CHAPTER 19

Assessing the Vulnerability of Crop Productivity to Climate Change Thresholds Using an Integrated Crop-Climate Model

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ABSTRACT: Extreme climate events and the exceedance of climate thresholds can dramatically reduce crop yields. Such events are likely to become more common under climate change. Hence models used to assess the impacts of climate change on crops need to accurately represent the effects of these events. We present a crop-climate modelling system which is capable of simulating the impact on crop yield of threshold exceedance, changes in the mean and variability of climate, and adaptive measures. The predictive skill of this system is demonstrated for the current climate using both climate-driven simulations and fully coupled crop-climate simulations.

The impacts of climate change on crop productivity are then examined using the A2 emissions scenario. Exceedance of high temperature thresholds at the time of flowering reduces the yield of crops in some areas. The nature of this response can be moderated by the choice of variety, and in some areas this choice makes the difference between an increase and a decrease in yield. Therefore dangerous climate change in this context is related to temperature threshold exceedance and the ability of farming systems to adapt to it. This will vary in a non-linear manner with the climate change scenario used.

19.1 Introduction: Simulation of the Impacts of Climate Change on Crop Productivity

Estimates of the impacts of climate change on crop productivity usually rely on crop simulation models driven by weather data downscaled from General Circulation Models (GCMs). An important consequence of this approach is that differences in the spatial and temporal scales of crop and climate models may introduce uncertainties into assessments of the impacts of climate change (e.g. Mearns et al., 2001). Most crop models are designed to run at the field scale. They can provide good simulations of crop productivity at this scale, but not at the regional scale. However, policy decisions on the stabilisation of greenhouse gases require regional assessments of impacts on food systems. Thus, to provide this information, crop model outputs have to be aggregated to a regional scale. The assumptions implicit in this process are a source of error in regional yield estimation (Hansen and Jones, 2000).

An alternative approach is to design a crop model to operate on spatial and temporal scales close to the scale of the GCM output (Challinor et al., 2003). By using a large area process-based crop model as part of a more integrated modelling approach, errors in the aggregation of yield to the regional scale may be reduced. This paper aims to show how an integrated crop – climate modelling system can be used to assess the impacts of climate variability and change on crop productivity. Such a system can take explicit account of the impact of climate extremes on crop productivity.

19.1.1 *The Importance of Extreme Events and Climate Threshold Exceedance*

Many studies have shown that increases in atmospheric concentrations of CO_2 will benefit the yield of most crops, with the exception of those that have the C4 photosynthetic pathway, such as maize, millet and sugar cane (for example, Kimball, 1983; Idso and Idso, 1994). However, other aspects of climate change are expected to have a negative impact on the yield of annual crops, and these may partly, or entirely, offset the yield gains due to elevated CO_2. For example, warmer mean seasonal temperatures reduce the duration from sowing to harvest of wheat. This results in a reduction in the amount of light captured by the crop leaf canopy, and hence biomass and yield at harvest decline with an increase in temperature (Mitchell et al., 1993; Wheeler et al., 1996a).

Even where the sensitivity of crop yields to the seasonal mean climate is well known, large impacts on crop production can also occur when climate thresholds are transgressed for short periods (Parry et al., 2001). Floods, droughts and high temperature episodes are likely to become more frequent under climate change (IPCC, 2001b) and this will have an impact on crop productivity. Important climate thresholds for food crops include episodes of high temperatures that coincide with critical phases of the crop cycle (Wheeler et al., 2000), as well as changes in the sub-seasonal distribution of rainfall (Wright et al., 1991). Experimental studies have led research in this field and these are beginning to be understood in

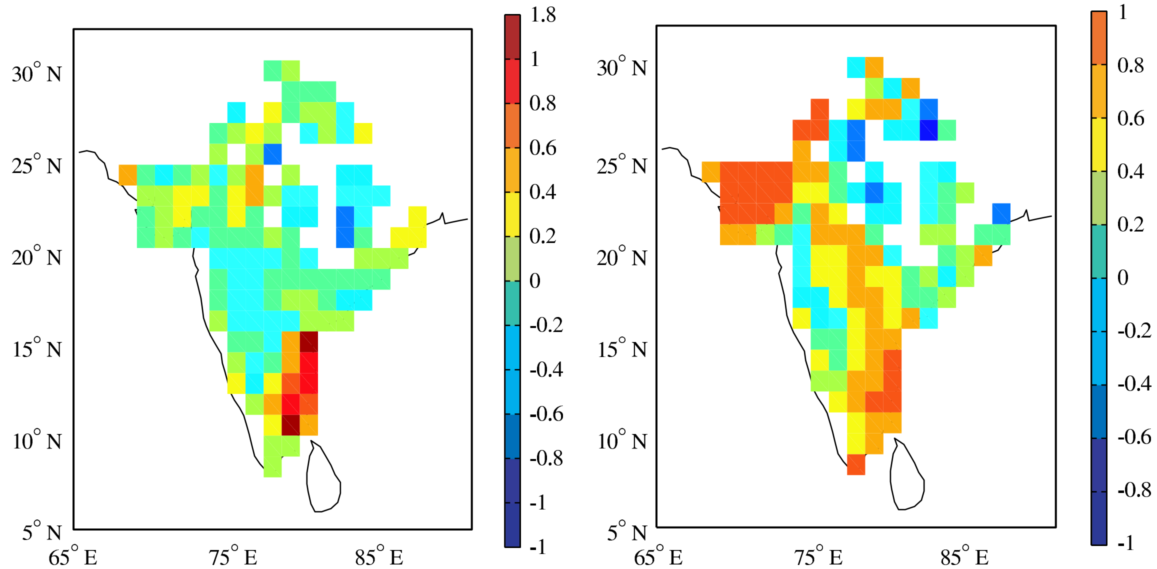

Figure 19.1 Left: mean (24 years) fractional difference between GLAM yield and an empirical fit to GLAM (Yield = $b_0 + b_1D + b_2P + b_3D^2 + b_4P^2 + b_6PD$ where b_i are constants, D is simulated crop duration and P is precipitation during that period). Right: correlation coefficient for the same period between GLAM yields and yields from the empirical fit. GLAM simulations and associated weather data are taken from Challinor et al. (2005a).

terms of simple physiology (Prasad et al., 2000; Ntare et al., 2001).

High temperature events near flowering disrupt pollination and cause yield losses due to reduced numbers of grains or seeds at the harvest. This response has been observed in wheat (Wheeler et al., 1996b), groundnut (Prasad et al., 2000) and soybean (Ferris et al., 1999), amongst others. Such studies have shown that the threshold temperature above which grain-set is reduced is usually between 31 and 37°C, provided that this short term high temperature event coincides with a sensitive stage of the crop such as flowering. The increasing recognition of the importance of weather events and climate thresholds such as these is reflected in crop modelling studies (e.g. Hansen and Jones, 2000; Semenov and Barrow, 1997; Easterling et al., 1996).

19.1.2 *Simulation Methods Used to Date*

In recognition of the socio-economic nature of climate change impacts, integrated assessments of the global impacts of climate change to date often simulate crop yield, land-use change and world food trade (Fischer et al., 2002; Parry et al., 2004). The treatment of crop growth and development in such assessments is frequently based on empirical methods (either parameterisations of crop model functions or direct use of statistical relationships such as those of Doorenbos and Kassam, 1979). This is a pragmatic way forward, but needs to be complemented with more detailed studies of the response of crops to climate. These more detailed studies focus on fundamental processes such as those related to changing CO_2 levels, intra-seasonal weather variability, and climate threshold exceedance. When these processes begin to impact seriously on yield, statistical relationships developed under the current climate may no longer be valid (Challinor et al., 2005a).

The choice of crop model has been shown to provide a significant source of uncertainty in the simulation of yield under climate change (Mearns et al., 1999). In the present-day climate the use of an empirical regression (also called a yield function) based on crop model output can produce results that differ from direct use of crop model output. The following analysis, based on the use of reanalysis data with the crop model of Challinor et al. (2004), demonstrates this.

An empirical regression of model yields based on simulated crop duration (which is determined by mean temperature) and seasonal rainfall is compared to the model yields in figure 19.1. A good empirical fit to the crop model (right panel) does not necessarily imply that the mean yields simulated by both methods are similar (left panel). For example, in Gujarat (the western-most region shown), where simulated yields correlate significantly ($r = 0.4–0.8$) with observed yields (Challinor et al., 2005a), the empirical regression provides a good fit ($r > 0.8$) and yet the difference between the model yields and the regression can be greater than 40%.

Similar issues exist in considering how to use climate information for impacts studies. Different GCMs produce different climates, and any simulated yield changes contingent on those climates may differ in magnitude and sign (e.g. Tubiello et al., 2002). Hence no single simulation can be considered to be a prediction of a future climate. Even if the climate is correctly simulated, the statistics of weather may not be correct. For example, seasonal mean values of rainfall and temperature may be correct, but the daily values may not be realistic. Lack of confidence in daily weather data, coupled with the coarse resolution of GCMs has lead to the use of weather generators to generate downscaled time series for climate change scenarios. The downscaling relationships are based on changes between the current and future climate in the mean and the variability of weather (Semenov and Barrow, 1997). This method has the advantage of not relying on the correct simulation by the GCM of the basic mean state. It has the disadvantage of relying on a set of assumptions, embedded in the weather generator, regarding the relationship between mean climate and weather and between different weather variables. Such weather statistics may not remain constant as climate changes (Jenkins and Lowe, 2003) and correcting for this has inherent uncertainties. The impact of these uncertainties could be significant since the choice of parameters for a weather generator can alter the magnitude and even the sign of the changes in yield associated with climate change (Mavromatis and Jones, 1998).

The variety of methods used to simulate the yields associated with future climate scenarios leads to a large range of predictions and associated uncertainties. Luo and Lin (1999) reviewed estimates of the potential yield impacts of climate change in the Asia-Pacific region. Estimates of yield for future climates using climate models varied in both magnitude and in stated ranges. For example the two estimates of rice yield in Bangladesh (incorporating the CO_2 fertilisation effect) were '−12 to −2%' and −35%. Estimates of yield which did not include the CO_2 effect tended to have larger uncertainties (e.g. −74 to +32% for spring wheat in Mongolia). When a large range of sites and of GCM scenarios is used, the resulting uncertainty can be very large: Reilly and Schimmelpfennig (1999) projected wheat yield impacts for a doubling of CO_2 of between −100 and +234% for the USA and Canada. Only by dealing effectively with the disparity in spatial scale between GCMs and crop models can the uncertainty associated with yield estimates be reduced.

19.2 An Integrated Approach to Impacts Prediction

19.2.1 *Scientific Basis*

The scientific basis for a large-area crop model has been established by looking at the relationship between crop yield and weather data on a number of spatial scales (Challinor et al., 2003). Such a large-area model has the advantage of addressing the issues in sections 2.1 and 2.2: use of a process-based model which operates on the spatial scale of the GCM avoids the need for downscaling of weather data whilst maintaining a process-based modelling approach. Also, intra-seasonal variability can be represented and the impact of temperature threshold exceedance can be simulated. Further, full integration of the crop and climate models (see section 3.4) allows the GCM to capture feedbacks between the crop and the

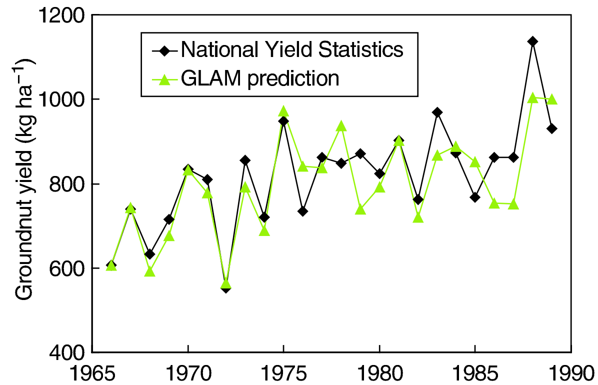

Figure 19.2 All-India groundnut yields simulated using GLAM on a 2.5° by 2.5° grid (Challinor et al., 2004). The time trend in the GLAM yields is taken from the (linear) time trend in observations.

climate and also diurnal temperature variability, which is important in determining the impact of temperature threshold exceedance.

19.2.2 *The General Large-Area Model for Annual Crops*

The General Large-Area Model for Annual Crops (GLAM; Challinor et al., 2004) is a process-based crop model. It has a daily time-step, allowing it to resolve the impacts of sub-seasonal variability in weather. It has a soil water balance with 25 layers which simulates evaporation, transpiration and drainage. Roots grow with a constant extraction-front velocity and a profile linearly related to Leaf Area Index (LAI). LAI evolves using a constant maximum rate of change of LAI modified by a soil water stress factor. Separate simulation of biomass accumulation, by use of transpiration efficiency allows Specific Leaf Area (SLA, the mass of leaf per unit area of leaf) to be used as an internal consistency check: leaf area and leaf mass can be derived independently of each other and used to calculate values of SLA which can be compared to typical observed values. The sowing date is simulated by applying an intelligent planting routine to a given sowing window. The crop is planted when soil moisture exceeds a threshold value. If no such event occurs within the window then crisis planting is simulated on the final day of the sowing window.

19.2.3 *Results for the Current Climate*

The geographical focus of work to date with GLAM is the tropics. Much of the world's food is grown in this region. Also, there is a well-documented dependence on rainfed agriculture across much of the tropics. Farmers rely on monsoon rains to bring sufficient water for crop cultivation. Preliminary work focussed on simulations in the current climate as predictive skill here is seen as a pre-requisite for predictive skill in future climates. Figure 19.2 shows the ability of GLAM to capture interannual

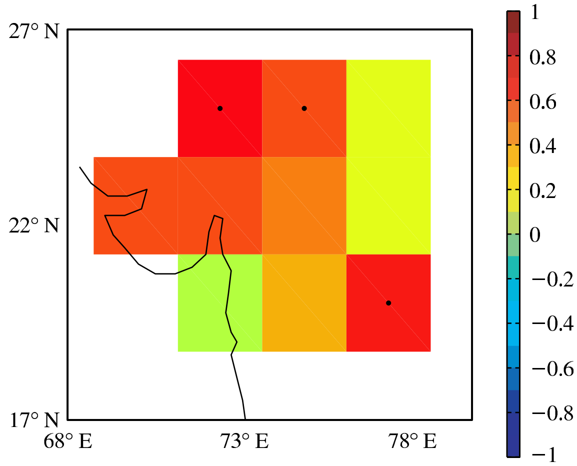

Figure 19.3 Correlation between observed and simulated yields (Challinor et al., 2005b). Dots indicate 95% significance. The simulated yields were formed from an ensemble mean GLAM simulation of crop yield in Gujarat, India. Time series of yield were formed by driving the crop model with each individual ensemble member.

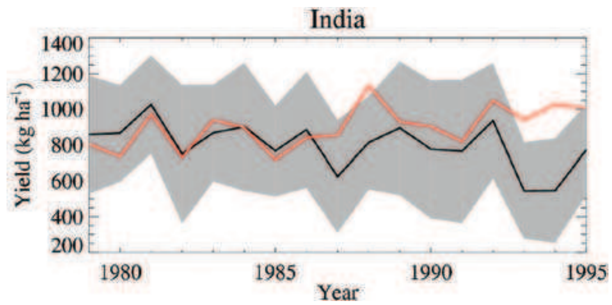

Figure 19.4 Observed FAO groundnut yield statistics (red line) with simulated mean values (black line) and spatial standard deviation (grey shading).

variability in yields when driven with observed weather data. Agreement between simulated and observed yields tends to be greatest in regions where the area under cultivation is greatest, and where there is a strong climate influence on yields. Hence the all-India yields shown mask some regional variability in skill. See Challinor et al. (2004) for a more detailed analysis.

GLAM has also been used with seasonal hindcast ensembles (Challinor et al., 2005b). This study showed that an ensemble of crop yields can contain useful information in both the mean (figure 19.3) and in the spread (not shown). Probabilistic methods of yield estimation are relevant to future as well as current climates, since they provide a tool for the quantification of the uncertainty outlined in section 2.2.

19.2.4 *Fully Coupled Crop-Climate Simulation*

Full integration of crop and climate models is the logical progression of the work described so far. Advantages of a fully coupled crop-climate model include:

- Resolution of the diurnal cycle would enable more accurate simulation of temperature threshold exceedance.
- Feedbacks between the crop and its environment can be simulated. This may have a significant impact on yield for irrigated crops.
- Integration of management decisions such as sowing date allows an assessment of the vulnerability of farming systems to changes in the mean and variability of climate.

Accordingly, the crop growth and development formulations of GLAM have been incorporated into the land surface scheme of the Hadley Centre atmospheric GCM, HadAM3 (Osborne, 2004). Crop growth is determined according to the GLAM parameterisations in accordance with the simulated weather and climate of HadAM3. Dynamical crop growth within the land surface scheme alters the important surface characteristics for the determination of fluxes to the atmosphere such as leaf area, albedo and roughness length, while the simulated rates of surface evaporation (soil evaporation and/or plant transpiration) will affect the humidity of the crop environment.

Initial evaluation of the coupled crop-climate model has focused on the simulation of groundnut by GLAM throughout the Tropics. Figure 19.4 shows the simulated and observed yields for India. GLAM was not regionally calibrated for these simulations, yet the mean and variability of yields compare well with observations.

The coupled model HadAM3-GLAM was forced with observed interannual variations in sea surface temperatures which play a large role in determining interannual variations in climate; e.g. ENSO variations. Figure 19.5 illustrates the capacity of HadAM3-GLAM to simulate interannual variability of crop growth simulations in response to the simulated variations in climate for two regions in India.

Sowing of the crop is dependent on the onset of the monsoon and exhibits considerable interannual variability at both regions. Subsequent crop biomass production requires the transpiration of considerable amounts of water and is therefore dependent on the amount of water in the soil profile. Consequently, variability in the amount and distribution of the rainfall results in the large range of crop biomass simulated at harvest. For the NW India region, the duration and amount of rainfall is only sufficient to grow one crop. In contrast, the temporal distribution of the rainfall in SE India is more bimodal, allowing a second crop to be sown in 8 out of the 17 years. However, these growing seasons are terminated by the model due to water stress in January or February, indicating a need for supplementary irrigation. These results illustrate the potential of the coupled model to assess the vulnerability of crop production to climate.

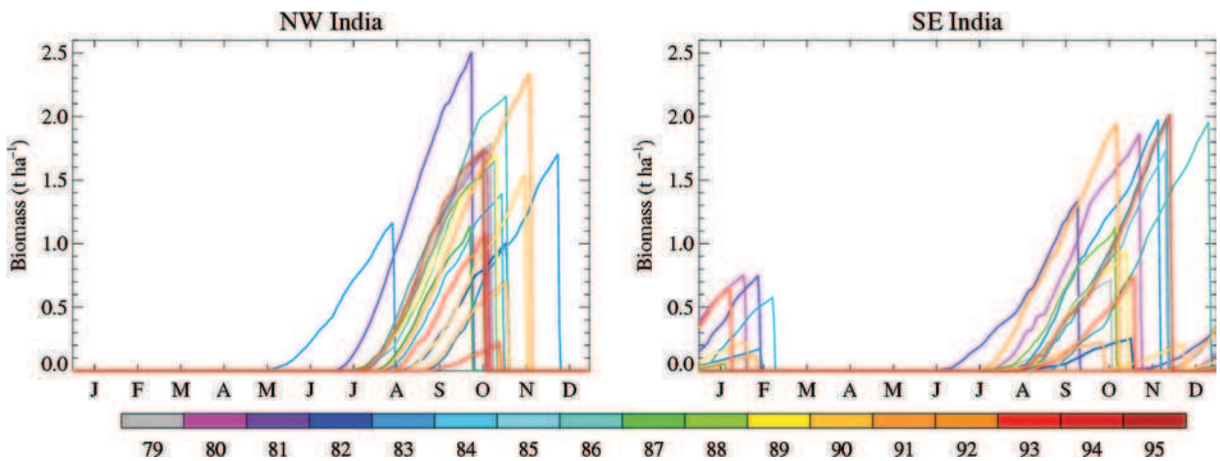

Figure 19.5 Time series of simulated groundnut biomass at two HadAM3 grid points in India. Coloured lines represent growth of the crop during each year from 1979–1995.

19.3 Regional Crop Modelling Study for India 2071–2100 Under the A2 Scenario

19.3.1 *Methods*

Parameterisations of the impacts of high temperature episodes (see section 2.1) have been added to GLAM (Challinor et al., 2005c). These methods are based on the mean 8am–2pm temperatures (T_{AM}) during the flowering stage of the crop. Only flowering that is associated with subsequent pegs and pods (and therefore yield) is considered. Accumulated thermal time is used to determine the start and end dates (t_1 and t_2) of flowering. Daily T_{AM} is examined for the period $t_1 - 6$ to $t_2 + 12$. Temperature threshold exceedance is defined as $T_{AM} > 34°C$ (sensitive variety), 36°C (moderately sensitive variety) or 37°C (tolerant variety). For each day (i) during the flowering stage, these high temperature events are characterised according to their timing relative to i and their duration in days. Only one of the high temperature events impacts yield. For each event, the following is carried out: (i) two critical temperatures are calculated as a function of the timing and duration of the event; (ii) The fraction of pods setting as a result of the flowers forming on day i (P_i) is reduced linearly from one to zero for values of T_{AM} between these two critical temperatures; (iii) The total fraction of pods setting (P_{tot}) is determined as a sum over all days in the flowering stage, using a prescribed fraction of total flowers forming each day (F_i). The lowest value of P_{tot} is then used to reduce the rate of change of harvest index. Steps (i) and (iii) include parameters which vary according to the crop variety (sensitive, moderately sensitive, or tolerant).

Challinor et al., 2005c did not account for the impact of water stress on pod-set. Hence step (iii) in the description above has been modified accordingly:

$$P_{tot} = \sum_{i=t_1}^{t_2} P_i F_i \min\left(\frac{S_i}{S_{cr}}, 1\right) \quad (1)$$

where S_i is the soil water stress factor (ratio of available water to transpirative demand) and S_{cr} is a threshold value of S_i below which pod-set is affected by water stress. In sensitivity tests, three values of S_{cr} were used (0.2, 0.3 and 0.4) and yields were found to be insensitive to the value chosen. $S_{cr} = 0.2$ was used for all the simulations in this study.

A regional climate simulation from the joint Indo-UK program on climate change was used to drive GLAM for the study presented here. As part of this program the PRECIS regional climate model (http://www.metoffice.com/research/hadleycentre/models/PRECIS.html) was run using boundary conditions derived from global climate models: a coupled general circulation model (HadCM3) was used to simulate changes in climate, and these changes were added to the baseline (current) climate of the atmosphere-only model HadAM3. In order to understand the role of sulphate aerosols, simulations both with and without the sulphur cycle were carried out (see IITM, 2004). Availability of data at the time of the present study limited the scenario used to a 2070–2100 A2 simulation without sulphur. The A2 scenario is one of the most extreme scenarios, with emissions rising monotonically from present-day values (<10 Gt of carbon) to over 25 Gt in 2100 (IPCC, 2001a). Hence the impacts on crop yield presented here are not predictions, but rather a demonstration of both the methods used and of one potentially plausible future scenario.

19.3.2 *Results*

Use of the modified version of GLAM driven by, but not coupled with, regional climate modelling data allows the importance of extremes of temperature and water stress to be assessed. Also, the water-stress parameterisation can be turned off, allowing an assessment of the impact of temperature alone. When used to drive GLAM, the PRECIS simulations of the A2 scenario project an increase in the importance of temperature and water stress near

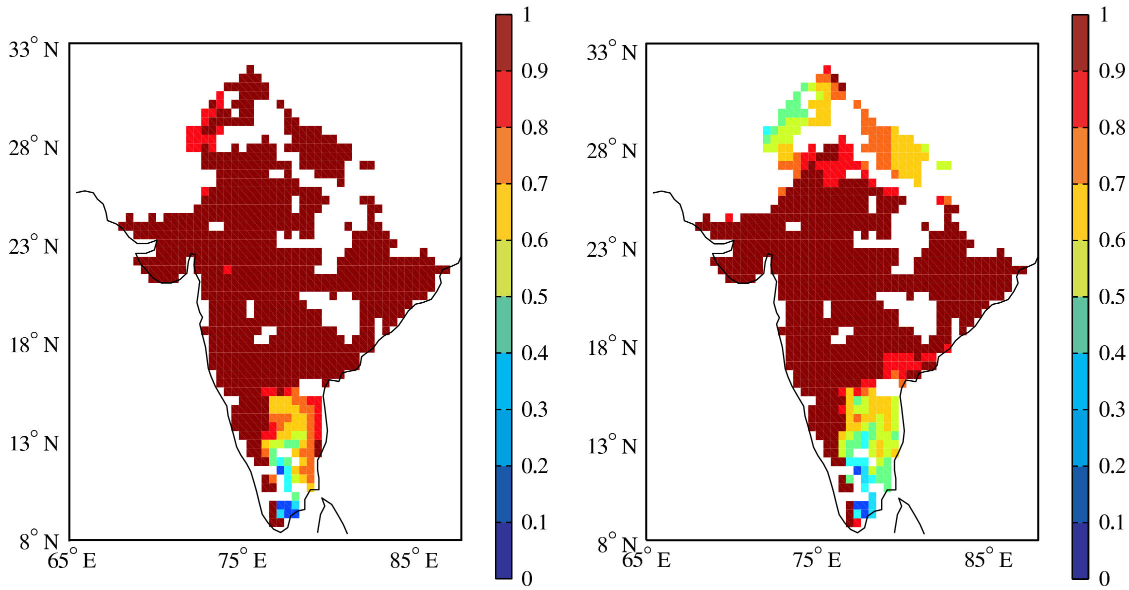

Figure 19.6 Mean fraction of setting pods in groundnut for 1960–1990 (left panel) and 2071–2100 (right panel) as simulated by GLAM, driven by the Hadley centre PRECIS model under the A2 scenario. Both panels show a variety which is moderately sensitive to high temperature stress near flowering.

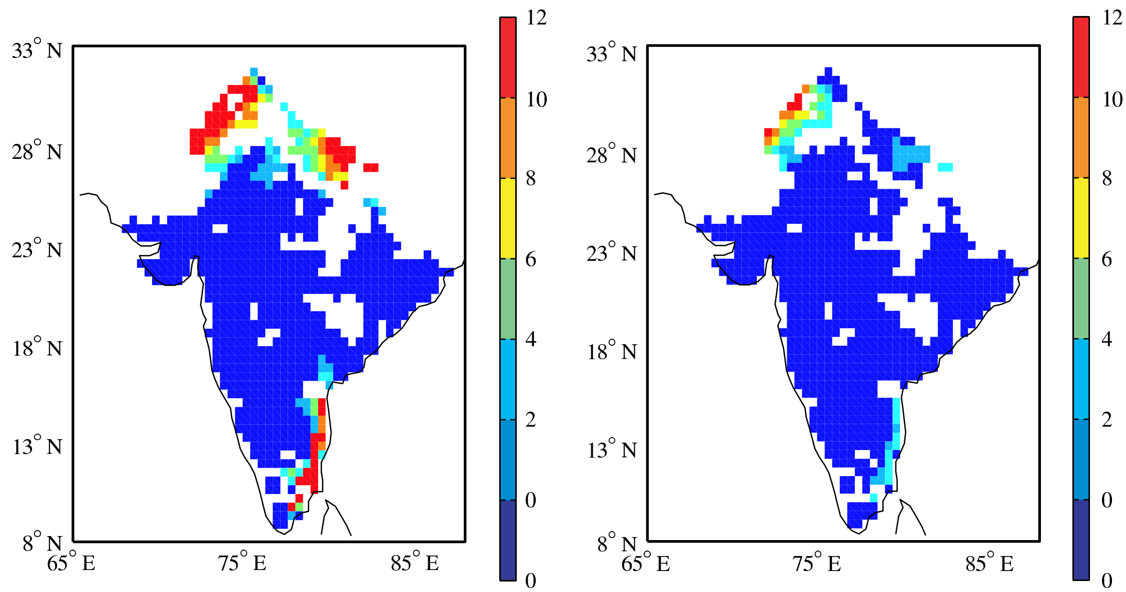

Figure 19.7 Number of years from the period 2071–2100 (Hadley centre PRECIS model under the A2 scenario) when the total fraction of pods setting in groundnut simulated by GLAM is below 50% when temperature stress only is considered. The left panel shows a variety which is sensitive to high temperature stress near flowering and the right panel shows a variety which is tolerant.

flowering (figure 19.6). In particular the north of India shows very little impact on the mean number of pods setting in the current climate, but a significant impact in the 2071–2100 projection.

One possible adaptation to climate change is the cultivation of crops more tolerant to high temperatures. Simulations were performed using two crop types, one that is sensitive, and one tolerant, to high temperature events. The contrast between these two sets of (figure 19.7) shows the potential importance of crop variety in providing adaptation options for high temperature stress. The choice of variety makes the difference between an increase and a decrease in yields in the north-east of the study region.

19.4 Discussion

19.4.1 *Adaptation to climate change*

The choice of crop variety is only one amongst many possible options for adaptation to high temperature threshold exceedance. Changes in planting date and irrigation levels provide alternative methods of continuing to grow the same crop in a climate with increased incidence of high temperatures. Broader adaptation options include a change to another crop type altogether. Furthermore, adaptation to climate change implies adaptation not only to temperature extremes, but also to other changes, such as those in rainfall, mean temperature and ambient CO_2 levels. Adaptation to these changes may involve the use of a crop with different thermal time and/or water requirements. Adaptation to CO_2 increases may involve changes in applied nutrient and irrigation levels, since the magnitude of the CO_2 fertilisation effect may depend upon these decisions (Tubiello and Ewert, 2002).

It is clear, then, that in determining effective adaptation strategies, it is important to consider all the impacts of CO_2 increases. The range of possible adaptation responses to these impacts depends upon the resources available and upon the uptake time for technological change (see e.g. Easterling et al., 2003); only when these factors are taken into consideration can vulnerability to climate change be assessed (Reilly and Schimmelpfennig, 1999). Ultimately, it is farmers who will have to adapt to climate change, and studies of potential adaptation measures need to be considered within the full socio-economic context of local farming practices (e.g. Easterling et al., 1993). This may mean that adaptation is considered in the context of responses on seasonal timescales (e.g. Gadgil et al., 1999; O'Brien et al., 2000; Kates, 2000).

19.4.2 *Research needs and opportunities*

The choice of crop model, and the way in which climate change simulations are used to drive the crop model, are an important factor in determining the results of an agricultural climate change impacts assessment (section 2.2). Crop models that simulate the impact of key processes, such as high temperature stress, provide an opportunity to quantify the relationship between greenhouse gas emissions and crop productivity (section 4). In particular, off-line studies present a pragmatic way to create the crop yield projections that are associated with climate change projections. Fully interactive crop-climate simulation, whilst being more computationally expensive and less widely tested, provides a tool for the investigation of the impact of coupled vegetation-atmosphere processes and of the diurnal cycle.

Whichever crop modelling methods are chosen, observations of crop yield are critical to the assessment of the accuracy of crop simulations. Many studies use proxies for observed yields, such as yields simulated by a crop model using observed weather (e.g. Hansen and Indeje, 2004). This is clearly problematic if we are to quantify the uncertainty associated with our projections. Ground-truthing of both crop and climate projections for the coming years and decades has an important role in ensuring the reliability of the scenarios that are developed.

19.5 Conclusions

An integrated approach to crop-climate modelling provides tools for the estimation of the vulnerability of food systems to climate variability and change. A number of recent advances have been highlighted: firstly, the simulation of yields under the current climate using the General Large-Area Model for annual crops is presented as a necessary condition for the simulation of the impacts of climate change using GLAM. Secondly, fully coupled GLAM-HadAM3 simulations allow simultaneous estimation of the impact of climate change on farming practices and on yield. Thirdly, off-line studies have shown the importance of crop variety as a means of adaptation to climate threshold exceedance. Fully coupled studies of the impact of climate thresholds would allow the impact of diurnal variability of temperature to be explicitly represented.

The further research needs and opportunities outlined in section 5.2 highlight the potential of both fully coupled and off-line large-area integrated crop-climate modelling. Key processes such as the impact on crop yield of high temperature stress, changes in rainfall and CO_2, and changes in management strategies, can be simulated using such a system. The assessment of the accuracy of yield simulation in current and evolving climates, and the associated data sets of observed yields, have an important role in the development of reliable yield projections with quantified levels of uncertainty.

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REFERENCES

Challinor, A. J., T. R. Wheeler and J. M. Slingo, 2005c: Simulation of the impact of high temperature stress on the yield of an annual crop. *Agricultural and Forest Meteorology* (accepted).

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

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, 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 (99–120).

Challinor, A. J., J. M. Slingo, T. R. Wheeler, P. Q. Craufurd, and D. I. F. Grimes (2003, February). Towards a combined seasonal weather and crop productivity forecasting system: Determination of the spatial correlation scale. *J. Appl. Meteorol.* 42, 175–192.

Doorenbos, J. and A. H. Kassam (1979). Yield response to water. FAO Irrigation and Drainage 33, FAO, Viale delle Terme di Caracalla, 00100 Rome, Italy.

Easterling, W. E., N. Chhetri and X. Niu (2003). Improving the realism of modelling agronomic adaptation to climate change: simulating technological substitution. *Climatic Change*, 60, 149–173.

Easterling, W. E., X. F. Chen, C. Hays, J. R. Brandle, and H. H. Zhang (1996). Improving the validation of model-simulated crop yield response to climate change: An application to the EPIC model. *Climate Research* 6 (3), 263–273.

Ferris R., Wheeler T. R., Ellis R. H. and Hadley P. (1999). Seed yield after environmental stress in soybean groan under elevated CO_2. *Crop Science* 39, 710–718.

Fischer, G., M. Shah, and H. van Velthuizen (2002). Climate change and agricultural vulnerability. Technical report, International Institute for Applied Systems Analysis. Available at http://www.iiasa.ac.at/Research/LUC/.

Gadgil, S., P. R. S. Rao, K. N. Rao, and K. Savithiri (1999, September). Farming Strategies for a variable climate. Technical Report 99AS7, CAOS, Indian Institute of Science, Bangalore 560012, India.

Hansen, J. W. and M. Indeje (2004). Linking dynamic seasonal climate forecasts with crop simulation for maize yield prediction in semi-arid Kenya. *Agric. For. Meteorol.* 125, 143–157.

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

Idso K. E and Idso S. B. (1994). Plant responses to atmospheric CO_2 enrichment in the face of environmental constraints: a review of the past 10 years' research. *Agricultural and Forest Meteorology* 69, 153–203.

IPCC (2001a). 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.

IPCC (2001b). 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 University Press. 1032 pp.

IITM (2004, December). Indian climate change scenarios for impact assessment. Technical report, Indian Institute of Tropical Meteorology, Homi Bhabha Road, Pune 411 008, India.

Jenkins, G. and J. Lowe (2003). Handling uncertainties in the ukcip02 scenarios of climate change. Technical note 44, Hadley Centre.

Kates, R. W. (2000). Cautionary tales: Adaptation and the global poor. *Clim. Change* 45 (1), 5–17.

Kimbal B. A. (1983). Carbon dioxide and agricultural yield; an assemblage and analysis of 430 prior observations. *Agronomy Journal*, 75, 779–788.

Luo, Q. Y. and E. Lin (1999). Agricultural vulnerability and adaptation in developing countries: The Asia-pacific region. *Clim. Change* 43 (4), 729–743.

Mavromatis, T. and P. D. Jones (1998). Comparison of climate change scenario construction methodologies for impact assessment studies. *Agric. For. Meteorol.* 91 (1–2), 51–67.

Mearns, L. O., W. Easterling, C. Hays, and D. Marx (2001). Comparison of agricultural impacts of climate change calculated from the high and low resolution climate change scenarios: Part I. the uncertainty due to spatial scale. *Clim. Change* 51, 131–172.

Mearns, L. O., T. Mavromatis, and E. Tsvetsinskaya (1999). Comparative response of EPIC and CERES crop models to high and low spatial resolution climate change scenarios. *J. Geophys. Res.* 104 (D6), 6623–6646.

Mitchell, R. A. C., Mitchell, V. J., Driscoll, S. P., Franklin, J. and Lawlor, D.W. (1993). Effects of increased CO_2 concentration and temperature on growth and yield of winter wheat at 2 levels of nitrogen application. *Plant Cell and Environment* 16, 521–529.

Ntare, B. R., J. H. Williams and F. Dougbedji, 2001: Evaluation of groundnut genotypes for heat tolerance under field conditions in a Sahelian environment using a simple physiological model for yield. *J. Ag. Sci.* 136, 81–88.

O'Brien, K., L. Sygna, L. O. Næss, R. Kingamkono, and B. Hochobeb (2000). Is information enough? user responses to seasonal climate forecasts in southern Africa. Technical Report ISSN: 0804–4562, Center for International Climate and Environmental Research – Oslo. Report to the World Bank, AFTE1-ENVGC. Adaptation to climate change and variability in sub-Saharan Africa, Phase II.

Osborne, T. M. 2004: Towards an integrated approach to simulating crop-climate interactions. Phd Thesis, University of Reading. pp. 184.

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

Parry M., Wheeler, T. R. and others (2001). Investigation of thresholds of impact of climate change on agriculture in England and Wales. Final report to the MAFF for Project CC0358.

Reilly, J. M. and D. Schimmelpfennig (1999). Agricultural impact assessment, vulnerability, and the scope for adaptation. *Clim. Change* 43 (4), 745–788.

Prasad, P. V. V., P. Q. Craufurd, R. J. Summerfield, and T. R. Wheeler (2000). Effects of short episodes of heat stress on flower production and fruit-set of groundnut Arachis hypogaea l. *J. Exp. Bot.* 51 (345), 777–784.

Semenov, M. A. and E. M. Barrow (1997). Use of a stochastic weather generator in the development of climate change scenarios. *Climatic Change* 35, 397–414.

Tubiello, F. N. and F. Ewert (2002). Simulating the effects of elevated co_2 on crops: approaches and applications for climate change. *Eur. J. Agron.* 18 (1–2), 57–74.

Tubiello, F. N., C. Rosenzweig, R. A. Goldberg, S. Jagtap, and J. W. Jones (2002). Effects of climate change on us crop production: simulation results using two different GCM scenarios. part I: Wheat, potato, maize, and citrus. *Climate Research* 20 (3), 259–270.

Wheeler T. R., Batts G. R., Ellis R. H., Hadley P. and Morison J. I. L. (1996a). Growth and yield of winter wheat (*Triticum aestivum*) crops in response to CO_2 and temperature. *Journal of Agricultural Science*, 127, 37–48.

Wheeler T. R., Hong T. D. Ellis R. H., Batts G. R., Morison J. I. L. and Hadley P. (1996b). The duration and rate of grain growth, and harvest index, of wheat (*Triticum aestivum* L.) in response to temperature and CO_2. *Journal of Experimental Botany*, 47, 623–630.

Wheeler T. R., Craufurd P. Q., Ellis R. H., Porter J. R. and Vara Prasad P.V. (2000). Temperature variability and the yield of annual crops. *Agriculture, Ecosystems and Environment*, 82, 159–167.

Wright G. C., Hubick K. T. and Farquahar G. D. (1991). Physiological analysis of peanut cultivar response to timing and duration of drought stress. *Australian Journal of Agricultural Research*, 42, 453–470.