Hindawi
Advances in Meteorology
Volume 2019, Article ID 1376980, 10 pages
https://doi.org/10.1155/2019/1376980

Research Article

Influence of Asian-Pacific Oscillation on Precipitation in Central Eastern China during Autumn (1960–2016)

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Received 6 August 2019; Revised 23 October 2019; Accepted 13 November 2019; Published 1 December 2019

Academic Editor: Budong Qian

The Asian-Pacific Oscillation (APO) plays an important role in precipitation in Central Eastern China (CEC). This study analyzed observational and reanalysis data to investigate CEC precipitation during autumn (1960–2016) and its association with the APO. The APO index (APOI) was redefined, and an autumn CEC precipitation index (CECPI) was calculated to elucidate the relationship between the APO and CEC precipitation. Significant positive correlation (correlation coefficient: 0.60) was found between the APOI and CECPI. Further analysis revealed anomalous southerly winds at 850 hPa over CEC when the APO was strong, which corresponded to anomalous strengthened (weakened) sea level pressure and increased 500-hPa geopotential height over Asia (the Pacific), together with strong meridional shear of the East Asian jet. This configuration is conducive to transportation of warm moist air to CEC during strong APOI years (SAY), but the effect is much diminished during weak APOI years. Moreover, strengthening of both the Walker Circulation of the tropical Pacific and the anomalous upward movement (and convergence) over the Western Pacific (WP) observed during SAY is also conducive to the formation of precipitation in CEC. A possible physical explanation for the close association of the APO with tropical circulation changes is that decreased (increased) sea surface temperature in the tropical eastern Pacific (WP and extratropical Pacific) is beneficial for stimulating a strong APO teleconnection pattern, which further affects precipitation in CEC by strengthening the connection between tropical and subtropical regions.

1. Introduction

The Fifth Assessment Report of the Intergovernmental Panel on Climate Change warns that increased uncertainty regarding the future supply of fresh water under the conditions of global warming could have serious socio-economic impacts. Therefore, the study of global precipitation change is a research topic recognized as becoming increasingly important. Autumn is a season of transition in China's climatic system that generally brings reduced precipitation. However, the significant interannual and interdecadal variabilities of autumn precipitation in China can cause floods and droughts, which means autumn precipitation is of crucial importance to the annual water budget, autumn streamflow magnitude, time of crop sowing, and agricultural production. For example, the county-level drought in autumn 2009 affected more than 16 million people and 11 million livestock in southern China, and directly related economic losses totaled 19 billion yuan (~US$3.04 billion) [1, 2]. Thus, information on the variability of physical mechanisms driving autumn precipitation in China is required urgently, not only for scientific interest but also for various applications such as assessment of social risk and disaster management.

With the socioeconomic boom in China during recent decades, precipitation-related disaster losses are not only due to abundant rainfall in summer but also increasingly to anomalies of autumn precipitation. However, most previous related research has focused mainly on the summertime precipitation that accompanies the East Asian Summer Monsoon [3, 4, 5], whereas the precipitation received in autumn has been somewhat overlooked. Fortunately, both the Chinese government and the academic community have begun to explore the anomalies of autumn precipitation, including the variation characteristics and related atmospheric circulation mechanisms. For instance, studies have shown that the change of precipitation intensity in autumn in China has significant relationship with sea surface temperature (SST), anomalies of which can affect atmospheric circulation and thus affect precipitation [6, 7, 8]. In relation to drought in southern China, Gu et al. [9] suggested an increase in the east-west thermal contrast along the Pacific equator is favorable for precipitation. Moreover, numerical simulation based on the downscaling method has also shown that both the SST and the 500-hPa geopotential height can act as prediction factors, considerably improving predictions of autumn precipitation [10]. In addition, other studies have shown that certain oscillation patterns (e.g., the Pacific Decadal Oscillation (PDO) and El Niño-Southern Oscillation (ENSO)) can play a crucial role in modulation of regional-scale autumn precipitation over China [11–14].

Previous studies have shown that the Asian-Pacific Oscillation (APO) is a very important teleconnection pattern affecting the Asian-Pacific climate (e.g., temperatures, precipitation, and tropical cyclones); however, most relevant studies have focused on summer [15–17]. Therefore, it is necessary to analyze autumn precipitation in China in relation to the APO. The APO is defined as a zonal atmospheric mode characterized by a seesaw pattern of change in the variability of the upper-tropospheric temperature (geopotential height) between Asia and the North Pacific [18–20], which reflects the thermal contrast between the Asian continent and the Pacific Ocean. Furthermore, it is also noteworthy that the APO pattern exists not only in summer but also in autumn [21], prompting the question of whether the autumn APO causes associated changes in the precipitation pattern. Thus, the relationship between the autumn APO and concurrent precipitation in China remains to be clarified.

The remainder of this paper is arranged as follows. Section 2 describes the data and the methods used in this study. Section 3 presents the results of the analysis, and Section 4 presents the conclusions.

2. Data and Methods

2.1. Data and Indices. The data used in this study comprised daily precipitation from 839 Chinese stations (CHNS) from 1960–2016, monthly accumulated precipitation from the Climatic Research Unit TS4.01 (on a 0.5° grid from 1901–2016) [22] and monthly mean SST from the National Oceanic and Atmospheric Administration (NOAA) Extended Reconstructed SST V5 (on a 2° grid from 1854–present) [23]. The atmospheric data were obtained from a monthly mean reanalysis dataset provided by the National Centers for Environmental Prediction/National Center for Atmospheric Research. This dataset has 2.5° × 2.5° horizontal resolution, and it covers the period 1948–present [24].

Several climate indices were used to facilitate our analysis, i.e., Niño1, Niño3.4, and Niño4 [25–27] that were obtained from NOAA and the PDO index obtained from the Joint Institute for the Study of the Atmosphere and Ocean [28].

2.2. Method. To study the relationship between the two variables, we used correlation, regression, and composite analyses. An unrotated empirical orthogonal function (EOF) analysis without latitudinal weighting was also used. In this study, autumn was considered to refer to the period from September to October. The study period encompassed 1960–2016. To emphasize interannual variability and to avoid the effect of long-term trends on the relationship, linear trends of the aforementioned data were removed for the correlation, regression, and composite analyses.

3. Results

3.1. Definition of Autumn APO Index and It's Relation with Precipitation. Figure 1 shows the first unrotated EOF1 mode (multiplied by 0.01) and climatology of the autumn mean upper-tropospheric (500–200 hPa) T' (°C) over the Asian-Pacific region (0°–60°N, 0°–360°) for the period from 1960 to 2016. It is clear that there is an obvious zonal temperature difference between the Asian and Pacific regions, with positive T' over Eurasia and negative T' over the midlatitude area of the central and eastern Pacific. Similar to previous studies [21], the areas of 15°–40°N, 60°–120°E, 15°–40°N, and 150°E–130°W were chosen to represent the middle- and lower-latitude regions of the Asian continent and the eastern Pacific, respectively. Therefore, the autumn APO index (APOI) was defined as follows:

$$\mathrm{APOI} = T'_{60^\circ-120^\circ E,\,15^\circ-40^\circ N} - T'_{150^\circ E-130^\circ W,\,15^\circ-40^\circ N}, \quad (1)$$

in which $T' = T - \overline{T}$, where T is the vertically averaged (500–200 hPa) air temperature, $\overline{T}$ is the zonal mean of T, and T' represents the eddy temperature.

To investigate the relationship between the APOI and autumn-accumulated precipitation in China, we calculated the correlation between the APOI and precipitation. Figure 2(a) shows the calculated dependence of the correlation coefficient upon the APOI and precipitation data from CHNS. Results show that precipitation is highly correlated with the APOI over Central Eastern China (CEC; 28°–38°N, 100°–122°E), with a correlation coefficient of ≥0.4 observed in autumn. In contrast, beyond the CEC region, the correlation coefficient is small and statistically insignificant in most regions. As suggested by previous studies, thermal condition in the Asian-Pacific sector has considerable impact on the autumn climate of East Asia [21]. Therefore,

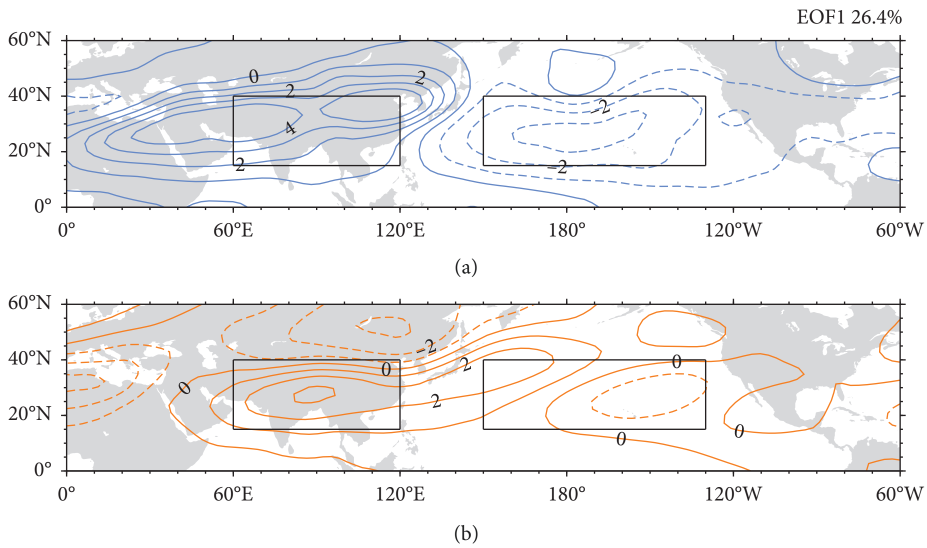

FIGURE 1: (a) Unrotated EOF1 mode (multiplied by 0.01) and (b) climatology of the autumn mean upper-tropospheric (500–200 hPa) T' (°C) over the Asian-Pacific region (0°–60°N, 0°–300°E) for the period from 1960 to 2016.

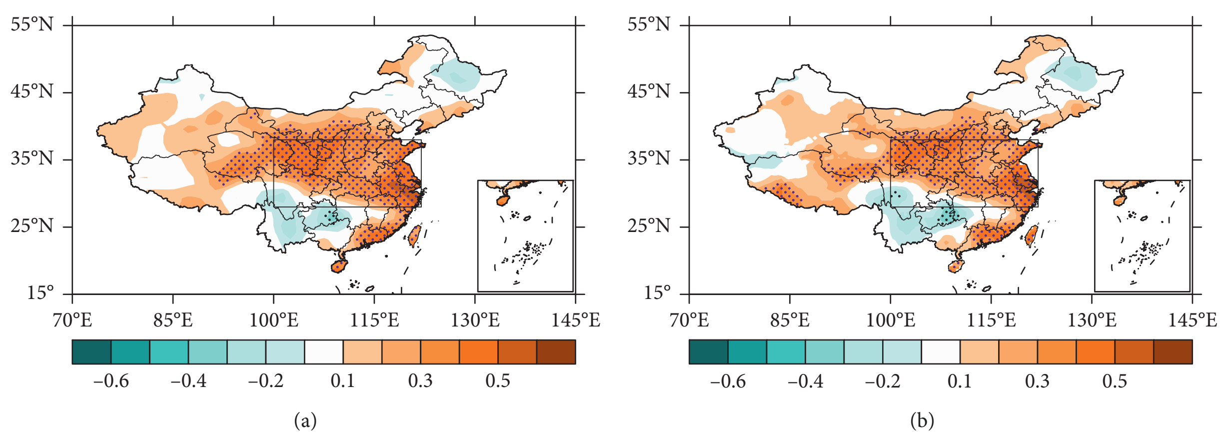

FIGURE 2: Correlation coefficients (colored shading) between the APOI and precipitation over China during autumn. The precipitation data were obtained from (a) CHNS and (b) CRU, respectively. Stippled regions indicate correlation coefficients statistically significant at the 95% confidence level.

accordingly, we can say that CEC precipitation is associated closely with the zonal thermal contrast between the Asian land mass and the Pacific Ocean.

For comprehensive understanding of the impact of the APO on CEC precipitation, the CEC precipitation index (CECPI) was defined as the normalized precipitation regionally averaged over the CEC, and it was used to perform correlation regression analysis with the APOI. Temporal evolutions of the standardized CECPI and APOI for autumn, presented in Figure 3, reveal their significant in-phase relationship with a correlation coefficient of 0.60, significant at the 0.05 confidence level. Furthermore, extreme precipitation events in CEC were defined as the standard deviation of the CECPI above (below) 1.0 (−1.0). The results show that the APOI is highly consistent with precipitation, except for 1998 and 2014, with a corresponding same sign rate between them of approximately 87%. However, the same sign rate between normal precipitation and APOI is

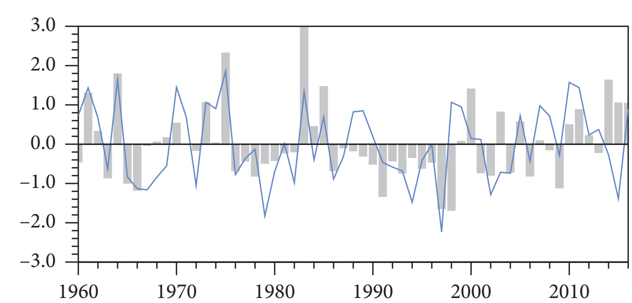

FIGURE 3: Time series of normalized regionally averaged autumn precipitation (gray bars) and the APOI (blue line).

approximately 64%, i.e., the performance is slightly worse. In addition to the strong interannual variability, both series mainly exhibit pronounced interdecadal variability with a decreasing trend before the late 1990s and an increasing trend after the late 1990s. The case for autumn-accumulated precipitation is similar with decreasing CEC precipitation before the late 1990s and increasing CEC precipitation after the late 1990s. Thus, the relationship between the APO and CEC precipitation in autumn is robust on both interannual and interdecadal timescales. When the autumn APO is stronger (weaker) than normal, CEC precipitation is expected to increase (decrease).

Before proceeding with the analysis of circulation anomalies forced by the APO, the climatological mean pattern of the atmospheric circulation and related moisture transport over East Asia are demonstrated first. The distribution of the climatological mean of the vertically integrated water vapor flux reveals two major pathways of moisture delivery to CEC: one from the Indian Ocean (IO) and the other from the South China Sea (SCS) and WP (Figure 4(a)). The change in water vapor transportation caused by anomalies of the APO can be seen in Figure 4(b), in which the APOI is regressed against the vertically integrated water vapor flux. It is clear that strong APO events can induce anomalous cyclones over the SCS and the Indochina Peninsula (IP) that intensify the transfer of moisture from the IO and SCS to CEC. Meanwhile, a flow of moisture from the WP to CEC is also reinforced. Consequently, these factors lead to enhanced supply of moisture to the region, which results in greater amounts of precipitation in CEC.

3.2. Atmospheric Circulation Anomalies Associated with APO and Precipitation. Fluctuations and changes in the large-scale atmospheric circulation play a key role in regulating regional climate variability [29]. The spatial patterns of sea level pressure (SLP), 850-hPa wind vector, 500-hPa geopotential height, 200-hPa zonal wind, and vertical structure of geopotential height regressed on the APOI and CECPI are presented in Figure 5. It is clear that the most pronounced negative SLP and cyclonic anomalies at 850 hPa are centered over South Asia and the IO, while positive SLP and anticyclonic anomalies are located over the North Pacific. This configuration results in significant anomalous southerly winds along the East Asia coast (Figure 5(a)). For geopotential height anomalies at 500 hPa, the regression pattern indicates strengthening of both the East Asian trough and the North Pacific high is accompanied by an increase of the APO (Figure 5(b)). Meanwhile, consistent with the strengthening of the East Asian trough, the meridional shear of the East Asian jet stream is also strengthened (Figure 5(c)), causing anomalous southerly winds. Furthermore, regression of the longitude-height cross section (averaged over 30°–50°N) of the zonal vertical circulation against the APOI (Figure 5(d)) also exhibits a reasonably similar seesaw pattern over East Asia and the North Pacific. The content of Figures 5(e)–5(h)) is the same as that of Figures 5(a)–5(d)) but for the CECPI, which has the same pattern as the APOI. From this perspective, it can be concluded that the APO can be regarded a key control of CEC precipitation via an anomaly of the atmospheric circulation over Asia and the Pacific.

To further elucidate the role of the APO, composite analysis was performed by choosing the 10 strongest (1961, 1964, 1970, 1973, 1975, 1983, 2010, 2011, 1998, and 2007) and 10 weakest (1966, 1967, 1972, 1979, 1982, 1986, 1994, 1997, 2002, and 2015) APO years to illustrate the impact of the APO on CEC precipitation. The composite plots of precipitation, vertically integrated water vapor flux, pseudoequivalent potential temperature, and vertical velocity corresponding to strong APO years (SAY) and weak APO years (WAY) are shown in Figure 6.

As shown in Figure 6(a), precipitation during SAY tends to be 40–100 mm greater than during WAY in most parts of CEC, which is similar to the correlation outcomes (Figure 2(a)), indicating APO has important influence on extreme precipitation. The composite diagram of water vapor flux during SAY and WAY also suggests a greater amount of water vapor is transported from the SCS and WP across the East Asia coast to CEC during the former relative to the latter (Figure 6(b)). This finding is also highly consistent with the results of the water vapor regression (Figure 2(b)). In addition, the pseudoequivalent temperature indicates the WP to be warmer during SAY, when the transportation of warm moist air to CEC is accompanied by unusually strong upward movement, conducive to convergence of water vapor and the formation of precipitation (Figures 6(c) and 6(d)).

3.3. Possible Mechanism. The abovementioned discussion indicates that tropical moisture transport is a key factor for precipitation in CEC and therefore the relationship between the APO and tropical circulation needs to be explored further. Thus, the climatology and composite plots of the vertical circulation are presented in Figure 7. As shown in Figure 7(a), the climatology of the zonal vertical circulation averaged along 5°S–5°N shows easterly (westerly) winds in the lower (upper) troposphere over the Pacific. Moreover, the upward (downward) branch is located in the WP (eastern Pacific (EP)). This equatorial vertical circulation over the tropical Pacific is called the Walker Circulation [30]. It is considered one of the most important factors in climate regulation on both sides of the Pacific, and it has profound impact on the global climate system [31, 32]. Furthermore, the composite plots of the vertical circulation show that the Walker Circulation is strengthened during SAY, but that this configuration becomes much diminished during WAY (Figure 7(b)). In addition, the anomalous upward (downward) branch of the Walker Circulation is also located in the WP (EP) during SAY (WAY). The climatology of the meridional vertical circulation averaged along 100°–120°E shows upward movement in the lower latitudes of the Northern Hemisphere (NH), but downward movement in the higher altitudes of the NH (Figure 7(c)). This means that the warm moist air of low-low latitude ocean areas is characterized by upward movement (and convergence), whereas the cold dry air of high-latitude areas of the NH shows downward movement (and divergence). However, the composite plot of meridional vertical circulation shows the anomalous upward movement (and convergence) and southerly movement at mid and low latitudes of the NH are stronger during SAY than during WAY (Figure 7(d)).

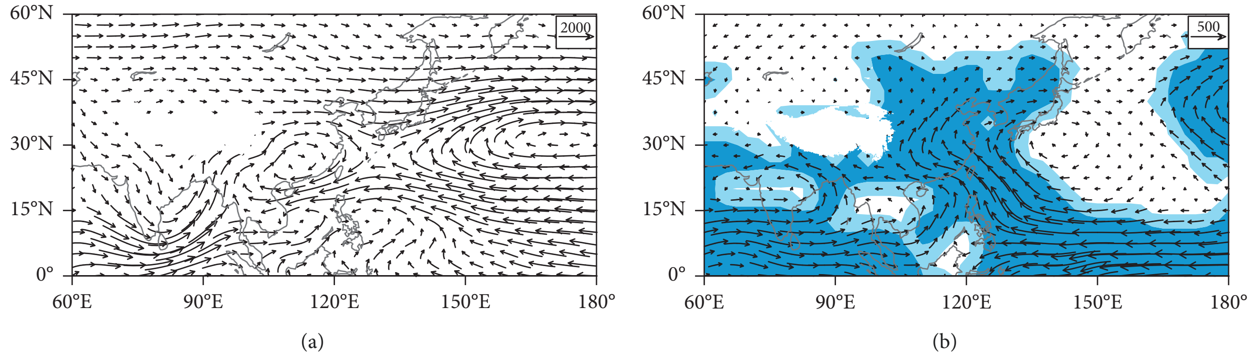

FIGURE 4: (a) Climatology and (b) regression of the APOI onto vertically integrated water vapor flux. Areas significant at the 95% (light) and 99% (dark) confidence level are shaded.

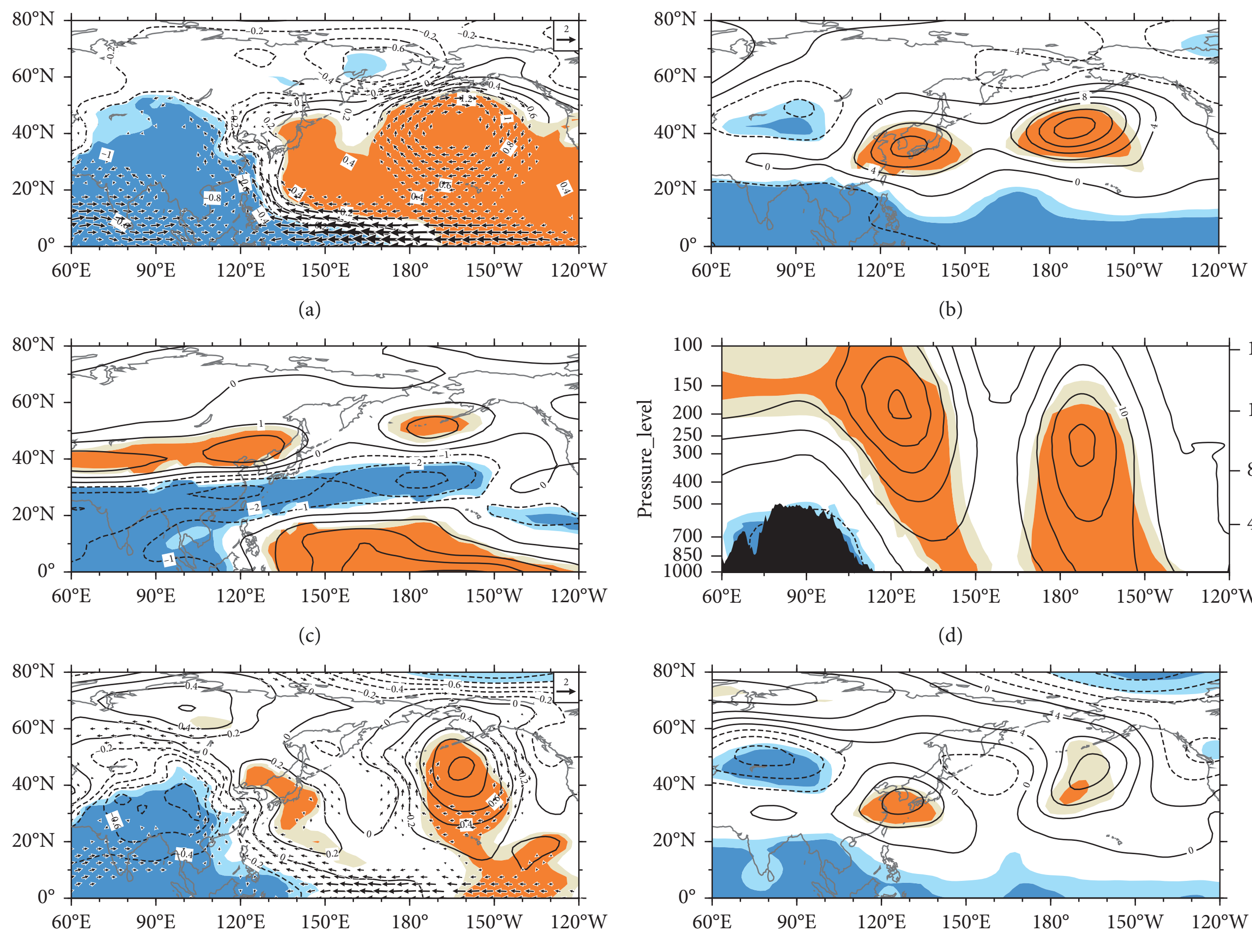

FIGURE 5: Continued.

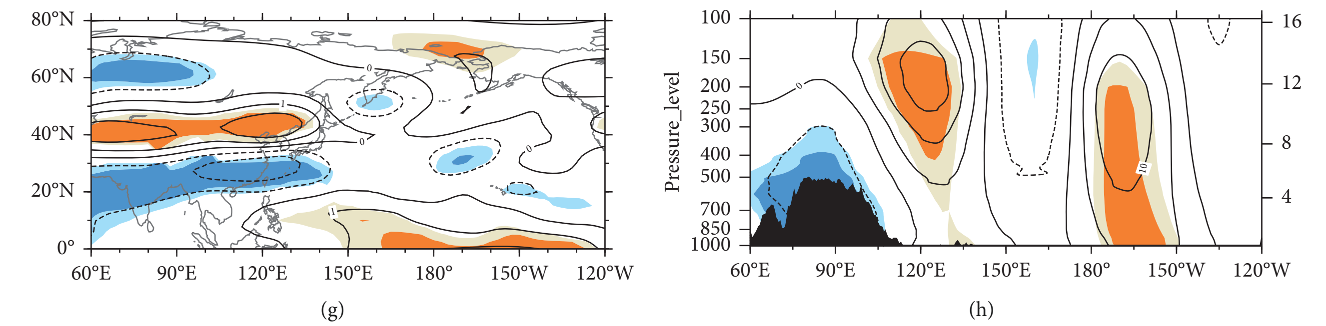

Figure 5: Regression of (a) sea level pressure (SLP) (contours) and 850-hPa wind (vectors), (b) 500-hPa geopotential height (contours), (c) 200-hPa zonal wind (contours) anomalies, and (d) vertical structure of anomalous geopotential height (contours) averaged over 30°–50°N on the APOI. (e)–(h), same as (a)–(d) but for the CECPI. Solid (dashed) contours indicate positive (negative) values. The wind vector is significant at 95% confidence level and shaded values are significant at 95% (light) and 99% (dark) confidence level from a two-tailed Student's *t*-test.

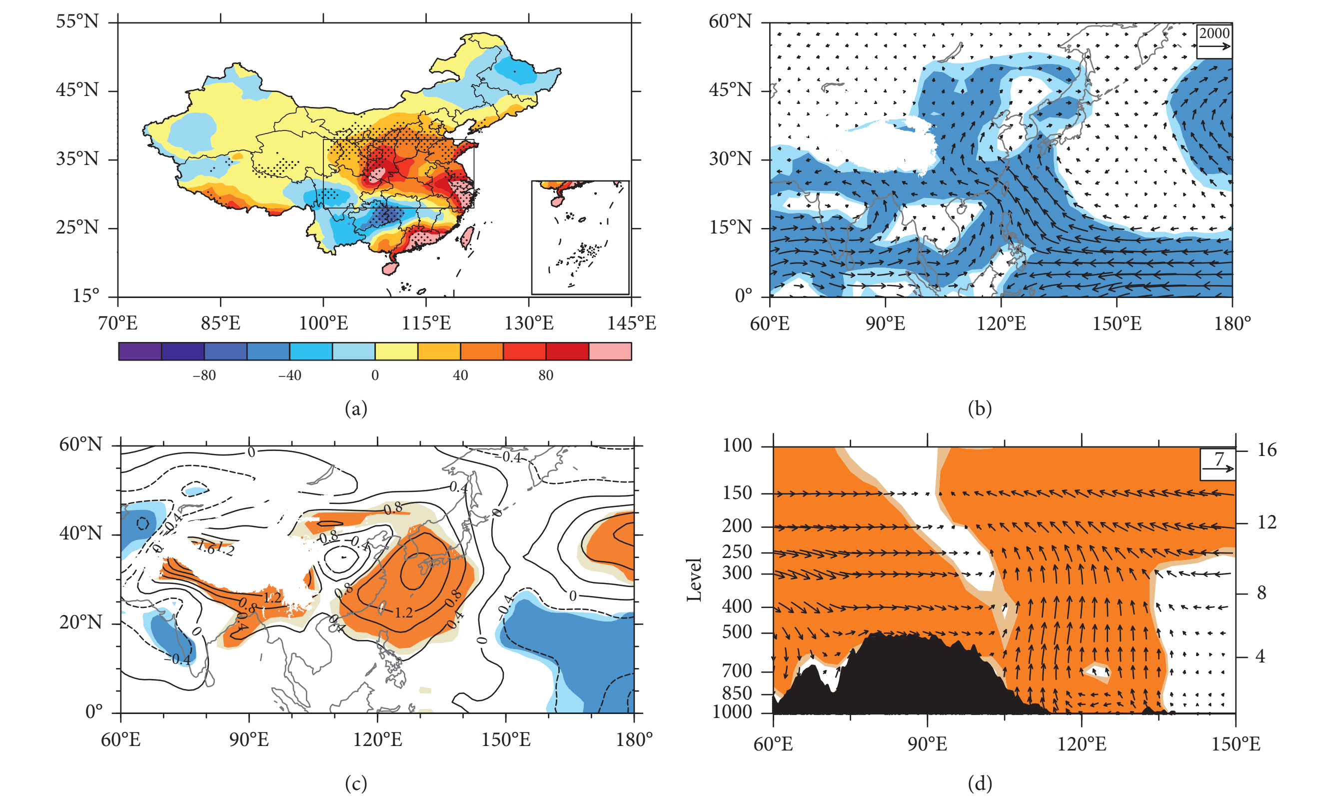

Figure 6: Composite maps of (a) total precipitation (unit: mm, shading), (b) vertically integrated water vapor flux (unit: kg•m·s^{-1}; vectors), (c) pseudoequivalent potential temperature (θ_{se}; unit: K; contours) at 850 hPa, and (d) vertical wind (horizontal wind m·s^{-1}, vertical p-velocity: 0.01 Pa·s^{-1}; vectors) averaged along 30°–40°N between high and low APOI years. Shaded values are significant at the 90% (light) and 95% (dark) (stippled regions; 95%) confidence level from a two-tailed Student's *t*-test.

Figure 8 presents composite maps of the 850- and 200-hPa velocity potential and divergent wind component anomalies between SAY and WAY to explain the changes in the tropical circulation. It can be seen from Figure 8(a) that an anomalous convergence (divergence) center in the lower troposphere is presented over the tropical WP (EP) during SAY (WAY). However, the opposite is true in the upper troposphere (Figure 8(b)), indicating that air coupling between the lower and upper troposphere in SAY is much stronger than in WAY. The above analysis suggests that warm moist air has strong anomalous convergence (and upward movement) in the lower troposphere over the WP during SAY, which is conducive to the formation of CEC precipitation, while this configuration is weaker in WAY, leading to reduced precipitation.

SST is considered an important factor affecting the variation of the tropical circulation [33, 34] and the abovementioned analysis indicates that the APO is closely

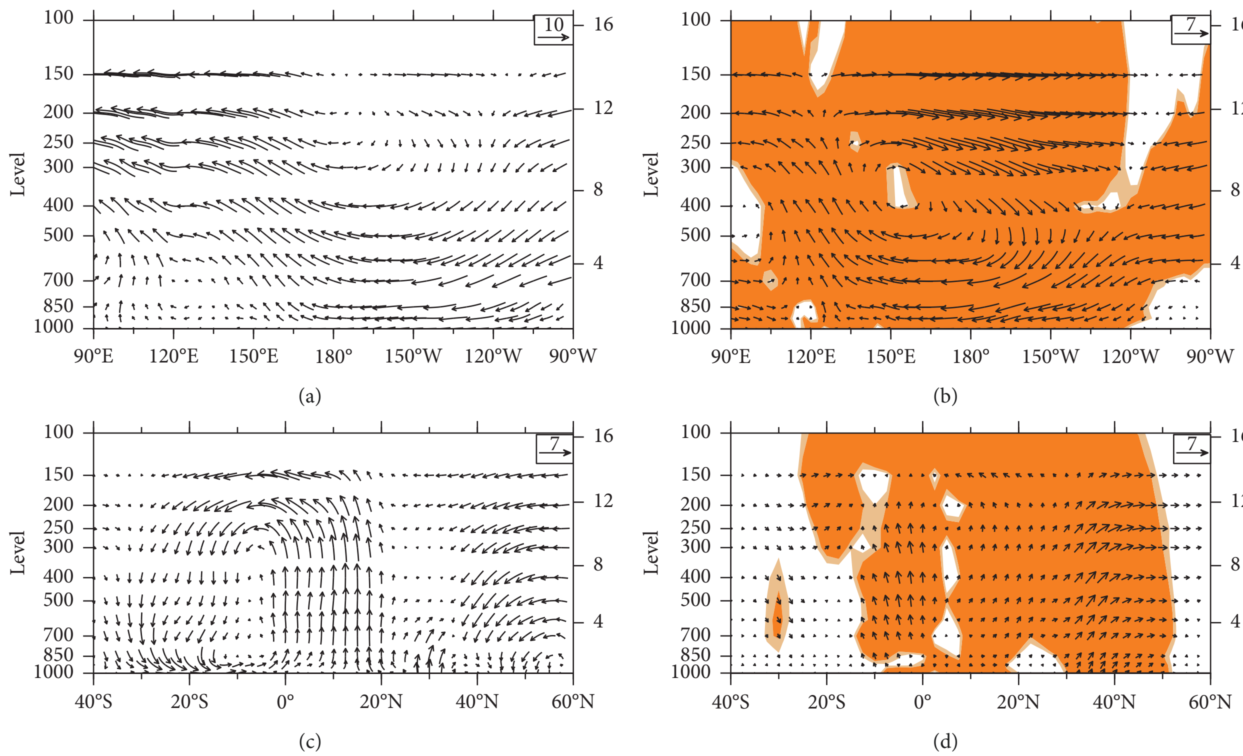

Figure 7: (a) Climatology and (b) composite vertical circulation (unit: horizontal wind m·s^{-1}, vertical p-velocity: 0.01 Pa·s^{-1}; vectors) averaged along 5°S–5°N between strong and weak APOI years. (c) and (d) are the same as (a) and (b), respectively, but averaged along 100°–120°E. Shaded values in (b) and (d) are significant at the 95% (light) and 99% (dark) confidence level.

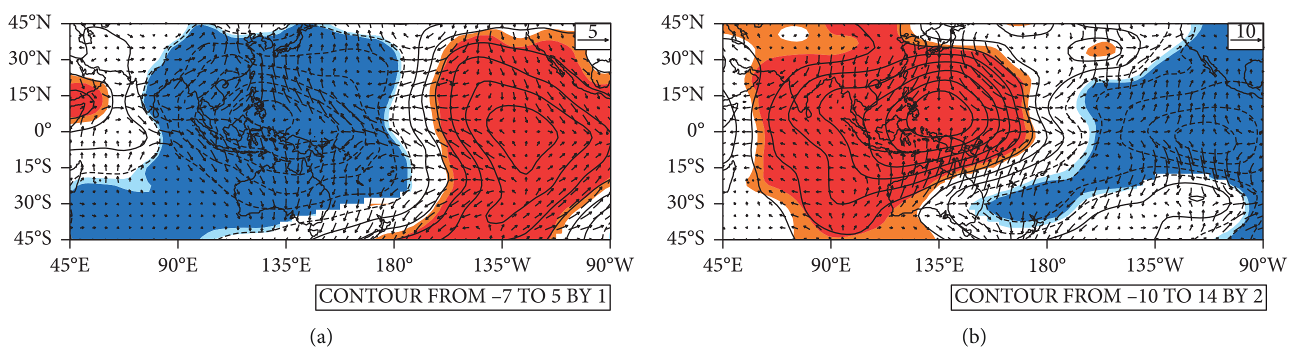

Figure 8: Composite maps of (a) 850-hPa and (b) 200-hPa velocity potential (unit: 10^5 m^2·s^{-1}; contours) and divergent wind component (m·s^{-1}; vectors) anomalies between strong and weak APOI years. Shaded values are significant at the 95% (light) and 99% (dark) confidence level from a two-tailed Student's t-test.

related to the tropical circulation. Therefore, we try to explain the possible physical mechanism of the close relationship between the APO and the tropical circulation from the perspective of SST. Thus, Figure 9 presents the correlation coefficients between the APOI and the concurrent SST for the period from 1960 to 2016. It shows that the APO is correlated negatively (positively) with SST in the tropical central-eastern Pacific (extratropical Pacific and WP) with a minimum (maximum) correlation coefficient below −0.8 (exceeding 0.7), which implies a close relationship between the APO and the ENSO/PDO. Figure 10 also shows that the anomalous fluctuation of the negative APOI (multiplied by −1.0) is highly consistent with that of the Niño4/PDO indices with correlation coefficients of 0.81 and 0.58, respectively. In addition, the correlation coefficients of the other Niño indices (i.e., Niño1 and Niño3.4) and the APOI in the same period were −0.63 and −0.80, respectively, which further reflect the close connection between the APO and Pacific SST.

Previous statistical studies have shown that SST change in the Pacific is closely correlated with the variability of climate over Asia and the Pacific Ocean [19, 35]. When SST increases (decreases) in the extratropical Pacific (tropical eastern Pacific), it is favorable for T' to decrease (increase) in

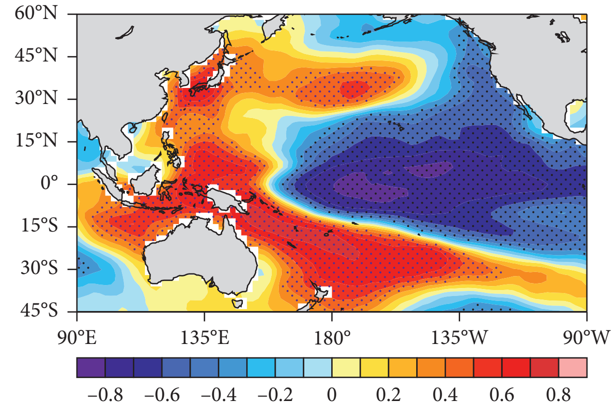

FIGURE 9: Correlation coefficients (colored shading) between the APOI and SST. Stippled regions indicate correlation coefficients are statistically significant at the 99% confidence level.

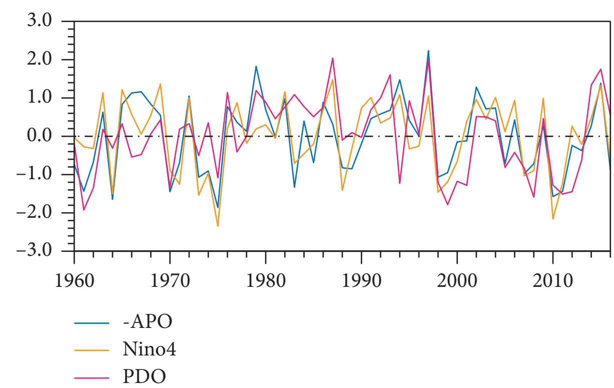

FIGURE 10: Time series of the APOI (multiplied by −1.0), Nino4, and PDO indices.

the upper troposphere over the North Pacific (Asian continent) during summer. Moreover, the model results also exhibit a similar relationship between SST in the extratropical Pacific and tropical Pacific and the APO teleconnection pattern in the CCSM3· The abovementioned result indicates that the close relationship between SST and the APO remains in autumn. Therefore, we can conclude that SST in the tropical Pacific and extratropical Pacific is closely linked to the APO, which is an important factor in stimulating the APO during autumn. According to the results of this study, its manifestation affects not only East Asia but also the Indian Peninsula, Australia, and even the global climate, and this should be explored further in future research.

4. Conclusions

Based on observations and reanalysis data, we redefined an appropriate APO index for autumn during 1960–2016. A relationship between the redefined APO index and autumn-accumulated precipitation in China was found using correlation, regression, and composite analyses. The possible underlying physical mechanisms were determined and the following conclusions were drawn.

Investigation of the relationship between the APOI and precipitation in China revealed that the APO is correlated significantly and positively with CEC precipitation in autumn during 1960–2016 with a correlation coefficient of 0.60.

During SAY, an anomalous southerly wind blows toward land along the eastern coast of Asia, and a negative (positive) barometric anomaly exists over the Asian continent (Pacific Ocean) in the mid and lower troposphere. In addition, there is significant meridional shear of the East Asian jet stream in the upper troposphere. These anomalies suggest that the APO is closely related to the circulation changes of the Asian-Pacific region, which is similar to the atmospheric circulation field affecting precipitation. Moreover, even though autumn in CEC is dominated by dry weather, anomalous southerly winds can transport additional water vapor to CEC during SAY, where it merges with dry cold air from the north causing obvious anomalous upward movement. This configuration strengthens the upward movement (and convergence) of water vapor, which is conducive to the formulation of precipitation. However, this configuration is much diminished during WAY.

Further analysis of the tropical circulation revealed that both southward movement over the WP and the Walker Circulation were strengthened during SAY relative to WAY, with corresponding anomalous strengthened upward movement (and convergence) over the WP and downward movement (and divergence) over the EP in the lower troposphere. A possible physical mechanism is that SST decrease (increase) in the tropical EP (WP and extratropical Pacific) stimulates a strong APO teleconnection pattern, which strengthens the connection between the tropical and subtropical regions and further affects precipitation in CEC.

Although the relationship between the APO and CEC precipitation has been revealed, some problems have not been studied. For example, questions of how the APO might contribute to climate change in other regions (e.g., Australia and the Indian Peninsula), whether the relationship between the APO and precipitation is stable, and could the APOI in summer be used as a predictor of autumn precipitation, are all worthy of further research.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

Acknowledgments

The authors are grateful for access to NCEP Reanalysis dataset, SST dataset and Nino Indices (https://www.esrl.noaa.gov/psd/), the gridded data of precipitation from CRU (http://crudata.uea.ac.uk/cru/data/hrg/cru_ts_4.01/), the PDO index from JISAO (http://research.jisao.washington.edu/pdo/), and data from the surface meteorological observation stations provided by China Meteorological Administration (CMA). The authors also thank Prof. Dr. Klaus Schäfer for all his kind advice and James Buxton, MSc, from Liwen Bianji, Edanz Group China (http://www.liwenbianji.cn./ac/), for editing the English text of this manuscript. Besides, this research was jointly funded by the National Natural Science Foundation of China (91537214 and 41775072), the National Key R&D Program of China (2018YFC1505702), the Outstanding Young Talents Project of Sichuan Province (2019JDJQ0001), the Scientific Research Foundation of CPI Power Engineering Company LTD (CPIPEC-XNYF-91208000100), the Scientific Research Foundation of Chengdu University of Information Technology (S201910621105), and the Scientific Research Foundation of Key Laboratory of Meteorological Disaster (KLME), Ministry of Education (KLME201803).

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