Climate change impact on rainfed wheat in south-eastern Australia

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Abstract

Low, mid and high daily climate scenarios (2000–2070), as per the International Panel on Climate Change (IPCC) were generated using the Australian Commonwealth Scientific and Industrial Research Organisation’s (CSIRO’s) global atmosphere models. These scenarios based on IPCC’s 21st century emission scenarios that combine a variety of assumptions about demographic, economic and technological driving forces likely to influence such emissions in the future, were used as input to a crop model to predict the impact of climate change on wheat yield at a location in south-eastern Australia. At this locality there are important likely changes in the primary climatic variables of temperature, rainfall and solar radiation. 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 CO2 concentration. It is possible that negative trends identified over the future decades may be artefacts of the method of substituting historical variance for future variance. We observed that from present climate to projected low, mid and high global warming scenarios, median wheat yield may decrease by about 29%. Under these scenarios, but with an elevated atmospheric CO2 climate, median wheat yield may decrease by about 25%. The effect of elevated CO2 reduces the severity of the warmer air temperatures and lower rainfall but the effect is small (4%). Advances in agronomy and breeding must boost crop yields by around 25% over the coming decades, to keep in step with predicted climate change.

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1. Introduction

The Australian wheat industry is highly sensitive to climatic influences. The Australian Bureau of Meteorology and others (e.g., International Panel on Climate Change, IPCC) have released detailed reports on the evidence of climate change in primary climatological data, such as rainfall and temperature (Pittock, 2003). Rainfall has increased over the last 50 years over north-western Australia, but decreased in the southwest of Western Australia, and in much of south-eastern Australia, especially in winter (AGO, 2006). The changes are consistent with an observed increase in mean sea level pressure over much of southern Australia in winter. Atmospheric carbon dioxide (CO2) concentration may rise from the current levels (374 ppm) to between 520 and 720 ppm by the year 2070 (IPCC, 2001). Such changes in climate and CO2 levels would have potentially significant impacts on wheat yields in Australia as well as areas suitable for cropping wheat (Howden and Jones, 2001; Van Ittersum et al., 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 an assessment of the impact of climate change on wheat crops from a representative rainfed cropping area of Victoria, Australia, at Birchip (Fig. 1). The outputs of Australian Commonwealth Scientific and Industrial Research Organisation’s (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. The projected low, mid and high level of climate change scenarios are based on IPCC (SRES, 2000) greenhouse gas and sulfate aerosol emissions. These IPCC (SRES, 2000) emission scenarios for the 21st century combine a variety of assumptions about demographic, economic and technological driving forces likely to influence such emissions in the future. We highlight how the
weather perturbations simulated by the climate model would be reflected in crop performance. We also outline possible adaptations strategies to combat an expected climate change.

2. Methods

2.1. 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 40 greenhouse gas and sulfate aerosol emission scenarios for the 21st century that combine a variety of assumptions about demographic, economic and technologic driving forces likely to influence such emissions in the future. In this paper, three-climate scenarios (low, mid and high) inline with B2, A2 and A1F1 scenarios, respectively, of the IPCC (SRES, 2000) were generated using CSIRO’s global atmosphere models (McGregor and Dix, 2001; Hennessy et al., 2006) integrated with annual global warming values (°C) (Fig. 2). The CSIRO’s global atmosphere model (CCAM) simulation is driven by CSIRO’s Mark2 and Mark3 climate models, henceforth called CCAM (Mark2) and CCAM (Mark3). Both perform well over south-east Australia, although CCAM (Mark2) has a better simulation of average temperature. Hence, slightly more confidence can be placed in results from CCAM (Mark2). Climate projections from each model are considered independent since the Mark2 and Mark3 models have different parameterisations of physical processes. Regional climate change patterns from each model were expressed as a change per degree of global warming. This allows the results to be linearly scaled for any future year using the IPCC (2001) global warming estimates (Mitchell, 2003), which include the full range of IPCC SRES (2000) scenarios of greenhouse gas and aerosol emissions, and the full range of IPCC (2001) uncertainty in climate sensitivity to these emissions (Whetton, 2001).

In this study, we considered Birchip (35.98°S, 142.92°E) (Fig. 1), as a representative rainfed wheat growing location in the southern Mallee region of Victoria, Australia. This is a semi-arid region with an average annual rainfall of 368 mm, the long-term (1889–2005) average growing season (April–October) rainfall is 253 mm, the average minimum temperature in July is 3.6 °C and the average maximum temperature in January is 30.7 °C. The soils in the region are dominantly red-coloured Calcarosols (Nuttall et al., 2003) with about 94 mm plant available water capacity (PAWC). 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, http://plum.nre.vic.gov.au/silo/) 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 detrended historical data (1935–2005) is applied to future climate but the monthly means are amended to reflect the future climate scenarios. We also tested the assumption of substituting the historical variance for future variance by reversing the climatic sequence from 2005 to 1935. Table 1 shows by example the procedure applied to generate daily future climate scenarios for maximum temperature for Birchip, Victoria.

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. We observed changes in the monthly maximum and minimum temperatures, rainfall and solar radiation (percent per degree of global warming) and these changes

![Fig. 1. The Birchip (35°58′67″S, 142°54′58″E) study area at Victoria, Australia.](image-url)

![Fig. 2. The annual global warming values (°C) and CO₂ 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.](image-url)
To the right is a hypothetical example for 9 January 2030 maximum temperature (°C).

Pat is the January pattern of change. We generated a daily maximum temperature scenario using the low global warming database. 

Xjan19yy is the de-trended xth day of January maximum temperature for year 19yy.

Incorporate CSIRO’s global atmosphere models (CCAM-Mark2 and CCAM-Mark3) 50×50 km gridcell pattern (Pat) for Victoria (Fig. 1). We selected the cell containing Birchip for our analyses (PatB) (Fig. 1).

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.

The global warming database (°C) contains low, mid and high values for each year (2000–2070) and was used to scale de-trended observed daily data from years 1935 to 2005 for Birchip.

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.

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.

(positive or negative) have been applied in the methodology to create daily future climate (2000–2070) scenarios (Table 1). As an example for 1 month, Fig. 3 shows the solar radiation, rainfall, minimum and maximum temperature patterns of change per degree of global warming for the months of August, January and December, respectively, from CSIRO’s global atmosphere models (CCAM-Mark2 and CCAM-Mark3) for the state of Victoria, Australia (Fig. 1). Minimum and maximum temperature patterns have units of °C/°C and base climatology (average temperature for 1961–1990) units are °C. Rainfall patterns have units in %/°C and base climatology (average rainfall for 1961–1990) units are mm. Solar radiation patterns have units of %/°C and base climatology (average radiation for 1961–1990) units are MJ/m².

2.2. Yield simulation

Wheat (Triticum aestivum L. cv. Frame) yield simulation was undertaken using CropSyst version 4 (Stöckle and Nelson, 2001), including a new module of response to elevated atmospheric CO₂. 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 (Stöckle et al., 1997). CLIMGEN is based on historical data and is designed to preserve interdependence between variables as well as persistence and seasonal characteristics of each variable. 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). Crop parameters used in CropSyst were 3 g/MJ for above-ground RUE and 5 kPa/kg/m² for above-ground biomass-transpiration coefficient.

Starting conditions (soil water, soil N and residues) for each simulation (long-term 1904–2005, and low, med and high scenarios from 2000 to 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. Initial conditions for model simulations were reset to 10% of plant-
available water, 50 kg N/ha, and 1000 kg/ha of canola residues from previous crop. Every year, 50 kg N/ha were applied at sowing (i.e., 20 May). The CropSyst model has been previously satisfactorily tested against field studies in the Mallee region of south-eastern Australia (Diaz-Ambrona et al., 2005).

2.3. Simulation under elevated CO₂

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 Stöckle et al. (1992), and are summarised in Table 2. 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 assumes 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 transpiration efficiency coefficient ($k$) was also amended to be consistent with RUE adjustments after Tanner and Sinclair (1983) and increased transpiration efficiency due to lower transpiration. This involved amended transpiration as functions of canopy and air resistances and the fraction of intercepted radiation under a modified CO$_2$ environment compared to the base line environment (Table 2). The performance of the model (CropSyst with elevated CO$_2$) has successfully been evaluated for diverse environments (e.g., Tubiello et al., 2000; Stöckle et al., 1992).

### 3. Results

The projected climatic scenarios provide important observations. The most critical is the pattern of change seen in all variables (temperature, rainfall and solar radiation) where large gradients extend across the region of study (Fig. 3). There were differences in absolute changes between models (CCAM-Mark2 and CCAM-Mark3), but the direction of change was generally consistent. Consequently, we used the mean of both models for our future synthetic climate. At our study site (Birchip) in the month of August the CCAM-Mark2 model showed a 3% increase in solar radiation while the CCAM-Mark3 model showed no changes. In other months there were large predicted changes in temperature, rainfall and radiation (Fig. 3).

The historical annual rainfall at Birchip showed high variability with a negative trend toward the latter decades (Fig. 4). The drier periods are associated with El Niño Southern Oscillation (ENSO) (Power et al., 1998). In our projected climate for the three scenarios, we see a downward shift in the median annual rainfall. For the low global warming scenarios (low-GW) the annual rainfall is projected to be 351 mm compared to the historical value of 372 mm (Fig. 4). For the high global warming scenarios (high-GW) annual rainfall is projected to fall to 346 mm. Whilst the decline in annual rainfall seems small (7%) the distribution of rainfall in association with the shift in other variables is expected to have a large effect on crop production.

There are some quality concerns about the temperature data at Birchip prior to 1957, so our analysis excluded earlier data. We observed a significant positive (slope = +0.024 °C/year, $P = 0.004$) historical trend of mean diurnal temperature range at Birchip (Fig. 5A). Similarly, this trend was evident in all the future climate scenarios with the slope varying from +0.0075 to +0.0206 °C/year (Fig. 5B–D). An increase in the mean diurnal temperature range potentially can reduce the risk of frost risk for winter crops, but the rise in temperature will accelerate phenological development and shift the sensitive flowering stage to a higher frost risk window (Stone et al., 1996).

We observed significant decadal variability in simulated wheat yield in the historical data (Fig. 6A). The trend was negative with slopes ranging from −6.01 kg/ha/year from 1904 to 1970 and −11.5 kg/ha/year from 1970 to 2005 (Fig. 6A). The absolute yields are consistent with farm yield from the region (Rodriguez et al., 2006). Median 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-GW scenario (Fig. 6F) 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. 6C). Our analyses show that 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$_2$. The effect of elevated CO$_2$ is to minimise the negative effects of rising temperature and decreasing rainfall but it is unable to fully compensate (by 4%) for these more negative factors.
It is tempting to view the negative yield trends of the future scenarios as likely real trends because of the expected rising temperature and radiation changes and declining rainfall (see negative slopes $-5.86$ kg/ha/year to $-15.25$ kg/ha/year in Fig. 6). However, when we regenerated the future climate data using the reverse variance from 2005 to 1935 the trends were all positive (+7.25 kg/ha/year to +21.71 kg/ha/year), but the median negative changes were nearly identical to the analyses using the historical variance from 1935 to 2005 (Fig. 7).

Despite experiencing the historical or reverse historical variance in the future climate scenarios we conclude similar median crop yield declines (about 25–29% from current level) to occur at Birchip over the next 70 years without any genetic or agronomic improvement.

4. Discussion

This paper suggests that the projected climate change at Birchip in north-western Victoria will reduce wheat yields. There are a number of reasons why climate change may influence yields both positively and negatively. Firstly, an increase in temperature will shorten the phenological phases. This will reduce the time for light and water capture and will reduce water and light use. A simultaneous anticipated decrease

Fig. 5. Mean diurnal temperature range (annual) at Birchip, Victoria. (A) Historical (1957–2005) data, (B) low-global warming (GW) scenario, (C) mid-GW scenario and (D) high-GW scenarios data from 2000 to 2070.

Fig. 6. Boxplots of decadal wheat yield at Birchip, Victoria in the projected low, mid and high warming (low-GW, mid-GW and high-GW, respectively) scenarios with and without elevated CO$_2$ levels. Dashed line indicates long-term 25% quartile and solid line is long-term median yield. The line in the shaded box is the median yield, the box defines the 25th (lower) and 75th (upper) percentile and the ends of the vertical lines at whiskers define the 10th (lower) and 90th (upper) percentile yields.
in rainfall will reduce water availability (e.g., Whetton et al., 1993). Accelerated crop development and a short grain filling period will reduce wheat grain yield. While Mitchell et al. (1993) observed significant increases in winter wheat yields from a CO2 doubling at optimum temperature, high CO2 did not make up for yield losses when plants were grown at high temperatures that caused stress and a shortening of the grain filling period. A second likely response is the C-fertiliser effect that is expected under an elevated CO2 climate. While 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), in dry environments reduced water-use and water-use efficiency because of lower soil water availability and the shortened growth periods due to accelerated phenology will reduce yields. In dry environments with nutrient limitations the C-fertiliser effect has been considered small (Amthor, 2001). In general, our analyses concur with Luo and Mooney (1999) and Wolfe (1994) that the CO2 fertilisation effect cannot compensate for negative effects from other environmental stresses.

Climate variability is the consequence of an intrinsically non-linear and deterministically chaotic system (Ghil et al., 2002) and there are limits to what can be predicted about our future climate. We have attempted to analyse what might be achievable given such uncertain knowledge. Our analysis considers changes in temperature, solar radiation and rainfall unlike many other climate change studies. In many climate change impact studies (e.g., Tubiello, 1997; Tubiello et al., 1999; Howden and Jones, 2001; Ludwig and Asseng, 2006) the growth simulations only consider the predicted changes in mean temperature, elevated CO2 levels and precipitation ignoring future changes in solar radiation, and daily and interannual variability of all the climate variables. Had a larger variability of temperature and precipitation, and future solar radiation changes been included under climate change scenarios, as current studies indicate, the study might have resulted in more negative effects of climate change on simulated crop yields (Mearns et al., 1992). It is also possible that the equations used in present crop models (e.g., APSIM, CropSyst, CERES-wheat) to predict the effects of elevated CO2 on crop yield, based on the concept of radiation-use efficiency and transpiration efficiency and performed in daily time steps, are too simplistic to provide realistic predictions of yield. Some authors have argued that mechanistic feedbacks between photosynthetic rates and leaf stomatal conductance must be resolved, and that to this end smaller computing time-steps are necessary (Connor and Fereres, 1999; Grant et al., 1999).

One of the problems of climate change research is that the mean response is predicted but not the variance. But daily time-step models like CropSyst or APSIM need daily data that has some variance. The problem is what variance should be applied. Of course it is thought that the future climate will, become more varied so this is even more problematic. But to be conservative, Suppiah et al. (2001) and Watterson (2005) used the historical variance but applied in a way to preserve the historical auto-correlation. That is, a 10-year historical drought will be also present in the new climate but with different means following to the CGM predictions. It is this mirror image of the auto-correlation that is misleading with respect to trend, as demonstrated by our reverse analysis. But the mean response over the period is identical with either approach and it is therefore valid to rely on this analysis.

An important finding from our study is the problem of what variance to apply to future scenarios. 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. However, our reverse historical variance method highlights the uncertainty posed by this assumption and only the mean trends are likely to be indicative of the future crop performance in north-western Victoria.

Factors limiting crop responses to climate may include plant adaptation to CO₂, source-sink relationships, pest-crop interactions, and site-specific characteristics, such as soil structure, stoniness, salinity, etc. (e.g., Patterson and Flint, 1990). If these factors were incorporated in the simulation study, model predictions of crop response to elevated CO₂ and climate change might have predicted even more negative effects of climate change on crop yields (Mearns et al., 1992; Amthor, 2001; Van Ittersum et al., 2003). However, recently, Howden and Jones (2001) argue that enhanced production is possible if growers respond with appropriate adaptation strategies (up to 8% increase in mean production).

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. It is important to consider what constitutes climate change as either ‘beneficial’ or ‘disastrous’. In regions like southern Australia under a beneficial climate change, adaptations can extend the positive effects of increased CO₂ and temperature (up to 3°C) but only in scenarios where rainfall increases (Howden and Jones, 2001). In contrast, a drier climate may be considered as a disastrous scenario where wheat yield is reduced, especially on soils with low water storage capacity increasing the risk of crop failure (Wessolek and Asseng, 2006). Monocultures may also be more vulnerable to climate change, and changing to diversify agricultural production systems should allow farmers to cope better with climate variation from year to year (Bindi and Howden, 2004). In terms of management options available to farmers, strategies that increase water supply, such as stubble retention and reduced tillage. Changes of the magnitude indicated do suggest a need for farmers and researchers to work together to regain the predicted yield declines. There is clearly a need to maintain or even boost agricultural research investment along these lines.

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