The development of combined weather and crop yield forecasting systems for the tropics

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Abstract

The productivity of crops in tropical regions is highly vulnerable to inter-annual and sub-seasonal climate variability. The strong climatic seasonal cycle in seasonally arid regions make these areas ideal for the study of the predictability of the impacts of weather on crop yield. Where predictability exists, it can be capitalised upon using pragmatic crop models that simulate key processes, together with accurate meteorological data and model output. This paper describes issues and progress in this area, principally using a case study of groundnut in India.

Media summary

Crop yield forecasts using combined climate and crop modelling systems enable estimation of the impacts of climate variability and change on world food production.

Key words

Crop modelling; Regional Climate Models (RCMs); General Circulation Models (GCMs); Rain Fall Estimates; climate variability and change; India

Introduction

The provision of food for an increasing global population presents huge challenges to governments worldwide. Much of the world's population relies for their food supply on annual crops grown in the tropics under rain-fed conditions. The productivity of crops in these regions is highly vulnerable to inter-annual and sub-seasonal climate variability, making productivity forecasts to aid planning of food supplies difficult. Climate change adds further uncertainty, with changes in mean climate and variability expected to have non-linear impacts on crop yields. Forecasting how risks to food production in the tropics may change over the coming decades thus presents a major research challenge. Understanding the impact of climate variability and change on crop yields is fundamental to the success of such research. It is also an essential step towards the development of key adaptive strategies to cope with climate change.

The impacts on crops of an increase in mean seasonal temperatures are now reasonably well understood. However, the magnitude of changes in mean precipitation and in sub-seasonal and inter-annual climate variability in future climates is less certain, and the resulting impacts on crop production are also uncertain. Large impacts on food production can occur when climate thresholds, such as temperature, are transgressed for short periods (e.g. Wheeler et al. 2000).

A key issue in modelling crop production over large areas is dealing with the disparity in spatial scale between the crop model and the climate prediction model. Crop models are generally designed to operate at the field level, and they rely on detailed field-scale inputs, such as the soil, plant genotype and weather, to predict yield and other crop variables at that scale. In contrast, climate prediction models have a much coarser resolution, typically from tens (in regional models) to hundreds of kilometres (Figure 1). These disparities need to be resolved in order for a coupled crop / climate modelling system to produce plausible results. A common approach is to adopt some form of downscaling of the climate, but this assumes no change (i.e. stationarity) in the statistics of the climate (and weather variability)—which may not be appropriate for a changing climate.

Over the last four years, our group has been developing a combined crop and climate forecasting system that takes a different approach. This modelling system couples crop simulation and numerical weather models on a common spatial scale based on observed weather/yield relationships (Figure 1; Challinor et al., 2003). As a result, we have simulated crop yield on a regional scale using output directly from Regional Climate Model (RCM) scenarios.

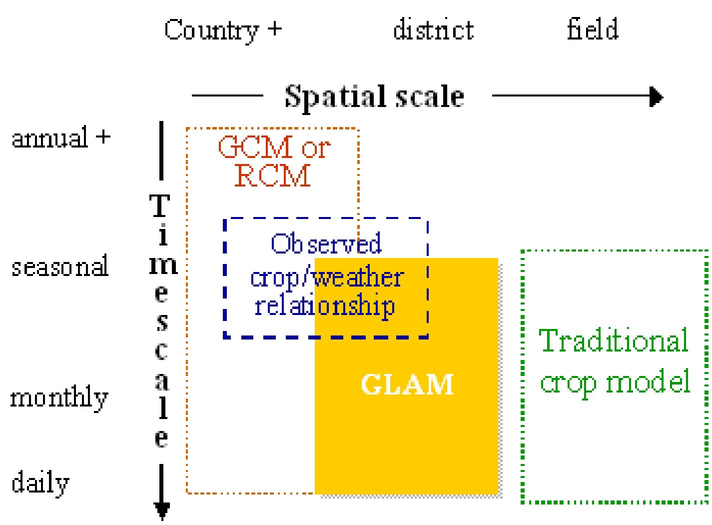

Figure 1: Schematic of the spatio-temporal scales of traditional crop models, General Circulation Models (GCMs), and the General Large-Area Model for annual crops (GLAM), which operates on the scale of the observed crop / weather relationship.

The General Large Area Model (GLAM) for annual crops

The General Large Area Model for annual crops (GLAM) is a process-based crop model with a daily time-step that can resolve the impacts of sub-seasonal variability in weather. The objective of the model is to reproduce the impact of weather on observed crop yield. This aim leads to two particular model characteristics. Firstly, complexity at a level far removed from yield-determining processes is omitted so that, in general, simple parameterisations are favoured over more complex methods. Hence, for example, photosynthesis is not modelled directly but is represented by a transpiration efficiency. Secondly, of the impacts on yield due to factors other than weather (pests, diseases, management factors, etc), only two are currently modelled explicitly: planting date and soil type. The rest, whilst in reality complex and varied, are modelled using a single yield-gap parameter. However, the modelling framework provided by GLAM will enable future development of more complex approaches to representing crop management and other factors that affect yield.

GLAM aims to combine the benefits of more empirical modelling methods with low input data requirements and validity over large areas with the benefits of a process-based approach (the potential to capture variability due to different sub-seasonal weather patterns). This means that the model is more likely to produce valid results under climate change than the pragmatic empirical models currently used in forecasts of seasonal productivity.

The model is flexible; changes in crop-specific parameter values allow simple and transparent operation across many annual crops. The development of GLAM has benefited from the detailed knowledge of crop behaviour in response to weather variability (e.g. temperature extremes at flowering) and climate change (e.g. CO_2 fertilization effects) obtained from experimentation at the Plant Environment Laboratory at The

University of Reading (http://www.rdg.ac.uk/pel/). To date, GLAM has been used to simulate groundnut, wheat, and maize. GLAM is fully described in Challinor et al. (2004a) and more details of the rationale can be found at http://www.met.rdg.ac.uk/~ajc/.

Results

Simulation of crop productivity at a country scale over 25 years

Using daily observations of rainfall, GLAM has been run at a sub-regional scale across India to simulate groundnut crop yield from 1966 to 1989. The optimal crop parameters were within observed reported ranges and were also stable over space and time, implying that crop growth and development were simulated realistically. The model accurately reproduced yields over large areas where there was a climate signal in the observed yields. The upscaled all-India yields matched well the yields recorded in national yields statistics (Figure 2). Of particular note is the ability of GLAM to reproduce much of the interannual variability in yield—a rare feat for crop simulation models—with, for example, good predictions in the extreme years of 1972 and 1975. Hence this simulation provides confidence that the GLAM system is able to capture the sensitivity of crop productivity to climate over a long time series.

The use of Reanalysis data in yield simulations

Accurate productivity forecasts will rely not only on crop simulation but on the quality of the input weather data. The simulation shown in Figure 2 used observed gridded data as input. However, climate model output is unlikely to be this accurate. Reanalysis data is output from General Circulation Models (GCMs) that have had observations assimilated into the analysis (see e.g. Annamalai et al. 1999). Hence reanalysis data are an ideal test-bed for a combined forecasting systems such as this. A study using GLAM with reanalysis data has shown that, where there is a climate signal, general circulation model output can also result in accurate simulation of the relationship between weather and yield (Figure 3), as well as accurate simulation of yield (Challinor et al. 2004b). Whilst the issue of GCM/RCM skill in representing the mean climate and its variability remains, it is encouraging to note that gridded model output can be used with some success. This is a particularly pertinent point when one considers that rainfall is the least reliable reanalysis output, whilst often being the most important weather variable for the simulation of crops and vegetation.

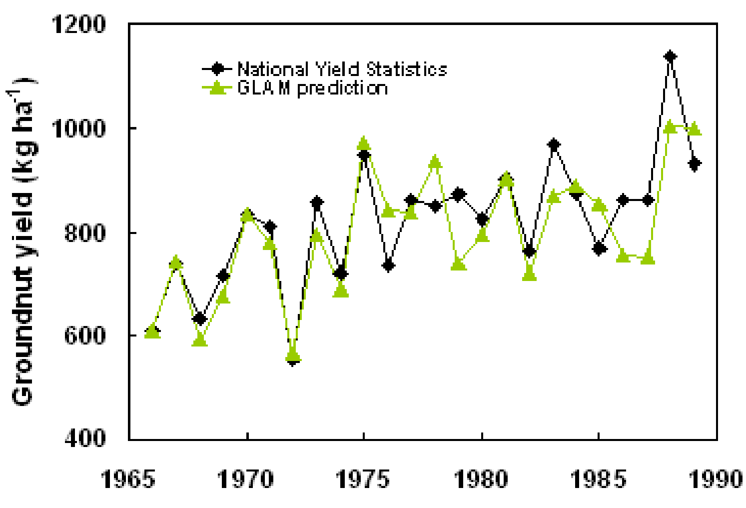

Figure 2: All-India groundnut yields simulated using GLAM on a 2.5? by 2.5? grid (Challinor et al., 2004a) using rainfall data from the Indian Institute of Tropical Meteorology. The simulation includes a specified linear technology trend.

Use of satellite rainfall estimates in the simulation of crop yield

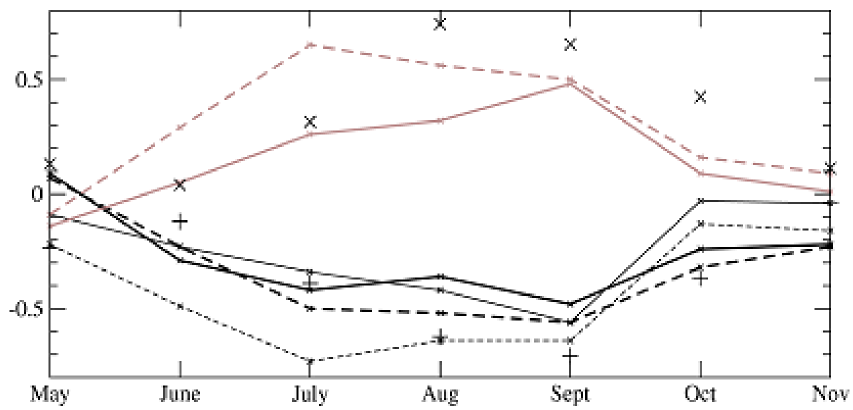

***Figure 3*: Observed (solid lines) and simulated (dashed lines) correlations, averaged over western Gujarat (13 grid points), between yield and ERA40 (i) net radiation (thin black lines), (ii) vapour pressure deficit (thick black lines) and (iii) precipitation (thick brown lines). Crosses show observed June and July precipitation correlations for a delayed sowing. Pluses mark the corresponding net radiation correlation. From Challinor et al. (2004b).**

Satellite estimates of rainfall provide excellent real-time input data for the combined system. Such rainfall estimates (RFEs) are often highly accurate for medium-to-low rainfall amounts but do not reproduce high rainfall amounts so well (Figure 4). Since high rainfall events are likely to produce high runoff and/or drainage, which is not then available to the crop, these errors may not be prohibitive. However, single rainfall events can be important if they occur during a dry spell. Use of GLAM with the two time series in Figure 4 results in yields which differ by more than 20%. Use of the RFE with the two indicated rain-gauge events inserted reduces that gap to less than 5%. Thus satellite data shows the potential to be used in a combined crop modelling system, but particular attention should be given to rainfall during dry spells.

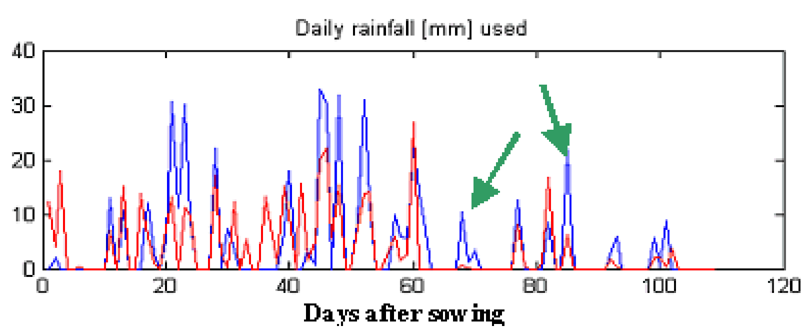

Figure 4: Raingauge (blue) and satellite-derived estimates (red) of rainfall (mm) for the Lower River Division of Gambia. Arrows indicate two key observed rainfall events not captured by the satellite estimate.

Probabilistic forecasting

GLAM is also currently being used with a multi-model ensemble of seasonal forecasts from the DEMETER project (http://www.ecmwf.int/research/demeter/). Ensembles of forecast simulations contain probabilistic information regarding the evolution of the weather over the season. This study addresses two questions:

(i) What is the impact on simulation skill of using GCM output and how should calibration, and potentially bias correction, be carried out?

(ii) How can the probabilistic nature of such long-range forecasts be exploited?

Question (ii) leads to the development of statistical methods to produce the best probabilistic yield forecast from a given set of climate realisations. Preliminary results show that useful predictions can result from the use of both the ensemble mean forecast, and from probabilistic methods which make use of individual ensemble members.

Quantification of the inherent uncertainty in the prediction of crop yields in future climates

Accurate prediction of yields under future climates relies upon an understanding of the inherent uncertainties. Changes in rainfall distribution, mean temperature, temperature variability and atmospheric CO_2 will have competing, interactive, and non-linear impacts on yields. In order to begin to understand these impacts, GLAM has been run with a future climate scenario from a Regional Climate Model (PRECIS; http://www.met-office.gov.uk/research/hadleycentre/models**/PRECIS)** over Gujarat, where there is a strong climate signal in groundnut yields. Initial results show that the impact of changing CO_2 levels on crop transpiration efficiency (from crop growth experiments) results in yields between one and two times the yields from control simulations with no CO_2 fertilisation, provided that other aspects of the climate remain the same. However, there are also regions where precipitation remains the limiting factor and no CO_2 effect is seen. Currently, the impact of exceeding high temperature thresholds (Wheeler et al., 2000) in future climates is being assessed, and preliminary results suggest that groundnut yields could be greatly affected by changes in mean temperature variability.

Conclusions

The studies summarised in the paper show that the integration of seasonal weather and crop yield forecasting systems using a large-area crop model is capable of high quality simulations. Ongoing work on probabilistic methods and future climate scenarios should further capitalise on the predictability that has been found. The success of the RFE-driven model suggests the possibility of operational applications. Future challenges include prediction in regions where the climate signal in crop yields is less strong.

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