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Interannual Relationship between the Winter Aleutian Low and Rainfall in the Following Summer in South China

SONG Lin-Ye[1,2] and DUAN Wan-Suo[1*]

[1] *State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, China*
[2] *University of Chinese Academy of Sciences, Beijing 100049, China*

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Abstract Using observations and reanalysis data, this study investigates the interannual relationship between the winter Aleutian Low (AL) and the rainfall anomalies in the following summer in South China (SC). Results show that the winter AL is significantly positively (negatively) correlated with the SC rainfall anomalies in the following July (August). Specifically, SC rainfall anomalies have a tendency to be positive (negative) in July (August) when the preceding winter AL is stronger than normal. The winter AL-related atmospheric circulation anomalies in the following summer are also examined. When the winter AL is stronger, there is a significant anticyclonic (cyclonic) circulation anomaly over the subtropical western North Pacific in the following July (August). Southerly (northerly) wind anomalies to the west of this anomalous anticyclonic (cyclonic) circulation increase (decrease) the northward moisture transportation and contribute to the positive (negative) rainfall anomalies over SC in July (August). This study indicates that the AL in the preceding winter can be used as a potential predictor of the rainfall anomalies in the following July and August over SC.

Keywords: Aleutian Low, South China, rainfall, atmospheric circulation

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1 Introduction

South China (SC), with its large population and rapid socioeconomic development, is one of the most prosperous regions in China. SC receives the bulk of its annual rainfall in the boreal summer season (e.g., Wu et al., 2012; Duan et al., 2013). The interannual and intraseasonal variations of summer rainfall in SC are very large, often bringing extreme floods and droughts that can exert significant impacts on agriculture, industry, and the daily lives of people (e.g., Huang et al., 2003). Hence, to skillfully forecast the summer rainfall in SC is of great importance for both society and economic development, urging a better understanding of the summer rainfall variability in SC, as well as its influencing factors.

It has been demonstrated in previous studies that the variability of summer rainfall in SC is influenced by many factors, such as the El Niño-Southern Oscillation (ENSO) cycle (e.g., Wu et al., 2003; Wang et al., 2010), Indian Ocean and Atlantic Ocean sea surface temperature (SST) (e.g., Tang et al., 2008; Wu et al., 2009; Xie et al., 2009), Eurasian or Tibetan snow cover (e.g., Wu and Kirtman, 2007), the Arctic Oscillation (e.g., Gong et al., 2011; Chen et al., 2015), the circulation anomaly over the Ural Mountains (e.g., Mao et al., 2011), the East Asian westerly jet (e.g., Liang and Wang, 1998), the western North Pacific subtropical high (e.g., Tao et al., 2001), and the East Asian summer monsoon (e.g., Yang and Lau, 2006). The Aleutian Low (AL) is the first dominant mode of North Pacific atmosphere circulation variability (e.g., Overland et al., 1999). It is characterized by a semi-permanent low pressure center located near the Aleutian Islands during boreal winter. Previous studies have demonstrated that variability of the AL is an important indicator of winter climate change around its surrounding regions (e.g., Parkinson, 1990; Trenberth and Hurrell, 1994; Niebauer et al., 1999). For instance, Trenberth and Hurrell (1994) showed that the boreal winter AL is closely connected with the Pacific-North America teleconnection pattern. Niebauer et al. (1999) reported that the winter temperature anomaly in the Bering Sea tends to be positive (negative) when the strength of the AL is above (below) normal.

Previous studies have also found that variability of the AL can influence the climate anomalies over remote regions (e.g., Zhu and Wang, 2010; Yu and Kim, 2011; Park et al., 2012; Xiao et al., 2014). For example, Xiao et al. (2014) suggested that the summer surface temperature over the Arctic is modulated by interannual variability of the preceding AL. Zhu and Wang (2010) detected a significant relationship between winter AL and the simultaneous Australian summer monsoon rainfall on interannual time scales.

As discussed above, the AL can exert significant influences on the climate anomalies in its surrounding regions and remote areas. However, it remains unexplored as to whether the AL has an influence on the summer rainfall over SC. If such an influence exists, it could potentially be a good precursory signal for seasonal rainfall prediction in SC. In addition, previous studies regarding the connection of the AL with climate anomalies focused mainly on the simultaneous boreal winter (austral sum-

*Correspongding author: DUAN Wan-Suo, duanws@lasg.iap.ac.cn

mer) climate. Few attempts have been made to study the delayed influence of the boreal winter AL on the climate of the following summer.

In the present study, we investigate the possible linkage between the boreal winter AL and the rainfall in the following summer over SC (hereafter referred to simply as 'following summer SC rainfall'). We find a significant connection between the intensity of the winter AL and the rainfall anomalies in July and August of the following year over SC. Hence, the objective of this study is to investigate the influence of the boreal winter AL on the rainfall in the following July and August. The remainder of the paper is organized as follows: The data used in the study are described in section 2. Section 3 examines the relationship between the AL and summer rainfall over SC, describes the atmospheric circulation, and discusses the possible mechanism by which the AL influences the rainfall. Section 4 concludes the study.

2 Data

This study uses a monthly high-resolution precipitation dataset over land from the University of Delaware (UD) for the period 1900–2010 (Legates and Willmott, 1990). This dataset has a horizontal resolution of 0.5° × 0.5°. Also employed are the 160-station rainfall data from the National Climate Center of the China Meteorological Administration (CMA) from 1951 to the present.

The monthly mean sea level pressure (SLP) dataset is from the HadSLP2 product of the UK Met Office Hadley Centre, which has a horizontal of 5° × 5° and is available for the period 1850–2004 (Allan and Ansell, 2006).

Horizontal winds and geopotential heights are extracted from the 20th Century Reanalysis, version 2 (20CR2), of the National Oceanic and Atmospheric Administration-Cooperative Institute for Research in Environmental Sciences, for the period 1871–2010 (Compo et al., 2011), with a horizontal resolution of 2° × 2°. The analysis in this study focuses on interannual variation. Hence, all data are subjected to a nine-year high-pass filter. The results shown in this analysis are not sensitive to a reasonable variation of the cutoff period from 5 to 11 years. Previous studies have found that boreal winter ENSO events could exert influences on the variability of the winter AL (e.g., Roeckner et al., 1996; Alexander et al., 2002), which may confuse the influence of the winter AL on the following summer SC rainfall. As ENSO possesses a phase-locking feature with a mature peak in boreal winter, we subtract the ENSO signal in the variables by means of linear regression with respect to the Niño3.4 index during December-January-February (DJF). The Niño3.4 index is defined as the area-averaged SST anomalies over the region (5°S–5°N, 170–120°W). The removal of signals associated with the DJF Niño3.4 index from the DJF AL index and analysis data can exclude the possibility that any significant correlation between the DJF AL and following summer SC rainfall is due to the influence of the DJF ENSO on both the DJF AL and following summer SC rainfall.

3 Results

3.1 Definition of the AL and SC rainfall

Following Yu and Kim (2011), an empirical orthogonal function (EOF) analysis is performed to obtain the AL index (ALI). The region chosen for the EOF analysis is (20–60°N, 120°E–80°W). Figure 1a shows the leading EOF mode of monthly SLP anomalies over the selected region for the period 1900–2004. The corresponding time series of the leading EOF mode is displayed in Fig. 1b and is defined as the ALI in this study. The first EOF mode explains about 36.5% of the total SLP variance and can be separated well from the other eigenvalues. The spatial pattern of the first EOF mode is characterized by a center of action of negative SLP anomalies near the Aleutian region (Fig. 1a), which is consistent with the result in Yu and Kim (2011).

In this study, the region of SC is selected as (22–30°N, 105–118°E). There are 29 China Meteorological Administration (CMA) stations over this region, all distributed to the south of the Yangtze River. The time series of SC rainfall is defined as the area-mean rainfall over the selected SC region for the gridded rainfall dataset. For the CMA station rainfall dataset, the time series of SC rainfall is defined as the 29-station-averaged rainfall.

3.2 AL-rainfall connection

In this section we examine the possible connection between the AL and SC rainfall by computing their correlation coefficients. Table 1 shows the correlation coefficients between the winter (DJF-averaged) ALI and the following summer (June-July-August, JJA-averaged and three individual months) rainfall over SC, after removing the influence of ENSO signal. Interestingly, the winter ALI is significantly and positively correlated with July

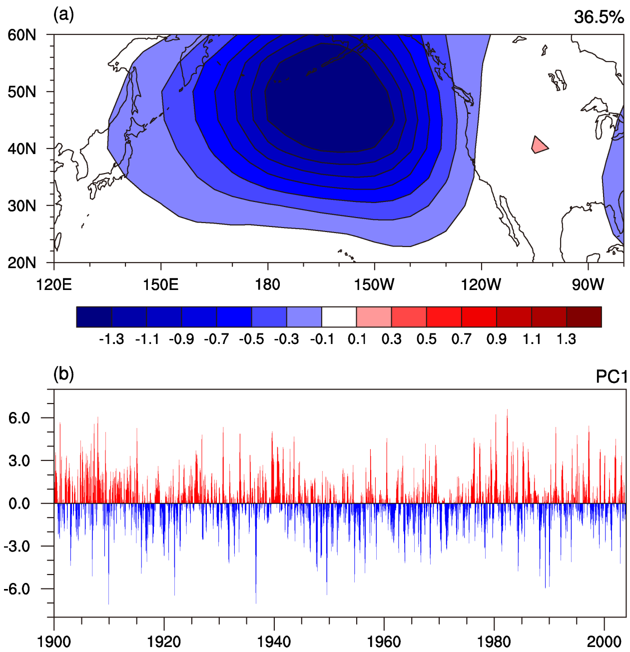

Figure 1 (a) The first EOF mode of monthly sea level pressure (SLP) anomalies over the North Pacific during 1900–2004. (b) The corresponding principle component (PC) time series.

Table 1 Correlation coefficients of South China summer rainfall (JJA, June, July, and August, separately) with the preceding winter (December-January-February, DJF) Aleutian Low index. The rainfall dataset are from the University of Delaware (UD) grid dataset and China Meteorological Administration (CMA) station dataset. All indices have been subjected to a nine-year high-pass filter and the DJF ENSO signal has been linearly removed in constructing this table.

	UD grid dataset (1901–2004)	UD grid dataset (1951–2004)	CAM station dataset (1951–2004)
JJA rainfall	−0.05	−0.03	−0.12
June rainfall	−0.12	−0.15	−0.18
July rainfall	0.32*	0.39*	0.37*
August rainfall	−0.33*	−0.35*	−0.37*

*95% confidence level

rainfall but significantly and negatively correlated with August rainfall over SC. The standardized time series of the ALI and SC rainfall in July and August are displayed in Fig. 2. The correlation coefficient of the ALI with July (August) SC rainfall from the UD rain dataset is 0.32 (−0.33) for the period 1901–2004, significant at the 95% confidence level based on the Student's *t*-test (Table 1). This indicates that an anomalously strong AL in the preceding winter tends to be followed by flood (drought) conditions in July (August) over SC. Note that no significant relationship is found between the ALI and JJA-averaged or June rainfall (Table 1). The insignificant correlation in the JJA-averaged rainfall might be attributable to the remarkably different behavior in these three individual months. In addition, the above correlation is computed using the station rain dataset for the period 1951–2004. The interannual variations of the station rainfall and UD rainfall are generally consistent with each other (Fig. 2). The correlation coefficient of the winter ALI is 0.37 (−0.37) with July (August) rainfall for the

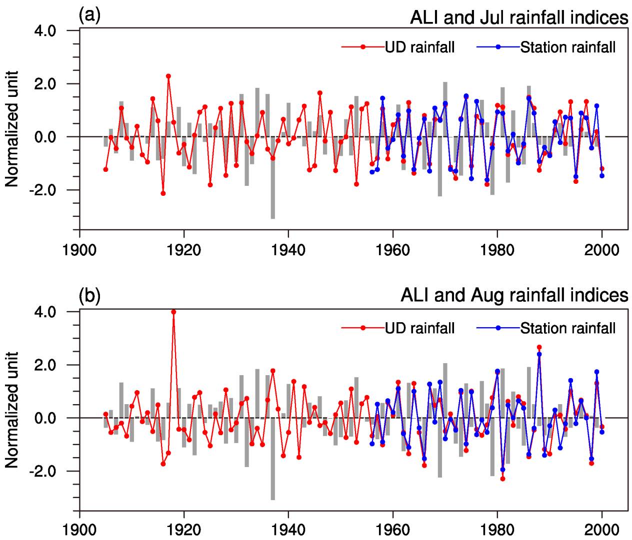

Figure 2 Normalized time series of DJF Aleutian low index (ALI) (bars) and (a) July rainfall indices from the University of Delaware (UD) rainfall dataset (red lines) and from China Meteorological Administration (CMA) 160-station dataset (blue lines). (b) As in (a) but for August rainfall indices. DJF ALI is also shown in (b) for comparison. Note that all indices have been subjected to a nine-year high-pass filter and the DJF ENSO signal has been linearly removed in constructing this figure.

period 1951–2004 using the station rain dataset, significant at the 95% confidence level—consistent with that using the UD rain dataset (Table 1).

Previous studies regarding the summer SC rainfall have focused mainly on the JJA-averaged rainfall (e.g., Wu et al., 2003, 2012). Our present study finds that the correlation between the boreal winter ALI and the following JJA-averaged SC rainfall is statistically insignificant. This may be due to the fact that the correlation of the ALI with the following July (August) SC rainfall is significantly positive (negative). Therefore, the subseasonal features of summer rainfall should be taken into account when investigating the SC summer rainfall. For example, Wang et al. (2009) suggested that a separate prediction of the bi-monthly anomalies for May–June and July–August may help improve the seasonal prediction of summer rainfall over East Asia.

Figures 3a and 3b show the correlation patterns of the boreal winter ALI with SC rainfall in July and August, respectively. Very different features appear between the two periods. In July, significant and positive correlations are seen over the SC region, with the maximum value centered at about (25°N, 110°E) (Fig. 3a). In contrast, significant and negative correlations are observed over the SC region in August, with the center of maximum correlation located more northeastward compared to that in July (Fig. 3b). We also examine the correlations of the ALI in other preceding months with the July and August SC rainfall. Figures 3c and 3d display the lag-lead correlations of the three-month means of the ALI with the SC rainfall index in July and August, respectively. The ALI is from preceding autumn (September-October-November, SON) to simultaneous summer (June-July-August, JJA). The results clearly show that the correlations are significant at the 90% confidence level both in July and August from the preceding early to late winter, with the maximum value appearing in DJF (Figs. 3c and 3d). The above results indicate that SC rainfall anomalies tend to be positive (negative) in July (August) when the AL is stronger than normal in the preceding winter.

The relationship between the winter AL and following summer SC rainfall is unstable. Figure 3e (3d) shows the sliding correlation between the DJF AL index and July (August) SC rainfall index with a window of 21 years. The correlation between the DJF AL and July SC rainfall is positive and statistically significant at the 90% confidence level around the 1910s, 1920s, late 1930s, and after the late 1970s; while the correlation is weak during the 1940s to the late 1970s (Fig. 3e). In addition, significant negative correlation between the DJF AL and August SC rainfall can be observed during the 1940s to 1950s and after the early 1970s; while before the 1940s and during the late 1950s to 1960s, the connection between the DJF AL and August SC rainfall is weak (Fig. 3f). The above results suggest that the connection of boreal winter AL with July and August SC rainfall experienced significant interdecadal changes in the past. The possible reasons leading to interdecadal change in the connection between the DJF AL and following summer SC rainfall will be

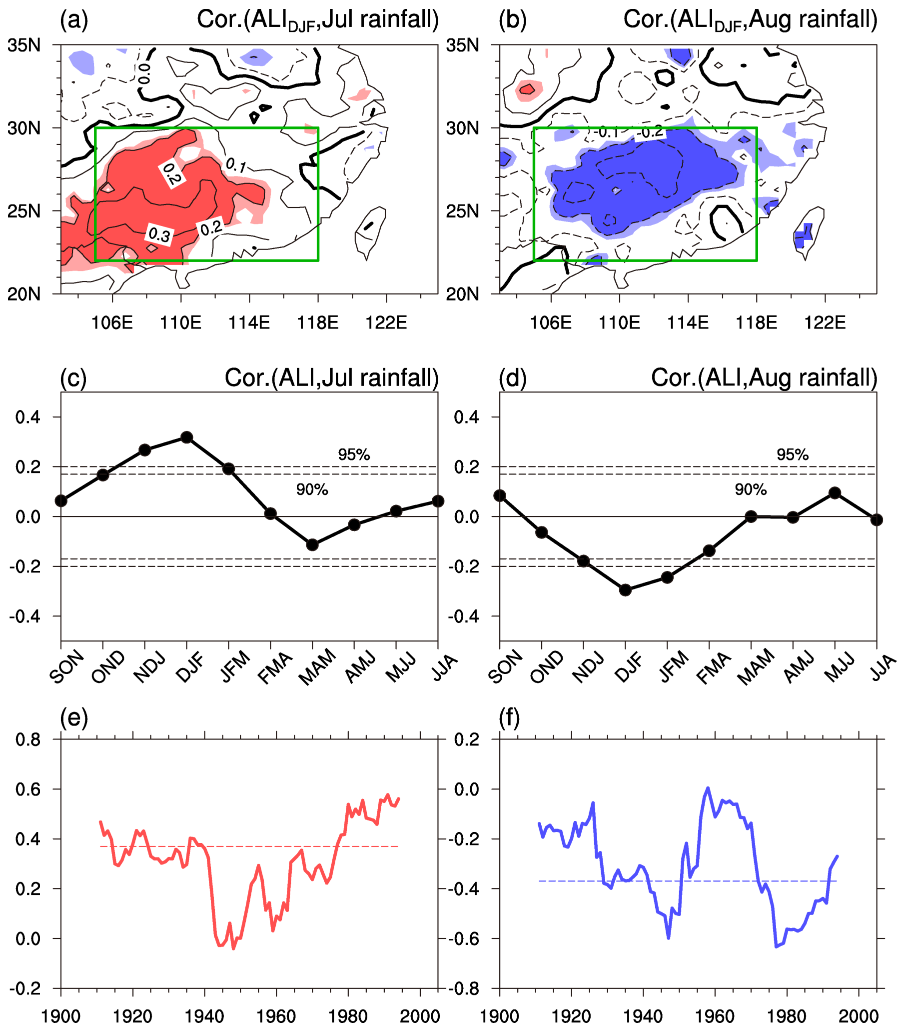

Figure 3 Correlation of DJF ALI with (a) July and (b) August rainfall in the following year. Heavy (light) shading in (a, b) indicates correlation coefficients significant at the 95% (90%) confidence level. Contour intervals are 0.1 in (a, b), and the green box is the region of South China (22–30°N, 105–118°E) in this study. Lag-lead correlation of ALI from preceding SON to JJA with (c) July and (d) August rainfall indices obtained from the UD rainfall dataset during 1901–2004. The dashed lines indicate significance at the 95% and 90% confidence level. (e) Sliding correlations between the winter (DJF) AL index and July South China rainfall index displayed at the central year of a 21-yr window. (f) As in (e) but for the August rainfall index. Horizontal dashed lines in (e, f) indicate the correlation coefficient is significant at the 90% confidence level. Note that all variables have been subjected to a nine-year high-pass filter and the DJF ENSO signal has been linearly removed in constructing this figure.

pursued in a future study. As the connection between the DJF AL and following summer SC rainfall is better after the late 1970s (Figs. 3e and 3f), in the following analysis, we focus on the period 1979–2004 to investigate the possible physical process underlying the influence of the DJF AL on the following summer SC rainfall. It should be pointed out that atmospheric circulation anomalies in the following summer over the subtropical western North Pacific associated with the DJF AL during 1979–2004 are in close agreement with the results during 1900–2004 (not shown).

3.3 Associated atmospheric circulation anomalies in July and August

Changes consistent with rainfall anomalies are identified in July and August atmospheric circulation anomalies in association with the DJF ALI over East Asia and the western North Pacific. Figures 4a–c display the anomalies of geopotential height at 1000 hPa, winds at 850 hPa, and geopotential height at 500 hPa, in July, as obtained by regression on the DJF ALI during 1979–2004. At 1000 hPa, significant and positive geopotential height anomalies are seen over the subtropical western North Pacific and significant and negative anomalies are observed over the midlatitudes of the North Pacific and northwest of China (Fig. 4a). At 850 hPa, a significant anticyclonic circulation appears in the subtropical western North Pacific, together with easterly wind anomalies over the tropical western North Pacific and southwesterly wind anomalies over SC (Fig. 4b). These southwesterly wind anomalies, in association with the DJF ALI over SC, increase the northward transportation of moisture from the South China Sea and then concur with anomalous ascending motion there (not shown), finally resulting in positive rainfall anomalies over SC (Fig. 3a). The geopotential height anomalies over the North Pacific at 500 hPa are similar to those at 1000 hPa (Figs. 4a and 4c), with significant positive anomalies over the subtropical western

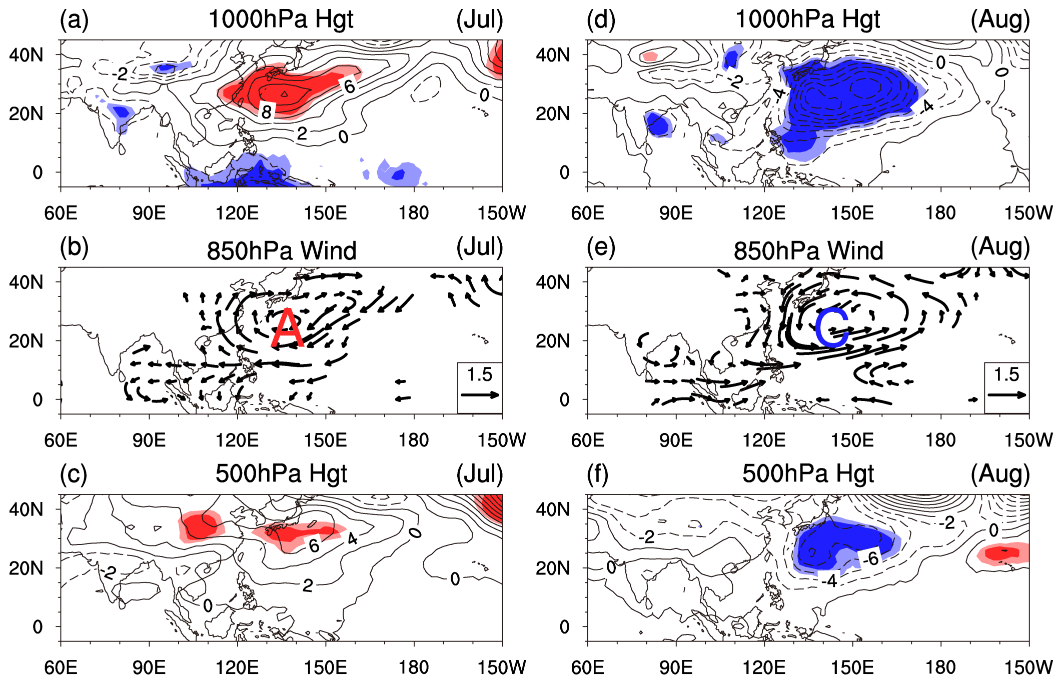

Figure 4 Anomalies of (a, d) 1000 hPa geopotential height (units: m), (b, e) 850 hPa horizontal winds (units: m s^{-1}) and (c, f) 500 hPa geopotential height (units: m) in (a–c) July and (d–f) August regressed on the normalized DJF ALI during 1979–2004. Heavy (light) shading indicates geopotential anomalies that are significantly different from zero at the 95% (90%) confidence level. Note that all variables have been subjected to a nine-year high-pass filter and the DJF ENSO signal has been linearly removed in constructing this figure.

North Pacific and negative anomalies over the midlatitudes of the North Pacific. Note that significant negative geopotential height anomalies at 1000 hPa over Northwest China are replaced by positive anomalies at 500 hPa (Figs. 4a and 4c).

Correspondingly, Figs. 4d–f show atmospheric circulation anomalies in August, as obtained by regression on the DJF ALI. The anomalies in August display remarkable differences to those in July. There is an anomalous cyclone over the Philippine Sea in the lower troposphere (Fig. 4e), accompanied by negative geopotential height in the lower-to-middle troposphere (Figs. 4d and 4f), but with a slightly northeastward location in contrast with July. Significant northeasterly wind anomalies are observed over SC (Fig. 4e) associated with anomalous descending motion (not shown), which can explain the negative rainfall anomalies over SC in August (Fig. 3b).

At present, we find that the boreal winter AL index has a significant positive (negative) connection with the following July (August) SC rainfall. Hence, the preceding winter AL may be used as an effective predictor of July and August rainfall anomalies. The key system connecting the preceding winter AL and July (August) SC rainfall is the anticyclonic (cyclonic) circulation anomaly over the subtropical western Northern Pacific. However, the possible physical processes responsible for the formation of the winter AL-related anticyclonic (cyclonic) circulation anomalies in July (August) remain unclear. We speculate that winter AL-related boundary forcing (e.g., land/ocean) may play important roles in the formation of atmospheric circulation anomalies over the subtropical western North Pacific in the following summer.

4 Conclusion

This study investigates the influence of the winter AL on SC rainfall in the following summer. Results show that the wintertime AL is significantly positively (negatively) correlated with the SC rainfall in the following July (August). Specifically, SC rainfall anomalies tend to be positive (negative) when the preceding winter AL is stronger. The results of this study indicate that the preceding winter ALI can be used as a potential predictor of the following July and August rainfall anomalies over SC.

A significant anticyclonic (cyclonic) circulation anomaly can be observed over the subtropical western North Pacific in the following July (August), which can explain the pronounced positive (negative) correlation of SC rainfall in July (August) with the preceding winter AL. Southerly (northerly) wind anomalies to the west of the anomalous anticyclonic (cyclonic) circulation increase (decrease) the northward moisture transportation and thus contribute to the positive (negative) rainfall anomalies over SC in July (August).

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