Do Changes in Climatic Variability Matter in Agricultural Impact Assessment?

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Abstract: Daily outputs of the CSIRO Conformal Cubic Atmospheric Model (C-CAM) for the periods of 1961-1990 and 2065-2094 were used in this study to derive changes in mean climate and in climatic variability which were used by the LARS-WG to generate climatic change scenarios for three sites in southeast Australia. Climatic scenarios were coupled with the Agricultural Production System sIMulator (APSIM)-Wheat/Canola models to identify the influence of changes in climatic variability on wheat and canola production at three sites (Condobolin, Nhill and Wagga Wagga). Changes in climatic variability had negative effects on average wheat and canola yield at Wagga Wagga and Condobolin. Changes in climatic variability in most cases had a negative effect on the coefficients of variation (CV) of wheat yield. Changes in climatic variability had both positive (50% of the cases) and negative (50% of the cases) effects on the CV of canola yield. Changes in climatic variability had no (50% of the cases) or positive (50% of the cases) effects on the average harvest index (HI) of wheat while they had no (67% of cases) or negative (33% of cases) effects on the average HI of canola. Negative effects of changed climatic variability on the CV of HI for both crops were found. Our results demonstrate that the effects of changes in climatic variability on crop production vary across locations and impact indicators. Changes in climatic variability therefore need to be taken into account in agricultural impact assessment.

Key words: Australia, Climatic Change, Climatic Variability, Crop Yields, Harvest Index, LARS-WG

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1. INTRODUCTION

A feature of previous agricultural impact assessment is that changes in mean climate such as rainfall, maximum temperature and minimum temperature were used in crop models to quantify their effects on crop production. The possible impacts on crop production of changes in climatic variability (e.g., in the length of wet and dry spells, and in temperature variability) have been ignored in most previous studies. The focus on mean climatic change has provided useful but limited information on how future changes in climatic variability (through extreme events such as drought and extreme high temperatures) might affect agriculture (Mearns et al. 1997). It has long been recognised that changes in climatic variability can have serious effects on agricultural yield (Parry and Carter 1985). One of the main means by which crops are affected is through changes in the frequency of extreme climatic events (e.g., heat waves, droughts) (Mearns et al. 1984, Semenov and Barrow 1997). Changes in climatic variability have a greater effect on the frequency of extremes than changes in mean climate (Katz and Brown 1992). The possible impact of changes in climatic variability aroused attention in the early 1990s.

Several earlier studies have tested the sensitivity of crop yield to changes in climatic variability using arbitrary changes in the variability of temperature and of rainfall (Mearns et al. 1992, 1996, 1997, Riha et al. 1996, Luo and Lin 1999). The potential impacts of changes in climatic variability and in mean climate (derived from GCM outputs) on crop production have also been performed. For instance, Semenov and Barrow (1997) examined the importance of changes in climatic variability on wheat yields in Spain based on outputs of a transient GCM (UKTR) and found that there were significant differences in the distribution of wheat yield once changes in climatic variability were taken into account. Mearns et al. (1997) investigated the impacts of changes in climatic variability on wheat yields in the USA by using the outputs of a RCM. Torriani et al. (2007) quantified the effects of changes in mean climate and in climatic variability on the yield of winter and spring crops in Switzerland. There has been recent progress in this field, with expanded computer resource volume, daily outputs of GCMs/RCMs ever more widely available, and longer term simulation of GCMs/RCMs at daily time steps, enabling stable signals of climatic change to be obtained. There has also been progress in GCM performance in simulating the behaviour of climatic variability, in downscaling techniques, and in the coupling techniques between the outputs of GCMs/RCMs and crop models. For example, Semenov (2007) developed a methodology for incorporating changes in climatic variability into climatic change scenarios for agricultural risk assessment. Climatic change scenarios constructed in this study are more robust than the direct use of the 30-year downscaled daily outputs of GCMs as the later may encompasses bias from climate model itself without integrating with historical climate data. Another advantage of this approach is that longer time series climatic change scenarios can be generated which is appropriate for risk assessment rather than short period of time series such as 30 years. These advances stimulated us to study the potential impacts of changed climatic variability on cropping systems in southeast Australia. Building on recent developments in climatic change modelling, our study aims to quantify the effects of changes in climatic variability on crop production in southeast Australia. Our wider objective is to show that changes in climatic variability need to be taken into account in agricultural impact assessment rather than relying simply upon mean climate change.

2. METHODS AND MATERIALS

2.1 Study sites and background

This study focused on three locations: Condobolin, Nhill and Wagga Wagga in southeast Australia (Table 1). Nhill and Wagga Wagga belong to the medium rainfall area with growing season (GS: May-Oct. inclusive) rainfall of 265 mm and 312 mm, respectively, while Condobolin belongs to the lower rainfall area with a GS rainfall of 218 mm (Table 1). Condobolin and Wagga Wagga have a uniform rainfall distribution throughout the year while Nhill has a winter dominant rainfall pattern (Figure 1). GS rainfall amount is the key determinant of dryland crop production levels while starting rain is crucial for the successful establishment of the crop in the study region. The sowing window for crops in the study region ranges from April to August depending on seasonal break (starting rain) and crop types.

Figure 1

Table 1

2.2 Tools and data

Computer simulation is one of the most important techniques to quantify the potential impacts of climatic change on ecosystems. The Agricultural Production Systems sIMulator (APSIM)-Wheat/Canola models (version 5.0) were used in this study to project crop yields and harvest indices under changed climatic conditions, including changes in both mean climate and in climatic variability. Daily rainfall, maximum and minimum temperature and solar radiation are common climatic inputs to the APSIM package. The APSIM model has been widely applied in climatic change/variability impact studies and in farming system studies in Australia, Europe and China.

Description and validation of this model can be found in Keating et al. (2003), Luo (2003) and Yunusa et al. (2004).

2.2.1 Climatic Change Projections and Climatic Change Scenarios

The Conformal-Cubic Atmospheric Model (C-CAM)

It is well known that the direct outputs of GCMs cannot be used in impact assessment due to their coarse spatial resolution of hundreds of kilometres (Wilby et al., 2004; Mearns et al., 2003). They need to be downscaled before being used in impact assessment studies. Statistical and dynamic downscaling are common downscaling techniques. Statistical downscaling includes analogue (Timbal et. al., 2008), circulation pattern downscaling/pattern scaling (Mitchell, 2003) and synoptic downscaling (Charles et al., 2003). Dynamic downscaling comprises Regional Climate Models (RegCMs, McGregor, 1997), High Resolution Limited Area Models (HRLAMs, Zhang et al., 2001) and variable resolution climate models (McGregor, 2002). Dynamic downscaling has the advantage over statistical downscaling techniques that have frequently been used to increase the resolution of climate model results in that the resulting higher resolution climate is physically based, and the assumption of constancy of derived empirical relationships between large scale and local climate conditions under perturbed climate conditions need not be made (Mearns et al., 1997).

For this reason, we have used dynamically downscaled outputs of C-CAM to derive changes in mean climate and in climatic variability and to construct climatic change scenarios for specific locations. This climate model is the only model which had dynamically downscaled outputs for application in Australia (McGregor, 2002). C-CAM is a stretched-grid model, which has a roughly uniform grid (50x50km) over the area of interest, and a reduced-resolution grid over the remainder of the globe. C-CAM was nested in the CSIRO Mk3.0 model fields and ran for the Special Report on Emission Scenarios (SRES)-A2 scenario. The A2 scenario simulation includes changes in greenhouse gases, ozone and sulphate aerosol (direct effect only). It does not include changes in the solar constant, volcanic aerosols, the indirect effects of sulphate aerosols, nor in carbonaceous, mineral dust and sea salt aerosols (Dr. Tony Hirst, pers. comm.). The C-CAM model performed quite well in the study region (Hennessy et al., 2004).

Derivation of climatic changes and construction of climatic change scenarios

Two time periods: 1961-1990 centred on 1975 and 2065-2094 centred on 2080 representing current and future climates, respectively, were used to derive monthly changes in mean climate and in climatic variability in this study. Mean climate refers to monthly mean temperature, monthly rainfall and monthly solar radiation. Climatic variability refers to the monthly mean duration of wet and dry spells and variability in monthly mean temperature. Derived monthly changes in mean climate and in climatic variability were then used in a stochastic weather generator (LARS-WG) to produce 100-year climatic change scenarios for 2080 based on the characteristics of historical climatic data covering the period 1958-2005. The rationale for using this period of historical climatic data is that we have good quality temperature data since 1958. Detailed description of the LARS-WG can be found at www.rothamsted.bbsrc.ac.uk/mas-models/larswg.php, Semenov and Stratonovitch (2010) and Luo et al. (2003). The performance of LARS-WG in diverse climates around the world was evaluated in Semenov et al. (1998), Qian et al. (2004) and Semenov (2008). To examine the effects of changes in climatic variability on crop production, two types of climatic change scenarios were developed. One considered changes in mean climate only. The other incorporated changes in both mean climate and climatic variability into climatic change scenarios.

2.2.2 Soil

To investigate the impact pattern of rising atmospheric CO_2 and climatic change on crop production, we deliberately used the same soil profile for the locations under investigation. A sandy loam soil was used in this study. Two levels of plant available water capacity (PAWC) were considered: high PAWC (161mm) and low PAWC (85mm). The high PAWC corresponds to the original soil profile while the low PAWC is derived from the original soil profile with the two deepest soil horizons removed. Table 2 shows soil water and nitrogen parameters used by the APSIM-Wheat/Canola Model.

Table 2

2.2.3 Simulation experimental design and model setting

Two wheat cultivars (*Chara* and *Janz*) were considered in this study. *Chara* is a mid-late maturity cultivar while *Janz* is an early maturing cultivar. *Chara* is sown when cumulative rainfall in three consecutive days is ≥20 mm and ≥15 mm for medium rainfall area (Neil and Wagga Wagga) and for low rainfall area (Condobolin) respectively during the period of 15 Apr-15 June. *Janz* is sown for the period of 16 June-15 Aug with the same sowing criterion as *Chara*. If this condition can not be met, the wheat crop is forced to be sown on the last day (15^{th} Aug) of the sowing window with *Janz*. Sowing depth is set at 3cm.

Similarly two canola cultivars (*Oscar* and *paCN145*) were used in this study. *Oscar* is sown when cumulative rainfall in three consecutive days is ≥20 mm and ≥15 mm for medium rainfall area and for low rainfall area respectively during the period of 8 Apr-7 May. *paCN145* is sown for the period of 8 May-7 June with the same sowing criterion as *Oscar*. If this condition cannot be met, the canola crop is forced to be sown on the last day (7 June) of the sowing window. Sowing depth is set at 2cm.

For both crops, soil water, nitrogen and residue were reset to initial condition on the 1st of March each year. Atmospheric CO_2 concentration was set at 682 ppm for 2080, which corresponds to the SRES A2 marker scenario. Other systematic information such as amount of nitrogen application, residue, planting density was set differently across rainfall areas and crops. In general, the higher the GS rainfall, the higher the amount of nitrogen and residue applied and the higher the plant density. Table 3 details these three kinds of information for the locations and crops considered in this study.

Table 3

3. RESULTS

3.1 Climatic changes in 2080

Table 4 summarises the growing season climatic change information for the three locations under study based on the monthly changes mentioned in section 2.2.1. Climatic variables include mean rainfall, the length of wet and dry spells, average temperature, variability of average temperature and solar radiation for the period centred on 2080. There was a slight increase (1-2%) in GS rainfall at Condobolin and Wagga Wagga and an 8% decrease at Nhill. Wet spells for GS decreased 15%, 13%

and 5% at Nhill, Wagga Wagga and Condobolin, respectively, while dry spells for the GS increased 18-19% across the three locations. Increases in average temperature range from 1.7~2^{o}C. The increase in the variability of average GS temperature ranges from 7~10%. A 1~3% increase in solar radiation was found.

Table 4

3.2 Mean and coefficients of variation of crop grain yield

Table 5 shows the mean and coefficients of variation (CV) of wheat and canola crop yield under baseline, and under future climatic scenarios which considered changes in mean climate only, and changes in both mean climate and in climatic variability across the two soil conditions. Under both soil conditions (high and low PAWC), compared with baseline yield, average wheat grain yields slightly increased at Wagga Wagga and Condobolin and decreased at Neil under mean climatic change scenarios owing to the small increase in GS mean rainfall at Wagga Wagga and Condobolin and the decrease at Nhill. When changes in climatic variability are incorporated into the mean climatic change scenarios, the average wheat grain yield decreased at Wagga Wagga and Condobolin indicating the potentially adverse effects of changes in climatic variability on wheat crop yields at those sites, but increased slightly at Nhill.

Average canola yields decreased under both climatic change scenarios and soil conditions. When changes in climatic variability were also considered, there was a greater decrease at Wagga Wagga and Condobolin. However, at Condobolin under high PAWC with mean climatic change scenario, the average canola yield increased compared with baseline. This once again demonstrated the negative impacts of changes in climatic variability on crop yields. The impact of the two types of climatic change scenarios on canola yield at Nhill is similar to that of wheat yield across the two soil conditions at this location.

From Table 5, it can be seen that compared with mean climatic changes only, the CV of (shown in brackets) wheat grain yield increased across three locations and the two soil conditions under scenarios with both changes in mean climate and in climatic variability except at Condobolin under low PAWC. The CV of canola yield increased at Wagga Wagga under high PAWC and at Condobolin under both soil conditions when changes in climatic variability were also considered. However, the CV of canola yield slightly deceased at Wagga Wagga under low PAWC and at Nhill across the two soil conditions under changed climatic variability compared with mean climatic change only.

Table 5

3.3 Average and coefficients of variation of crop harvest index

Compared with mean climatic change only, the average wheat harvest index (HI) remained unchanged at Wagga Wagga and at Nhill under low PAWC or was enhanced at Condobolin and Nhill under high PAWC with changed climatic variability (Table 6). The mean canola HI was unchanged under changed climatic variability in comparison with mean climatic change only except at Condobolin under high PAWC and at Nhill under low PAWC where decreases in average HI were found (Table 6).

Table 6 also shows that the HI CV (in brackets) for both wheat and canola increased across the three locations and two soil conditions under changed climatic variability in comparison with only mean climatic change except for canola at Wagga Wagga under low PAWC.

Table 6

4. DISCUSSION AND CONCLUSIONS

Daily outputs of the C-CAM model for the 30-year periods centred on 1975 and 2080 were used in this study to derive changes in mean climate and in climatic variability. The derived changes were reapplied to the LARS-WG to generate 100-year climatic change scenarios which were then coupled with the APSIM-Wheat/Canola models to project crop yields and harvest index across two soil conditions. A decrease in the average length of wet series and an increase in the average length of dry series and in temperature variability were projected by the C-CAM model for the period of 2065-2094 under SRES A2 emission scenario at the three sites in southeast Australia analysed here. Changes in climatic variability reduced mean wheat and canola yields at Wagga Wagga and Condobolin and increased them at Nhill when compared with changes in mean climate only. The reason for the increase of crop yields at Nhill may attribute to higher median growing season rainfall (with higher intensity but less frequency) under changed climatic variability compared to other two sites. Negative impacts of changes in climatic variability on CV of wheat yield were also found in the majority of the cases (across locations and soil water conditions). Changes in climatic variability have both positive (50% of the cases) and negative (50% of the cases) effects on the CV of canola yield. Changes in climatic variability have no (50% of the cases) or positive (50% of the cases) effects on the average HI of wheat while they have no (67% of cases) or negative (33% of cases) effects on the average HI of canola. Negative effects of changes in climatic variability on the CV of HI for both crops were found. Semenov and Barrow (1997) also found negative effects on the average and CV of wheat yield from changes in climatic variability. Our work has demonstrated that when changes in climatic variability considered, differences exist in the mean and CV of yield and HI for both wheat and canola compared with mean climatic change only. This implies that changes in climatic variability need to be taken into account in agriculture impact assessment. Derivation of changes in climatic variability and their incorporation into climatic change scenarios should be taken as normal practice in agricultural impact assessments. In this way, uncertainties in the construction of local climate change scenarios specifically and in the agricultural impacts assessment more broadly will be substantially reduced.

This study examined the effects of changed climatic variability on two crops (wheat and canola) with two impact indicators (yield and harvest index) and two statistics considered (mean and CV). A robust research methodology in the construction of climatic change scenarios was adopted in terms of the integration of changes in climatic variability into climatic change scenarios and the use of LARS-WG in producing long time series climatic change scenarios based on historical climatic characteristics rather than direct use of downscaled daily outputs. This study contributes to the understanding of the effects of changes in climatic variability on crop production systems.

This study bears a number of limitations. For example, limited number of emission scenarios and climate models were considered in this analysis. This study has focused on the effects of changes in climatic variability on crop production. Effects of management options were not directly addressed but were partially and indirectly considered as illustrated in Section 2.2.3. We note that uncertainty may exist in extrapolating from specific sites to the wider region. We also note that uncertainties may arise from the use of the weather generator to represent changed climatic variability and the crop models to capture the effects of changed climatic variability.

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Table 1 Study Locations, Annual and Growing Season Rainfall

Station	Station_ID	Latitude	Longitude	Altitude (m)	Annual Rainfall (mm)	GSR* (mm)
Condobolin	050052	33°04’S	147°14’E	195	449	218
Nhill	078031	36°20’S	141°38’E	133	415	265
Wagga Wagga	074114	35°08’S	147°18’E	222	558	312

*GSR: growing season rainfall May-Oct. inclusive.

Table 2 Soil Water and Soil Nitrogen Used in the APSIM-Wheat Model

Depth (mm)	ll15 (mm/mm)	Dul (mm/mm)	PAWC (mm)	NO3 (kg/ha)
100	0.09	0.19	10	19.56
250	0.1	0.21	16.5	23.51
420	0.11	0.24	22.1	14.92
700	0.11	0.24	36.4	22.51
900*	0.18	0.3	24	13.71
1300*	0.23	0.36	52	18.06
total			**161(85)**	**112.27 (80.5)**

Figures in bracket are for soil condition with low plant available water capacity (PAWC).
*The last two layers of soil profile were not used in the low plant available water capacity soil.

Table 3 Management information at sowing

Locations	N application (kg/ha)	Residue (kg/ha)	Plant density- wheat (plants/m^2)	Plant density -canola (plants/m^2)
Condobolin	25	1000	100	60
Neil	75	2000	150	60
Wagga Wagga	75	2000	150	60

Table 4 Changes in mean climate and in climate variability for growing season in 2080 derived from monthly changes based on daily outputs of C-CAM

Locations	Rainfall*	Wet series*	Dry series*	Temperature (°C)	Temperature variability*	Radiation*
Condobolin	1.02	0.95	1.18	2.12	1.07	1.02
Nhill	0.92	0.85	1.18	1.57	1.10	1.01
Wagga Wagga	1.01	0.87	1.19	2.04	1.07	1.03

*Ratio change: 2080 value divided by corresponding baseline value. Others are absolute change.

Table 5 Average (kg/ha) and coefficients of variation (in brackets) of crop yield in 2080

Crops	Locations	High PAWC			Low PAWC		
		Baseline	MC+CV[1]	MC[2]	Baseline	MC+CV	MC
Wheat	Wagga	3868 (30)	3827 (32)	4090 (29)	2934 (31)	2997 (33)	3285 (30)
	Condobolin	1482 (76)	1611 (70)	1669 (70)	1360 (75)	1418 (69)	1494 (70)
	Neil	2023 (65)	1895 (78)	1638 (76)	1803 (64)	1674 (76)	1521 (75)
Canola	Wagga	2354 (27)	2134 (30)	2263 (28)	2022 (28)	1828 (28)	1989 (29)
	Condobolin	1007 (71)	910 (70)	1011 (69)	960 (71)	849 (70)	931 (69)
	Neil	1301 (59)	1054 (69)	932 (71)	1253 (58)	1004 (68)	911 (69)

1. changes in mean climate and in climate variability; 2. mean climate change.

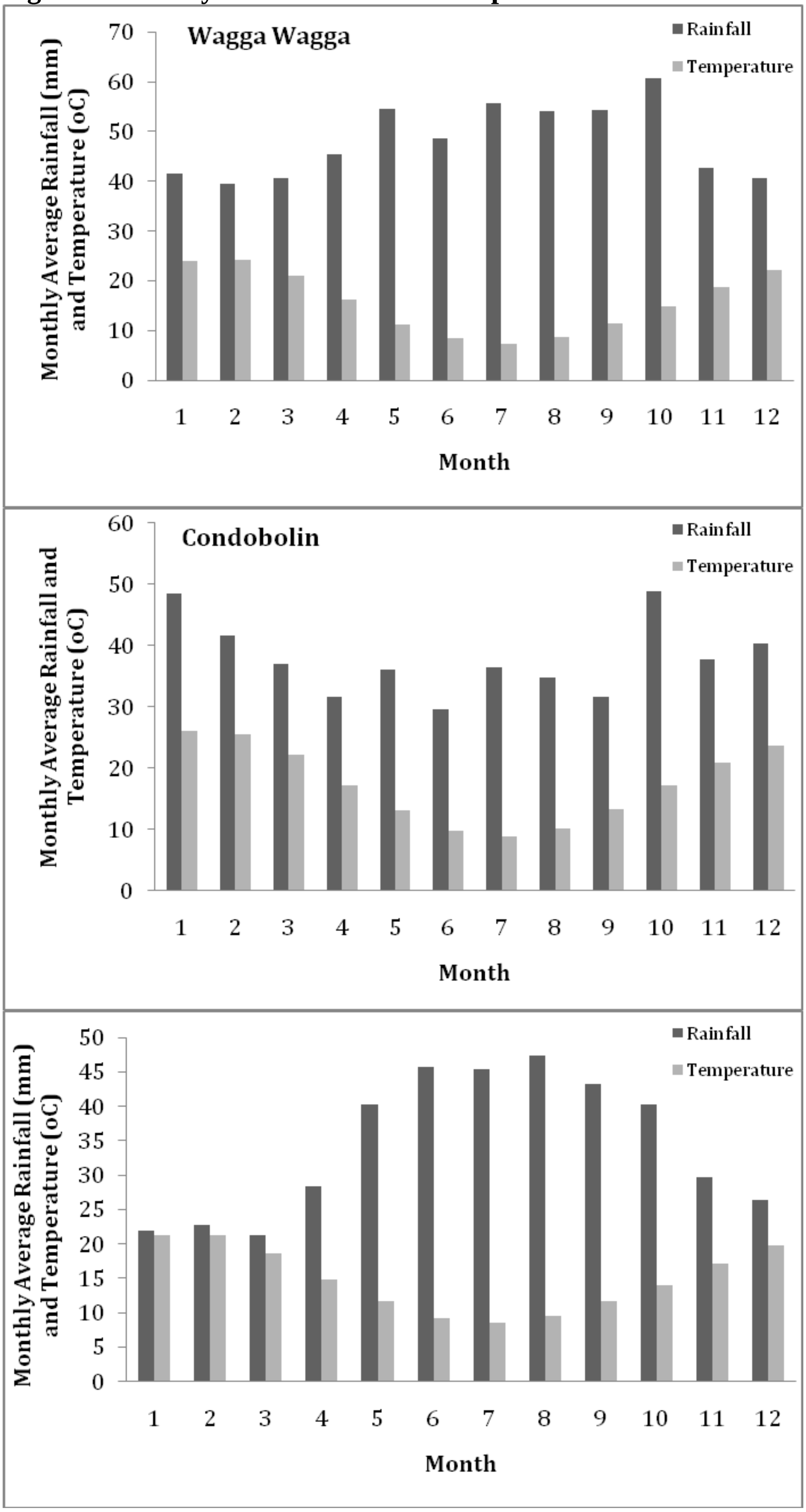
Table 6 Average (kg/ha) and coefficients of variation (in brackets) of wheat harvest index in 2080

Crops	Locations	High PAWC			Low PAWC		
		Baseline	MC+CV[1]	MC[2]	Baseline	MC+CV	MC
Wheat	Wagga	0.33 (11)	0.33 (12)	0.33 (10)	0.31 (12)	0.32 (14)	0.32 (12)
	Condobolin	0.28 (23)	0.30 (25)	0.28 (21)	0.28 (24)	0.29 (25)	0.28 (23)
	Neil	0.30 (21)	0.29 (25)	0.28 (23)	0.29 (22)	0.28 (25)	0.28 (23)
Canola	Wagga	0.30 (0.7)	0.30 (1.5)	0.30 (1.4)	0.30 (1.0)	0.30 (2.1)	0.30 (2.3)

Condobolin	0.27 (22)	0.26 (26)	0.27 (21)	0.26 (24)	0.26 (27)	0.26 (23)
Neil	0.29 (10)	0.28 (19)	0.28 (16)	0.29 (11)	0.27 (19)	0.28 (16)

1. changes in mean climate and in climate variability; 2. mean climate change.

Figure 1 Monthly mean rainfall and temperature



Role of changes in climate variability