Is There a Relationship between the SAM and Southwest Western Australian Winter Rainfall?

JUAN FENG

State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, and College of Atmospheric Sciences, Lanzhou University, Lanzhou, China

JIANPING LI

State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China

YUN LI

CSIRO Mathematical and Information Sciences, Wembley, Western Australia, Australia

(Manuscript received 9 February 2010, in final form 5 August 2010)

ABSTRACT

Previous studies have raised the possibility that the recent decline in winter rainfall over southwest Western Australia (SWWA) is related to the concurrent upward trend in the southern annular mode (SAM). On the basis of an analysis of 60-yr (1948–2007) reanalysis and observed data, the authors suggest that the apparent inverse relationship between the SAM and SWWA winter rainfall (SWR) is caused by a single extreme year—1964. It is shown that both the negative and positive phases of the SAM have little impact on SWR in the case that data for 1964 are excluded from the analysis. In addition, for periods prior to and after 1964 in the case that data for 1964 are excluded, the apparent relationship between the SAM and SWR becomes insignificant, and the circulation anomalies with respect to SWR appear to be an SAM-like pattern for which the anomalies at high latitudes are not significant. The result indicates that the SAM does not significantly influence the winter rainfall over SWWA. Instead, the variation of SWR would be more closely linked to the variability in regional circulations.

1. Introduction

Southwest Western Australia (SWWA; Fig. 3) bounded to the southwest by the line joining 30°S, 115°E and 35°S, 120°E receives the bulk of its annual rainfall during the Southern Hemisphere (SH)'s winter half year (May–October). Since the middle of the twentieth century, the observed winter rainfall in the SWWA has decreased by about 15%–20% of the preceding 50-yr average (IOCI 2002). This reduction has resulted in an even sharper fall in streamflow in southwestern Australia, strongly influencing the availability of water resources in the state. The prominent mode of climatic variability across the SH is the southern annular mode (SAM; Thompson and Wallace 2000), which is characterized by approximately zonally symmetric, with pressure anomalies of one sign centered in the Antarctic and anomalies of the opposite sign centered about 40°–50°S. The mode has been increasing toward its high polarity since the late 1960s (e.g., Gong and Wang 1999; Marshall 2003; Visbeck 2009). Previous studies have suggested that the decreased SWWA winter [June–August (JJA)] rainfall (SWR) is related to the concurrent upward trend in the SAM (e.g., Ansell et al. 2000; Cai and Watterson 2002; Li et al. 2005; Cai and Cowan 2006; Meneghini et al. 2007). However, Hendon et al. (2007) noted that there was little evidence that the SAM contributed to the seasonal precipitation change over Australia during the past 25 years (1979–2004), except in summer. In addition, Feng et al. (2010) indicated that the relationship

Corresponding author address: Dr Jianping Li, State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, China.
E-mail: ljp@lasg.iap.ac.cn

DOI: 10.1175/2010JCLI3667.1

© 2010 American Meteorological Society

between the SAM and SWR depends on the period of analysis.

These previous studies suggest that the role of SAM in influencing SWR remains inconclusive, with some ambiguities remaining to be resolved. Thus, is there an inherent relationship between the SAM and SWR? If so, is the relationship stable? If not, what is the cause of the unstable relationship? A better understanding of these issues would assist future investigations of the variations in SWR. These considerations provide the motivation for the present study. The remainder of the paper is organized as follows: the datasets and method are described in section 2, the results are presented in section 3, a brief discussion is provided in section 4, and the main conclusions are presented in section 5.

2. Data and methodology

The data used in this study include high-resolution gridded rainfall with 0.25° × 0.25° resolution, provided by the Australian Bureau of Meteorology. These are described by Lo et al. (2007), who indicate their confidence in the validity of the data after 1948. The atmospheric fields are from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis (Kalnay et al. 1996). The SAM index (SAMI) used here is defined as the difference in the normalized monthly zonal mean sea level pressure (SLP) between 40° and 70°S (Nan and Li 2003), using the NCEP–NCAR reanalysis (available online at http://web.lasg.ac.cn/staff/ljp/Eindex.html). This SAMI is a modification of the Antarctic Oscillation (AAO) index defined by Gong and Wang (1999), which represents the difference in the normalized zonal mean SLP between 40° and 65°S. The modified SAMI is used because the negative correlation in the zonal mean SLP anomalies between 40° and 70°S is stronger than that between 40° and 65°S. In addition, the SAMI used here is strongly correlated with the SAM index, defined as the leading empirical orthogonal function (EOF) of SLP anomalies south of 20°S [referred to as ''SAMI_EOF'' by Thompson and Wallace (2000) and available online at http://jisao.washington.edu/data/aao/slp/], yielding a correlation coefficient of 0.96 for the period 1948–2007. Thus, the SAMI used in the present study is appropriate in terms of capturing the features of SAM. Moreover, two additional station-based SAM indices, from Marshall (2003; referred to as ''SAMI_M,'' available for 1957–2007) and Visbeck (2009; referred to as ''SAMI_V,'' available for 1948–2005), are employed to verify the reliability of the result based on the NCEP–NCAR SAMI.

Given that both the SAM and SWR show obvious linear trends, detrended correlation is employed to examine the relationship between the SAM and SWR using a sliding correlation. Moreover, the effect of autocorrelation is accounted for when calculating the statistical significance, following Santer et al. (2000).

3. Results

Temporal variations in the SAM and SWR can be seen from normalized time series of the SAMI and SWR (Fig. 1a). The correlation coefficient between the two series is −0.41 during 1948–2007 (Table 1), reflecting the fact that a recent significant decrease in SWR is associated with the strengthening of the SAM. Temporal variations in the relationship are further illustrated by a time evolution of detrended correlations using a 31-yr sliding window (Fig. 1b). Note that the relationship is robust before 1980 (as the central correlation year), after which an abrupt weakening occurs. This weakening in correlation in recent decades is statistically significant, as determined from bootstrap confidence limits. Also shown are sliding correlations between SWR and zonal averaged SLP at 40° and 70°S (the sign is reversed to facilitate a direct comparison) of the SAM branches (Fig. 1b). The correlations show abrupt drops in 1980, from significantly negative to insignificant for SLP at 40°S and from significantly positive to insignificant/negative for SLP at 70°S. This result indicates that the abrupt weakening in the SAM–SWR relationship occurs in both mid- and high-latitude SLP of the SAM.

To investigate the possible cause of temporal changes in the relationship between the SAM and SWR, the scatterplot of the SAMI versus SWR is shown in Fig. 2. The impacts of the positive and negative SAM phases are asymmetric. For the negative phase of SAM, the correlation between the SAMI and SWR is −0.49, exceeding the 0.05 level of significance. For the positive phase of SAM, in contrast, the impact is not significant, yielding a correlation coefficient of −0.02. Moreover, there exists an outlier (large red circle in Fig. 2) that diverges from others with rainfall of 540 mm compared with ~300 mm in the climatology, which equals 3 times the standard deviation in the SAMI. This outlier represents the data for the year 1964, which is the wettest winter over SWWA and the minimum value of SAMI during 1948–2007 (Fig. 1a). Moreover, the covariance between the SAMI and SWR in 1964 accounts for as much as 47% of the total covariance for 1948–2007 (Table 1), thereby demonstrating that 1964 was an extreme year.

When the correlation and linear fit are repeated while excluding the data for 1964 in the negative phase of the SAM, the SAM–SWR relationship breaks down and the correlation coefficient drops to −0.20 (not significant at the 0.1 level; Fig. 2). This result suggests that the significant

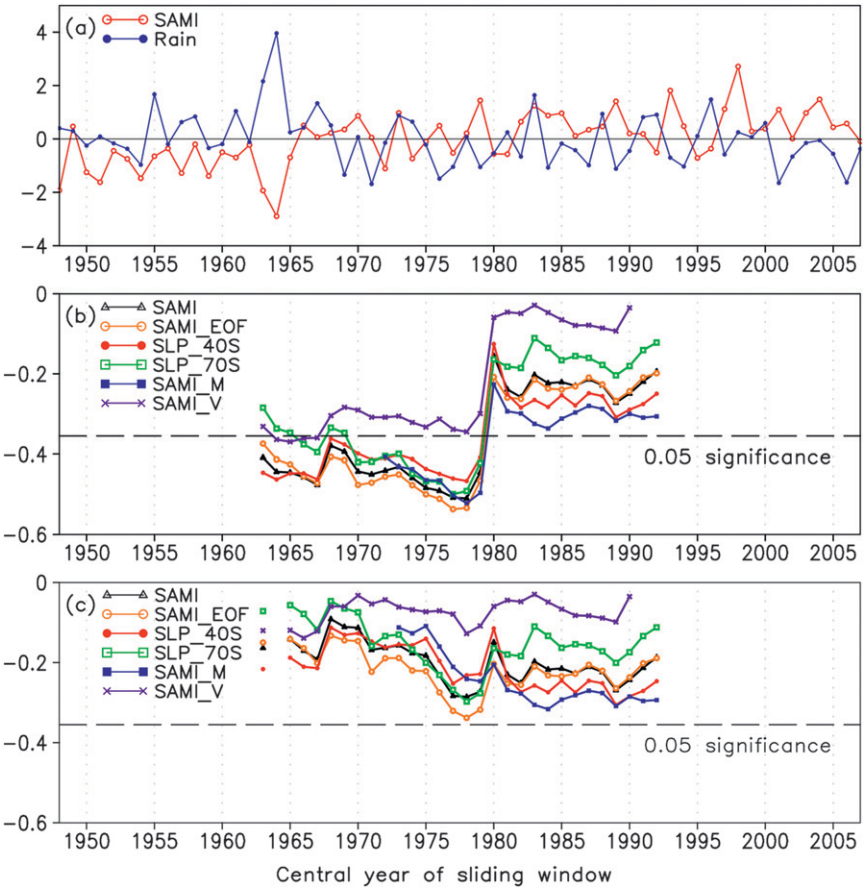

FIG. 1. (a) Normalized time series of the winter SAMI (red line) and SWWA winter rainfall (blue line). (b) Times series of detrended correlation coefficients using a 31-yr sliding window between SWR and each of winter SAMI (black line), SAMI_EOF (yellow line), zonal mean SLP at 40°S (red line), zonal mean SLP at 70°S (green line), SAMI_M (blue line), and SAMI_V (purple line). The sign of the relation between the zonal mean SLP at 70°S and SWR is reversed to enable a direct comparison with other data. (c) As in (b), but excluding the data for extreme year 1964.

relationship between the negative SAM phase and SWR is largely due to the extreme year 1964, implying that the SAM does not significantly influence SWR in both its positive and negative phases. This interpretation is corroborated by the fact that a correlation coefficient of −0.50 is obtained when using data up to and including 1964 (i.e., 1948–64; Table 1), yet this value drops to −0.11 in the case that the data for 1964 are excluded (i.e., 1948–63; Table 1), and is −0.27 with the addition of post-1964 data. Similarly, a correlation coefficient of −0.43 is obtained for the period 1964–2007, yet this drops to −0.16 in the case that data for the year 1964 are excluded (i.e., 1965–2007). These findings indicate that the apparently significant linkage between the SAM and SWR is dependent on the data for one year—1964. The disproportionate role played by data for 1964 in modulating the relationship between the SAM and SWR can be assessed by computing the covariance contribution (Table 1). The contribution of covariance in 1964 is more than 70% for the periods 1948–64 and 1964–2007 and is close to 50% for the period 1948–2007. The covariance in 1964 is 28 times the average covariance for 1948–2007.

In terms of the data in Fig. 1b, the above findings explain the abrupt weakening of the SAM–SWR relationship in the central correlation year 1980. In using a 31-yr sliding window, the central year 1980 corresponds to the period 1965–95, which is the first 31-yr sliding window to exclude 1964. To investigate this point in detail, the detrended sliding correlations between the SAMI and SWR using a 31-yr window are examined again, excluding the data for 1964 (Fig. 1c). In this case, the SAM–SWR relationship is not statistically significant for the entire study period. A similar result is obtained in an analysis of the relationship between SWR and SLP at 40°S or 70°S.

TABLE 1. Simultaneous correlation coefficients and their corresponding two-tailed P value (parentheses), averaged covariance (square brackets), and the ratio of covariance in 1964 to the total covariance in the corresponding period (brace) between SWR and each of the SAMI, zonal mean SLP at 40°S (SLP_40S) and 70°S (SLP_70S), SAMI_EOF, SAMI_M, and SAMI_V. The heading "–year" indicates the period leading up to and including the stated year; the heading "year–" indicates the period including and after the stated year. Significant correlation coefficients at the 0.05 level are marked in bold. The effects of autocorrelation were taken into account in calculating the statistical significance.

	–1964	–1963	1964–	1965–	Entire period
SAMI and SWR	**−0.50**(0.04)[−42.1]{83%}	−0.11(0.73)[−5.4]	**−0.43**(0.00)[−36.9]{73%}	−0.16(0.30)[−9.6]	**−0.41**(0.00)[−36.8]{47%}
SLP_{40S} and SWR	**−0.65**(0.01)[−42.5]{67%}	−0.35(0.21)[−12.9]	**−0.36**(0.02)[−22.0]{72%}	−0.13(0.41)[−5.9]	**−0.38**(0.00)[−21.3]{51%}
SLP_{70S} and SWR	0.22(0.43)[49.6]{127%}	−0.13(0.67)[−18.3]	**0.40**(0.01)[94.9]{72%}	0.15(0.36)[25.2]	**0.34**(0.01)[96.2]{43%}
SAMI_EOF and SWR	−0.39(0.13)[−19.3]{92%}	−0.02(0.95)[−0.05]	**−0.44**(0.00)[−23.7]{70%}	−0.18(0.26)[−6.8]	**−0.39**(0.00)[−24.2]{43%}
SAMI_V and SWR	**−0.65**(0.01)[−27.2]{73%}	−0.30(0.28)[−6.6]	−0.28(0.08)[−11.7]{87%}	−0.04(0.80)[−1.3]	**−0.28**(0.04)[−10.5]{68%}
SAMI_M and SWR	−0.71(0.09)[−80.6]{90%}	0.08(0.89)[2.8]	**−0.45**(0.00)[−33.4]{73%}	−0.17(0.30)[−8.6]	**−0.43**(0.00)[−31.8]{64%}

The correlations between SWR and each SAMI, zonal mean SLP at 40°S, and zonal mean SLP at 70°S are listed in Table 1. The relationships become insignificant in the case that data for 1964 are removed from the analysis. This result demonstrates that the linear relationship between the SAM and SWR is dominated by a single extreme year—1964. It is possible that this weakening change in the SAM–SWR relationship may be an artifact, as satellite data were not introduced to the NCEP–NCAR reanalysis until 1979 (Kistler et al. 2001; Trenberth et al. 2001) and the SAMI based on NCEP–NCAR shows biases (Hines et al. 2000; Marshall and Harangozo 2000; Marshall 2002, 2003).

To validate the result from the SAMI based on NCEP–NCAR, we repeat the same reanalysis to the station-based SAM indices (SAMI_M and SAMI_V) and SWR (Figs. 1b,c; Table 1). The abrupt drops in correlation coefficients in 1980 are evident in both the SAMI_M and SAMI_V cases, which are consistent with the above results about sliding correlations between the SAMI and SWR. Note that the correlation between the SAMI_V and SWR in the 31-yr sliding window is close to statistical significance level even if data for 1964 are included (i.e., before the central correlation year 1980) and that it has dropped almost to zero since then. The correlation coefficients between the SAMI_M and SWR for the periods 1957–64 and 1964–2007 are −0.71 and −0.45, respectively; however, these values fall to 0.08 and −0.17, respectively, in the case that data for 1964 are excluded (Table 1). The data for 1964 contribute to 64% of the covariance during 1957–2007 and to more than 70% of the covariance for the periods 1957–64 and 1964–2007 (Table 1). Moreover, when data for 1964 are removed from the analysis, the sliding correlations between the SAMI_M and SWR are insignificant for the entire period (Fig. 1c). A similar result about the relationship between the SAMI_V and SWR is obtained (Figs. 1b,c). These results suggest that the apparent relationship between the SAM and SWR induced by an extreme event is supported by the station-based data.

The correlation coefficients between SWR and the SAMI_EOF for periods that include and exclude 1964 (Fig. 1; Table 1) are in agreement with the above results. The consistent results obtained for station-based SAM indices and the NCEP–NCAR-derived SAMI_EOF indicate that the SAMI used in the present study is reliable and that the general conclusions reached in this study are not dependent on the choice of SAM indices. Furthermore, we obtained similar results for sliding windows with different lengths (e.g., 11-, 15-, and 21-yr windows; figures not shown), indicating that the above results are not dependent on the length of the sliding window.

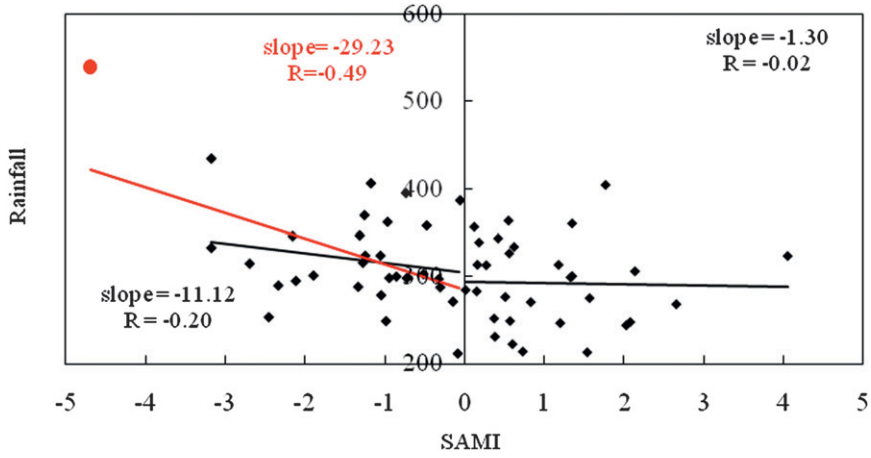

FIG. 2. Scatterplot of the winter SAMI against SWR. Black lines are linear fits for data of negative and positive SAM phases, for which the correlation and regression coefficients are shown. The red outlier (minimum SAM in 1964) is not included in the linear fit shown by the black line, but it is included in the linear fit for the negative SAM phase (red line).

The spatial variations in the relationship between the SAM and SWR are also examined, with and without the data for 1964 (Fig. 3). Similar regions with significant correlations over SWWA are found for the periods 1948–64 and 1964–2007 (Figs. 3a,c) but not for 1948–63, nor for 1965–2007 (Figs. 3b,d). This finding indicates that the relationship between the SAM and SWR is dominated by the extreme year 1964; that is, a significant relationship

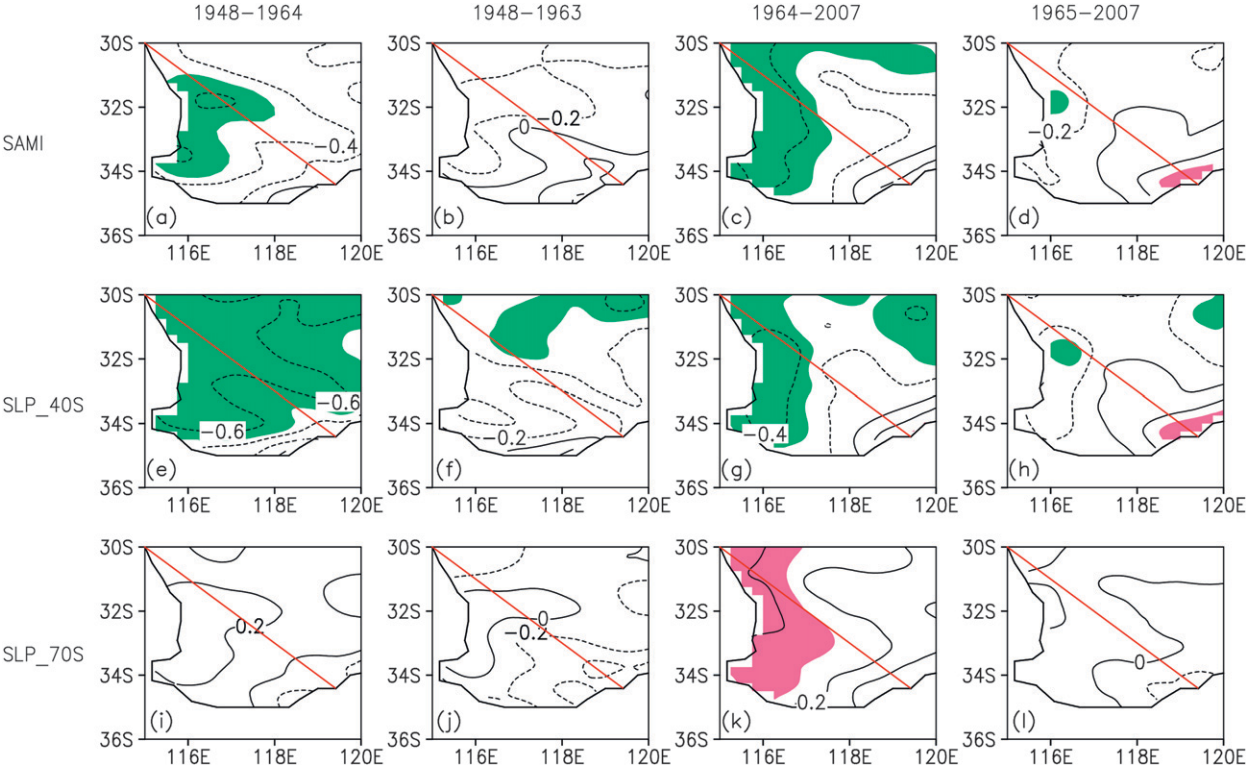

FIG. 3. Spatial distribution of the correlation coefficients between the winter SAMI and SWWA winter rainfall during (a) 1948–64, (b) 1948–63, (c) 1964–2007, and (d) 1965–2007. The second (e)–(h) and third (i)–(l) rows are the same as the first, but for the correlation between the SWR and zonal mean SLP at 40° and 70°S, respectively. Red (green) shading denotes regions of positive (negative) significance at the 0.05 level. The SWWA area lies southwest of the red line joining 115°E, 30°S and 120°E, 35°S.

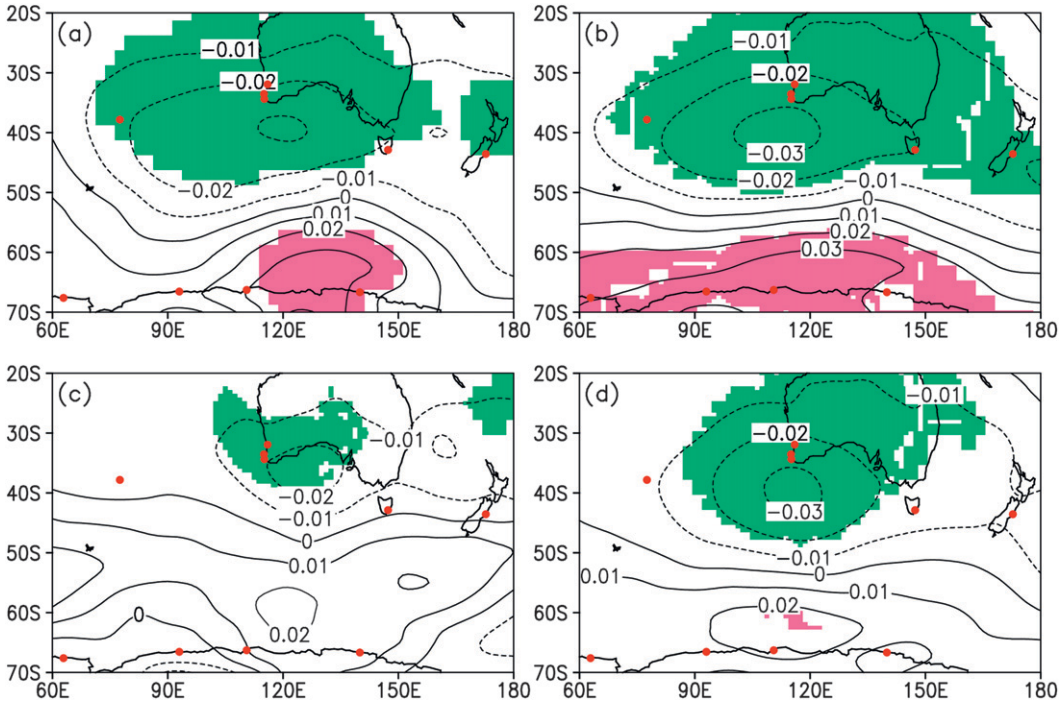

FIG. 4. Regression patterns of simultaneous SLP with respect to SWR for (a) 1948–64, (b) 1964–2007, (c) 1948–63, and (d) 1965–2007. Red (green) shading denotes regions of positive (negative) significance at the 0.05 level. Red dots indicate the locations of stations listed in Table 2.

between the SAM and SWR is only found in the case that the year 1964 is included in the analysis period. This point is further confirmed by the correlations between rainfall and zonal mean SLP at 40° and 70°S (Figs. 3e–l). Significant negative correlations are obtained between SLP at 40°S and SWR for the periods 1948–64 and 1964–2007. For these periods, the correlation is positive over SWWA for SLP at 70°S. However, in the case that the data for 1964 are excluded, these significant correlations essentially disappear.

4. Discussion

The above findings suggest that the SAM does not significantly influence temporal variations in winter rainfall over SWWA, as the apparent relationship between these factors is caused by the extreme year 1964. This year is characterized by a full hemispheric SAM pattern (Jones et al. 2009) that is believed to reflect the Agung eruption of the previous year (Angell 1988). Given this conclusion, it is important to determine the atmospheric anomalies associated with variations in SWR.

Figure 4 shows the regression patterns of SLP with respect to SWR for four subperiods. In 1948–64, significant low pressure anomalies cover the wider part of southwest Australia and significant positive pressure anomalies are seen at high latitudes (south of 50°S), indicating an inverse relationship between the SAM and SWR. After excluding data for 1964, although the SLP anomalies show a SAM-like pattern, the significant low pressure anomalies at midlatitudes are reduced in extent and are located at 100°–140°E (Fig. 4c). Moreover, the significant positive anomalies at high latitudes have almost completely disappeared. A similar result is obtained when comparing the distribution of anomalies between the periods 1964–2007 and 1965–2007. Thus, based on the effect of excluding data for 1964 from the analysis, SWR appears to have no significant relationship with the SAM.

The SLP anomalies at midlatitudes are maintained at 100°–140°E in the cases for which data for 1964 are included and excluded. This finding indicates that temporal variations in SWR are more closely linked to variability in regional circulation over the Indian Ocean and southwest Australia (Smith et al. 2000; England et al. 2006; Hope et al. 2006; Feng et al. 2010).

Station SLP data are analyzed to verify the above conclusion. The correlation coefficients between SWR and station SLP data are listed in Table 2. Six of the stations are located at midlatitudes, and four stations are located at high latitudes. Only three of the stations (Perth Airport, Cape Naturaliste, and Cape Leeuwin) show significant correlations with SWR when data for 1964 are

TABLE 2. Correlation coefficients between SWR and station SLP data and their corresponding two-tailed *P* value (parentheses). Headings defined as in Table 1.

Station name	Period	Lat	Lon	–1964	–1963	1964–	1965–
Perth Airport	1951–2002	31°56′S	115°59′E	**−0.94**(0.00)	**−0.86**(0.01)	**−0.84**(0.00)	**−0.78**(0.00)
Cape Naturaliste	1957–90	33°32′S	115°01′E	**−0.96**(0.00)	**−0.89**(0.02)	**−0.81**(0.00)	**−0.69**(0.00)
Cape Leeuwin	1957–90	34°22′S	115°08′E	**−0.97**(0.00)	**−0.90**(0.02)	**−0.73**(0.00)	**−0.61**(0.00)
Ile Nouvelle	1957–2007	37°49′S	77°33′E	−0.45(0.36)	0.09(0.89)	**−0.39**(0.01)	−0.20(0.21)
Hobart	1957–2007	42°52′S	147°19′E	−0.72(0.05)	−0.12(0.87)	**−0.40**(0.01)	−0.24(0.13)
Christchurch	1957–2007	43°33′S	172°47′E	**−0.76**(0.02)	−0.22(0.76)	−0.28(0.07)	−0.13(0.40)
Casey	1957–2007	66°17′S	110°32′E	**0.87**(0.03)	0.52(0.22)	**0.49**(0.00)	0.25(0.12)
Mirny	1957–2007	66°33′S	93°01′E	**0.85**(0.04)	0.49(0.31)	**0.52**(0.00)	0.24(0.13)
Dumont	1957–2007	66°40′S	140°E	**0.79**(0.01)	0.31(0.67)	0.26(0.10)	0.08(0.64)
Mawson	1957–2007	67°36′S	62°53′E	0.54(0.25)	−0.07(0.93)	**0.34**(0.02)	0.15(0.34)

excluded. These three stations are located within the SWWA region (see Fig. 4). Although some of the seven other stations show significant correlations with SWR for periods ending or starting in 1964, the correlations are insignificant in the case that data for 1964 are removed from the analysis. Therefore, the above discussion is consistent with these station SLP data, indicating the reliability of the present results.

5. Conclusions

This study considered whether the SAM plays a significant role in influencing temporal variations in winter rainfall over SWWA. The reported inverse relationship between the SAM and SWR is entirely dependent on the inclusion of data for an extreme year—1964. In this year, an extreme negative value of the SAM is associated with the wettest winter in SWWA during the period 1948–2007. When data for 1964 are removed from the analysis, despite the fact that the circulation anomalies related to SWR display a SAM-like pattern, the significant anomalies at high latitudes essentially disappear, which is different from the SAM pattern with significant anomalies at both mid- and high latitudes. This implies that the SAM shows a nonsignificant relationship with SWR. This finding is further supported by an analysis of station data. The present result raises the possibility that SWR is more associated with the variability in regional circulation over the Indian Ocean and southwest Australia, and that SAM has no significant influence on temporal variations in SWR. Finally, we suggest that caution should be taken when a simple linear correlation is employed to investigate the relationship between two variables, as the finding in such cases may be distorted by the inclusion of extreme events in the database.

Acknowledgments. We thank Professor Todd Mitchell and Professor Martin Visbeck for kindly providing the relevant SAM indices, and we thank Professor Gareth Marshall for providing station SLP data. Comments and suggestions by four anonymous reviewers improved the paper. This work was jointly supported by the 973 Program (2010CB950400), the Australia–China Bilateral Climate Change Partnerships Program of the Australian Department of Climate Change, and the NSFC Project (40821092).

REFERENCES

Angell, J. K., 1988: Variations and trends in tropospheric and stratospheric global temperature, 1958–87. *J. Climate,* **1,** 1296–1313.

Ansell, T. J., C. J. C. Reason, I. N. Smith, and K. Keay, 2000: Evidence for decadal variability in southern Australian rainfall and relationships with regional pressure and sea surface temperature. *Int. J. Climatol.,* **20,** 1113–1129.

Cai, W., and I. G. Watterson, 2002: Modes of interannual variability of the Southern Hemisphere circulation simulated by the CSIRO climate model. *J. Climate,* **15,** 1159–1174.

——, and T. Cowan, 2006: SAM and regional rainfall in IPCC AR4 models: Can anthropogenic forcing account for southwest Western Australian winter rainfall reduction? *Geophys. Res. Lett.,* **33,** L24708, doi:10.1029/2006GL028037.

England, M. H., C. C. Ummenhofer, and A. Santoso, 2006: Interannual rainfall extremes over southwest Western Australia linked to Indian Ocean variability. *J. Climate,* **19,** 1948–1969.

Feng, J., J. Li, and Y. Li, 2010: A monsoon-like southwest Australian circulation and its relation with rainfall in southwest Western Australia. *J. Climate,* **23,** 1334–1353.

Gong, D., and S. Wang, 1999: Definition of Antarctic Oscillation index. *Geophys. Res. Lett.,* **26,** 459–462.

Hendon, H. H., D. W. J. Thompson, and M. C. Wheeler, 2007: Australian rainfall and surface temperature variations associated with the Southern Hemisphere annular mode. *J. Climate,* **20,** 2452–2467.

Hines, K. M., D. H. Bromwich, and G. J. Marshall, 2000: Artificial surface pressure trends in the NCEP–NCAR reanalysis over the Southern Ocean and Antarctica. *J. Climate,* **13,** 3940–3952.

Hope, P. K., W. Drosdowsky, and N. Nicholls, 2006: Shifts in the synoptic systems influencing southwest Western Australia. *Climate Dyn.,* **26,** 751–764.

IOCI, 2002: *Climate Variability and Change in South West Western Australia.* Indian Ocean Climate Initiative Panel, 34 pp.

Jones, J. M., R. L. Fogt, M. Widmann, G. J. Marshall, P. D. Jones, and M. Visbeck, 2009: Historical SAM variability. Part I: Century-length seasonal reconstructions. *J. Climate,* **22,** 5319–5345.

Kalnay, E., and Coauthors, 1996: The NCEP/NCAR 40-Year Reanalysis Project. *Bull. Amer. Meteor. Soc.,* **77,** 437–471.

Kistler, R., and Coauthors, 2001: The NCEP–NCAR 50-Year Reanalysis: Monthly means CD-ROM and documentation. *Bull. Amer. Meteor. Soc.,* **82,** 247–267.

Li, Y., W. J. Cai, and E. P. Campbell, 2005: Statistical modeling of extreme rainfall in southwest Western Australia. *J. Climate,* **18,** 852–863.

Lo, F., M. C. Wheeler, H. Meinke, and A. Donald, 2007: Probabilistic forecasts of the onset of the north Australian wet season. *Mon. Wea. Rev.,* **135,** 3506–3530.

Marshall, G. J., 2002: Trends in Antarctic geopotential height and temperature: A comparison between radiosonde and NCEP–NCAR reanalysis data. *J. Climate,* **15,** 659–674.

——, 2003: Trends in the southern annular mode from observations and reanalyses. *J. Climate,* **16,** 4134–4143.

——, and S. A. Harangozo, 2000: An appraisal of NCEP/NCAR reanalysis MSLP data viability for climate studies in the South Pacific. *Geophys. Res. Lett.,* **27,** 3057–3060.

Meneghini, B., S. Ian, and I. N. Smith, 2007: Association between Australian rainfall and the southern annular mode. *Int. J. Climatol.,* **27,** 109–121.

Nan, S., and J. Li, 2003: The relationship between the summer precipitation in the Yangtze River valley and the boreal spring Southern Hemisphere annular mode. *Geophys. Res. Lett.,* **30,** 2266, doi:10.1029/2003GL018381.

Santer, B. D., T. M. L. Wigley, J. S. Boyle, D. J. Gaffen, J. J. Hnilo, D. Nychka, D. E. Parker, and K. E. Taylor, 2000: Statistical significance of trends and trend differences in layer-average atmospheric temperature time series. *J. Geophys. Res.,* **150** (D6), 7337–7356.

Smith, I. N., P. McIntosh, T. J. Ansell, C. J. C. Reason, and K. McInnes, 2000: Southwest Western Australian winter rainfall and its association with Indian Ocean climate variability. *Int. J. Climatol.,* **20,** 1913–1930.

Thompson, D. W. J., and J. M. Wallace, 2000: Annular modes in the extratropical circulation. Part I: Month-to-month variability. *J. Climate,* **13,** 1000–1016.

Trenberth, K. E., D. P. Stepaniak, and J. W. Hurrell, 2001: Quality of reanalyses in the tropics. *J. Climate,* **14,** 1499–1510.

Visbeck, M., 2009: A station-based southern annular mode index from 1884 to 2005. *J. Climate,* **22,** 940–950.