Climate change impact on field crops and adaptation options in Southeastern Australia

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Abstract

As per International Panel on Climate Change a low, mid and high daily climate scenarios (2000-2070) were generated by using CSIRO's global atmosphere models. These scenarios were used as input to a crop model to predict the impact of climate change on wheat yield at Birchip (southeastern Australia). Generally, we found a strong and consistent positive trend in mean diurnal temperature range, followed by a significant negative trend in wheat yield under three climate scenarios with and without elevated CO_2 concentration. However, we found little evidence of climate change impacts in the rainfall data. We observed that from present climate to projected low, mid and high global warming scenarios, wheat yield may decrease by about 29%. Under these scenarios with an elevated atmospheric CO_2 climate, wheat yield may decrease by about 25%. This reduction in yield may be due to the combined effects of elevated CO_2 and warmer air temperatures resulting early high developmental rates and shorter phenophases.

Key Words

CropSyst, CCAM outputs, Carbon dioxide, Global warming, Simulation

Introduction

The Australian Bureau of Meteorology and others (e.g., International Panel on Climate Change, IPCC) has released detailed reports on the evidence of climate change in primary climatological data such as rainfall and temperature (Pittock, 2003). Australia's average temperatures have increased by 0.8?C since 1900 (DSE, 2004). This evidence leads to the question; what effect will climate change have on crop production? To partially answer this question, this study focuses on assessment of the impact of climate change on wheat crops from a representative rainfed cropping area of Victoria. The outputs of CSIRO's global atmosphere model (Hennessy *et al*., 2006) with projected low, mid and high level of climate change scenarios were used as inputs for a crop model to predict the impact of climate change on wheat yield. We highlight how the weather perturbations simulated by the climate model are reflected in the crop model outputs.

Methods

Future climate scenarios: The IPCC (2001) attributes most of the global warming observed over the last 50 years to greenhouse gases released by human activities. To estimate future climate change, the IPCC (SRES, 2000) prepared forty greenhouse gas and sulfate aerosol emission scenarios for the 21st century that combine a variety of assumptions about demographic, economic and technological driving forces likely to influence such emissions in the future. In this paper, three climate scenarios (low, mid and high) inline with IPCC (SRES, 2000) were generated using CSIRO's global atmosphere models (CCAM-Mark2 and CCAM-Mark3) (McGregor and Dix, 2001; Hennessy *et al*., 2006) integrated with annual global warming values (?C) (Fig. 1).

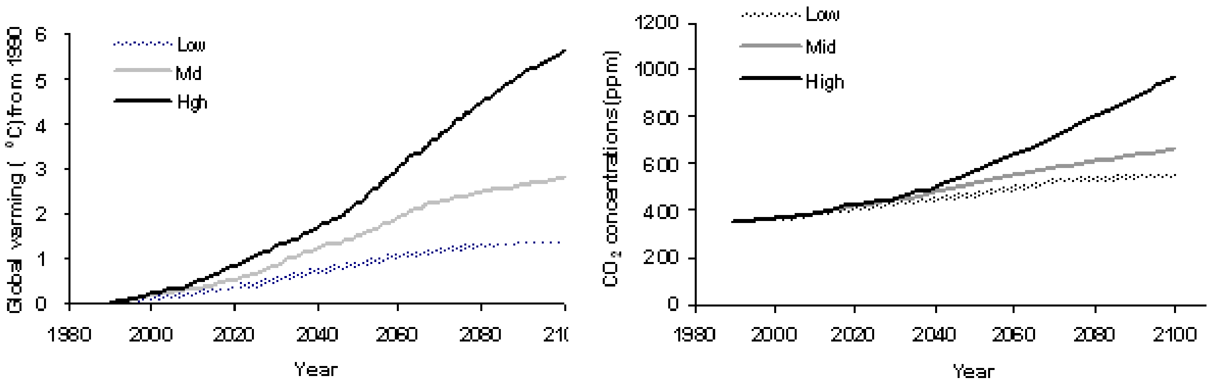


Figure 1. The annual global warming values (?C) and CO_2 concentrations (parts per million) for low, mid and high scenarios for years between 2000 and 2070 are relative to 1990 which is the IPCC (2001) standard baseline.

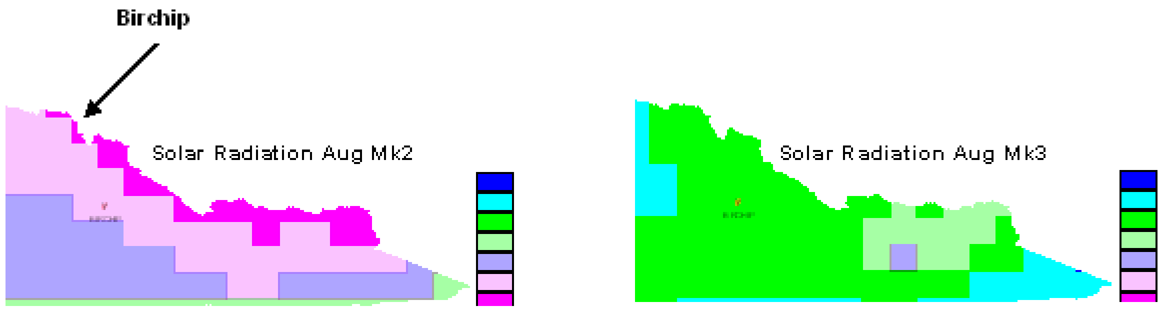
In this study, we considered Birchip (35.98?S, 142.92?E), as a representative rainfed wheat growing location in the southern Mallee region of Victoria. We determined patterns of climate change per degree of global warming on a monthly basis for four climate variables (rainfall, maximum and minimum temperature, and solar radiation) across Victoria (Hennessy *et al*., 2006). The pattern applied to 71-years (1935-2005) of daily data for Birchip (obtained from SILO patch-point) which was then used to create a 71-year future scenario from 2000 to 2070 by the method described by Suppiah *et al*. (2001). This method assumes that the identical variance of the historical data is applied to future climate but the monthly means are amended to reflect the future climate scenarios. As an example, Table 1 shows the procedure applied to generate daily future climate scenarios for maximum temperature for Birchip.

Table 1. Methodology to create daily future climate (2000-2070) scenarios using outputs of CSIRO's global atmosphere models (CCAM-Mark2 and CCAM-Mark3).

Step	Mathematical Expression
Create an anomaly series with no time-trend at Birchip. First, calculate trends for each calendar month for Birchip, then subtract the trend-increment from the daily data. This de-trended time-series will have a monthly mean of M. Second, subtract M to create a monthly anomaly time-series with a mean of zero, e.g., assume the January mean is MJan and the max temp trend is TJan ^{o}C/year at a Birchip, and the first year of record is 1935, then the de-trended anomaly value for the xth day of January in year 19yy is xJan19yy.	xJan19yy = xJan19yy(observed) - TJan * (19yy - 1935) - MJan
Estimate a baseline value (Baseline1990) for the year 1990, for each calendar month, based on the observed linear monthly trend from 1935 to 1990. This is needed to anchor the projections from the IPCC reference year of 1990.	Baseline1990Jan = MJan + TJan * (1990 - 1935) / 2

Xjan19yy is the de-trended xth day of *January maximum temperature for year 19yy* for Birchip (as above) (?C). Example B is 9 January 1965.	B = [37]
Incorporate CSIRO's global atmosphere models (CCAM-Mark2 and CCAM-Mark3) 50x50 km gridcell pattern (Pat) for Victoria (Fig. 2). We selected the cell containing Birchip for our analyses (PatB) (Fig.2). Pat is the *January pattern of change* for maximum temperature (?C per degree of global warming) from the climate model across Victoria. PatB is the selected Cell representing Birchip.	Pat = [1.1 1.1 1.1 PatB= [1.0] 1.1 1.0 1.0 1.0 0.9 0.8]
The *global warming database* (?C) contains low, mid and high values for each year (2000-2070) and will be used to scale de-trended observed daily data from years 1935 to 2005 for Birchip.	2000 low00 mid00 high00 2001 low01 mid01 high01 … 2030 low30 mid30 high30 ... 2070 low70 mid70 high70
We generated a daily maximum temperature scenario using the low global warming scenario. *x* is the day of the month. Values for the first (second, third, etc.) year in the de-trended observed time-series are scaled by the first (second, third, etc.) year in the global warming dataset. The process is the same for mid or high global warming scenario – this procedure was repeated for mid and high scenarios.	xJan2000 = xJan1935 + baseline1990Jan + (Pat * low00) xFeb2000 = xFeb1935 + baseline1990Feb + (Pat * low00) … xJan2001 = xJan1936 + baseline1990Jan + (Pat * low01) xFeb2001 = xFeb1936 + baseline1990Feb + (Pat * low01) … xJan2070 = xJan2005 + baseline1990Jan + (Pat * low70) xFeb2070 = xFeb2005 + baseline1990Jan + (Pat * low70)
To the right is a hypothetical example for 9 January 2030 maximum temperature (?C) derived from de-trended data for 9 January 1965 and the high global warming scenario	Assuming B and PatB values from above, and assuming high30=1.5 in the global warming database, then Jan2030High = [37.9]

A similar procedure was performed for minimum temperature, rainfall and solar radiation applying the relevant monthly pattern of change and global warming value to each observed daily matrix. As an example, Figure 2 shows the solar radiation pattern of change per degree of global warming for the month of August from CSIRO's global atmosphere models (CCAM-Mark2 and CCAM-Mark3).



(A) (B)

Figure 2. Solar radiation pattern of change per degree of global warming for the month of August from CSIRO's global atmosphere models. A: CCAM-Mark2 and B: CCAM-Mark3.

Yield simulation: Wheat yield simulation was undertaken using CropSyst version 4 (Stockle and Nelson, 2001), including a new module of response to elevated atmospheric CO_2. We generated an additional three input variables needed for CropSyst – i.e., relative humidity (%), dew point (?C) and wind speed (m/s) using CLIMGEN weather generator (Stockle *et al*., 1997). CropSyst calculates dry matter accumulation as a function of daily intercepted solar radiation and daily crop transpiration, using constant coefficients of radiation-use efficiency, RUE (Monteith, 1981), and transpiration efficiency, K (Tanner and Sinclair, 1983). Modifications were introduced to CropSyst in order to account for the effects of atmospheric CO2 concentration on plant growth and water use. These modifications are similar to those presented by Stockle *et al*. (1992), and are summarised in Table 2. For more information on CropSyst growth and water-use calculations, the reader is referred to Stockle *et al*. (1994) and Jara and Stockle (1999). For selecting values of Gratio, a coefficient used to increase daily crop RUE (Table 2), one differentiated between C3 (wheat, barley, sunflower, and soybean) and C4 crops (maize and sorghum), but assumed the same response for crops within each of the two classes. For a doubling of atmospheric CO2 from 350 to 700 ppm, potential crop growth was specified to increase by 25% for C3 crops, and by 10% for C4 crops. The performance of the model (CropSyst with CO_2) has been evaluated for diverse environments (e.g. Tubiello *et al*., 2000; Stockle *et al*., 1992).

Table 2. Equations for calculation of biomass production at given CO_2 concentrations in CropSyst[a]

Biomass production	B = Min (εIPAR, KT)
Effective transpiration efficiency	$K = k$/VPD
CO_2 dependence of ε	$\varepsilon = \text{Gratio}*\varepsilon_0$
CO_2 dependence of k	$K = \text{Gratio}*k_0/F$
CO_2 dependence of r	$r = r_0*([CO_2]/350)/\text{Gratio}$
CO_2 dependence of F	$F = (\delta + \gamma\,(r_0 + r_a)/r_a)/(\delta + \gamma\,(r + r_a)/r_a)$

[a]K = canopy water-use efficiency; IPAR = intercepted photosynthetically-active radiation; ε_0 = crop radiation-use efficiency at reference CO_2 concentration (350 ppm); ε = crop radiation-use efficiency at specified CO_2 concentration, $[CO_2]$; k_0 = crop water-use efficiency at reference CO_2 concentration; k = crop water-use efficiency at specified CO_2 concentration; T = crop transpiration at specified CO_2 concentration; VPD = air vapour pressure deficit; Gratio = ratio of potential growth at specified to reference CO_2 concentration; F = ratio of transpiration at specified to reference CO_2 concentration; r_0 = canopy resistance to water-vapour transfer at reference CO_2 concentration; r = canopy resistance to water-vapour transfer at specified CO_2 concentration; r_a = aerodynamic resistance to water-vapour transfer; δ = slope of the saturation vapor pressure function of temperature; γ = psychrometric constant.

Starting conditions (soil water, soil N and residues) for each simulation (long-term 1904-2005, and low, med and high scenarios from 2000-2070) were set on the 1st of January of each simulated year based on typical crop practices at Birchip so that the response in the yield over time was due solely to climate and not adaptive management or technological innovation occurrence. The CropSyst model has been previously satisfactorily tested against field studies in the Mallee region of southeastern Australia (Diaz-Ambrona *et al*. 2005).

Results and Discussion

The annual rainfall (Fig. 3), both in the historical and future scenarios is subject to significant natural variability, independent of the effects of climate change due to the enhanced greenhouse effect (DSE, 2004). The annual rainfall trend was negative (slope varies from -0.008 to -0.727, data not shown) though not statistically significant with median rainfall decreasing in low, mid and high scenarios. It is easier to identify periodicity in temperatures (Fig. 4) than in rainfall because of the homogenous nature of temperature data. Rainfall data, particularly at monthly frequencies and higher, have both discrete and continuous properties (i.e., either rain or no rain, with varying rainfall amounts) and can vary seasonally.

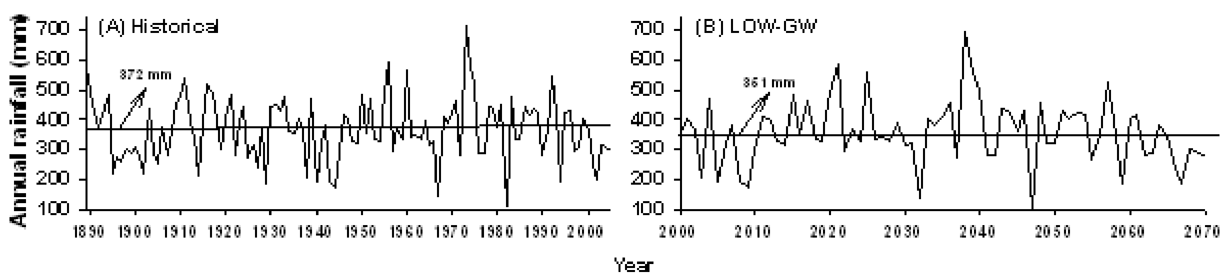


Figure 3. Highly variable annual rainfall at Birchip. Solid line indicates long-term median rainfall. A: Long-term historical (1889-2005) and B: Low global warming from 2000-2070.

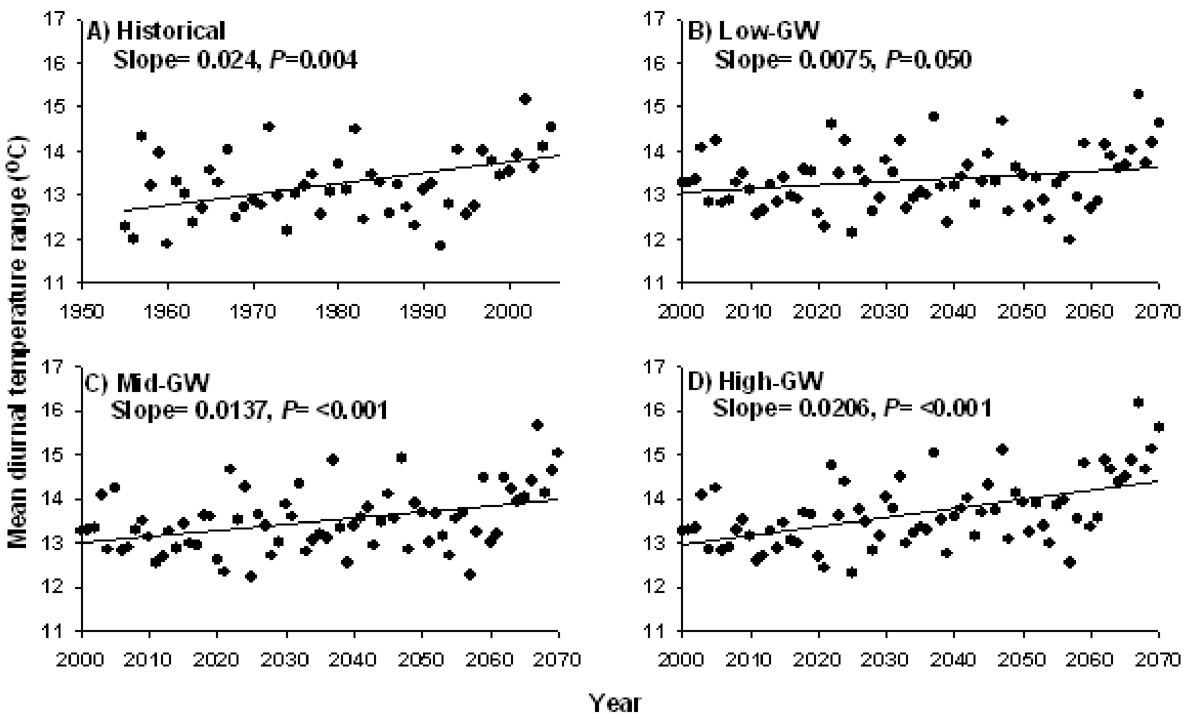


Figure 4. Mean diurnal temperature range (annual) showing a significant trend at Birchip. A: Historical (1957 – 2005), B: Low global warming scenario (GW from 2000-2070), C: Mid GW and D: High GW.

Long-term daily maximum and minimum temperature data prior to 1957 are quality issue at Birchip; hence data on temperature are analysed from 1957 to 2005 for historical and 2000 scenario is considered as the baseline for low, mid and high scenarios. Figure 4 summarises a significant positive temporal trend of mean diurnal temperature range at Birchip for historical and under low, mid and high scenarios. Projection for 2070 indicated a significant temperature change (data not shown). These projections suggest that by 2070 the period of coolest average maximum temperatures may be reduced by up to six weeks and, conversely, the period of average maximum temperatures above 30^{o}C may be extended by up to six weeks.

Figure 5 shows that the simulated wheat yield would decrease by about 29% from the present climate in the projected low, mid and high scenarios and by about 25% in the projected climates with enhanced CO_2. Median simulated wheat yield were highest (1651 kg/ha) in the historical long-term scenario (1904-2005) with a coefficient of variation (CV) of 42% and lowest (1151 kg/ha) in the high-global warming (GW) scenario (Fig. 5F) with high yield variability (CV=50%). Future wheat yield was highest (1436 kg/ha) under the low-GW scenario with enhanced CO_2 concentration (Fig. 5C). The yearly trend in wheat yield was significant and negative in all low, mid and high scenarios both with and without enhanced levels of CO_2.

It is difficult to say what is the main cause of this yield decrease, but a number of possibilities exist that may influence yields both positive and negative. Firstly, an increased temperature will shorten the phenological phases. This will reduce time for light and water capture and will also reduce both water and light use. A simultaneous anticipated decrease in rainfall will reduce water availability (e.g., Whetton *et al*., 1993). A second likely response is the C-fertiliser effect that is expected under an elevated CO_2 climate. Additional available carbon will create an initial yield increase, because of increased efficiency of use of light, water, nitrogen and other minerals such as phosphorous (Gifford *et al*., 2000, Drake *et al*., 1997, Barrett and Gifford, 1999). However, in the later decades (after 2050) under elevated CO_2 climate, the water-use efficiency reduced and yields declined. The benefits of a C-fertiliser effect have previously been discounted in regions where water supply is reduced (Amthor, 2001).

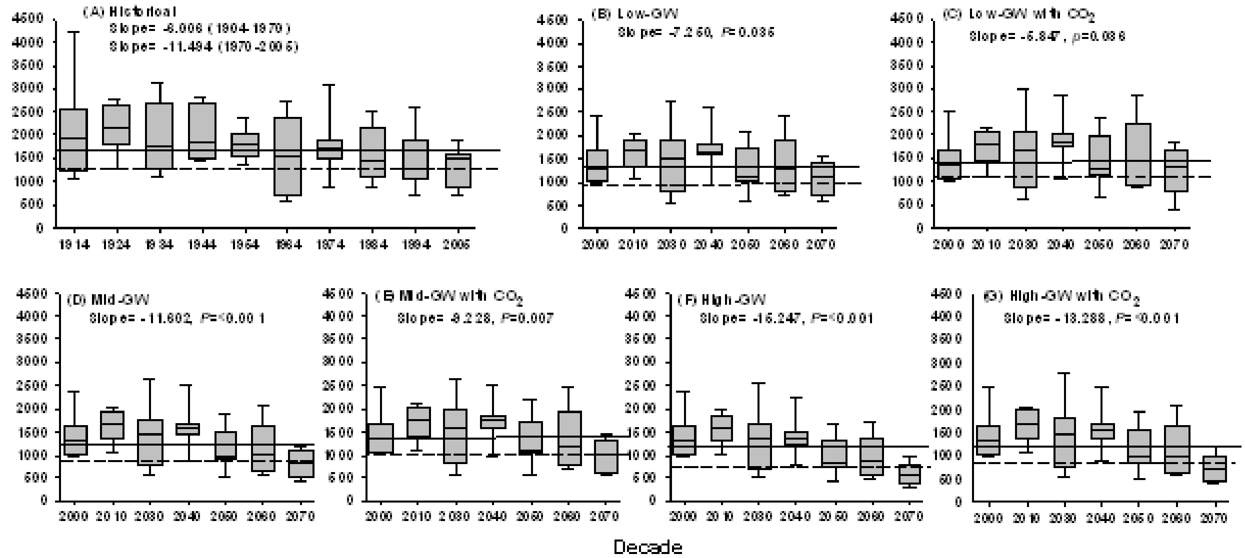


Figure 5. Boxplots of decadal wheat yield at Birchip. Dashed line indicates long-term 25% quartile and solid line is long-term median yield.

An increase in the mean diurnal temperature range (Fig.4), is likely to reduce the frost risk for winter crops. Thus, some benefits of climate change seem to be outweighed by the increasing temperature and slight reduction in water supply.

Strategies to adapt to climate change should concentrate on the greatest impact of higher temperatures and reduced rainfall and its effect on lowering crop yields. Such strategies include breeding more drought-tolerant cultivars, increasing water-use efficiency and better matching phenology to the new environmental conditions. In terms of management options available to farmers strategies that increase water supply such as stubble retention and reduced tillage should also become more important. Use of seasonal climate forecasts should also play an important part in reducing risk in climate variability. We have assumed that the current variability we see in the historical data is indicative of future climate variability, but it is possible that there might be increased variability making the management of dryland cropping systems even more problematic.

Conclusions

The projected climate change will have an apparently negative effect on wheat yield in northwestern Victoria. This effect will only partly be compensated for by increasing CO_2 availability. However, it may be possible to partially adapt to the new climate by breeding plants better adapted to that scenario and better managing water supply through practices such as stubble retention and reduced tillage. Changes of the magnitude indicated do suggest a need for growers and researchers to incorporate the changes into their policy decisions for the future.

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