

A comparative synoptic climatology of cool-season rainfall in major grain-growing regions of southern Australia

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Abstract Two distinct synoptic weather systems, cut-off lows and fronts, deliver most of the cool-season rainfall to the cropping regions of southern Australia. A comparative synoptic climatology of daily rainfall events over approximately five decades reveals both spatial and temporal variations of the dominant synoptic types. The rainfall characteristics and associated large-scale drivers differ between the two synoptic types. Understanding regional rainfall depends on understanding these differences. Cut-off lows contribute one half of growing season rainfall in southeast Australia, while frontal systems associated with Southern Ocean depressions contribute about a third. The proportions are reversed in the Central Wheat Belt (CWB) of Western Australia where Southern Ocean fronts are the dominant source of growing season rainfall. In the southern island state of Tasmania, topography strongly influences the outcome with cut-off lows contributing about half the rainfall near the east coast and fronts dominating a short distance to the west. Cut-off lows generally contribute their highest proportion of rainfall in the austral autumn and spring while frontal rainfall is at its maximum in late winter. Cut-off low rainfall contributes more strongly in percentage terms to the recent decline in rainfall. The distribution of synoptic types is explained by the dominant long-wave structure in the winter half of the year. The major trough near Western Australia favours frontogenesis to the southwest of the CWB but fronts moving out of the region encounter a persistent meridional ridge in the Tasman Sea where there is a high frequency of blocking events.

1 Introduction

The inland plains of southern Australia are relatively dry and experience high rainfall variability on a range of time scales. Despite these limitations, the cool half of the year generally provides favourable conditions for the germination and production of high quality grain crops in parts of the region. Wheat is the dominant crop grown but is often planted in rotation with other grain crops and frequently, a pasture phase. According to the Food and Agriculture Organization (FAO) of the United Nations, Australia produces on average about 23 million tonnes of wheat per annum and this equates to approximately 3.5 % of total world production of the grain (FAO and United Nations 2011). Although the percentage contributed to world production is modest, Wheat Exports Australia (WEA), an Australian Government Agency, reports that a significant majority (typically 60–70 %) of the Australian crop is exported, thus contributing significantly to Australia's export earnings (WEA 2012).

Ignoring soil fertility and other agronomic considerations, the major constraints on wheat growth in this region are meteorological and climatological. Firstly, the timing of the arrival of adequate autumn rains for sowing, the so-called autumn 'break', is a key factor in the establishment phase (Pook et al. 2009). The duration of the winter minima in solar radiation and temperature during the vernalization phase is another constraint on growth followed by the timing of the subsequent reproductive phase of growth in relation to frost incidence and the occurrence of late-season high temperature and water-stress events (Nix 1987). Overall, the water supply during crop growth is the most critical factor affecting wheat yields (French and Schultz 1984; Stephens and Lyons 1998) although the soil moisture profile at the time of planting also influences crop success (French and Schultz 1984; Carberry et al. 2000). In particular, the timing of rainfall events in relation to crop requirement is regarded as more important

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than the total rainfall received during the life cycle of the crop (e.g., Pook et al. 2009).

Although it is common practice to represent regional rainfall on seasonal time-scales as a single value, actual rainfall is delivered to the crop in a finite number of relatively short-lived and well-separated events that can be associated in most cases with identifiable synoptic-scale systems. The mix of the synoptic systems responsible for rainfall is known to vary regionally and seasonally but the precise influences of synoptic types have not been determined previously for most Australian grain-growing regions. Identification of the dominant synoptic types and their contribution to rainfall is likely to be an important step in understanding the underlying processes connecting remote large-scale drivers to regional rainfall. When interannual climate variability and longer term climate trends are considered, changes in broad-scale atmospheric circulation may reasonably be expected to change the characteristics of particular synoptic types in different ways.

Since the distribution of rainfall is related to the occurrence and frequency of particular synoptic weather systems, we have compiled synoptic climatologies for four grain-growing regions in southern Australia. The individual synoptic systems predominantly responsible for daily rainfall events have been identified and classified in each case, thus allowing a comparison across the regions. The grain-growing period in southern parts of mainland Australia extends over the cool part of the year from about April to the end of October (French and Schultz 1984; Pook et al. 2006, 2012). The analyses have been confined to these months in each year and the term, growing season, will be applied to this period. The total period over which the climatologies have been compiled ranges from 1956 to 2009 but the actual periods of the individual analyses vary from region to region because of various factors. The regions studied are: the Murray Mallee in South Australia, the Northwest of Victoria, the Central Wheat Belt (CWB) of Western Australia and selected grain-growing areas of Tasmania (Fig. 1). An additional two decades of analysis data have been added to the previous analysis for northwestern Victoria presented by Pook et al. (2006). The synoptic analysis for the Murray Mallee region from 1956 to 2009 is novel. The analysis for the CWB of Western Australia is taken from Pook et al. (2012) and the analysis for Tasmania from Pook et al. (2010). This paper therefore categorises the respective contributions of the relevant synoptic systems over approximately five decades and provides the first comparison of the synoptic climatologies of growing-season rainfall in the grain regions of southwestern and southeastern Australia.

Studies applying synoptic climatological techniques to identify and document the synoptic systems associated with daily rainfall in a particular region over an extended period are relatively rare in Australia. Wright (1989) classified rainfall events in south-eastern Australia into five synoptic types for the June to September period in a 12-year study (1971 to

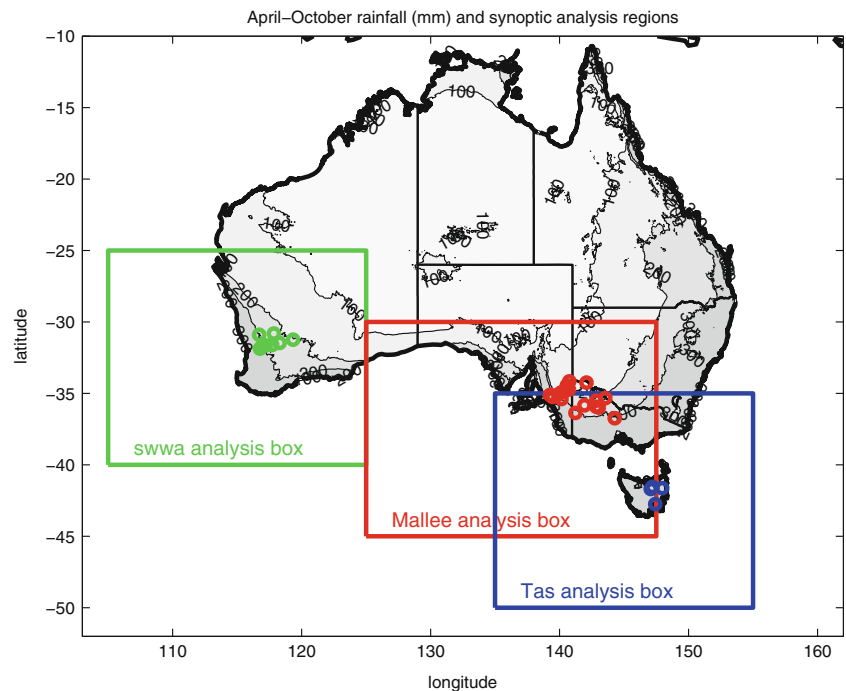
1982). Godfred-Spenning and Gibson (1995) performed an analysis of the synoptic weather systems that produced rainfall over the hydroelectric catchments of Tasmania, for a period of approximately 30 years. Landvogt et al. (2008) carried out a synoptic analysis of precipitation in an elevated region of northeast Victoria for the limited period 2000–2005. These studies suggest that cold fronts are the dominant source of cool season rainfall in southern Australia except for southeastern Victoria, where Wright (1989) found that his 'cold low' category of systems was more important than fronts.

The dominance of cold fronts as rain producers has been disputed for other parts of the southeast by Pook et al. (2006, 2009, 2010). They have shown the pre-eminent role of cut-off lows and associated atmospheric blocking in the rainfall distribution of northwestern Victoria and the east coast and adjacent region of Tasmania. Additionally, Pook et al. (2012) have found that cut-off lows also make a substantial but not dominant contribution to the growing season rainfall in the CWB of Western Australia (WA).

In an attempt to understand the stratification of synoptic types with respect to rainfall, Risbey et al. (2009a) contrasted the dynamical and thermal characteristics of cut-off lows and fronts associated with rainfall events in the southeastern region. They concluded that the wetter years in southeastern Australia are usually produced by cut-off systems and identified the positive Southern Annular Mode (SAM) pattern as being conducive to enhanced rainfall in the southeast via local intensification of blocking and cut-off systems. Risbey et al. (2009a) found that frontal systems can also be responsible for wetter than normal seasons but in those cases the mid-tropospheric flow pattern is suggestive of the negative phase of the SAM. However, in a separate study, Risbey et al. (2009b) examined the remote large-scale drivers of rainfall variability over Australia and found that all four major climate drivers, El Niño/Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD), the SAM and atmospheric blocking (a proxy for the dominant meridional ridge), were important influences on Australian rainfall. Their analysis showed that these influences are expressed in preferred but different, geographic locations and seasons. In an attempt to illustrate how the climate drivers may connect to regional rainfall variability via synoptic systems, Risbey et al. (2009b) developed a basic conceptual model of the dominant processes (their Fig. 1).

Computer models used for numerical weather prediction (NWP), seasonal forecasts and the prediction of future climates are expected to simulate the important weather systems accurately in order to justify confidence in their predictions. Although NWP has made great strides in the past two decades, coupled atmosphere–ocean climate models continue to have relatively poor representations of some synoptic processes and are unable to simulate a realistic mix of the synoptic types. For example, Palmer et al. (2008) have demonstrated that the frequency of winter blocking is systematically underestimated

Fig. 1 Map of Australia showing coloured boxes which represent the analysis regions for the Central Wheat Belt (*green*) in southwestern Western Australia (*swwa*; *green*), for the Murray Mallee region of South Australia combined with the Mallee region of northwestern Victoria (Mallee analysis box; *red*) and the Tasmanian grain-growing regions (Tas analysis box; *blue*). The small coloured circles represent the selected rainfall stations in each of the analysis regions. The background contours of April to October rainfall are based on Australian Water Availability Project (AWAP) data (see Jones et al. 2009)



in the Northern Hemisphere (NH) by a selection of these climate models. Pook et al. (2010) found that a group of climate models simulated a markedly lower number of cut-off low systems than the number found in analyses for the southern Australian state of Tasmania. Recently, Grose et al. (2012) have reported results of a dynamical downscaling experiment for Tasmania that produced modest improvements in the simulation of cut-off lows in the Australian region but revealed that biases were still present in the treatment of the broader circulation. This paper provides a benchmark for assessing the performance of climate models in accurately representing the synoptic mix in southern Australia.

The data sources and method used in our analysis are presented along with brief descriptions of each of the synoptic types in the next section. Section 3 provides a brief description of the significant features of the regional climate of southern Australia, including Tasmania, and the results are presented in Section 4. The factors influencing the distribution of synoptic types in relation to growing season rainfall is discussed in Section 5, and the conclusions are presented in Section 6.

2 Data and method

2.1 Data sources

In each of the three main grain-growing regions of the southern Australian mainland, a network of eight rainfall stations was selected to best represent the daily rainfall. The stations were predominantly obtained from a high-quality Australian historical data set (Lavery et al. 1997) but some supplementary

stations identified from Bureau of Meteorology records as having a long historical record were chosen to provide a balanced geographical distribution (Fig. 1). In the CWB of Western Australia the station network comprises Kellerberrin, Meckering, Merredin, Southern Cross, York, Cunderdin, Bencubbin and Wongan Hills (see Pook et al. 2012). In northwestern Victoria, the network was made up of Bendigo Prison, Birchip (Woodlands), Kaniva, Mildura Airport, Narraport, Rainbow (Pella), Sea Lake and Swan Hill (see Pook et al. 2006). The Murray Mallee stations are Geranium, Karoonda, Loxton, Murray Bridge, Paruna, Renmark, Sandalwood and Tailem Bend. Finally, the four Tasmanian stations chosen as representatives of the respective districts are Cressy (Research Station) and Launceston Airport in the central north, Fingal in the northeast and Richmond (Brookbanks) in the southeast (see Pook et al. 2010).

The daily rainfall data for each station were obtained from the SILO Patched Point Dataset supplied by the Queensland Department of Science, Information Technology, Innovation and the Arts (Jeffrey et al. 2001). This approach provided a consistent technique for inserting estimates of missing data. The Patched Point Dataset uses original Bureau of Meteorology measurements for a particular meteorological station but interpolated data are inserted to fill any gaps in the observation record. Additionally, gridded rainfall data for the analysis regions have been obtained from the $0.05^\circ \times 0.05^\circ$ Australian Water Availability Project (AWAP) monthly data set (Version 3) for the period 1900–2009 (Jones et al. 2009).

The synoptic analysis was primarily based on the National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR) climate reanalysis data set

(Reanalysis 1) (Kalnay et al. 1996; Kistler et al. 2001). The NCEP data consist of four analyses per day (at 6-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. The key fields sampled in the analysis were mean sea level pressure (MSLP), the 500 hPa geopotential height and the (computed) 1,000–500 hPa atmospheric thickness. Additionally, the 1,000–500 hPa thickness anomaly relative to the long-term climatology (1979 to 2001) for a particular month was calculated and displayed for each analysis.

The Reanalysis data set was supplemented by daily weather maps (0000 UTC) published in the Australian Bureau of Meteorology's *Monthly Weather Review* series (Simmonds and Richter 2000). These charts include frontal analysis which has been performed manually by expert analysts employing interpretation of satellite imagery in addition to standard analysis of synoptic data (Guymer 1978) and evaluation of output from a suite of NWP models. Although several automated methods of frontal identification have been developed for application to reanalyses and climate models (see Hope et al. 2013 and references therein) these charts provide consistent guidance from trained and experienced synopticians on the occurrence of cold fronts, important rain-producing systems in southern Australia.

NCEP analyses for the Southern Hemisphere have been found to have some systematic biases prior to 1970, particularly at high latitudes (Hines et al. 2000). However, methods for dealing with analysis in the years from 1956 to 1969 have been developed for southeastern Australia (Pook et al. 2009). Hence, 1956 was selected as the nominal starting point for the analysis in the southeast. A more conservative approach was taken for the CWB where 1965 was chosen for the starting year of the analysis, as discussed by Pook et al. (2012). The lack of a sufficiently dense upper air data network for the Australian region prior to 1956 precludes a comprehensive synoptic analysis for earlier periods (Bradshaw 1997). The Tasmanian synoptic analysis was undertaken for the shorter period from 1985 to 2009 and was intended to provide a preliminary synoptic climatology of the most southerly grain-growing regions of Australia. Subsequently, this synoptic climatology was adopted as a baseline against which climate model simulations for Tasmania could be compared (Pook et al. 2010; Grose et al. 2012).

3 Method

For each day on which rainfall was recorded at any of the rainfall stations in one of the respective cropping regions, a particular synoptic system was identified as being responsible for the precipitation event. Expert judgement from forecasting and analysis experience was applied in order to make realistic estimates of the typical displacement of synoptic systems in a 24-h period. This approach resulted in the choice of analysis

regions defined by fixed boxes (see Fig. 1). Synoptic systems were classified according to the classification scheme which was developed by Pook et al. (2006) for the southeast and extended to Tasmania (Pook et al. 2010) and the CWB of WA (Pook et al. 2012). The broad categories of synoptic systems that have been adopted are cold frontal systems associated with Southern Ocean depressions, cold-cored lows which have become cut-off from the westerly airstream (cut-off lows) and warm-cored low pressure systems associated with thermal ridges, including troughs in the easterlies. The final category includes all other systems not found in the main three categories, including airstreams of various directions and open troughs aloft. It also contains cold troughs in the middle and upper atmosphere where a closed circulation is not analysed at 500 hPa but the rainfall is considered to have been produced or enhanced by upper divergence and instability associated with the trough. The mainland regions under consideration are largely devoid of topographical features and most of the rainfall stations are located at a considerable distance from the nearest coast. Consequently, onshore airstreams are not major contributors to rainfall in these locations. This contrasts with the Tasmanian situation where topography is critically important and the regions are relatively close to the coast.

Within the broad category of cold frontal systems, three separate types of cold front were distinguished within the analysis exercise. The first type is the simple or conventional cold front represented on a synoptic chart by a single line. It is normally located near the surface pressure trough and within the region of maximum gradient on the 1,000–500 hPa thickness chart and is associated with low-level cold advection (Guymer 1978; Sturman and Tapper 1996). This class of front usually exists as a narrow zone of discontinuity of air mass properties and is identified on satellite imagery by its characteristic cloud band appearance (Fig. 2a). The second type of cold front in Australia, classified here as a complex front, is often preceded by a well defined prefrontal trough (Fig. 2b). These systems are particularly common in summer when they are referred to as 'cool changes' (Reeder and Smith 1998) but are less common in the growing season. However, early autumn and late spring are occasionally associated with this type of system, as well. Cases of multiple fronts, quasi-stationary fronts and those involving interaction with pre-existing subtropical cloud bands were also included in our 'complex fronts' category (Fig. 2b). The latter are similar to the 'interacting frontal types' of Wright (1989, 1997). Thirdly, a significant number of frontal systems approaching Australia undergo a process in which a wave develops on a section of the front and the northern and southern portions of the system move at different speeds. Zillman and Price (1972), Stretten and Troup (1973) and Guymer (1978) have identified systems of this type from satellite imagery. Under certain circumstances, these systems may develop into individual closed low pressure systems (Troup and Stretten 1972; Stretten and Troup 1973).

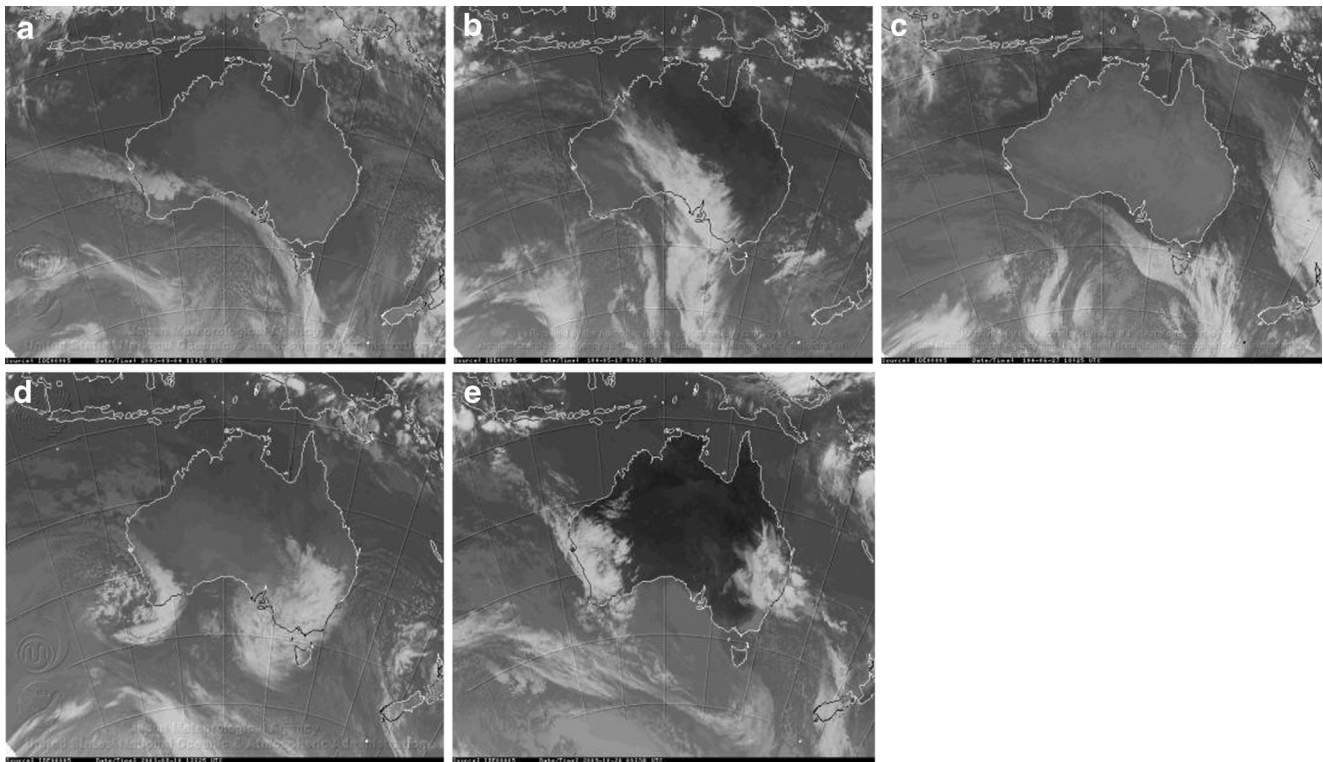


Fig. 2 Infrared satellite imagery depicting the dominant synoptic types encountered in the analysis: **a** a simple or common cold front, **b** a complex cold front, **c** a wave on a cold front near Tasmania, **d** a cut-off low near southwestern Australia and **e** a 'warm' trough over Western Australia and a

cloud mass over eastern Australia associated with a developing cut-off low. (Japanese geostationary satellite data via the Australian Bureau of Meteorology)

We classified these fronts as 'frontal waves' (Fig. 2c). Although these frontal types appear distinct and may provide insight into the underlying rainfall mechanisms there is an element of subjectivity involved in separating them into individual categories. Therefore, in the overall analysis of rainfall all the variations of cold fronts discussed above have been combined into one 'frontal' category.

Following previous practice (Pook et al. 2006, 2009, 2010, 2012) the cut-off low has been identified (Fig. 2d) according to criteria that adhere to the concept of an upper air disturbance associated with a 'cold pool' in the mid-troposphere. However, in certain situations some circulations are more significant near the surface at particular stages in their development. The criteria which we have adopted in this study are:

(a) A closed low is present in the relevant analysis box at 500 hPa and is clearly separated from the westerly flow to the south. There is an associated cold trough evident in the 1,000–500 hPa thickness field. A negative thickness anomaly from the long-term mean (NCEP Analysis 1) of at least 20 geopotential metres exists within the designated box.

or

(b) A closed low is present within the analysis box in the surface MSLP field (central pressure $\leq 1,008$ hPa) and an

associated cold trough is located aloft with a negative thickness anomaly from the long-term mean for that month of at least 20 geopotential metres.

Cut-off low systems typically develop in conjunction with blocking highs located from the Great Australian Bight to the South Tasman Sea region (Qi et al. 1999; Pook et al. 2006, 2012). These lows often form in amplifying troughs in the vicinity of southwest Western Australia and the Great Australian Bight and 'pinch off' to form the cyclonic component of the block. The cut-offs may be quasi-stationary, or may even retrogress westwards, but usually move eastwards as they decay and get incorporated back into the mean westerly flow.

The warm trough category includes warm-cored cyclones (including tropical depressions) and waves in the easterlies and the deep troughs in the easterlies inland of the east coast and near the west coast of Australia (e.g., Fig. 2e). Troughs of this type are regularly observed during the summer months but are also active in the early autumn and late spring. Although tending to form in warm air which has been advected from the northeast, these systems can subsequently migrate eastwards ahead of approaching fronts and upper troughs. This category will be referred to as 'warm rain' in the following sections.

4 Cool-season climatological influences

The climate of coastal regions of southern Australia, including the island of Tasmania, has been classified in broad terms as temperate whereas the climate of the majority of the inland grain-growing region of the mainland more closely aligns with the 'hot (summer drought) Grassland' classification of Australian Climate (Stern et al. 2000). Detailed examination of the 'climates' of Australia was undertaken by Gentilli (1971). Wright (1974a, b) examined particular regional aspects of the climate of southwestern WA and a regional climatology of Tasmania was presented by Langford (1960). Broader overviews of the climates of individual Australian states have been compiled by the Bureau of Meteorology (1993a, b, 1995). Recently, synoptic climatologies of daily rainfall events in the southeast, Tasmania and the CWB have been produced for the cool season by Pook et al. (2006, 2010, 2012).

Within the main grain-growing regions (see Fig. 1), mean growing season rainfall varies between approximately 200 and 400 mm. Conditions are slightly drier in the far north of the Victorian Mallee and rather wetter in the far south and east. Similarly, in the CWB, average growing season rainfall increases to around 500 mm in the far south and approximately 550 mm at the western edge. By way of contrast, although growing season rainfall in Tasmania is broadly similar to the mainland (250–450 mm) it tends to be more reliable and does not have the winter-dominant structure of the CWB. Additionally, Tasmania experiences much lower temperatures than the mainland cropping regions.

The constraints on rainfall in the respective regions become more apparent when monthly rainfall means are examined. A notable feature of the mean monthly rainfall distribution in the CWB of WA is the abrupt change during autumn from the dry summer to a winter-biased rainfall regime. The return to dry conditions during the spring is similarly abrupt. By way of comparison, the monthly rainfall distribution in the southeast cropping region exhibits the abrupt change during autumn from the dry summer but is thereafter followed by an evenly distributed rainfall regime during the months from May to October. Figure 3 shows the monthly rainfall distribution for eight-station averages in the CWB, the Murray Mallee and the northwest of Victoria, together with a four-station average for Tasmania.

The marked seasonality of the rainfall distribution over southern Australia is commonly explained by reference to the monthly MSLP field. The average MSLP pattern over southern Australia is dominated by the subtropical ridge (STR) of high pressure, the surface manifestation of the descending branch of the Hadley Circulation (e.g., Sturman and Tapper 1996). Following the apparent northwards movement of the sun (insolation maximum) in the austral winter, the latitude of this ridge migrates equatorward to about 30°S. It

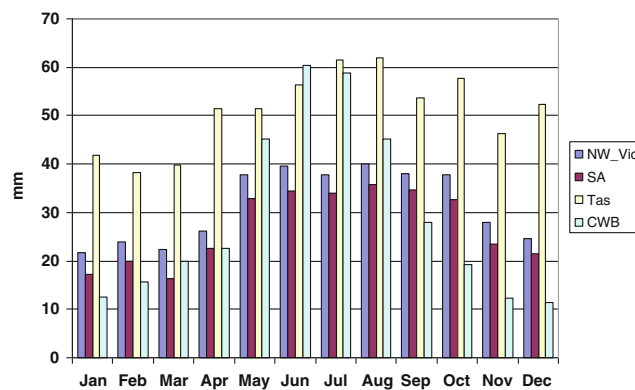
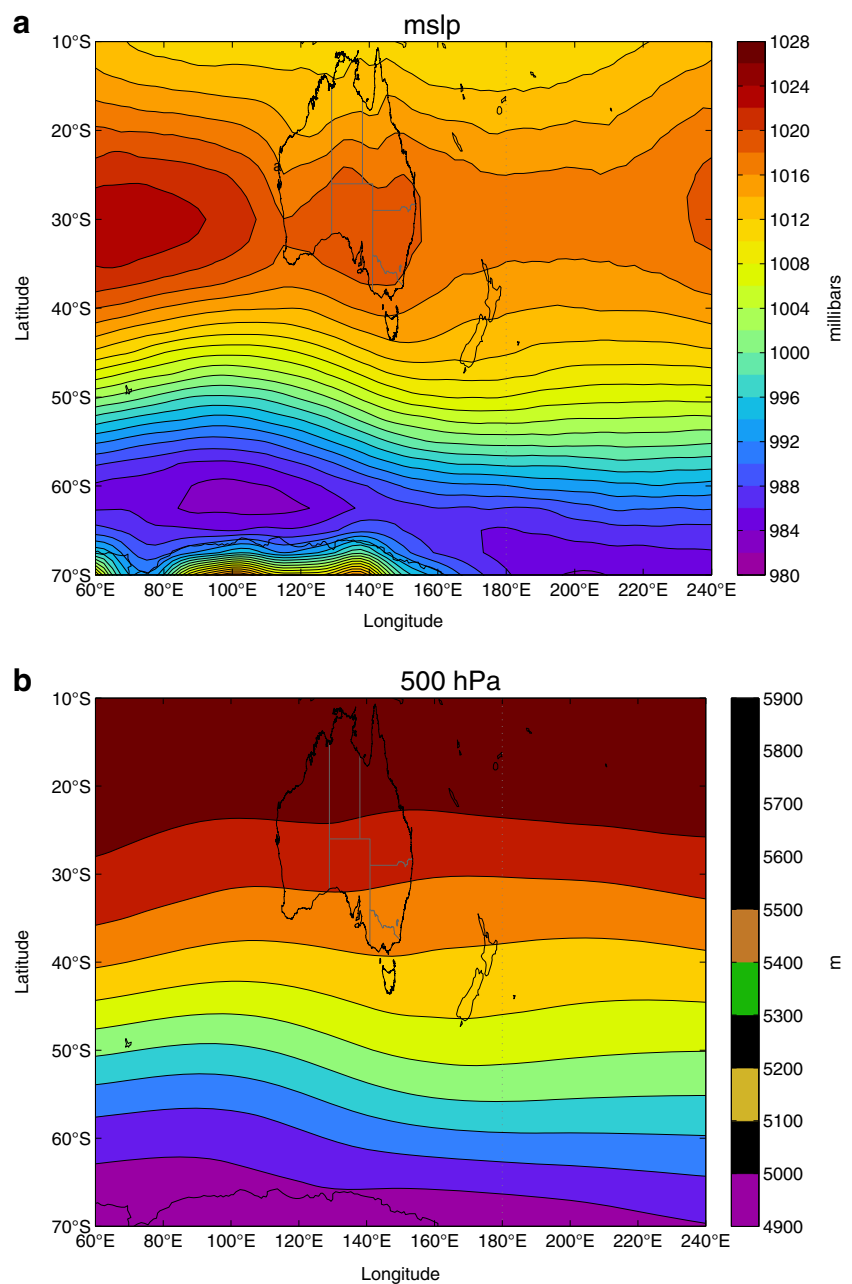


Fig. 3 Mean monthly rainfall (mm) averaged over the selected eight stations in the Central Wheat Belt (CWB) of Western Australia, in the Murray Mallee region of South Australia (SA), in northwestern Victoria (NW_Vic) and over the four rainfall stations in Tasmania (Tas). Patched Point Data Set (Jeffrey et al. 2001) for the period 1889–2009

then moves poleward again during the latter part of the growing season as temperatures rise and 'heat troughs' develop over northern Australia (Pook et al. 2006). Importantly, this meridional movement of the ridge is accompanied by the intensification and slow eastwards migration of a distinct north–south trough of low pressure near the south west coast of the continent. Figure 4a shows the mean position and intensity of the STR and the trough at mean sea level for the April to October period. The MSLP trough is accompanied by a well-defined trough in the upper atmosphere at longitudes from about 100°E to 110°E (Fig. 4b). In the east a meridional ridge extends from the southeastern mainland to the South Tasman Sea at the surface and in the upper air (Fig. 4a and b). While much emphasis is placed on the STR, there has been little comment in the literature on this meridional ridge of high pressure in the MSLP field over the southeast. This seems curious since the STR is a relatively shallow feature which is hardly detectable above 850 hPa, yet Fig. 4b shows that the meridional ridge persists in the upper troposphere and reflects the predisposition to blocking in the Tasman Sea and New Zealand region (Trenberth and Mo 1985; Pook and Gibson 1999; Pook et al. 2006).

The STR is closest to the equator in the July to August period and the belt of westerly winds on its southern flank becomes well established over southern Australia at this time. This period of persistent westerly winds is associated with an increased frequency of rain-bearing cold fronts crossing southern Australia. However, the maximum rainfall is clearly experienced in southwestern WA in June and July. Gentilli (1971) and Wright (1974a, b) ascribed this behaviour to the tendency for the mean airflow to be predominantly from the northwest early in winter with a strong interaction with the Darling Scarp. The contrast with monthly mean rainfall in the southeastern cropping regions is particularly interesting. As noted by Pook et al. (2006, p.1158), "...the STR undergoes changes in position, intensity and orientation from May to

Fig. 4 Long-term means (1956–2010) for the growing season period (April–October) of **a** mean sea level pressure (hPa) and **b** 500 hPa geopotential (m). (NCEP Reanalysis data)



October while the mean monthly rainfall over the region remains almost constant.” Hence, in order to understand the distribution of rainfall in southeastern Australia during the grain-growing season it is essential to consider the influence of the meridional ridge to the southeast of the continent and particularly, its role in the upper troposphere.

The upper air is an important player in influencing the regional rainfall processes as significant changes in atmospheric circulation occur in the middle and upper troposphere from summer to winter (Pook et al. 2006; Risbey et al. 2009a; Pook et al. 2013). These include the intensification and equatorward movement of the subtropical jet stream to about 30°S when the STR reaches its northernmost position (Radok 1971;

Sturman and Tapper 1996; Hurrell et al. 1998) and the development of a 'split' in the westerly flow over the Tasman Sea and New Zealand region accompanied by a maximum frequency of occurrence of atmospheric blocking (Trenberth and Mo 1985; Pook and Gibson 1999; Bals-Elsholz et al. 2001; Pook et al. 2013).

The changes in circulation in the upper air have been attributed mainly to the major changes in the land-sea temperature contrast between southeastern Australia and surrounding oceans from summer to winter (Taljaard 1972; Pook et al. 2013). The cooling over the continental southeast results in a steady decrease in 1,000–500 hPa thickness during autumn and the development of a winter thermal minimum in this

region. The split in the westerlies forms in response to this cooling of the atmospheric column and the intensification and retrogression of the high latitude thickness ridge (polewards of 45°S) from the central Pacific to about 160°E (Bals-Elsholz et al. 2001; Pook et al. 2006, 2013).

5 Results

The comparative results of this study for the months of April to October are summarised in Fig. 5. For the purposes of a strict comparison across the regions the period shown here is 1985 to 2009. In the Murray Mallee district of South Australia and in northwestern Victoria, Fig. 5 shows that cut-off lows account for approximately 50 % of the rainfall recorded by the selected stations. Cold frontal systems contribute approximately one third of growing season precipitation. The remainder (13–17 %) is provided largely by warm-cored systems such as waves in the easterlies and shallow lows which we have designated 'warm rain' in the figure (approximately 4 %), various airstreams (not shown) and upper level troughs where a closed low is not identified (also not shown). It is important to note that the percentage contributions of synoptic systems to rainfall shown in Fig. 5 vary only by about 1 % to 2 % from the means for the entire analysis period (1956–2009) (not shown). Over this complete analysis period, the mean number of days when a cut-off low is analysed in the 'Mallee analysis box' (see Fig. 1) during the April to October growing season (a total of 214 days) is 43.6 compared to a mean of 37.7 days on which frontal rain occurs.

In the CWB of Western Australia, Fig. 5 indicates that frontal systems associated with Southern Ocean depressions account for approximately 50 % of the rainfall averaged over the selected stations. By way of comparison, cut-off low pressure systems contribute approximately one third of growing season precipitation in the region. Additionally, Fig. 5 shows

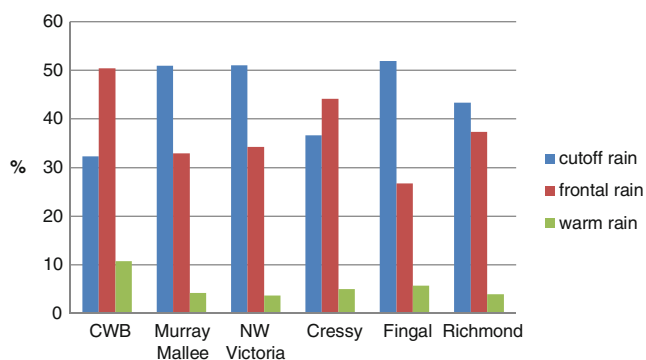


Fig. 5 Percentage contributions to growing season (April to October) rainfall of the main synoptic types in the Central Wheat Belt (CWB) of Western Australia, in the Murray Mallee region of South Australia, in northwestern Victoria and at three rainfall stations in Tasmania (Cressy in central north, Fingal in the northeast and Richmond in the southeast). The period of comparison is from 1985 to 2009

that the remainder largely falls into the category of 'warm rain' (11 %) as defined in Section 2. The balance of about 5 % is associated with various low-level airstreams and upper level troughs where a closed low is not identified (not shown). The percentage contributions for the synoptic types shown in Fig. 5 are robust with very little change over the entire 1965 to 2009 analysis period (not shown). Over this complete analysis period, the mean number of days when a cut-off low is analysed in the 'SWWA analysis box' (see Fig. 1) during the growing season is 29.5 days compared to a mean of 48.2 days on which frontal rain occurs.

The synoptic analysis for Tasmania reveals that the relative contributions made to daily rainfall by the selected synoptic types vary substantially across the cropping regions (Fig. 5). In particular, cut-off lows have been found to be responsible for approximately 50 % of April to October rainfall in the northeast (at Fingal), a lower proportion (39 %) in the south-east (Richmond) while the proportion of rainfall attributed to cut-off lows declines to about 35 % in the central north. The other large contribution to rainfall is from southern frontal systems which account for approximately 50 % of growing season precipitation in the central north at Cressy and also at Launceston Airport (not shown) but less than 30 % a short distance to the east at Fingal. The relative effects of the two main synoptic types vary widely across Tasmania, mainly as a result of the complex topography. Pook et al. (2010) argued that the effect of topography is exemplified by the contrast between rain associated with northwest and southwest airstreams (not shown). In their study, northwest airstreams contribute about 8 % of rainfall in the central north but only 3 % in the Fingal Valley and about 4 % in the southeast. By way of contrast, the southwest airstream is associated with 7 % of rainfall in the southeast but only around 1 % in the sheltered north and northeast.

The recent availability of the AWAP gridded rainfall product (Jones et al. 2009) enables synoptic system statistics obtained for the analysis boxes (see Fig. 1) to be applied to the gridded rainfall across each of the analysis regions for the growing season period (Fig. 6). It is important to note that the use of the gridded rainfall has to be treated with caution throughout the remoter inland parts. Rainfall in these regions is quite low and highly variable and the relatively few rainfall stations are separated by large distances, all of which may contribute to significant errors in interpolation (King et al. 2012). Nevertheless, Fig. 6 provides a useful comparison between the proportional contribution of frontal rain and the proportional contribution from cut-off lows in the cropping and adjoining regions. In the southeast (Fig. 6a) the proportion of cut-off rain increases to 0.5 or more in northwestern Victoria and further inland, which is broadly consistent with the station results in Fig. 5. In the southwest (Fig. 6c), the proportion of cut-off rain reaches at least 0.3 in the inland and even near the central west coast. There is a stark contrast between

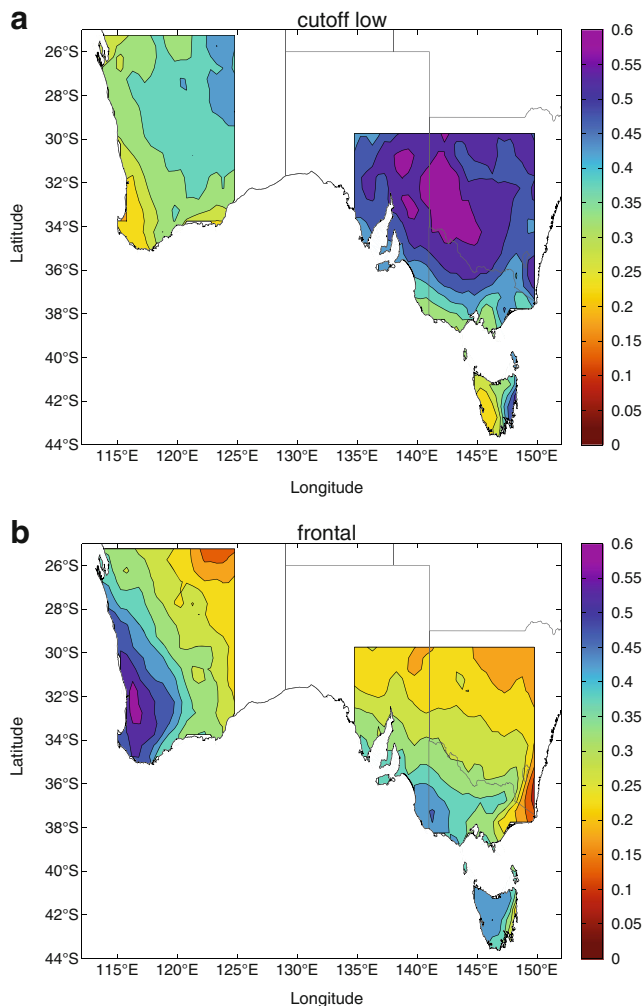


Fig. 6 Proportional contributions from synoptic types to growing season (April to October) rainfall confined to the period 1985–2009, in the Central Wheat Belt (*CWB*) of Western Australia, in southeastern Australia and in Tasmania for **a** cut-off rain and **b** frontal rain

the frontal dominance in the southwest of the continent (Fig. 6d) and the relatively low percentage contribution of cut-off rainfall observed in inland Western Australia and the almost exactly opposite proportions of synoptic contributions in the cropping regions of the southeast mainland. The situation in Tasmania is more complex with a clear gradation of proportional contribution from cut-off lows from less than 0.3 in the west to more than 0.4 in the east rising to 0.5 or more on the central east coast (Fig. 6e). (Note that western Tasmania is very wet, and 0.3 is still a large amount of rainfall.)

Monthly proportions of cut-off rain and frontal rain are quite different in the *CWB* of Western Australia from those found in the South East (Fig. 7). However, Fig. 7 shows that the two distinct regions have similar profiles of percentage contribution during the season with the cut-off rain proportion at a maximum in April but steadily decreasing to a minimum in July and August (Fig. 7a). The percentage contribution from cut-off lows increases again in spring to be similar to

its early autumn value. From Fig. 7b, it is apparent that the frontal rain percentage peaks in late winter in each region and this corresponds to the lower percentage contributions from cut-off rain at this time.

Time series of growing season rain indicate that over the full period of the analysis, rainfall associated with frontal systems has remained relatively constant in southern Australia (Fig. 8). An exception was found in the *CWB* during the first decade or so of its record (1965–1976) where an apparent decline in frontal rainfall occurred. This period corresponds to the well-known decline experienced in the southwest of Western Australia (*SWWA*) in the mid 1970s (e.g., Allan and Haylock 1993). Additionally, Risbey et al. (2013a) reported a decline in frontal rain during the 1996–2009 drought in southeastern Australia. On the other hand, rainfall associated with cut-off lows has declined markedly in the past two decades in the *CWB* (Pook et al. 2012) and in southeastern Australia (Risbey et al. 2013a, b). Pook et al. (2009) also found that the reduction in cut-off low rainfall in the southeast accounted for the absence of abnormally wet growing seasons, fewer 'autumn breaks' and reduced crop yields in the recent past. However, Fig. 8a shows that cut-off rain and frontal rain do not exhibit clear trends in the Murray Mallee region of South Australia when considered over the entire period.

6 Discussion

The agricultural production of southern Australia is critically dependent on winter rainfall. In order to better understand the sources of rainfall in the region, our analysis has categorised the respective contributions of the relevant synoptic systems over approximately five decades of reanalysis data. The analysis establishes that frontal systems contribute approximately one half of the growing season rainfall in the *CWB* of Western Australia but this proportion reduces to only about one third in the Murray Mallee of South Australia and in northwestern Victoria. The results for Tasmania are quite variable and are strongly influenced by topography.

Despite the regional variations in contributions to growing season rainfall the importance of the cut-off low as a rain-producing system is clearly demonstrated in this study. In fact, these systems are responsible for about one third of the growing season rainfall in the west of the country and as much as one half in the southeast and in the vicinity of the east coast of Tasmania. Significantly, Pook et al. (2006) also found that cut-off lows are responsible for about 80 % of the heavy rainfall events in the southeast. According to Pook et al. (2009), they are also the dominant delivery systems for so-called 'autumn breaks' in the Mallee region of northwest Victoria. Hence, cut-off lows have major importance for contributing to the soil moisture profile for agriculture, for filling farm dams and public

Fig. 7 Percentage contributions to monthly rainfall during the growing season (April to October) of the main synoptic types in the Central Wheat Belt (CWB) of Western Australia and in northwestern Victoria (Vic Mallee) for **a** rain associated with cut-off lows and **b** rain associated with Southern Ocean fronts. The period of analysis is from 1965 to 2009

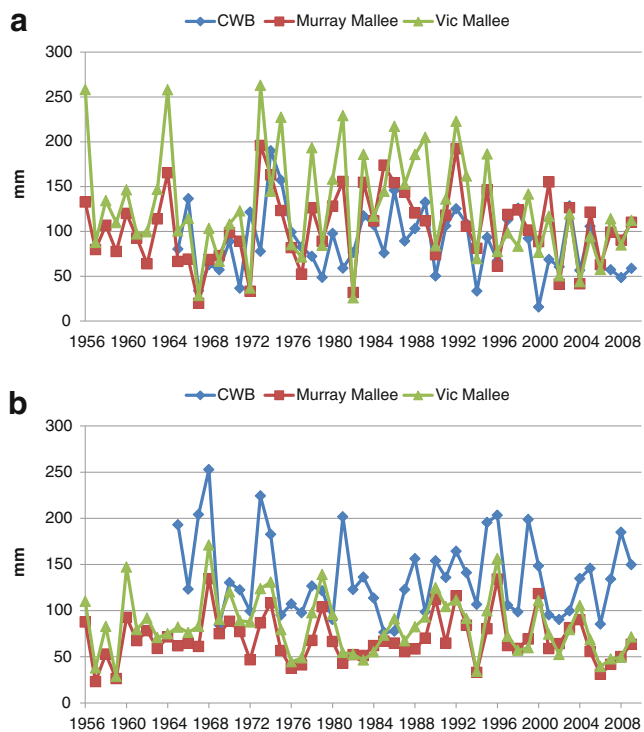
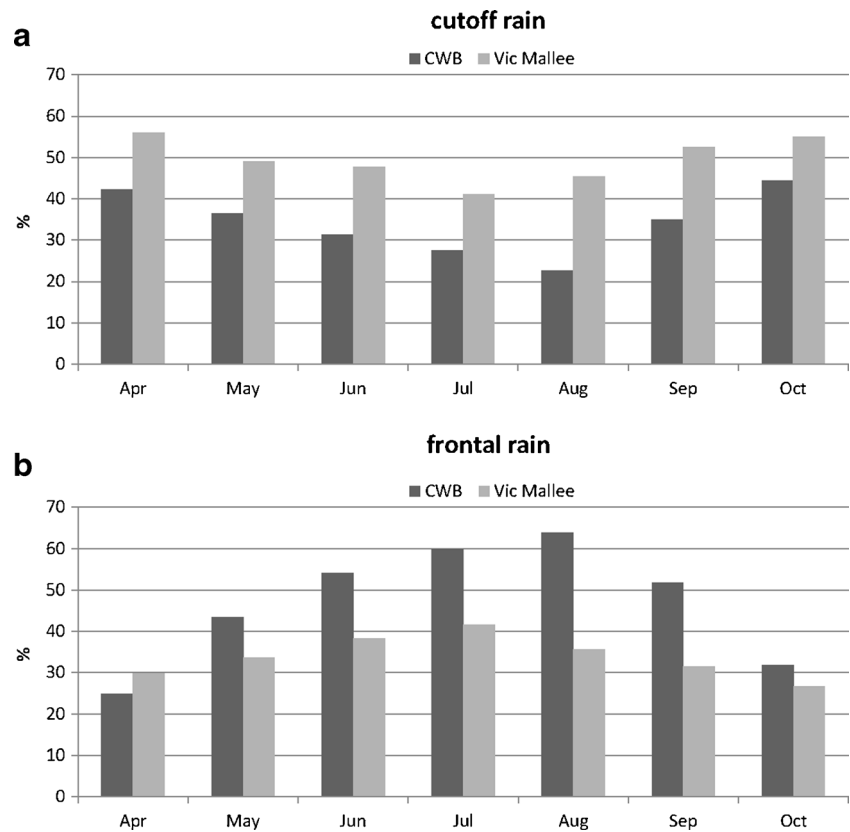


Fig. 8 Time series of the contributions to growing season (April to October) rainfall (mm) in the Central Wheat Belt (CWB) of Western Australia, in the Murray Mallee region of South Australia and in northwestern Victoria from **a** cut-off low pressure systems and **b** from Southern Ocean frontal systems

water storages as well as being a major cause of flooding events (e.g., Mills and Wu 1995). Moreover, cut-off lows have contributed more significantly to the recent decline in rainfall in southern Australia than the frontal component and account for most of the overall downward trend in these regions (Pook et al. 2006, 2012; Risbey et al. 2013a,b).

These results and Fig. 4b suggest that the explanation for the observed rainfall characteristics of the southern Australian growing season should be sought in the middle and upper troposphere. Following the broad schematic representation of the dominant planetary or so-called long-wave pattern in the Australian region presented by Risbey et al. (2009b), it is proposed here that frontogenesis occurring in the semi-permanent long-wave trough near Western Australia (Wright 1974b) produces a maximum of frontal activity to the west of the continent. However, as fronts travel eastwards they tend to come under the influence of the persistent meridional ridge to the southeast of Australia (Pook et al. 2012, and references therein). For the most part, the ridge causes them to weaken and predominantly steer southeastwards. Periods of enhanced frontal activity over southeastern Australia are likely to coincide with temporary eastwards excursions of the long-wave trough. Additionally, Pook et al. (2012) proposed that the tilting orientation of the WA trough from southwest to northeastwards with decreasing latitude combines with the meridional ridge in the east to favour the occasional 'shearing' or cutting off from the westerlies of the cut-off lows that subsequently grow under the

influence of the subtropical jet stream and move eastwards. Dowdy et al. (2013) have recently presented a physical model for the way the interaction between the sub-tropical jet and a southerly jet streak migrating around an anticyclonic involution south of Australia can lead to the rapid development of an 'east coast low', an intense cyclone at sea level on Australia's eastern seaboard. The proposed mechanism appears to provide a more general explanation for the observed occurrences of cut-off lows in the upper troposphere but Dowdy et al. (2013) caution that it has not been determined how often these upper atmospheric patterns occur without the subsequent development of an east coast low.

It has previously been established that atmospheric blocking is correlated with cool season rainfall over southern parts of the Australian continent and the link between rainfall and blocking is thought to be a consequence of the dynamic interaction between the high-latitude anticyclonic component of blocking and the formation of cut-off lows or upper troughs equatorward of the high (Risbey et al. 2009b; Pook et al. 2013). Additionally, Pook et al. (2006) demonstrated that the number of cut-off low days relative to an analysis box for southeastern Australia was highly correlated with an index of blocking in the longitude band between 125°E and 155°E and that the meridian of maximum correlation oscillates in position during the growing season. A significant correlation has also been found between blocking at 120°E and the number of cut-off low days in the CWB (Pook et al. 2012). According to Risbey et al. (2009b), the response of rainfall across southern Australia to blocking depends on the precise location of the block structure with blocks centred south of the Great Australian Bight (approximately between 120°E and 135°E) favouring rainfall in Western Australia and blocking centred from 140°E eastwards influencing the south-east of Australia. In their Fig. 12, Pook et al. (2012) demonstrated that blocking during the growing season centred at longitude 120°E, near the eastern boundary of the SWWA analysis region (see Fig. 1), is highly correlated with gridded rainfall for the southern Australian continent over the analysis period. It is apparent that the region of highest correlation is also the region where the percentage contribution from cut-off low rain was found to be highest and includes the CWB but not the high rainfall portion of SWWA. Certainly, blocking slows the eastwards movement of cut-off low systems, thus enabling them to produce more rain in a particular location, but the influence of blocking on the efficiency with which cut-off lows access moisture is less clear and will continue to be a focus of research.

7 Conclusions

Daily rainfall for selected cropping regions of southern Australia during the grain-growing season has been related to identifiable types of synoptic weather systems over a total

analysis period of approximately 50 years. Additionally, a limited study has also been completed for Tasmania and has been used for the purposes of comparison. The resulting climatology reveals that frontal rainfall dominates in the CWB of Western Australia, producing approximately 50 % of the total precipitation while cut-off lows contribute about 33 %. Significantly, the reverse is the case in the southeastern cropping regions where about 50 % of growing season rainfall is contributed by cut-off lows and 33 % by fronts. In Tasmania, the proportions vary markedly across small distances because of the topography.

There is a strong seasonal cycle as demonstrated by the monthly contributions. The proportion of rainfall attributed to cut-off lows is highest in autumn and spring while the percentage contribution from frontal rain is greatest in mid to late winter. The cut-off proportion of rainfall is highest in the southeast relative to the CWB in each month of the growing season. By way of contrast, the frontal proportion of rainfall is higher in the CWB than in the southeast for each month studied.

Frontal rain has been relatively steady over time but cut-off rainfall is highly variable and has declined significantly in the past two decades, at least in the CWB and northwestern Victoria. In the Murray Mallee region of South Australia, the trends in cut-off and frontal rain are not statistically significant.

The underlying control on the synoptic mix and its variability and trends in the region is believed to be related to the location and intensity of the major planetary or 'long' waves in the upper troposphere. The dominant pattern is anchored by a long-wave trough near Western Australia and a long-wave ridge to the southeast of the continent. The long-wave trough favours cyclogenesis to the SWWA and the long-wave ridge the incidence of blocking to the southeast of Australia. There is a close relationship between cut-off lows and blocking although not every cut-off low is found with an associated block. Hence, the development of a better understanding of the mechanism of blocking and the climatological factors controlling its interannual and long-term variability could lead to a more complete explanation of rainfall variability and trend in the southern cropping regions of Australia. Additionally, a major strand of continuing research involves the identification of possible teleconnections between the variability of the contributions of particular synoptic types to growing season rainfall and key components of the atmospheric circulation of the Southern Hemisphere.

The results presented here provide objective criteria for the evaluation of climate models. We contend that climate models must be able to reproduce realistic synoptic systems in order for their rainfall forecasts to be credible. It is not acceptable for a model to get the right amount of rainfall via the wrong physical mechanism. The challenge for climate models is to simulate faithfully the observed mix of synoptic systems if forecasts and projections of regional rainfall are to have acceptable accuracy.

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