The Synoptic Climatology of Cool-Season Rainfall in the Central Wheatbelt of Western Australia

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ABSTRACT

Synoptic weather systems form an important part of the physical link between remote large-scale climate drivers and regional rainfall. A synoptic climatology of daily rainfall events is developed for the Central Wheatbelt of southwestern Australia over the April–October growing season for the years 1965–2009. The climatology reveals that frontal systems contribute approximately one-half of the rainfall in the growing season while cutoff lows contribute about a third. The ratio of frontal rainfall to cutoff rainfall varies throughout the growing season. Cutoff lows contribute over 40% of rainfall in the austral autumn and spring, but this falls to about 20% in August when frontal rainfall climbs to more than 60%. The number of cutoff lows varies markedly from one growing season to another, but does not exhibit a significant long-term trend. The mean rainfall per cutoff system is also highly variable, but has gradually declined over the analysis period, particularly in the past decade. The decline in rainfall per frontal system is less significant. Cutoff low rainfall has contributed more strongly in percentage terms to the recent decline in rainfall in the Central Wheatbelt than the frontal component and accounts for more than half of the overall trend. Atmospheric blocking is highly correlated with rainfall in the region where cutoff low rainfall makes its highest proportional contribution. Hence, the decline in rain from cutoff low systems is likely to have been associated with changes in blocking and the factors controlling blocking in the region.

1. Introduction

The state of Western Australia (WA) produces over one-third of the total Australian winter grain crop and around 40% of the average annual Australian wheat crop according to official Australian government statistics (Australian Bureau of Agricultural and Resource Economics 2010). The grain crop is grown mainly in the inland parts of the southwestern portion of Western Australia (SWWA) where the climate is highly variable. Grain farmers in this region will be better equipped to manage climate risk if they have a better understanding of the variability and trends in weather systems responsible for rainfall. Computer models used for weather and seasonal forecasts must simulate the important weather systems accurately to build confidence in predictions. In this study, we identify the main synoptic weather systems responsible for daily rainfall during the growing season in the Central Wheatbelt (CWB) of WA and investigate the seasonal and interannual variability of the dominant synoptic types.

The growing season for grains extends from about April to the end of October, the period during which the majority of the annual rainfall occurs. The winter months of June and July are the wettest. Growing-season rainfall over most of the CWB is relatively low, ranging from 350 mm on the western boundary to as low as 200 mm at the eastern edge (Fig. 1). While crop success depends on a range of factors, the natural supply of water is the most significant factor affecting wheat yields in this and other nonirrigated parts of Australia (French and Schultz 1984; Stephens and Lyons 1998).

Many studies of Australian climate have examined the relationship between monthly, seasonal, or annual rainfall and atmospheric indices and sea surface temperature patterns (e.g., Gentilli 1971; Pittock 1973; Streten 1981; Whetton 1988; Nicholls 1989; Allan and Haylock 1993; Suppiah 2004). The Indian Ocean Climate Initiative (IOCI; e.g., Ryan and Hope 2005) examined the significant rainfall decline since about 1970 in the southwest corner of WA, between the coast and the CWB. The decline was attributed to a shift in the storm tracks. Risbey

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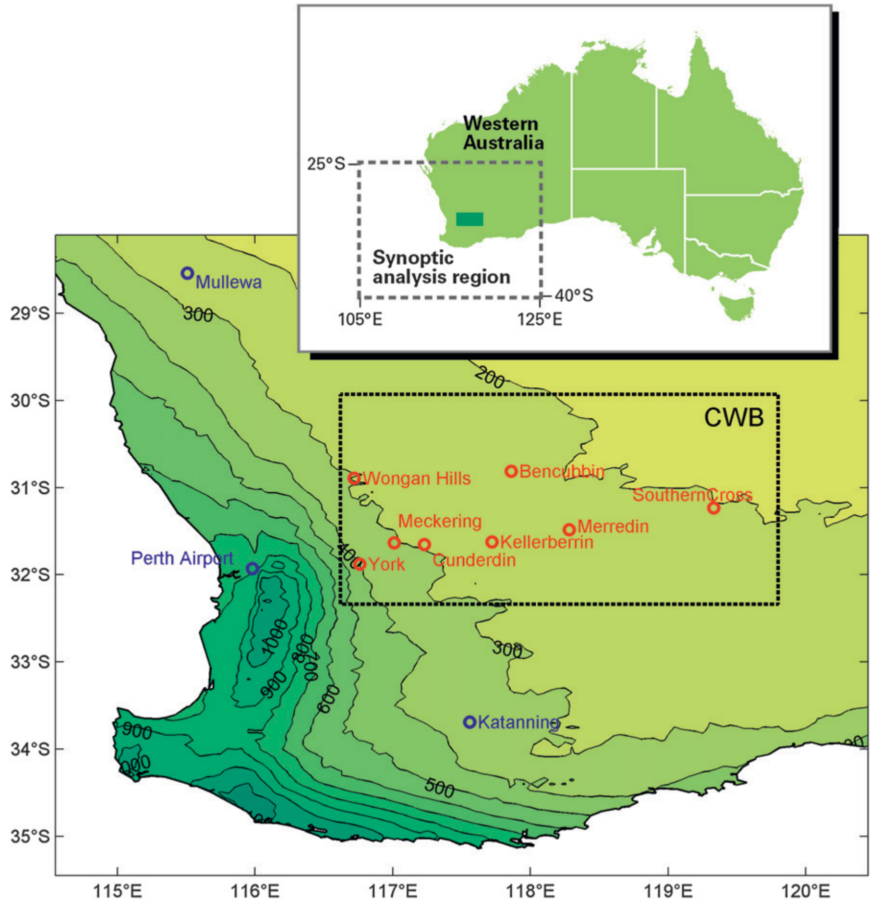

FIG. 1. The southwest region of WA showing the rainfall stations mentioned in the text and the isohyets representing the means of the rainfall for the growing season (April–October) from the AWAP high-resolution dataset (Jones et al. 2009). The dotted rectangle in the bottom part of the diagram represents the approximate boundary of the Central Wheatbelt (labeled CWB). The dotted rectangle in the top part of the diagram depicts the area of the synoptic analysis. The dark green rectangle within the synoptic analysis region shows the CWB district of southwestern Australia, which is enlarged in the lower part of the diagram.

et al. (2009b) examined the remote large-scale drivers of rainfall variability over Australia. They showed that all four major drivers—El Niño–Southern Oscillation, the Indian Ocean dipole, the southern annular mode, and atmospheric blocking—were important in SWWA depending on season and location.

Although regional rainfall on seasonal time scales is regularly represented by single values such as monthly or 3-monthly totals, actual rainfall is delivered via a finite number of relatively short-lived and well-separated synoptic events. 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 for most regions. Identification of the dominant synoptic types and their contribution to rainfall can be an important step in understanding the underlying processes connecting remote large-scale drivers to regional rainfall. For example, in the context of interannual climate variability and longer-term climate trends, changes in broadscale atmospheric circulation can be expected to change the characteristics of particular synoptic types in different ways.

Relatively few studies have been carried out in Australia to apply synoptic climatological techniques to identify and document the synoptic systems associated with daily rainfall in a particular region over an extended period. Wright (1989) classified rainfall events in southeastern Australia into five synoptic types for the June–September period of 1971–82. Godfred-Spenning and Gibson (1995) performed an analysis of the synoptic weather systems that produced rainfall over the hydroelectric catchments of Tasmania, Australia's southernmost island state, for an approximately 30-yr period. Recently, Landvogt et al. (2008) carried out a synoptic analysis of precipitation in an elevated region of northeast Victoria for the limited period 2000–05. These studies all suggest that cold fronts are the dominant source of cool-season rainfall in southern Australia.

The dominance of cold fronts has been disputed for parts of the southeast by Pook et al. (2006, 2009), who demonstrate the preeminent role of cutoff lows and associated atmospheric blocking in the rainfall distribution of northwestern Victoria and also in eastern Tasmania (Pook et al. 2010). Risbey et al. (2009a) have contrasted the dynamical and thermal characteristics of cutoff lows and fronts associated with rainfall in that region. Previously, Qi et al. (1999) produced a climatology for southern Australia of the occurrence of cutoff lows from 14 yr of Australian Bureau of Meteorology analyses, but did not analyze their contribution to rainfall except in one case study. They demonstrated that there is a maximum frequency of cutoff low incidence in southern Australia during the May–October period and identified the southwestern region of the continent as the most active area for the genesis of cutoff lows. According to Qi et al. (1999) almost all cutoff lows move either eastward or southeastward from this region, but they noted the high degree of interannual variability in the occurrence of these systems. Fuenzalida et al. (2005) produced a climatology of cutoff lows for the entire Southern Hemisphere in the latitudinal band between 10° and 60°S. They examined the key dynamical features of these systems and identified trends in their frequency of occurrence, but did not study their association with rainfall.

In SWWA, Hope et al. (2006) employed a statistical self-organizing map (SOM) approach to impose 20 circulation types on June and July rainfall in order to associate the decline in winter rainfall with changes in the atmospheric circulation. They found a decrease in trough activity, which is consistent with the conclusions of Frederiksen and Frederiksen (2007) who reported a decline in baroclinicity in the region and a southward migration of storm tracks.

This study analyzes the synoptic systems associated with daily rainfall in the CWB of WA during the April–October growing season for the years 1965–2009. The analysis techniques and objective rules developed by Pook et al. (2006) for southeast Australia are adapted for use in SWWA. This allows the long-term mean and the seasonal and interannual variability of the main synoptic types in SWWA to be documented for the first time.

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 the CWB and the results are presented in section 4. The association of atmospheric blocking with growing-season rainfall is discussed in section 5 and the conclusions are presented in section 6.

2. Data and method

Eight rainfall stations were chosen to represent the CWB of WA. Four stations (Kellerberrin, Meckering, Merredin, and Southern Cross) were selected from a high-quality Australian historical dataset (Lavery et al. 1997) and the remaining four stations (York, Cunderdin, Bencubbin, and Wongan Hills) were identified from Bureau of Meteorology records as having a long historical record and were chosen as additional stations to provide a balanced geographical distribution (Fig. 1). In the case of the individual station records, we have employed the patched point dataset supplied by the Queensland Department of Environment and Resource Management (Jeffrey et al. 2001) to provide a consistent technique to insert 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. The gridded growing-season rainfall in Fig. 1 has been derived from the $0.05° \times 0.05°$ Australian Water Availability Project (AWAP) monthly dataset (version 3) for the period 1900–2009 (Jones et al. 2009).

The synoptic analysis was carried out primarily with the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) climate reanalysis dataset (Kalnay et al. 1996; Kistler et al. 2001). The analysis will be identified as NCEP Reanalysis 1 in this paper. The data consist of four analyses per day at a resolution of 2.5° latitude by 2.5° longitude for the standard atmospheric levels from the surface to the lower stratosphere. In this study the main fields extracted and analyzed were mean sea level pressure (MSLP), the 500-hPa geopotential height, the 1000–500-hPa atmospheric thickness, and the 1000–500-hPa thickness anomaly. The latter was calculated relative to the 1979–2001 climatology for the appropriate month as it was necessary to fix a period for the calculation of anomalies at the time of starting the synoptic analysis procedure and, additionally, this was found to be a common period for comparison with some other reanalysis datasets.

An important additional data source was provided by the daily weather maps (valid at 0000 UTC) which are published in the Australian Bureau of Meteorology's "Monthly Weather Review" series (Simmonds and Richter 2000). The particular value of these charts lies in the 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). These charts provided additional assistance in determining the location of cold fronts, which are important rain-producing systems in southern Australia. Where available, satellite imagery from the Japanese Geostationary Satellite series was scanned. However, imagery from this source only became available for the Australian region in 1978.

Evidence that a ''climate shift'' had occurred in the mid-1970s (Allan and Haylock 1993) made it particularly important to extend the record back sufficiently. After careful consideration, the growing season of 1965 was chosen as the starting point for the analysis. Although NCEP Reanalysis 1 has been found to have some systematic biases in the Southern Hemisphere prior to 1970, particularly at high latitudes (Hines et al. 2000), we are confident that the surface observational network in the SWWA region was well balanced by 1965 and had been greatly enhanced by the opening of a new upper-air station in 1965 near the south coast at Albany Airport, due south of Katanning, Australia (see Fig. 1; see online at http://www.bom.gov.au/wa/albany/history.shtml). Significantly, automatic picture transmission of satellite imagery from polar-orbiting meteorological satellites became available with the launch of the *Television and Infrared Observation Satellite VIII* (*TIROS VIII*) in 1963 (Bradshaw 1997; Griersmith and Wilson 1997) and it and subsequent satellites provided data directly to ground stations. This imagery was used in the Australian manual analyses although the systematic incorporation of satellite cloud imagery into an objective analysis scheme only became established practice in the World Meteorological Centre, Melbourne, in the 1970s (Guymer 1978; Seaman and Hart 2003).

Furthermore, experience with reanalysis over southern Australia in the years from 1956–69 has been gained recently for southeastern Australia (Pook et al. 2009) and this knowledge has been applied in the analysis for SWWA. To achieve this extension a selection of MSLP, 700-hPa, and 500-hPa analyses were obtained from the Australian Bureau of Meteorology for 2300 and 1100 UTC each day. It should be noted that the Australian analyses are copies of the actual operational charts and may lack the dynamical consistency of the later period (from 1970), but they nevertheless assist in the identification of synoptic features since the full suite of observations is plotted on the charts and the original analyst has placed major features such as fronts and troughs. Other reported errors in NCEP, such as those related to the absence of satellite temperature sounding prior to 1979 (Kistler et al. 2001), are not regarded as significant in this analysis because of the proximity of our analysis region to the Australian radiosonde network.

For each day on which rainfall was recorded at any of the eight rainfall stations, a particular synoptic system was identified as being responsible for the precipitation event. Expert judgment from forecasting and analysis experience was applied in order to make a realistic estimate of the displacement of synoptic systems in a 24-h period. This approach resulted in the choice of an analysis region defined by a fixed box between latitudes 25°–40°S and longitudes 105°–125°E (see inset in Fig. 1). Synoptic systems were classified according to the classification scheme that was developed by Pook et al. (2006). The broad categories of synoptic systems that have been adopted are cold frontal systems of all types (see Figs. 2a–c); cold-cored lows, which have become cut-off from the westerly airstream (cutoff lows; Fig. 2d); and warm-cored low pressure systems associated with thermal ridges, including troughs in the easterlies (Fig. 2e). 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 analyzed at 500 hPa, but the rainfall is believed to have been produced or enhanced by convergence and instability associated with the trough. The region under consideration is 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 at the eight stations that constitute the network.

Within the broad category of cold frontal systems it is possible to distinguish three separate types of cold front. First, the simple or conventional cold front represented on a synoptic chart by a single line is instantly recognizable. It is normally located near the surface pressure trough and within the region of maximum gradient on the 1000–500-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 airmass properties and is identified on satellite imagery by its characteristic cloud band appearance (Fig. 2a). The second type of cold front in Australia is often preceded by a well-defined prefrontal trough. 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 and those involving interaction with preexisting subtropical cloud bands in a manner similar to that described by Wright (1989, 1997) and classified as ''interacting frontal types'' in his classification system were also included in the ''complex fronts'' category in our analysis system along with quasi-stationary fronts (Fig. 2b). Third, a significant number of frontal systems

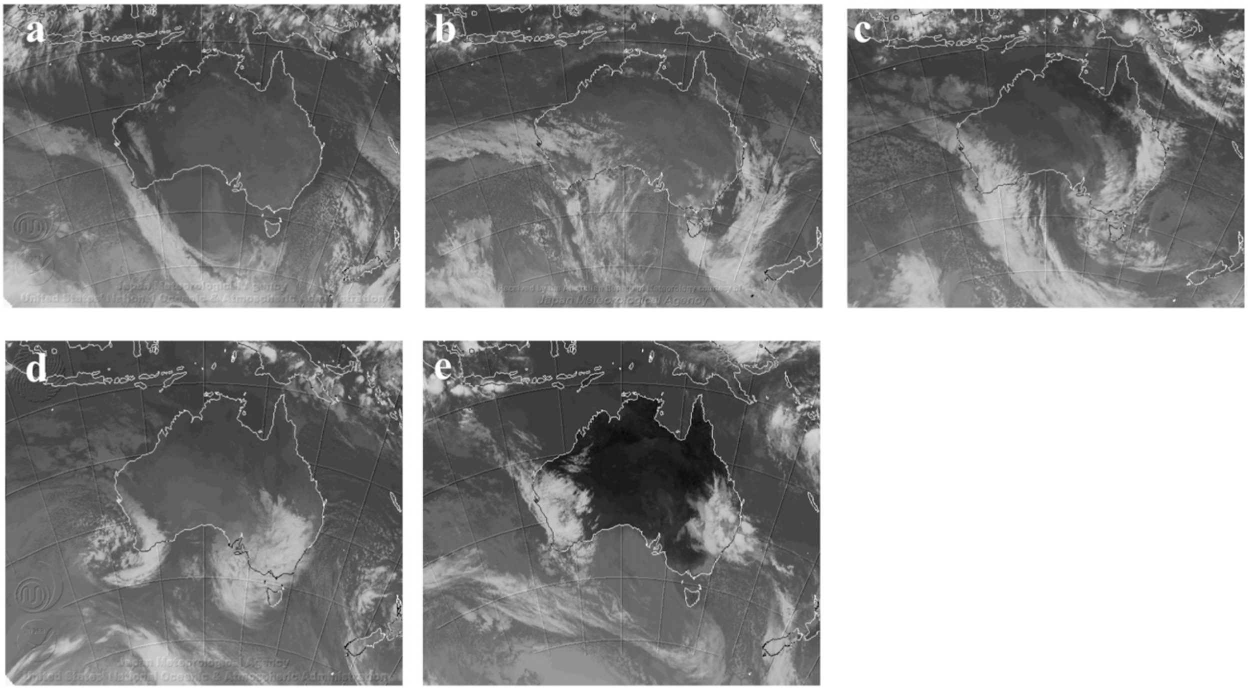

FIG. 2. Infrared satellite imagery depicting the dominant synoptic types encountered in the analysis over SWWA: (a) a simple or common cold front, (b) a complex cold front, (c) a wave on a cold front, (d) a cutoff low, and (e) a ''warm'' trough. (Courtesy of Japanese geostationary satellite data via the Bureau of Meteorology.)

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), Streten and Troup (1973), and Guymer (1978) have identified systems of this type from satellite imagery. In certain circumstances these systems may develop into individual closed low pressure systems (Troup and Streten 1972; Streten and Troup 1973). 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) we have identified the cutoff low (Fig. 2d) according to criteria that adhere to the traditional concept of an upper-air disturbance associated with a ''cold pool'' in the midtroposphere. However, we take account of situations where some circulations are more significant near the surface at particular stages in their development. The criteria that we have adopted in this study are the following:

1) A closed low is present in the analysis box (i.e., north of 40°S) at 500 hPa and is clearly separated from the westerly flow to the south. There is an associated cold trough evident in the 1000–500-hPa thickness field. A negative thickness anomaly from the long-term mean (NCEP Reanalysis 1) of at least 20 geopotential meters (gpm) exists within the designated box.

or

2) A closed low is present within the analysis box in the surface MSLP field (central pressure $\leq$1008 hPa) and an associated cold trough is located aloft with a negative thickness anomaly from the long-term mean (NCEP Reanalysis 1) for that month of at least 20 gpm. Note that the application of this scheme was used to determine all days during which a cutoff low could be identified in the analysis scheme, whether or not rain was reported.

Cutoff low systems in the WA region typically develop in conjunction with blocking highs located in the vicinity of the Great Australian Bight. These lows often form in amplifying troughs in the vicinity of southwest WA and ''pinch off'' ahead of the block. The cutoffs may be quasi-stationary, or may even regress westward, but usually move eastward as they decay and get incorporated back into the mean westerly flow. Figure 3 depicts the life cycle of a cutoff low of this type.

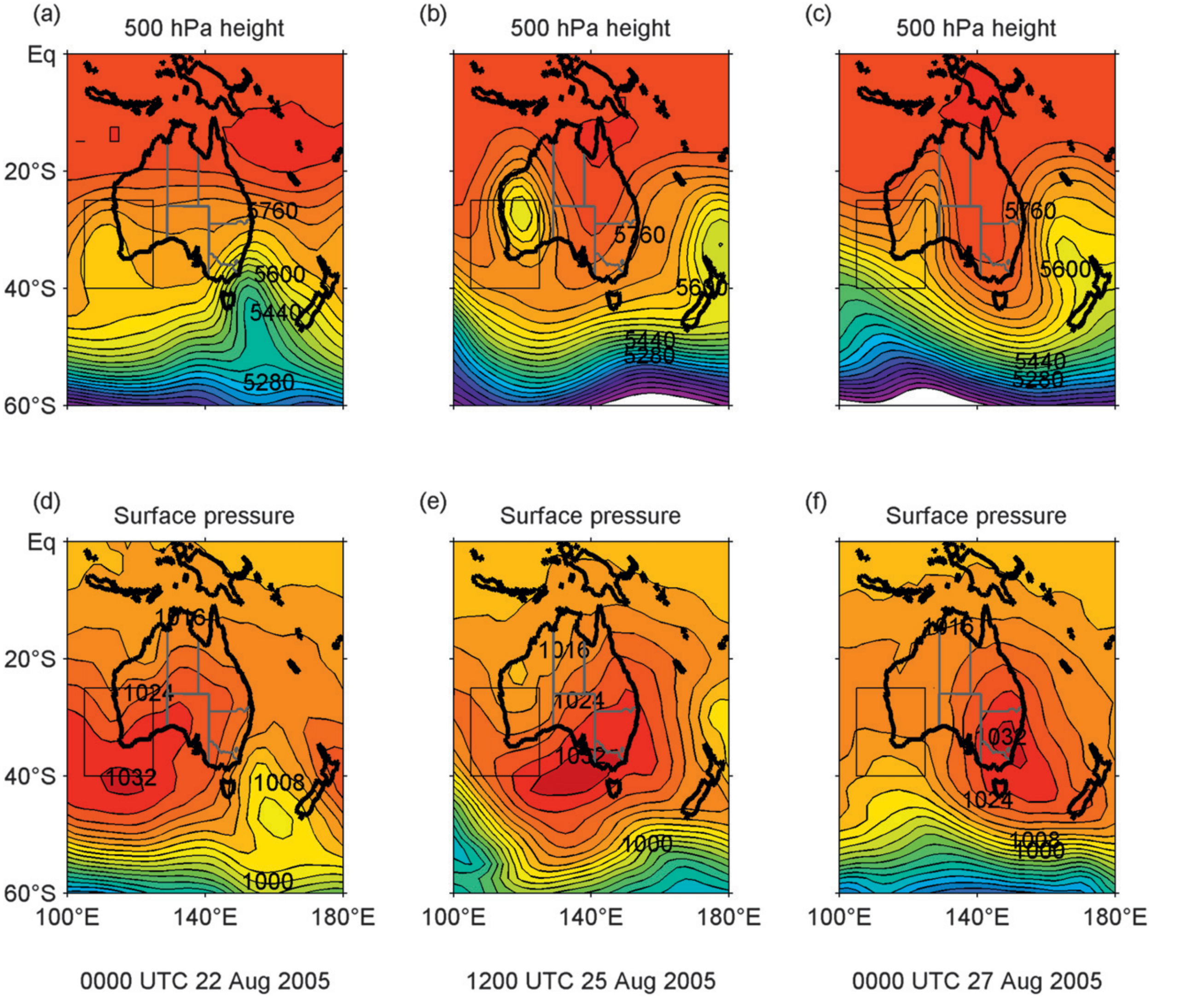

FIG. 3. The evolution of a cutoff low over SWWA in the (a)–(c) midtroposphere (500 hPa) and its reflection as a trough at the (d)–(f) surface (MSLP). (a),(d) The incipient phase at 0000 UTC 22 Aug 2005; (b),(e) the mature stage at 1200 UTC 25 Aug 2005; and (c),(f) the dissipating stage at 0000 UTC 27 Aug 2005.

The warm trough category includes warm-cored cyclones (tropical depressions) and troughs such as waves in the easterlies and the deep troughs in the easterlies near the coast of WA, which are regularly observed during the summer months, but are also active in the early autumn and late spring. Although regularly forming in the warm air, which has been advected from the east to the coast, these systems subsequently migrate eastward ahead of an approaching front and upper trough (Fig. 2e).

3. Regional climate of the Central Wheatbelt

The CWB occupies part of the dry inland plains of Australia. The climate of the west and southwest of the region has been described in broad terms as temperate, but with a warm to hot summer (Bureau of Meteorology 1995). However, the east and north of the CWB more closely aligns with the "hot (summer drought) grassland" classification of Australian climate according to the objective classification scheme developed by Stern et al. (2000). The region is located inland of the Darling Scarp with elevations generally in the range of 150–350 m and only isolated peaks exceeding 400 m. The part of the southwest region of SWWA, which has been the subject of intense investigation in the IOCI Project (Ryan and Hope 2005) intersects the southwest corner of the CWB.

Detailed examinations of the regional climatology of SWWA have been undertaken by Gentilli (1971) and

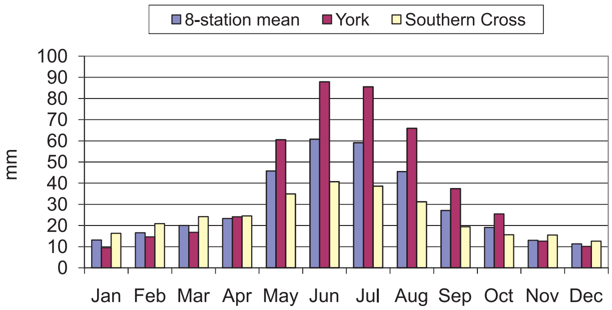

FIG. 4. Mean monthly rainfall (mm) for the average of the eight stations in the CWB, at York on the western edge of the CWB, and at Southern Cross in the far east of the area. The patched point dataset (Jeffrey et al. 2001) for the period 1889–2009 (inclusive).

P. B. Wright (1974a,b) while a broader overview has been presented by the Bureau of Meteorology (1995). Within the CWB (see Fig. 1) mean annual rainfall varies from less than 250 mm in parts of the east to nearly 500 mm in the south and 550 mm at the western edge (Bureau of Meteorology, 1995). A notable feature of the mean monthly rainfall distribution 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. Figure 4 shows the monthly rainfall distribution for an eight-station average in the CWB and for comparison, the western station of York and the eastern station of Southern Cross.

The marked seasonality of this rainfall distribution is normally explained by reference to the monthly MSLP field, which is dominated by the subtropical ridge (STR) of high pressure. The latitude of this ridge migrates equatorward in winter to about 30°S and then poleward again during the latter part of the growing season as a "heat trough" develops over northern Australia. However, this meridional movement of the ridge is accompanied by the intensification and eastward migration of a distinct north–south trough of low pressure near the west coast, which is strongly supported in the upper air. Figure 5 shows the mean monthly position and intensity of the STR and the trough at mean sea level for May–August during the growing season. 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 WA this time. This period of persistent westerly winds has been associated with an increased frequency of rain-bearing cold fronts crossing southern Australia. However, the maximum rainfall is experienced in June and July. Gentilli (1971) and P. B. Wright (1974a,b) ascribed this behavior to the tendency for the mean airflow to be predominantly from the northwest early in winter with a strong interaction with the Darling Scarp. This flow of moist air from the west-to-northwest sector experiences orographic uplift over the escarpment and a steady decrease in rainfall inland (Gentilli 1971; P. B. Wright 1974a).

Significantly, the trough at 35°S is located near 115°E in June but moves to around 120°E in August as the Indian Ocean high pressure cell intensifies and moves closer to WA. As the trough migrates eastward in August (Fig. 3d) the mean stream direction over the CWB becomes west to southwesterly near the surface. The steep gradient from higher rainfall at the coast to lower rainfall inland becomes more noticeable in August as the airstream tends more south of west and the effect of the slightly drier airstream is accentuated (Gentilli 1971; P. B. Wright 1974a,b). The MSLP pattern is accompanied by a well-defined trough in the upper atmosphere at longitudes from about 100°–110°E (Fig. 6). The trough provides a marked contrast with the intense high-latitude ridge and split-jet structure on the eastern side of the Australian continent (Bals-Elsholz et al. 2001; Pook et al. 2006). Again, this upper trough intensifies and migrates eastward during winter. The 500-hPa pattern depicted in Fig. 6 draws attention to one of the principal waves in the long-wave circulation of the Southern Hemisphere. In its winter configuration, the WA upper trough provides a background state conducive to the amplification of short-wave synoptic features as they pass through the region while the ridge to the east is closely associated with the predisposition to blocking near New Zealand and at Tasman Sea longitudes (A. D. F. Wright 1974; Coughlan 1983; Trenberth and Mo 1985; Tibaldi et al. 1994; Pook and Gibson 1999; Wiedenmann et al. 2002). Other prominent characteristics of the trough include its eastward tilt from high latitudes (55°S) to lower latitudes (35°S) and its diffluent pattern. This tilting trough configuration combined with the ridge to the east favors shearing of low pressure systems and is consistent with the findings of Qi et al. (1999) who reported that the highest frequency of cutoff lows in southern Australia is found near WA in the May–October period. However, cutoff lows appear to move relatively quickly in this sector and they are generally steered eastward or southeastwards out of the genesis region (Qi et al. 1999).

4. Results

The analysis for the growing-season months of April–October over the period 1965–2009 reveals that frontal systems account for approximately 50% of the rainfall averaged over the selected stations in the CWB (central column in Fig. 7). The frontal rainfall is made up of contributions from conventional cold fronts (13%), complex fronts (17%), and waves on fronts (21%) as previously identified in Fig. 2. By way of comparison, cutoff low pressure systems contribute approximately one-third of

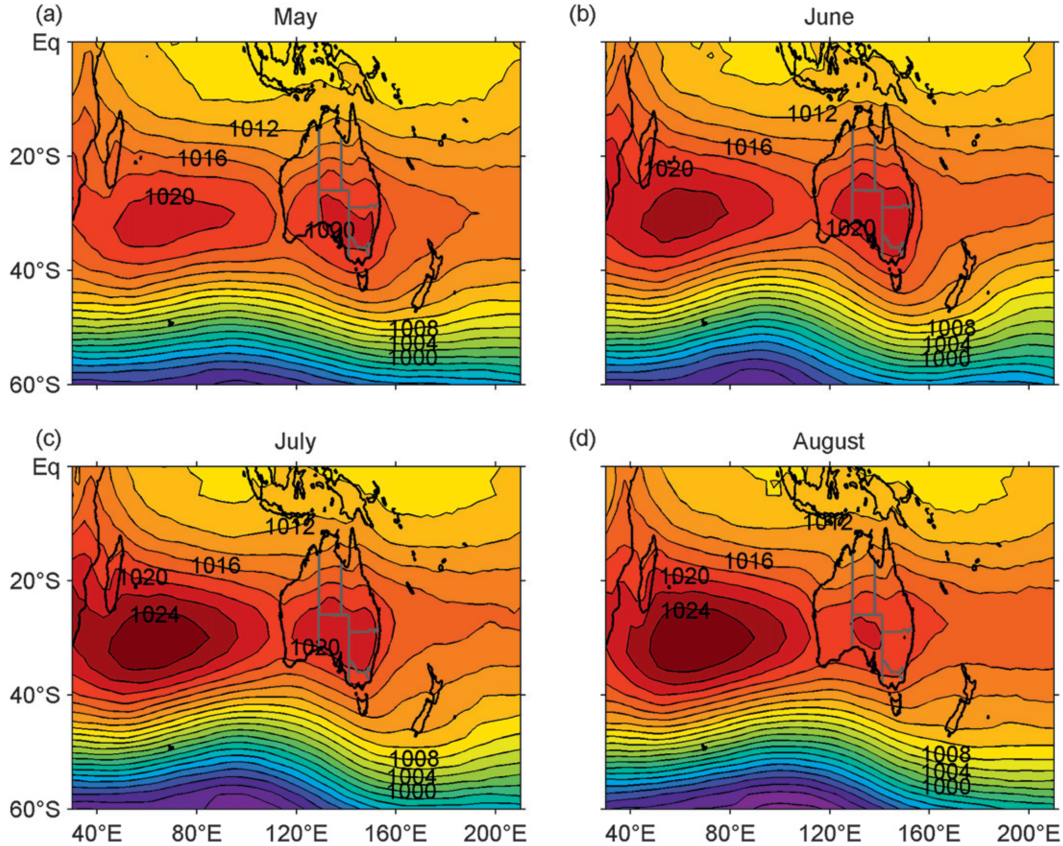

FIG. 5. Monthly means (1958–2010) of MSLP (hPa) for the months of (a) May, (b) June, (c) July, and (e) August from NCEP Reanalysis 1.

growing-season precipitation in the region. Figure 7 indicates that the remainder is predominantly associated with ‘‘warm troughs’’ (11%) followed by pre- and post-frontal airstreams (approximately 2% in each case). The balance of about 2.5% is associated with other airstreams and upper-level troughs where a closed low is not identified (not shown).

In addition to the analysis of CWB rainfall separate analyses have been carried out for Mullewa, Katanning, Perth Airport, and York (see Fig. 1 for locations). In relation to these sites, Fig. 7 indicates that the northernmost location (Mullewa) has the highest percentage of rain attributed to cutoff lows and also rain associated with the warm trough category but has a noticeably lower contribution from frontal rain than Katanning, which is about 570 km to the south. For the single station of York in the far west of the CWB, the result is almost 54% for frontal rain and this figure rises to 56% at Katanning in the south and 58% at the near-coastal location of Perth Airport. In each case, frontal systems produce the highest percentage of rain, but the proportion falls to as low as 44% at Mullewa. The proportion of rain due to cutoff lows ranges from about 33% at Mullewa to 26% in the south at Katanning and to 25% in the west at Perth Airport. Figure 7 also reveals that the proportion of rainfall associated with warm troughs (mainly troughs in the easterlies) is about 11% in the CWB but tends to be a little higher in the north at Mullewa (over 13%) and lower in the south at Katanning (about 9%).

The recent availability of the AWAP gridded rainfall product (Jones et al. 2009) enables synoptic system statistics obtained for the analysis box (see Fig. 1) to be applied to the gridded rainfall across the state of WA for the growing-season period (Fig. 8). The analysis box does not encompass the entire state. In particular, the tropical northern section of WA (north of 25°S) lies outside the box and this portion has been left blank in the figure. This region is extremely dry during the growing-season period and relies almost entirely on summer rainfall. It should also be noted that the use of the gridded rainfall has to be treated with caution throughout the remote inland parts of southern WA. Rainfall in this region is 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. Nevertheless, Fig. 8 provides a useful comparison between the percentage

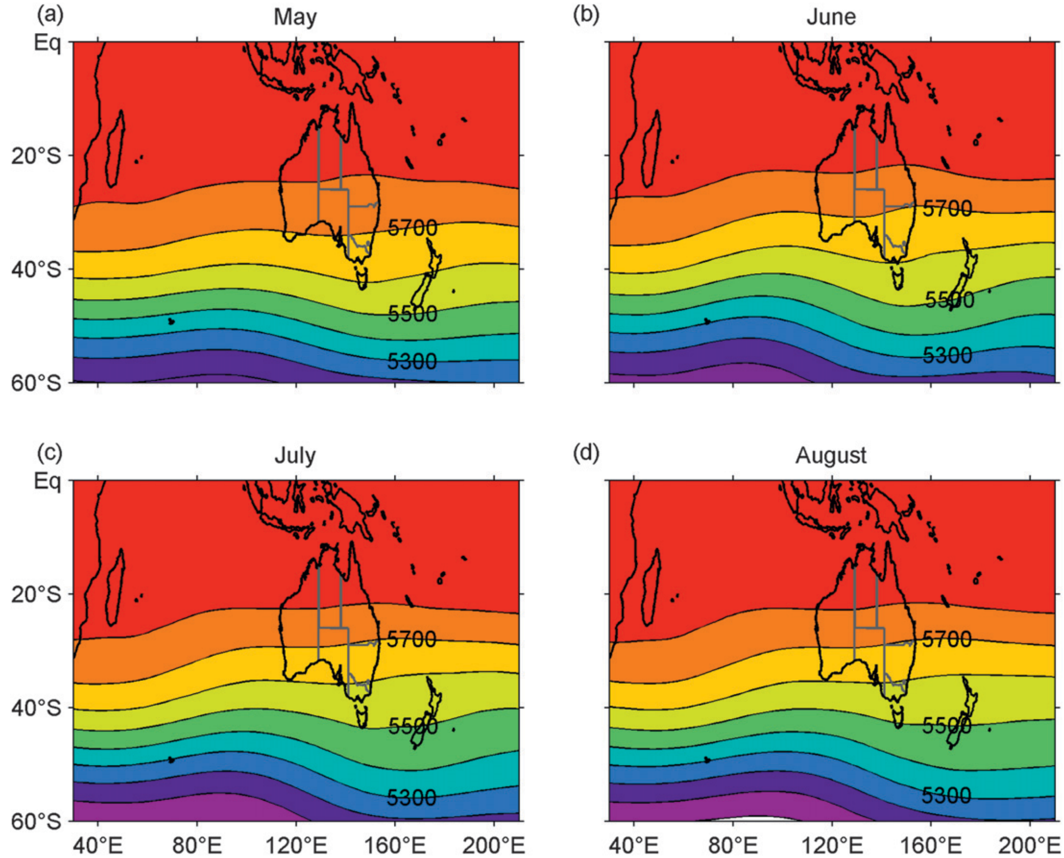

FIG. 6. Monthly means (1958–2010) of 500-hPa geopotential height (m) for the months of (a) May, (b) June, (c) July, and (e) August from NCEP Reanalysis 1.

contribution of frontal rain and the percentage contribution from cutoff lows for SWWA. There is a stark contrast between the frontal dominance in the far southwest (Fig. 8a) and the increasing percentage contribution of cutoff rainfall observed to the north and east of that region (Fig. 8b). Notwithstanding the northeastwards gradient from frontal to cutoff rainfall it should be noted that Fig. 8 confirms that the mean percentage of frontal rain during the growing season is at least 40% throughout the entire cropping region.

The proportional contribution of frontal rain increases during the growing season to reach its maximum in July and August (Fig. 9). For the CWB (Fig. 9a) and Katanning (Fig. 9c) the maximum percentage of frontal rain reaches 60% or more in July and August while at Mullewa (Fig. 9b), the highest monthly percentage of rainfall contributed by fronts reaches at least 50% in June, July, and August. By way of contrast, cutoff lows make their highest percentage contribution to rainfall at the start and end of the growing season, while the lowest percentage contribution for the locations in Fig. 9 (approximately 20%) occurs in August. Cutoff rainfall exceeds the frontal contribution in April and also in October at Mullewa (Fig. 9b) and in the CWB (Fig. 9a). Additionally, the percentage of rainfall contributed by cutoff lows at the northern station of Mullewa is higher than the frontal percentage in September (Fig. 9b).

Not only is the percentage contribution of cutoff rainfall higher than frontal rainfall at the start of the growing

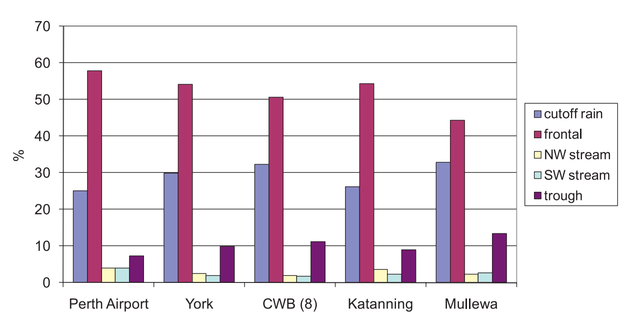

FIG. 7. The percentage contribution of the main synoptic types to growing-season rainfall for the eight-station average in the CWB (8), at York in the far west of the CWB, Mullewa to the northwest, Katanning to the south, and Perth Airport near the west coast.

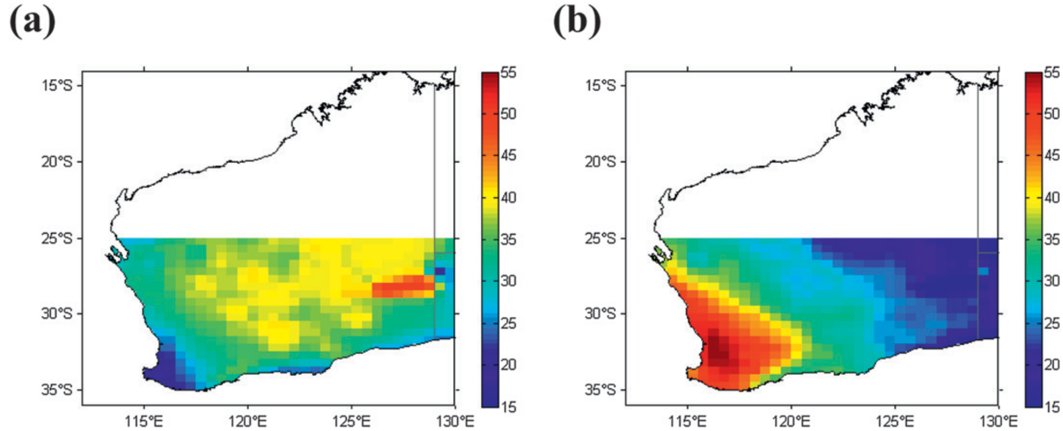

FIG. 8. A comparison between (a) the percentage contribution of rainfall from cutoff lows and (b) the percentage contribution of frontal rain for the southern half of WA. The northern portion has been left intentionally blank as the synoptic classification is not applicable there. The gridded rainfall has been obtained from the AWAP dataset (Jones et al. 2009).

season in the CWB and at Mullewa, but the contribution from warm troughs (>30%) also exceeds frontal rain at those locations in April. At Katanning (Fig. 9c), the contribution from warm troughs in April is approximately 20%. Figure 9b also shows that the contribution to rainfall in May from warm troughs is around 20% at Mullewa. This has important implications for sowing winter crops and pasture during autumn as it is clear that the vital early rains, which provide the so-called autumn break can be associated with any of the three main synoptic types identified in this study.

Time series have been constructed of the total, cutoff, and frontal rainfall during the growing season over the 45-yr study period and the results are displayed in Fig. 10 for the CWB, Mullewa, and Katanning. There is a high degree of interannual variability in growing-season rainfall and its principal components. It is clear from Fig. 10 that extremes of total rainfall can be associated with extremes of cutoff or frontal rainfall independently or as a combination of both. This point can be illustrated with reference to Fig. 10a by standardizing the rainfall data and observing that the highest growing-season rainfall in the CWB in 1974 [+2.2 standard deviation (SD)] was associated with record high cutoff low rainfall (+2.8 SD) and high frontal rainfall (+1.1 SD). On the other hand, the high growing-season rainfall in 1968 (+1.7 SD) was associated with record high frontal rainfall (+2.7 SD), but well below-average cutoff rainfall (−0.7 SD). The lowest growing-season rainfall in 1969 (−1.7 SD) was due to a combination of low cutoff (−0.8 SD) and low frontal (−1.2 SD) rain, while the very low growing-season rainfall in 2000 (−1.4 SD) was caused by the lowest contribution of cutoff low rainfall in the time series (−2.0 SD) accompanied by slightly above-average frontal rain. Although it is not shown here it should be noted that the 2000 event was also affected by a low contribution from rain associated with the warm trough category (−1.3 SD). Table 1 shows that rain from cutoff

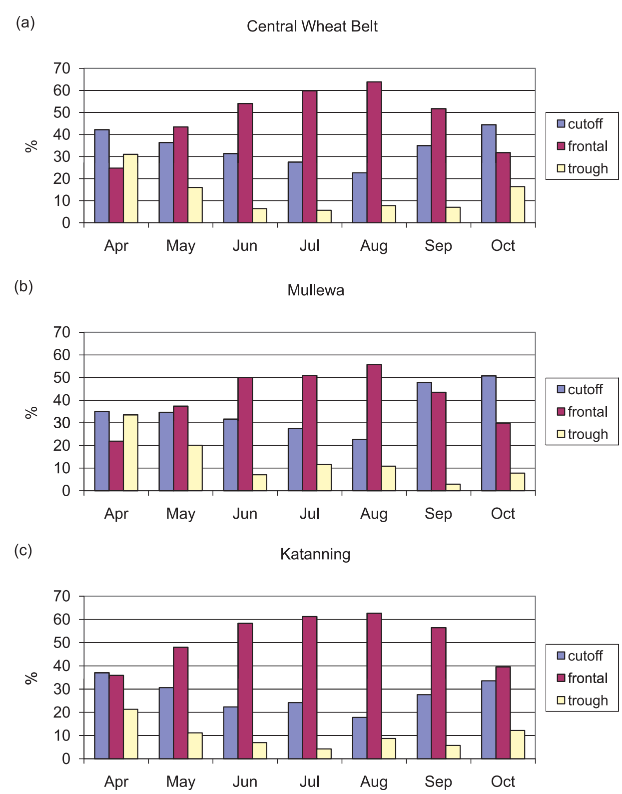

FIG. 9. The proportional contribution of frontal rain, the rain due to cutoff lows, and rain associated with troughs in each month of the growing season for (a) the CWB, (b) Mullewa, and (c) Katanning.

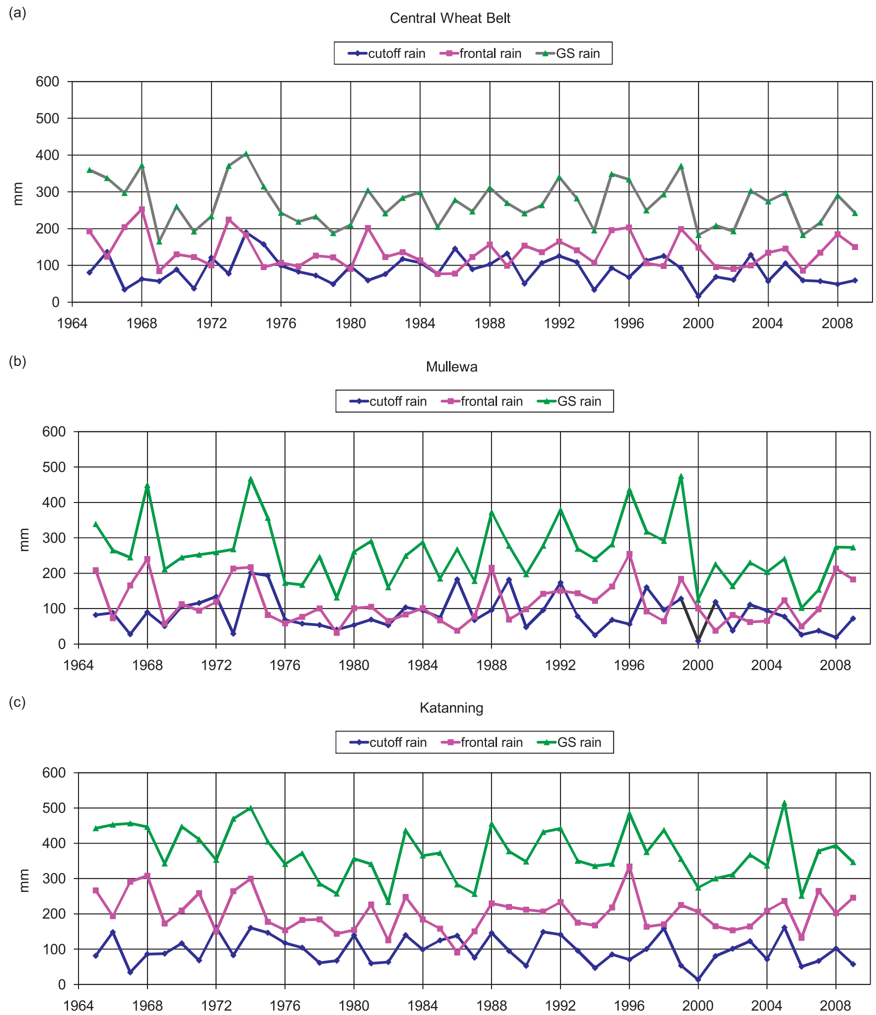

FIG. 10. Time series of total growing-season (GS) rainfall, rain due to cutoff lows, and rain due to frontal systems for (a) the CWB, (b) Mullewa, and (c) Katanning over the period from 1965 to 2009.

lows has a higher coefficient of variation (0.42) than rain from frontal rain (0.32). Rain from warm troughs has a very high coefficient of variation (0.61), since these systems are less common and their mean contribution to the total growing-season rainfall is quite small.

Since growing-season rainfall appears to be affected by rainfall contributed by several synoptic types, it is instructive to calculate the correlations between these components. This will illustrate to what degree the systems act independently or in concert. Table 2 shows that the growing-season rainfall in each year is highly correlated with the frontal rain component ($r = 0.70$, $n = 45$) and displays a moderate correlation with the warm rain component ($r = 0.52$, $n = 45$) and the cutoff rain component ($r = 0.50$, $n = 45$). Values of the Pearson product moment correlation coefficient greater than 0.35 are significant at the 99% level for a one-tailed test. However, the correlation between cutoff low rain and frontal rain in the growing season is very low ($r = -0.19$, $n = 45$), indicating that the two most important rain-producing systems act independently of each other.

Application of the time series analysis beyond the CWB to the northern location of Mullewa (Fig. 10b) reveals that

TABLE 1. Long-term mean, standard deviation, and coefficient of variation of growing-season rainfall and its components for the CWB eight-station network (1965–2009).

Rainfall (mm)	Mean	Std dev	Coef of variation
Growing-season rain	269.8	60.5	0.22
Frontal system rain	136.3	43.4	0.32
Cutoff low rain	87.2	36.4	0.42
Warm trough rain	29.9	18.4	0.61

TABLE 2. Correlations among rainfall contributions from the main synoptic types and total rainfall for the growing season (April–October) in the CWB of WA. In each case there are 45 pairs of observations. (Correlations greater than 0.38 are significant at the 99% confidence level.)

	Tot rain	Frontal rain	Cutoff rain	"Warm" rain
Tot rain		0.7	0.5	0.52
Frontal rain	0.7		−0.19	0.2
Cutoff rain	0.5	−0.19		0.17
Warm rain	0.52	0.2	0.17	

there have been two significant rainfall regime changes there. The well-known decline experienced in SWWA in the mid-1970s (e.g., Allan and Haylock 1993) is evident at Mullewa. It was followed by a decade of low growing-season rainfall during which the mean frontal rainfall fell substantially below its long-term mean. The average contribution from frontal rain was similar to the mean contribution from cutoff rainfall during that period. Figure 10b shows that there was a steady climb in growing-season rainfall in the 1990s followed by another sudden decline in 2000. The upward trend at Mullewa prior to the minimum in 2000 is not apparent on the time series for the CWB and Katanning. The mean growing-season rainfall at Mullewa for the decade from 2000 to 2009 of 199-mm contrasts with the long-term mean of 261 mm. The final decade of the series is particularly notable for the very low contribution from cutoff lows and is similar to the profile for the CWB over this period (Fig. 10a), but not Katanning (Fig. 10c). The lowest values of growing-season rain in the 45-yr series at Mullewa were recorded in 2006 (102 mm), 2000 (125 mm), and 1979 (131 mm). In relation to the year 2000, cutoff rain fell to its lowest value in the series. Only 8 mm of rainfall (−1.6 SD) was attributed to cutoff lows in that year while frontal rain was only slightly below average (−0.3 SD). In contrast, the series minimum of growing-season rainfall at Mullewa in 2006 occurred because of the coincidence of extremely low cutoff (−1.2 SD) and frontal (−1.1 SD) rain. Similarly, the 1979 minimum resulted from the combination of low values of cutoff and frontal rain. The coefficient of variation at Mullewa is 0.57 for cutoff low rainfall, 0.51 for the frontal component, and 0.34 for growing-season rainfall.

Figure 10c reveals that although Katanning also experienced a sudden decline in growing-season rainfall in the mid-1970s the period of reduced rainfall following the decline was relatively short. Then, in a similar manner to the CWB and Mullewa, Katanning also recorded low growing-season rainfall in 2000 and this was almost entirely due to the record-low contribution from cutoff lows. However, the minimum value in the time series (−2.0 SD) occurred in 1982, a year in which the cutoff low component (−0.9 SD) and frontal component (−1.5) combined to produce the growing-season minimum. By way of contrast, the highest growing-season rainfall was recorded at Katanning in 2005 (+2.0 SD) and it was associated with the equal highest contribution of cutoff rainfall in the time series (+1.7 SD) combined with above-average frontal rain. The 2005 peak is not mirrored in the time series for the CWB or Mullewa.

An analysis of the apparent trends in growing-season rainfall and its components (refer to Fig. 10) has been carried out by isolating the number of systems and the amount of rain per system for the two dominant synoptic classes. Figure 11 shows a time series for the CWB of the contributions from frontal systems and cutoff systems expressed as number of systems (system days) and rain per system (rain per system day). A locally weighted scatterplot smoothing (LOESS) filter is applied to smooth the high-frequency signal. The numbers of cutoff systems (and cutoff days) during the growing season have increased slightly over the period but the trend is not significant (Fig. 11a). In support of this result, Fuenzalida et al. (2005) found that the trend in the annual number of cutoff lows for the Australian sector is not significant over the period of their analysis (1969–99). The numbers of frontal systems (and frontal days) in Fig. 11b have not changed significantly. However, rainfall per system is at a maximum for both fronts and cutoff lows at the start of the time series (Figs. 11c,d). Fluctuations in rainfall amounts per system on approximately decadal scales are apparent, though there is no discernible trend for the frontal component over the entire time period. Rain per cutoff day has a negative linear trend of approximately 0.02 mm yr^{-1}, which is significantly different from zero at the 90% confidence level (Draper and Smith 1998). There is an apparent decline in rain per cutoff system (day) from the mid-1970s, which coincides with the decline in SWWA rainfall previously mentioned (Allan and Haylock 1993). Additionally, there is a downward trend in rainfall in the region since the mid-1990s. Rain per cutoff system (day) reached a secondary maximum during the 1990s followed by a steady decline (Fig. 11c) indicating that the recent overall trend in rainfall mostly results from a reduction in rainfall from cutoff lows with little contribution from frontal systems. Figures 11a,b also show that there has not been much change in either the number of cutoffs or fronts during the period of rainfall decline since 1995.

5. The association of blocking with rainfall

The agricultural production of the CWB is critically dependent on winter rainfall. Dominated as it is by the seasonal migration of the STR and the trough of low

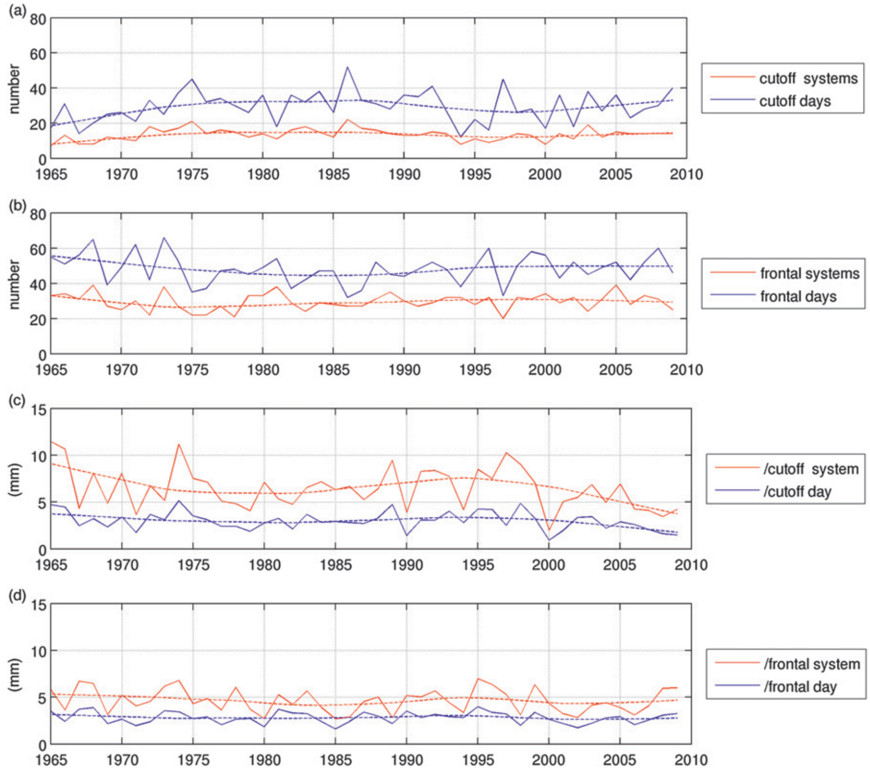

FIG. 11. The time series for the CWB of the contributions to rainfall from (a) the number of cutoff systems (red) and number of days on which cutoff systems occur (blue), (b) the number of frontal systems (red) and number of days on which frontal systems occur (blue), (c) rain (mm) per cutoff day (blue) and rain (mm) per cutoff system (red), and (d) rain (mm) per frontal day (blue) and rain (mm) per frontal system (red). A LOESS filter is applied to smooth the high-frequency signal over the period 1965–2009.

pressure in the westerlies, the synoptic climatology of the region and its rainfall suggest a predominant role of cold frontal systems. Our analysis confirms that frontal systems contribute approximately 50% of the growing-season rainfall. However, the importance of the cutoff low as a rain-producing system is also demonstrated in this study as these systems are responsible for about one-third of the growing-season rainfall. Furthermore, the cutoff low rainfall has contributed more strongly to the recent decline in rainfall in the CWB than the frontal component and accounts for most of the overall trend.

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 cutoff lows or upper troughs equatorward of the high (Risbey et al. 2009b). Additionally, Pook et al. (2006) demonstrated that the number of cutoff low days relative to an analysis box for southeastern Australia was highly correlated with an index of blocking activity in the longitude band between 125° 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 this index of blocking at 120°E and the number of cutoff low days in the analysis box used in this study (r = 0.36, n = 45). 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 centered south of the Great Australian Bight (approximately between 120° and 135°E) favoring rainfall in WA and blocking centered from 140°E eastward influencing the southeast of Australia. Blocking activity can be represented by a simple blocking index (BI) employed by the Australian Bureau of Meteorology (Pook and Gibson 1999; Pook et al. 2006; Risbey et al. 2009b). Unlike other commonly used indices which measure meridional geopotential differences across the midlatitudes (e.g., Lejenäs 1984; Tibaldi et al. 1994) the BI provides a measure of the degree of splitting of the midtropspheric westerly flow into two distinct branches: a subtropical arm and

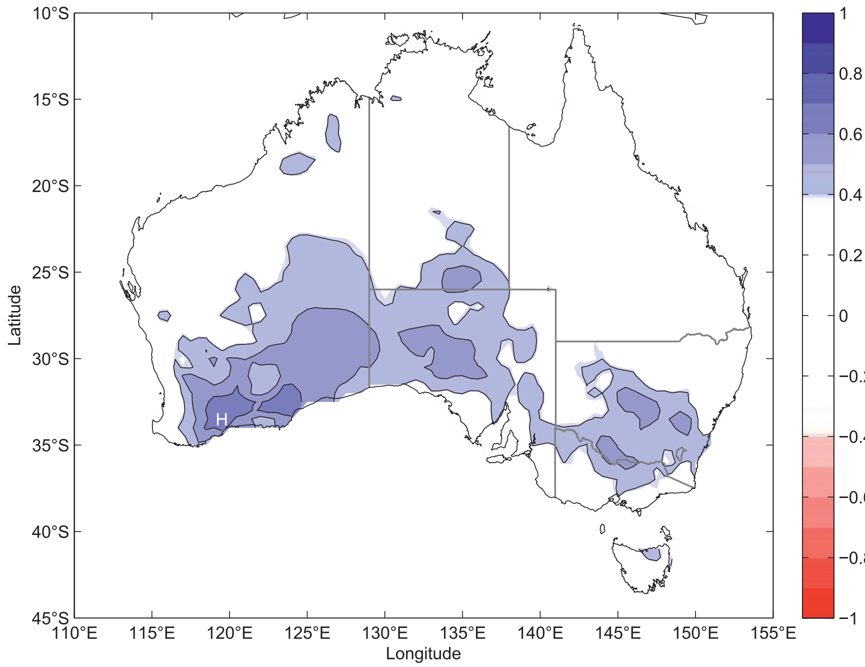

FIG. 12. Correlation coefficients between the Bureau of Meteorology BI at 120°E and AWAP rainfall for the growing-season months, April–October, over the period 1965–2007. Only correlations significant at the 99% confidence level are shown. The white ''H'' marks the grid point of maximum positive correlation.

a subpolar arm separated by a region of reduced westerly flow or even weak easterly winds. A value of the BI (m s^{-1}) is obtained at a given meridian by summing the westerly component (*U* component) of the 500-hPa wind at selected latitudes between 25° and 60°S.

In Fig. 12, the mean BI during the growing season at longitude 120°E, near the eastern boundary of the analysis region, is correlated with gridded rainfall for the Australian continent over the analysis period. Only values of the correlation coefficient that are significant at the 99% confidence level ($r > 0.39$, $n = 43$) are shown (shaded) in the diagram. It is apparent that the region of highest correlation is also the region where the percentage contribution from cutoff low rain was found to be highest (see Fig. 8) and includes the CWB, but not the high rainfall portion of SWWA. When growing-season rainfall is partitioned into its frontal and cutoff components it is possible to determine the correlations with mean BI separately. There is a high correlation (99% confidence) between cutoff rainfall during the growing season and the mean BI ($r = 0.48, n = 45$) but the correlation with frontal rainfall is low ($r = 0.1$, $n = 45$). When this knowledge of correlation is combined with Fig. 12 we infer that trends in blocking activity are likely to be associated with trends in cutoff low rainfall in the CWB. Hence, the decline in rain from cutoff low systems is likely to have been linked to changes in blocking behavior in some way. However, as there is no significant downward trend in the number of cutoff lows, it remains to be determined how blocking has influenced the detectable decline in the amount of rain per cutoff system. Certainly, blocking slows the eastward movement of these systems, thus enabling them to produce more rain in a particular location, but the influence of blocking on the efficiency with which cutoff lows access moisture is less clear and will continue to be a focus of research.

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 regions of WA.

6. Conclusions

Daily rainfall during the growing season for grains averaged across an eight-station network in the CWB of WA has been related to identifiable types of synoptic weather systems over a 45-yr analysis period. The resulting climatology reveals that frontal systems are responsible for at least 50% of all growing-season rainfall, while cutoff lows account for about 33%. Approximately 11% is associated with warm-cored low pressure systems, including troughs in the easterlies. Moreover, the mean proportion of rainfall contributed by the synoptic types varies throughout the growing season. The proportion of rain attributable to cutoff lows is highest in the austral autumn and spring months, which have been included in the growing season (approximately 40%) and falls to a minimum in August (23%). By way of contrast, the percentage contribution of frontal rain by month reaches a maximum (about 60%) in July and August. Application of the synoptic analysis to rainfall beyond the confines of the CWB reveals that the proportion of rainfall contributed by cutoff lows increases inland and northward from the high rainfall far southwest corner of WA, while the frontal component declines.

This study has demonstrated that the number of cutoff lows (or cutoff low days) varies markedly from one growing season to another, but does not exhibit a significant long-term trend. The mean rainfall per cutoff day is also highly variable, but has gradually declined over the analysis period and more significantly in the recent past. The reduction in cutoff rain is closely associated with the lower-than-average growing-season rainfall in the recent decade while a smaller contribution to the decline can be assigned to frontal rainfall. Variability in the circulation characteristics leading to the genesis of cutoff lows such as atmospheric blocking and variability in the availability of moisture to fuel precipitation events are not well understood and a concentration of research into these areas is required if seasonal predictions are to be improved.

Clearly, there is always an element of subjectivity in this type of analysis and each analyst brings a different range of skills and experience to the task. An element of judgement is involved in the selection of an appropriate analysis box and in the identification and locations of features such as fronts and troughs. Nevertheless, we believe that the selection of a network of recognized high-quality rainfall stations, the use of the NCEP–NCAR reanalysis data for a defined 45-yr period and the application of the techniques we have employed have ensured the objectivity and consistency of the overall analysis. Future research will involve the identification of possible teleconnections between the variability of the contributions of particular synoptic types to growing-season rainfall and the remote drivers of the atmospheric circulation in the Australian region.

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