Joint effect of East Asia–Pacific and Scandinavian teleconnections on summer precipitation in Southwest China

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Abstract

Based on the summer precipitation data from 328 meteorological stations in Southwest China and the monthly mean reanalysis data from the National Centers for Environmental Prediction/National Center for Atmospheric Research, the relationships of summer precipitation in Southwest China with the East Asia–Pacific (EAP) teleconnection pattern and the Scandinavian (SCA) teleconnection pattern are explored by using correlation analysis and composite analysis. The results show that the two teleconnections are significantly negatively correlated with the summer precipitation in Southwest China in the same period. The EAP teleconnection pattern and the SCA teleconnection pattern can affect the summer precipitation in Southwest China by affecting the atmospheric circulation situation in the middle and high latitudes, the north–south and east–west movement of the WPSH, and the water vapor transport in southwest China. In particular, the EAP and SCA teleconnections jointly affect the summer precipitation in Southwest China, which can be divided into four categories of configurations, that is, (I) positive EAP + positive SCA, (II) negative EAP + negative SCA, (III) positive EAP + negative SCA, and (IV) negative EAP + positive SCA. The distribution of summer precipitation in Southwest China varies under different categories of configurations. Category I (II) corresponds to an opposite distribution pattern of precipitation anomalies between the north and south of Southwest China. In the configuration of category I(II), the cold air from high latitudes is weaker (stronger), the WPSH is more north(south) and more west(east) than the climatological mean, and the water vapor mainly comes from the Western Pacific (Bay of Bengal), thus resulting in category I(II), the opposite distribution of precipitation. While for configuration of category III(IV), no similar symmetrical distribution of precipitation anomalies can be found, and no obvious other distribution characteristics as well.

1 Introduction

The East Asia–Pacific (EAP) teleconnection pattern, also known as the Pacific-Japan (PJ) teleconnection pattern, was first proposed by Huang and Li, 1987 and Nitta 1987. The formation of this teleconnection pattern is related to the anomalous convective activity over the western Pacific warm pool (Huang and Sun 1992, 1994). By analyzing the evolution process of EAP in the pre-flood season in South China, Shi et al. (2008) believed that the maintenance and development of EAP teleconnection pattern are related to the Rossby wave activities in middle and high latitudes. Huang (2004) defined an EAP index according to the centers of action of the EAP teleconnection pattern in atmospheric circulation anomalies and pointed out that the EAP pattern has a strong relationship with the summer climate in East Asia. Based on this EAP index, Cai et al. (2009), found that the EAP teleconnection pattern is closely related to the distribution of summer precipitation in China. In particular, the EAP teleconnection pattern can influence the East Asian summer monsoon and cause summer precipitation anomalies in the middle and lower reaches of the Yangtze River (Min et al. 2005; Lyu et al. 2006). The anomalous EAP wave train corresponds to a stronger subtropical high with a more northward position, resulting in the droughts in the droughts in the Yangtze-Huaihe River basin (Huang 1990; Lin et al. 1999; Chen et al.
Yang et al. (2009) proposed that the EAP teleconnection with the “\(-++(-+\pm)\)” pattern can promote (inhibit) the northward jump of the western Pacific subtropical high (WPSh). Li et al. (2016) pointed out that persistent heavy precipitation occurs in the Yangtze River basin under the influence of low-frequency oscillations of the EAP teleconnection pattern on the 10–30-day timescale. Yin et al. (2021) revealed that the northeastward movement of the centers of action of the EAP teleconnection pattern near Japan weakens its connection with the summer precipitation in the Yangtze-Huaihe River basin.

The Scandinavian (SCA) teleconnection pattern was first proposed by Barnston and Livezey 1987, which was obtained by decomposing the Eurasian teleconnection pattern. Bueh and Nakamura (2007) investigated the maintenance mechanisms of the SCA teleconnection pattern. They suggested that the two centers of action in the upstream portion of the SCA teleconnection pattern over North Atlantic and Scandinavia is maintained by the baroclinic positive feedback forcing from transient eddies, and the center of action in the downstream of the pattern over Siberia is formed and maintained due to the energy dispersion of the upstream Rossby wave. Bueh et al. (2008) concluded similar conclusions by investigating the maintenance mechanism of the SCA pattern in its positive phase that prevailed in the winter of 2000/2001. While Liu et al. (2014) pointed out that the maintenance of the SCA teleconnection pattern is also related to the anomalous convergence (divergence) over the Mediterranean Sea caused by the variation of sea surface temperature (SST) in the Indian Ocean. As an important teleconnection pattern in Eurasia, the SCA teleconnection pattern has a significant impact on the temperature and precipitation in Europe (Bueh and Nakamura 2007; Zveryaev 2009; Liu et al. 2014), which also significantly affects the climate change in East Asia. Yang et al. (2010a, b) pointed out that the SCA teleconnection pattern plays an important role in precipitation anomalies in winter and spring of Xinjiang, where the circulation anomalies during the positive (negative) phase of the SCA pattern cause anomalously abundant (deficient) precipitation. Lin (2014) proposed that there is a connection between the SCA teleconnection pattern and the summer precipitation in East Asia. When the SCA teleconnection pattern is in its positive phase, the low pressure in the northern part of East Asia moves northward, resulting in the transportation of water vapor to the northwestern part of Northeast Asia, which will significantly reduce the precipitation in North China. Gao et al. (2017) revealed a close relationship between the SCA teleconnection pattern and the westerlies in summer, when the westerlies become stronger during the negative phase of the SCA pattern, causing a more eastward position of the East Asian shallow trough. Yao and Yan (2018) pointed out that the precipitation anomaly in Yunnan in January is closely related to the SCA teleconnection pattern. The positive (negative) phase of the SCA pattern corresponds to less (more) precipitation in January in Yunnan. Choi et al. (2020) indicated that the SCA teleconnection pattern in summer plays an important role in the development of heatwaves in East Asia.

The existing studies have revealed that the EAP and SCA teleconnection patterns have significant impacts on the summer climate change in China. For Southwest China, however, the precipitation phase is rather complex, and the precipitation is unevenly distributed (Dong and Duan 1998). The interannual variation characteristics of precipitation vary in different regions (Liu et al. 2002). The precipitation in high-altitude areas is significantly less than that in low-altitude areas, and the large-value center of precipitation is staggered in rainy areas (Xiong et al. 2012). Moreover, precipitation in Southwest China mainly occurs in summer (Xu 1991; Guo and Li 2009), accounting for more than 50% of the annual total. As Southwest China is located at the junction of the East Asian monsoon and South Asian monsoon, precipitation in this region is strongly affected by the monsoon climate (Xu 1991; Qi et al. 2009). The SCA teleconnection pattern in summer is significantly associated with the subtropical high (Gao et al. 2017; Choi et al. 2020), and also has an important impact on the precipitation in late autumn in Southwest China (Liu and Liu 2016, 2017).

Therefore, what effects will the EAP and the SCA teleconnection patterns have on summer precipitation in Southwest China? As is known that the EAP teleconnection pattern mainly reflects the meridional variations of circulations in East Asia, while the SCA teleconnection pattern reflects the variation of zonal circulations in middle and high latitudes propagating eastward from the North Atlantic, which can reach as far as Siberia. As the climate in Southwest China is jointly affected by the cold and dry airflows from middle and high latitudes as well as the warm and humid airflow from low latitudes, it is thus necessary to study the influences of the EAP and SCA teleconnection patterns on summer precipitation in Southwest China under different configurations, which can help to understand the formation mechanism of precipitation in this region. This is of great significance to the prediction during the flood season in Southwest China, aiming to reduce the losses caused by droughts and floods.

This study mainly investigates the summer precipitation in Southwest China under the influences of the EAP and the SCA teleconnection patterns. The remainder of this paper is organized as follows. Section 2 introduces the data and methods. Section 3 explores the relationships of the precipitation in Southwest China with the EAP and SCA teleconnection patterns. Section 4 investigates the spatial distributions of summer precipitation in Southwest China under different configurations of the SCA and EAP teleconnection patterns. Moreover, possible influencing mechanisms for summer precipitation in Southwest China are discussed.
in terms of the circulation characteristics and water vapor transport under different configurations. Finally, the main conclusions are provided in Section 5.

2 Data and methods

This study uses the following datasets. The first is the daily precipitation observation data from 328 meteorological stations in three provinces and one city (Yunnan, Guizhou, Sichuan Provinces, and Chongqing City) in Southwest China from 1970 to 2019, and the distribution of station locations is shown in Fig. 1. The second is the monthly reanalysis data during 1970–2019 provided by the National Centers for Environmental Prediction/ National Center for Atmospheric Research (NCEP/NCAR), which includes the variables of geopotential height, horizontal wind, and specific humidity with a horizontal resolution of 2.5° × 2.5° and a total of 17 layers from 1000 to 10 hPa in the vertical direction. Third, the monthly SCA teleconnection index from 1970 to 2019 is provided by the Climate Prediction Center of the National Oceanic and Atmospheric Administration. In this study, the summer season covers June, July and August. The WPSH index (including the intensity, area, ridge line, and western ridge point of WPSH) is provided by the National Centers for Environmental Prediction/National Centers for Atmospheric Research (WKB) approximation. If defined in the log-pressure coordinate, the formation expression of T-N wave activity flux is:

\[ \mathbf{w} = \frac{P}{2|\mathbf{U}|} \left\{ U \left( v'^2 - \psi' \psi' \right) + V \left( -u' \psi' + \psi' u' \right) \right\} \]

Rosby wave source (RWS) formation expression, as defined by Sardeshmukh and Hoskins (1988), is:

\[ S = -\nabla \cdot \left\{ V \phi' (f + \zeta') \right\} - \nabla \cdot \left\{ V \phi' \psi' \right\} \]

where \( S \) represents the RWS, \( V \) represents divergent component, and \( \zeta \) represents divergent component relative vorticity.

In this study, the correlation analysis, regression analysis, and composite analysis also are applied to study the influence of the EAP and SCA teleconnection patterns on summer precipitation in Southwest China and use a two-tailed Student’s t-test to assess statistical significance levels.

3 Relationships of two teleconnection patterns with the summer precipitation in Southwest China

3.1 Characteristics of the summer precipitation in Southwest China and its correlations with two teleconnection patterns

The spatial distributions of the EAP teleconnection, the SCA teleconnection at 500 hPa and the 500-hPa geopotential height regressed onto the summer precipitation averaged in Southwest China are shown in Fig. 2. The EAP teleconnection pattern shows a meridional tripole distribution of “− + −” structure from low latitude to high latitude over East Asia (Fig. 2a). The SCA teleconnection pattern presents significant positive anomalies over Scandinavia and significant negative anomalies over North Atlantic and Siberia (Fig. 2b). In addition, the regressed geopotential height at 500 hPa also displays spatial distribution characteristics similar to those of the EAP and SCA patterns, as shown in Fig. 2c. Therefore, it can be concluded that the summer
precipitation in Southwest China is jointly affected by the EAP and SCA teleconnection patterns to a certain extent. Furthermore, the correlations of the EAP and SCA teleconnection indices with the summer precipitation in Southwest China are calculated to explore their relationships detailedly. Figure 3 reveals that the SCA and EAP teleconnection indices are significantly negatively correlated with the summer precipitation in the north part of Southwest China. For the EAP pattern, the negative correlations are mainly distributed in the western Sichuan Plateau, Guizhou, Chongqing, and eastern Sichuan (Fig. 3a). While the situation of the SCA pattern are consistent with that of the EAP pattern, the negative correlation coefficients in Guizhou have not passed the significance test at the 95% confidence level (Fig. 3b). In addition, the basin area presents an opposite distribution of correlations between its eastern and western regions, indicating that the formation mechanism of summer precipitation in the basin area is different from that in its surrounding areas, which is also confirmed by Chen et al. (2009) and Yang et al. (2014).

Fig. 2 Regressed 500 hPa geopotential height onto the EAP index (a), the SCA index (b), and precipitation time series (c). The shaded area indicates statistical significance at the 95% confidence level.
The above analysis reveals that the correlations of summer precipitation in Southwest China with the two teleconnection indices are similar in the spatial distribution. Furthermore, it is found that there is a significantly positive correlation between the two teleconnection indices, with the correlation coefficient being 0.44, which has passed the significance test at the 95% confidence level. The result indicates that there is a strong interaction between the EAP and SCA teleconnection patterns. In order to ensure a sufficient sample size under different combinations, the teleconnection index greater (less) than 0.3 times its standard deviation is taken as the threshold to screen the abnormal years. On this basis, the abnormal years in the EAP (SCA) teleconnection pattern are excluded from the years with positive (negative) phases in the SCA (EAP) pattern. Table 1 displays that the number of years with positive and negative phases of the EAP pattern is close to that of the SCA pattern during 1970–2019. After excluding the abnormal years, there are a total of 12 years with positive and negative phases for the EAP pattern, which are 15 years for the SCA pattern. Figure 4 shows the spatial distributions of summer precipitation in southwest China under different situations of two teleconnections according to Table 1. It can be seen that during the abnormal years of the EAP (SCA) teleconnection, the summer precipitation presents opposite distribution characteristics between the north and the south of Southwest China (Fig. 4a–d). However, after excluding the abnormal years with respect to the teleconnection index, the opposite distribution pattern of summer precipitation between the north and the south of Southwest China disappears (Fig. 4e–h). Thus, it can be concluded that the opposite distribution of summer precipitation between the north and the south of Southwest China is jointly affected by the EAP and SCA teleconnection patterns.

3.2 Wave activity flux

According to the above analyses, there is a significant positive correlation between the EAP and SCA teleconnection indices, and the opposite distribution of summer precipitation between the south and the north of Southwest China is caused by the combined effects of the EAP and SCA teleconnection patterns. Therefore, the interaction between the EAP and SCA teleconnection patterns is further investigated, which can help understand the formation mechanism of summer precipitation in Southwest China. Figure 5 displays the wave activity flux regressed onto the EAP and the SCA indices. For the propagation of the 200 hPa wave activity flux associated with the EAP teleconnection pattern (Fig. 5a), there are obvious eastward-propagating Rossby waves in mid-high latitudes. Lyu et al. (2006) pointed out the quasi-stationary Rossby waves in the westerly jet can trigger the EAP teleconnection pattern. At the same time, the mid-latitude geopotential height anomaly of the EAP is also affected by the southward dispersion of energy at high latitudes. For the propagation of the 200 hPa wave activity flux associated with the SCA teleconnection pattern (Fig. 5b), there are obvious Rossby waves that
propagate eastward from Scandinavia to the eastern part of Lake Baikal, and the area affected by the energy dispersion corresponds to the area with obvious geopotential height anomalies in the EAP pattern and the area affected by the energy dispersion corresponds to the area with obvious geopotential height anomalies in the EAP pattern, indicating that the SCA teleconnection pattern could help maintain the EAP pattern. Shi et al. (2008) also proposed that the positive height anomaly around the Scandinavian Peninsula maintains its intensity and position, and the Rossby waves propagate persistently toward East Asia in the downstream, which is conducive to the maintenance of the positive EAP

Table 1 Corresponding years under different conditions of SCA and EAP indices

| Year | EAP EAP > 0 | EAP EAP < 0 | SCA SCA > 0 | SCA SCA < 0 | EAP EAP > 0, |SCA|< 0.3 | EAP EAP < 0, |SCA|< 0.3 | SCA SCA > 0, |EAP|< 0.3 | SCA SCA < 0, |EAP|< 0.3 |
|------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
|      | 1970 1971 1972 1973 1975 1976 1977 1978 1979 1981 | 1982 1984 1985 1989 1990 1994 1997 1999 2000 2001 | 2004 2006 2007 2010 2012 2013 2016 2018 | 1974 1980 1983 1986 1987 1988 1991 1992 1993 1995 | 1996 1998 2002 2003 2005 2008 2009 2011 2014 2015 | 2017 2019 | 1970 1971 1972 1973 1974 1975 1976 1977 1978 1984 | 1985 1988 1989 1995 1996 1997 2002 2006 2007 2008 | 2011 2014 2018 | 1979 1980 1981 1982 1983 1986 1987 1989 1990 1991 1992 | 1993 1994 1998 1999 2000 2001 2003 2004 2005 2009 | 2010 2012 2013 2015 2016 2017 2019 | 1984 1985 1999 2000 2007 2010 2018 | 1983 1986 1992 2005 2008 | 1970 1971 1974 1976 1977 1988 1989 2006 2008 2011 | 1982 1990 2001 2005 2016 |

Fig. 4 Distribution of summer precipitation in southwest China under the EAP (a, b, e, f) and SCA (c, d, g, h) teleconnection pattern of positive(negative) phases. Unexcluded abnormal years (a, b, c, d) and excluded abnormal years (e, f, g, h). The dotted area indicates statistical significance at the 95% confidence level

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For the propagation of the 500 hPa wave activity flux associated with the EAP and SCA teleconnection patterns (Fig. 5c, d), the wave activity flux distribution is similar to the 200 hPa. There are also obvious eastward-propagating Rossby waves in the middle and high latitudes. In addition, the energy dispersion is enhanced in the eastern part of Lake Baikal to the middle latitude. In addition, the energy dispersion from the eastern part of Lake Baikal to the middle latitude is enhanced. The wave flux propagation of EAP and SCA teleconnection is less related at 850 hPa (Fig. 5e, f). The wave flux of the EAP teleconnection pattern turns to propagate from low latitude to high latitude, but the SCA teleconnection pattern still keeps zonal propagation in high latitude. The above results reveal that the SCA teleconnection pattern is conducive to the development and maintenance of the EAP teleconnection pattern.

Figure 6 display the spatial distributions of Rossby wave source anomalies at different levels. The wave source anomalies are more significant at 200 hPa than 500 hPa and 850 hPa. The wave source anomaly of the EAP teleconnection pattern has obvious meridional distribution in East Asia and zonal distribution in mid-high latitudes (Fig. 6a). The wave source anomaly of the SCA teleconnection pattern also has an obvious zonal distribution in mid-high latitudes (Fig. 6b), and the wave source anomalies over the North Atlantic favor eastward propagation of the Rossby wave. At the same time, the EAP and SCA teleconnection wave source anomalies show obvious positive anomalies in the Mediterranean region at 30°E. The anomalous convergence (divergence) over the Mediterranean Sea can affect the maintenance of the SCA teleconnection pattern (Liu et al. 2014). At 500 hPa, the wave source anomaly of the SCA teleconnection pattern is significantly reduced in high latitudes, and the EAP teleconnection pattern is mainly affected by the wave train anomalous at the mid-latitude (Fig. 6c, d). The wave source anomaly distribution of EAP and SCA teleconnection does not show an obvious connection at 850 hPa (Fig. 6e, f). The above results show that the influence of
SCA teleconnection on EAP teleconnection is mainly shown in the middle and upper troposphere.

### 3.3 Sea surface temperature

Figure 7 displays the sea surface temperature (SST) in the preceding winter, spring, and summer regressed onto the EAP and the SCA indices. It can be seen that the regression coefficients are generally negative, but there are some differences in the regions with the values that have passed the significance test. The negative coefficients of the SST during the three periods with the EAP teleconnection index all appear in East Pacific, which all have passed the significance test at 95% confidence level (Fig. 7a, c, and e). Among them, the negative coefficients of the SST with the EAP index are the most significant in preceding winter, which then gradually weaken in the following spring and summer. The regression coefficients indicate that the EAP teleconnection pattern is significantly associated with the El Niño–Southern Oscillation (ENSO). In addition, in the preceding winter and spring, positive coefficients of the SST with the EAP index appear around Philippines and the sea area to its east. Previous studies have also revealed that the EAP teleconnection caused by the anomalous heating of the tropical western Pacific and eastern tropical Pacific is induced by the convective activities over the western Pacific warm pool (Huang and Sun 1994; Kosaka and Nakamura 2006). For the SCA teleconnection index, significantly negative coefficients of the SST in three periods with the SCA index are also found in the East Pacific region, with the most significant occurring in the preceding winter (Fig. 7b and d), which also indicates the significant relationship between the SCA teleconnection pattern and the ENSO event. Therefore, the SST anomaly in East Pacific during the preceding winter may be a common external forcing affecting both the EAP and the SCA teleconnection patterns. Meanwhile,
there are also significantly negative regression coefficients of the SST in the Atlantic and the Indian Ocean with the SCA index, indicating that the SST in these regions also affects the SCA teleconnection. This is consistent with the conclusions in Liu et al. (2014), that is, the anomalously cold SST in tropical Indian Ocean will induce the positive phase of SCA teleconnection pattern. At the same time, Yang et al. (1992) and Rong et al. (2010) also pointed out that the warm SST anomalies in the equatorial Atlantic and the “capacitor effect” of the Indian Ocean will cause anomalous anticyclonic circulations over the Northwest Pacific. Therefore, the SST anomaly in the Indian Ocean may impact the connection between the EAP teleconnection pattern and the SCA teleconnection pattern.

### 3.4 Western Pacific subtropical high

The WPSH has an important impact on the summer precipitation in Southwest China (Tao and Wei 2006; Yan and Wang 2019), and it is affected by both the EAP and the SCA teleconnection patterns (Yang et al. 2009; Gao et al. 2017; Choi et al. 2020). Table 2 shows the correlation coefficients of the EAP and SCA teleconnection indices with the four indices representing the WPSH (area, intensity, ridge line, and western ridge point). It can be seen that the EAP teleconnection index has significantly negative correlations with the indices of area and intensity, and positive correlations with the indices of ridge line and western ridge point. The correlation coefficient is the largest between the EAP index and the ridge line index (0.68). There is no significant correlation between the SCA teleconnection index and the ridge line index. However, the correlations of the SCA teleconnection index with the indices of area, intensity, and western ridge point are stronger than those of the EAP teleconnection index. There is a positive correlation between the SCA teleconnection index and the western ridge point index. In the partial

![Fig. 7](image-url) Regressed preceding winter (a, b), spring (c, d), summer (e, f) SST onto the EAP index (left column) and the SCA index (right column). The dotted area indicates statistical significance at the 95% confidence level.

| Controlling variables | Area  | Intensity | Ridge line | Ridge point |
|-----------------------|-------|-----------|------------|-------------|
| EAP                   | -0.48*| -0.46*    | 0.68*      | 0.39*       |
| SCA                   | -0.61*| -0.59*    | 0.20       | 0.57*       |
| EAP SCA               | -0.29*| -0.27     | 0.67*      | 0.19        |
| SCA EAP              | -0.75*| -0.49*    | -0.15      | 0.48*       |
correlation coefficient, the EAP teleconnection index still has significant positive correlations with the indices of ridge line, the correlation coefficient is 0.67. However, the correlation between the EAP teleconnection index and other indices is significantly weakened. The correlation between the SCA teleconnection index and four indices decreases slightly, but still has significant positive correlations with the western ridge point, the correlation coefficient is 0.48. Tao and Wei (2006) pointed out that the mid-high latitude Rossby wave train could affect the position of WPSH. In the SCA (Fig. 5), the energy of the Rossby wave train propagates eastward to 110° E, forming a long wave ridge (trough) in the region. This will lead to the WPSH advances westward (eastward). In addition, the significant relationship between the SCA teleconnection patterns and the WPSH may be caused by common external forcing. Wu et al. (2000) also pointed out that the anomalously warm SST in Indian Ocean will induce the WPSH advances westward. From the above results, the EAP teleconnection pattern significantly impacts the WPSH, especially on its northward jump or southward retreat. The SCA teleconnection significantly impacts the east–west movement of the WPSH. When the SCA teleconnection pattern is in a positive phase, the WPSH is more eastward.

### 3.5 Vertical velocity

Figure 8 displays the vertical velocity regressed onto the EAP and the SCA indices. The regressed of the EAP index shows the vertical velocity (ω) > 0 appears in the north of Southwest China, especially in the western Sichuan Plateau and Guizhou, which corresponds to obvious descending motions and will thus reduce the precipitation in these regions, while ω < 0 appears in the southern part of Southwest China, corresponding to obvious ascending motions, which will increase the precipitation in these regions (Fig. 8a). In the regressed of SCA index, the distribution pattern is consistent with that in Fig. 8a, showing the ω > 0 in the north and ω < 0 in the south in Southwest China.

### 4 Effects of different configurations of EAP and SCA teleconnection patterns on summer precipitation in Southwest China

The EAP and SCA teleconnection patterns can be divided into four categories of configurations based on their phases (Table 3): (I) positive EAP + positive SCA, (II) negative EAP + negative SCA, (III) positive EAP + negative SCA, and (IV) negative EAP + positive SCA.

Figure 9 displays the spatial distributions of composite summer precipitation anomalies in Southwest China under different configurations. For configuration of category I, the summer precipitation anomalies in Southwest China show a distribution characteristic similar to “negative in the north and positive in the south” (Fig. 9a). There are negative precipitation anomalies in the western Sichuan Plateau, eastern Sichuan, Chongqing, and Guizhou, and positive anomalies in Yunnan and Sichuan basin. For configuration of category II, the precipitation anomalies present an opposite spatial distribution to that of category I, that is, “negative in the north and positive in the south” (Fig. 9b). The results reveal that when the two teleconnection patterns are both in positive or negative phases, the precipitation distribution is consistent with the results in Section 3.1. For configuration of category III, the summer precipitation in Southwest China generally shows negative anomalies, while the positive anomalies mainly appear in Sichuan basin but have not passed the significance test (Fig. 9c). The center of negative precipitation anomalies is located in Chongqing, where the values have passed the significance test. For configuration of category IV (Fig. 9d), the southwestern region is dominated by positive precipitation anomalies, and the center of positive precipitation anomalies is located in Guizhou. While the negative precipitation anomalies mainly appear in northeastern and northwestern Sichuan. It is found that no opposite distribution of precipitation anomalies...
anomalies between the north and the south can be found in configurations of categories III and IV. For precipitation anomalies under configurations of categories I and II, the results are consistent with the conclusions of correlation analysis in Section 3.1. The positive phases of EAP and SCA will reduce the precipitation in western Sichuan Plateau, eastern Sichuan, Chongqing, and Guizhou, while the negative phases of EAP and SCA correspond to an opposite precipitation anomaly distribution. The results are related to the geographical location of Southwest China, which is a region not directly affected by the EAP and SCA teleconnection patterns. Therefore, the influences on the precipitation in this region under different configurations may not be completely symmetrical.

Table 3  Corresponding years under four categories of configurations based on the EAP and SCA patterns phases

| Year | EAP > 0.3 | SCA > 0.3 |
|------|----------|----------|
| I    | 1972     | 1973     | 1978     | 1997     |
| II   | 1980     | 1987     | 1993     | 1998     | 2003     | 2009     | 2017     | 2019     |
| III  | 1979     | 1981     | 2004     | 2012     | 2013     |
| IV   | 1995     | 1996     | 2014     |

Fig. 9  Distribution of summer precipitation anomalies in Southwest China under different configurations of SCA and EAP indices (a EAP(+)SCA(+), b EAP(−)/SCA(−), c EAP(+)/SCA(−), d EAP(−)/SCA(+)). The dotted area indicates statistical significance at the 95% confidence level.
4.1 Atmospheric circulations under different configurations

Figures 10 and 11 display the spatial distributions of 500 hPa geopotential height anomaly and 850 hPa wind vector anomaly under different configurations, respectively. For configuration of category I (Fig. 10a), the 500 hPa geopotential height anomalies over East Asia present a meridional distribution of “− + −” pattern, and the middle and high latitudes in 45°–70° N are dominated by a wide range of negative anomalies. Two centers of obviously negative anomalies appear over the regions north of the Balkhash Lake east of Ural Mountains and over the region of Northeast Asia east of Baikal Lake (Fig. 10a). While significantly positive anomalies appear over the Sea of Japan, where no persisting blocking high is formed. In this case, the East

![Image of Figure 10](image-url)  
**Fig. 10** The anomaly distribution of 500 hPa height field under different configurations of four teleconnections (a EAP(+)SCA(+), b EAP(−)/SCA(−), c EAP(+)SCA(−), d EAP(−)/SCA(+)); the shaded part is the area passed the level significance test of 99%, 95%, and 90% in descending order, the blue box part is Southwest China region, and red lines are 5860 gpm and 5880 gpm

![Image of Figure 11](image-url)  
**Fig. 11** The anomaly distribution of 850 hPa wind field under different configurations of four teleconnections (a EAP(+)/SCA(+), b EAP(−)/SCA(−), c EAP(+)/SCA(−), d EAP(−)/SCA(+)); the shaded part is the area passed the level significance test of 99%, 95%, and 90% in descending order, and the blue box part is Southwest China region
Asian trough weakens, causing weak meridional circulation in middle and high latitudes, which is not conducive to the southward movement of cold air. The location of subtropical high is more northward and eastward than normal, and the water vapor from the South China Sea and western Pacific is difficult to reach Southwest China. At the same time, significantly negative anomalies appear in low-latitude areas, and the southwest monsoon is stronger with a more northward position, which enhances the southwesterly airflow transporting from the Arabian Sea to the east through the Bay of Bengal. Thus, the water vapor is transported to an region more eastward, which decreases the water vapor transported to Southwest China, especially in the northern part. On the corresponding 850 hPa wind field (Fig. 11a), in the low latitudes of 10°–20° N, there are obvious westerlies from the Arabian Sea to the western Pacific, an obvious cyclonic circulation anomaly north of Philippines, and an obvious anticyclonic circulation anomaly over the Sea of Japan. The co-action of circulation anomalies affects the north of Southwest China through easterly airflows, and induces a weak cyclonic circulation over the south of Southwest China, resulting in the opposite spatial distribution of deficient precipitation in the western Sichuan Plateau, eastern Sichuan and basins, and abundant precipitation in Yunnan.

For configuration of category II, the spatial distribution of 500 hPa geopotential height is opposite to that of category I (Fig. 10b). Specifically, the 500 hPa geopotential height anomalies present a meridional distribution of “− +” pattern over East Asia, while a wide range of negative anomalies appear over the Sea of Japan. Positive anomaly centers appear over the region north of the Balkhash Lake to the east of the Ural Mountains and the region north of the Okhotsk Sea, and the meridional circulation dominates the middle and high latitudes, which is conducive to the southward movement of cold air. Meanwhile, the location of subtropical high is more southward and westward than normal, while Yunnan is directly controlled by the subtropical high, causing less precipitation in this region. Besides, the southwest monsoon is relatively weak, which is conducive to the southwest water vapor transporting to the north of Southwest China. Chen et al. (2010) pointed out that this circulation situation is conducive to the summer precipitation in western Sichuan Plateau. On the corresponding 850 hPa wind field, there is an anticyclonic circulation anomaly near the Sea of Japan (Fig. 11b). An obvious meridional airflow appears to the south of this circulation anomaly, which transports the cold air from the middle and high latitudes to Southwest China, while the warm and moist air is brought to Southwest China by the westerly airflow in middle and low latitudes brings the warm and humid air to Southwest China, thus causing abundant precipitation in this region.

For configurations between categories III and IV, the difference in the WPSH is small, except that the WPSH with a more southward location in category IV is more conducive to the water vapor transport to Southwest China. The 500 hPa geopotential height anomalies in middle and high latitudes present opposite spatial distributions under the two categories of configurations (Fig. 10c and d). For configuration of category III, the distribution of “− + −” pattern in middle and high latitudes is not conducive to the southward movement of cold air, while the circulation under configuration of category IV is on the contrary, which is conducive to the southward movement of cold air. On the corresponding 850 hPa wind field under the configuration of category III, the Southwest China is mainly dominated by anticyclonic circulations, causing deficient precipitation in this region (Fig. 11c), while under the configuration of category IV, there is an obvious convergence of north and south airflows, thus causing abundant precipitation in this region (Fig. 11d).

### 4.2 Water vapor transports under different configurations

The water vapor transporting to East Asia mainly comes from the Indian Ocean and the Bay of Bengal, followed by the Pacific, while the Tibetan Plateau has an eastward turning effect on the water vapor from the south (Miao et al. 2005; Zhou et al. 2008). The water vapor transporting to the east of Southwest China is mainly affected by the intensities of water vapor transports from the Indian Ocean and Pacific Ocean (Li et al. 2010, 2013).

For configuration of category I (Fig. 12a), the water vapor in low-latitude region south of 20° N is mainly transported through zonal belts. For one transport belt, the water vapor is transported eastward from the Arabian Sea and continues eastward after crossing the Indian Peninsula and the Bay of Bengal and converging with the water vapor from the Indochina Peninsula. For another transport belt, the water vapor is transported westward from the equatorial region of the northern New Guinea, makes a turning over the ocean west of the Philippine Islands and merges into the previous water vapor channel, which then makes another turning over the ocean east of the Philippine Islands and is finally transported to Southwest China from the western Pacific. After that, the water vapor splits into two branches in the middle and lower reaches of the Yangtze River and weakens. One branch continues westward, enters Southwest China, and is further transported to the southern region of Southwest China. The other branch turns north over the eastern Southwest China and is transported to North China, which diverges over the northern part of Southwest China and thus is not conducive to the formation of precipitation in the northern part.

For configuration of category II (Fig. 12b), there is also an obvious zonal transport of water vapor in low-latitude region, but the transport direction is opposite to that under the configuration of category I, with the water vapor being transported westward from the western Pacific. While the northern part...
of the water vapor turns northward over the Bay of Bengal and further reaches the south side of the plateau, which then turns eastward to Southwest China due to the blocking effect of Tibetan Plateau. In addition, there is a water vapor convergence center on the Korean Peninsula. The water vapor from middle and high latitudes is transported southward to Southwest China across the south side of this convergence center and intersects with the water vapor which turns eastward from the southern plateau over the northern part of Southwest China, forming a strong water vapor convergence over this region, which is favorable for the formation of precipitation in the region.

For configuration of category III (Fig. 12c), the water vapor in low-latitude region is transported eastward, which is similar to that of category I. However, category III corresponds to less southwestward-transported water vapor and thus less water vapor transported to Southwest China compared with the situation under the configuration of category I. As affected by the SCA teleconnection, the divergence of water vapor over the Sea of Japan weakens, leading to less water vapor transported westward to Southwest China.

For configuration of category IV (Fig. 12d), the water vapor over the low-latitude regions is transported westward from the western Pacific, which is similar to that under the configuration of category II. However, the water vapor in this situation makes a northward turning earlier than that under category II, which turns northward around 95° E. A water vapor convergence center extending southwestward appears over the Sea of Japan, through which the water vapor from the middle and high latitudes is transported to Southwest China and converges with the water vapor that is transported to the southeast part of Southeast China after a northward turning over the low-latitude regions. On this basis, a water vapor convergence center is formed over the east part of Southwest China, which favors the precipitation in this region.

5 Conclusions

Based on the summer precipitation data in Southwest China and the NCEP/NCAR reanalysis data from 1970 to 2019, the characteristics of summer precipitation in Southwest China
is analyzed, and the relationships of the summer precipitation in Southwest China with the SCA and EAP teleconnection patterns are further investigated. It is found that the SCA and EAP teleconnection patterns are closely related to the summer precipitation in Southwest China. The SCA and EAP teleconnection patterns can be divided into four categories of configurations based on their phases. On this basis, the interaction between the SCA teleconnection and the EAP teleconnection as well as the spatial distributions of summer precipitation in Southwest China under different configurations are further explored. Finally, the influences of two teleconnections under four configurations on the summer precipitation in Southwest China are investigated from the aspects of circulation situations and water vapor transport. The main conclusions are as follows.

The EAP and SCA teleconnection patterns are negatively correlated with the summer precipitation in Southwest China during the same period. While the positive (negative) phase of both teleconnection patterns corresponds to above (below) normal precipitation in the northern part of Southwest China.

There is a significantly positive correlation between the EAP and SCA teleconnection patterns. The SCA teleconnection is beneficial to the development and maintenance of the EAP teleconnection pattern. Moreover, both the EAP and SCA teleconnection patterns are related to the SST anomaly in the eastern equatorial Pacific, with the influence of the SST anomaly in preceding winter being the most significant. Therefore, the EAP and SCA teleconnection index anomalies in the same phase (the same positive or negative anomalies) affect the precipitation in Southwest China the most.

The EAP and SCA teleconnection patterns have an important impact on the WPSH and the water vapor transported to Southwest China. When the EAP teleconnection pattern is in its positive (negative) phase, the location of WPSH is more northward (southward) than normal; when the SCA teleconnection pattern is in its positive (negative) phase, the location of subtropical high is more eastward (westward) than normal. When the two teleconnection patterns are both in positive or negative phases, the water vapor transferred is less (more) from the south side of the Tibetan Plateau to the southwest. When the two teleconnection patterns are in opposite phases, the water vapor transport is more complex in southwest China and not exist obvious vapor transport characteristics.

Author contribution Yang Mingxin contributed to the conception of the study, performed the data analyses, and wrote the manuscript; Xiao Tiangui contributed significantly to analysis and manuscript preparation; Li Yong contributed significantly to analysis and manuscript preparation; Zhao Ping, Huang Wei, and Huang Wei helped perform the analysis with constructive discussions.

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Data availability The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

Code availability Not applicable.

Declarations

Conflict of interest The authors declare no competing interests.

Consent for publication All authors agree to publish this paper.

Ethics approval Not applicable.

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