Assessing the vulnerability of food systems to climate change thresholds using an integrated crop-climate model

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1. Abstract

The importance of extreme events and climate threshold exceedance for crop production is well-established. Such events are likely to become more common under climate change. We present a crop-climate modelling system which is capable of simulating the impact of threshold exceedance, changes in the mean and variability of climate, and adaptive measures. The use of crop variety types which are tolerant and non-tolerant to temperature thresholds is examined. The choice of variety can make the difference between an increase and a decrease in yields. The sensitivity of growing-season length and yield to climate is also examined. The results are presented in the context of impacts studies to date.

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 non-linearly with the climate change scenario used. Results are presented here for the A2 emissions scenario. Further results presented at the meeting will examine a range of scenarios.

2. Introduction

Much research to date has provided estimates of the impacts of climate change on food systems. This has demonstrated the importance of changes in seasonal mean weather, and of short-term extremes such as drought and high temperatures, on the productivity of crops. A common approach has been to simulate the impacts of human-induced climate change on crop productivity using 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. Most crop models are designed to run at small spatial scales. They can provide good simulations of crop productivity at the scale of fields, but not necessarily for regions. 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, resulting in a loss of information. An alternative approach is to design a crop model to operate on spatial and temporal scales close to the scale of the GCM output [1]. By using a large area process-based crop model, a more integrated modelling approach may reduce uncertainties in predictions of crop productivity over regions, and so perhaps provide better estimates of the vulnerability of crops to climate change. This paper aims to show how a more integrated crop – climate modelling system can be used to assess the impacts of climate variability and change on crop productivity.

2.1. Studies of the impacts of climate change on crop productivity 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 [2,3]. The treatment of crop growth and development in such assessments tends to be based on empirical methods (either parameterisations of crop model functions or direct use of statistical relationships such as those of [4]). 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 the more fundamental processes such as those related to changing CO2 levels, intra-seasonal weather variability, and threshold exceedance. When these processes begin to impact seriously on yield, statistical relationships developed under the current climate may no longer be valid [5].

A similar issue exists in considering how to use climate information for impacts studies. Daily time series from climate change simulations are often distrusted on account of low climate model skill for current climates. The resolution of the climate models can be too coarse to use as an input to a crop model. Hence weather generators are often used to generate downscaled time series for climate change scenarios based on changes, between the current and future climate, in the mean and the variability of weather [6]. 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 or may not remain constant as climate changes.

The variety of methods used leads to a large range of predictions and associated uncertainties. For example, whilst most impacts studies predict a reduction of maize yields in Africa (by up to 98% [7]) under climate change, some predict an increase.

2.2. The importance of extreme events and climate threshold exceedance

Floods, droughts and high temperature episodes are likely to become more frequent under climate change [8] and this will have an impact on crop productivity. 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 [9]. Important climate thresholds for food crops include episodes of high temperatures that coincide with critical phases of the crop cycle [10], as well as a change in the sub-seasonal distribution of rainfall [11]. Experimental studies have led research in this field and these are beginning to be understood in terms of simple physiology [12]. There is a need for modelling studies to incorporate this knowledge so that the impact of climate threshold exceedance can be simulated.

3. An integrated approach to impacts prediction

3.1. 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 [1]. Such a large-area model has the advantage of addressing the issues in section 2.1: 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. The issues outlined in section 2.2 are also addressed: intra-seasonal variability can be represented and the impact of temperature threshold exceedance is 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 climate and also diurnal temperature variability, which is important in determining the impact of temperature threshold exceedance.

3.2. The General Large-Area Model for Annual Crops

The General Large-Area Model for Annual Crops (GLAM; [13]) is a process-based crop model which has been designed by the authors. 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. Quantitative methods to simulate and predict the impacts of high temperature episodes have been included in the second version of GLAM, which is called GLAM-HTS (high temperature stress).

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.

3.3. 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 1 shows the ability of GLAM to capture interannual variability in yields when driven with observed weather data.

GLAM has also been used with reanalysis data [5] and seasonal hindcast ensembles [14]. This second study showed that an ensemble of crop yields can contain useful information in both the mean (figure 2) and in the spread (not shown).

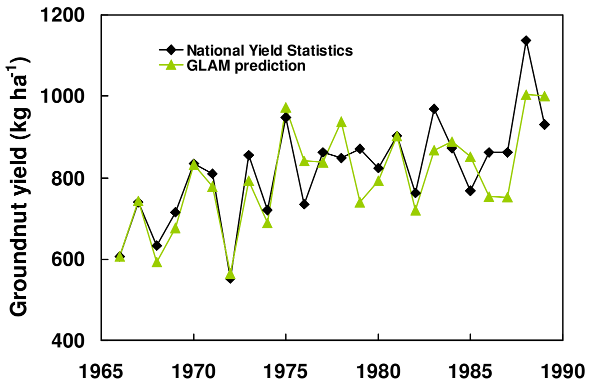

Figure 1: All-India groundnut yields simulated using GLAM on a 2.5° by 2.5° grid [13]. The time trend in the GLAM yields is taken from the (linear) time trend in observations.

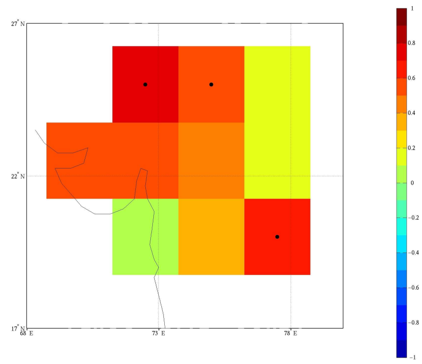

Figure 2: Correlation between observed and simulated yields [14]. Dots indicate 95% significance. The simulated yields were formed from an ensemble mean GLAM simulation of crop yield in Gujarat, India. Time series of yield were formed by driving the crop model with each individual ensemble member.

3.4. 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 [15,16].
- 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 yield and of growing seasons.

Accordingly, the crop growth and development formulations of GLAM have been incorporated into the land surface scheme of the Hadley Centre atmospheric GCM, HadAM3 [16]. Crop growth evolves in accordance with the simulated weather and climate of HadAM3. Initial evaluation of the coupled crop-climate model has focused on the simulation of groundnut by GLAM throughout the Tropics. Figure 3 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.

Figure 4 illustrates the capacity of HadAM3-GLAM to simulate interannual variability of growing season length. The timing and number of seasons are shown, as well as biomass production which is used to determine yield. For both the regions shown, the size of the crop at harvest varies widely from year to year. For the NW India grid point, the variability in the onset of the monsoon results in a large range of simulated

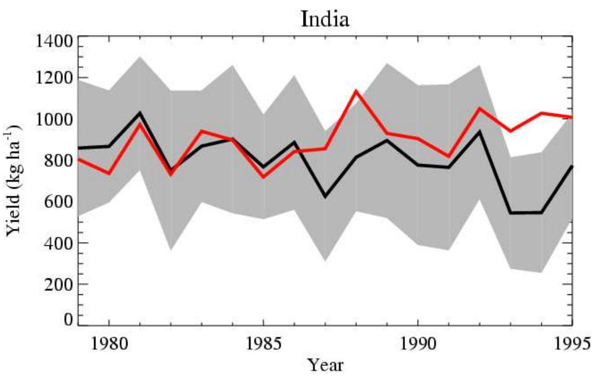

Figure 3 Observed FAO groundnut yield statistics (red line) with simulated mean values (black line) and spatial standard deviation (grey shading).

crop sowing dates. In general, 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, indicating a need for supplementary irrigation. These results illustrate the potential of the coupled model to assess the vulnerability of crop production to climate.

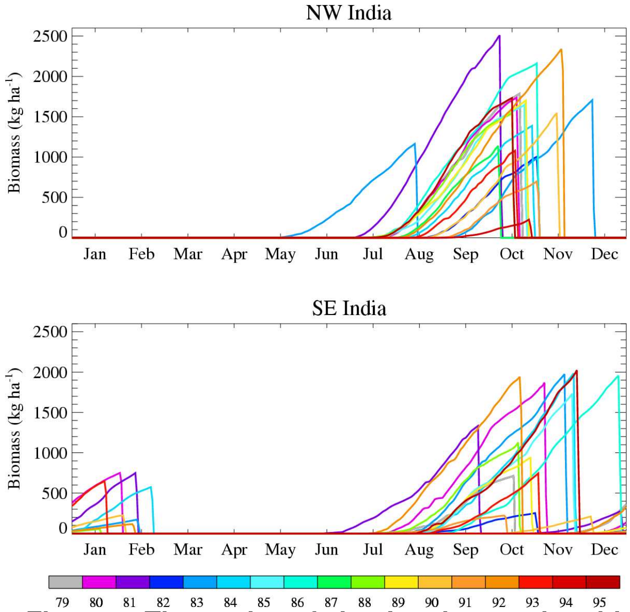

Figure 4. Timeseries of simulated groundnut biomass at two HadAM3 grid points in India, for the years 1979 – 1995.

4. Regional crop modelling study for India 2071-2100 under the A2 scenario

Use of GLAM with regional climate modelling data allows high resolution scenarios to be created. PRECIS [17] simulations from the DEFRA-funded Indo-UK project have been used with GLAM-HTS. Results from the A2 scenario show the potential importance of crop variety type (figure 5). 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 was sensitive, and one tolerant, to high temperature events. Whilst the broad pattern of change in yield under climate change was similar for each crop type, the sign of the change was different in parts of the north, and the magnitude of the change varies in the south-east. Thus, change in the characteristics of crop variety is one method of adaptation to climates with increased occurrence of high temperature threshold exceedance.

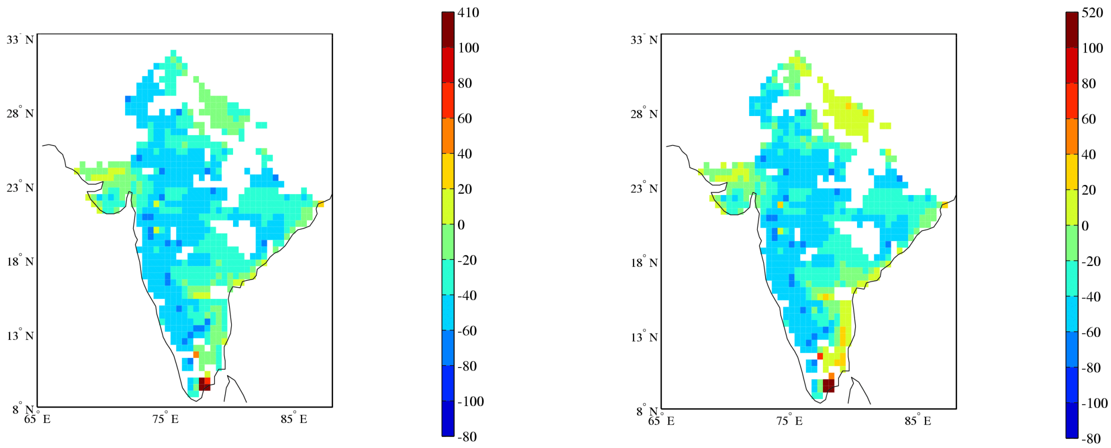

Figure 5: Percentage change in yields between control climate (1961-1990) and A2 scenario (2071-2100). Left panel shows a type of variety which is sensitive to temperature threshold exceedance. Right panel shows a more tolerant variety.

5. Conclusions

The integrated approach to crop-climate modelling provides tools for the estimation of vulnerability of food systems to climate variability and change. In particular, fully coupled simulations allow simultaneous estimation of the impact of climate change on farming practices and on yield. Off-line studies have shown the importance of crop variety type as a means of adaptation to climate threshold exceedance. Fully coupled studies of the impact of thresholds would allow the impact of diurnal variability to be represented.

The brief review in section two puts the results presented here in context. One suggestion in particular emerges: a consolidated effort from the research community is needed if studies of this type are to have the maximum impact on our understanding of the relationship between carbon emissions and crop productivity. Specifically, a full inter-comparison of the methods used, choosing a particular region, crop, and set of scenarios, would tell us how much we are truly sampling uncertainties and how much is due to methodology.

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