

REVIEW PAPER

Crops and climate change: progress, trends, and challenges in simulating impacts and informing adaptation

Andrew J. Challinor^{1,*}, Frank Ewert², Steve Arnold¹, Elisabeth Simelton³ and Evan Fraser³

¹ Institute for Climate and Atmospheric Science, School of Earth and Environment, University of Leeds, Leeds LS2 9JT, UK

² Institute of Crop Science and Resource Conservation, University of Bonn, Germany

³ Sustainability Research Institute, School of Earth and Environment, University of Leeds, Leeds LS2 9JT, UK

Received 16 December 2008; Revised 12 February 2009; Accepted 16 February 2009

Abstract

Assessments of the relationships between crop productivity and climate change rely upon a combination of modelling and measurement. As part of this review, this relationship is discussed in the context of crop and climate simulation. Methods for linking these two types of models are reviewed, with a primary focus on large-area crop modelling techniques. Recent progress in simulating the impacts of climate change on crops is presented, and the application of these methods to the exploration of adaptation options is discussed. Specific advances include ensemble simulations and improved understanding of biophysical processes. Finally, the challenges associated with impacts and adaptation research are discussed. It is argued that the generation of knowledge for policy and adaptation should be based not only on syntheses of published studies, but also on a more synergistic and holistic research framework that includes: (i) reliable quantification of uncertainty; (ii) techniques for combining diverse modelling approaches and observations that focus on fundamental processes; and (iii) judicious choice and calibration of models, including simulation at appropriate levels of complexity that accounts for the principal drivers of crop productivity, which may well include both biophysical and socio-economic factors. It is argued that such a framework will lead to reliable methods for linking simulation to real-world adaptation options, thus making practical use of the huge global effort to understand and predict climate change.

Key words: Adaptation, climate change, crops, model integration, modelling frameworks, uncertainty.

Introduction

Crops exhibit known observed responses to weather and climate that can have a large impact on crop yield (e.g. Porter and Semenov, 2005). Since atmospheric concentrations of greenhouse gases continue to rise at rates that are both unprecedented (Siegenthaler *et al.*, 2005; Spahni *et al.*, 2005) and alarming (Anderson and Bows, 2008), efforts have been made to understand the implications for crop production. These efforts are primarily based on climate models, which use spatial grids with resolutions typically of the order of a hundred kilometres. Such simplification of the spatial heterogeneity of processes has direct implications for the assessment of the impacts of climate change. Some of these assessments are performed at the regional scale (referring here to from tens to a couple of hundred

kilometres—commensurate with climate model grids). In contrast, location-specific methods have also been developed, to account for the variety of climatic and non-climatic stresses on crop productivity often not observable at aggregated spatial scales. It is at this smaller field scale that crop models were originally designed to operate (for reviews, see, for example, Sinclair and Seligman, 1996; van Ittersum *et al.*, 2003), resulting in applications in decision support (Boote and Jones, 1998) and ‘discussion support’ (Hansen, 2005).

This review examines the use of crop and climate models in climate change research. As with the bulk of the literature, it focuses primarily on crop yield, which has the greatest impact on food security. By their nature, regional-scale

* To whom correspondence should be addressed. E-mail: a.j.challinor@leeds.ac.uk

assessments lend themselves more clearly to generalization than do local-scale assessments; hence the focus here is primarily, though not exclusively, on larger scales. The methods used to link crop and climate models are examined, including the implications of the disparity in spatial scale between these two types of model. Recent progress in modelling methods and in our resultant understanding of the impacts of climate change is reviewed. Questions are asked regarding how we can generate useful information on impacts and adaptation with the methods reviewed. Finally, future trends and challenges are identified, leading to concluding comments and recommendations.

Linking crop and climate models

Overview

Simulation models act as a surrogate laboratory. They are a particularly important tool for understanding climate change and its impacts, since only one physical realization of climate is possible, thus limiting the amount of observed data available for comparison with model output. (This is in contrast to the forecasting of weather, which can be tested repeatedly against observations.) A number of different methods can be used to link crop and climate models. Figure 1 summarizes the methods discussed herein (a more detailed review is presented by Hansen *et al.*, 2006). The box labelled ‘climate model’ represents a range of models, from short-term local-scale numerical weather prediction to longer term simulations of climate change. These models are based on the same fundamental physics, and efforts are underway to carry out and present weather and climate simulation as part of a ‘seamless’ continuum, such that the commonality of methods across weather and climate prediction is strengthened and made more clear to users (see, for example, Challinor *et al.*, 2009b). For this reason, all

model-derived climate and weather information is represented in this simple fashion.

Climate model output can be used with crop models either directly (Mavromatis and Jones, 1999; Challinor *et al.*, 2005a, b, c) or via some post-processing. In the latter case, a weather generator (Semenov and Barrow, 1997) may be used, and/or the change in climate simulated using a model can be applied to observed climate (Zalud and Dubrovsky, 2002 compare the two methods; Southworth *et al.*, 2002 use both methods). Results when using processed output are sensitive to the underlying assumptions (Mearns *et al.*, 1997; Mavromatis and Jones, 1998). Unprocessed climate model output has the advantage of being a consistent representation of climate, thus avoiding the need for such assumptions. The corresponding disadvantage is that any errors in the climate model may have implications for the simulation of crop growth. For example, climate models tend to overestimate the number of rainy days whilst underestimating amounts of rainfall (i.e. ‘drizzle’), and may also fail to represent the observed month-to-month variation in rainfall; some of these biases are easier to correct than others, and this can affect crop simulation (Challinor *et al.*, 2005a). However, model error may not be overly problematic: Challinor *et al.* (2005c) found predictability in crop yields using climate model output both with and without correction of bias in the simulation of mean climate.

As well as dealing with climate model error, post-processing can deal with the disparity in spatial scale between climate and crop models (see, for example, Hansen and Jones, 2000; Challinor *et al.*, 2003, 2004). The former uses a grid that is coarse relative to the spatial scale at which field-scale crop models typically operate. The disparity can either be ignored (Trnka *et al.*, 2004) or it can be dealt with by downscaling climate model output (Wilby and Wigley, 1997; Kidson and Thompson, 1998; Wilby *et al.*, 1998). With or without downscaling, it is clear (Moen *et al.*, 1994; Faivre *et al.*, 2004) that regional prediction using crop and climate models cannot rely solely on methods developed as part of the longer standing tradition of crop simulation at the field scale. Whilst the results of field-scale models can be compared directly with regional-scale yields (Yun, 2003; Nain *et al.*, 2004; Xiong *et al.*, 2007), it can be argued that this requires design or selection of crop models that have a low input data requirement (Priya and Shibasaki, 2001; de Wit *et al.*, 2005). An alternative is to take a field-scale crop model and make it applicable to the regional scale through one or more procedures, such as calibration (Chipanshi *et al.*, 1999; Jagtap and Jones, 2002), aggregation of inputs (Haskett *et al.* 1995), and aggregation of outputs from multiple subgrid simulations. This latter method can use either simulations sampled by varying model inputs such as planting date and crop variety (Jagtap and Jones, 2002; Irmak *et al.*, 2005) or else simulations explicitly carried out at the subgrid scale (Thornton *et al.*, 1996).

Estimates of yields at the regional scale can also be made by designing a crop model that operates on that scale. Such

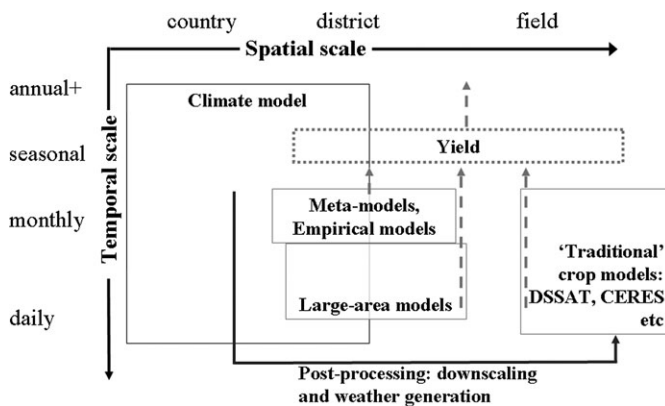


Fig. 1. Schematic representation of methods used to combine crop and climate models. Solid arrows show climate information; dashed arrows and lightly shaded boxes show crop growth simulation. Solid boxes show numerical models; boxes with dotted outlines show model output. Areas where boxes overlap indicate models that operate on commensurate spatial and temporal scales.

a model may be empirical, with weather variables used within a statistical regression of output from a field-scale crop model (Iglesias *et al.*, 2000) or of observed yield data (Lobell *et al.*, 2008). The use of regressions of field-scale crop models can introduce significant errors through the linearization of the equations for crop yield and/or an inability to account for subseasonal climate variability (Challinor *et al.*, 2006). More generally, the validity of empirical methods under climate change is limited by the necessity of using data outside the range for which the models were fitted. Also, statistical models have no explanatory power to enable understanding as to why certain changes have occurred. This is one reason why process-based regional-scale (or large-area) methods have been developed.

Large-area crop modelling

Large-area crop modelling resulted mainly from the need to simulate the impacts of climate variability and change on crops in a process-based fashion using the output from climate models directly (i.e. without any downscaling). The rationale for such techniques (Challinor *et al.*, 2004) lies in the combination of the benefits of empirical approaches (low input data requirement; validity over large spatial scales, thus avoiding site specificity) with those of field-scale process-based models (validity under a range of environments, including climate change). The development of meta-models, based on existing simulation models, takes a similar approach, but for simulation at the field scale (Brooks *et al.*, 2001). The focus here is on larger scales, at which the modelling methodology is based upon a number of principles.

(i) *A basis in observed relationships.* Where a response to climate variability exists in observations, the possibility of simulating that response also exists. Challinor *et al.* (2003) examined observed relationships between yield and climate in India at a number of spatial scales, and concluded that large-area modelling (i.e. using the same grid as climate models) of that response was possible. Such empirical studies are prone to the risk of confounding causality (Bakker *et al.*, 2005); this is the reason that subsequent modelling should be based both on physiological processes and at an appropriate level of complexity. The limited length of historical records means that studies of observed relationships have focused principally on year-to-year variability (e.g. Challinor *et al.*, 2003; Kumar *et al.*, 2004). However, climate change implies longer term relationships, and these are beginning to be explored (see Lobell and Field, 2007).

(ii) *Appropriate complexity.* The crop modelling community has long been aware of the dangers associated with modelling at a level of complexity unwarranted by the degree of uncertainty and potential error associated with the parameterizations used (Monteith, 1996). The greater the number of processes simulated, the greater the number of potential interactions between them and the number of

parameters that require calibration, thereby increasing the potential for error. Sinclair and Seligman (2000) discuss this issue using the concept of hierarchical levels of biological organization, from molecules to ecosystems. They argue that it is rarely justified for a crop model to simulate processes more than one hierarchical level below the level of immediate interest, because of the 'burgeoning complexity inherent in increasing the number of lower hierarchical levels'. Therefore, if yield is the variable of interest, then only the mechanisms near to the yield-determining processes should be simulated. This approach reduces the risk of overtuning a model to one environment (i.e. confounding causality), which can result in a lack of applicability in other environments. The spatial scale and complexity of a model are related, as discussed by Challinor and Wheeler (2008b) and Tubiello and Ewert (2002).

(iii) *High fraction of observable parameters.* In order to avoid overtuning, parameters should, where possible, be based on observations. This means that the parameterizations used are directly testable. Empirically determined parameters can be based entirely on processes (Challinor *et al.*, 2004), or else a semi-empirical approach can be used, for example with a process-based plant water stress index being empirically related to yield (Potgeiter *et al.*, 2005). Care should be taken not to use parameters observed for the current climate in situations where their value may have changed, as occurs for some processes under climate change. For current climates, discrepancies between the yield simulated by process-based models and observed regional yields can be minimized through a process-based yield gap parameter (Challinor *et al.*, 2004) or an explicit error metric (Casellas *et al.*, 2009). The choice of calibration method and the level of model complexity have implications for the reliability of model simulations (see later).

The principles above result in large area-crop models differing substantially from field-scale crop models. Large-area models tend to be less complex and have fewer parameters, and fewer non-observable parameters in particular. For example, the model of Challinor *et al.* (2004) simulates leaf area growth by using a parameter specifying the maximum rate of change of leaf area index, rather than simulating the appearance of individual leaves. The model uses transpiration efficiency, another observable parameter, to simulate the accumulation of biomass, rather than employing leaf-level assimilation equations, as most field-scale models do. Such an approach is appropriate in water-limited environments; a parallel approach in the UK might employ radiation-use efficiency.

As with any model, large-area crop models should be used judiciously. By design, they have the advantage of being both process based and applicable over large areas. However, their focus on the influence of weather and climate, and their basis in observed relationships, means that large-area crop models do not currently simulate the non-climatic determinants of crop yield. These non-climatic stresses contribute to the yield gap, which is the difference between the potential yield for a current crop variety (i.e.

under the given climate and for optimal agronomic practices) and the corresponding observed farm yields (see, for example, Herdt and Mandac, 1981; van Ittersum *et al.*, 2003). These observed (farm and regional) yields include the effects of weeds, pests and diseases, and air pollutants such as tropospheric ozone. Where variability in yield is driven by these factors, rather than climate, or where there is high subgrid spatial variability in weather (see Baron *et al.* 2005), the rationale for large-area modelling may be undermined. However, the significance of the climate signal tends to be greatest at regional scales (Challinor *et al.*, 2003; Bakker *et al.*, 2005). Thus, the proven ability to simulate current yields (Challinor *et al.*, 2004), together with assessment of skill under likely climate change conditions (Challinor *et al.*, 2005d), has built confidence in the use of large-area models as part of efforts to simulate the response of crops to climate change.

Progress in modelling and understanding the impact of climate change on crops

Ensemble modelling

Under climate change, inherent uncertainties in the predictability of climate limit the precision with which impacts can be assessed. Furthermore, the response of crops to elevated carbon dioxide is not known with precision at field and larger scales (Ewert *et al.*, 2002; Tubiello and Ewert, 2002). Quantification of uncertainty is therefore an important endeavour in climate impacts research (see, for example, Challinor *et al.*, 2009b). Estimates of ranges of yield impacts vary across studies (see, for example, the review of Luo and Lin, 1999). The simulated responses of maize in Africa to a doubling of carbon dioxide, for example, can be as broad –98% to +16%, or as narrow as –14% to –12%. These ranges have been determined using different methods and are therefore not directly comparable (Challinor *et al.*, 2007). Ensemble modelling is a technique that enables more objective quantification of uncertainty. It is commonly used in climate change prediction, which is based on estimates of future emissions of greenhouse gases, and on the simulation of the resultant influence on climate. Multiple climate simulations, known as ensembles, are used to sample the inherent uncertainties in this process. Uncertainty in model structure can be assessed by using more than one model (Randall *et al.*, 2007) or by varying model parameters (Murphy *et al.*, 2004; Stainforth *et al.*, 2005). These ensembles of climate simulations can be used with crop models, and sometimes weather generators, to produce an ensemble of crop yields that captures uncertainty due to climate simulation (Trnka *et al.*, 2004).

The response of crops to any projected climate also contains uncertainties (see, for example, Mearns, 2003). Inputs to crop models, such as the choice of variety and planting date, can be varied in order to produce an ensemble of crop simulations (Jagtap and Jones, 2002; Irmak *et al.*, 2005). Large-area modelling studies have been

carried out where both crop and climate parameters have been varied, thus permitting a better estimate of total uncertainty and of the relative contributions to that uncertainty (Challinor *et al.*, 2005b, 2009a). Large-area crop modelling is well suited to this approach, since it operates with direct climate model output. Studies using this technique have contributed to our understanding of the key processes that are likely to reduce crop yield, and the quantification of associated uncertainty.

Understanding biophysical processes under climate change

Direct impact of atmospheric composition: Elevated levels of carbon dioxide and ozone will have direct impacts on crops: C3 crops are likely to accumulate more biomass, and both C3 and C4 crops are likely to use less water as atmospheric carbon dioxide concentrations increase. These processes have received much attention from both experimentalists and modellers in recent decades. Significant increases in plant growth and yield due to CO₂ elevation have been reported from controlled, semi-controlled, and open-field experiments for a range of crops, and to a lesser extent for crops grown in the field (Kimball *et al.*, 1983, 2002). Many recent studies modelling the impact of climate change on crops have simulated the effects of elevated CO₂; however, the number of free air carbon dioxide enrichment (FACE) experiments available to validate these models under field conditions is still limited (Tubiello and Ewert, 2002).

It has been argued (Long *et al.*, 2006) that crop models overestimate the effect of CO₂ on plant growth and yield, as a result of the CO₂-related model parameters being mainly derived from controlled and semi-controlled experiments, which typically show a higher CO₂ response than observed under field conditions. However, there is growing evidence that crop models are able to reproduce the observed crop responses in the FACE experiments (Ewert *et al.*, 2002; Asseng *et al.*, 2004; Tubiello *et al.*, 2007a). This evidence is contributing to an ongoing dialogue (see Ainsworth *et al.*, 2008a). Progress in modelling CO₂ effects on crops at the field scale will mainly depend on the ability to improve simulations of leaf area dynamics as compared with photosynthesis or radiation-use efficiency (Ewert, 2004). For modelling CO₂ effects at larger areas, the relative importance of other factors, such as diversity in climate, and soil and crop management including land-use change for explaining yield variability (and possible interactions with the effects of elevated CO₂), need to be better understood (Ewert *et al.*, 2007).

Crops are subject to multiple stresses, so that analysis of climate change alone provides only a partial view of likely future crop yields. In order to produce robust results of climate change impacts, a range of drivers need to be assessed. Such assessment is beyond the scope of this review. However, one further environmental variable that affects crop yield is considered here. We choose ozone since it is a second atmospheric gas that can have serious implications for yield. Atmospheric ozone is formed in the

Earth's lower atmosphere through sunlight-driven chemical reactions involving volatile organic compounds and nitrogen oxides. It is a strong oxidant that is harmful to plants and crops. Exposure of plants to elevated ozone concentrations can result in acute visible injury, which may have economic implications for food producers, as the damaged crop commands a reduced market price or cannot be sold at all (Velissariou, 1999). Plants chronically exposed to enhanced ozone take up an increased flux of ozone through their leaves, resulting in reduced capacity for photosynthesis and accelerated leaf senescence (McKee *et al.*, 1997). Protection mechanisms allow the plant to repair ozone damage and detoxify leaf tissue, meaning that plant function can remain unaffected up to a threshold value of ozone uptake. The reduced photosynthetic productivity and allocation of plant resources to these mechanisms leads to reduced carbon assimilation for plant growth, and a reduction in biomass and crop yield (Mauzerall and Wang, 2001; Emberson *et al.*, 2003). At higher ozone exposures, plant protection mechanisms may be overwhelmed completely, and ozone entering the plant can result in direct damage to plant tissue. There is also evidence that exposure to enhanced ozone reduces the nutritional value of crops. European wheat crops have demonstrated an ozone-induced reduction in protein yield per area grown (Piikki *et al.*, 2007).

Ozone is likely to play an increasingly important role in determining crop yields as anthropogenic sources of its precursors continue to increase in developing economies, leading to increasing background concentrations, especially in the northern hemisphere. Studies suggest large enhancements in surface ozone over SE Asia, central Africa, and tropical South America over the next 50 years under projected emissions and climate changes (Royal Society, 2008). Many of these regions are those where food security is already at risk from rising populations, loss of cultivated land, and climate change. Reductions of 5% in current yields due to ozone enhancement have been estimated in China, and projected to rise to 30% by 2050 (Long *et al.*, 2005). A wide range of sensitivity to ozone damage is exhibited between crop species and between strains within a species (e.g. wheat) (Ainsworth *et al.* 2008b). This may make it possible to reduce ozone impacts on crop yield and food security through the targeted planting of more ozone-resistant crop strains.

Progress to date in modelling ozone and its impacts includes global-scale estimates of future ozone impacts on crop yield over the next 30 years, based on modelled surface ozone concentrations (on a one degree square spatial grid) and an exposure-based ozone damage relationship (Van Dingenen *et al.*, 2008). Yield losses for wheat and rice in India and for wheat in sub-Saharan Africa were found to be particularly significant. These results are subject to large uncertainties, due to application of ozone exposure–damage relationships over large scales, uncertainties in modelled ozone, and choice of exposure index. Some local experimental data indicate that ozone-induced crop losses exceed those predicted by the large-scale model predictions, which

rely on US-based exposure–response relationships. Additional uncertainty stems from the reliability of modelled surface ozone fields. These rely on estimates of ozone precursor emissions, which are particularly poorly constrained in developing regions of the world such as Asia and Africa. The sensitivity of future ozone concentrations to climate change is also poorly understood, and depends on future land-use change, and how natural emissions from the biosphere, and the stratospheric flux of ozone to the lower atmosphere, will respond to future climate. These impacts are not well understood and are currently only rudimentarily considered by current generation atmospheric chemistry–climate models.

Indirect impact of atmospheric composition: As greenhouse gas emissions continue to rise, and climate changes, crops in the majority of regions will increasingly be grown in a warmer environment. These increases in mean temperature are already resulting in longer growing seasons (Rosenzweig *et al.*, 2007), although there is no indication that this is having a positive effect on yield, at least up to 2002 (Lobell and Field, 2007). Projections of the future impacts of warming seem to indicate a negative response of crop growth and yield to 1–2 °C warming at low latitudes and small beneficial response at higher latitudes; yet large uncertainties remain (Easterling *et al.*, 2007).

Mean temperature, together with photoperiod (Nigam *et al.*, 1994), determines the rate of plant development. The fundamental thermal time response functions that determine the rate of crop development (Challinor *et al.*, 2004) suggest that warming will decrease both duration and yield, at least up to the optimum temperature for development. However, since a given response function of development rate to temperature may not fit observations (Zhang *et al.*, 2008), care should be exercised in their use. Challinor and Wheeler (2008b) showed that differences in the form of these response functions, particularly at temperatures beyond the optimum temperature for development, mean that different models can respond very differently to increases in mean temperature.

In addition to large-scale changes in mean temperature, regional changes in climate will probably affect crops. These regional changes, particularly where they involve rainfall and/or variability in weather (as opposed to changes in mean quantities, such as season-mean temperature), are particularly difficult for a climate model to predict. Examples of potentially important regional changes include atmospheric humidity, which affects assimilation and alters transpiration efficiency (Kemanian *et al.*, 2005). This process may be very important in determining future yields in India (Challinor and Wheeler, 2008b) and other regions. There is also evidence that anthropogenic aerosols and other air pollutants have changed the optical properties of clouds, with resultant implications for solar radiation and hence agricultural productivity (Stanhill and Cohen, 2001).

The short-term events that are most likely to affect crops are extremes of temperature (Wheeler *et al.*, 2000) and drought, particularly during anthesis. Challinor *et al.*

(2005*a*) reported reductions of up to 20% in both observed and simulated crop yield when a 6 d heat stress event was imposed on groundnut. The importance of subseasonal variability in rainfall is illustrated in Figs 2 and 3. Figure 2 shows that whilst rainfall during the development of the crop has a clear influence on observed yield (44% of the variance explained), the crop model simulations (55% of observed variance explained) suggest the importance of other processes. One such process is likely to be the subseasonal variability of rainfall. This can be illustrated by noting that 2 years with different yields (44% lower in 1981 than in 1975), but with very similar total rainfall (see Fig. 2), have different subseasonal rainfall distributions (Fig. 3): the timing of rainfall in the 1975 season is such that water availability during pod filling (from ~50 d after planting) is likely to be higher than that of 1981. This indicates the beneficial value of considering important processes in large-area models.

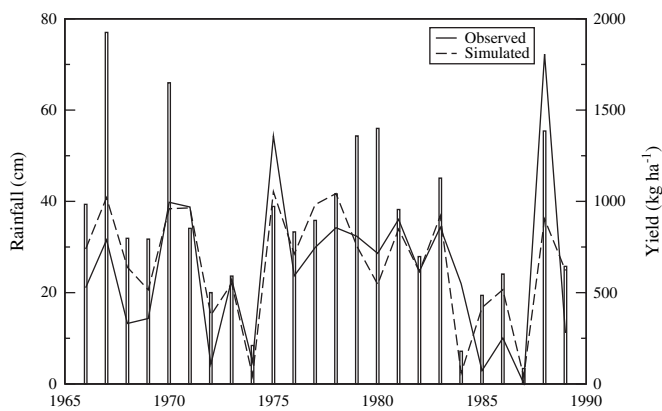


Fig. 2. Observed and simulated crop yield (lines) for a grid cell in western India taken from the study of Challinor *et al.* (2004). Bars indicate total rainfall during the simulated development period of the crop (planting to physiological maturity).

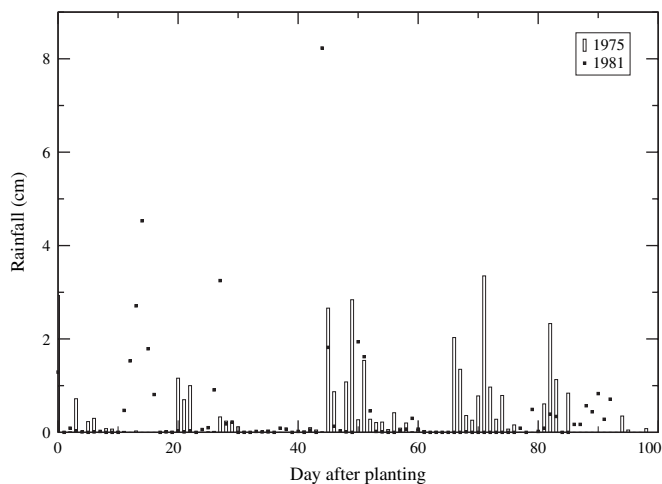


Fig. 3. Time series of rainfall, starting with the simulated planting date, from two of the years shown in Fig. 2. Redrawn from Challinor *et al.* (2004).

The predictability of the above indirect influences of increased atmospheric greenhouse gases varies across environmental variable and across space. Temperature is generally more predictable than rainfall, for example, and consensus across climate models in tropical seasonal total rainfall tends to be weaker than consensus at mid and high latitudes. The lead time of a forecast also affects the predictability: any prediction of weather beyond a few days contains inherent uncertainties, which can amplify as the predictions are made further into the future. At multi-decadal time scales, it is uncertainties in the concentrations of greenhouse gases that limit predictability. Further discussion on this topic can be found in Challinor *et al.* (2009*b*).

Interactions between biophysical processes: Crop yield is the result of many non-linear interactions between a range of processes, including those outlined above. Experimental field studies and crop models are two complementary tools that can be used to examine these interactions. The importance under field conditions of interactions between elevated CO₂ and other factors such as ozone exposure and temperature, water, and nitrogen stress is not fully understood. Evidence from field experiments is limited and also points in different directions.

Consider as an example the interaction between water stress and CO₂. From a physiological perspective, water-stressed crops are expected to show greater CO₂ stimulation than well-watered crops. This expectation has been cited in the literature as a reason for believing that rainfed cropping systems will benefit more from elevated CO₂ than irrigated systems (IPCC, 2001; Easterling *et al.*, 2007). Tubiello and Ewert (2002) showed that for a range of models and observations, water-stressed crops did indeed show a greater percentage increase in yield under elevated CO₂. However, when Challinor and Wheeler (2008*a*) reviewed FACE meta-analyses and presented results from a range of crop models, this response was not seen consistently in either the models or the observations. Detailed analysis led to the preliminary conclusion that the relationship between water stress and assimilation may vary with spatial scale. The associated level of model complexity was also shown to be a factor. Despite the lack of a consistency across studies, model comparison studies with the few experiments available have shown that, at the field scale, crop responses to elevated CO₂ can be satisfactorily reproduced for a range of models under a range of conditions of water availability (Ewert *et al.*, 2002; Asseng *et al.*, 2004), nitrogen supply (Jamieson *et al.*, 2000), and ozone exposure (Ewert *et al.*, 1999; van Oijen and Ewert, 1999).

Ozone also interacts with the environment in a way that alters its effect on plants. Since these interactions are non-linear, assessing the response of crops to future ozone concentrations requires consideration of future changes in atmospheric CO₂ and other environmental variables affecting plant function and stomatal conductance (Fuhrer, 2003; Ashmore, 2005; Harmens *et al.*, 2007). The interaction between ozone and CO₂ is mediated by stomata, which, in

addition to admitting ozone, allow CO₂, water vapour, and oxygen to pass in and out of the plant during photosynthesis and respiration. Increased atmospheric CO₂ reduces stomatal conductance, and the flux of ozone into the plant, and can provide additional carbon for repair and detoxification against ozone damage (Royal Society, 2008).

The interactions between ozone and carbon dioxide have implications for the way in which ozone damage is modelled. Dose–response relationships based on ozone flux are preferable to atmospheric ozone exposure (e.g. accumulated dose over a threshold of 40 parts per billion, AOT40; see Fuhrer *et al.* 1997), since they are able to account for the varying influences of temperature, water vapour, radiation, soil water, phenology, and atmospheric ozone on ozone uptake. With exposure-related indices, different meteorological and environmental conditions may result in a given atmospheric ozone exposure producing different crop impacts. In addition, several studies have shown that plant response is more closely related to stomatal ozone flux than to a time-integrated atmospheric ozone exposure (Pleijel *et al.*, 2000). This puts a high priority on the development of coupled process-based models that explicitly calculate the stomatal flux of ozone into the crop, and its dependence on a range of environmental drivers. Limited efforts have so far been made to model ozone effects at the explanatory process level, accounting for interactions with other factors such as CO₂ and climate (Ewert *et al.*, 1999; van Oijen and Ewert, 1999; Ewert and Porter, 2000; van Oijen *et al.*, 2004). The validity of these approaches for large-scale applications awaits further testing against reliable experimental data. Such data are still scarce (van Oijen and Ewert, 1999; see also Long *et al.*, 2006) and are urgently required for a range of important crop species under a range of climatic conditions.

Abiotic stresses are also likely to interact with biotic stresses. For example, the effects of ozone on plant function (allocation of resources to ozone resistance) and structure (e.g. leaf damage) may leave plants more susceptible to damage from pests, disease, and extreme weather, which are themselves likely to be affected by global climate change. Detailed discussion on biotic stresses is beyond the scope of this review.

Generating useful information

Ensuring reliability

How can the progress highlighted above be used to generate useful information? At least two conditions apply (see Patt and Gwata, 2002): useful information should be both reliable and relevant to the user of the information. The existence of complex interactions such as those described above presents a challenge to the reliability of process-based crop models. As shown above, mechanistic modelling necessarily involves a reduction of real-world processes to a set of fallible rules. A model that is too simple will fail to represent some of the interactions that strongly influence

output variables. A model that is too complex will have more parameters than can be constrained by observations, increasing the risk of reproducing observations without correctly representing the processes involved. Some parameters are not directly observable, and must be inferred as part of the calibration procedure. The risk of overtuning—where the right answer is obtained for the wrong reason, due to an excess of tuneable parameters that cannot be related directly to observations—is compounded by the existence of non-linear interactions in biological systems. A range of observations under a range of conditions is therefore needed to ensure that each of these interactions is correctly represented. When an overtuned model is run in a new environment (such as under climate change), the errors may be large. This implies that, despite the progress highlighted above, we should be wary of being overconfident in our assessments of the impacts of climate change, especially where it is based on the ‘validation’ of a model followed by subsequent ‘black box’ use of that model (see Monteith, 1996). Judicious model choice and calibration are therefore crucial, as is the evaluation of historical performance (Easterling *et al.*, 1996), if our simulations are to be consistently accurate (i.e. reliable).

Calibration parameters may be process based, acting on, for example, leaf area index (Challinor *et al.*, 2004) or soil fertility (Boote and Jones, 1998). Calibration may also be applied to model output as a yield correction factor (Jagtap and Jones, 2002; Casellas *et al.*, 2009). A range of more detailed approaches have also been tried and compared (Irmak *et al.*, 2005). The potential for overtuning means that calibration should be performed by using observations of as many growth variables as possible. For example, leaf area index can be used in addition to yield (Guerif and Duke, 2000; Jones and Barnes, 2001). Internal consistency checks are also very important in spotting unrealistic simulations. Possible checks include radiation-use efficiency and specific leaf area (where these are not input parameters; see, for example, Challinor *et al.*, 2004). Checks such as these can be combined with the methods outlined above: observations can be used to constrain ensembles of crop simulations (Challinor and Wheeler, 2008a). This approach can result in a reduction in the associated uncertainty from the estimates with unconstrained ensembles, as shown by Challinor *et al.* (2008a). That study, which accounted for both crop and climate uncertainty, also showed that, for the region and crop studied, doubled CO₂ without adaptation was highly likely to result in a reduction in yield. Thus quantifying uncertainty does not preclude relatively certain statements. Ensemble methods can ensure that we avoid unwarranted precision in our simulations, and observations can ensure that we avoid unnecessarily large uncertainty ranges.

Informing adaptation

Once we are confident that our estimates of climate change impacts are reliable, they can be used to create information relevant to the adaptation actions taken by stakeholders.

Challinor (2009) discusses this topic at length, and assesses the potential for adaptation to climate for a crop in India. In that study, a number of existing model results were used to assess the extent to which genotypic variation might be used to adapt to climate change. The requisite crop genetic properties determined from the simulations were compared with those of existing germplasm. Interestingly, a separate study showed that under doubled CO₂ in India, the uncertainty in the simulation of adapted crops may be greater than that of non-adapted crops (Challinor *et al.*, 2008a).

When considering adaptation, it is important to consider how weather and crop yield forecasts will be used, and what spatial and temporal scales will be the most appropriate for the users. Useful weather/climate forecasts can range from a few days ahead for some crop management decisions, to decades in the future for infrastructure and strategic planning. For example, ensemble climate modelling can be used with crop models in order to predict crop yield a season ahead of the harvest (Challinor *et al.*, 2005c). Information should also be provided in relevant formats (Stone and Meinke, 2005). Whether the information best suited to users is based on computer-intensive systems, or on less high-tech systems such as observational networks and capacity building, depends to a large extent on the particular users considered (see, for example, Patt *et al.*, 2005). In Africa, for example, a prudent way to address the threat of climate change may be to focus on strategies for coping with climate variability, rather than longer term climate change (Washington *et al.*, 2006). This may mean a greater focus on *in situ* and remotely sensed observations as well as consideration of the multiple stresses that act on food security (Gregory *et al.*, 2005; Haile, 2005; Verdin *et al.*, 2005).

In the seasonally arid regions of the developing world, people are particularly vulnerable to interannual and intra-seasonal rainfall variability, through dependence on rainfed agriculture. The skill of forecasts is also often higher in these mid-latitude regions than it is further north (DTI, 2001). Hence the potential benefits of climate forecasting may be particularly high in tropical regions, where there may be strong relationships between climate and impact variables such as crop yield (see also WCRP, 2007).

Future trends and challenges: holistic impacts and adaptation research

Having reviewed progress in modelling the impact of climate change on crops, and examined how reliable and useful information may come from this endeavour, what can be said of the progress needed in the near future? Part of generating relevant and reliable information is synthesizing knowledge effectively and applying it appropriately. One of the tools that enables this endeavour is the hardware on which models are run. Ongoing increases in computer power create the potential for increasingly sophisticated modelling techniques. For climate and impacts modellers,

this presents a choice (see Challinor *et al.*, 2009b): increase the complexity of the model, increase the number of simulations, or increase the spatial resolution. Increases in complexity are subject to the constraints identified earlier. Increases in the number of simulations create larger ensembles and hence more objective quantification of uncertainty (see above). Increases in spatial resolution will permit analyses across a broader range of spatial scales. This in turn may create one of the ingredients in a synergistic modelling approach that aims to increase the accuracy and reliability with which yield is simulated.

Synergistic approaches to yield prediction

Efforts to synthesize knowledge on the response of crops to climate change have increased in recent years (see Easterling *et al.*, 2007; Tubiello *et al.*, 2007b). These studies, which review existing modelling efforts and try to form a consensus, are an important part of the process of increasing our understanding. They are faced with a difficult task, since each of the individual studies tends to use only one method for one region, and for a limited number of crops (see above and Challinor *et al.*, 2007). In order to address this, some crop model intercomparison studies have been performed (Jamieson, 1998; van Oijen and Ewert, 1999; Jamieson *et al.*, 2000; Ewert *et al.*, 2002). These have shown that simulations differ across models, due to significant differences in the structure of the models. For example, some models are based on the concept of radiation-use efficiency, whilst others are based on water- or nitrogen-use efficiency; some models emphasize sink development, whilst others focus mainly on sources. Clearly, the structure of a model and the processes considered, including their relative importance, are determined by the aims for which the models are developed. These aims are in part determined by the region for which the model was developed, since there are considerable regional differences in the factors determining crop responses (Reidsma *et al.*, 2009b).

As a result of this spatial heterogeneity in the determinants of yield, several studies show that crop models have difficulties in reproducing yields at multiple sites (Ewert *et al.*, 1999; van Oijen and Ewert, 1999), farms (Ewert *et al.*, 2002), and regions (Reidsma *et al.*, 2009a). Unsatisfactory model performance at the regional scale can be due to the inappropriate consideration of factors and processes determining yield variability (Reidsma *et al.*, 2009a) and/or the aggregation of input data which may inconsistently reproduce the spatial variability of growing conditions (e.g. climate and soils) within a region (e.g. Hansen and Jones, 2000). Also, factors explaining spatial yield variability across regions can be different from those explaining temporal variability within regions (Reidsma *et al.*, 2007, 2009b). Thus, there is no single modelling approach that performs equally well across regions.

Similar reasoning can be applied to simulation across a range of spatial scales, since this is another determinant of the structure of a model. For some scales and regions, climate may be the dominant determinant of crop yield.

Where biotic stresses (see, for example, Tubiello *et al.*, 2007b) or other non-climatic processes dominate, there may be no observed relationship between climate and crops; here, more detailed site-specific modelling may succeed in demonstrating predictability (Gadgil *et al.*, 2002; Carbone *et al.*, 2003), by explicitly including determinants of yield variability other than climate. Bakker *et al.* (2005) showed that the significance of the climate signal increases with spatial scale, suggesting that non-climatic factors such as management or soils may become more important at smaller scales.

Given the importance of scale and geography in determining crop productivity, perhaps the greatest challenge for future syntheses of knowledge on the response of crops to climate change is the balance between generality and specificity in region and scale. Reducing complexity to the most important yield-determining factors and processes may result in different region- and/or scale-specific models. This in itself may reduce the generality of the results. Efforts to improve synergy between crop modelling approaches must therefore choose whether to emphasize generality or specificity. Increasing generality has been proposed by Yin and van Laar (2005), who developed improvements to the underlying physiological relationships in the GECROS model, resulting in wider applicability across a range of conditions. Adam *et al.* (2009) propose a generic modelling framework that assembles regional-scale models depending on the regions and the relative importance of the determinants of yield in those regions.

The ensemble techniques reviewed above are an attempt to avoid unwarranted precision (i.e. specificity). The techniques have been used to examine the form of the response of crop yield to mean temperature (Challinor *et al.*, 2008a). The results showed that the response derived from an ensemble systematically varying both climate and crop responses to elevated CO₂ can have a different form from that derived from a study synthesizing a range of disparate results (that of Easterling *et al.*, 2007). The results also showed variation in response of crop development and yield to mean temperature across a range of crop models. Similar techniques were used by Challinor and Wheeler (2008a, b), who used a crop simulation ensemble combined with sensitivity analyses on two other crop models. Coupled with observational studies, approaches such as these can be used to understand the fundamental biophysical processes determining crop yield across scales and across regions.

Combining biophysical and socio-economic drivers

Biophysical processes are not the only determinants of crop yield and productivity. The role of socio-economic drivers is increasingly being realized by the climate and impacts modelling community. Efforts to increase the reliability, and also the relevance, of predictions are therefore beginning to draw on a parallel body of work that has explored the influence of human action (e.g. adaptation) on crop productivity. Unsurprisingly, these studies show that productivity relies on capital and labour inputs and a range of

other factors (Mendelsohn, 2007). Such factors may trigger a range of inseparable responses in yield, including step-changes (e.g. policy, infrastructure, pest), smooth trends (e.g. technical innovation), or cyclical changes (e.g. crop rotation, rainfall). Drawing on development studies, and household/village-scale livelihoods work in poorer parts of the world (see, for example, Adger, 1999), a range of more qualitative data suggests that the way farmers adapt to climatic problems results from the complex and unpredictable interactions between society and the environment (O'Brien and Leichenko, 2000).

Much of this work has involved asking key informants about how weather-related problems were overcome in the past. As such, these studies tend to use participatory methods (Dougill *et al.*, 1999) and find their intellectual foundations in the work of Amartya Sen who studied the causes of 20th century famines and presented his 'food entitlement theory'. Sen concluded that those socio-economic factors that constrain an individual's ability to switch entitlements are more important in creating a famine than simple meteorological anomalies (Sen, 1981). Food entitlement theory has been expanded on by researchers doing field work where key interviews, focus groups, and questionnaires are used to conduct studies on how households and villages adapt to overcome weather-related problems (Bebbington, 1999). Researchers have explored how household members switch between different livelihood strategies (Scoones, 1995), and found that by diversifying their income sources householders can become less vulnerable to climate variability (Hageback *et al.*, 2005). Thus far, however, it has proven difficult to 'up-scale' results from these field studies, and current attempts have only generated quite general and qualitative conceptual frameworks (Turner *et al.*, 2003; Ericksen, 2008).

Recent studies have analysed relationships between farm characteristics and yield variability (Reidsma *et al.*, 2007, 2009b) across regions in Europe. As evident from these studies, farm intensity, farm size, and land use have been identified as important characteristics for explaining a significant part of the spatial and temporal yield variability. It was also shown that farm diversity in a region can strongly affect (and cancel out) the climate signal (Reidsma and Ewert, 2008). Considering these farm characteristics in a model evaluation study revealed that some of the deviation of the simulated regional yields from observations could be explained by these characteristics. Yet, the integration of this information into biophysical models remains difficult (Vincent, 2008).

In order to bring socio-economic and biophysical approaches together and develop formal mathematical models of climate impacts on food security, those socio-economic factors that limit or enhance production and adaptation can be identified and quantified using the same spatial scale as climate models and large-area crop models. Work supporting this has been undertaken by characterizing those socio-economic factors that, in the past, seem to have buffered harvest from drought (Fraser *et al.*, 2008) and the development of indicators of socio-climatic exposure

(Diffenbaugh *et al.*, 2007). Simelton *et al.* (2009) have shown that regions may be vulnerable to drought due to land, labour, or capital constraints, and that, as regions develop economically, the source of vulnerability may shift from economic constraints to a lack of land or labour. However, these results are preliminary; more work is needed to understand fully how socio-economic processes influence climate–crop relationships, and trends in production, at the regional scale. Once this has been done, the socio-economic and biophysical aspects of crop productivity can be examined together using state-of-the-art methods and at common spatial scales, resulting in more holistic assessments of climate change impacts and adaptation. Methodologies are therefore required that can integrate the main food system processes (Schmidhuber and Tubiello, 2007; Tubiello *et al.*, 2007b) and suggesting adaptation options that take account of the full range of stresses on agriculture (see Howden *et al.*, 2007; Morton, 2007). Integrative work such as this needs to be based on an understanding of fundamental processes and their associated uncertainties (see above).

Linking simulation with adaptation

The challenges identified above have focused principally on increasing the reliability of simulations. How can we go about increasing the relevance of the information produced by crop and climate models? Closer links with efforts to develop adaptation options would seem to be an effective way to do this. For example, plant breeding operates on a 7–10 year time scale, producing the varieties that are best adapted to the environment (Austin, 1999). This time scale is unlikely to be sufficient to prepare for the increase in extreme events expected under climate change (see Randall *et al.*, 2007). Also, plant breeding cannot take place at all the locations where adaptation to climate change will be needed. Just as judicious use of crop models can complement field studies, there is the potential to link simulation studies more closely to plant breeding and other adaptation measures. Such methods could be used to identify the regions where newly bred varieties may perform well, thus broadening their domain of applicability. They also provide a tool for making the simulation studies relevant to a specific adaptation endeavour. A sequence of links is likely to be needed in order to connect simulation and plant breeding; existing concepts [e.g. ideotypes (Donald, 1968; Sylvester-Bradley and Riffkin, 2008)] may prove to be a useful part of this.

Efforts such as these can only be carried out with the will and ability of a range of scientists. Our understanding and modelling of climate impacts is based on fundamental physics, biology, and chemistry, and the interactions between them. Our ability to predict is therefore dependent on the quality of our single- and cross-disciplinary research. Similarly, our ability to inform adaptation will depend upon the extent to which we can combine all relevant scientific analyses into holistic assessments. Just as there are many successful studies linking crop and climate science

(Huntingford *et al.*, 2005; see also Slingo *et al.*, 2005), it should be possible to link simulation studies more closely with a range of adaptation endeavours.

Conclusions

There are many complex processes and interactions that determine crop yield under climate change. These include the response of crops to mean temperature, the interaction between water stress and CO₂, and the interaction between ozone and a range of environmental variables. As a result of this, and of the importance of scale and geography in determining crop productivity, perhaps the greatest challenge for future syntheses of knowledge on the response of crops to climate change is the balance between generality and specificity in region and scale. It is clear that climate impacts research requires appropriate degrees of integration and specialization (Challinor *et al.*, 2009b). To date, efforts to generate knowledge for policy and adaptation have been largely based on syntheses of published studies. Synergistic approaches are now needed that include the following.

(i) *Reliable quantification of impacts uncertainty.* This should be carried out as objectively as possible and is likely to include the use of crop simulation ensembles and/or sensitivity analyses. Since the quantification of uncertainty does not preclude a high degree of certainty regarding some statements, there is every reason to believe that this approach will prove to be productive.

(ii) *Techniques for combining diverse modelling approaches and observations.* A focus on processes, employing a range of models and observations in order to increase our understanding of non-linear interactions, is likely to be an effective strategy for reducing uncertainty. Coupled modelling approaches are likely to form a part of this strategy, since non-linear interactions between yield-determining processes may result in complex coupling between; for example, atmospheric composition and climatic drivers. Observations are also important: whilst ensemble methods can ensure that we avoid unwarranted precision in our simulations, observations can ensure that we avoid unnecessarily large uncertainty ranges.

(iii) *Judicious choice and calibration of models,* including simulation at appropriate levels of complexity that accounts for the principal drivers of crop productivity. Even when a range of models is combined in some way, judicious choice and use of models is required. Since no one model can claim to represent reality entirely accurately, models should not be calibrated or run as ‘black boxes’. Thus different models may be used for different regions, depending on the relative importance of driving variables in these regions. Also, modelling methods are needed that can account for both the biophysical and socio-economic determinants of crop productivity.

In addition to providing a new paradigm for the generation of knowledge, such an approach will lead to reliable methods for linking simulation with adaptation.

Thus we can move beyond synthesizing knowledge and begin to make the best use of the huge global effort to understand and predict climate change.

Acknowledgements

The support of the Economic and Social Research Council (ESRC) is gratefully acknowledged. The work was part of the programme of the ESRC Centre for Climate Change Economics and Policy.

References

- Adam M, Ewert F, Leffelaar PA, Corbeels M, van Keulen H, Wery J.** 2009. Towards a generic crop modelling framework: combining expert knowledge with modelling approaches. *Environmental Modelling and Software*, in press.
- Adger N.** 1999. Social vulnerability to climate change and extremes in coastal Vietnam. *World Development* **27**, 249–269.
- Ainsworth EA, Leakey ADB, Ort DR, Long SP.** 2008a. 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**, 5–9.
- Ainsworth EA, Rogers A, Leakey ADB.** 2008b. Targets for crop biotechnology in a future high-CO₂ and high-O₃ world. *Plant Physiology* **147**, 13–19.
- Anderson K, Bows A.** 2008. Reframing the climate change challenge in light of post-2000 emission trends. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* **366**, 3863–3882.
- Ashmore MR.** 2005. Assessing the future global impacts of ozone on vegetation. *Plant, Cell and Environment* **28**, 949–964.
- Asseng S, Jamieson PD, Kimball B, Pinter P, Sayre K, Bowden JW, Howden SM.** 2004. Simulated wheat growth affected by rising temperature, increased water deficit and elevated atmospheric CO₂. *Field Crops Research* **85**, 85–102.
- Austin RB.** 1999. Yield of wheat in the United Kingdom: recent advances and prospects. *Crop Science* **39**, 1604–1610.
- Bakker MM, Govers G, Ewert F, Rounsevell M, Jones R.** 2005. Variability in regional wheat yields as a function of climate, soil and economic variables: assessing the risk of confounding. *Agriculture, Ecosystems and Environment* **110**, 195–209.
- Baron C, Sultan B, Balme M, Sarr B, Teadore S, Lebel T, Janicot S, Dingkuh M.** 2005. From GCM grid cell to agricultural plot: scale issues affecting modelling of climate impacts. *Philosophical Transactions of the Royal Society B: Biological Sciences* **360**, 2095–2108.
- Bebbington A.** 1999. Capitals and capabilities: a framework for analyzing peasant viability, rural livelihoods and poverty. *World Development* **27**, 2021–2044.
- Boote KJ, Jones JW.** 1998. Simulation of crop growth: CROPGRO model. In: Peart RM, Curry RB, eds. *Agricultural systems modelling and simulation*. New York: Marcel Dekker, 651–692.
- Brooks RJ, Semenov MA, Jamieson PD.** 2001. Simplifying sirus: sensitivity analysis and development of a metamodel for wheat yield prediction. *European Journal of Agronomy* **14**, 43–60.
- Carbone GJ, Mearns LO, Mavromatis T, Sadler EJ, Stooksbury D.** 2003. Evaluating CROPGRO-soybean performance for use in climate impact studies. *Agronomy Journal* **95**, 537–544.
- Casellas E, Therond O, Belhouchette H, Wallach D, Russell G, Ewert F, Adam M, Oomen R, Wery J.** 2009. Using a cropping system model for large scale impact assessment in Europe. In: Brouwer F, van Ittersum MK, eds. *Integrated assessment of agriculture and sustainable development (AgSAP)*. Egmond aan Zee, The Netherlands, 10–12 March 2009, in press.
- Challinor AJ.** 2009. Developing adaptation options using climate and crop yield forecasting at seasonal to multi-decadal timescales. *Environmental Science and Policy*, in press.
- Challinor AJ, Osborne T, Morse A, Shaffrey L, Wheeler T, Weller H.** 2009b. Methods, skills and resources for climate impacts research. *Bulletin of the American Meteorological Society*, in press.
- Challinor AJ, Slingo JM, Wheeler TR, Craufurd PQ, Grimes DIF.** 2003. Toward a combined seasonal weather and crop productivity forecasting system: determination of the working spatial scale. *Journal of Applied Meteorology* **42**, 175–192.
- Challinor AJ, Slingo JM, Wheeler TR, Doblus-Reyes FJ.** 2005c. Probabilistic hindcasts of crop yield over western India. *Tellus* **57A**, 498–512.
- Challinor AJ, Wheeler TR.** 2008a. Use of a crop model ensemble to quantify CO₂ stimulation of water-stressed and well-watered crops. *Agricultural and Forest Meteorology* **148**, 1062–1077.
- Challinor AJ, Wheeler TR.** 2008b. Crop yield reduction in the tropics under climate change: processes and uncertainties. *Agricultural and Forest Meteorology* **148**, 343–356.
- Challinor AJ, Wheeler TR, Craufurd PQ, Slingo JM.** 2005d. Simulation of the impact of high temperature stress on annual crop yields. *Agricultural and Forest Meteorology* **135**, 180–189.
- Challinor AJ, Wheeler TR, Garforth C, Craufurd P, Kassam A.** 2007. Assessing the vulnerability of food crop systems in Africa to climate change. *Climatic Change* **83**, 381–399.
- Challinor AJ, Wheeler TR, Hemming D, Upadhyaya HD.** 2009a. Crop yield simulations using a perturbed crop and climate parameter ensemble: sensitivity to temperature and potential for genotypic adaptation to climate change. *Climate Research* **38**, 117–127.
- Challinor AJ, Wheeler TR, Osborne TM, Slingo JM.** 2006. Assessing the vulnerability of crop productivity to climate change thresholds using an integrated crop-climate model. In: Schellnhuber J, Cramer W, Nakicenovic N, Yohe G, Wigley TML, eds. *Avoiding dangerous climate change*. Cambridge: Cambridge University Press, 187–194.
- Challinor AJ, Wheeler TR, Slingo JM, Craufurd PQ, Grimes DIF.** 2004. Design and optimisation of a large-area process-based model for annual crops. *Agricultural and Forest Meteorology* **124**, 99–120.
- Challinor AJ, Wheeler TR, Slingo JM, Craufurd PQ, Grimes DIF.** 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**, 516–531.

- Challinor AJ, Wheeler TR, Slingo JM, Hemming D.** 2005b. Quantification of physical and biological uncertainty in the simulation of the yield of a tropical crop using present day and doubled CO₂ climates. *Philosophical Transactions of the Royal Society B: Biological Sciences* **360**, 1981–2194.
- Chipanshi AC, Ripley EA, Lawford RG.** 1999. Large-scale simulation of wheat yields in a semi-arid environment using a crop-growth model. *Agricultural Systems* **59**, 57–66.
- de Wit AJW, Boogaard HL, van Diepen CA.** 2005. Spatial resolution of precipitation and radiation: the effect on regional crop yield forecasts. *Agricultural and Forest Meteorology* **135**, 156–168.
- Diffenbaugh N, Giorgi F, Raymond L, Bi X.** 2007. Indicators of 21st century socioclimatic exposure. *Proceedings of the National Academy of Sciences, USA* **104**, 20195–20198.
- Donald CM.** 1968. The breeding of crop ideotypes. *Euphytica* **17**, 385–403.
- Dougill AJ, Thomas DSG, Heathwaite AL, et al.** 1999. Environmental change in the Kalahari: integrated land degradation studies for nonequilibrium dryland environments. *Annals of the Association of American Geographers* **89**, 420–442.
- DTI. 2001. Seasonal weather forecasting for the food chain. Pub 5232/4k/2/01/NP. Foresight, Office of Science and Technology, Department of Trade and Industry, UK. Available at: http://www.foresight.gov.uk/Previous_Rounds/Foresight_1999__2002/Food_Chain__Crops_for_Industry/Reports/Seasonal%20Weather%20Forecasting%20for%20the%20Food%20Chain/Index.htm.
- Easterling WE, Aggarwal PK, Batima P, et al.** 2007. Food, fibre and forest products. In: *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: Cambridge University Press, 23–78.
- Easterling WE, Chen XF, Hays C, Brandle JR, Zhang HH.** 1996. Improving the validation of model-simulated crop yield response to climate change: an application to the EPIC model. *Climate Research* **6**, 263–273.
- Emberson LD, Ashmore MR, Murray F.** 2003. *Air pollution impacts on crops and forests—a global assesment*. London: Imperial College Press.
- Eriksen P.** 2008. Conceptualizing food systems for global environmental change research. *Global Environmental Change* **18**, 234–245.
- Ewert F.** 2004. Modelling plant responses to elevated CO₂: how important is leaf area index? *Annals of Botany* **93**, 619–627.
- Ewert F, Porter JR.** 2000. Ozone effects on wheat in relation to elevated CO₂: modelling short-term and long-term responses of leaf photosynthesis and leaf duration. *Global Change Biology* **6**, 735–750.
- Ewert F, Porter JR, Rounsevell MD.** 2007. Crop models, CO₂, and climate change. *Science* **315**, 459–460.
- Ewert F, Rodriguez D, Jamieson P, et al.** 2002. Effects of elevated CO₂ and drought on wheat: testing crop simulation models for different experimental and climatic conditions. *Agriculture, Ecosystems and Environment* **93**, 249–266.
- Ewert F, van Oijen M, Porter JR.** 1999. Simulation of growth and development processes of spring wheat in response to CO₂ and ozone for different sites and years in Europe using mechanistic crop simulation models. *European Journal of Agronomy* **10**, 231–247.
- Faivre R, Leenhardt D, Voltz M, Benoît M, Papy F, Dedieu G, Wallach D.** 2004. Spatialising crop models. *Agronomie* **24**, 205–217.
- Fraser E, Termansen M, Sun N, Guan D, Simelton E, Dodds P, Feng K, Yu Y.** 2008. Quantifying socio economic characteristics of drought sensitive regions: evidence from Chinese provincial agricultural data. *Comptes Rendus Geosciences* **340**, 679–688.
- Fuhrer J.** 2003. Agroecosystem responses to combinations of elevated CO₂, O₃ and global climate change, Agriculture. *Ecosystems and Environment* **97**, 1–20.
- Fuhrer J, Skarby L, Ashmore MR.** 1997. Critical levels for ozone effects on vegetation in Europe. *Environmental Pollution* **97**, 91–106.
- Gadgil S, Rao PRS, Rao KN.** 2002. Use of climate information for farm-level decision making: rainfed groundnut in southern India. *Agricultural Systems* **74**, 431–457.
- Gregory PJ, Ingram JSI, Brklacich M.** 2005. Climate change and food security. *Philosophical Transactions of the Royal Society B: Biological Sciences* **360**, 2139–2148.
- Guerif M, Duke CL.** 2000. Adjustment procedures of a crop model to the site-specific characteristics of soil and crop using remote sensing data assimilation. *Agriculture, Ecosystems and Environment* **81**, 57–69.
- Hageback J, Sundberg J, Ostwald M, Chen D, Knutsson P.** 2005. Climate variability and land-use change in Danangou watershed, China—examples of small-scale farmers' adaptation. *Climatic Change* **72**, 189–212.
- Haile M.** 2005. Weather patterns, food security and humanitarian response in sub-Saharan Africa. *Philosophical Transactions of the Royal Society B: Biological Sciences* **360**, 2169–2182.
- Hansen JW.** 2005. Integrating seasonal climate prediction and agricultural models for insights into agricultural practice. *Philosophical Transactions of the Royal Society B: Biological Sciences* **360**, 2037–2047.
- Hansen J, Challinor AJ, Ines A, Wheeler TR, Moron V.** 2006. Translating climate forecasts into agricultural terms: advances and challenges. *Climate Research* **33**, 27–41.
- Hansen JW, Jones JW.** 2000. Scaling-up crop models for climatic variability applications. *Agricultural Systems* **65**, 43–72.
- Harmens H, Mills G, Emberson LD, Ashmore MR.** 2007. Implications of climate change for the stomatal flux of ozone: a case study for winter wheat. *Environmental Pollution* **146**, 763–770.
- Herdt RW, Mandac AM.** 1981. Modern technology and economic efficiency of Philippine rice farmers. *Economic Development and Cultural Change* **29**, 375–399.
- Howden SM, Soussana J-F, Tubiello FN, Chhetri N, Dunlop M, Meinke H.** 2007. Adapting agriculture to climate change. *Proceedings of the National Academy of Sciences, USA* **104**, 19691–19696.
- Huntingford C, Lambert FH, Gash JHC, Taylor CM, Challinor AJ.** 2005. Aspects of climate change prediction relevant to crop productivity. *Philosophical Transactions of the Royal Society B: Biological Sciences* **360**, 1999–2009.

- Iglesias A, Rosenzweig C, Pereira D.** 2000. Agricultural impacts of climate change in Spain: developing tools for a spatial analysis. *Global Environmental Change: Human and Policy Dimensions* **10**, 69–80.
- IPCC.** 2001. *Climate change 2001: impacts, adaptation, and vulnerability*. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press.
- Irmak A, Jones JW, Jagtap SS.** 2005. Evaluation of the CROPGRO-soybean model for assessing climate impacts on regional soybean yields. *Transactions of the ASAE* **48**, 2343–2353.
- Jagtap SS, Jones JW.** 2002. Adaptation and evaluation of the CROPGRO-soybean model to predict regional yield and production. *Agriculture Ecosystems and Environment* **93**, 73–85.
- Jamieson PD, Porter JR, Goudriaan J, Ritchie JT, van Keulen H, Stol W.** 1998. A comparison of the models AFRCWHEAT2, CERES-Wheat, Sirius, SUCROS2 and SWHEAT with measurements from wheat grown under drought. *Field Crops Research* **55**, 23–44.
- Jamieson PD, Berntsen J, Ewert F, Kimball BA, Olesen JE, Pinter PJ Jr, Porter JR, Semenov MA.** 2000. Modelling CO₂ effects on wheat with varying nitrogen supplies. *Agriculture, Ecosystems and Environment* **82**, 27–37.
- Jones D, Barnes EM.** 2000. Fuzzy composite programming to combine remote sensing and crop models for decision support in precision crop management. *Agricultural Systems* **65**, 137–158.
- Kemanian AR, Stöckle CO, Huggins DR.** 2005. Transpiration-use efficiency of barley. *Agricultural and Forest Meteorology* **130**, 1–11.
- Kidson JW, Thompson CS.** 1998. A comparison of statistical and model-based downscaling techniques for estimating local climate variations. *Journal of Climatology* **11**, 735–753.
- Kimball BA.** 1983. Carbon dioxide and agricultural yield: an assemblage and analysis of 430 prior observations. *Agronomy Journal* **75**, 779–788.
- Kimball BA, Kobayashi K, Bindi M.** 2002. Responses of agricultural crops to free-air CO₂ enrichment. *Advances in Agronomy* **77**, 293–368.
- Kumar KK, Kumar RK, Ashrit RG, Deshpande NR, Hansen JW.** 2004. Climate impacts on Indian agriculture. *International Journal of Climatology* **24**, 1375–1393.
- Lobell DB, Burke MB, Tebaldi C, Mastrandrea MD, Falcon WP, Naylor RL.** 2008. Prioritizing climate change adaptation needs for food security in 2030. *Science* **319**, 607–610.
- Lobell DB, Field CB.** 2007. Global scale climate–crop yield relationships and the impacts of recent warming. *Environmental Research Letters* **2**, 014002.
- Long SP, Ainsworth EA, Leakey A, Morgan PB.** 2005. Global food insecurity. Treatment of major food crops to elevated carbon dioxide and ozone under large-scale fully open-air conditions suggest models may seriously over-estimate future yields. *Philosophical Transactions of the Royal Society B: Biological Sciences* **360**, 2011–2020.
- Long SP, Ainsworth EA, Leakey ADB, Nosberger J, Ort DR.** 2006. Food for thought: lower-than-expected crop yield stimulation with rising CO₂ concentrations. *Science* **312**, 1918–1921.
- Luo QY, Lin E.** 1999. Agricultural vulnerability and adaptation in developing countries: the Asia-Pacific region. *Climatic Change* **43**, 729–743.
- Mauzerall DL, Wang X.** 2001. Protecting agricultural crops from the effects of tropospheric ozone exposure: reconciling science and standard setting in the United States, Europe and Asia. *Annual Review of Energy and Environment* **26**, 237–268.
- Mavromatis T, Jones PD.** 1998. Comparison of climate change scenario construction methodologies for impact assessment studies. *Agricultural and Forest Meteorology* **91**, 51–67.
- Mavromatis T, Jones PD.** 1999. Evaluation of HADCM2 and direct use of daily GCM data in impact assessment studies. *Climatic Change* **41**, 583–614.
- Mckee IF, Bullimore JF, Long SP.** 1997. Will elevated CO₂ protect the yield of wheat from O₃ damage? *Plant, Cell and Environment* **20**, 77–84.
- Mearns LO, ed.** 2003. *Issues in the impacts of climate variability and change on Agriculture. Applications to the southeastern United States*. Dordrecht: Kluwer Academic Publishers.
- Mearns LO, Rosenzweig C, Goldberg R.** 1997. Mean and variance change in climate scenarios: methods, agricultural applications, and measures of uncertainty. *Climatic Change* **35**, 367–396.
- Mendelsohn R.** 2007. Measuring climate impacts with cross-sectional analysis. *Climatic Change* **81**, 1–7.
- Moen TN, Kaiser HM, Riha SJ.** 1994. Regional yield estimation using a crop simulation model—concepts, methods and validation. *Agricultural Systems* **46**, 79–92.
- Monteith JL.** 1996. The quest for balance in crop modeling. *Agronomy Journal* **88**, 695–697.
- Morton JF.** 2007. The impact of climate change on smallholder and subsistence agriculture. *Proceedings of the National Academy of Sciences, USA* **104**, 19680–19685.
- Murphy JM, Sexton DMH, Barnett DN, Jones GS, Webb MJ, Collins M, Stainforth DA.** 2004. Quantification of modelling uncertainties in a large ensemble of climate change simulations. *Nature* **430**, 768–772.
- Nain AS, Dadhwal VK, Singh TP.** 2004. Use of CERES-wheat model for wheat yield forecast in central Indo-Gangetic Plains of India. *Journal of Agricultural Science* **142**, 59–70.
- Nigam SN, Rao RCN, Wynne JC, Williams JH, Fitzner M, Nagabhushanam GVS.** 1994. Effect and interaction of temperature and photoperiod on growth and partitioning in 3 groundnut (*Arachis Hypogaea* L.) genotypes. *Annals of Applied Biology* **125**, 541–552.
- O'Brien K, Leichenko R.** 2000. Double exposure: assessing the impacts of climate change with the context of economic globalization. *Global Environmental Change* **10**, 221–232.
- Patt A, Gwata C.** 2002. Effective seasonal climate forecast applications: examining constraints for subsistence farmers in Zimbabwe. *Global Environmental Change: Human and Policy Dimensions* **12**, 185–195.
- Patt AG, Suarez P, Gwata C.** 2005. Effects of seasonal climate forecasts and participatory workshops among subsistence farmers in Zimbabwe. *Proceedings of the National Academy of Sciences, USA* **102**, 12623–12628.
- Piikki K, Vorne V, Ojanpera K, Pleijel H.** 2007. Impact of elevated O₃ and CO₂ exposure on potato (*Solanum tuberosum* L. cv. Bintje)

tuber macronutrients (N, P, K, Mg, Ca). *Agriculture, Ecosystems and Environment* **104**, 55–64.

Pleijel H, Danielsson H, Karlsson GP, Gelang J, Karlsson PE, Sellden G. 2000. An ozone flux-response relationship for wheat. *Environmental Pollution* **109**, 453–462.

Porter JR, Semenov MA. 2005. Crop responses to climatic variation. *Philosophical Transactions of the Royal Society B: Biological Sciences* **360**, 2021–2038.

Potgieter AB, Hammer GL, Doherty A, de Voil P. 2005. A simple regional-scale model for forecasting sorghum yield across North-Eastern Australia. *Agricultural and Forest Meteorology* **132**, 143–153.

Priya S, Shibasaki R. 2001. National spatial crop yield simulation using GIS-based crop production model. *Ecological Modelling* **135**, 113–119.

Randall DA, Wood RA, Bony S, et al. 2007. Climate models and their evaluation. *Climate change 2007: the physical science basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press, 589–662.

Reidsma P, Ewert F. 2008. Regional farm diversity can reduce vulnerability of food production to climate change. *Ecology and Society* **13**, 38.

Reidsma P, Ewert F, Oude Lansink A. 2007. Analysis of farm performance in Europe under different climatic and management conditions to improve understanding of adaptive capacity. *Climatic Change* **84**, 403–422.

Reidsma P, Ewert F, Boogaard H, van Diepen K. 2009a. Regional crop modelling in Europe—the impact of climatic conditions and farm characteristics on maize yields. *Agricultural Systems* doi:10.1016/j.agsy.2008.12.009, in press.

Reidsma P, Ewert F, Oude Lansink A, Leemans R. 2009b. Vulnerability and adaptation of European farmers: a multi-level analysis of yield and income responses to climate variability. *Regional Environmental Change* **9**, 25–40.

Rosenzweig C, Casassa G, Karoly DJ, et al. 2007. Assessment of observed changes and responses in natural and managed systems. In: Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, 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: Cambridge University Press, 79–131.

Royal Society. 2008. *Ground-level ozone in the 21st century: future trends, impacts and policy implications*. RS Policy document 15/08. ISBN: 978085403–7131.

Schmidhuber J, Tubiello FN. 2007. Global food security under climate change. *Proceedings of the National Academy of Sciences, USA* **104**, 19703–19708.

Scoones I. 1995. *Living with uncertainty: new directions in pastoral development in Africa*. London: Intermediate Technology Publications.

Semenov MA, Barrow EM. 1997. Use of a stochastic weather generator in the development of climate change scenarios. *Climatic Change* **35**, 397–414.

Sen A. 1981. *Poverty and famines*. Oxford: Clarendon Press.

Simelton E, Fraser EDG, Termansen M, Forster PM, Dougill AJ. 2009. Typologies of drop-drought vulnerability: an empirical analysis of the socio-economic factors that influence the sensitivity and resilience to drought of three major food crops in China (1961–2001). *Environmental Science and Policy*, in press.

Sinclair TR, Seligman N. 2000. Criteria for publishing papers on crop modelling. *Field Crops Research* **68**, 165–172.

Sinclair TR, Seligman NG. 1996. Crop modeling: from infancy to maturity. *Agronomy Journal* **88**, 698–704.

Siegenthaler U, Stocker T, Monnin E, et al. 2005. Stable carbon cycle–climate relationship during the late Pleistocene. *Science* **310**, 1313–1317.

Slingo JM, Challinor AJ, Hoskins BJ, Wheeler TR. 2005. Food crops in a changing climate. *Philosophical Transactions of the Royal Society B: Biological Sciences* **360**, 1983–1989.

Southworth J, Pfeifer RA, Habeck M, Randolph JC, Doering OC, Rao DG. 2002. Sensitivity of winter wheat yields in the midwestern United States to future changes in climate, climate variability, and CO₂ fertilization. *Climate Research* **22**, 73–86.

Spahni R, Chappellaz J, Stocker T, et al. 2005. Atmospheric methane and nitrous oxide of the late Pleistocene from Antarctic ice cores. *Science* **310**, 1317–1321.

Stainforth DA, Alna T, Christensen C, et al. 2005. Uncertainty in predictions of the climate response to rising levels of greenhouse gases. *Nature* **433**, 403–406.

Stanhill G, Cohen S. 2001. Global dimming: a review of the evidence for a widespread and significant reduction in global radiation with discussion of its probable causes and possible agricultural consequences. *Agricultural and Forest Meteorology* **107**, 255–278.

Stone RC, Meinke H. 2005. Operational seasonal forecasting of crop performance. *Philosophical Transactions of the Royal Society B: Biological Sciences* **360**, 2109–2124.

Sylvester-Bradley R, Riffkin PA. 2008. Designing resource-efficient ideotypes for new cropping conditions: wheat in the UK and Australasia. *Aspects of Applied Biology* **88**, 127–134.

Thornton PK, Bowen WT, Ravelo AC, Wilkens PW, Farmer G, Brock J, Brink JE. 1996. Estimating millet production for famine early warning: an application of crop simulation modelling using satellite and ground-based data in Burkina Faso. *Agricultural and Forest Meteorology* **83**, 95–112.

Trnka M, Dubrovsky M, Semerádova D, Zalud Z. 2004. Projections of uncertainties in climate change scenarios into expected winter wheat yields. *Theoretical and Applied Climatology* **77**, 229–249.

Tubiello FN, Amthor JS, Boote KJ, Donatelli M, Easterling W, Fischer G, Giord RM, Howden M, Reilly J, Rosenzweig C. 2007a. Crop response to elevated CO₂ and world food supply a comment on ‘food for thought...’ by Long *et al.*, *Science* **312**:1918–1921, 2006. *European Journal of Agronomy* **26**, 215–223.

Tubiello FN, Ewert F. 2002. Simulating the effects of elevated CO₂ on crops: approaches and applications for climate change. *European Journal of Agronomy* **18**, 57–74.

- Tubiello FN, Soussana J-F, Howden SM.** 2007b. Crop and pasture response to climate change. *Proceedings of the National Academy of Sciences, USA* **104**, 19686–19690.
- Turner BL, Kasperson RE, Matson PA, et al.** 2003. A framework for vulnerability analysis in sustainability science. *Proceedings of the National Academy of Sciences, USA* **100**, 8074–8079.
- Van Dingenen R, Dentener FJ, Raes F, Krol MC, Emberson L, Cofala J.** 2008. The global impact of ozone on agricultural crop yields under current and future air quality legislation. *Atmospheric Environment* **43**, 604–618.
- van Ittersum MK, Leffelaar PA, van Keulen H, Kropff MJ, Bastiaans L, Goudriaan J.** 2003. On approaches and applications of the Wageningen crop models. *European Journal of Agronomy* **18**, 201–234.
- van Oijen M, Dreccer MF, Firsching KH, Schnieders B.** 2004. Simple equations for dynamic models of the effects of CO₂ and O₃ on light-use efficiency and growth of crops. *Ecological Modelling* **179**, 39–60.
- van Oijen M, Ewert F.** 1999. The effects of climatic variation in Europe on the yield response of spring wheat cv. Minaret to elevated CO₂ and O₃: an analysis of open-top chamber experiments by means of two crop growth simulation models. *European Journal of Agronomy* **10**, 249–264.
- Velissariou D.** 1999. Toxic effects and losses of commercial value of lettuce and other vegetables due to photochemical air pollution in agricultural areas of Attica, Greece. In: Fuhrer J, Achermann B, eds. *Critical levels for ozone—level II*. Bern, Switzerland: Swiss Agency for Environment, Forest and Landscape, 253–256.
- Verdin J, Funk C, Senay G, Choularton R.** 2005. Climate science and famine early warning. *Philosophical Transactions of the Royal Society B: Biological Sciences* **360**, 2155–2168.
- Vincent K.** 2008. Uncertainty in adaptive capacity and the importance of scale. *Global Environmental Change* **17**, 12–24.
- Washington R, Harrison M, Conway D, Black E, Challinor A, Grimes D, Jones R, Morse A, Kay G, Todd M.** 2006. African climate change: taking the shorter route. *Bulletin of the American Meteorological Society* October **2006**, 1355–1366.
- WCRP.** 2007. World Climate Research Programme Workshop on Seasonal Prediction. Position Paper. Available online at http://www.clivar.org/organization/wgsip/spw/spw_position.php.
- Wheeler TR, Craufurd PQ, Ellis RH, Porter JR, Vara Prasad PV.** 2000. Temperature variability and the annual yield of crops. *Agriculture, Ecosystems and Environment* **82**, 159–167.
- Wilby RL, Wigley T.** 1997. Downscaling general circulation model output: a review of methods and limitations. *Progress in Physical Geography* **21**, 530–548.
- Wilby RL, Wigley TML, Conway D, Jones PD, Hewitson BC, Main J, Wilks DS.** 1998. Statistical downscaling of General Circulation Model output: a comparison of methods. *Water Resources Research* **34**, 2995–3008.
- Xiong W, Matthews R, Holman I, Lin E, Xu Y.** 2007. Modelling China's potential maize production at regional scale under climate change. *Climatic Change* **85**, 433–451.
- Yin X, van Laar HH.** 2005. *Crop systems dynamics: an ecophysiological simulation model for genotype-by-environment interactions*. Science Publishers Inc.
- Yun JI.** 2003. Predicting regional rice production in South Korea using spatial data and crop-growth modeling. *Agricultural Systems* **77**, 23–38.
- Zalud Z, Dubrovsky M.** 2002. Modelling climate change impacts on maize growth and development in the Czech Republic. *Theoretical and Applied Climatology* **72**, 85–102.
- Zhang T, Zhub J, Yang X.** 2008. Non-stationary thermal time accumulation reduces the predictability of climate change effects on agriculture. *Agricultural and Forest Meteorology* **148**, 1412–1418.