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The autumn break for cropping in southeast Australia: trends, synoptic influences and impacts on wheat yield

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ABSTRACT: The autumn break is the first significant rainfall event of the winter growing season. Two definitions of the autumn break have been developed for northwestern Victoria; a so-called ideal break and a minimum rainfall condition for sowing a wheat crop termed a minimal break. Application of the ideal break definition for an eight-station average reveals that 41 autumn breaks occurred in the first half of the record (1889–1947) and 34 in the second half (1948–2006) with a trend towards breaks occurring later in the season. In the decade to 2006, there have been only 3 ideal breaks (1999, 2000 and 2005) and none of the selected rainfall stations has recorded an 'extreme' wet autumn over the last 11 years, the longest period recorded for this criterion. A synoptic analysis for the period 1956–2006 has established that breaks are predominantly associated with systems known as cutoff lows. The influence of these systems has varied markedly throughout the analysis period and only one autumn break has been caused by a cutoff low in the final decade of the analysis. Additionally, the total rainfall associated with cutoff lows in the April to June period has declined significantly over the past 30 years.

A farming system model has been employed to simulate a wheat crop in northwestern Victoria under historical conditions for a range of management options. Average yield across all years of the simulation declines with delay in the sowing date after late April, but there is a marked interannual variability in yield response to the sowing date which is related to rainfall distribution in the growing season in each year. The simulated in-crop rainfall indicates that the most recent drought in southeastern Australia is comparable in severity with the two major droughts in the 20th Century. Copyright © 2008 Royal Meteorological Society

KEY WORDS autumn break; Australia; rainfall; cutoff low; wheat crops

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1. Introduction

The first significant rainfall event of the winter growing season, the so-called autumn break, is a keenly anticipated occurrence in the southern Australian agricultural calendar. It sets the time when successful sowing of grain crops can proceed, and initiates pasture growth which can then be 'autumn saved' for grazing during the dormant winter period. Failure to have an autumn break can have severe financial repercussions, particularly when available soil moisture is low following a dry summer.

The definition of the autumn break is problematic since farmers and graziers can have differing opinions on the effectiveness of autumn rainfall depending on the predominant enterprise of the farm, soil types, regional climatology and farming methods. Hence, the definition of the autumn break will vary to some extent from farmer to farmer and district to district. In order to set the parameters of meaningful definitions we have conducted meetings and surveys with groups of grain farmers in southeastern Australia. The definitions adopted for this study and presented in Section 3 of the paper have been developed from these discussions.

The grain-growing season in southeastern parts of mainland Australia extends from about April to the end of October (French and Schultz, 1984; Robertson and Kirkegaard, 2005; Pook *et al*., 2006). During this period the region receives the majority of its annual rainfall, evaporation is lowest and the number of rain days per month is highest. The mean growing season rainfall over the majority of the region is less than 300 mm, and rainfall events tend to be infrequent (less than 35% of days receive at least 0.2 mm of rain). Crop success also depends on soil moisture at the time of planting (French and Schultz, 1984; Carberry *et al*., 2000).

The portion of northwestern Victoria shown in Figure 1 is an important grain-growing region of Australia and

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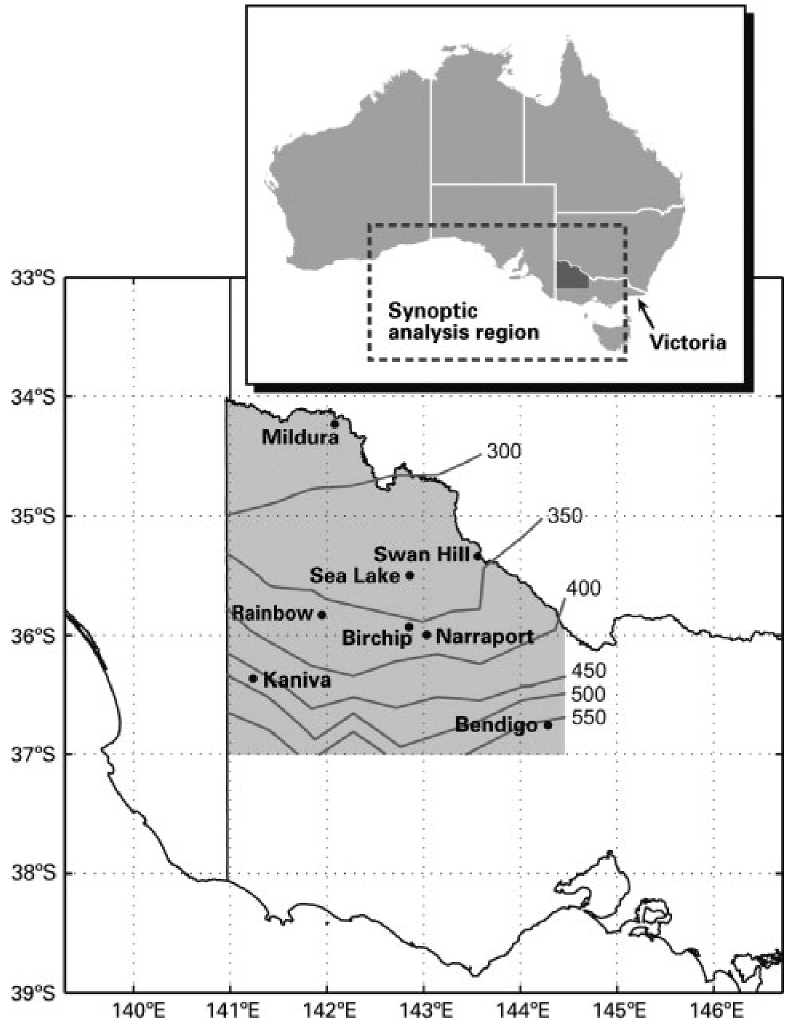

Figure 1. Map of northwestern Victoria showing the network of high-quality rainfall stations used in the analysis. The large dotted box over the map of Australia defines the region within which the analysis of synoptic systems was confined. The dark shaded area indicates the region of southeastern Australia included in the lower part of the diagram. Annual rainfall (mm) for northwestern Victoria is represented by isohyets (after Pook *et al*., 2006).

produces the majority of grain grown in the State of Victoria. Based on an average over the 5 years to 2004–2005, Victoria contributes about 11% of the total Australian wheat crop and 13% of Australia's total winter crop production (ABARE, 2007). Wheat is the dominant crop grown in this region often (but not always) in rotation with other grain crops (e.g. barley, oats, canola, lentils, lupins, chickpeas) and a pasture phase. In the absence of nutrient deficiencies in the soil, major constraints on wheat growth in this region include the timing and amount of autumn rains for sowing, duration of the winter minima in solar radiation and temperature, timing of the earliest 'safe-ear' emergence in relation to frost occurrence, and late-season high temperature and water-stress events (Nix, 1987). The water supply to the growing crop is the most critical factor affecting wheat yields in this area as in many other water-limited environments of Australia (French and Schultz, 1984; Stephens and Lyons, 1998).

Although cereal crops are normally sown in May and June, varying seasonal conditions and farming methods may dictate that sowing begins as early as April or is postponed until as late as August in an extremely dry season (Stephens and Lyons, 1998). As sowing is typically carried out from April to June we consider the autumn break to occur in any of the months, March to June.

Some farmers wait for an autumn break before sowing but an increasing number sow into a dry seed bed, especially those that employ minimum tillage techniques in order to preserve soil moisture. In these operations, crops are planted according to a schedule rather than in response to individual rain events. As crops are almost exclusively rainfed there are considerable risks in committing to a sowing program very early in the season, but the potential gains in yield of sowing when soil temperatures are favourable for germination, survival and plant vigour are very attractive to farmers (Stephens and Lyons, 1998). Notwithstanding these potential gains there is, nevertheless, a risk of severe damage from frost for those plantings which result in flowering prior to early October and consequently, cultivation techniques which

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minimize this risk have been developed in some regions (Rebbeck *et al.*, 2007).

Improved prediction skill for autumn break events would minimize the risk of crop failure and contribute to improved efficiency by influencing the total area sown, the choice of crop and variety, the management of fertilizer usage and better control of production costs such as those associated with seed and fuel. Current predictions of seasonal climate based on the El Niño-Southern Oscillation (ENSO) state are relatively unreliable in the austral autumn as there is a significant reduction in the forecast skill of statistical schemes around this time of the year (McIntosh *et al.*, 2005) and there is a corresponding drop in the skill assigned to persistence.

Pook *et al.* (2006) have argued that seasonal rainfall represents the integrated contribution of a number of discrete synoptic weather systems and it is important to identify those systems responsible for rainfall events and the mechanisms contributing to rainfall generation. In this study we have employed the techniques of synoptic climatology to identify the synoptic systems responsible for the significant autumn rainfall events which contribute to the autumn break in a given year in order to better understand the physical processes and detect trends in frequency of occurrence of particular synoptic types. In order to better represent the effects of the autumn break on crop performance this paper explores trends in wheat yield simulated in a farming system model under a range of sowing conditions at one location in the study region.

2. Data and method

2.1. Data sources

Daily rainfall was extracted from the Patched Point Dataset supplied by the Queensland Department of Natural Resources and Mines (Jeffrey *et al.*, 2001) for eight rainfall stations which were selected to represent north-western Victoria from a high-quality Australian historical dataset (Lavery *et al.*, 1997). The Patched Point Dataset uses original Bureau of Meteorology observations for a particular meteorological station infilled where necessary with interpolated data. Data were extracted for the period from 1889 to 2006. Although there are considerably more rainfall stations available in the study region we have restricted analysis to those identified as satisfying the 'high-quality' criteria established by Lavery *et al.* (1997). The station locations are shown in Figure 1 and are the same as those employed in Pook *et al.* (2006) with the exception that Rainbow (Pella) which was found to have unacceptable data quality from 1998 onwards (I. Barnes-Keoghan, personal communication 2007) was replaced by a composite Rainbow site from 1998 to 2006.

The synoptic analysis was conducted using the National Centers for Environmental Prediction (NCEP)-National Center for Atmospheric Research (NCAR) climate reanalysis dataset (Reanalysis 1) that will be referred to as the NCEP dataset (Kalnay *et al.*, 1996; Kistler *et al.*, 2001). NCEP produces 4 analyses per day (at six-hourly intervals from 0000 UTC) at a resolution of 2.5° latitude by 2.5° longitude for the standard atmospheric levels from the surface to the lower stratosphere. For the purposes of this study, fields were extracted for mean sea level pressure (MSLP), the 500 hPa pressure surface, the (computed) 1000–500 hPa atmospheric thickness and the 1000–500 hPa thickness anomaly relative to the long-term climatology.

Daily weather maps at 2300 UTC published in the Australian Bureau of Meteorology's 'Monthly Weather Review' series (Simmonds and Richter, 2000) were used in parallel with NCEP for the period from 1970 to 2006. These charts have been prepared by expert analysts and include frontal analysis which has been performed manually by interpretation of satellite imagery in addition to conventional analysis of synoptic data (Guymer, 1978). The inclusion of the manual analyses was considered to be an essential component of the analysis project as the NCEP numerical reanalyses lack this human input and do not have sufficient horizontal resolution to locate fronts reliably (Pook *et al.*, 2006). The starting point for the original analysis of Pook *et al.* (2006) was set at 1970, since techniques for incorporating the subjective interpretation of satellite cloud imagery into an objective analysis scheme became established practice in the World Meteorological Centre, Melbourne, around that time (Guymer, 1978; Seaman and Hart, 2003) and secondly, NCEP analyses for the Southern Hemisphere have been found to have systematic biases prior to 1970, particularly at high latitudes (Hines *et al.*, 2000). Other reported errors in NCEP, such as those related to the absence of satellite temperature soundings prior to 1979 (Kistler *et al.*, 2001), are not regarded as significant because of the proximity of our analysis region to the Australian radiosonde network, and since the Australian MSLP analyses were consistently consulted in parallel. Nevertheless, the NCEP dataset is considered to be unreliable in the Southern Hemisphere prior to 1958 (Kistler *et al.*, 2001).

In order to extend this study further back in time a selection of MSLP, 700 hPa and 500 hPa analyses was obtained from the Australian Bureau of Meteorology for 2300 UTC and 1100 UTC each day. This chart series was available from 1956 to 1969. The lack of a sufficiently dense upper air data network for the Australian region prior to 1956 precludes a comprehensive synoptic analysis for an earlier period (Bradshaw, 1997). It should be noted that the Australian analyses (1956–1969) are copies of the actual operational charts and may lack the dynamical consistency of the later period (from 1970). However, when these charts are used in parallel with the NCEP data, we believe that a reliable synoptic classification can be made for the major rainfall events associated with the autumn break over southern Australia from 1956 onwards.

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2.2. Method

For each autumn break, according to the definitions adopted, an assessment was made of the nature of the synoptic system responsible for the precipitation event. The analysis region was defined by a fixed box with limits, 30 °S, 125 °E; 30 °S, 147.5 °E; 45 °S, 147.5 °E and 45 °S, 125 °E as shown in Figure 1. Synoptic systems were classified according to the classification scheme which is discussed by Pook *et al.* (2006).

The four categories of synoptic systems that have been adopted are cold frontal systems of all types, cold-cored lows which have become cutoff from the westerly airstream (cutoff lows), troughs in the easterlies and a combined category designated 'others' that includes systems not found in the main three categories.

The relationship between crop performance and autumn rainfall was explored within an agricultural systems model. Crop production systems are characterized by complex interactions between climate, soil attributes, management operations and varietal characteristics. Dynamic simulation models that capture this inherent complexity provide an efficient means for analysing systems performance across a wide range of conditions. In this study, the farming system model Agricultural Production Systems sIMulator (APSIM) (Keating *et al.*, 2003) has been used to explore seasonal trends in selected wheat growth variables under a range of sowing conditions at Birchip, northwest Victoria (for location, see Figure 1). APSIM simulates agricultural production systems by combining modules describing the specific processes within the system under investigation. The soil water module SOILWAT2 (Probert *et al.*, 1997), the soil nitrogen module SOILN2 (Probert *et al.*, 1997), and the surface residue module RESIDUE2 (Probert *et al.*, 1997) were linked with the wheat crop module APSIM-WHEAT (Keating *et al.*, 2001), which simulates wheat growth and development in response to climatic, soil and management inputs. All management details were specified via the MANAGER module. For comprehensive descriptions of each of these modules see the relevant link on the APSIM website: http://www.apsim.info/apsim/.

The wheat variety, Yitpi, was sown in each year of the historical climate record between 1890 and 2005 on particular days (sowing dates), according to a range of rainfall-related sowing conditions based on a prescribed rainfall total ('rain threshold', mm) accumulated over a prescribed period ('rain window', days). The sowing conditions were applied over a fixed 'sowing window' from March 1 to June 30. Years in which the sowing conditions were not met over this sowing window were sown dry on June 30. Combinations of sowing conditions include a 10 mm threshold accumulated over a 3-day window, 10 mm over 7 days, 15 mm over 3 days, 15 mm over 7 days, 25 mm over 3 days, 25 mm over 7 days and 30 mm over 7 days. The simulation was set up such that nitrogen was non-limiting. APSIM assumes that all other nutrients are non-limiting and that the crop is free of disease, insect damage, weed competition and other related yield constraints. No irrigation was applied. These conditions enabled a focused analysis of the effect of sowing condition and the distribution of rainfall during the growing season on the performance of the wheat cropping system.

A hypothetical clay soil was used for the simulations, with parameters derived from selected references and expert knowledge of 'average' parameter values for soils of this texture. The profile had a maximum rooting depth of 90 cm divided into four layers with a total plant extractable soil water (PESW) content of 126 mm. The analysis employed the long-term (1889–2005) climate record for Birchip (Woodlands) obtained from the Patched Point Dataset which provides daily maximum and minimum temperatures, radiation and rainfall totals (Jeffrey *et al.*, 2001).

3. Characteristics of autumn rainfall in northwestern Victoria

The autumn season in southern Australia generally coincides with the period of soil preparation and planting of winter crops which are subsequently harvested in the austral summer. Although autumn is officially defined as the season extending over the three calendar months of March, April and May (Crowder, 1995), planting often continues well into June, depending on seasonal conditions (Stephens and Lyons, 1998). Therefore, in this study, we consider that the four-month period from March to the end of June is a more meaningful period over which to investigate rainfall variability and trends as well as the autumn break itself. This crop establishment period (March–June) will be referred to as autumn for the remainder of this paper.

Autumn rainfall and annual rainfall have been averaged over the eight-station network and smoothed with a centred eleven-year running mean starting in 1894. Figure 2 demonstrates that the running means of autumn rainfall and annual rainfall have been decreasing during the last decade of the series. In particular, the autumn mean has declined to its lowest value in more than 100 years. This contrasts with the annual rainfall mean which was lower in 1940 and 1900. More broadly, Murphy and Timbal (2008) have reported that all of southeastern Australia has experienced low annual rainfall in the decade to 2006 with the most significant rainfall decline in autumn. Historically, the drought that persisted from 1895 to 1903 is known as the 'Federation Drought' and is regarded by most authors as the longest, most severe and widespread in the history of Australia dating from European settlement (Foley, 1957; Wright, 2004). The 1939 to 1945 drought is the second longest period of major drought since the Federation Drought and was responsible for devastating stock losses (Foley, 1957; Wright, 2004).

Not only has there been a major decline in autumn mean rainfall in northwestern Victoria since 1991 but there has also been a change in the characteristics of rainfall events. Autumn rainfall anomalies for each of the eight stations in the network have been extracted

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and 'extreme' wet (dry) years defined as years in which the anomaly is at least one standard deviation above (below) the long-term mean for that station. The number of stations indicating an 'extreme' wet season during the period 1889 to 2006 is shown in Figure 3. The length of the most recent period from 1996 to 2006 where no station has recorded an 'extreme' wet autumn is unprecedented in the record. By way of contrast, the occurrence of 'extreme' dry autumns in this period (not shown) is unremarkable.

As a preliminary step in the investigation of the autumn break, the overall characteristics of daily rainfall in northwestern Victoria were examined for all months. The distribution of daily rainfall in the region is strongly biased towards falls of 5 mm or less (Figure 4). More than 40% of daily rainfall is found in this category with a further 25% in the range from 5 to 10 mm. Over the period from 1889 to 2005, approximately 6% of daily rainfall events are represented by falls of 25 mm or more. For this group of heavy rainfall events, Figure 5 shows the percentage which has occurred in each month. From Figure 5 it is apparent that the highest frequency of occurrence of these heavy rainfall days is in February (20%) with a secondary maximum in October (13%). Approximately 27% of these events have occurred in the March to June period with the highest incidences during autumn occurring in March (10.3%) and May (9%).

4. Defining the autumn break

A useful definition of the autumn break is required to determine a rainfall threshold that provides sufficient moisture to induce germination of the crop and which is then able to supply the necessary soil moisture to sustain the plants in the first phase of their growth. A common problem for all crops and pastures is the occurrence of a 'false break' where sufficient rain falls to trigger germination but the subsequent soil moisture is insufficient to allow the seedlings to survive (Clark *et al.*, 2003).

A series of workshops conducted with groups of grain growers in southeastern Australia revealed that there was considerable variation of opinion as to what constituted the autumn break for cropping in a region. Considerations of mean rainfall for the area, soil type, crop type, individual farmer preferences and available technology

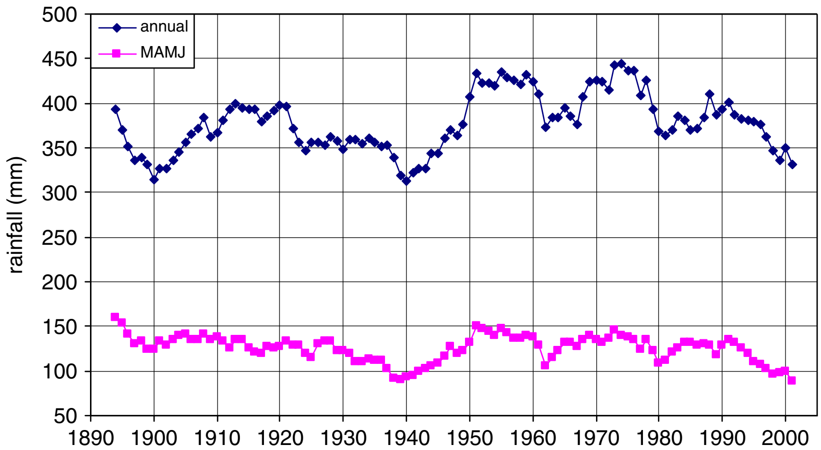

Figure 2. Growing season autumn (MAMJ) rainfall and annual rainfall (mm) averaged over the eight stations in northwestern Victoria which have been selected for their 'high-quality' status (Lavery *et al.*, 1997). The data have been smoothed with an eleven-year running mean centred on the year shown on the x-axis. This figure is available in colour online at www.interscience.wiley.com/ijoc

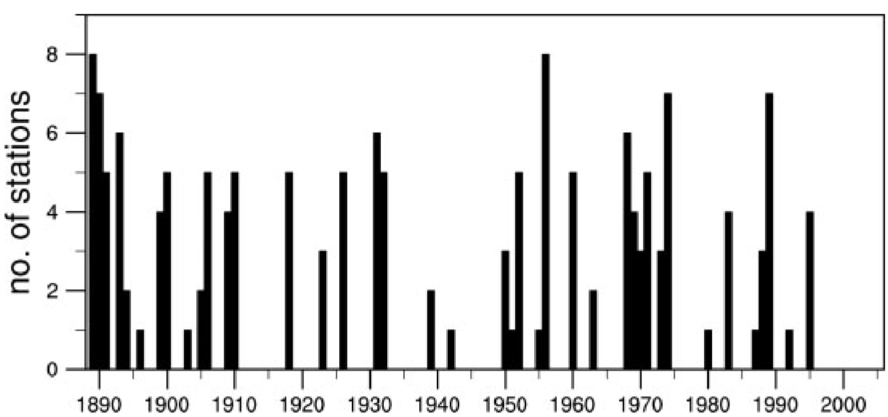

Figure 3. The number of stations (from the total of eight) indicating an extreme wet (rainfall exceeds +1 standard deviation) MAMJ season for the period 1889–2006.

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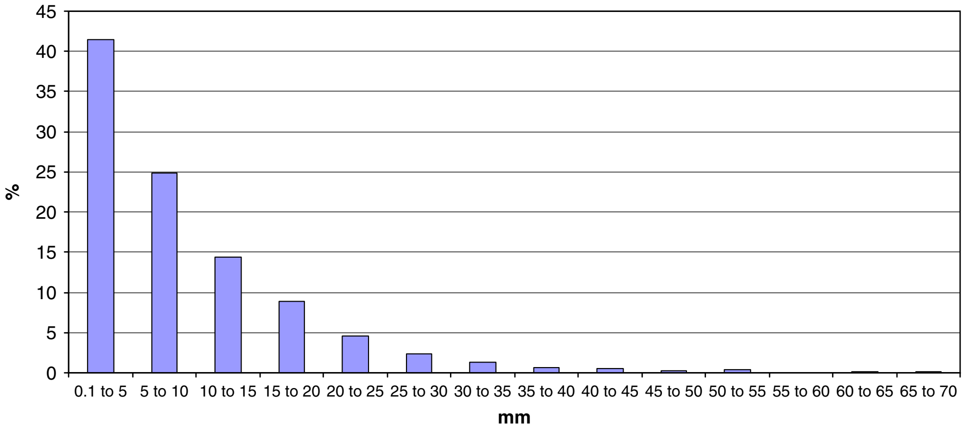

Figure 4. Distribution of daily rainfall in 5 mm intervals for the eight-station average, expressed as a percentage of the total rainfall for all months over the period 1889–2005. This figure is available in colour online at www.interscience.wiley.com/ijoc

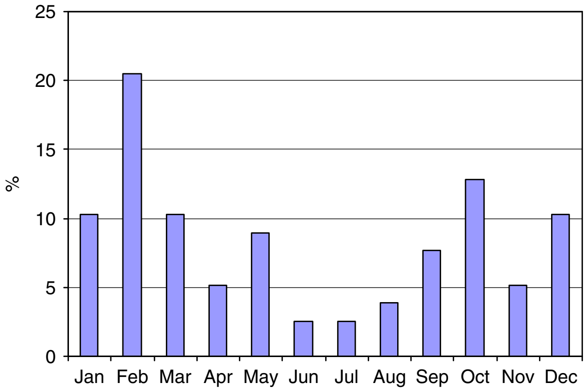

Figure 5. Monthly percentage of daily rainfall events resulting in at least 25 mm for the 8-station average (period from 1889 to 2005). This figure is available in colour online at www.interscience.wiley.com/ijoc

were all influences on the amount of rain required to achieve the autumn break for any given farm. In any event, most farmers were prepared to sow a crop in response to a rainfall event that was less than the ideal for their location and cropping plan. There was general agreement though that the autumn break consisted of a significant fall of rain over a period of several days and ideally, this was followed by another fall within the subsequent fortnight. Since the primary purpose of this study was to investigate the synoptic systems responsible for the autumn break and to determine long-term trends, two definitions based on rainfall over selected periods were developed.

The first definition developed from the consultations with farmers was that of an 'ideal' break which was considered to have occurred when a mean fall of 25 mm or more across the 8-station network was received over a period of 3 days or less. Application of this threshold revealed that there were also occasions in the record when, although the strict three-day criterion had not been met, rainfall of the order of the monthly average occurred over a period of a week. Hence, this definition was widened to include a second condition; 'or, falls of 30 mm or more over 7 days or less'.

Since some farmers in the drier regions of the study area indicated that they would sow a crop given a lower rainfall than required for an 'ideal' break, alternative definitions setting lower rainfall thresholds were investigated. Thresholds requiring mean falls of 20 and 15 mm across the 8-station network over a period of 3 days or less were suggested. However, in order to set a realistic minimum requirement across the study region the lowest threshold for an autumn break was set at 15 mm or more over 7 days or less. This process resulted in an 'ideal' break definition and a 'minimal' break definition for application in this study.

In summary, an ideal break is defined as occurring if either:

1. A mean fall of 25 mm or more across the 8-station network is received over a period of 3 days or less, or
2. A mean fall of 30 mm or more across the 8-station network occurs over 7 days or less.

The definition adopted for a minimal break is: A mean fall of 15 mm or more across the 8-station network is received over a period of seven days or less.

5. Results

5.1. Heavy rainfall events

The effectiveness of the definition of the ideal break was initially tested by determining the number of rainfall events throughout the historical record which satisfy either of the criteria for an ideal break. In order to obtain a clearer indication of trend, the data were filtered with a centred eleven-year running mean. Figure 6(a) demonstrates that for each criterion, the mean number of events in the crop establishment period has declined over the record. The trend to lower numbers of wet events has a similar magnitude for each of the criteria, and the trends are significant at the 99.9% confidence level (Draper and Smith, 1998).

In the case of the first criterion, the lowest values of the running mean (0.4 rainfall events per year) occurred in

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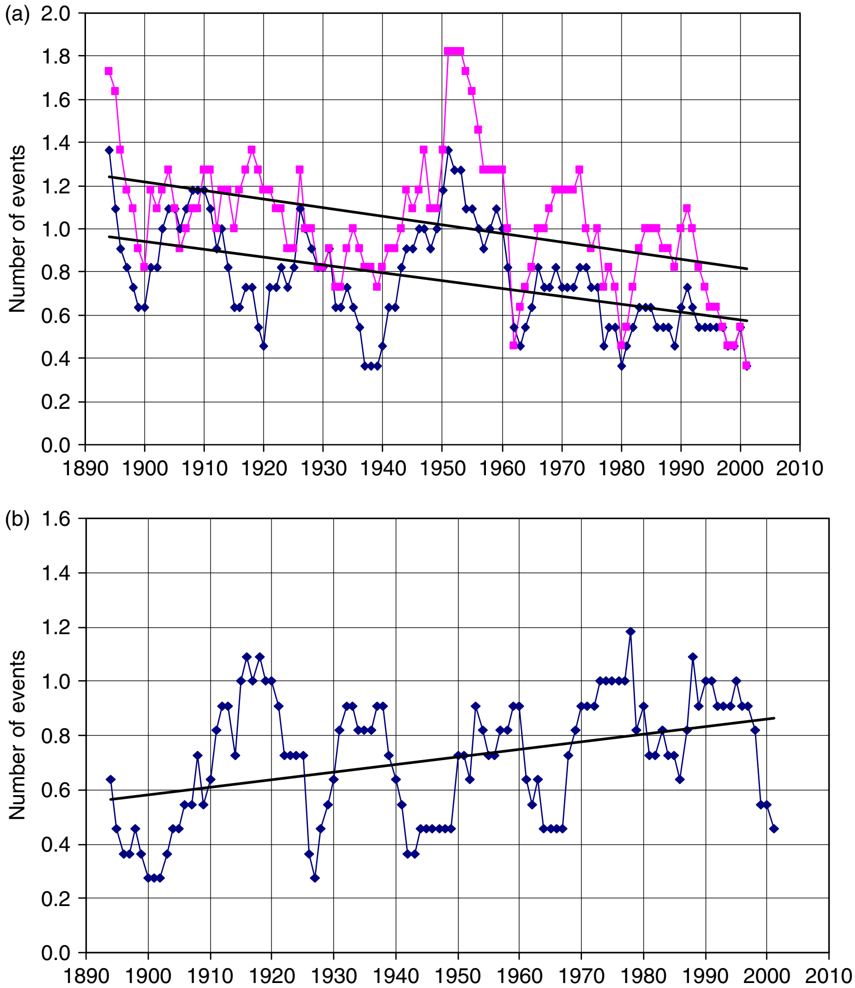

Figure 6. Eleven-year running mean (centred) of the number of rainfall events for (a) March to June, resulting in 25 mm or more over 3 days or less (diamond, dark line) and 30 mm or more over 7 days or less (square, light line), and for (b) July to October, resulting in 25 mm or more over 3 days or less (averaged across the 8-station network). Linear trends are significant at 99.9% confidence. This figure is available in colour online at www.interscience.wiley.com/ijoc

1937, 1938, 1939, 1980 and 2001. Since 1966, there has been a noticeable decline in the mean and the variability in this series. For this period (1966–2001), the mean is 0.6 and the coefficient of variation is 21.2% compared to the long-term values of 0.8 and 31.4%, respectively. However, the period from 1977 to 2001 is unprecedented in the record with a further decline of the mean to 0.5 while the coefficient of variation has decreased to 16.1%. Examination of the time series for the second criterion of the ideal break definition in Figure 6(a) reveals that the lowest value of the running mean (0.4 rainfall events per year) occurs at the end of the series in 2001.

The change in the statistics of wet events in the crop establishment period suggests the possibility of a shift in the seasonal atmospheric circulation over time. For the first criterion of the ideal break definition, Figure 6(b) shows the time series of the mean number of wet events in the second half of the growing season (July to October). There is a gradual trend to higher numbers of wet events in the record, which is also significant at the 99.9% confidence level. The lowest value (0.3) occurred in 1900, 1901, 1902 and 1927. Despite the overall upward trend, it is apparent that there has been an abrupt decline in the running mean since 1998.

5.2. Timing of the break

Not only has there been a downward trend in the number of autumn ‘wet’ events over the record, but the timing of the autumn break has been getting progressively later. A trend to later breaks is apparent for each of the ideal break criteria and also for the minimal break criterion. Figure 7(a) demonstrates that the number of days until the first criterion for an ideal break is met each year shows an increasing trend. The trend of 6.3 days per decade is significant at the 97% confidence level (Draper and Smith, 1998). In this analysis, events prior to March are not considered, and the autumn break can only occur from Julian Day 61. For the minimal break rule requiring at least 15 mm in 7 days or less, Figure 7(b) indicates that the long-term trend is also towards later breaks (3 days later per decade), which is significantly different from zero at the 98% confidence level (Draper and Smith, 1998). A trend to later breaks of approximately 3 days

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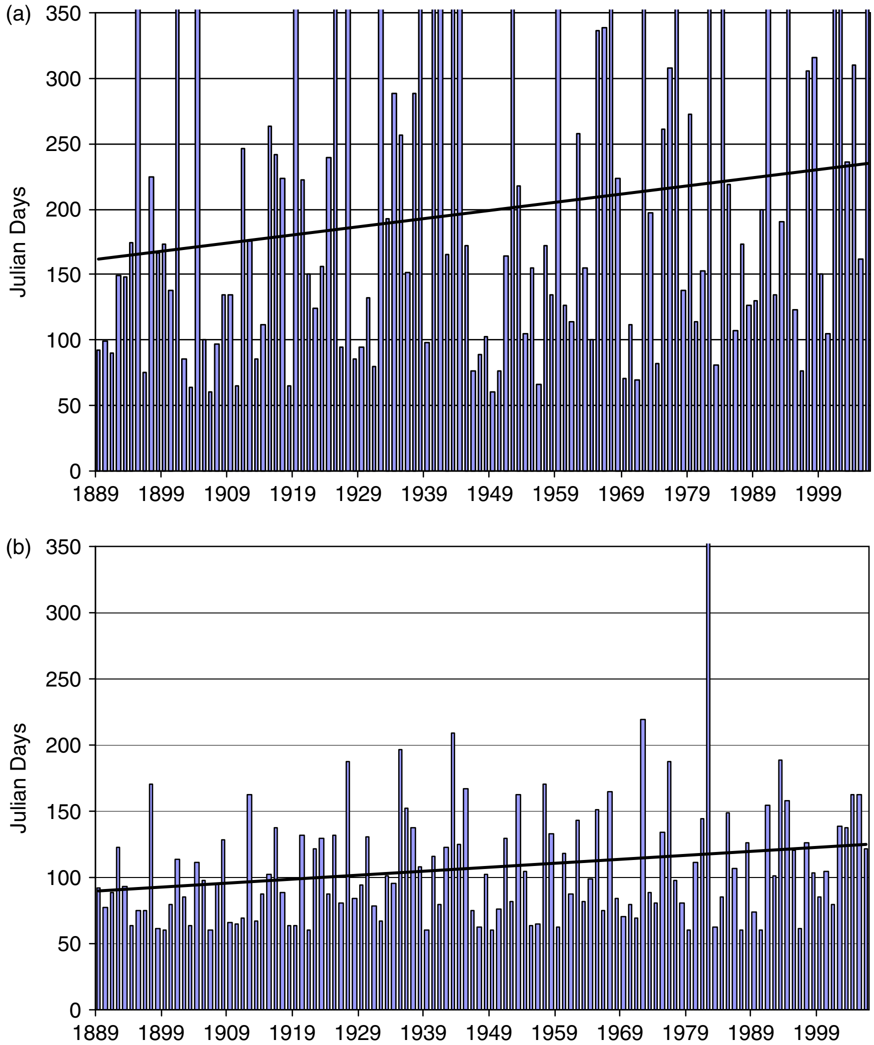

Figure 7. Number of days to first event satisfying autumn break criteria for (a) 25 mm in 3 days or less; and (b), 15 mm in 7 days or less (period from 1889 to 2006). This figure is available in colour online at www.interscience.wiley.com/ijoc

per decade is also obtained when the second criterion of the ideal break is applied (not shown).

Application of the full definition of the ideal break in which both criteria are considered identifies all years and the particular month in which an ideal autumn break occurred (Figure 8). Years in which an autumn break did not occur by the end of June are shaded grey in Figure 8. Clearly, there are more breaks in the first half of the record than in the second half of the 20th Century. For the period from 1889 to 1947, there were 41 ideal breaks according to our definition (approximately 70% of years) while from 1948 to 2006, there were only 34 (58% of years). Furthermore, breaks occur earlier in the first half of the record than in the second half. In particular, 15 breaks identified in the first half of the record occurred in the month of March while only 8 breaks in the second half were in March. The numbers of breaks occurring in the other three months were roughly equal in each half of the record.

In Figure 8, the years from 1956 to 2006 span the period covered in the synoptic analysis. There were 28 ideal breaks during this period (55% of years). The period from 1997 to 2006 is particularly noteworthy as it has the lowest number of ideal breaks (3) of any decade in the record. Although it was demonstrated in Figure 2 that the eleven-year running mean of annual rainfall was slightly lower in 1900 and 1940 than the present, the running mean of autumn rainfall (March–June) is at its lowest in 1938 and 2001.

5.3. Synoptic climatology of autumn breaks

The dominant synoptic systems generating rainfall in the target area were found to be cutoff lows and frontal systems which included simple cold fronts, cold fronts where a wave had formed, or complex systems comprising several fronts or front and pre-frontal trough combinations. Descriptions of these synoptic types can be found in Pook *et al.* (2006), and an example of an autumn break event associated with a cutoff low (2 June 1981) is given in Figure 9. The significance of the cutoff low as a rain-producing system in the Australian context has been demonstrated by numerous authors (see, for example: Hill, 1969; Wright, 1989; Mills and Wu, 1995; Sturman and Tapper, 1996; Griffiths *et al.*, 1998; Reeder and

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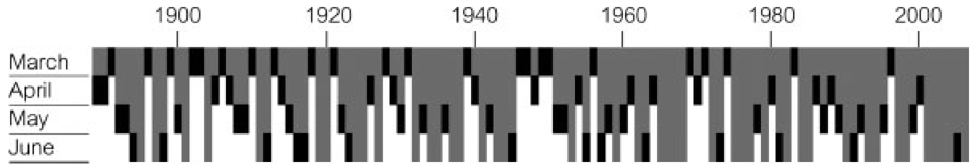

Figure 8. Month in which an ideal autumn break occurred (in black) for the period from 1889 to 2006. The columns representing years where an autumn break did not occur by the end of June are shaded grey.

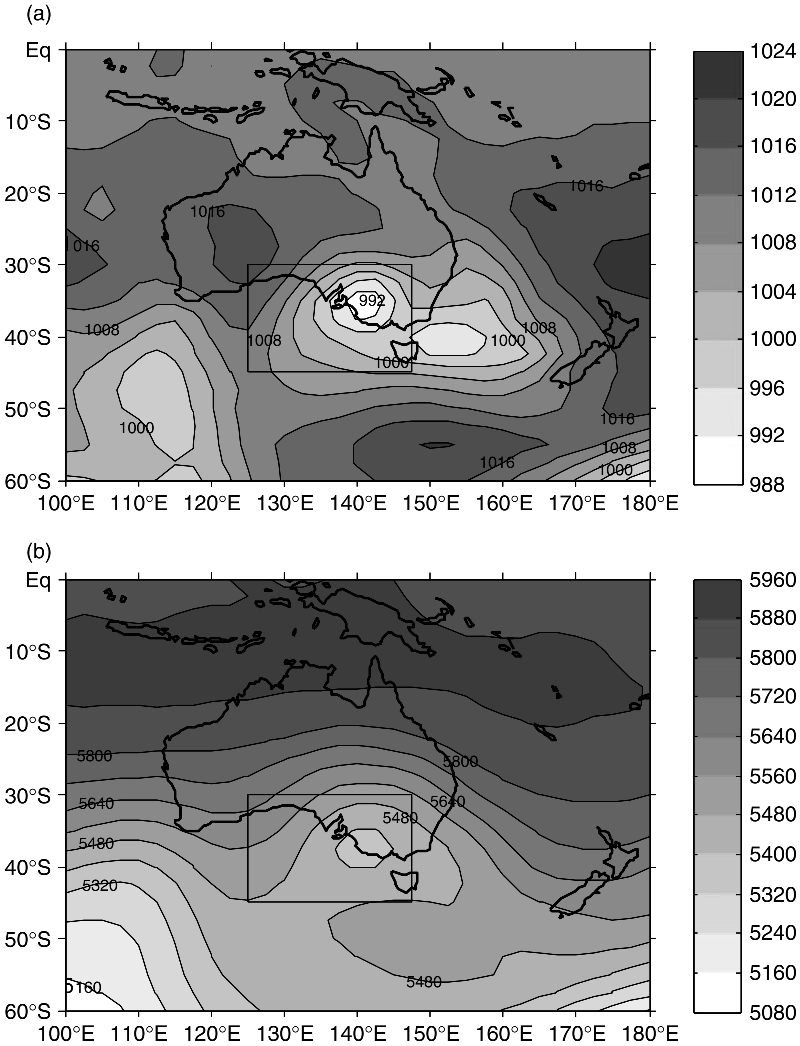

Figure 9. A cutoff low which produced an autumn break in NW Victoria in June 1981. The system was analysed over southeast Australia at 00 UTC on 2 June 1981 at (a) mean sea level (isobars at 4 hPa intervals), and (b) 500 hPa (contours at 80 geopotential-metre intervals). The box in the diagram represents the synoptic analysis region. (NCEP/NCAR data).

Smith, 1998; Qi *et al*., 1999; Pook *et al*., 2006). In the two years where the second criterion of the ideal break definition applied (viz. 1987 and 1991), it was necessary to classify two separate synoptic systems in combination in order to account for the requisite 30 mm of rain over 7 days or less. These cases are included under the classification 'combined systems' in Table I which gives the statistics of the synoptic analysis.

Of the 28 years (55%) of the synoptic analysis set (1956–2006) in which the ideal autumn break definition was satisfied, cutoff lows independently accounted for 61% of the breaks while 25% of the breaks were attributed to frontal systems. Tropical dips or easterly troughs were found to have been responsible for only 7% of autumn break occurrences. Figure 10 gives the relative frequency of occurrence of ideal autumn breaks and the two dominant synoptic types. It should be noted that the autumn breaks in May 1987 and June 1991 were attributed to both cutoff and frontal influences (the combined category in Table I) and each of these synoptic types has been classified as producing the autumn break in the respective year when compiling the statistics for Figure 10. The 11-year running mean of the number of ideal breaks reached its lowest value in 1980, 1998, 1999

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Table I. The number of synoptic systems in each month assessed as being responsible for the Autumn Break (1956–2006).

	March	April	May	June
Easterly Trough	2	0	0	0
Cutoff Lows	2	5	7	3
Frontal Systems	2	3	1	1
Combined Systems	0	0	1	1

and most recently in 2001, but there is a marked variation in the number of autumn breaks attributable to cutoff lows and frontal systems throughout the five decades under consideration. From Figure 10, the cutoff low clearly emerges as the dominant system associated with autumn breaks in the 20-year period from 1976 to 1996. The raw data reveal that cutoff lows were directly responsible for 9 of the breaks (75%) during this period and were partly responsible for another 2. Cutoffs had their least influence on autumn breaks in the decade from 1965 and in the most recent decade while frontal systems had the most impact in the late 1960s.

It has previously been demonstrated that cutoff lows are responsible for the highest proportion of April (approximately 55%) and May (52%) rainfall in the region of Northwest Victoria shown in Figure 1 and that these synoptic systems account for 80% of daily rainfall events exceeding a mean value of 25 mm across the 8 stations during the entire April to October growing season (Pook *et al*., 2006). Furthermore, the analysis of synoptic systems and rainfall for the 8-station network reveals that total rain and cutoff rain in the three-month period from April to June are highly correlated ($r = 0.85$; $n = 51$). Figure 11 demonstrates that cutoff rain and total rain in these months has declined markedly in the past three decades while frontal rain does not show a significant trend. Note that March was not included in the original analysis of Pook *et al*. (2006). The observed decline in the occurrence of heavy rainfall events in the

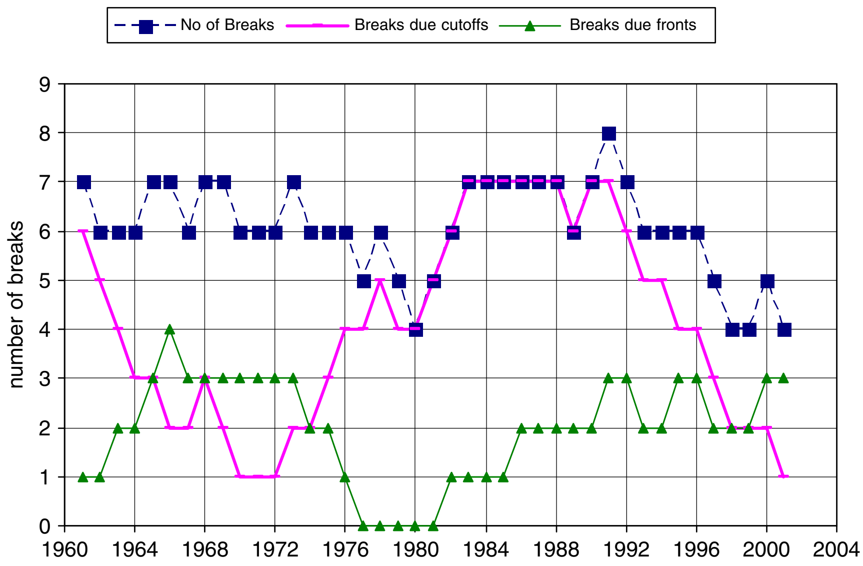

Figure 10. Eleven-year running sum (centred on year shown) of the total number of autumn breaks, the number of breaks due to cutoff lows and the number of breaks due to frontal systems calculated for the period from 1956 to 2006. This figure is available in colour online at www.interscience.wiley.com/ijoc

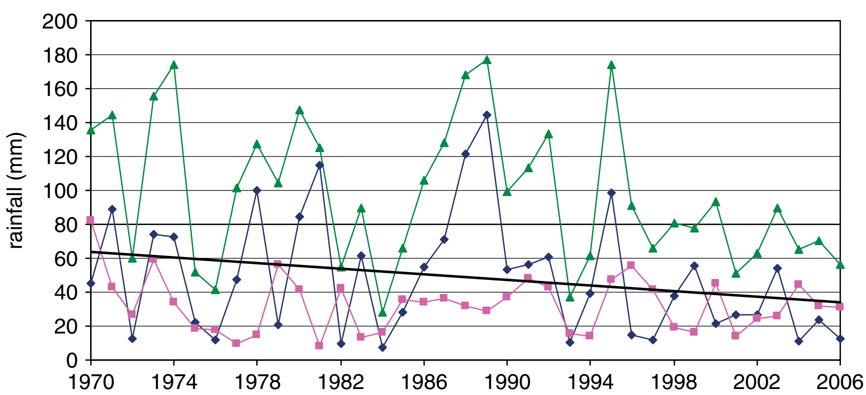

Figure 11. Rainfall amount in April, May and June by year due to cutoff lows (blue) and fronts (magenta) with total rainfall for these three months (green). The linear trend line indicates the decline in rainfall associated with cutoff lows.

crop establishment period and the complete absence of 'extreme' wet autumns from 1996 to 2006 has occurred in parallel with the decline in the contribution of cutoff lows to the April to June rainfall. Hence, it appears highly likely that these changes have occurred largely as a consequence of the decrease in the frequency of occurrence of active cutoff lows. Such a reduction could be the result of a decrease in frequency and/or intensity of these systems, changes in preferred tracks, or in the ability of cutoff lows to access moisture.

A preliminary examination does not indicate any marked decrease in the frequency of occurrence of cutoff lows within our analysis region during the autumns of this period (not shown). It is important to note, however, that the analysis technique employed in this phase of the study detects all cutoff systems (recorded as cutoff low days) that meet the specified criteria, whether they produce rain or not (Pook *et al*., 2006). The decline in cutoff rain in autumn is therefore related to the decline in the amount of rain per cutoff day which is consistent with the finding reported for the entire growing season by Pook *et al*. (2006).

5.4. Simulated impacts of the autumn break on wheat yield

Typically, the more demanding the sowing condition, as exemplified by a shorter rain window and/or larger rain threshold, the later the sowing date (Table II). The average yield across all years of the simulation declines with delay in sowing date as broadly demonstrated in Figure 12. This can be generally attributed to a shorter vegetative growth phase (i.e. reduced yield potential) and increased water stress as crop maturity is pushed later into the hotter and drier months of the year. Nevertheless, yield response to sowing date varies substantially from year to year (results not shown). In some years, later sowings result in a more favourable alignment of rainfall supply and crop demand, leading to higher yields compared with earlier sowings. Average pre-sow and in-crop rainfall totals were relatively consistent across the sowing treatments.

Figure 13 gives the 5-year running average to the year shown for wheat yield, sowing day and in-crop rainfall for the 15 mm over the 7-day sowing rule treatment. Trends for the other sowing rule treatments were similar and are not shown. In Figure 13(a), the most recent simulated 5-year running average yield of 1542 kg/ha is the lowest since 1944. While this yield is substantially higher than the lows experienced during the droughts of the early 1900s (298 kg/ha) and early 1940s (586 kg/ha), the trend in the recent decade is downward.

Figure 13(b) demonstrates that the mean date of sowing has been getting progressively later over the last decade. In 1996, the 5-day average sowing day was day 105 but this had increased to day 150 in 2005. While somewhat earlier than the peak during the extreme drought in the 1940s (day 175), the current trend is for increasingly later sowings. The most recent average sowing date in the model run is much later than the latest

Table II. Seasonal averages (1889–2005) for wheat yield (kg/ha), day of sowing, pre-sow rainfall total from harvest of previous season crop to sowing of current season crop (mm) and in-crop rainfall total from sowing to harvest (mm) for each sowing treatment.

	Sowing treatment						
Rain threshold (mm)	10	10	15	15	25	25	30
Rain window (days)	3	7	3	7	3	7	7
Yield (kg/ha)	2622	2722	2340	2530	1934	2200	2079
Sow day	114	103	131	119	155	141	149
Pre-sow rainfall (mm)	158	160	156	159	170	161	165
In-crop rainfall (mm)	195	193	197	194	183	192	188

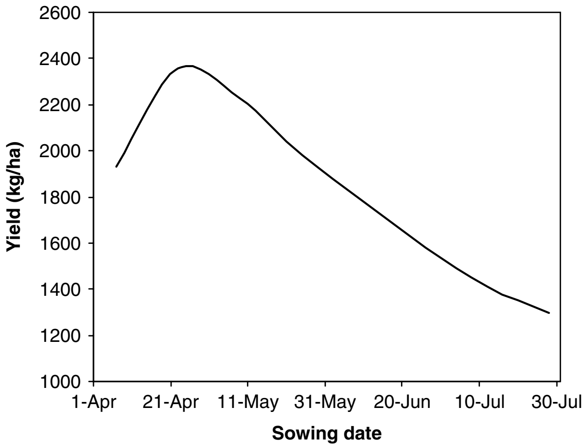

Figure 12. Simulated wheat yield response to fixed sowing date at Birchip (see location map in Figure 1) using APSIM and averaged over the period from 1890 to 2005. Simulations are based on a generic soil with plant extractable soil water volume of 126–90 cm. Crops are rainfed, and nutrient unlimited.

sowing date during the severe drought of the early 1900s (viz. day 131 in 1901).

The in-crop rainfall plot in Figure 13(c) shows that the current running average is at or near the lowest level over the period of simulation and has been declining steadily over the past ten years. There is no evidence from the modelling study to suggest a decline in pre-sow rainfall at the Birchip site in recent times, nor a decline in deep drainage below the root zone (not shown).

6. Discussion

A clearer understanding of the role of cutoff lows and other synoptic types in autumn rainfall and the autumn break, and their more general contribution to the inter-annual variability of rainfall has important implications for agricultural production in southern Australia. The predominance of particular types of synoptic systems influences the way rainfall is distributed throughout the

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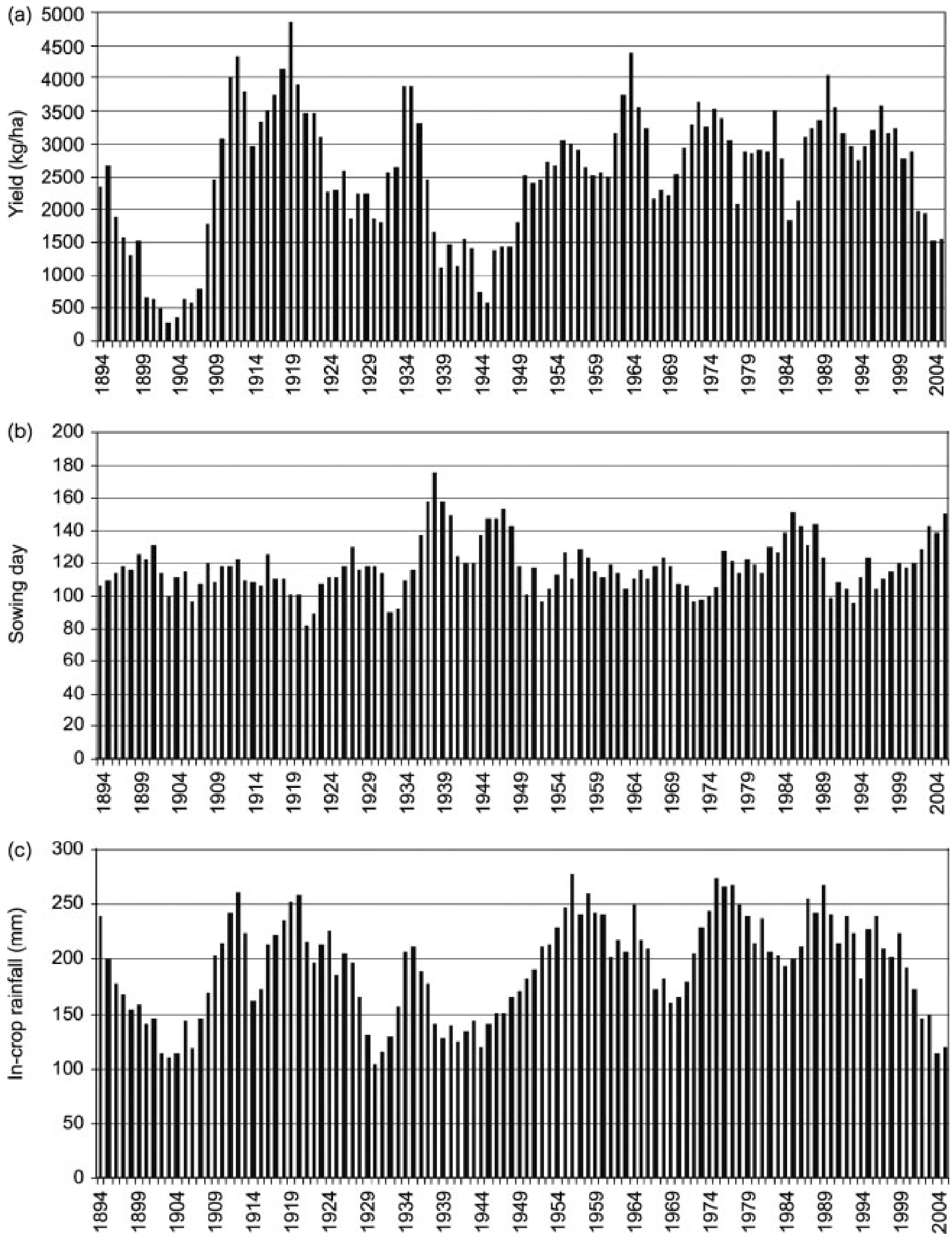

Figure 13. Simulated five-year running mean from the APSIM model ending on the year shown for (a) wheat yield (kg/ha), (b) day of sowing, and (c) in-crop rainfall (mm) at the Birchip site. The sowing rule applied was for a threshold value of 15 mm of rain over 7 days.

growing season and the rainfall amount in a given event. This is important since the relationship between crop performance and climatological variables is complex and it is not unusual for the interannual variability of crop yields to run counter to that expected intuitively from the broad climate indicators in a given season, such as total rainfall. Ultimately, it is the way rainfall matches the needs of the growing crop that will determine the success of the season.

Additionally, as cutoff lows are responsible for the majority of heavy rainfall events from autumn through the growing season they provide key inputs to stream flows, water storages and the recharge of groundwater in the region. Autumn breaks are important influences on the hydrology of catchments and changes in reliability of these major rainfall events, such as have occurred during the last decade of the time series, can have serious repercussions for water availability in subsequent seasons.

The frequency of occurrence of cutoff lows in autumn does not appear to have changed significantly in our analysis but there has been a reduction in the amount of rain associated with each system. No single explanation for the declining contribution of cutoff lows to autumn

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rainfall in recent decades is apparent but reasons have to be sought in the characteristics of individual systems and their ability to access moisture. System characteristics that can undergo change on interannual and longer time-scales include the mean intensity of the cutoff lows, their speed of movement and the mean tracks followed by the lows. The intensity of these cold-cored cyclonic systems is strongly influenced by the upper level divergence associated with the subtropical jet stream which is located equator-wards of the low and warm air advection which develops on the eastern flank. Variations in intensity of cutoff systems can be ascribed to local variations in baroclinicity, vorticity, and the strength of the subtropical jet itself (Risbey *et al*., 2008). Speed of movement and the tracks described by the systems are influenced by the background flow and are particularly dependent on the location and persistence of atmospheric blocking which is highly correlated with the numbers of cutoff lows in our analysis region (Pook *et al*., 2006). All these behavioural characteristics of cutoff lows are under investigation, but further research is needed to identify the dominant factors controlling variability.

The origin of atmospheric moisture contributing to cloud and rain systems can be investigated by back-tracking air parcels from the region where the rain has fallen to a recognizable source many days prior to the rainfall event. Mean back-trajectory analysis of cutoff lows over southeastern Australia indicates that air parcels convey moisture from oceanic source regions, with tropical sources dominating in the higher rainfall events (McIntosh *et al*., 2007). However, McIntosh *et al*. (2007) have demonstrated that the atmosphere is highly variable and trajectories are observed from the oceans to the northeast, north and northwest of Australia, as well as occasionally originating over the southern Ocean.

Access to moisture is influenced by the background state of the tropical ocean and atmosphere. However, the dominant tropical climate drivers are known to be poorly correlated with rainfall in southeastern Australia in autumn. Correlations between southeastern Australian rainfall and ENSO are strongest in winter and spring (Allan, 1988). Similarly, the Indian Ocean zonal dipole mode (IODM) (Saji *et al*., 1999; Webster *et al*., 1999) develops towards the end of autumn and influences winter rainfall in western and southern Australia (Ashok *et al*., 2003). Meyers *et al*. (2007) have demonstrated that the combined states of the Indian and Pacific Oceans influence the probabilites of June to November rainfall across Australia.

Individual rainfall events over southern Australia also appear to be influenced on the intraseasonal time-scale by the Madden-Julian Oscillation (MJO), a large-scale east-ward propagating wave in the tropical atmosphere which produces periods of enhanced and diminished convection as it migrates across the Indian and Pacific Oceans (Donald *et al*., 2006). The MJO can be classified into eight phases based on the leading patterns of variability of the zonal wind in the near-equatorial latitudes (Wheeler and Hendon, 2004). Wheeler *et al*. (2008) have demonstrated that extratropical rainfall signals are detectable in two of these phases of the MJO in autumn. However, systematic interactions between the mid-latitude systems and the MJO have yet to be established.

It is increasingly evident that the complexity and non-linearity of the interactions among the underlying climate drivers requires the application of coupled atmosphere–ocean models to take account of all the influences on autumn rainfall. There has been considerable progress in the ability of models to represent many of the large-scale drivers. However, the mechanisms by which each of the drivers transmits its influence via synoptic systems to rainfall are still poorly known and simulated. Steps towards improving this understanding have mainly been carried out with atmospheric general circulation models with prescribed SST patterns (e.g. Ummenhofer *et al*., 2008) and further research is required to make robust connections between Australian rainfall districts and oceanic regions.

7. Conclusions

Two definitions of the autumn break developed for north-western Victoria (the ideal break and the minimal break) have been employed to produce a synoptic climatology of the break phenomenon and identify trends in the climate record. Ideal autumn breaks occurred in approximately 70% of years (41 events) in the first half of the historical record (1889–1947) while from 1948 to 2006 only 58% of years (34 events) had ideal breaks according to our definition. In the period for which a synoptic analysis has been completed (1956–2006) ideal autumn breaks have occurred across the 8-station network in 55% of years (28 events) but, in the most recent decade (1997–2006) there have been only 3 ideal breaks (1999, 2000 and 2005). The decline in the number of ideal autumn breaks has been accompanied by a trend towards breaks occurring later in the season (by 6.3 days per decade for the first criterion of the ideal break). In the case of the minimal autumn break, the long-term trend over the record is also towards later breaks (by 3 days per decade). During the 11 years from 1996, none of the 8 stations recorded an ‘extreme’ wet autumn (at least 1 standard deviation above the rainfall mean), the longest period that such a sequence has occurred in more than a century.

The synoptic analysis has established that the cutoff low is the dominant mechanism responsible for ideal autumn breaks. Cutoff lows accounted for 61% of the ideal breaks identified from 1956 to 2006, while 25% of the breaks were attributed to frontal systems. Tropical dips or easterly troughs were found to have been responsible for only 7% of autumn break occurrences. However, the contribution of the cutoff low to autumn and growing season rainfall has declined markedly in the past decade and there has been only one ideal break attributed to a cutoff low in this period (1999). Hence, it is likely that the decline in the occurrence of heavy rainfall events in the crop establishment period and the complete absence

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of 'extreme' wet autumns after 1995 is largely a consequence of the decline in active cutoff lows.

Simulations were carried out with the APSIM farming systems model to explore the response of wheat growth and yield at Birchip in northwest Victoria to the timing of the autumn break and the resultant seasonal rainfall distribution and total. A key conclusion was that the average wheat yield across all years of the simulation tended to decline with delay in sowing date beyond the end of April due to the truncation of the vegetative growth phases and increased exposure to high temperatures and water stress for late maturing crops. In spite of this overall tendency, there is marked interannual variability in yield response to sowing date highlighting the importance of seasonal rainfall distribution and how this aligns with crop demand. Based on a sowing rule of 15 mm over 7 days, the 5-year running mean of the in-crop rainfall has declined sharply in the last decade of the simulation period (1894–2005) and was only slightly above its lowest value on record at the end of the run. Similarly, the mean date of sowing has become progressively later during the most recent decade reaching day 150 (30 May) in 2005, placing it between the latest sowing date simulated during the major drought in the early 1900s (11 May) and the simulated peak during the drought which began in the late 1930s (24 June). In response to these trends, wheat yield has also been steadily declining over the past 10 years and at the end of the simulation period had fallen to its lowest value since 1944.

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