set of climate ensemble members, rather than only a subset, should be used as input to impacts models. In the development of climate model projections, careful attention should be given to the balance between ensemble size, spatial resolution and complexity, since this has serious implications for both quality and value (Challinor et al., 2008a).

In addition to accounting for multiple stresses, food system research should account for multiple outcomes – including the direct and indirect benefits of agroecosystems – and multiple perspectives (section 2iii). In many cropping systems, outcomes include both food and greenhouse gases. Strategies that are optimal for food production will not necessarily be optimal for mitigation; trade-offs exist. One example of holistic food systems research is therefore joint treatment of adaptation and mitigation. Assessment of multiple drivers, processes, and outcomes only becomes possible when researchers with the full range of relevant skills and disciplines communicate and engage with each other. This has clear implications for individual researchers, academic institutions and funding bodies. It also suggests the need to strengthen the coherence of the food systems research community through regular focussed meetings, such as the GECAFS conference where this study was presented.

Acknowledgements

The author is grateful to two anonymous reviewers and to Evan Fraser for providing extremely valuable comments on earlier drafts of this manuscript.

Appendix: calculation of the magnitude and extent of the impact of biophysical stresses

The analysis for figure 3 was carried out using results from Challinor et al. (2007b) [C07] and Challinor and Wheeler (2008b) [CW08]. The second of these studies included the direct impact of elevated CO_2, the first did not. Both of these studies used regional climate model output to simulate the growth and development of groundnut, in the grid cells in India where groundnut was cultivated during the period 1966-1989. For each biophysical process, the number of grid cells where that process resulted in a yield decrease was calculated. This number was then divided by the total number of grid cells (787), to give a percentage. Both studies used the same climate change scenario (SRES A2 2071-2100) and are therefore directly comparable. The A2 scenario results in an approximate doubling of atmospheric CO_2 concentrations by the end of the century (IPCC, 2001).

The calculations of yield decrease were as follows:

1. More frequent temperature extremes: Figure 5 of C07 presents the area affected by heat stress during anthesis for crop varieties with tolerant (9%) and sensitive (20%) genotypic properties. Of the grid cells indicated, only a subset show a decrease in yield (figure 3 of C07); the percentages in figure 3 are based on this subset. Figure 9 of C07 suggests that the magnitude of this effect varies between around 50% reduction in yield for sensitive varieties, and around 5-10% for tolerant varieties. Whilst C07 did not consider the direct impact of elevated CO_2, this process does not interact significantly with heat stress (Vara Prasad et al., 2003), and therefore its inclusion is would be unlikely to affect the results.

2. Mean temperature increases: Through the impact of temperature on crop duration, yield can be reduced by over 50%, even when the direct impact of elevated CO_2 is included (figure 4 of CW08). Figure 5a of

CW08 presents the area affected for a variety with no adaptation to mean temperature change. As this was an ensemble study, there are number of possible metrics for the area affected. The minimum area affected is given by counting the grid cells where all ensemble members show a decrease in yield (58%). A less conservative estimate can be taken by using the grid cells where 70% or more of the ensemble members show a yield decrease (75%). The percentage given in figure 3 is the mean of these two numbers.

In addition to the non-adapted variety, CW08 presented results for simulations where crop durations were held constant between the baseline and scenario climates. In these fixed-duration simulations, the crop has no response to mean temperature change. They therefore represent a form of adaption for those regions affected by a reduction in duration due to mean temperature increase. If the germplasm exists to achieve this zero change in crop duration between the baseline and scenario climates, then the impact of temperature on duration can be mitigated. The change in thermal time requirement, θ, needed to maintain crop duration under climate change can be calculated following Challinor et al. (2008b):

$$\frac{\theta_a}{\theta_c} = \frac{\overline{T}_f - T_b}{\overline{T}_c - T_b} \quad \text{for } \overline{T}_c < T_o \text{ and } \overline{T}_f < T_o$$

where $\overline{T}$ is mean seasonal temperature, subscript *f* refers to the future climate, subscript *c* refers to current (baseline) climate/crop, subscript *a* refers to the adapted crop, and T_b is the base temperature for development. T_o is the optimum temperature for development, which is in the range 28-37 ^{o}C. Mean temperatures over the period of simulated crop growth in the baseline simulations of C07 and CW08 vary geographically between 20 and 32.5 ^{o}C (though they are less than 27.5 ^{o}C for most of India). In the climate change scenario, temperatures increase by between 2 and 6 ^{o}C (3-4 ^{o}C for most of India; see figure 1 of CW08). Increases in temperature beyond 4 ^{o}C were only seen in regions where the baseline temperature exceeded 27.5 ^{o}C. Representative maximum values of θ_a / θ_c can therefore be found by taking T_o in the centre of the observed range (32.5 ^{o}C) with T_b = 10 ^{o}C (Challinor et al., 2004) and using (i) $\overline{T}_c$ =20 ^{o}C , $\overline{T}_f$ =24 ^{o}C and (ii) $\overline{T}_c$ =26.5 ^{o}C , $\overline{T}_f$ =32.5 ^{o}C. These two pairs of mean temperatures give θ_a / θ_c in the range 1.36 to 1.40 – i.e. an increase in thermal time requirement between the baseline and scenario climates of 36-40%. A simple analysis suggests that the maximum value of θ_a / θ_c found in current germplasm is between 14 and 40% (Challinor et al., 2008b). Thus it is possible that across all regions of India where crop durations fall under climate change, they can be maintained equal to the baseline values by using an appropriately–chosen variety (i.e. one that is adapted to local changes in mean temperature). However, it is also possible that this adaptive capacity is not contained within existing germplasm. A more precise measure of θ_a / θ_c in current germplasm is required if the capacity to adapt to mean temperature increases is to be quantified.

3. Reduced humidity: In C07 and CW08, mean vapour pressure deficit (VPD) during simulated crop growth (for the fixed-duration crop) increased in all locations under climate change. This process therefore affects all groundnut growing areas. Based on two representative regions, reductions in yield due to this process are approximately 20-25% (figure 3 CW08). In order to compensate for this, a similar increase in transpiration efficiency would be needed (see equation 6 of Challinor et al., 2004). This is comfortably with the range of measured values in the current climate (e.g. Challinor et al., 2004), and it is of the order of the increase expected to occur naturally under elevated CO_2 (e.g. Challinor et al., 2005b). Therefore, no area is affected by this process when an appropriate existing crop variety is used.

4. Increased water stress: 14% of grid cells show a decrease in mean growing-season rainfall (figure 1a of CW08). However, for the fixed-duration crop, at least 45% of these grid cells show an increase in yield (figure 6a of CW08). Changes in rainfall therefore adversely affect a maximum of 7.7% of all grid cells. The magnitude of this effect can be considerable: figure 6a of CW08 shows that for the fixed-duration crop, reductions of up to 50% in yield occur in water-stressed regions. However, approximately half of this is likely to be due to changes in humidity (see above). The impact of water stress is therefore estimated as a 25% reduction in yield.

5. All processes: all the grid cells are affected by at least one process under climate change, and the effect can be as large as, or greater than, the impact of any single process. The all-processes non-adapted bar in figure 3 is therefore 100%. The adapted bar is more difficult to calculate, since the appropriate genotypic adaptation varies geographically, as the relative importance of the biophysical processes varies. One estimate was obtained by making the plausible assumption that θ_a / θ_c is as large as 40% (see 2 above): first, the number of grid cells in figures 5a and 5b of CW08 where both the non-adapted crop and the fixed-duration crop show a reduction in yield was estimated. Two values of this number were calculated, using 100% and 70% thresholds for ensemble members (see 2, above). This gave a range of 9-20% of grid cells that are affected (i.e. yield is reduced) by the combination of all climate change processes, with or without adaptation to mean temperature change. All of the affected grid cells are in regions where crop growth is subject to significant water stress (though not necessarily increases in water stress between the two climates). The adapted crop represents a minimum of adaptation, since adaptation to water stress was not considered, and since the altered response to mean temperature could also, in theory at least, be combined with heat-stress tolerance (see 1, above) and increased transpiration efficiency (see 3, above). It is likely that such combination would reduce both the area affected and the magnitude of the climate change signal.

Whist some of the assumptions above imply that 9-20% is an upper estimate of the area affected under climate change, the assumption of θ_a / θ_c =40% may be rather optimistic, since the lower estimated value in the germplasm is 14% (see 2 above). Figure 3 of Challinor et al. (2008b) suggests that this lower value is likely to show some degree of adaptive capacity. However, in the absence of a dedicated study to quantify this adaptive capacity, a second estimate for the adapted crop was based on the assumption that: (i) θ_a / θ_c =14% is insufficient for adaptation to mean temperature changes anywhere in India; (ii) the effect of shorter crop duration on yield is not mitigated by any other process. This second estimate results in 66.5% of area affected with an adapted crop. This value is used in figure 3, since it far exceeds the first estimate.

Figure captions

Figure 1. Observed and simulated crop yield for a grid cell in Gujarat, India, taken from the study of Challinor et al. (2004). The crop model simulations, performed using GLAM, were driven by observed gridded weather data.

Figure 2. The relationship between quantitative, accurate, precision and relevance to adaptation decisions. For a given change in carbon dioxide emissions, there is a resultant and uncertain change in climate, which results in increasingly uncertain impacts on crop yield and in food systems. Feedbacks between each of the systems also contribute to uncertainty. Non-climatic drivers of food systems, which become increasingly important as relevance increases, are not shown.

Figure 3. Percentage of the total area under groundnut cultivation (using the climate model grid) where crop yield is projected to fall under climate change (SRES A2 scenario, 2071-2100; an approximate doubling of CO_2). For three of the four processes considered, an adapted crop is shown in addition to the non-adapted crop. Dotted lines denote that the estimate is an upper limit on the area affected; solid lines denote estimates near the centre of the uncertainty range. The magnitude of estimated crop yield reductions varies from severe (over 50%, dark grey shading) to mild (less than 10%, white shading); intermediate severity (20-30%) is shown with light grey shading. No shading indicates that an estimate of magnitude was not possible. Supporting calculations are presented in the appendix.

Figures

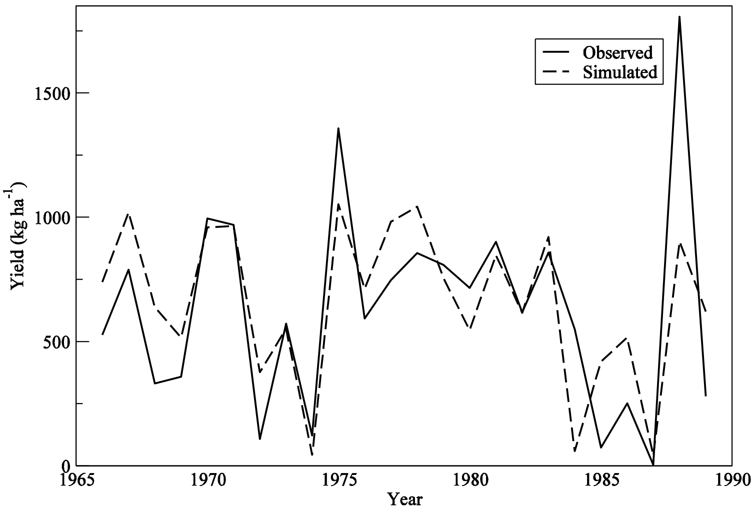

Figure 1. Observed and simulated crop yield for a grid cell in Gujarat, India, taken from the study of Challinor et al. (2004). The crop model simulations, performed using GLAM, were driven by observed gridded weather data.

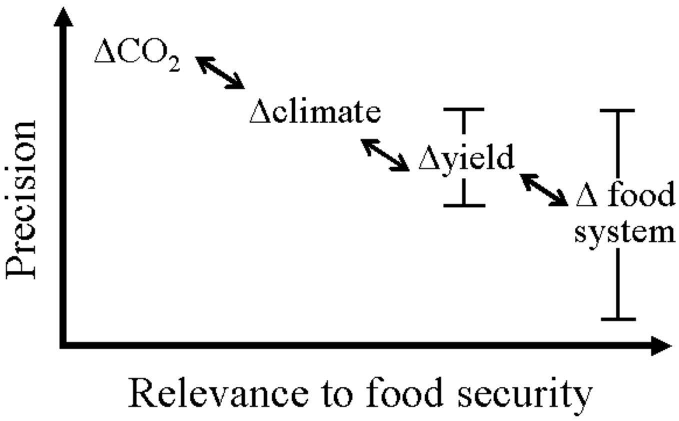

Figure 2. The relationship between quantitative accuracy and relevance to adaptation decisions. For a given change in carbon dioxide emissions, there is a resultant and uncertain change in climate, which results in increasingly uncertain impacts on crop yield and in food systems. Feedbacks between each of the systems also contribute to uncertainty. Non-climatic drivers of food systems, which become increasingly important as relevance increases, are not shown.

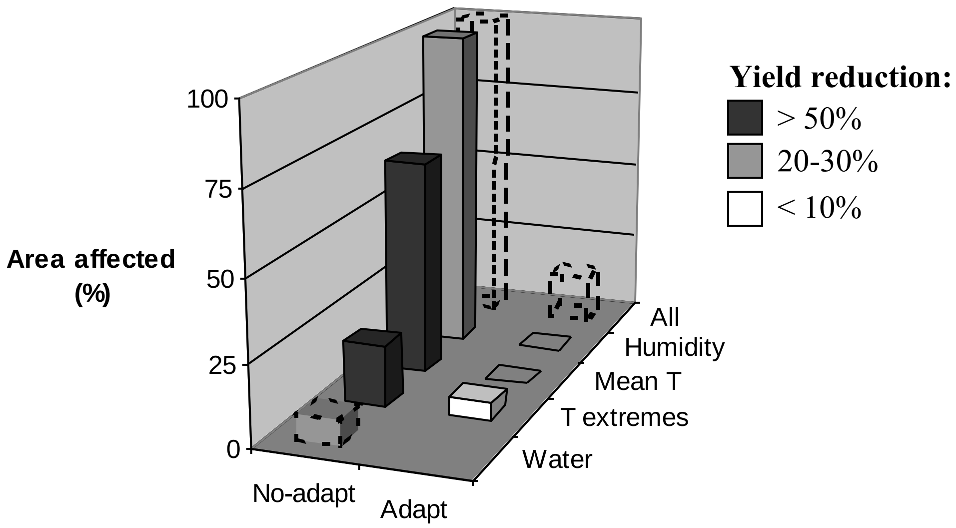

Figure 3. Percentage of the total area under groundnut cultivation (using the climate model grid) where crop yield is projected to fall under climate change (SRES A2 scenario, 2071-2100; an approximate doubling of CO_2). For three of the four processes considered, an adapted crop is shown in addition to the non-adapted crop. Dotted lines denote that the estimate is an upper limit on the area affected; solid lines denote estimates near the centre of the uncertainty range. The magnitude of estimated crop yield reductions varies from severe (over 50%, dark grey shading) to mild (less than 10%, white shading); intermediate severity (20-30%) is shown with light grey shading. No shading indicates that an estimate of magnitude was not possible. Supporting calculations are presented in the appendix.

References

Adger, W. N., N. W. Arnell and Emma L. Tompkins (2005). Successful adaptation to climate change across scales. Global Environmental Change 15, 77-86.

Broad, K. and Agrawala, S., 2000. The Ethiopia food crisis: uses and limits of climate forecasts. Science, 289(September 8, 2000): 1693-1694.

Balmford, A., R. E. Green and J. P. W. Scharlemann (2005). Sparing land for nature: exploring the potential impact of changes in agricultural yield on the area needed for crop production. Global Change Biology 11, 1594-1605.

Baron, C., B. Sultan, M. Balme, B. Sarr, S. Teaore, T. Lebel, S. Janicot, and M. Dingkuh (2005). From GCM grid cell to agricultural plot: scale issues affecting modeling of climate impacts. Phil. Trans. Roy. Soc. B 1463 (360), 2095-2108.

Bharwani, S., Bithell, M., Downing, T. E., New, M., Washington, R. & Ziervogel, G. 2005 Multi-agent modelling of climate outlooks and food security on a community garden scheme in Limpopo, South Africa. Phil. Trans. R. Soc. B 360, 2183–2194. (doi:10.1098/rstb. 2005.1742.)

Brown, K., E. Tompkins and W. N. Adger (2001). Trade-off Analysis for Participatory Coastal Zone Decision-Making. Publications Office, Overseas Development Group,
University of East Anglia, Norwich, NR4 7TJ, U.K. ISBN 1 873933 16 9

Challinor, A. J., T. Osborne, A. Morse, L. Shaffrey, T. Wheeler, H. Weller (2008a). Methods, skills and resources for climate impacts research. Bulletin of the American Meteorological Society, submitted.

Challinor, A. J., T. R. Wheeler, D. Hemming and H. D. Upadhyaya (2008b). Crop yield simulations using a perturbed crop and climate parameter ensemble: sensitivity to temperature and potential for genotypic adaptation to climate change. Climate Research (submitted).

Challinor, A. J., T. R. Wheeler, C. Garforth, P. Craufurd and A. Kassam, 2007a. Assessing the vulnerability of food crop systems in Africa to climate change. Climatic Change, 83 381-399.

Challinor, A. J., T. R. Wheeler, P. Q. Craufurd, C. A. T. Ferro and D. B. Stephenson (2007b). Adaptation of crops to climate change through genotypic responses to mean and extreme temperatures. Agriculture, Ecosystems and Environment, 119 (1-2) 190-204.

Challinor, A. J. and T. R. Wheeler (2008a). Using a crop model ensemble to quantify CO2 stimulation of water-stressed and well-watered groundnut. Agricultural and Forest Meteorology, In press.

Challinor, A. J. and T. R. Wheeler (2008b). Crop yield reduction in the tropics under climate change: processes and uncertainties. Agric. For. Meteorol, 148 3433-356.

Challinor, A. J., T. R. Wheeler, T. M. Osborne and J. M. Slingo (2006). Assessing the vulnerability of crop productivity to climate change thresholds using an integrated crop-climate model. In: Avoiding Dangerous Climate Change. Schellnhuber, J., W. Cramer, N. Nakicenovic, G. Yohe and T. M. L. Wigley (Eds). Cambridge University Press. Pgs 187-194.

Challinor, A. J., T. R. Wheeler, J. M. Slingo, P. Q. Craufurd and D. I. F. Grimes (2005a). Simulation of crop yields using the ERA40 re-analysis: limits to skill and non-stationarity in weather-yield relationships. Journal of Applied Meteorology 44 (4) 516-531.

Challinor, A. J., T. R. Wheeler, J. M. Slingo and D. Hemming, 2005b. Quantification of physical and biological uncertainty in the simulation of the yield of a tropical crop using present day and doubled CO2 climates. Phil. Trans. Roy. Soc. B. 360 (1463) 1981-2194.

Challinor, A. J., J. M. Slingo, T. R. Wheeler and F. J. Doblas-Reyes (2005c). Probabilistic hindcasts of crop yield over western India. Tellus 57A 498-512.

Challinor, A. J., T. R. Wheeler, P. Q. Craufurd, and J. M. Slingo, 2005d. Simulation of the impact of high temperature stress on annual crop yields. Agric. For. Meteorol, 135 (1-4) 180-189.

Challinor, A. J., T. R. Wheeler, J. M. Slingo, P. Q. Craufurd and D. I. F. Grimes (2004). Design and optimisation of a large-area process-based model for annual crops. Agricultural and Forest Meteorology, 124, (1-2) 99-120.

Chee-Kiat, T. (2006) Application of satellite-based rainfall estimates to crop yield forecasting in Africa. PhD thesis, University of Reading, 233pp.

Cox, P. and D. Stephenson (2007). A changing climate for prediction. Science 317, 207-208.

Cox, G. M., J. M. Gibbons, A. T. A. Wood, J. Craigon, S. J. Ramsden, and N. M. J. Crout (2006). Towards the systematic simplification of mechanistic models. Ecological Modeling 198 (1-2): 240-246.

Díaz Nieto, J., S. Cook, M. Lundy, M. Fischer, D. Sanchez and E. Guevara (2006). A system of drought insurance for poverty alleviation in rural areas. Available at http://www.ciat.cgiar.org/news/pdf/drought_insurance_report.pdf

Diffenbaugh, N., F. Giorgi, L. Raymond and X. Bi (2007). Indicators of 21st century socioclimatic exposure. Proceedings of the National Acadamy of Sciences 104 (51) 20195-20198.

ERFARM (2008). Extended range forecasts for agricultural risk management: planning session for risk management components. Unpublished proceedings of the ERFARM meeting, 18-21st December, 2007.

Erkineh, T., 2007. Food security in Ethiopia. In: M. Hellmuth, A. Moorhead, M.C. Thomson and J. Williams (Editors), Climate risk management in Africa: learning from practice. International Research Institute for Climate and Society (IRI), Columbia University, New York, pp. 31-44.

Ferreyra, A. et al., 2001. A linked-modeling framework to estimate maize production risk associated with ENSO-related climate variability in Argentina. Agricultural and Forest Meteorology, 107: 177-192.

Financial Times (2008). “High food prices may force aid rationing.” Available at http://www.ft.com/cms/s/0/451604c4-e30b-11dc-803f-0000779fd2ac.html?nclick_check=1

Fraser, E.D.G. (2007) Travelling in antique lands: using past famines to develop an adaptability/resilience framework to identify food systems vulnerable to climate change, Climatic Change, 83, pp.495-514.

Fraser, E.D.G. (2006). “Agro-ecosystem vulnerability. Using past famines to help understand adaptation to future problems in today’s global agri-food system.” Journal Ecological Complexity. 3: 328-335.

Fraser, E. D. G. (2004). “Land tenure and sustainable agriculture: soil conservation on rented and owned fields in Southwest British Columbia.” *Agriculture and Human Values.* 21: 73-79.

Gepts, G. (2006). Plant genetic resources conservation and utilization: the accomplishments and future of a societal insurance policy. Crop Science 26, 2278-2292.

Gadgil S., Rao P. R. S., Rao K. N. (2002). Use of climate information for farm-level decision making: rainfed groundnut in southern India. Agricultural Systems 74 (3): 431-457 Dec.

Gregory, P. J., Ingram, J. S. I. & Brklacich, M. (2005). Climate change and food security. Phil. Trans. R. Soc. B 360, 2139–2148. (doi:10.1098/rstb.2005.1745.)

Haile, M. (2005). Weather patterns, food security and humanitarian response in sub-Saharan Africa. Phil. Trans. R. Soc. B 360, 2169–2182. (doi:10.1098/rstb.2005.1746.)

Hansen, J. W. 2005. Integrating seasonal climate prediction and agricultural models for insights into agricultural practice. Phil. Trans. R. Soc. B 360, 2037–2047. (doi:10.1098/rstb.2005.1747.

Hansen, J. W. and J. W. Jones 2000. Scaling-up crop models for climatic variability applications. Agric. Syst. 65, 43-72.

Hellmuth, M., Moorhead, A., Thomson, M.C. and Williams, J. (Editors), 2007. Climate risk management in Africa: learning from practice. Climate and Society Publication Series. International Research Institute for Climate and Society (IRI), Columbia University, New York.

Howden, S. M., J.-F. Soussana, F. N. Tubiello, N. Chhetri, M. Dunlop and H. Meinke (2007). Adapting agriculture to climate change. Proceedings of the National Academy of Sciences 104 (50) 19691-19696.

Huntingford, C., Lambert, F. H., Gash, J. H. C., Taylor, C. M. & Challinor, A. J. (2005). Aspects of climate change prediction relevant to crop productivity. Phil. Trans. R. Soc. B 360, 1999–2009. (doi:10.1098/rstb.2005.1748.)

IAASTD (2008). Synthesis report of the International Assessment of Agricultural Knowledge, Science and Technology for Development. Available at http://www.agassessment.org/

Iglesias, A., C. Rosenzweig, and D. Pereira (2000). Agricultural impacts of climate change in Spain: developing tools for a spatial analysis. Global Environmental Change 10 (1), 69-80.

IPCC (2001). Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. 881 pp.

IRI, 2006. A gap analysis for the implementation of the global climate observing system in Africa. IRI Technical Report Number IRI-TR/06/01, International Research Institute for Climate and Society, New York.

Johnston, P., Ziervogel, G. and Matthew, M., 2007. The uptake and usefulness of weather and climate forecast information among water resource mangers in the SW Cape region of South Africa, Applied Geography Conference, Indianapolis, Indiana.

Jones, D. and E. M. Barnes, 2000. Fuzzy composite programming to combine remote sensing and crop models for decision support in precision crop management. Agric. Syst. 65 (3), 137-158.

Lobell, D. B., M. B. Burke, C. Tebaldi, M. D. Mastrandrea, W. P. Falcon, R. L. Naylor (2008). Prioritizing Climate Change Adaptation Needs for Food Security in 2030. Science 319 (5863), 607 – 610.

Marletto, V., F. Ventura, G. Fontana and F. Tomei, 2007. Wheat growth simulation and yield prediction with seasonal forecasts and a numerical model. Agric. For. Met. 147 71-79

Meinke, H., R. Nelson, P. Kokic, R. Stone, R. Selvaraju and W. Beathgen, 2006. Actionable climate knowledge: from analysis to synthesis. Climate Research 33, 101-110.

Meinke, H. et al., 2001. Increasing profits and reducing risks in crop production using participatory systems simulation approaches. Agricultural Systems, 70: 493-513.

Morton, J. F (2007). The impact of climate change on smallholder and subsistence agriculture. Proceedings of the National Academy of Sciences (2007) 104 (50) 19680-19685.

Murphy, J. M., Sexton, D. M. H., Barnett, D. N., Jones, G. S., Webb, M. J., Collins, M. & Stainforth, D. A. 2004 Quantification of modelling uncertainties in a large ensemble of climate change simulations. Nature 430, 768–772.

National Research Council (2006). Completing the forecast: characterizing and communicating uncertainty for better decisions using weather and climate forecasts. The National Academies Press, Washington.

New Statesman (2008). “How the rich starved the world.” Available at http://www.newstatesman.com/200804170025

Orlove, B. and Tosteson, J., 1999. The application of seasonal to interannual climate forecasts based on El Niño - Southern Oscillation (ENSO) events: lessons from Australia, Brazil, Ethiopia, Peru, and Zimbabwe. Berkley workshop on environmental politics, Working Paper 99-3, Institute of International Studies, University of California, Berkeley. Available at http://globetrotter.berkeley.edu/EnvirPol/pubs.html

Osborne, T. M., D. M. Lawrence, A. J. Challinor, J. M. Slingo, T. R. Wheeler (2007). Development and assessment of a coupled crop-climate model. Global Change Biology 13 169-183.

Parry, M. L., C. Rosenzweig, A. Iglesias, M. Livermore, and G. Fischer (2004). Effects of climate change on global food production under RSES emissions and socio-economic scenarios. Global Environmental Change - Human and Policy Dimensions 14 (1), 53-67.

Patt, A. (2007). Assessing model-based and conflict-based uncertainty. Global Environmental Change 17, 37-46.

Patt, A.G., Ogallo, L. and Hellmuth, M., 2007. Learning from 10 years of Climate Outlook Forums in Africa. Science, 318: 49 - 50.

Patt, A.G., Suarez, P. and Gwata, C., 2005. Effects of seasonal climate forecasts and participatory workshops among subsistence farmers in Zimbabwe. Proceedings of the National Academy of Sciences of the United States of America, 102: 12623-12628.

Patt, A. and C. Gwata (2002). Effective seasonal climate forecast applications: examining constraints for subsistence farmers in zimbabwe. Global Environmental Change: Human and Policy Dimensions 12, 185-195.

Phillips, J., 2003. Determinants of forecast use among communal farmers in Zimbabwe. In: K. O'Brien and C. Vogel (Editors), Coping with climate variability: the use of seasonal climate forecasts in southern Africa. Ashgate, Aldershot, UK, pp. 110-128.

Robinson (2007). Being undisciplined: Transgressions and intersections in academia and beyond. Futures 40 (70-86).

Randall, D.A., R.A. Wood, S. Bony, R. Colman, T. Fichefet, J. Fyfe, V. Kattsov, A. Pitman, J. Shukla, J. Srinivasan, R.J. Stouffer, A. Sumi and K.E. Taylor, 2007: Climate Models and Their Evaluation. In: Climate Change 2007: The Physcial Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Righelato, R.; Spracklen D.V. (2007) Carbon mitigation by biofuels or by saving and restoring forests?, Science, 317, pp.902-902.

Rijks, D., F. Rembold, T. Negre, R. Gommes and M. Cherlet, Eds (2003). Crop and rangeland monitoring in Eastern Africa for Early Warning and Food Security (Proceedings of an international workshop organised by JRC-FAO, Nairobi, 28th - 30th January 2003). Available at http://cram-forum.jrc.it/Nairobi%20Workshop%202003/Forms/AllItems.aspx

Rougier, J. & Sexton, D.S. 2007 Inference in ensemble experiments. Phil. Trans. R. Soc. A 365, 2133–2143, (doi:10.1098/rsta.2007.2071).

Sinclair, T. R. and N. Seligman 2000. Criteria for publishing papers on crop modelling. Field Crops Research 68, 165-172.

Schmidhuber, J. and F. N. Tubiello (2007). Global food security under climate change. Proceedings of the National Academy of Sciences 104 (50) 19703-19708.

Shackley, S., P. Young, S. Parkinson and B. Wynne (1998). Uncertainty, complexity and concepts of good science in climate change modelling: are GCMs the best tools? Climatic Change 38, 159-205.

Southworth, J., R. A. Pfeifer, M. Habeck, J. C. Randolph, O. C. Doering, and D. G. Rao (2002). Sensitivity of winter wheat yields in the midwestern United States to future changes in climate, climate variability, and co2 fertilization. Climate Research 22 (1), 73-86.

Stainforth, D. A., T. E. Downing, R. Washington, A. Lopez and M. New, 2007. Issues in the interpretation of climate model ensembles to inform decisions. Phil. Trans. Roy. Soc. A 365 (1857) 2163-2178.

Stone, R. C. & Meinke, H. (2005). Operational seasonal forecasting of crop performance. Phil. Trans. R. Soc. B 360, 2109–2124. (doi:10.1098/rstb.2005.1753.)

Troccoli, A. & Palmer, T.N. 2007 Ensemble decadal prediction from analysed initial conditions. Phil. Trans. R. Soc. A 365, 2179–2191, (doi:10.1098/rsta.2007.2079).

Tubiello, F. N., J.-F. Soussana and S. Mark Howden (2007). Crop and pasture response to climate change. Proceedings of the National Academy of Sciences 104 (50) 19686-19690.

Vara Prasad, P. V., K. J. Boote, L. Hartwell Allen Jr., and J. M. G. Thomas (2003). Super-optimal temperatures are detrimental to peanut (Arachis hypogaea l.) reproductive processes and yield at both ambient and elevated carbon dioxide. Global Change Biology 9, 1775-1787.

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

Verdin, J., Funk, C., Senay, G. & Choularton, R. (2005). Climate science and famine early warning. Phil. Trans. R. Soc. B 360, 2155–2168. (doi:10.1098/rstb.2005.1754.)

WCRP (2008). World Climate Research Programme position paper on seasonal prediction. Available online at http://www.clivar.org/organization/wgsip/spw/spw_position.php