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Shifts in the synoptic systems influencing southwest Western Australia

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Abstract A self-organising map is used to classify the winter circulation affecting southwest Western Australia (SWWA) into 20 different synoptic types. The changes in the frequency of these types and their links to observed rainfall are analysed to further understand the significant, prolonged, rainfall drop observed in this region since 1975. The temporal variability of the different synoptic types link well with the observed rainfall changes. The frequency of the troughs associated with wet conditions across SWWA has declined markedly since 1975 while the frequency of the synoptic types with high pressure over the continent, associated with dry conditions, has increased. Combining the frequency of the synoptic systems with the amount of observed rainfall allows a quantitative analysis of the rainfall decline. The decreased frequency of the troughs associated with very wet conditions accounts for half of the decline. Reductions in the amount of rainfall precipitating from each system also contribute to the decline. Large-scale circulation changes, including increases in the mean sea-level pressure and a decrease in the general baroclinicity of the region have been associated with the rainfall decline. These changes are suggested to be linked to increasing levels of greenhouse gases. Due to the strong link between the number of trough types and the rainfall over SWWA, the shifts in the frequency of these synoptic types could be used as a tool to assess simulated rainfall changes, particularly into the future.

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1 Introduction

The southwest of Western Australia (SWWA) receives reasonably consistent rainfall, with the majority falling in winter. The region with annual rainfall greater than 500 mm is small, approximately the area to the southwest of the diagonal line in Fig. 1. The annual rainfall declines rapidly inland. Although historically the region has had consistent winter rains (Gentilli 1972), there has been a strong down-turn in autumn and early winter rainfall since the mid 1970s (IOCI 2002). This study concentrates on changes at the height of winter, June and July, and Fig. 1 shows the proportional decline in rainfall. There are extensive regions where the recent rainfall is less than 80% of the long-term average. This decline is now impacting on water needs in the region (IOCI 2002; Power et al. 2005). The future rainfall is of utmost interest to the water-users in the southwest and a key to confidence in future projections is a full understanding of the synoptic signature related to the recent observed rainfall decline. The aim of this study is to extend the current understanding of this.

The general winter synoptic signature over SWWA is a series of troughs and fronts in the westerly air stream (Gentilli 1972; Wright 1974a) and the majority of winter rainfall along the western coast and further inland is from pre-frontal air-masses. The dominant surface wind direction associated with this rainfall has a northerly component (Wright 1974a). There are also systems that bring rainfall predominantly to the south coast, generally when the Indian Ocean high pressure is strong and southerly on-shore flow is dominant (e.g. State "6" of Charles et al. 1999).

On the broad-scale, there has been a strong increasing trend in MSLP (Smith et al. 2000; IOCI 2002), which is known to be linked to the decreasing rainfall (Allan and Haylock 1993; Ansell et al. 2000; Smith et al. 2000; Li et al. 2005). Locally, average June and July gridded station MSLP shows a strong upward trend, significant at the 90% level (Fig. 2). This trend is significantly correlated with the rainfall changes, with a correlation of −0.81 (significant at the 99% level); removing the trend by correlating first differences produces an even stronger correlation of −0.84. To assess the association at all time-scales, Ansell et al. (2000) used a cross-spectrum analysis of Perth MSLP and SWWA rainfall and found that there was strong coherency between the two on time-scales less than 3 years and another peak at about 8 years. Ansell et al. (2000) found little coherency at longer time-scales. The variability on an 8-year time-scale in both SWWA MSLP and rainfall (Fig. 6 in Allan and Haylock (1993)) shows that the shift in the mid-1970s is beyond the variability seen in the previous 100 years.

Thus, an important feature associated with the rainfall changes in SWWA is the change in the mean MSLP. Whether this change is driven by a decrease in the number of low-pressure circulation features or an increase in the number of high-pressure systems over the region is only hinted at in previous studies.

Low pressure centres and troughs have been identified in gridded data, analyses or reanalyses using a variety of methods. The number of low pressure systems in a region has been calculated using the automatic locating and tracking scheme of Murray and Simmonds (1991) by Smith et al. (2000). The number of cyclones in the decades 1959–1968 and 1969–1978 were calculated and Smith et al. (2000) found a reduction in the number of low pressure systems in the latter period across the SWWA region, with an increase to the south and north. Simmonds and Keay (2000), also using the scheme of Murray and Simmonds (1991), found a negative trend from 1958 to 1997 in the number of cyclones in the SWWA region. Cyclonicity is a measure of the time that

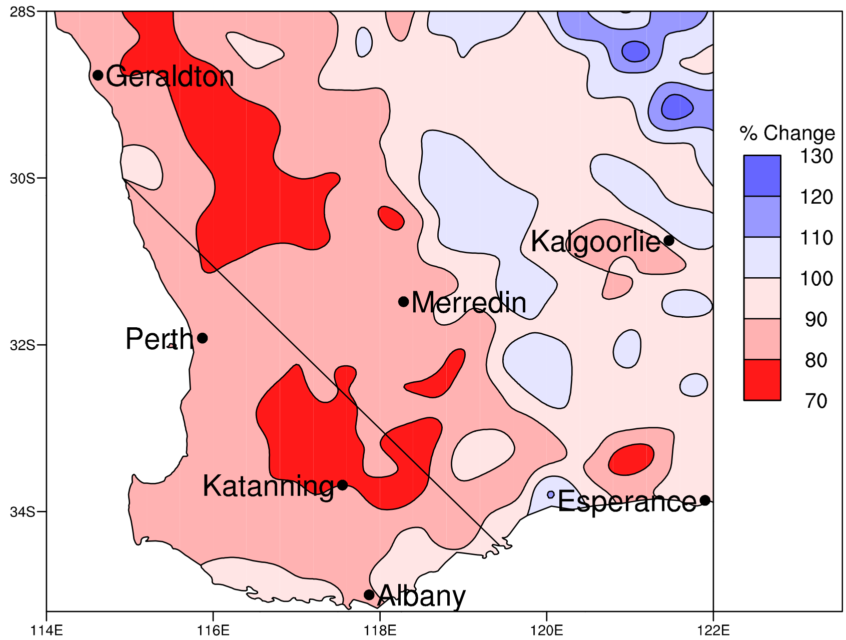


Fig. 1 The June and July (1976–2003) average gridded station rainfall from the National Climate Centre of the Australian Bureau of Meteorology as a percentage of the 1900–1975 average. The 1976–2003 values less than the 1900–1975 mean (less than 100%) are *shaded red* and values greater than the 1900–1975 mean are *shaded blue*. Blue shading is only evident in the northwest of this region. Southwest of the diagonal line corresponds to the region with annual rainfall totals greater than 500 mm and is the area over which rainfall totals are calculated

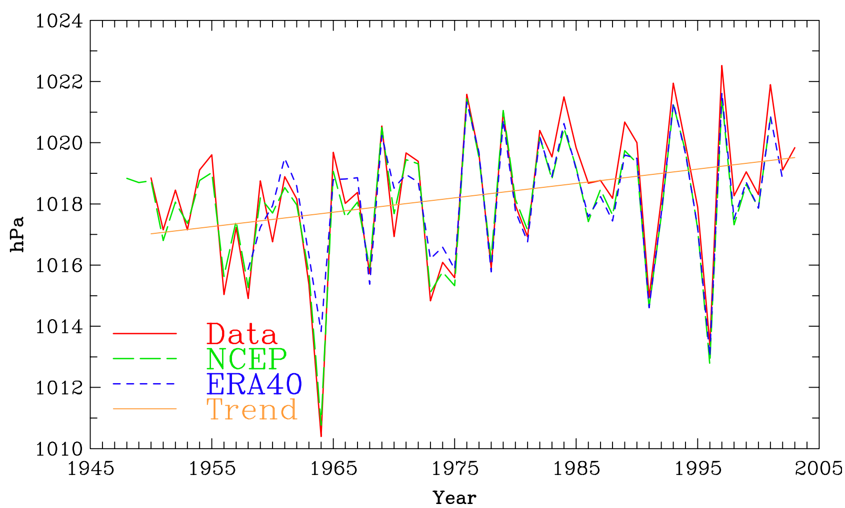


Fig. 2 June and July mean MSLP in the SWWA region. The values are from gridded station data, termed "Data" (Drosdowsky 2005), the linear trend of this and NCEP/NCAR and ERA40 reanalyses

a low pressure system is evident in a particular location. Leighton et al. (1997) found a strong correlation between the annual rainfall in the agricultural districts of Western Australia and high cyclonicity to the south of SWWA. They also found a strong negative trend from 1965 to 1993 in the cyclonicity in a square centred on 37.5° S and 122.5° E. A type of low-pressure system that is often associated with high rainfall totals is cut-off lows. These were identified by Qi et al. (1999), by way of a manual inspection of analysis charts over Australia. They found that the region encompassing the southwest has more cut-off lows than other regions in Australia's south. They also found that across southern Australia there were more cut-off lows in the winter half-year (May–October) and there were in general fewer in 1990–1996 than in 1983–1989. All of these results suggests a decline in the number of cyclones in the mid-latitudes and over the SWWA region particularly. This would suggest that the increasing regional MSLP is due at least in part to a decrease in the number of low-pressure systems.

The alternative hypothesis that there has been an increase in the number of anti-cyclones crossing the region has not been assessed as extensively in the literature. Average climatologies of anticyclones produced by Jones and Simmonds (1994) and Sinclair (1996) show that indeed there are high pressure centres crossing SWWA in winter over the periods they examined, but no time series analysis was undertaken by these authors. Leighton and Deslandes (1991) show the July anti-cyclonicity (the persistence of anticyclones over a particular area) for the period 1965–1987 and 1946–1960. They found a distinct shift in the centre of maximum anticyclonicity on the Australian continent from a broad maxima extending from just above the Bight to the east coast in the early period to a strong maxima in the southeast. Little anti-cyclonicity was evident over SWWA; however, the figures in Leighton and Deslandes (1991) suggest a slight increase in the 1965–1987 period compared to the earlier period. This would be either due to a greater number of high pressure systems crossing SWWA in the later period or that they remain in the region longer. Either way this suggests that there has also been an increase in the number of high pressure systems as well as a decrease in low pressure features.

Changes in the atmosphere as demonstrated through shifts in highs and lows are also evident aloft. Frederiksen and Frederiksen (2005) found that the mean location of the sub-tropical jet at SWWA longitudes in July had weakened and broadened in the 1975–1994 period compared to the 1949–1968 period. They also found that the meridional gradient in the vertically averaged July potential temperature had weakened right across the Indian Ocean and Western Australia. These shifts alone would suggest a decline in the baroclinicity required to drive surface cyclones in this region. Frederiksen and Frederiksen (2005) then used a primitive equation model to determine the dominant modes of instability in the atmosphere. They found that the atmosphere was less conducive to storm development in the later period (1975–1994) and the dominant centre of development, that was centred over SWWA in the 1949–1968 period, had shifted to the east.

On a smaller temporal and spatial scale, Charles et al. (1999) used a number of atmospheric predictors (average MSLP, the north–south gradient in MSLP and the 850 hPa dew-point depression) to define six common spatial rainfall patterns across SWWA. Charles et al. (1999) then formed composites of MSLP on days corresponding to each of those six rainfall patterns and created six synoptic "types". However, the range of dominant synoptic patterns affecting SWWA has not been classified directly from the broad-scale atmospheric data before. In this study, the dominant synoptic "types" will be determined, their temporal changes discussed and linked to SWWA rainfall.

Historically, early classification of synoptic systems into dominant types includes Lamb (1950), who subjectively defined types over Britain, and Hess and Brezowsky, who described a catalogue of large-scale weather patterns over middle Europe (Flohn and Hess 1949, and references therein). An objective version of the Lamb classification is now used by Jones et al. (1993).

There are many different methods to determine the dominant synoptic situations, as summarised in Huth (2000), Barry and Perry (2001) and Yarnal et al. (2001). A recent addition to the range of methods is the artificial neural network algorithm used to create a self-organising map (SOM) (Kohonen 2001). This method has been used extensively in a range of different fields from robotics to linguistics but only recently has it been used in climate studies (Hewitson and Crane 2002).

A SOM relevant to SWWA will be developed here. The data used in this study will be described in Sect. 2 and the method described in Sect. 3. Sect. 4 outlines the results along with some interpretation and in Sect. 5 these results, and their possible drivers are briefly discussed. Conclusions are presented in Sect. 6.

2 Data

The twice-daily MSLP from the NCEP/NCAR reanalysis (1948–2003) (Kalnay et al. 1996; Kistler et al. 2001) were used to develop the SOM. The monthly rainfall from the NCEP/NCAR reanalysis were also used in this study. Digitised daily MSLP charts over the Australian region (METANAL), available from the Australian Bureau of Meteorology, and daily MSLP grids from ERA40 reanalyses (1958–2001) (Simmons and Gibson 2000) were also analysed. Monthly mean 9 am MSLP (1950–2003) gridded from the Australian continental station data using a Barnes analysis and described in Drosdowsky (2005) (referred to here as "Data") and monthly MSLP from the HadSLP1 dataset (an update of GMSLP2, Basnett and Parke 1997) are used for validation of the reanalyses MSLP in the SWWA region.

The NCEP/NCAR reanalysis (referred to here as ‘‘NCEP’’) was used in the analysis for a number of reasons. The METANAL data are only available for the period 1979–1993 and thus do not cover the earlier period of interest. Of the two reanalyses, there are concerns with ERA40 in the Australian region prior to 1967. This is because there was limited assimilation of surface fields prior to this time (Simmons et al. 2004). Figure 2 shows the June and July average sea-level pressure from gridded station pressure (‘‘Data’’) and the grid point closest to SWWA in ERA40 and NCEP. Prior to 1976, it can be seen that ERA40 does not match the actual measurements well, whereas NCEP matches the Drosdowsky (2005) analysis more closely. After 1976, NCEP and ERA40 match each other closely, although they both exhibit a bias from the gridded observations after 1980. As the aim of this study is to describe the changes in the synoptic conditions before and after the 1970s, Fig. 2 suggests that the NCEP/NCAR reanalysis MSLP is the best available for this purpose.

For some of the analysis, only NCEP data after 1958 were used. This is because 1958 was the International Geophysical Year when many more observations began being taken and included in the reanalysis; observation times were standardised in many places and NCEP thus became more reliable (Kistler et al. 2001). There are also concerns that satellite data assimilated into the reanalysis after 1978 will alter the synoptic signature around this time (Tennant 2004). To assess the extent of this influence, the monthly time-series of MSLP near SWWA from NCEP was compared to that of HadSLP1, which had only surface observations included. After 1958, the correlation between the two is strong through all periods, suggesting little need for concern in this region.

The daily rainfall data used here are the 0.25° latitude by 0.25° longitude grids, analysed from station data (Jones and Weymouth 1997), from the National Climate Centre at the Australian Bureau of Meteorology. These will be referred to as ‘‘NCC’’.

3 Method to examine synoptic types

The method chosen to determine the dominant synoptic types over the southwest is the artificial neural network system of self-organising maps (SOM), described in detail by Kohonen (2001). The software used to create the SOM is part of the SOM_PAK, available from http://www.cis.hut.fi/research/som-research. The SOM method was chosen because the types it produces represent the expected synoptic situations well and the data are evenly spread across the different types. Each day can be matched to a particular synoptic type in the SOM. These features of the SOM allow analysis of the frequency of specific types of systems through time.

Two other methods to describe the different synoptic types were trialled. The first method was Empirical Orthogonal Function (EOF) analysis in T mode (Drosdowsky 1993). Both rotated and unrotated EOFs were examined and they revealed a shift in the modes of variability over time, but neither displayed obvious ‘‘weather’’ pattern types. The European project EMULATE also uses this method as a supplementary approach to a clustering technique more similar to the SOM method http://www.cru.uea.ac.uk/cru/projects/emulate/. The other approach tested here was a clustering method using pattern matching between all the days analysed, with all matches greater than (or less than) a certain critical value clustered into the first group, removed from the process and then the remaining data clustered in the same manner (Lund 1963; Key and Crane 1986). Three methods of pattern matching were used: sum of least squares, pattern correlation and pattern congruence. The number of clusters was highly dependent on the critical value: there was either one large class with a few infrequently occurring classes or a very large number of classes. Reducing the area of the spatial region helped to produce a more even spread of classes, but the clusters were still uneven and did not represent all the expected synoptic situations well. Of these three methods trialled, the SOM was considered the best method for the questions asked here.

SOMs are a mapping of many vectors onto a two dimensional array of archetypal vectors or nodes. The algorithm is similar to clustering techniques in the initial steps: for each input vector $x(t)$, the best matching node is determined by the minimum Euclidean distance. Once found, this best matching node, and those ‘‘close’’ to it are updated towards the input vector as described in Kohonen (2001), particularly in Fig.3.8. This updating of adjacent nodes as well as the closest match is the main difference between SOMs and clustering techniques and leads to an array of nodes that span the input vectors in an ordered manner. The extent to which each new observation influences the best matching node is determined by the ‘‘learning rate’’, which is a monotonically decreasing function of the observation number, set here to start at 0.03. The sphere of influence was set to the smallest dimension of the SOM, reducing with each training iteration, and the influence to the surrounding nodes followed a step function. The topology of the SOM here is rectangular.

In common with all clustering or classification techniques, there is a degree of subjectivity involved in determining the number of nodes, the area of the region of interest and the learning rate and sphere of influence.

3.1 Data preparation, years and season

The reanalyses were not standardised. The usual method of standardisation by removing the mean and then dividing by the standard deviation at each point would result in more weight given to regions with lower variability. It is the troughs, fronts and highs in the westerly flow that are of interest here and thus the variability in the data in this region needs to be emphasised. The day-to-day variability increases with latitude through this region and thus by virtue of the underlying background state the emphasis is appropriate for this study and no standardisation was required.

All available years of (1948–2003) NCEP/NCAR reanalysis MSLP were used to develop the SOM. The whole period is used to allow synoptic systems present before and after the mid-1970s rainfall decline to influence the range of synoptic types. The change in each type's frequency through time will then better reflect the true shift in the circulation.

The rainfall decline in SWWA is only evident during autumn and early winter and thus it is this period for which the shifts in synoptic types are of most interest. A preliminary analysis was made of the climatological conditions in each month to determine if, even though all these months show a rainfall decline, their synoptic conditions were similar. If the climatology in any month was dramatically different from the others it would be likely to also exhibit a different range of synoptic systems. The climatological trough in the longitudes of SWWA is dominant during June and July but less deep in May and shifted to the east in August. The continental high pressure region over Australia is also strong in June and July but not in the other months. It was also shown by Smith et al. (2000) that the correlation between local MSLP and SWWA rainfall is strong (greater than −0.75 in three different periods since 1907) for the June, July and August average but much lower in May. For these reasons only June and July will be considered in the analysis here.

3.2 The selected region

The selected spatial region which will be presented to the SOM algorithm is of great consequence to both the types characterised by the SOM and the frequency of those types over time. Hewitson and Crane (2002) selected a reasonably small region (30–60° N and 270–292.5° E), while Tennant (2004) used larger regions (e.g. 70–20° S and 190–290° E).

The full Australian region (50–10° S and 90–170° E) was first tested since changes in the location of the ridge in the Tasman have been suggested by Lamb and Johnson (1961) and Wright (1974b) to modify flow over SWWA. The location of the continental high would also be expected to modify the propensity to increase northwesterly flow over SWWA. However, the variability in the east of Australia dominated both the pattern of the preferred synoptic types and the trends in the number of each type over time. A strong feature was the increasing pressure of the continent-wide high pressure cell type when the SOM was calculated on two different periods of data (1948–1975 and 1976–2003). This may not be the relevant feature to capture when assessing changes in SWWA rainfall. Therefore, the region selected to highlight the changes over the southwest of Australia is from 50 to 15° S and 90 to 130° E. This region extends far enough south to include the depth of the majority of troughs affecting the southwest, far enough north to include low pressure features reaching south from the tropics and covers enough longitudes to capture full troughs and their progression.

3.3 Size of the SOM array

The size of the SOM array is pre-defined and has a strong bearing on the range of synoptic situations represented. The fewer the number of nodes in the SOM array the more general each pattern must be, while with a greater number of nodes a wider range of situations can be represented. The size of the SOM array was selected subjectively. A rectangular 5×7 array was chosen first, following the work of Hewitson and Crane (2002). The synoptic types in the resulting SOM were then subjectively assessed to determine if they represented the expected range of synoptic situations. Types representing deep troughs and extensive high pressure regions were expected to appear along with the appropriate transition of troughs and highs across the region. With 5×7 nodes, all expected synoptic types were apparent, although it was obvious that the spectrum could be represented with fewer nodes. A smaller rectangular array was then chosen, 4×5, and this also captured all the expected types. Any fewer nodes and the expected synoptic types were no longer evident. The mean error per sample (the average of the Euclidean distance between each input data vector and the synoptic type it matches to) for the 4×5 SOM was 77 hPa, a little greater than for the 5×7 SOM (71 hPa), but much less than the 2×3 SOM (92 hPa).

A further test of the appropriate size for the SOM array was to test the synoptic types produced by SOMs of various sizes against the six synoptic types determined in Charles et al. (1999). The MSLP composites of Charles et al. (1999) were for the entire Australian region and the months May–October. A 2×3 SOM was created from the same MSLP (METANAL) and the composites of Charles et al. (1999) were found to match only three of the SOM types. Extending the SOM array to 12 nodes led to the Charles et al. (1999) MSLP composites corresponding to States "2" and "3" mapping onto only one node and those for States "4" and "5" also mapping onto only one. Only with a SOM array of 4×5 nodes did the Charles et al. (1999) composites match individual nodes.

4 Results

4.1 Dominant synoptic types

The SOM for the full 1948–2003 period of the NCEP/NCAR reanalyses is shown in Fig. 3. By virtue of the method, similar types are near each other on the SOM while more distinct types are further apart. The types are robust with similar types present in SOMs created using the ERA40 and METANAL data. The types displaying the expected deep troughs are in the lower portion of the

SOM and types with broad regions of high pressure are near the top (Fig. 3). Synoptic types with a trough to the west of the region are to the left of the SOM, types of a zonal nature are in the centre, and types with a trough to the east of the region are in the lower right of the SOM.

Each map of twice-daily MSLP falls into a particular synoptic type on the SOM. The daily transitions between types can be determined by noting the new type at the same time on the following day. The transitions between the synoptic features identified by the SOM would be expected to reflect the generally eastward movement of weather systems in this region. Figure 4a shows the forward transitions (the vectors point towards the type on the next day and the length of each vector is relative to the occurrence of that direction of transition). Figure 4b indicates the percentage of days on which no transition out of the type is made. The more persistent types (Fig. 4b) are at the edges of the SOM, types with the greatest coverage of low (A5) or high (D1) pressure being the most persistent. The path of daily transitions does

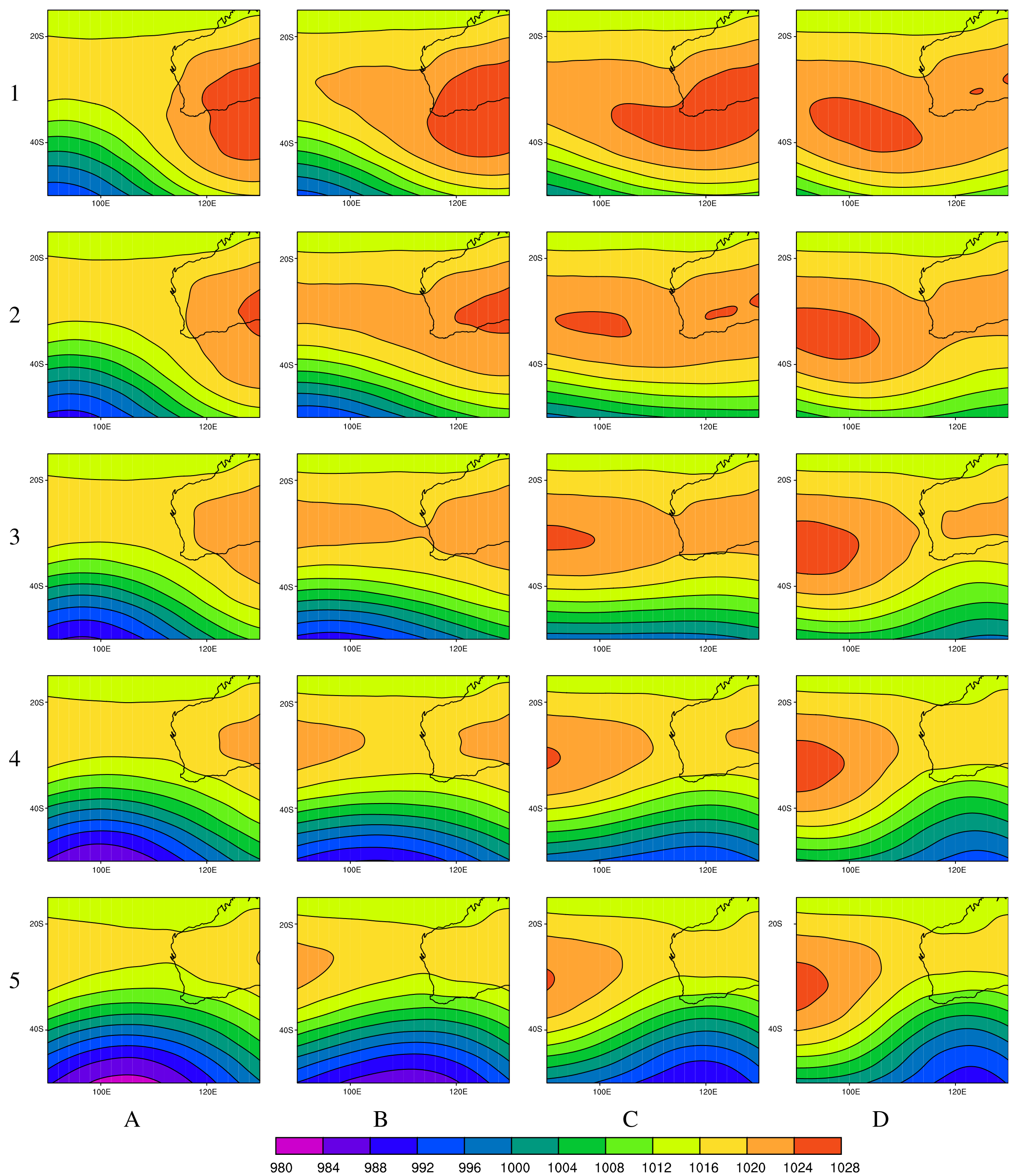


Fig. 3 The 4×5 SOM built using 1948 to 2003 NCEP/NCAR reanalyses MSLP. The *reds* indicate high pressure and the *blues* lower pressure. References to individual synoptic types in the text are to, for example, A5, which is the bottom left type. Contour interval is 4 hPa

indeed follow an anti-clockwise path around the outside of the SOM, as expected, highlighting the movement of troughs and highs in the westerlies across the region. The dominant timescales of these transitions could be assessed further as a potential aid for weather forecasting in the region. This has not been pursued here.

The changes in the frequency of each synoptic type over time can be shown in a number of ways. Figure 5 shows the percentage of time that the atmospheric conditions are represented by each synoptic type in each year. The "bluer" colours correspond to the deep troughs along the bottom of the SOM (row 5) and the "redder" colours correspond to the types with large areas of high pressure along the top of the SOM. Strong inter-annual variability is evident in the representation by each type. In particular, type A5, the deepest trough, is dominant in 1964 (an extremely wet year) with about half the days falling into this type, whereas very few days are of this type in 2001 (a very dry year).

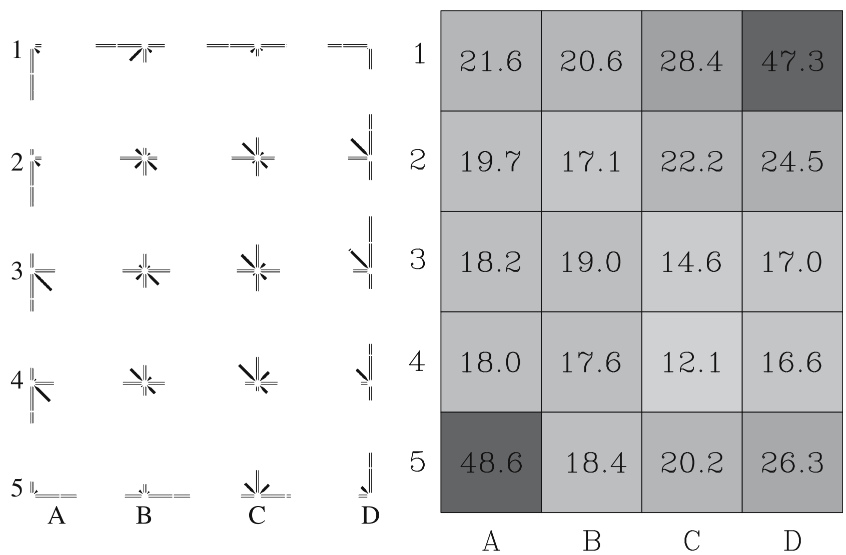
As it is particularly the rainfall decline through the 1970s that is of interest, the average number of half-days in each synoptic type for the period 1976–2003 was compared against the average number for the 1958–1975 period. The average number (per year) for each synoptic type is shown in Table 1. The expected number is 6.1 each year for each synoptic type (61 days of June and July, twice daily data divided over 20 types). Figure 6 shows the percentage change between the two periods relative to the earlier period. The shift that is immediately obvious is the decrease in the number of occurrences of the trough types (to the right of Fig. 6) in the more recent period, while the occurrence of types with higher pressure (to the left of the plot) has increased. Type A3 with flow over SWWA from the north and type D3 with flow onto the southern coast have also increased in number more recently. All of these shifts in the synoptic types through time provide some explanation of the observed changes in SWWA rainfall.

4.2 Link with rainfall

The amount of rainfall associated with each synoptic type can be determined by matching the total rainfall on any one day to the synoptic types associated with the twice daily MSLP data on that day. The synoptic type at 0Z on a particular day was allocated rainfall from that day, while the type at 12Z was allocated rainfall from the following day. The anomalies from the full period rainfall are shown in Fig. 7. Blue shading indicates more rainfall than the 1958–2003 mean while red shading indicates less.

The trough types (D4, A5, B5, C5 and D5) in the SOM clearly correspond to wet conditions across the southwest (Fig. 7). By summing these types, potential links with the actual rainfall time-series can be assessed. The gridded NCC rainfall was spatially averaged (with area-weighting) over the land southwest of the diagonal line shown in Fig. 1. The time-series of the sum of the number of "wet" types in each year and the NCC rainfall is shown in Fig. 8 and they track closely. The correlation between the rainfall and the wet types is 0.70, which is significant at the 99% level. The number of wet type half-days drops away at the same rate as the rainfall. The axes are scaled in Fig. 8 so that the horizontal lines represent the averages for both the number of wet types and the rainfall. The 1958–1975 mean number of wet type half-days is 33.4, while the mean gridded rainfall is 220 mm; both display a 16% decline to the 1976–2003 period, with the number of wet type half-days dropping to 27.8 and the average rainfall to 184 mm. Although these synoptic types do not bring all the rainfall to the SWWA, this result indicates that a major driver of the rainfall decline is simply fewer MSLP troughs.

The average pressure over the region has been rising over this time (Fig. 2), while the decrease in the number of synoptic types with predominantly low pressure



(a) Forward **(b)** Stationary

Fig. 4 Daily transitions from each synoptic type. **a** Forward transition: away from a particular type. The length of the vectors indicates the frequency of the transition. **b** Stationary: the percentage of days where the synoptic type remains the same. *Shading* reflects the magnitude of the percentage in each square

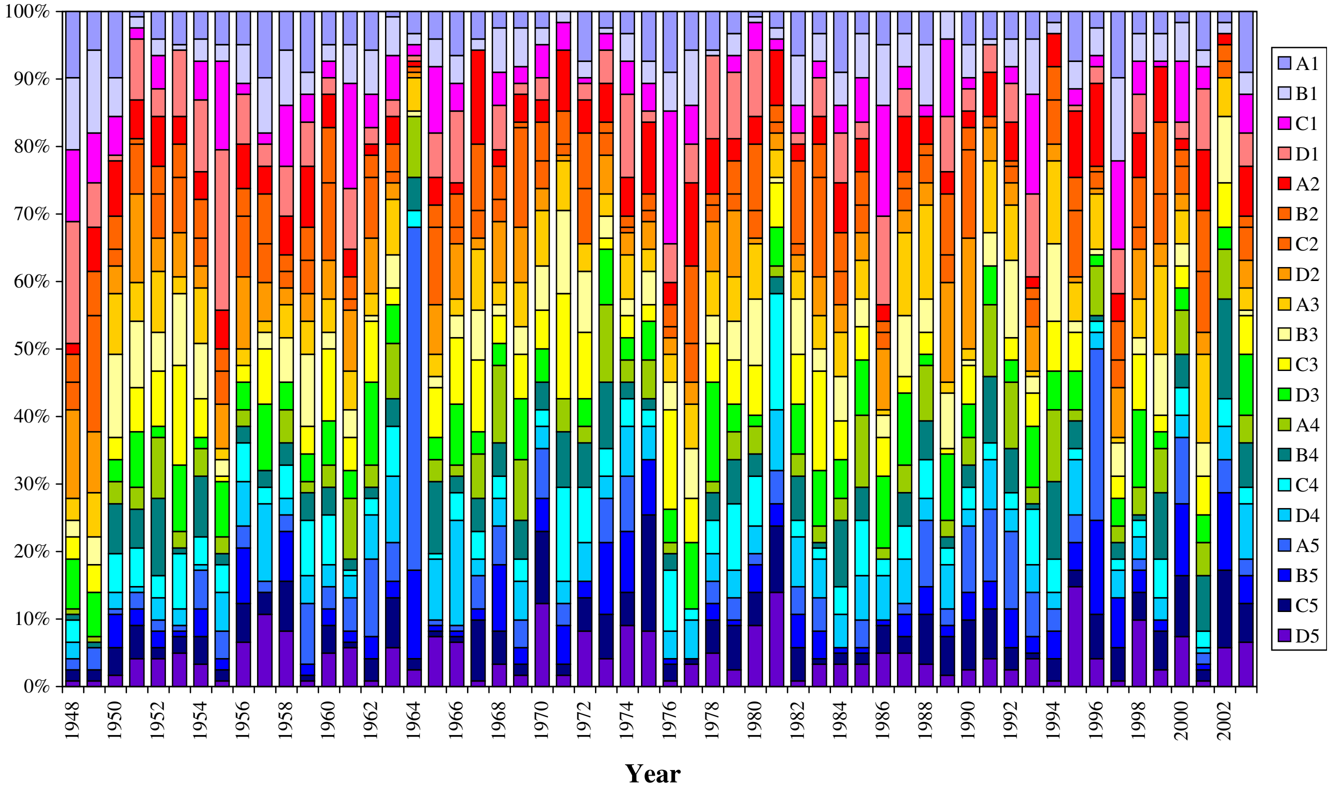


Fig. 5 The annual percentage frequency of each type in the 4×5 SOM. Each colour refer to a different synoptic type referenced by the letters and numbers in Fig. 3

Table 1 Average statistics (per year) for each synoptic type for the early (1958–1975) and late (1976–2003) periods: the average number of occurrence, the average daily rainfall and the total rainfall

	Number		Rainfall (mm/day)		Rainfall (mm)	
Type	1958–1975	1976–2003	1958–1975	1976–2003	1958–1975	1976–2003
A1	5.2	5.5	0.8	1.2	2.1	3.3
B1	4.8	5.8	0.8	0.5	1.8	1.5
C1	5.9	6.3	0.8	0.7	2.3	2.3
D1	5.5	6.3	2.6	2.1	7.1	6.4
A2	6.5	6.9	2.3	1.4	7.5	4.9
B2	5.1	5.8	1.9	1.0	4.7	2.9
C2	5.9	5.7	1.2	1.0	3.6	2.9
D2	5.7	5.9	3.4	3.0	9.6	8.9
A3	6.4	7.9	3.2	2.1	10.2	8.2
B3	5.9	6.5	3.1	1.8	9.1	5.8
C3	7.3	6.8	2.0	2.0	7.3	6.6
D3	6.2	7.7	2.5	3.4	7.7	13.2
A4	6.7	5.8	4.6	2.5	15.4	7.0
B4	5.8	6.0	3.1	2.9	9.1	8.7
C4	5.7	5.6	2.8	2.6	8.1	7.2
D4	6.4	6.0	5.3	4.9	16.9	14.6
A5	8.8	5.8	7.1	6.9	31.3	19.8
B5	6.0	4.8	7.1	7.4	21.4	17.7
C5	6.0	5.8	6.9	6.9	20.8	19.8
D5	6.2	5.5	7.6	8.0	23.6	21.9
Total					219.6	183.6

The expected number for each type is 6.1:twice daily for 61 days over June and July (= 122), divided among 20 types. The total rainfall can be calculated by multiplying the number (divided by two) by the daily rainfall

would contribute to this, it is of interest to determine if an increasing number of high pressure synoptic types has also contributed to the pressure increase. Types A1, B1, B2, C1 and C2 were classified as "dry". All these types have a region of high pressure over the west of the Australian continent (particularly A1, B1 and C1), while

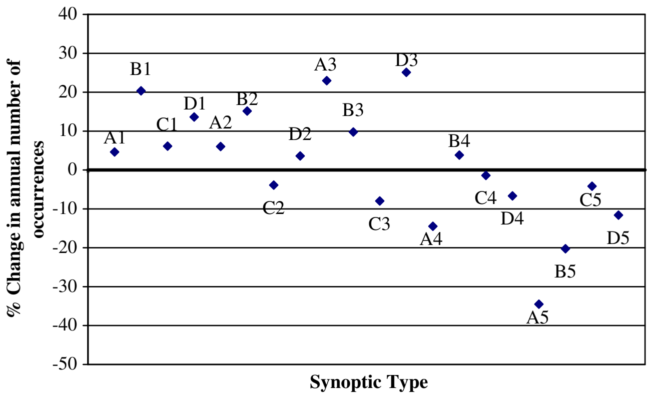
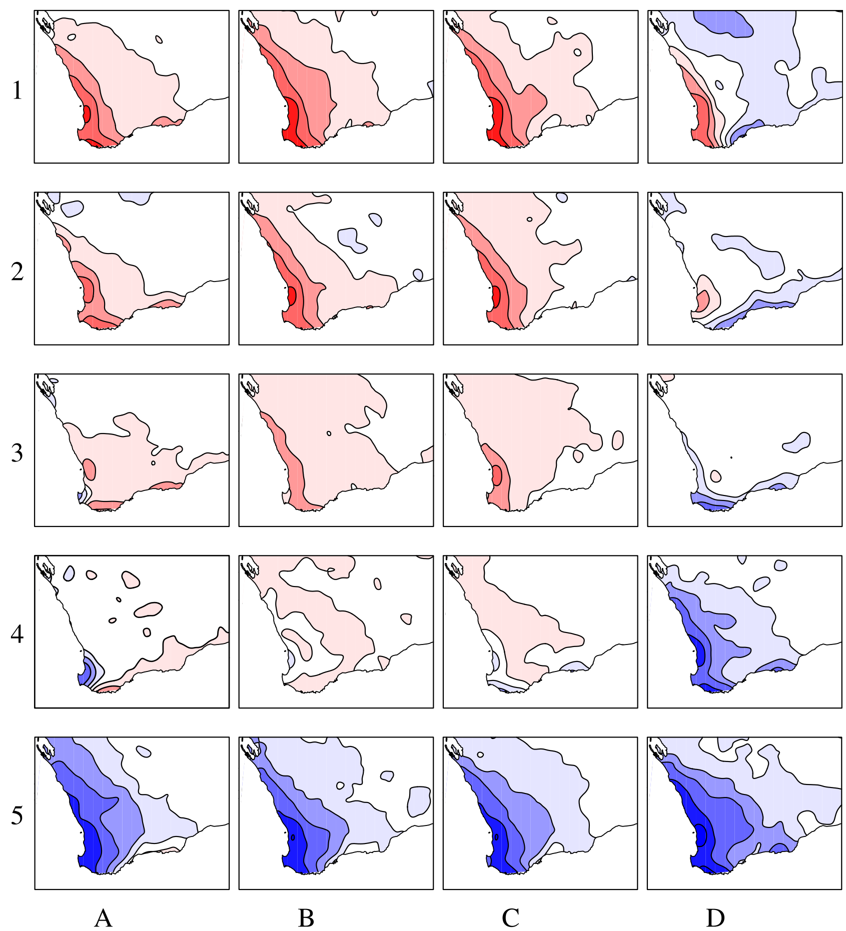


Fig. 6 The percentage change in the average annual number of occurrences of each type in the 4×5 SOM (1976–2003 period minus the 1958–1975 period relative to 1958–1975). The labels correspond to the letters and numbers on the SOM (Fig. 3)

the high pressure extends over the SWWA region and to the west in types B2 and C2. These types correspond reasonably closely with the MSLP composite corresponding to State "5" of Charles et al. (1999). The time-series of the frequency of the dry types shows that these types do increase over time by 8%. They do not, however, increase by as much as the trough, or "wet", types decrease. Thus the pressure increases are more strongly driven by fewer troughs rather than a greater number of high pressure systems. This was suggested from the strong trends in the number of cyclones (Simmonds and Keay 2000) compared to the more subtle shifts in anti-cyclonicity through time (Leighton and Deslandes 1991).

The drivers of the spatial variability of the rainfall change in Fig. 1 can be examined more closely by analysing the shifts in related synoptic types. The anomalies in Fig. 1 show only a small decline or even an increase in rainfall along the southern coast. The rainfall anomalies of types D2 and D3 in Fig. 7 show enhanced rainfall along the south coast suggesting that it is these types that have contributed to the minimal change in that region. The synoptic situation for types D2 and D3 shown in Fig. 3 is one with strong southerly on-shore flow across the southern coast. The shift in the mean frequency of these types (Fig. 6) shows that they have, on average, become more prevalent. However, on examining the inter-annual variability through time in Fig. 9, although the occurrences has increased from 1960 to 1990, since 1990 the occurrence of these types has declined markedly. The anomaly map of 1990–2003 rainfall (not shown) shows that the mean early winter rainfall in the south has now declined to a greater extent, in line with the rest of the region.

Fig. 7 The NCC rainfall anomalies associated with each type in the 4×5 SOM. *Red shading* indicates conditions drier than the 1958–2003 mean and *blue* wetter than the mean. Types in row 5 and D4 are wetter than average, as is the south coast for types D1, 2 and 3, and the west coast for type A4. The contour interval is variable: −8, −4, −2, −1, −0.3, 0.3, 1, 2, 4, 8 mm/day



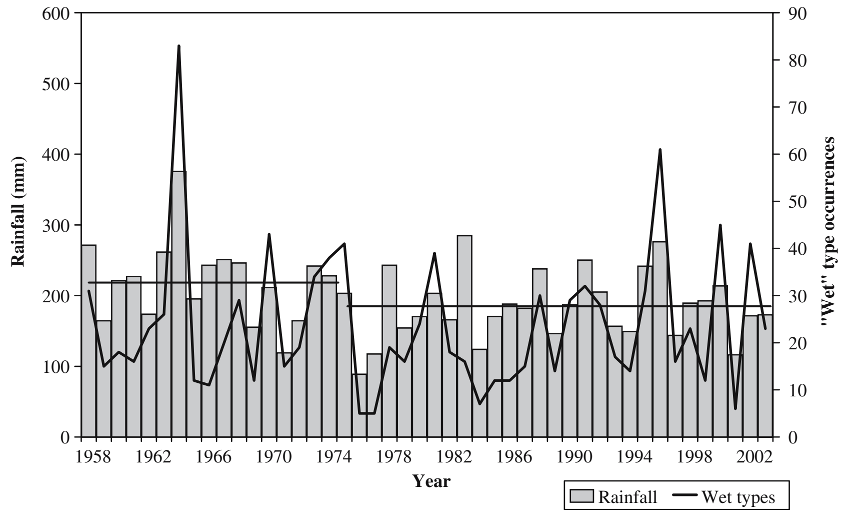


Fig. 8 The time-series of the NCC rainfall averaged over the southwest (*solid bars*) and the sum of the occurrences of the five "wet" synoptic types from the 4×5 SOM (*black curve*). The averages for both variables (which are at the same level on the two different scales) for the 1958–75 and 1976–2003 periods are also shown

It would be expected that there might be changes in the amount of rainfall associated with each synoptic type over time. Table 1 gives the average observed rainfall in the south west corner per day for each synoptic type for the early (1958–1975) and late (1976–2003) periods, while Fig. 10 shows the differences (late–early). As the NCEP/NCAR reanalyses improve through time with more data assimilated, the timing of the synoptic systems in the reanalyses would be expected to better align with the observed rainfall. Thus synoptic types with predominantly wet conditions would be expected to be wetter in the later period and "dry" types would be expected to be drier. The increases in rainfall associated with wet types D4, B5, C5 and D5 in the later period (1976–2003) might be the evidence of this improvement in the reanalyses and not a true reflection of changes in the rainfall amount associated with these synoptic types. Type A5, however, shows a decrease in the later period compared to the earlier period. Thus the deep troughs that bring a great deal of rainfall to the region, particularly on the west coast, have less rainfall associated with them in the later period.

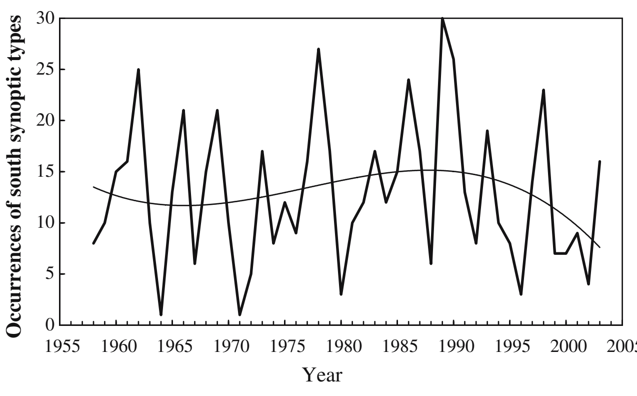


Fig. 9 The sum of the number of occurrences of types D2 and D3; types that have positive rainfall anomalies along the south coast. A polynomial of the third order fitted to the data is also shown

There is a consistent decrease in the amount of rainfall linked to types with a trough to the west of the continent (A2, A3 and particularly A4). This decrease would also contribute to the rainfall decline seen on the west coast. Type B3 also shows a strong decrease in rainfall associated with it, although the frequency of occurrence increases slightly (Table 1), suggesting that it is also being driven by the changes influencing the types with a prominent trough to the west of the continent.

The total rainfall per year that is linked to each synoptic type was calculated by combining the observed rainfall (per day) with the number of occurrences of each synoptic type (divided by 2). Totals of these values are shown in the last two columns of Table 1, while Fig. 11 shows the difference (1976–2003 minus 1958–1975). All types except A1 and D3 have less mean rainfall associated with them in the later period.

For each synoptic type, the rainfall differences plotted in Fig. 11 can be broken up into the contribution from the change in the number of occurrences and the mean daily rainfall. The method and the table of contributions are detailed in the Appendix. For all types except C3 and the "wet" types described earlier, it is a change in the amount of rainfall that is driving the changes in total rainfall (Fig. 11). The increase in total rainfall in type D3, which has positive rain anomalies along the south coast, has an almost equal contribution from both an increase in the occurrences of the type and the amount of rainfall associated with it. Types A5 and A4 stand out as contributing the greatest amount to the total decline. Types A5 and A4 show a decrease in their frequency (Fig. 6) and a decrease in the amount of rainfall linked to them (Fig. 10); however, the decrease in frequency is the main component of the rainfall reduction for type A5 (92%) while a decrease in the rainfall associated with each occurrence of type A4 (80%) drives its contribution to the rainfall decline.

The full rainfall decline was 36 mm but to calculate the contribution from each synoptic type in the SOM to the rainfall decline all negative anomalies (Fig. 10) were

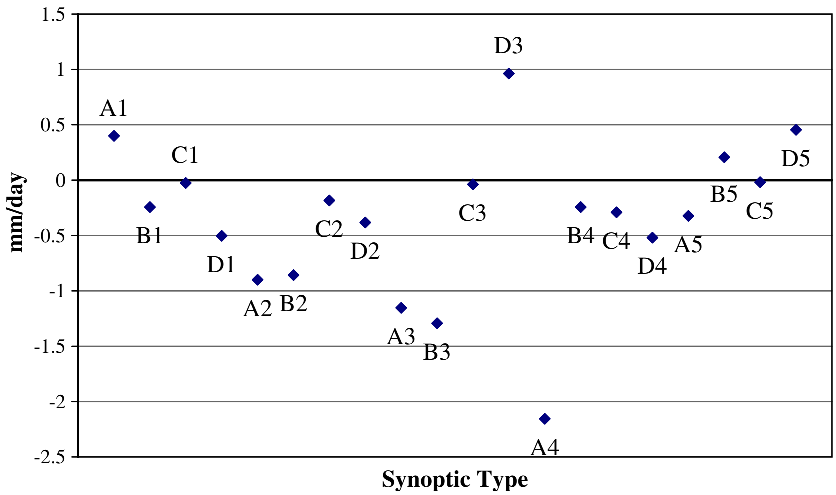


Fig. 10 The difference in the amount of average observed rainfall per day (mm/day) for the 1976–2003 period minus the 1958–1975 period for each synoptic type in the SOM. The rainfall totals are averaged across the region to the southwest of the line in Fig. 1. Table 1 shows total values

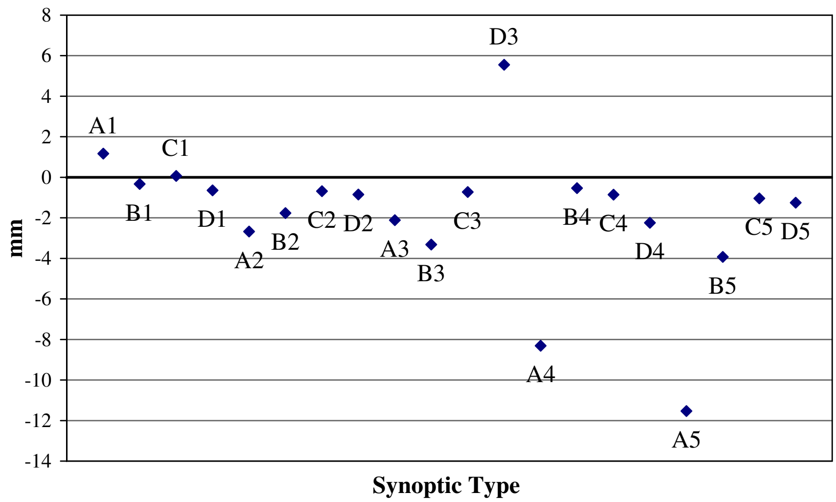


Fig. 11 The difference in the average (per year) amount of total June and July observed rainfall (mm) for each synoptic type between the 1976–2003 period and the 1958–1975 period

summed (−43 mm), while the positive values were not included (7 mm). Those synoptic types with negative anomalies would then be considered as a proportion of −43 mm. The contribution to the rainfall decline from the wet types (D4, A5, B5, C5 and D5) is almost 50% (20/43) and it is about 30% (13/43) from troughs to the west (A2, A3 and A4).

5 Discussion

The decline in the amount of rainfall associated with many synoptic types, in particular those with troughs to the west of the continent suggest either a reduction in the amount of atmospheric moisture available or a change in the dynamics leading to rainfall from these systems. Wright (1974a) suggested two different types of rainfall influencing SWWA which could reasonably be described as pre- and post-frontal rain. At this time of year, along the west coast, rainfall is predominantly pre-frontal (Wright 1974a). The analysis of sea-surface temperature trends and the different patterns of sea-surface temperature anomalies in wet and dry years by Allan and Haylock (1993) suggest, if anything, an increase in the potential for gaining moisture from the usual source for pre-frontal rainfall and thus the likely reason for this decrease in rainfall amount is due to a shift in the dynamics of the fronts. Pitman et al. (2004) proposed that this shift in dynamics was brought about by a reduction in land-surface roughness length over time. Shifts in the large-scale circulation, such as a southward shift of the low associated with the front could also lead to lower rainfall totals associated with the system.

What might be driving the large-scale shifts in the atmosphere and will the trends continue? Explanations for the broad-scale increases in pressure at SWWA latitudes have included changes in polar stratospheric ozone (Gillett and Thompson 2003) and natural variability along with anthropogenically forced changes in greenhouse gases (Marshall et al. 2004). The seasonal timing of the ozone changes have not, at this stage, been linked to winter conditions. More locally, Timbal et al. 2006 found that the decline in rainfall over the southwest could not be reproduced in a model with only natural forcing, and anthropogenically driven forcing must be included. Thus natural variability (volcanic eruptions and solar variability) may have played a role in the timing of the rainfall changes in SWWA, particularly in the wet conditions through the 1950s and early 1960s; however, these studies strongly suggest that the enhanced greenhouse effect has contributed to the current dry conditions. The recent reduction in the frequency of troughs with flow across the SWWA south coast might reflect an increasing influence of these large-scale changes in this region.

Linking the rainfall associated with certain synoptic situations can also help in better describing the rainfall produced by climate models. Rainfall is a field that is difficult to simulate accurately with atmospheric models. The reanalyses also have shortcomings in simulating rainfall accurately, as rainfall is a variable produced directly from model output, with little information from assimilated observations (Kalnay et al. 1996). Rainfall from a point closest to the southwest in the NCEP/NCAR reanalyses and ERA40 reanalyses reflects the year-to-year variability quite well (not shown), but the trend is to more rainfall in recent times rather than drier conditions. The demonstrated link between rainfall and certain synoptic types suggests a new method of interpreting large-scale changes in reanalyses and models and linking those changes back to SWWA rainfall. This could be described as a "downscaling" tool. Charles et al. (1999) and Timbal (2004) use two reasonably complex methods to downscale large-scale features to rainfall on a station scale. Their methods use a number of variables, including a measure of moisture. Analysing shifts in the frequency of the synoptic systems is a simple way to determine regional rainfall changes without requiring a wide range of variables. This method may also be useful in interpreting simulations of the future.

6 Conclusions

The 4×5 SOM developed with NCEP/NCAR reanalysis MSLP identifies the synoptic types that would be expected in the SWWA region in winter, including extensive troughs and types with large regions of high pressure and a full range in between. The analysis of the changes in the frequency of each type and the shifts in rainfall associated with those types has led to a more exact understanding of the shifts in the system leading to the rainfall decline in SWWA.

Almost half the reduction in observed rainfall from 1958–1975 to 1976–2003 was due to a reduction in the number of troughs linked to wet conditions across SWWA. This reduction in the number of troughs is tied to changes in the large-scale circulation that have been suggested by previous studies to be due to increasing greenhouse gases.

The remaining half of the decline was largely due to a reduction in the amount of rainfall associated with most other synoptic types, but particularly those that bring rainfall specifically to the west coast. This reduction in the precipitation from the systems is probably linked to the large-scale atmospheric shifts that are driving the reduction in the number of troughs; however, land cover change and the associated decrease in surface friction (Pitman et al. 2004) may have contributed to this part of the rainfall decline.

The synoptic types with on-shore flow over the southern coastline showed an increase in rainfall along the southern coast from 1958–1975 to 1976–2003. Analysing the time-series of these types reveals that although these systems were increasing from 1960 to 1990 they have declined in frequency markedly since then. The same shift in large-scale circulation that has led to the reduction in the number of large troughs may now be impacting on these synoptic types also.

The strong link between the number of trough types and the rainfall over SWWA suggests that the SOM can be used as a "downscaling" tool. Downscaling tools often require a number of predictors. In this case only MSLP is required. Many modelling groups provide only limited output on daily timescales, but this range of fields generally includes MSLP. Comparing the model output with the SOM developed here will provide an excellent tool for assessing simulated changes, particularly into the future.

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Appendix: calculation of the relative contributions to the rainfall changes

For each synoptic type, the rainfall differences plotted in Fig. 10 (Δ) can be broken up into the contribution from the change in the number of occurrences and the mean daily rainfall. The raw values for these calculations are in Table 1. If the change in the number of occurrences is of a different sign to the change in rainfall then the component with the same sign as Δ is counted as contributing 100%. If both components are of the same sign then the proportions are calculated as:

$$\begin{array}{cl}
\text{Contribution}_f & +\text{Contribution}_r = \Delta \\
(f_2 - f_1)\bar{r} & +(r_2 - r_1)\bar{f} = \Delta \\
\frac{(f_2-f_1)\bar{r}}{\Delta} & +\frac{(r_2-r_1)\bar{f}}{\Delta} = 1 \\
\text{Proportion}_f & +\text{Proportion}_r = 1
\end{array}$$

where f is the number of occurrences divided by 2 and r refers to the rainfall. Subscript 2 refers to the later period (1976–2003), while subscript 1 refers to the early (1958–1975) period. The overbar corresponds to the mean value over the full period. The proportions are expressed as a percentage in Table 2. The contributions towards Type C1 cannot be calculated as the total change is near zero.

Table 2 The percentage proportion of the contribution from the change in the average number of occurrence ($Proportion_f$) and the average daily rainfall ($Proportion_r$) to the total rainfall anomaly, Δ (1976–2003 minus 1958–1975)

Type	$Proportion_f$	$Proportion_r$
A1	10	90
B1	0	100
C1	–	–
D1	0	100
A2	0	100
B2	0	100
C2	19	81
D2	0	100
A3	0	100
B3	0	100
C3	81	19
D3	42	58
A4	20	80
B4	0	100
C4	12	88
D4	46	54
A5	92	8
B5	100	0
C5	91	9
D5	100	0

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