Available online at www.sciencedirect.com
ScienceDirect
Field Crops Research 104 (2007) 139–147
Field Crops Research
www.elsevier.com/locate/fcr

# Climate change impact on rainfed wheat in south-eastern Australia

Muhuddin Rajin Anwar [a,*], Garry O'Leary [a], David McNeil [a], Hemayet Hossain [b], Roger Nelson [c]

[a] Department of Primary Industries, 110 Natimuk Road, Horsham, Vic. 3400, Australia
[b] Department of Primary Industries, 621 Sneydes Road, Werribee, Vic. 3030, Australia
[c] Biological Systems Engineering Department, Washington State University, Pullman WA 99164-6120, USA

Received 20 October 2006; received in revised form 19 December 2006; accepted 7 March 2007

## 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 $CO_2$ 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 $CO_2$ climate, median wheat yield may decrease by about 25%. The effect of elevated $CO_2$ 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.

*Keywords:* CropSyst; CCAM outputs; Carbon dioxide; Global warming; Simulation

## 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 ($CO_2$) 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 $CO_2$ 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

---

[*] Corresponding author. Tel.: +61 3 5362 2111; fax: +61 3 5362 2187.
*E-mail address:* muhuddin.anwar@dpi.vic.gov.au (M.R. Anwar).

0378-4290/$ – see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.fcr.2007.03.020

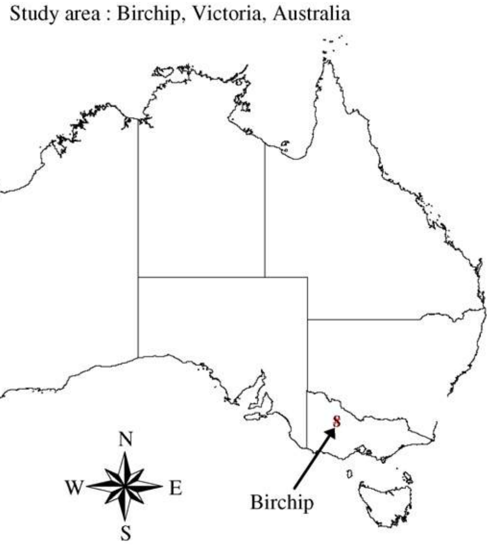

Fig. 1. The Birchip (35°58′67″S, 142°54′58″E) study area at Victoria, Australia.

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 de-trended 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

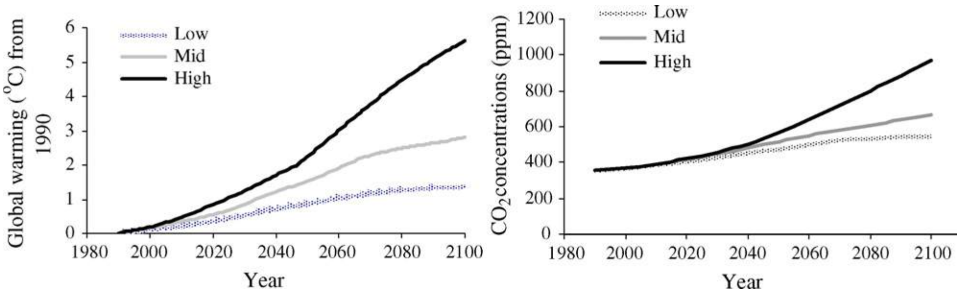

Fig. 2. The annual global warming values (°C) and $CO_2$ concentrations (parts per million) for low, mid and high scenarios for years between 2000 and 2070 are relative to 1990 which is the IPCC (2001) standard baseline.

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

| Step | Mathematical Expression |
|---|---|
| Create an anomaly series with no time-trend at Birchip. | xJan19yy = xJan19yy(observed) − TJan * (19yy-1935) − MJan |
| 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 °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. | |
| 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) 50×50 km gridcell pattern (Pat) for Victoria (Fig. 1). We selected the cell containing Birchip for our analyses (PatB) (Fig. 1). | Pat = [1.1 1.1 1.1 1.1 1.0 1.01.0 0.9 0.8] PatB = [1.0] |
| 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. | 2000 low00 mid00 high00<br>2001 low01 mid01 high01<br>⋮<br>2030 low30 mid30 high30<br>⋮<br>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)<br>xFeb2000 = xFeb1935 + baseline1990Feb + (Pat * low00)<br>⋮<br>xJan2001 = xJan1936 + baseline1990Jan + (Pat * low01)<br>xFeb2001 = xFeb1936 + baseline1990Feb + (Pat * low01)<br>⋮<br>xJan2070 = xJan2005 + baseline1990Jan + (Pat * low70)<br>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] |

(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/m$^2$.

### 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 $CO_2$. 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 (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/m$^3$ 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-

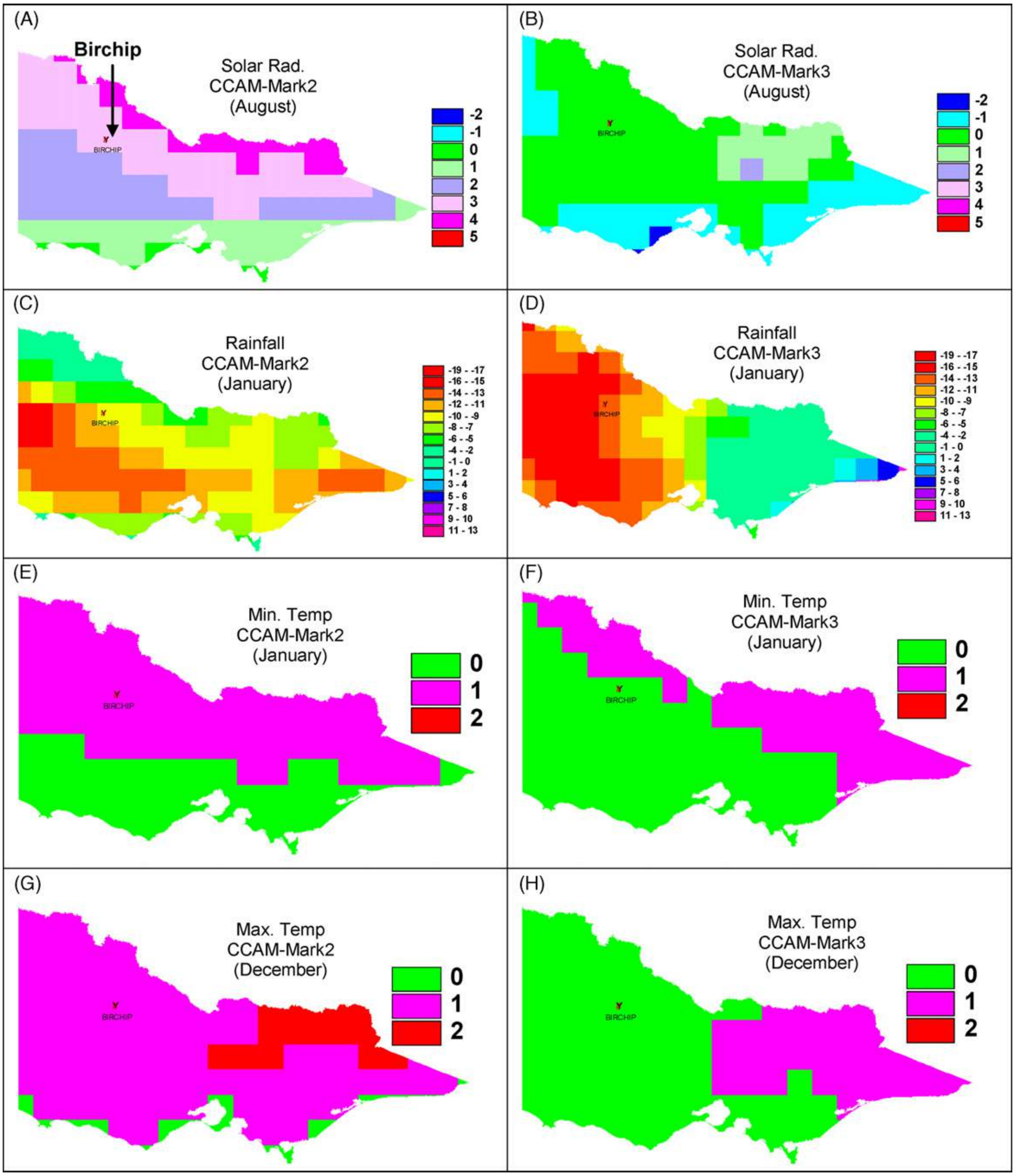

Fig. 3. Solar radiation (A and B), rainfall (C and D), minimum (E and F) and maximum (G and H) temperature patterns of change per degree of global warming in Victoria, Australia, for the months of August, January and December, respectively, from CSIRO's global atmosphere models (CCAM-Mark2 and CCAM-Mark3). Minimum and maximum temperature patterns have units of °C/°C of global warming (GW) and base climatology (average temperature for 1961–1990) units are °C. Rainfall patterns have units in %/°C of GW and base climatology (average rainfall for 1961–1990) units are mm. Solar radiation patterns have units of %/°C of GW and base climatology (average radiation for 1961–1990) units are MJ/m$^2$.

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 $CO_2$

Modifications were introduced to CropSyst in order to account for the effects of atmospheric $CO_2$ 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 $C_3$ (wheat, barley, sunflower and soybean) and $C_4$ crops (maize and sorghum), but assumes the same response for crops within each of the two classes. For a doubling of atmospheric $CO_2$ from 350 to 700 ppm, potential crop growth was specified to increase by 25% for $C_3$ crops and by 10% for $C_4$ crops.

Table 2
Equations for calculation of biomass production at given $CO_2$ concentrations in CropSyst

| | |
|---|---|
| Biomass production | $B = \text{Min}\ (\varepsilon\text{IPAR}, KT)$ |
| Effective transpiration efficiency | $K = k/\text{VPD}$ |
| $CO_2$ dependence of $\varepsilon$ | $\varepsilon = \text{Gratio}^*\varepsilon_0$ |
| $CO_2$ 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 $F$ | $F = (\delta + \gamma\ (r_0 + r_a)/r_a)/(\delta + \gamma\ (r + r_a)/r_a)$ |

$K$: canopy water-use efficiency; IPAR: intercepted photosynthetically active radiation; $\varepsilon_0$: crop radiation-use efficiency at reference $CO_2$ concentration (350 ppm); $\varepsilon$: 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; $\delta$: slope of the saturation vapor pressure function of temperature; $\gamma$: psychrometric constant.

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 project 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.

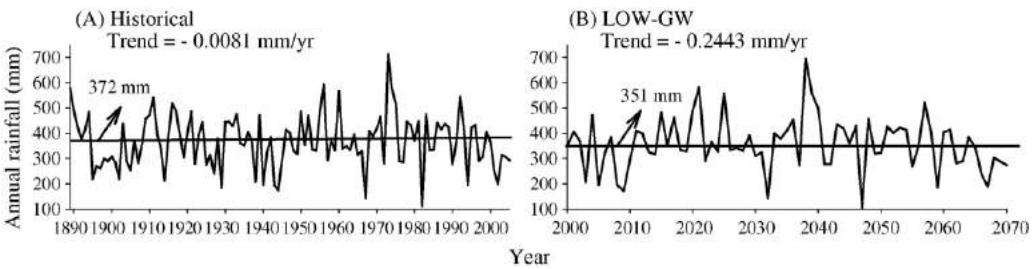

Fig. 4. Highly variable annual rainfall at Birchip. Solid line indicates long-term median rainfall. (A) Long-term historical (1889–2005) rainfall and (B) rainfall with the low global warming (low-GW) scenarios from 2000 to 2070.

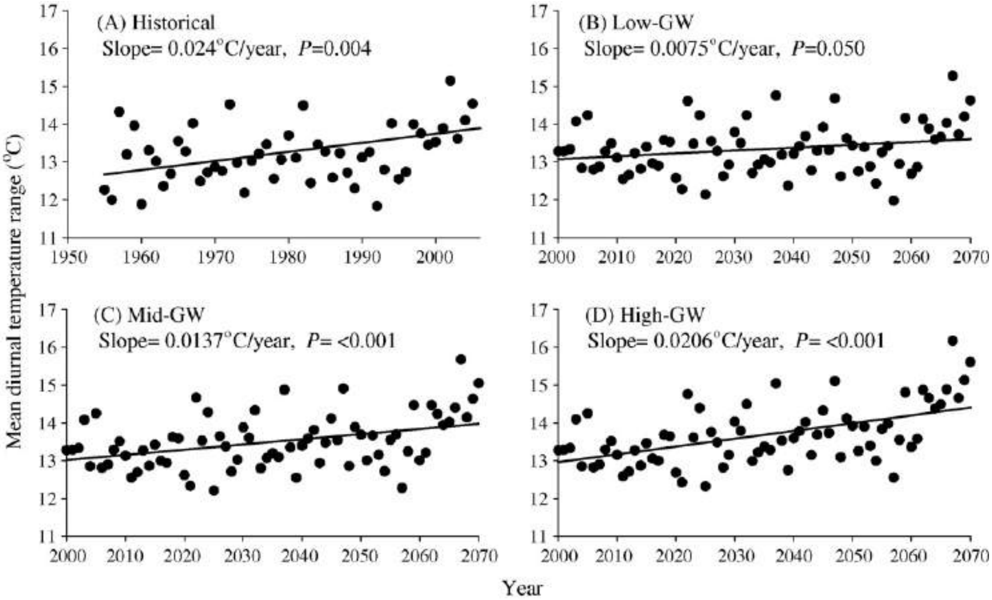

Fig. 5. Mean diurnal temperature range (annual) at Birchip, Victoria. (A) Historical (1957–2005) data, (B) low-global warming (GW) scenario, (C) mid-GW scenario and (D) high-GW scenarios data from 2000 to 2070.

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

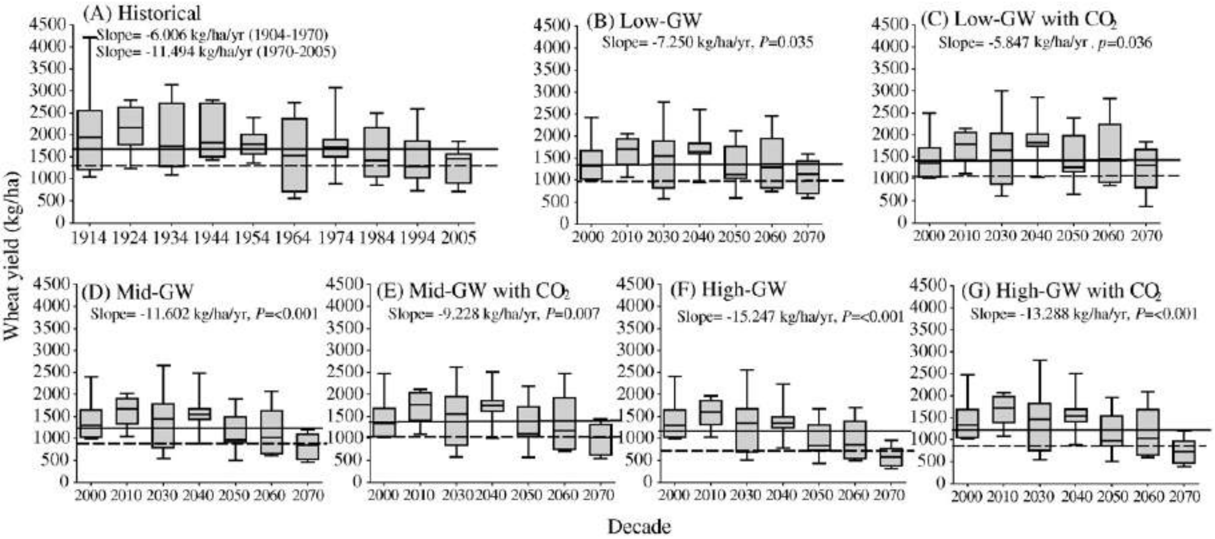

Fig. 6. Boxplots of decadal wheat yield at Birchip, Victoria in the projected low, mid and high warming (low-GW, mid-GW and high-GW, respectively) scenarios with and without elevated $CO_2$ levels. Dashed line indicates long-term 25% quartile and solid line is long-term median yield. The line in the 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.

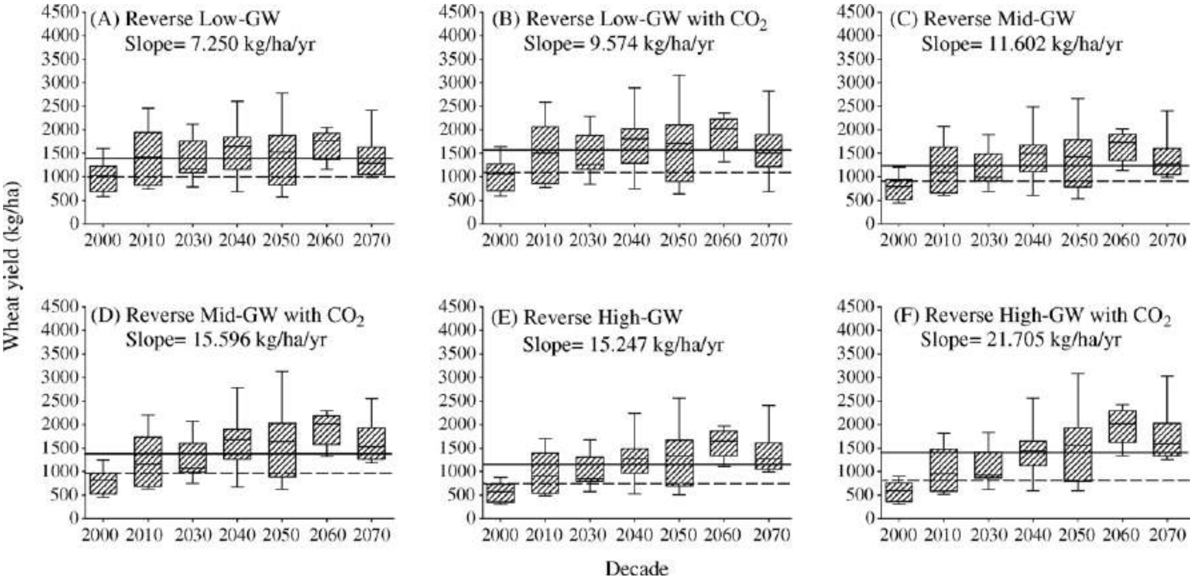

Fig. 7. Boxplots of decadal wheat yield at Birchip by reversing the historical variance (2005–1935) in the projected low (low-GW), mid (mid-GW) and high (high-GW) climate change scenarios. Dash line indicates long-term 25% quartile and solid line is long-term median yield. The line in the shaded box 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 $CO_2$ doubling at optimum temperature, high $CO_2$ 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 $CO_2$ 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 $CO_2$ 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 $CO_2$ 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 $CO_2$ 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 $CO_2$, 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 $CO_2$ 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 $CO_2$ 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 should also become more important. Use of seasonal climate forecasts could also play an important part in reducing risk in climate variability (Bindi and Howden, 2004).

Despite large yield declines predicted due to climate change, we do not see cause for alarm because it is possible, and indeed probable, that productivity advances in genetics and agronomy could overcome the negative trends, and indeed reverse the trend to higher crop yields by 2070. For this to occur, investment in plant breeding and agronomy should be maintained at present or increased levels (Howden and Jones, 2001).

## 5. Conclusions

The projected climate change will have an apparently negative effect on wheat yield in north-western Victoria. This effect will only partly be compensated by increasing $CO_2$ availability. However, it should be possible to 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 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.

## Acknowledgments

This study was supported by Primary Industries Research Victoria and the Grains Research and Development Corporation of Australia. We thank Prof. Ines Minguez, Victor Sposito and an anonymous referee for comments on an earlier manuscript.

## References

AGO 2006. Change Impacts & Risk Management—A Guide for Business and Government. ISBN: 1 921120 56 8, Australian Greenhouse Ofce. Department of the Environment and Heritage, GPO Box 787, CANBERRA ACT 2601, http://www.greenhouse.gov.au.

Amthor, J.S., 2001. Effects of atmospheric $CO_2$ concentration on wheat yield: review of results from experiments using various approaches to control $CO_2$ concentration. Field Crops Res. 73, 1–34.

Barrett, D.J., Gifford, R.M., 1999. Increased C-gain by an endemic Australian pasture grass at elevated atmospheric $CO_2$ concentration when supplied with non-labile inorganic phosphorous. Aust. J. Plant Physiol. 26, 443–451.

Bindi, M., Howden, M., 2004. Challenges and opportunities for cropping systems in a changing climate. In: New directions for a diverse planet. Proceedings of the 4th International Crop Science Congress, 26 September–1 October 2004, Brisbane, Australia, In: http://www.cropscience.org.au.

Connor, D.J., Fereres, E., 1999. A dynamic model of crop growth and partitioning of biomass. Field Crops Res. 63, 139–157.

Diaz-Ambrona, C.G.H., O'Leary, G.J., Sadras, V.O., O'Connell, M.G., Connor, D.J., 2005. Environmental risk analysis of farming systems in a semi-arid environment: effect of rotations and management practices on deep drainage. Field Crops Res. 94, 257–271.

Drake, B.G., Gonzales-Meler, M.A., Long, S.P., 1997. More efficient plants: a consequence of rising atmospheric $CO_2$? Annu. Rev. Plant Physiol. Mol. Biol. 48, 609–939.

DSE 2004. Victoria in Future 2004–Overview report. State of Victoria, Department of Sustainability and Environment 2004. ISBN: 1 74106 8746. In: http://www.dse.vic.gov.au/DSE/dsenres.nsf/LinkView/8B232276A311D5F1CA256EF6001BCFE706C7DF80826B65674A256-DEA002C0DCA.

Ghil, M., Allen, M.R., Dettinger, M.D., Ide, K., Kondrashov, D., Mann, M.E., Robertson, A.W., Sounders, A., Tian, Y., Varadi, F., Yiou, P., 2002. Advanced spectral methods for climatic time series. Rev. Geophys. 40, 1–41.

Gifford, R.M., Barrett, D.L., Lutze, J.L., 2000. The effects of elevated $CO_2$ on the C:N and C:P mass ratios of plant tissues. Plant Soil 224, 1–14.

Grant, R.F., Wall, G.W., Kimball, B.A., Frumau, K.F.A., Pinter, P.J., Hunsaker, D.J., LaMorte, R.L., 1999. Crop water relations under different $CO_2$ and irrigation: testing of ecosys with the free air $CO_2$ enrichment (FACE) experiment. Agric. For. Metereol. 95, 27–51.

Hennessy, K., Page, C., Durack, P., Bathols, J., 2006. Climate Change Projections for Victoria. CSIRO Marine and Atmospheric Research, Aspendale, Victoria 3195.

Howden, M., Jones, R., 2001. Costs and benefits of CO2 increase and climate change on the Australian wheat industry. Report to the Science, Impacts & Adaptation Section of the AGO.

IPCC, 2001. Summary for Policymakers. In: Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., Van Der Linden, P.J.,Xioaosu, D. (Eds.), 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, Cambridge, 944 pp.

Ludwig, F., Asseng, S., 2006. Climate change impacts on wheat production in a Mediterranean environment in western Australia. Agric. Syst. 90, 159–179.

Luo, Y., Mooney, H.A. (Eds.), 1999. Carbon dioxide and environmental stress, Academic Press, New York.

McGregor, J.L., Dix, M.R., 2001. The CSIRO conformal-cubic atmospheric GCM. In: Hodnett, P.F (Ed.), IUTAM Symposium on Advances in Mathematical Modelling of Atmosphere and Ocean Dynamics, Kluwer Dordrecht, pp. 197–202.

Mearns, L.O., Rosenzweig, C., Goldberg, R., 1992. Effects of changes in interannual climatic variability on CERES wheat yields: sensitivity and 2 x $CO_2$ general circulation model studies. Agric. For. Meteorol. 62, 159–189.

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

Mitchell, T.D., 2003. Pattern scaling—an examination of the accuracy of the technique for describing future climates. Climatic Change 60, 217–242.

Monteith, J.L., 1981. Climatic variations and the growth of crops. J. R. Met. Soc. 107, 749–774.

Nuttall, J.G., Armstrong, R.D., Connor, D.J., Matassa, V.J., 2003. Interrelationships between edaphic factors potentially limiting cereal growth on alkaline soils in north-western Victoria. Aust. J. Soil Res. 41, 277–292.

Patterson, D.T., Flint, E.P., 1990. Implications of increasing carbon dioxide and climate change for plant communities and competition in natural and managed ecosystems. In: Kimball, B.A., Rosenberg, N.J., Allen, Jr., L.H. (Eds.), Impact of Carbon Dioxide, Trace Gases, and Climate Change on Global Agriculture. ASA Special Publication 53, Madison, Wisonsin, pp. 83–111.

Pittock, B. (Ed.), 2003. Climate Change: An Australian Guide to the Science and Potential Impacts. Australian Greenhouse Office, Canberra.

Power, S., Tseitkin, F., Torok, S., Lavery, B., Dahni, R., McAvaney, B., 1998. Australian temperature, Australian rainfall and the Southern Oscillation 1910–1992: coherent variability and recent changes. Aust. Meteorol. Mag. 47, 85–101.

Rodriguez, D., Nuttall, J., Sadras, V.O., van Rees, H., Armstrong, R., 2006. Impact of subsoil constraints on wheat yield and gross margin on fine-textured soils of the southern Victorian Mallee. Aust. J. Agric. Res. 57, 355–365.

SRES 2000. *Special Report on Emission Scenarios:* Summary for Policymakers. A Special Report of Working Group 111 of the Intergovernmental Panel on Climate Change Cambridge University Press, Cambridge, UK, 27 pp. http://www.ipcc.ch/pub/sres-e.pdf.

Stöckle, C.O., Williams, J.R., Rosenberg, N.J., Jones, C.A., 1992. A method for estimating the direct and climatic effects of rising atmospheric carbon dioxide on growth and yield of crops: Part I Modification of the EPIC model for climate change analysis. Agric. Syst. 38, 225–238.

Stöckle, C.O., Campbell, G.S., Nelson, R., 1997. ClimGen for Windows, a weather generator program. Biological Systems Engineering Department, Washington State University, Pullman, WA, http://www.bsyse.wsu.edu/climgen.

Stöckle, C.O., Nelson, R., 2001. Cropping System Simulation Model User's Manual. Biological Systems Engineering Department, Washington State University. Available at http://www.bsyse.wsu.edu/cropsyst/.

Stone, R.C., Nicholls, N., Hammer, G.L., 1996. Frost in NE Australia: trends and influences of the Southern Oscillation Index. J. Climate 9, 1896–1909.

Suppiah, R., Whetton, P.H., Hennessy, K.J., 2001. Projected changes in temperature and heating degree-days for Melbourne, 2003–2007: a report for GasNet. Aspendale, Vic.: CSIRO Atmospheric Research, 19 p. http://www.cmar.csiro.au/e-print/open/suppiah_2001b.pdf.

Tanner, C.B., Sinclair, T.R., 1983. Efficient water use in crop production: research or re-search? In: Taylor, H.M., Jordan, W.R., Sinclair, T.R. (Eds.), Limitations to Efficient Water Use in Crop Production. Am. Soc. Agron. Crop Sci. Soc. and Soil Sci. Soc. Am., Madison, WI, USA, p. 154.

Tubiello, F.N., 1997. Global climate models. 3-D representations of the earth's climate system. In: Cross, B. (Ed.), World Directory of Environmental Testing, Monitoring and Treatment 1997:98. James & James, London, UK, pp. 110–114.

Tubiello, F.N., Rosenzweig, C., Kimball, B.A., Pinter Jr., P.J., Wall, G.W., Hunsaker, D.J., Lamorte, R.L., Garcia, R.L., 1999. Testing CERES-wheat with FACE data: $CO_2$ and water interactions. Agron. J. 91, 1856–1865.

Tubiello, F., Donatelli, M., Rozenweig, C., Stöckle, C.O., 2000. Effects of climate change and elevated $CO_2$ on cropping systems: model predictions at two Italian locations. Eur. J. Agron. 13, 179–189.

Van Ittersum, M.K., Howden, S.M., Asseng, S., 2003. Sensitivity of productivity and deep drainage of wheat cropping systems in a Mediterranean environment to changes in $CO_2$, temperature and precipitation. Agric. Ecosys. Environ. 97, 255–273.

Watterson, I.G., 2005. Simulated changes due to global warming in the variability of precipitation, and their interpretation using a gamma-distributed stochastic model. Adv. Water Res. 28, 1368–1381.

Wessolek, G., Asseng, S., 2006. Trade-off between wheat yield and drainage under current and climate change conditions in northeast Germany. Eur. J. Agron. 24., 333–342.

Whetton, P.H., Fowler, A.M., Haylock, M.R., Pittock, A.B., 1993. Implications of climate change due to the enhanced greenhouse effect on floods and droughts in Australia. Climate Change 25, 289–317.

Whetton, P.H., 2001. Methods used to prepare the ranges of projected future change in Australian region temperature and precipitation. CSIRO Technical Report, http://www.dar.csiro.au/impacts/docs/how.pdf.

Wolfe, D.W., 1994. Physiological and growth responses to atmospheric $CO_2$ concentration. In: Pessarakli, M. (Ed.), Handbook of Plant and Crop Physiology. Marcel Dekker, New York.