A Monsoon-Like Southwest Australian Circulation and Its Relation with Rainfall in Southwest Western Australia

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Abstract

Using the NCEP–NCAR reanalysis, the 40-yr ECMWF Re-Analysis (ERA-40), and precipitation data from the Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP) and the Australian Bureau of Meteorology, the variability and circulation features influencing southwest Western Australia (SWWA) winter rainfall are investigated. It is found that the climate of southwest Australia bears a strong seasonality in the annual cycle and exhibits a monsoon-like atmospheric circulation, which is called the southwest Australian circulation (SWAC) because of its several distinct features characterizing a monsoonal circulation: the seasonal reversal of winds, alternate wet and dry seasons, and an evident land–sea thermal contrast. The seasonal march of the SWAC in extended winter (May–October) is demonstrated by pentad data. An index based on the dynamics’ normalized seasonality was introduced to describe the behavior and variation of the winter SWAC. It is found that the winter rainfall over SWWA has a significant positive correlation with the SWAC index in both early (May–July) and late (August–October) winter. In weaker winter SWAC years, there is an anticyclonic anomaly over the southern Indian Ocean resulting in weaker westerlies and northerlies, which are not favorable for more rainfall over SWWA, and the opposite combination is true in the stronger winter SWAC years. The SWAC explains not only a large portion of the interannual variability of SWWA rainfall in both early and late winter but also the long-term drying trend over SWWA in early winter. The well-coupled SWAC–SWWA rainfall relationship seems to be largely independent of the well-known effects of large-scale atmospheric circulations such as the southern annular mode (SAM), El Niño–Southern Oscillation (ENSO), Indian Ocean dipole (IOD), and ENSO Modoki (EM). The result offers qualified support for the argument that the monsoon-like circulation may contribute to the rainfall decline in early winter over SWWA. The external forcing of the SWAC is also explored in this study.

1. Introduction

Rainfall in Australia shows a very high variability (Drosdowsky 1993; Murphy and Ribbe 2004). Southern Australia (30°S southward) receives the bulk of its annual rainfall during the winter half of the year (May–October). Rainfall in southern Australia during the winter months from June to August (JJA) is largely controlled by large-scale atmospheric circulation patterns, as opposed to convective dominated systems that dominate regions to the north in summer (Smith et al. 2008). Cai and Watterson (2002) indicated that rainfall over southwest Western Australia (SWWA; Fig. 1) tends to decrease as a result of decreased westerly winds, which bring less...
Analyses from Pittock and Allan (1990) have suggested that the large-scale, ocean–atmosphere circulation patterns are more likely to be the predominant influence on SWWA rainfall than more localized warming effects from the poleward-flowing, near-coastal Leeuwin Current. The winter patterns include incursions of cold air outbreaks from higher latitudes associated with depressions originating in the Indian Ocean or Southern Ocean (Simmonds and Richter 2000; Ashcroft et al. 2009). On the other hand, the persistence of anticyclones is associated with relatively dry conditions. Variability of winter rainfall over the SWWA is strongly linked to the relative strength and location of these patterns, which affect wind strength and direction (Sturman and Tapper 1996). The annual cycle of heavy winter rainfall and low summer rainfall is the result of the annual cycle of the planetary winds in SWWA (IOCI 2002). Hope et al. (2006) pointed out that large-scale circulation changes have contributed to the variations of the winter SWWA rainfall. These results support that the regional rainfall over SWWA may be associated with the variability of large-scale circulations.

Winter rainfall in SWWA has decreased substantially since the mid-twentieth century (IOCI 2002). The average winter (May–October) rainfall sharply and suddenly decreased in the mid-1970s by about 15%–20% (Fig. 2 in IOCI 2002), which causes a 50% decrease in dam inflow as a result. The portion of this decrease has been confined to the early winter (May–July) rainfall, whereas rainfall later in the season (August–October) has increased (Fig. 3 in IOCI 2002). There has been vigorous debate as to what caused the drying trend: that is, whether it is part of multidecadal variability or driven by secular forcing such as increasing atmospheric CO$_2$ concentration (Cai and Watterson 2002). Rainfall variations associated with the southern annular mode (SAM; Thompson and Wallace 2000) have been suggested by various studies (e.g., Silvestri and Vera 2003; Reason and Rouault 2005; Haylock et al. 2006; Cai and Cowan 2006); particularly, the decreased SWWA rainfall in June–August manifests as a reduction in high-intensity rainfall events has been attributed to the high polarity of the SAM since the late 1960s (e.g., Ansell et al. 2000; Cai et al. 2005; Li et al. 2005). However, Hendon et al. (2007) noted that there is little evidence that the SAM has contributed to seasonal precipitation changed over Australia, except the summer season during the past 25 yr (1979–2004). These studies imply that the relationship between the SAM and SWWA winter rainfall is still a contentious issue, because it appears that the relationship between the SAM and SWWA winter rainfall depends on various study periods.

The other well-known large-scale circulations such as the Indian Ocean dipole (IOD; Saji et al. 1999), El Niño–Southern Oscillation (ENSO), and ENSO Modoki (EM; Ashok et al. 2007a) may also have relations with the SWWA rainfall. For instance, the rather sudden drop in SWWA early winter rainfall in the mid-to-late 1970s was accompanied by a similarly sudden increase in atmospheric pressure and a drop in the Southern Oscillation index (SOI; Allan and Haylock 1993; Smith et al. 2000), but SWWA winter rainfall has no significant links with the SOI, except in late winter (correlation = 0.45) during 1979–2006. The IOD has been shown to have significant negative correlations with rainfall over western regions of Australia in June–September, when the IOD is in its
Table 1. Correlations between raw (detrended) time series of the SWWA rainfall and various indices in early and late winter seasons in 1948–2006, 1948–78, and 1979–2006, respectively.

<table>
<thead>
<tr>
<th>Period</th>
<th>Season</th>
<th>SWAC</th>
<th>SAM</th>
<th>Niño-3</th>
<th>IOD</th>
<th>EM</th>
</tr>
</thead>
<tbody>
<tr>
<td>1948–2006</td>
<td>MJJ</td>
<td>0.75*</td>
<td>−0.36* (−0.25)</td>
<td>−0.28* (−0.24)</td>
<td>−0.06 (−0.11)</td>
<td>−0.02 (−0.06)</td>
</tr>
<tr>
<td></td>
<td>ASO</td>
<td>0.68*</td>
<td>−0.18 (−0.22)</td>
<td>−0.20 (−0.21)</td>
<td>−0.17 (−0.17)</td>
<td>−0.21 (−0.21)</td>
</tr>
<tr>
<td></td>
<td>May–October</td>
<td>0.73* (0.73)*</td>
<td>−0.32* (−0.24)</td>
<td>−0.38* (−0.35)*</td>
<td>−0.20 (−0.22)</td>
<td>−0.18 (−0.21)</td>
</tr>
<tr>
<td>1948–78</td>
<td>MJJ</td>
<td>0.80* (0.78)*</td>
<td>−0.26 (−0.16)</td>
<td>−0.20 (−0.12)</td>
<td>−0.09 (−0.05)</td>
<td>0.01 (−0.07)</td>
</tr>
<tr>
<td></td>
<td>ASO</td>
<td>0.76* (0.79)*</td>
<td>−0.34 (−0.39)*</td>
<td>−0.10 (−0.14)</td>
<td>0.02 (−0.01)</td>
<td>−0.08 (−0.18)</td>
</tr>
<tr>
<td></td>
<td>May–October</td>
<td>0.80* (0.81)*</td>
<td>−0.29 (−0.31)</td>
<td>−0.27 (−0.22)</td>
<td>−0.09 (−0.06)</td>
<td>−0.06 (−0.11)</td>
</tr>
<tr>
<td>1979–2006</td>
<td>MJJ</td>
<td>0.64* (0.65)*</td>
<td>−0.28 (−0.25)</td>
<td>−0.27 (−0.29)</td>
<td>−0.16 (−0.18)</td>
<td>−0.14 (−0.12)</td>
</tr>
<tr>
<td></td>
<td>ASO</td>
<td>0.52* (0.55)*</td>
<td>0.13 (0.09)</td>
<td>−0.41* (−0.42)*</td>
<td>−0.59* (−0.61)*</td>
<td>−0.45* (−0.53)*</td>
</tr>
<tr>
<td></td>
<td>May–October</td>
<td>0.66* (0.66)*</td>
<td>−0.16 (−0.17)</td>
<td>−0.43* (−0.43)*</td>
<td>−0.42* (−0.42)*</td>
<td>−0.35 (−0.36)</td>
</tr>
</tbody>
</table>

* Significant correlation at the 0.05 level.

mature phase (Ashok et al. 2003). Later, England et al. (2006) showed that the IOD and SWWA rainfall are out of phase based on the annual rainfall rather than winter season. However, we will see (Table 1) that the IOD–SWWA rainfall relationship is only significant in late winter after 1979. Likewise, the EM only influences the SWWA rainfall in late winter after 1979 (Table 1), which is consistent with the known result that the EM occurs mainly after the late 1970s (Ashok et al. 2007a; Weng et al. 2007). Therefore, the well-known large-scale circulations (IOD, ENSO, and EM) have only influenced the late winter rainfall since the late 1970s; that is, they cannot explain the reduction of early winter rainfall over SWWA. Then, what causes the reduction of SWWA early winter rainfall still remains as an unsolved question.

These considerations provide us a background to investigate the existence of other circulations that may influence the winter rainfall in SWWA, with an aim to explain early winter rainfall decline in SWWA since the middle of the twentieth century. The structure of this paper is arranged as follows: Section 2 gives a short description of the methods and datasets that we have used. Section 3 demonstrates the existence of a monsoon-like southwest Australian circulation (SWAC). The seasonal evolution of the SWAC is described in section 4. The correlation between winter rainfall and the SWAC are studied in section 5. The influence of large-scale circulations on the SWAC–SWWA rainfall relationship is given in section 6. Possible drivers of the winter SWAC are given in section 7, with conclusions and discussion in section 8.

2. Data and methodology

The SWWA comprises the southwest corner of Western Australia bounded by the line joining 30°S, 115°E and 35°S, 120°E (Fig. 1). The winter period is from May to October (extended winter; e.g., IOCI 2002; Saji et al. 2005; Ashok et al. 2007b), early winter is from May to July (MJJ), and late winter is from August to October (ASO).

The rainfall data analyzed here were provided by the National Climate Centre of the Australian Bureau of Meteorology and consist of gridded data on a 0.25° × 0.25° grid. These are described by Lo et al. (2007), who indicate their confidence in the validity of the data after 1948. In addition, pentad mean rainfall data (Xie and Arkin 1997) from the Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP) are employed for the analysis of seasonal march of winter SWAC.

The primary data analyzed for other atmospheric fields were extracted from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis on a 2.5° × 2.5° grid (Kalnay et al. 1996). The 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40) data (Uppala et al. 2005) are employed as a comparison to verify results obtained from the NCEP–NCAR reanalysis data. The climatology state is averaged from 1961 to 2000, which is the period of record for both NCEP–NCAR reanalysis and ERA-40 datasets. Sea surface temperature (SST) data used in this study are the improved extended reconstruction SST (IERSST; Smith and Reynolds 2004) on a 2° × 2° grid. The Niño-3 index used for canonical ENSO phenomena (Rasmusson and Carpenter 1982) is available online (at http://www.cpc.noaa.gov/data/indices/) and the SAM index (SAMi) is defined as the difference in the normalized monthly zonal-mean sea level pressure (SLP) between 40° and 70°S (Nan and Li 2003). This SAMi is a modification of the SAMi defined by Gong and Wang (1999), which is the difference in the normalized zonal-mean SLP between 40° and 65°S. The IOD index (IODi; Saji et al. 1999) is available online (at http://www.jamstec.go.jp/frce/research/d1/iod/), and the EM index (EMi) is defined following Ashok et al. (2007a).
Correlation and composite analyses are employed to investigate the relationship between the winter SWAC and SWWA winter rainfall. Particularly, partial correlation method (e.g., Johnston 1980; Nicholls 1989; Ashok et al. 2003), which is often used to find correlation between two variables after removing the effects of another variable, is imported to describe the relationship between the winter SWAC and rainfall by taking away the effects of other large-scale circulations such as the SAM and ENSO. Furthermore, the multiple linear regression analysis is employed to check the influences of the SWAC, SAM, IOD, EM, and ENSO on the SWWA rainfall, respectively.

A unified dynamic normalized seasonality (DNS) monsoon index introduced by Li and Zeng (2000, 2002, 2003, 2005) is applied to delineate the magnitude and variability of the SWAC. This index is based on intensity of the seasonality of wind field, and it can be used to depict the seasonal cycle and interannual variability of monsoon over different areas. Given a pressure level and a grid point \((i, j)\), the DNS index in the \(m\)th month of the \(n\)th year [e.g., \(m\) is a month from winter months (May–October), and \(n\) is a year from 1948 to 2006] is given by

\[
\delta_{mn}(i, j) = \frac{\|V_1(i, j) - V_{nm}(i, j)\|}{\|V(i, j)\|} - 2, \tag{1}
\]

where \(V_1(i, j)\) (m \(s^{-1}\)) is the January climatology (averaged from 1968 to 1996 as the reference state) wind vector and \(V_{nm}(i, j)\) (m \(s^{-1}\)) is the wind vectors at grid point \((i, j)\) in the \(m\)th month of the \(n\)th year. Here, \(V(i, j)\) (m \(s^{-1}\)) is the mean of January and July climatology wind vectors (averaged from 1968 to 1996) at grid point \((i, j)\). The norm \(\|A\|\) is defined as \(\|A\| = \sqrt{\int \int \|A\|^2 dS}\), where \(S\) denotes the domain of integration. At a given grid point \((i, j)\),

\[
\|A_{i,j}\| \sim \Delta x \left[ (A_{i-1,j}^2 + 4|A_{i,j}^2| + |A_{i+1,j}^2|) \cos \phi_j 
\quad + |A_{i,j-1}^2| \cos \phi_{j-1} + |A_{i,j+1}^2| \cos \phi_{j+1} \right]^{1/2},
\]

where \(\phi_j\) is the latitude at the point \((i, j)\) and \(\Delta x = a \Delta \phi \Delta \lambda / 4\); \(a\) is the mean radius of the earth; and \(\Delta \phi\) and \(\Delta \lambda\) (in radians) are resolutions in the meridional and zonal directions, respectively. Here, January and July are chosen as the representation of winter [Northern Hemisphere (NH)]/summer [Southern Hemisphere (SH)] and summer (NH)/winter (SH), respectively (Zeng and Zhang 1998). Thus, the denominator in Eq. (1) could be considered as the annual mean winds or the average of the summer and winter winds, because the differences between the annual mean and the average between summer and winter are minor (Zeng 1994). Because it is winter-time we paid attention to, \(V_1(i, j)\) in the numerator is the opposite season relative to winter, which is taken as the reference state, then the numerator shows the amplitude of the seasonality of the wind vectors \(V_{nm}(i, j)\) related to the reference state. A value of 2 is subtracted in the right-hand side of the formula, because it is the critical value of significance of the quantity. The case when \(\delta_{mn}(i, j) > 0\) means that the prevailing wind direction shifts by at least 90° between winter and summer (Li and Zeng 2000).

Having obtained the DNS index \(\delta_{mn}(i, j)\) at a grid point \((i, j)\), we can define a large-scale monsoon index \(MI_{mn}\) in the \(m\)th month of the \(n\)th year as a measure of the averaged DNS over a monsoon domain given by

\[
MI_{mn} = \{\delta_{mn}(i, j)\}, \tag{2}
\]

where \(\{\cdot\}\) denotes the areal average of \(\delta\) values at grid points within a chosen monsoon domain at a certain pressure level. See more details on the physical definition from Li and Zeng (2000, 2002).

3. Existence of a monsoon-like SWAC

SWWA is located in the midlatitudes, and its climate is dominated by the subtropical high belt, which moves north and south with seasonal march. The high belt moves south during summer and reaches its southernmost extent in January or February. During autumn, it gradually moves toward the north and lies almost outside of southwest Australia during the winter months (Gentilli 1972). The rainfall in SWWA shows an obvious seasonality, with the majority falling in winter and with little in summer (IOCI 2002). This motivates us to hypothesize that SWWA rainfall variability may connect the impact of a monsoon-like circulation over wider southwest Australia (SWAC). Our hypothesis on the existence of the SWAC will be considered from three distinct features characterizing a monsoonal circulation: alternate wet and dry seasons, seasonal reversal of winds, and thermal contrast between land and sea.

a. Comparison of dry and wet seasons

Wright (1997) notes that over 80% of the annual rainfall in South Australia falls in the winter period. Figure 1 shows the climatology of the rainfall distribution of January and July having subtracted the annual mean from 1948 to 2006. In July (Fig. 1b), the negative departure is over different areas. Given a pressure level and a grid point (i, j), the DNS index in the mth month of the nth year [e.g., m is a month from winter months (May–October), and n is a year from 1948 to 2006] is given by
can be found in January (Fig. 1a) but with a contrary positive and negative distribution and a slightly south-westward boundary for the zero contour over SWWA. This analysis shows that SWWA receives a large amount rainfall in winter but a small quantity in summer. The alternating of wet and dry seasons in SWWA is the first evidence for the existence of the SWAC.

**b. Circulation systems**

Figure 2 shows the climatology of January and July winds at 925 hPa. In January (summer), there is an anticyclone centered round 32°S, 85°E (Fig. 2a). The whole SWWA is under the influences of southeasterlies, and the ridge of subtropical high lies to the south of 35°S. In July (winter), the situation is reversed (Fig. 2b). The predominant wind over SWWA changes into north-westerlies, and the high pressure ridge jumps to north of 30°S. The flow direction in SWWA is clearly reversed with the seasonal march: there is a strong subsidence in January over SWWA (Fig. 2c) but a rising flow in July (Fig. 2d). To see the seasonal variation more clearly, the seasonal evolution of areal zonal and meridional winds, zonal vapor transportation and air temperature, and vertical shearing of zonal wind averaged over most parts of southern Australia (considering all show similar rainfall distribution), as well as the vertical velocity over SWWA (35°–30°S, 112.5°–117.5°E; the vertical velocity is a more local signal), are shown in Fig. 3. The filled bars are for ERA-40, and the blank bars are based on NCEP–NCAR. Figure 3 shows that the annual cycle of these studied fields are consistent for the two reanalysis datasets. It is evident that the zonal and meridional winds, zonal vapor transportation, and vertical velocity over SWWA all have a reversal change during the annual cycle. In January SWWA comes a hot and dry summer under the influence of easterlies and southerlies associated with a strong downward vertical velocity, high air temperature, and low vertical shearing of zonal wind. In July, when the high pressure systems move north, SWWA is under the influence of westerlies and northerlies, accompanying ascending flow, low air temperature, and large vertical shearing (Figs. 2, 3) and leading to a cool, wet winter. Taking account of monthly rainfall evolution (not shown) with the wind changes, it could be found that rainfall increase in May is accompanied by the occurrence of northerlies (signal from the tropics), which

![Figure 2](image-url)
bring water vapor to drive the rainy season. This indicates that there is a circulation system with a strong seasonal variation controlling the climate in SWWA. The circulations in summer and winter have distinct features (e.g., reversal winds), which is another important aspect of the existence of the monsoon-like SWAC.

c. **Thermal contrast**

From this analysis, we can see that both synoptic circulation and rainfall in SWWA bear a strong seasonality. Based on the annual cycle of the large-scale circulation shift in SWWA (Fig. 2), we choose the area 35°–25°S, 70°–130°E as the domain to demonstrate the time evolution of land surface air temperature (SAT) and SST. From Fig. 4, it can be seen that the mean SAT has a strong seasonal variation: the maximum value could be beyond 25.0°C in January, but in July it reaches the minimum of around 12.0°C. Compared to radical changes in SAT, SST is much more stable around the year associated with a small change in amplitude, reaching the maximum (21.9°C) in February and minimum (16.9°C) in September. The difference between SAT and SST (SAT − SST) also has a strong seasonal variability, being positive in summer (DJF) around 4.0°C. The difference decreases with time and transfers into the negative phase in April, reaching the minimum in June, which is below −5.0°C. Then, the difference gradually returns to positive in October, which is consistent with the end of the rainy season. The difference between land and sea has an obvious change not only in magnitude but also in the temperature gradient. In January, the temperature gradient points to the ocean, accompanied by easterly winds; in July, the situation is opposite, with the temperature gradient pointing toward land accompanied by rain-bearing westerly winds. Strong difference and the reversal thermal gradient between land and sea is the third proof of the presence of the SWAC.

**Fig. 3.** Annual cycle of areal (a) zonal wind (m s⁻¹), (b) meridional wind (m s⁻¹), (c) vertical velocity (P s⁻¹), (d) zonal vapor transportation (g kg⁻¹ m s⁻¹) and (e) air temperature (°C) at 925 hPa, and (f) the vertical shearing of zonal wind at 200 and 925 hPa (m s⁻¹). (c) is over 35°–30°S, 112.5°–117.5°E, and (a), (b), (d)–(f) are over 35°–25°S, 115°–145°E. The filled and blank bars are based on ERA-40 and NCEP–NCAR reanalysis data, respectively.
In summary, the SWWA climate displays strong seasonal variations with alternating wet and dry periods, seasonal reversal of wind, and heating contrast of land and sea over the wider southwest Australian region. These results suggest that the SWWA climate is influenced by a monsoon-like circulation (i.e., the SWAC) with properties resembling the characteristics of monsoonal systems (e.g., Tao and Chen 1957; Ramage 1971; Webster et al. 1998). However, the rainfall bulk and the corresponding background (e.g., there are usually the convective rainfall in tropical monsoon regions but not in SWWA) are different from the classical tropical monsoons. Therefore, the SWAC is a monsoon-like system because of its own characteristics different from the classical tropical monsoons.

Despite the aforementioned differences, the conception and measurement of monsoon strength may be reasonable to delineate the magnitude and variability of this monsoon-like SWAC system. Of particular interest is to investigate the influence of the SWAC on the rainfall variability over SWWA. In addition, because SWWA receives the bulk of its annual rainfall during wintertime, we will focus on the investigation of the winter SWAC and its linkage to SWWA winter rainfall in the rest of the sections.

### 4. Seasonal march of the winter SWAC

In this section, we demonstrate more details of the winter SWAC and associated rainfall variability over SWWA. Pentad zonal and meridional winds are utilized to compute the pentad SWAC index (SWACI) by using the previous index [Eq. (1)]; here, the \( V_{\text{nn}}(i, j) \) is replaced with pentad mean winds, then the pentad variation of the \( \delta \) could be obtained. The pentad time series of the SWACI and SWWA rainfall series (as shown in Fig. 5a) are highly correlated with a correlation coefficient of 0.83 (there are 73 pentads in the two series).

This implies that the pentad rainfall variation over SWWA is closely linked with the variation of the SWAC.

Figure 5a shows that SWWA rainfall starts to rise from April to mid-May and then maintains until the start of July when rainfall exhibits an abrupt decrease. Rainfall then shows an increase and returns to the prior amount which lasts for about 10 days in July before decreasing again. In view of the monsoon-like SWAC and taking account of the evolution of other monsoon systems (e.g., Zhou and Lau 1998; Wu and Wang 2001; Wang and Lin 2002; Ding and Chan 2005), we may characterize the march of the winter SWAC into six phases: preonset (pentad 25–28), active (pentad 29–36), break (pentad 37–39), revival (pentad 40–41), decay (pentad 42–45), and die out (pentad 46–52) of the SWAC, respectively.

Figure 5b suggests that from the end of April (pentad 25) to mid-May (pentad 28), corresponding to the preonset phase, the rain belt gradually moves northward from the Southern Ocean to Australia. In pentad 29, the rainband has a steep north jump, reaching the northernmost position. From this time to pentad 36 (active phase), the rain belt is relatively stable between 35° and 30°S. The passage of the rain belt is followed by a break spell, which is also captured in the rainfall variations. The break phase
is short, with a half-month duration. A rainfall revival phase (about 10 days) is clearly observed after the break phase. Starting from pentad 42, the decay phase occurs and remains until early August when the rain belt returns to the Southern Ocean with significantly fluctuations approaching SWWA coast. The whole SWAC rainfall enters to a die-out phase and retreats to the Southern Ocean after pentad 46.

The composite differences of precipitation and winds at 850 hPa between two successive phases are given in Figs. 6 and 7, respectively. The phase difference (active minus preonset) of wind shows strengthened anomalous westerlies over SWWA and its adjacent coast (Fig. 7a), corresponding to significantly increased rainfall over SWWA (Fig. 6a). From active to break phase, there is an anomalous anticyclone over SWWA (Fig. 7b), accompanied by anomalous easterlies and causing a significant rainfall decrease over most SWWA inland northward of 34.5°S (Fig. 6b). From break to revival phase, the anomaly anticyclone is replaced with a cyclone (Fig. 7c). Associated with this, SWWA receives significant increased rainfall along the west coast (Fig. 6c). After

![Fig. 6. Phase differences of rainfall (mm day$^{-1}$): (a) active minus preonset, (b) break minus active, (c) revival minus break, (d) decay minus revival, and (e) die out minus decay.](image-url)
revival phase, the SWAC moves to its decay phase and then to die-out phase, an anomaly anticyclone is along the west coast of the southwest Australia, and SWWA is under anomalous southeasterlies (Fig. 7d); then, this anticyclone moves toward south and lies on the Southern Ocean, centered about 140°E, 50°S, in the last two phase differences (Fig. 7e), with rainfall amount decline continuously in these two phases (Figs. 6d,e). This implies that rainfall in SWWA is largely affected by the winter SWAC evolution.

These analyses show that the rain belt has an obvious northward leap and a gradual retreat during the seasonal
march. To further observe the accompanying atmospheric circulation evolutions, the ridge of subtropical high at SLP is shown in Fig. 7f. We can see that the ridge moves northward with time: before the active phase, it locates south of 30°S, and then it has an evident northward jump reaching north of 30°S in the active phase. Afterward, it turns over the direction of motion and moves southward in the break phase. Subsequently, the ridge moves northward and reaches the northernmost position in the revival phase. In the next two phases, the ridge moves southward and returns back to south of 30°S in the longitude between 110°E and 120°E but slightly north compared to the preonset phase.

In summary, SWWA winter rainfall is associated with the march of the winter SWAC. Rainfall in May, June, and July corresponds to the period before the decay phase of SWAC. It is different from the period from August to September, which corresponds to the decay and die-out phases of the winter SWAC system.

5. Relationship between the SWAC and rainfall

We have shown that a monsoon-like system (SWAC) exists over the wider southwest Australian region and that the SWWA winter half-year (May–October) rainfall is associated with the march of the SWAC. In this section, we will develop a SWACI using the DNS monsoon index [Eq. (1)] to delineate the magnitude and variability of the winter SWAC. The relationship between the winter SWACI and SWWA winter rainfall is also investigated. The domain of the winter SWAC is chosen as 35°–25°S, 100°–145°E, and the 850-hPa pressure level is chosen to derive the winter SWACI.

a. The SWAC and rainfall in wet winter half-year

Using the index introduced by Eq. (1), we present the normalized time series of the SWACI in the winter half-year (May–October) over 1948–2006 (Fig. 8a). We can see that the winter SWAC is strongly linked to the SWWA winter rainfall, and the correlation coefficient between raw (detrended) time series of the winter SWACI and SWWA rainfall is 0.73 (0.73), which is significant at the 0.01 level (Table 1). Additionally, both the SWAC and SWWA winter rainfall undergo strong interannual and interdecadal variability. In the past 59 yr, both SWACI and SWWA winter rainfall have displayed similar decreasing trends (Fig. 8a). There are 30 yr in the negative phase and 9 yr below one negative standard deviation of the SWACI after 1965, corresponding to the period when winter SWWA rainfall has decreased since then (IOCI 2002). The correlation distribution between the winter Australian rainfall and winter SWACI (Fig. 8b) indicates a significant positive correlation over SWWA region. Hence, the SWAC has a positive influence on SWWA winter rainfall. When the winter SWAC is stronger (weaker), there will be more (less) winter rainfall in the SWWA.

To provide insight for the rainfall variations associated with the SWAC, we investigate the changes in the lower-tropospheric flow in the Australian region by the composite difference map of wind and geopotential height at 850 hPa for the strong (high polarities of the SWACI that are larger than +1 standard deviation) minus weak (low polarities of the SWACI that are less than −1 standard deviation) SWAC years (Fig. 8c). The strong and weak index polarities of the SWACI have opposite sign as well as the identical climatic impacts. Thus, in the following discussion, we will refer to the strong minus weak composite differences as anomalous conditions during the strong polarity of the SWAC; similarly anomalous conditions associated with weak SWAC can be approximated as the reversal situation of the strong minus weak. Here, the strong minus weak index composite map corresponds to conditions associated with a roughly two standard deviation change in the SWACI.

There exist distinguish differences for the strong minus weak SWAC years. It is evident that there is an anomaly cyclone centered about 42°S, 110°E. There are anomalous westerlies over north of 42°S, and the strongest anomalous westerlies appear around 32°S. The differences in geopotential height are negative at midlatitudes (about north of 50°S, from 60°E eastward to 180°E) and positive at high latitudes (south of about 55°S). Moreover, the correlation between the winter SWACI and geopotential height at 850 hPa presents a significant negative correlation over the southern Indian Ocean and stretched across southern Australia, whereas there is a significant positive area at high latitudes. These results suggest that the influence of winter SWAC could reach to high latitudes, which implies a link to the SAM. Indeed, the correlation between the time series of the raw (detrended) SWACI and SAMI is −0.44 (−0.48), which is significant at the 0.05 level in the winter half-year during the period from 1948 to 2006.

b. The SWAC and rainfall in early and late winter

IOCI (2002) reported that the portion of the decreased rainfall over SWWA has been confined to early winter, whereas rainfall in late winter has slightly increased. In this section, we investigate the influence of the SWAC on the reduction of early winter rainfall and the weak increase of late winter rainfall in SWWA.

In early winter from 1948 to 2006, the SWACI has a strong link to the SWWA rainfall with a significant correlation 0.75 (0.74 for the detrended series) at the 0.01 level (Figs. 9a, 10a and Table 1). Moreover, there are same
significant downward linear trends in both SWACI and SWWA rainfall series (trend correlation $r = -0.28$ for MJJ rainfall and $r = -0.26$ for the MJJ SWACI; Fig. 9a). These results suggest that the early winter SWAC cannot only explain the interannual variability of the early winter rainfall but also the long-term decreasing trend. In late winter, there is a positive correlation between the SWACI and the SWWA rainfall, with a significant coefficient 0.68 (for both raw and detrended series) at the 0.01 level (Figs. 9b, 10b), and both series share a similar faint increase (trend correlation $r = 0.01$ for the ASO SWWA rainfall and $r = 0.08$ for the ASO SWACI; Fig. 9b). Therefore, the non-significant upward trend of SWWA rainfall in late winter could be attributed to the parallel trend in the SWACI over the past decades.

### c. The SWAC and rainfall in pre-1979 and post-1979

These results on the SWAC–SWWA rainfall relationship are obtained based on data from 1948 to 2006. Some studies indicated the poor quality of the Southern Hemisphere reanalysis data (Trenberth et al. 2001; Kistler et al. 2001) and recommended that the data after 1979 (postsatellite) are more reliable. To check the quality of the NCEP–NCAR data, we have recalculated the SWACI using the ERA-40 (1958–2001) data. It can be found that the SWACI calculated based on the two different reanalysis datasets are highly correlated with each other (not shown): the correlation coefficients are 0.87, 0.93, and 0.88 during MJJ, ASO, and MJJASO, respectively. This suggests that the SWACI based on the NCEP–NCAR reanalysis data is consistent with the one using ERA-40 data during the period 1958–2001, which allows us to have confidence of the SWACI calculated using the NCEP–NCAR reanalysis data before 1979.

Also, we have stratified the whole study period (1948–2006) into two subperiods (1948–78, the prior-satellite era, and 1979–2006, the postsatellite era) to evaluate the robustness of the relationship between the SWAC and SWWA winter rainfall. Results indicate that the
relationship between the SWACI and SWWA winter rainfall is significant at the 0.01 level for any seasons (MJJ, ASO, and MJJASO) in the two subperiods (Table 1). Therefore, the relationship between the SWAC and SWWA winter rainfall is well coupled and does not depend on the study period. In contrast, the robustness of the correlation does not exist between SWWA winter rainfall and each of the other well-known large-scale circulations (SAM, ENSO, IOD, and EM). The relationship between SAMI and SWWA winter rainfall is not significant in both subperiods, except the one in ASO during 1948–78, whereas correlations between SWWA rainfall and Niño-3 index, IODI, and EMI appear to be significant only in late winter after 1979 (Table 1).

6. The impacts of large-scale circulations on the SWAC–SWWA winter rainfall relationship

As shown in section 1, Australian winter rainfall has been affected by well-known large-scale circulations, including SAM, ENSO, IOD, and EM. All those previous studies raise one issue: the relationship between the SWAC and SWWA winter rainfall need further consideration. That is, the impacts from the known large-scale circulations on the well-coupled SWAC–SWWA winter rainfall relationship developed in the previous section should be taken into account considering that the SWWA winter rainfall is linked with other large-scale circulations.

a. Impacts in 1948–2006

In early winter during 1948–2006, both the SWAC and SWWA rainfall are correlated with SAM and ENSO but not with IOD and EM in 1948–2006 (Table 1). It is possible that the correlations between SWWA rainfall and the SWAC examined before may not imply a direct relationship but rather that both SWWA rainfall and SWAC are influenced by the SAM and ENSO. To check impacts of the SAM and ENSO on the SWAC–SWWA rainfall relationship in early winter, we have computed partial correlations between the SWAC and SWWA early winter rainfall after removing the effects of the ENSO and SAM, respectively (Fig. 10). Results show that there are little changes in the SWAC–SWWA rainfall relationship in early winter when the effect of ENSO is removed from SWAC and rainfall (Fig. 10c versus Fig. 10a). This suggests that the relationship of SWAC–SWWA rainfall is linearly independent of the impact of ENSO in early winter. The partial correlations between the SWAC and

Fig. 9. As in Fig. 8a, but for (a) early and (b) late winter. The corresponding trend correlations of the SWWA rainfall and SWACI are (a) $-0.28$ and $-0.26$ (both significant at the 0.05 level) and (b) 0.01 and 0.08, respectively.
SWWA early winter rainfall after removing the SAM
effect also show similar patterns to the total correlations in
early winter (Fig. 10e versus Fig. 10a), indicating that the
SWAC–SWWA rainfall relationship is not heavily con-
taminated by the SAM in early winter. However, this does
not necessarily imply that we can separate the contribu-
tions of ENSO and SAM to the early winter rainfall var-
ations in SWWA. Noting that the SWAC and rainfall are
not correlated with the IOD and EM in early winter
(Table 1), our partial correlation results after removing

Fig. 10. As in Fig. 8b, but for (a) early and (b) late winter. (c),(d) As in (a),(b), but for partial correlation map, after
removal the effect of the Niño-3 index. (e),(f) As in (a),(b), but for partial correlation map, after removing the effect
of the SAMI.
the effects of IOD and EM (not shown) also confirm that the SWAC–SWWA rainfall relationship is not contaminated by the impact of IOD and EM in 1948–2006.

In late winter (ASO) during 1948–2006, the SWAC is not significantly correlated with other larger-scale circulations (Table 1), implying that the relationship between the SWAC and SWWA rainfall in late winter is not influenced by other larger-scale circulations, including ENSO (Fig. 10d versus Fig. 10b), SAM (Fig. 10e versus Fig. 10b), IOD, and EM (not shown). Moreover, we have applied multiple linear regressions to model the relationship of SWWA rainfall average with the SWAC, SAM, ENSO, IOD, and EM indices in early and late winter (Table 2). Results in Table 2 indicate that the model containing a constant and the SWACI (i.e., models MJJ-I and ASO-I) appears to be better than other models, according to both a hypothesis test at the 0.05 level and the Akaike information criterion (AIC). For example, there is 56.9% explained variance of SWWA rainfall in early winter via the MJJ-I model,

\[
\text{Rain}(t) = 101 + 16.4 \times \text{SWACI}(t),
\]

and 45.6% variance in late winter via the ASO-I model,

\[
\text{Rain}(t) = 65.4 + 10.5 \times \text{SWACI}(t).
\]

Regression model performance is not enhanced by adding other indices (i.e., they only minimally increase explained variance from 56.9% to 60.0% for early winter and from 45.6% to 47.7% for late winter, and it has negligible effects on AIC). Further, estimated coefficients of the SAM, IOD, Niño-3, and EM indices in regression models (MJJ-II–V and ASO-II–V) are not significant at the 0.05 level because of their associated large standard errors. These results further demonstrate that the modeled SWAC–SWWA rainfall relationship is not influenced by involving the SAM, IOD, Niño-3, and EM indices, implying that the SAM, IOD, ENSO, and EM have negligible effects on the relationship between the SWAC and SWWA rainfall in both early and late winter during 1948–2006.

The large independence of the SWAC–SWWA winter rainfall relationship from SLP and 850-hPa wind fields has been further examined by the composite analyses of strong minus weak SWAC years after excluding the years of high (larger than 1 standard deviation) and low (less than −1 standard deviation) polarities of the large-scale circulation years (i.e., in the non-SAM, non-IOD, non-ENSO, and non-EM years), respectively (Fig. 11). It could be found that both the anomalous cyclonic circulation and the strengthened westerlies that favor more rainfall over SWWA, are captured in both early and late winter (Figs. 11c–j versus Figs. 11a,b) in all composite situations. This result indicates that the circulation anomalies in SLP and 850-hPa wind fields associated with the SWAC are not the responses of the large-scale circulations, and it again supports that the relationship between the SWAC and SWWA winter rainfall is not largely contaminated by the impact of the SAM, IOD, ENSO, and EM.

\[\text{Rain}(t) = 101 + 16.4 \times \text{SWACI}(t),\]

and
\[\text{Rain}(t) = 65.4 + 10.5 \times \text{SWACI}(t).\]

\[\text{Rain}(t) = 101 + 16.4 \times \text{SWACI}(t),\]

and
\[\text{Rain}(t) = 65.4 + 10.5 \times \text{SWACI}(t).\]

**b. Impacts in 1979–2006**

It is well known that the ENSO has experienced an abrupt change or “regime shift” in the mid-1970s (e.g., Zhang et al. 1997) and that the EM occurs mainly after the late 1970s. Table 1 shows that the SWWA rainfall is only significantly correlated with the IODI, Niño-3 index, and EMI but not with the SAMI in late winter after 1979. So if all years (1948–2006) are clubbed, the impacts of the IOD, ENSO, and EM on the relationship between the SWAC–SWWA winter rainfall in different regimes may be masked out. To examine whether ENSO, IOD, and EM play roles in modulating the relationship between the SWAC–SWWA rainfall in late winter after 1979, we have computed the partial correlations between the SWAC and SWWA late winter rainfall after

**Table 2. Results of the multiple regression analysis of the relationship between SWWA rainfall and various normalized indices (1948–2006). Constant is the regression intercept. Standard errors are in parentheses.**

<table>
<thead>
<tr>
<th>Model</th>
<th>Constant</th>
<th>SWAC</th>
<th>SAM</th>
<th>IOD</th>
<th>EM</th>
<th>Niño-3</th>
<th>$R^2$</th>
<th>AIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>MJJ-I</td>
<td>101* (1.9)</td>
<td>16.4* (1.9)</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>0.569</td>
<td>317.8</td>
</tr>
<tr>
<td>MJJ-II</td>
<td>101* (1.9)</td>
<td>16.5* (2.2)</td>
<td>0.08 (2.2)</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>0.569</td>
<td>319.8</td>
</tr>
<tr>
<td>MJJ-III</td>
<td>101* (1.9)</td>
<td>16.6* (2.2)</td>
<td>0.2 (2.2)</td>
<td>0.8 (2.0)</td>
<td>—</td>
<td>—</td>
<td>0.570</td>
<td>321.6</td>
</tr>
<tr>
<td>MJJ-IV</td>
<td>101* (1.9)</td>
<td>16.7* (2.2)</td>
<td>−0.8 (2.3)</td>
<td>1.2 (1.9)</td>
<td>−3.5 (2.0)</td>
<td>—</td>
<td>0.594</td>
<td>320.3</td>
</tr>
<tr>
<td>MJJ-V</td>
<td>101* (1.9)</td>
<td>16.2* (2.3)</td>
<td>−1.0 (2.3)</td>
<td>1.7 (2.0)</td>
<td>−3.8 (2.0)</td>
<td>−1.8 (2.1)</td>
<td>0.600</td>
<td>321.5</td>
</tr>
<tr>
<td>ASO-I</td>
<td>65.4* (1.5)</td>
<td>10.5* (1.5)</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>0.456</td>
<td>291.4</td>
</tr>
<tr>
<td>ASO-II</td>
<td>65.4* (1.5)</td>
<td>11.2* (1.7)</td>
<td>1.9 (1.7)</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>0.468</td>
<td>292.1</td>
</tr>
<tr>
<td>ASO-III</td>
<td>65.4* (1.5)</td>
<td>11.5* (1.8)</td>
<td>2.0 (1.7)</td>
<td>0.7 (1.6)</td>
<td>—</td>
<td>—</td>
<td>0.470</td>
<td>293.9</td>
</tr>
<tr>
<td>ASO-IV</td>
<td>65.4* (1.5)</td>
<td>11.3* (1.8)</td>
<td>1.9 (1.7)</td>
<td>1.0 (1.7)</td>
<td>−1.0 (1.7)</td>
<td>—</td>
<td>0.474</td>
<td>295.4</td>
</tr>
<tr>
<td>ASO-V</td>
<td>65.3* (1.5)</td>
<td>11.2* (1.8)</td>
<td>1.8 (1.7)</td>
<td>1.4 (1.9)</td>
<td>−1.0 (1.7)</td>
<td>−1.0 (1.8)</td>
<td>0.477</td>
<td>297.1</td>
</tr>
</tbody>
</table>

* Significant correlation at the 0.05 level.
removing the effects of IOD, EM, and ENSO (Fig. 12), respectively. Results show that the structure of partial correlations (in SWWA region) between the SWAC and SWWA late winter rainfall after 1979 remains roughly unchanged by removing effects of ENSO, IOD, and EM. Similar results could be derived from the early winter and the impact from SAM (not shown). Therefore, the relationship between the SWAC and SWWA rainfall after 1979 is not heavily influenced by the SAM, ENSO, IOD, and EM. However, this does not necessarily imply that we can separate the contributions of the SAM, ENSO, IOD, and EM to the late winter rainfall variations in SWWA.

**FIG. 11.** Composite SLP and 850-hPa wind differences between high and low SWACI polarities during (a) early and (b) late winter. (c)–(j) As in (a),(b), but in (c),(d) non-SAM years; (e),(f) non-IOD years; (g),(h) non-EM years; and (i),(j) non-ENSO years. The areas shaded indicate significance at the 0.05 level.
This is particularly true during the late winter after 1979, because the impacts of ENSO, IOD, and EM on SWWA late winter rainfall are integrated together (as shown as significant correlations between SWWA late winter rainfall and each of these circulation indices in Table 1).

7. Possible drivers of the SWAC

The correlation analysis (Table 1) shows that neither the tropical Indo-Pacific phenomena (ENSO, IOD, and EM) nor SAM have a consistent role to play in the variation of the SWWA rainfall, because they decoupled from the rainfall either during periods 1948–78 or 1979–2006. Hence, they cannot cause the decadal trend in early winter rainfall over SWWA since the middle of the twentieth century. On the other hand, we have found that the winter SWAC is well coupled to the winter rainfall of SWWA (Fig. 9 and Table 1), and the SWAC–SWWA winter rainfall relationship is not heavily contaminated by any of them. The winter SWAC can explain not only the interannual variability of the winter rainfall but also the long-term decreasing trend in early winter rainfall over SWWA. As a result, we can investigate the external forcing of the SWAC to understand causes for the winter rainfall decline in SWWA.

We suggest two possible drivers of the SWAC. The first driver may be the shift of the planetary-scale thermal convection (Zeng and Li 2002) associating with the shift of the subtropical high (Fig. 2) resulted the reversal winds over SWWA from summer to winter. We have known that the strength of the SWAC is related to the location of subtropical high ridge: the stronger SWAC in early and late winter implies that the ridge of subtropical high locates to the north of the SWWA region (Figs. 13a,b) and brings more synoptic rainfall events impinging on this region. The averaged positions of subtropical high ridge from 1948 to 2006 are displayed in Figs. 13c,d. In early winter (Fig. 13c), the position of the subtropical
high ridge bears a clearly southward linear trend, which favors weak SWAC years and associates with less rainfall over SWWA, because the position of high ridge is significantly correlated with the SWACI in MJJ at the 0.01 level, with a correlation coefficient of 0.89. Thus, the southward shift of the high ridge may cause the weak SWAC and less rainfall over SWWA in early winter. However, in late winter, the position of the high ridge exhibits a slight northward linear trend (Fig. 13d), which corresponds to the strong SWAC years and is accompanied by more rainfall. The correlation coefficient between the position of the high ridge and the SWACI during late winter is 0.84, which is significant at the 0.01 level. Therefore, the insignificantly faint upward trend of SWAC in ASO is associated with the weak northward of the subtropical high ridge, slightly favoring rainfall increase over SWWA in late winter.

The second driver is the Indian Ocean SSTs westward of SWWA, which may provide another external forcing to the SWAC. It could be seen that there is a significant negative relationship between the SWACI and SSTs westward of SWWA over the Indian Ocean (Fig. 14), and the correlation pattern does not change much for the detrended data (not shown). Note that the location with high correlations between SSTs and the SWACI is similar to the location P2 of Fig. 5 in England et al. (2006), and previous results have shown that Indian Ocean SST in this region is indeed instrumental in forcing midlatitude rainfall changes over regions of Western Australia (Ummenhofer et al. 2008). Our results suggest that the warming (cooling) SSTs westward of SWWA over the Indian Ocean are associated with the weak (strong) SWAC, which as a result leads to negative (positive) rainfall anomalies over SWWA.

8. Conclusions and discussion

In this paper, we have analyzed the dynamic of SWWA seasonal cycle over the period 1948–2006. It is found that the climate in SWWA bears a strong seasonality in the annual cycle, which is influenced by a monsoon-like circulation SWAC over the wider SWWA.

A winter SWACI is introduced to describe the behaviors of the winter SWAC. It is found that SWWA winter rainfall has a significant positive correlation with the winter SWACI. The variation of the SWAC captures
not only the interannual variability of winter rainfall over SWWA but also the long-term decreasing trend in the early winter rainfall. We have conducted the partial correlation, regression, and composite analyses to show that the SWAC–SWWA rainfall relationship is not heavily contaminated by the impact of the known large-scale circulations including SAM, ENSO, IOD, and EM in both early and late winter or the responses of them. The result offers qualified support for the argument that the monsoon-like SWAC may contribute to the rainfall decline in early winter over SWWA.

With regard to the external forcing of the SWAC, we have suggested two possible drivers. The first driver may be the shift of the planetary-scale thermal convection (Zeng and Li 2002) associating with the shift of the subtropical high resulted in the reversal winds over SWWA. Recent study has shown that a consistent weakening and poleward expansion of the Hadley circulation is diagnosed in the climate change simulations of the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4; Lu et al. 2007). Associated with this is a poleward expansion of the subtropical dry zone. Hence, further investigation of the impact of the weakening and poleward expansion of the Hadley circulation on SWWA winter rainfall via its impact on the SWAC may be explored. Second, the Indian Ocean SSTs westward of SWWA may provide another external forcing to the SWAC. Recent research by Ummenhofer et al. (2008) showed that the Indian Ocean SST is indeed instrumental in forcing midlatitude rainfall changes over regions of Western Australia. The impact of the Indian Ocean SST westward of SWWA on the SWAC and then SWWA rainfall changes warrants further investigation.

Independent of this study, Ashcroft et al. (2009) have studied the synoptic climatology and hemispheric structure of cold events over southern Australia. These cold fronts may interact with the SWAC. However, the extent that the cold event outbreaks are incorporated into the SWAC and their relations; the interactions between the SWAC and SAM, IOD, and EM; and the possible roles ENSO, SAM, IOD, and EM play in the decadal variability of the SWAC are all beyond the scope of this study and need further work. Additionally, it appears that the SWAC system could extend its impact on rainfall over parts of southeastern Australia (Fig. 8b); because we have only focused on SWWA in this study, the influence of SWAC on rainfall variability over southeastern Australia, including Victoria, is left for future study.

The present study shows that the strength of SWAC is closely linked with the SWWA winter rainfall. Therefore, it is important that the SWAC provides a criterion against which the output of general circulation models (GCMs) can be assessed and that the sensitivity of the SWWA winter rainfall to climate change forcing can be assessed using GCM models. Further work will investigate the application of the SWAC–SWWA rainfall linkage to the sensitivity of SWWA winter rainfall to different forcing using an ensemble of GCM results. This appears to provide a useful “fingerprinting” technique for this particular aspect of climate change in this particular region. It is also imperative to develop forecasting techniques to predict the SWACI that, in turn, can be used in the prediction of seasonal rainfall over SWWA.

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