Asia-Pacific Journal of Atmospheric Sciences
https://doi.org/10.1007/s13143-020-00187-1

Online ISSN 1976-7951
Print ISSN 1976-7633

ORIGINAL ARTICLE

Impact of the August Asian–Pacific Oscillation on Autumn Precipitation in Central Eastern China

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Received: 14 September 2019 / Revised: 10 February 2020 / Accepted: 25 February 2020

Abstract

The August Asian–Pacific Oscillation (APO) plays an important role in the variability of autumn (September ~ October mean) precipitation in central eastern China (CEC). Using observational and reanalysis data, the impact of the August APO on autumn CEC precipitation from 1960 to 2016 was studied. The statistical result showed that August APO is closely linked to the autumn precipitation anomalies in CEC with a significant positive correlation (r = 0.45). Further analysis revealed that when the APO is strong, the strengthened East Asian trough and the North Pacific high / vertical shear occur in the mid-lower / upper troposphere, resulting in anomalous southerly along the East Asia coast, which are favorable for strengthening the anomalous convergence and upward movement of moist warm air from the northwestern Pacific and arid cold air from the north China, introducing more precipitation, but that this configuration became much diminished during weak APO years. The possible mechanism can be explained as the thermal effect in the mid-upper troposphere can last from August until autumn, and the corresponding concurrent thermal effect would lead to anomalies in both atmospheric circulation and precipitation. Additionally, though an evidently negative relationship between preceding Niño indices and autumn CEC precipitation was revealed, the August APO induced changes in autumn CEC precipitation is greater than those of Niño indices, whether interannual or interdecadal changes, further indicating that the APO is an effective signal for precipitation prediction in CEC.

Keywords Asian–Pacific oscillation · Atmospheric circulation · Autumn precipitation · Central eastern China

1 Introduction

Autumn precipitation is closely related to productive activities such as agriculture in China. The droughts and floods caused by its intensity changes will lead to decreasing harvests, resulting in huge economic losses. For example, southern China suffered great economic losses totaled more than 19 billion yuan (~US$3.04 billion) due to drought during autumn 2009 (Barriopedro et al. 2012; Zhang et al. 2013). Therefore, it is necessary and urgent to increase understanding of the mechanism of autumn precipitation variability over China and its predictability. However, previous studies on precipitation in China mainly focused on the analysis and prediction of droughts and floods associated with the East Asian monsoon during summer (e.g., Chen and Wu 2007; Wu and Wang 2002; Ding and Johnny 2005; Ding et al. 2010). They show that the intensity of summer precipitation in China is closely related to the preceding Pacific sea surface temperature (SST) anomalies (Chang et al. 2000; Cherchi and Navarra 2003; Tan M 2014). When the El Niño–Southern Oscillation is strong, the East Asian summer monsoon often becomes weaker, corresponding to less precipitation in eastern China (Lau and Yang 1996).

Although there are many studies on the mechanisms involved in the formation and variability of summer precipitation in China, to our knowledge, there is a paucity of studies on autumn precipitation in China. Niu and Li (2008)

Responsible Editor: Soon-Il An.

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Published online: 12 March 2020

found that the western Pacific subtropical high and the SST anomalies of the Western and North Pacific are critical factors affecting precipitation over South China. Gu et al. (2015) reported the east-west SST contrast in the tropical Pacific also shows a strong signal through atmospheric circulation anomalies. Additionally, the increased aerosol concentration has been seen as one of the main reasons for decreasing precipitation in China during recent decades (Chen et al. 2014). Besides the above studies, the 500 hPa geopotential height and SST were used as predictors to better predict regional autumn precipitation in China through numerical simulation experiment (Liu and Fan 2013). In short, these studies suggest that autumn precipitation in China is closely tied to large-scale atmospheric circulation and SST anomalies in the Asian–Pacific region.

The APO is characterized as a zonal "seesaw" phenomenon in the mid-upper troposphere, which reflects the thermal differences over the Asian continent and the North Pacific Ocean (Zhao et al. 2007). The formation, evolution and variation of APO have been intensively studied. It is likely that the strong uplifting heating effect of the Tibetan Plateau plays an important role stimulating the APO teleconnection pattern (Liu et al. 2017). Besides, the SST anomalies over the North and tropical Pacific, and the larger-scale weather systems (e.g., the South Asian high, the westerly jet, the tropical cyclones, and the tropical easterly jet) are closely related to the APO (Zhou et al. 2008, 2010; Zhao et al. 2010; Zou and Zhao 2010; Zhao et al. 2011). In addition, the APO exists not only in summer but also in other seasons (Nan et al. 2009; Zhou and Zhao 2010). All these studies show that the APO is considered to be one of the most important factors contributing to climate change over the Asian-Pacific region.

Since the APO has a significant influence on the East Asian climate, one question arises that whether the preceding APO can be used as a precursory signal for autumn precipitation in China? With this question in mind, this paper attempts to investigate the impact of the preceding APO on autumn precipitation in China and explore the possible physical mechanism involved.

2 Data and Methods

2.1 Data and Indices

Two kinds of rainfall datasets were used in this study: 1) daily mean precipitation data from 839 China Health and Nutrition Survey (CHNS) stations were provided by the China Meteorological Administration and covered the period from 1960 to 2016; 2) TS4.01 data were provided by the Climatic Research Unit (CRU) on a 0.5° grid from 1901 to 2016 (Harris et al. 2014). Monthly mean reanalysis atmospheric data at a 2.5° × 2.5° horizontal resolution were obtained from the NCEP/NCAR and covered the period from 1948 to present (Kalnay et al. 1996).

Before the analysis, the APO index (APOI) was defined as follows (Zhao et al. 2007, 2011a, b), which reflects the thermal difference between the Asian continent (15–50°N, 60–120°E) and the North Pacific (15–50°N, 180–120°W):

$$APOI = T'_{15-50°N,\ 60-120°E} - T'_{15-50°N, 180W-240°W}$$

in which $T' = T - \overline{T}$, where T is the air temperature, $\overline{T}$ is the zonal mean of T, and is the vertically averaged (300–200 hPa) eddy air temperature. In addition, several climatic indices (Niño1, Niño3.4, and Niño4) based on SST anomalies averaged across a given region were used for comparative analysis, which is obtained from the National Oceanic and Atmospheric Administration (Rasmusson and Carpenter 1982; Trenberth 1997; Trenberth and Stepaniak 2001).

2.2 Methods

In order to study the relationship between the two variables, correlation and regression analyses were used to facilitate our research. Unrotated empirical orthogonal function (EOF) analyses without latitudinal weighting were also used. Furthermore, to emphasize the interannual variability, linear trends of the all-time series of the aforementioned data have been removed. Besides, we defined the index's excellent / excellent&good rate (the index's excellent rate = Number of the index's excellent years / Number of total extreme years, the index's excellent&good rate was conducted in the same way) to evaluation the performance of different indices on extreme precipitation, in which the excellent / good years were defined as standardized anomalies exceeding ±1 / exceeding ±0.5 but under ±1. Note that the period studied is restricted to the period from 1960 to 2016, and autumn refers to September to October in this study.

3 Results

3.1 Relationship between the Summer Asian–Pacific Oscillation and Autumn Precipitation in Central Eastern China

Before starting the main result, the relationship between autumn (September ~ October mean) APO and simultaneously accumulated precipitation in China was investigated for the purpose to determine whether autumn precipitation is closely related to APO. As shown in Fig. 1a, the significantly positive coefficients dominate over most parts of the China crossed from East to West, particularly the central eastern China (CEC; 28–38°N, 102–122°E), with the maximum correlation coefficient exceeding 0.5, which is the thresholds of the significant at 90% confidence level (Fig.1a). Due to the strong

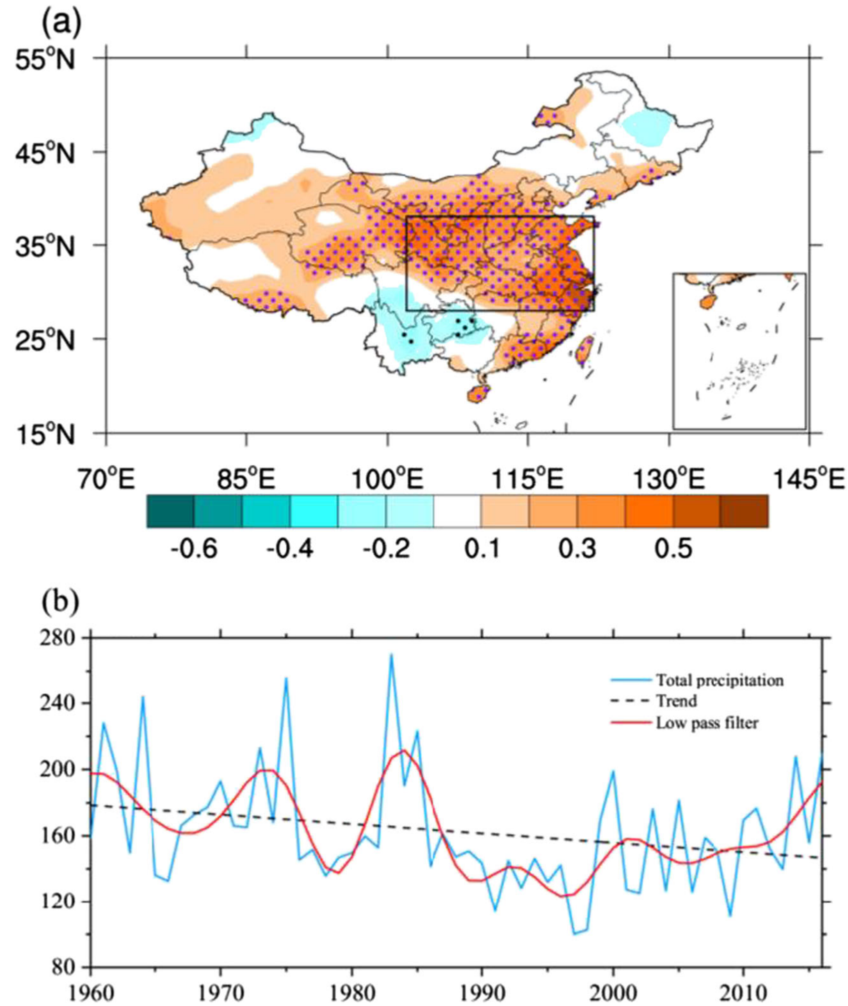

Fig. 1 **a** Distribution of correlation coefficient (colored shading) between the autumn APOI and precipitation in China (Stippled regions indicate correlation coefficients that are statistically significant at the 90% confidence level) and **b** time series of the regionally averaged autumn precipitation in CEC

response of the CEC autumn precipitation to APO, the temporal variability of precipitation in CEC was explored from the perspectives of regional average time series across CEC in CHNS data (Fig.1b). Results show that the climatology of annual accumulated precipitation over the regional reached 960 mm, with autumn / summer accounts for 163 mm / 459 mm, which occupies 17% / 48% of annual precipitation, indicating the autumn CEC precipitation is controlled by the change of moisture transport associate with the East Asian monsoon circulation system become much weaker than summer. Further analysis reveals the interannual and interdecadal changes in autumn CEC precipitation are very evident with a slight downward trend in recent decades, and a minimum (maximum) <100 mm (>270 mm) (Fig. 1b). In addition, the average precipitation can also better reflect the same changes of precipitation in CEC based on CRU data (not shown).

Due to the great variability of CEC precipitation in autumn and its close relationship to APO, it is important and necessary to have a better knowledge of whether the preceding APO can be used as a precursory signal for autumn precipitation prediction. Among the summer months (Fig. 2), the August APO showed the largest correlation, almost equivalent with the autumn APO, indicating the preceding August APO can be a good indicator for the autumn precipitation in CEC. Meanwhile, there is no clear relationship between November precipitation and the August APO (not shown). Therefore, in the following analysis, we will focus on finding the impact of the August APO on autumn (September ~ October mean) CEC precipitation.

To explore the interannual relationship between the August APO and autumn precipitation in CEC, the time series of CEC precipitation was standardized as an index (CECPI) to represent the precipitation intensity variation. It can be seen in Fig. 3 that the fluctuation of CECPI is consistent with that of the APOI with a significant positive correlation ($r = 0.45$, passed the significant at 90%), indicating the August APO has significant impact on the autumn precipitation in CEC.

3.2 Atmospheric Circulation Anomalies with Changes in CECPI and the APOI

Previous studies have shown that regional climate variability is mainly significantly influenced by fluctuations and changes

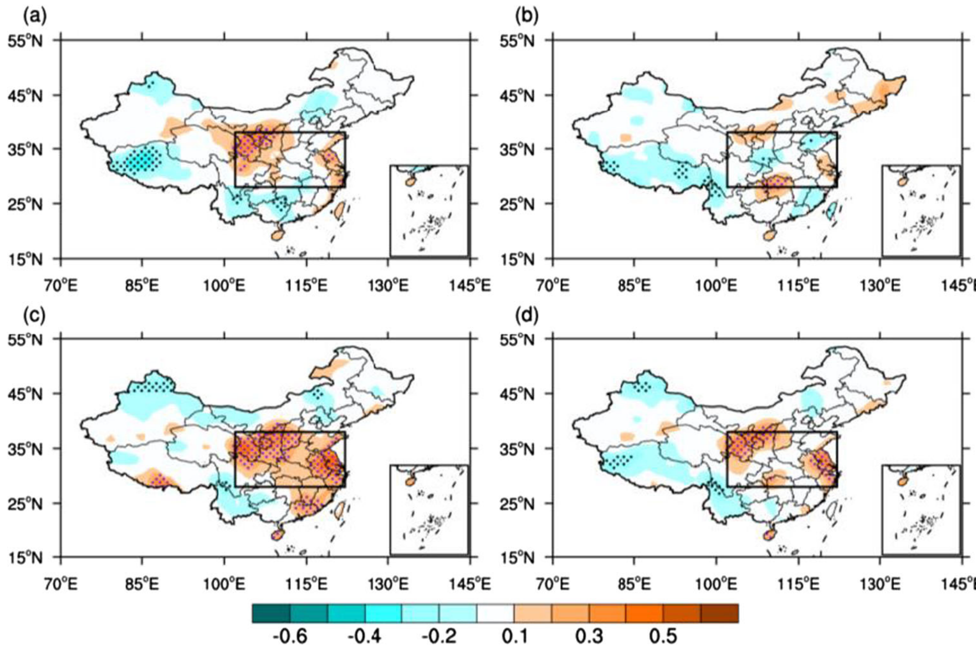

Fig. 2 Distribution of correlation coefficients between the autumn accumulated precipitation in China and **a** June, **b** July, **c** August and **d** summer APOI. Stippled regions indicate correlation coefficients that are statistically significant at the 90% confidence level

in atmospheric circulation (Trenberth 1990). To illustrate the positive correlation between the August APOI and autumn CECPI, the corresponding anomalous atmospheric circulation is described. Figure 4 presents the spatial patterns of sea-level pressure (SLP) and 850 hPa wind vectors, 500 hPa geopotential height, 200 hPa zonal wind, and the vertical circulation structure regressed on the CECPI and the APOI, respectively. It is noticed that the obviously negative (positive) SLP and cyclonic (anticyclonic) anomalies at 850 hPa are dominated over East Asia (North Pacific), which results in significant anomalous southerly winds along the east Asia coast in the lower troposphere (Fig. 4a). The regression of geopotential height at 500 hPa against the CECPI shows a strengthening in both the East Asian trough and the North Pacific high, which was accompanied by an increase of the CECPI (Fig. 4b). Meanwhile, the meridional shear of the East Asian jet stream is strengthened, corresponding to the strengthening of the East Asian trough and causing anomalous southerly wind (Fig. 4c). Furthermore, regression of the latitude–height cross section (averaged over 102–122°E) of the meridional vertical circulation against the CECPI also indicates anomalous upward motions and southerly over middle latitudes (20–40°N) (Fig. 4d). As can be seen from

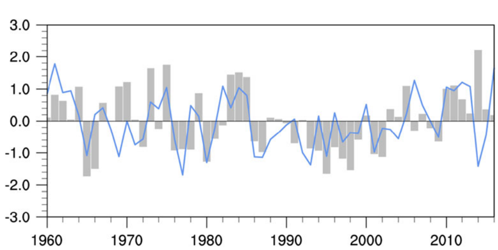

Fig. 3 Time series of the CECPI (bars) and APOI (blue line)

Fig. 4(e)–(h), the regression patterns obtained from the APOI are same as those in as in Fig. 4(a–d), implying that APO should be considered an important factor in determining CEC autumn precipitation through affecting the atmospheric circulation anomalies over the Asia-Pacific region.

Transport of water vapor through atmospheric circulation is regarded as one of the most critical factors in the formation of precipitation. To further explore the characteristics of water vapor transport in CEC, regression of the vertically integrated water vapor flux onto the CECPI and the APOI were conducted. As shown in Fig. 5a, there mainly are two branches of anomalous northward water vapor transport belts originating from the northwestern Pacific and the Indian Ocean, respectively. The anomalous southeasterly and southwesterly prevailing over East Asia enhanced a warm and moist flows transport to mainland China, which is favorable for water vapor convergence, and hence more precipitation over CEC. Similarly, this anomalous feature can be also found from the regression map of vertically integrated water vapor flux with APOI, which implies that the large positive value of the APOI, signifying large excess precipitation coincides with strengthening water vapor transport over CEC.

3.3 Possible Physical Mechanism

Although above findings revealed the atmospheric circulation anomaly associated with this positive correlation between the APOI and the CECPI, the physical mechanism for this close connection still needs to more explanations. As shown in Fig. 6, the explained variance of the unrotated EOF1 mode of autumn upper-tropospheric (300–200 hPa) T' is about 36%, reflecting the dominant role of the difference in the thermal

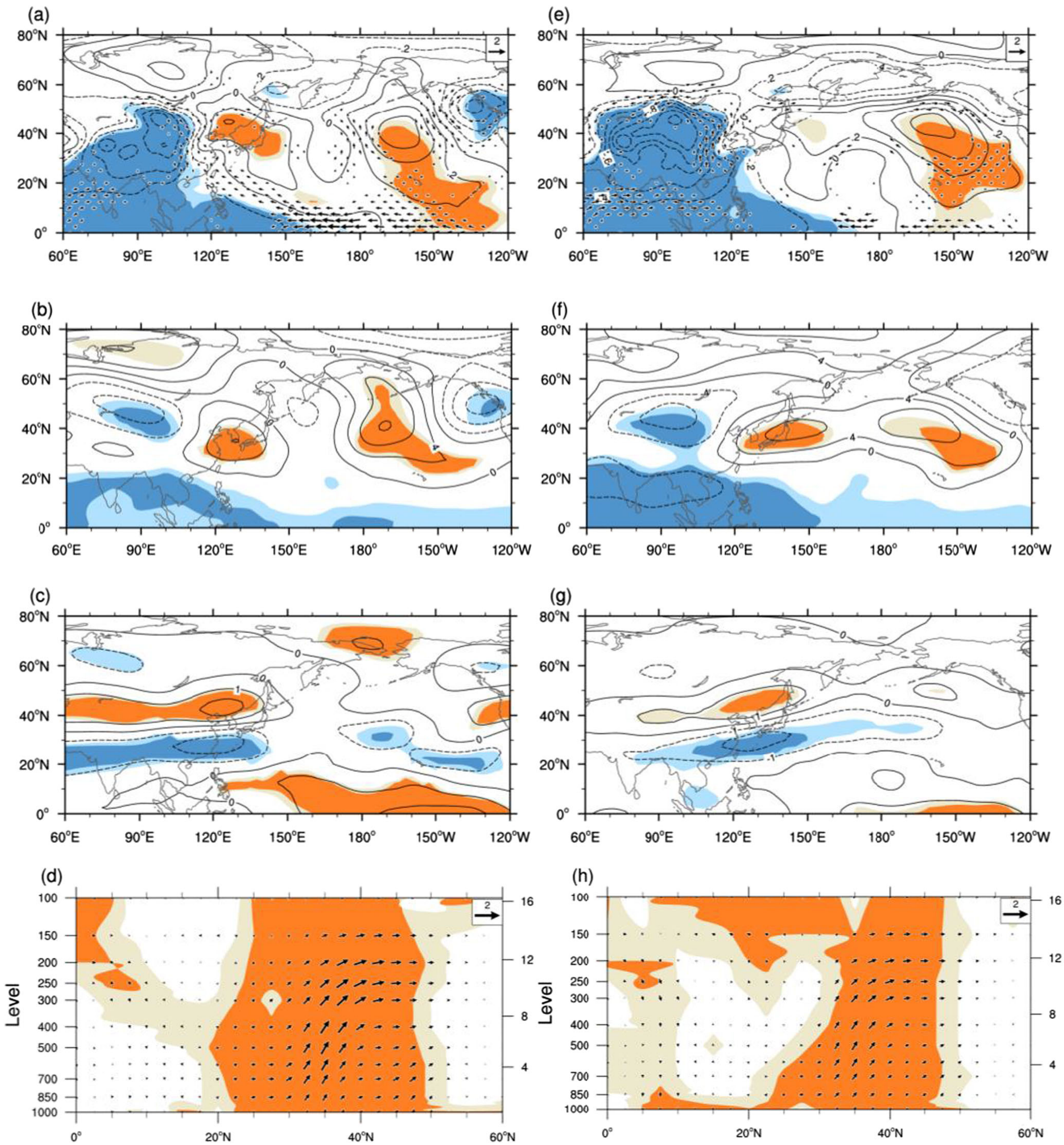

Fig. 4 Regression of **a** sea-level pressure (SLP) (contours) and 850 hPa wind (vectors), **b** 500 hPa geopotential height (contours), **c** 200 hPa zonal wind (contours), and **d** vertical structure of the meridional circulation (vectors) averaged over the region 102–122°E on the CECPI; **e**–**h** same as Fig. 4(a)–(d) but for APOI. Solid (dashed) contour lines indicate positive (negative) values. The wind vector is significant at the 95% confidence level, and significant areas at the 90% (light) and 95% (dark) confidence level are shaded from a two-tailed Student's *t* test

force over Eurasia and the North Pacific with a significant "seesaw" phenomenon (Fig. 6a), which represents a teleconnection pattern like summer APO. Furthermore, the EOF1 time series not only shows evident interannual variation but also obvious interdecadal variation using the low-pass filter (0.125 Hz) accompanied by a significant downward trend, which is similar to the changes of the APOI (Fig. 6b). Thus, there is an important question of what makes them so similar even as they rest in different months? In the following, we try to find a reasonable explanation for this high similarity.

Figure 7a shows that the correlation coefficients between the CECPI and the autumn mean upper-tropospheric (300–

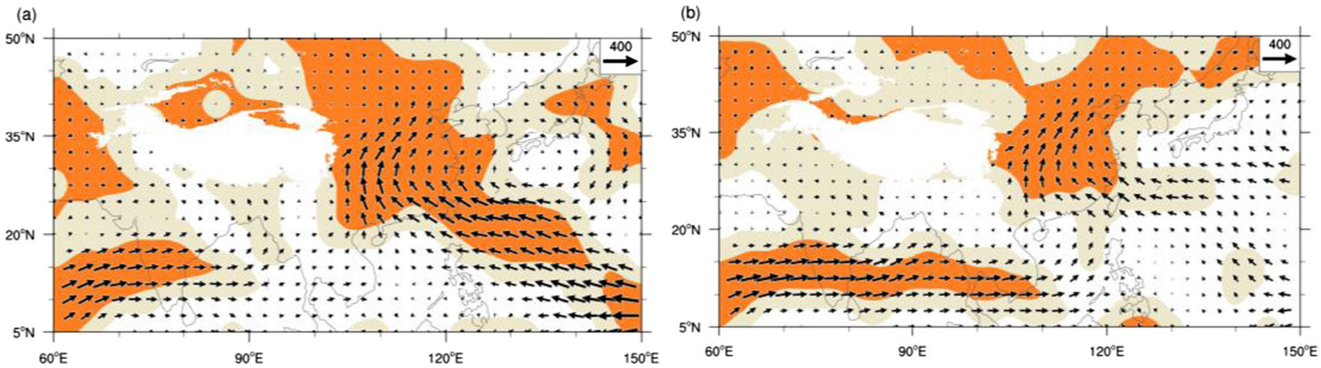

Fig. 5 **a** Regression of the CECPI onto vertically integrated water vapor flux and **b** same as (a) but for the APOI. Significant areas at the 90% (light) and 95% (dark) confidence level are shaded from a two-tailed Student's *t* test

200 hPa) *T'* over Eurasia (North Pacific) are positive (negative) anomalies with a maximum (minimum) of >0.6 (<−0.6). And the correlation coefficient patterns of the longitude–height cross section (averaged over 15–50°N) of the zonal vertical *T'* against the CECPI also presents positive (negative) correlation over Eurasia (North Pacific) in the mid-upper troposphere with a maximum (minimum) of >0.5 (< −0.5) (Fig. 7c), which indicate CECPI was controlled by thermal difference over Eurasia and North Pacific. The above-mentioned positive (negative) correlation of CECPI with autumn mean upper-tropospheric (300–200 hPa) *T'* has the same "seesaw" phenomenon as the consequence of EOF1 over Eurasia and North Pacific in the mid-upper troposphere. Subsequently displayed results of Figs. 7b and d are similar to Figs. 7a and c but for APOI, corresponding to a positive (negative) correlation over the Asian continent (Northern Pacific) in the mid-upper troposphere. In addition, an appreciable significant positive correlation between August and autumn APOI ($r = 0.45$, passed the 90% significance test) was recorded, further suggesting that the August thermal effect like APO mode over the Asia-pacific region in the mid-upper troposphere can be maintained until autumn, and in turn causes anomalous atmospheric circulation and variability of precipitation.

3.4 Comparison of the Impact of Different Indices on Autumn Precipitation in CEC

It is well known that different kinds of Niño indices have been widely used in the climate analysis of precipitation, especially in China (e.g., Wu et al. 2003; Zhang et al. 2007; Wu et al. 2009). This raises the question of does the change of preceding ENSO also can affect the autumn CEC precipitation? Hence, we selected different indices for comparison with

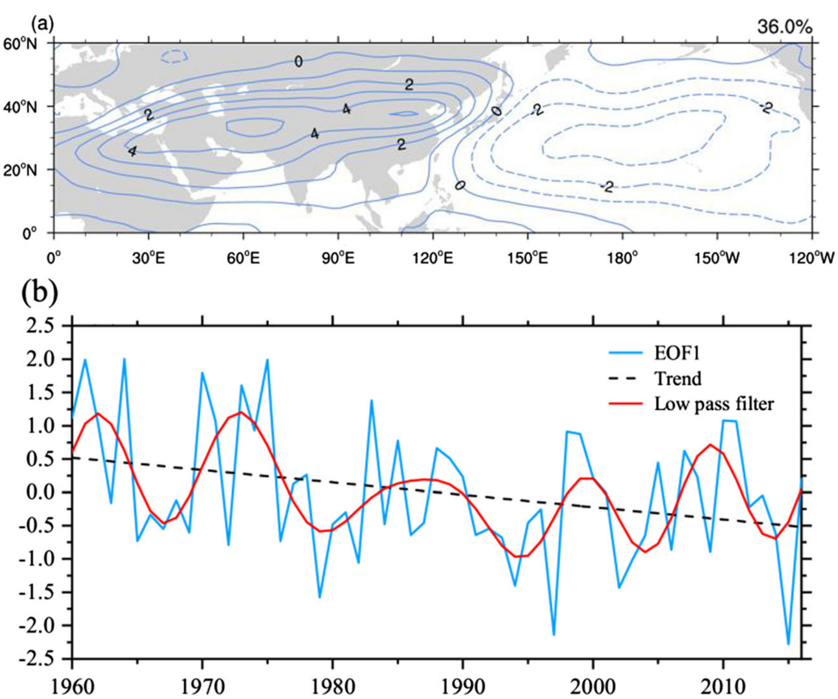

Fig. 6 **a** Spatial distribution and **b** time series for the unrotated EOF1 mode (multiplied by 0.01) of the normalized autumn mean upper-tropospheric (300–200 hPa) *T'* (°C) over the region 0–60°N, 0–270°E

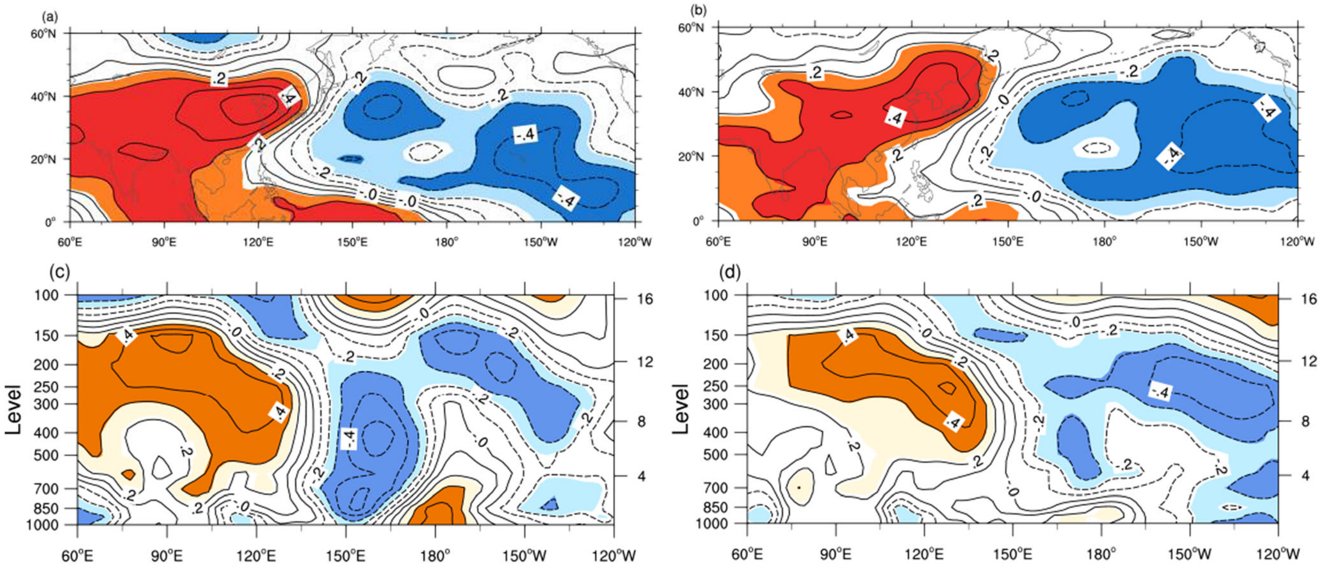

Fig. 7 Correlation coefficients between the autumn mean upper-tropospheric (300–200 hPa) T' (°C) over the region 0–60°N, 60°E–120°W and the **a** CECPI and **b** APOI. Correlation coefficients between the vertical structure of zonal T' (contours) averaged in the region 15–50°N and the **c** CECPI and **d** APOI. The shaded values are significant at the 90% (light) and 95% (dark) confidence level

APOI. The correlation coefficients between the CECPI and Niño indices of the preceding 12 months (Fig. 8a) indicate there is a significant negative correlation holds for CECPI with Niño3.4 in July (Niño3.4Jul) and Niño4 in August (Niño4Aug), with the correlation coefficient of −0.41 and − 0.40, respectively (passes the significance test at 90%). Furthermore, the 21-year sliding correlation was chosen to investigate the interdecadal relationship between the CECPI and the APOI (Niño3.4Jul and Niño4Aug), proving that all three indices had a significant interdecadal relationship with CECPI before 1985, while after 1985, the relationship with the APOI maintains significant (passes the significance test at 90%) until 2003, but the other indices abruptly decrease (Fig. 8b). The above analyses show the APO's performance is superior to Niño3.4Jul and Niño4Aug for prediction autumn CEC precipitation whether in interannual or interdecadal changes.

To more facilitate our research, we evaluated the prediction performance of different indices on CEC precipitation events, corresponding to the 15 strongest and the 15 weakest CECPI years. It is evident that the strongest positive (negative) CECPI shows differences, corresponding to the strongest positive (negative) APOI, negative (positive) Niño3.4Jul, and negative (positive) Niño4Aug during different years, respectively (Table 1). As shown in Table 2, the obtained statistical results show that the outcome of APOI's excellent / excellent&good rate was 36.7% / 56.7%, which is better than the other two indices, indicating the APO is an effective signal for precipitation prediction. However, the performance on prediction will be greatly improved by combining the strongest positive (negative) APOI, negative (positive) Niño3.4Jul and Niño4Aug (the excellent / excellent&good rate = 63% / 73.3%), suggesting that APO should not be used only as a single index, but also combined with other indices (e.g.

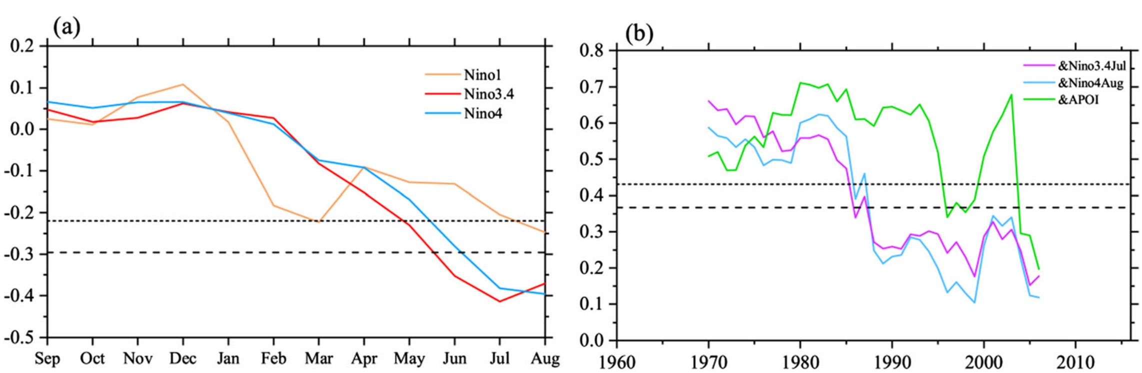

Fig. 8 **a** Correlation coefficients between the CECPI and different Niño indices of the past 12 months, and **b** the 21-year sliding correlation coefficients of CECPI with Niño3.4Jul, Niño4Aug (both multiplied by −1) and the APOI, respectively. The short (long) dashed line indicates a significance level of 90% (95%)

Table 1 The APOI, Niño3.4Jul (multiplied by −1) and Niño4Aug (multiplied by −1) values corresponding to the 15 strongest positive and negative years of the CECPI, respectively

Year	CECPI	APOI	Nino3 .4Jul	Nino4 Aug	Year	CECPI	APOI	Nino3 .4Jul	Nino4 Aug
1961	0.83	1.77	0.01	0.37	1985	1.37	0.80	0.76	0.45
1964	1.08	0.17	0.86	1.37	1987	-0.98	-1.14	-2.18	-1.62
1965	-1.74	-1.08	-1.41	-1.33	1993	-0.87	-1.37	-0.55	-0.64
1966	-1.51	0.20	-0.57	-0.70	1994	-0.94	0.16	-0.57	-1.66
1969	1.09	-1.12	-0.18	-1.24	1995	-1.66	-1.10	0.11	-0.09
1970	1.22	0.00	1.10	0.65	1996	-0.83	0.26	0.45	0.26
1973	1.65	0.60	1.79	1.55	1997	-1.19	-0.66	-2.46	-1.21
1975	1.75	1.04	1.61	2.34	1998	-1.55	-0.36	1.28	1.58
1976	-0.93	-0.58	-0.17	0.30	2001	-1.04	-0.97	-0.07	-0.29
1977	-0.89	-1.69	-0.53	-0.66	2002	-1.13	-0.23	-1.20	-1.33
1978	-0.90	0.48	0.42	0.29	2005	1.10	0.22	0.25	0.01
1979	0.88	0.15	0.31	0.06	2010	1.01	1.06	1.52	2.30
1980	-1.28	-1.30	-0.27	-0.20	2011	1.12	0.95	0.59	1.20
1983	1.45	0.41	-0.17	0.07	2012	0.69	1.21	-0.38	-0.04
1984	1.52	1.04	0.41	0.50	2014	2.23	-1.42	0.10	-0.32

* red number > =1.0, Excellent, 1 > blue number > =0.5, Good

Niño3.4Jul, and Niño4Aug) for the autumn precipitation prediction in CEC.

4 Summary and Discussions

Based on observations and ncep/ncar reanalysis data, a relationship between the preceding apo and autumn precipitation in china from 1960 to 2016 was investigated using correlation and regression analyses. The following conclusions were drawn.

There was a significant positive correlation between the August APO and the autumn CEC precipitation with a correlation coefficient of 0.45. Further analysis of the atmospheric circulation patterns associated with the APOI indicates that significant negative / positive SLP, 500 hPa geopotential height anomalies over East Asia / North Pacific and vertical shear of the East Asian jet stream at 200 hPa cause more warm and humid air transported by the southwesterly winds converged with dry and cold air from the north over CEC, which is conductive to strengthen convergence conditions and upward movement, introducing an increased precipitation. However, this configuration became much diminished during weak APOI years. The possible physical mechanism for such a colse connection is that the thermal effect of August APO can be maintained until autumn, which further causes atmospheric circulation anomalies and precipitation variability in CEC.

Besides, this study has shown that preceding SST anomalies can be important factors for predicting precipitation in CEC, with a significant negative correlation between CECPI and Niño3.4Jul ($r = -0.41$) / Niño4Aug ($r = -0.40$). However, the APOI's prediction performance for autumn CEC precipitation is greater than the Niño3.4Jul and Niño4Aug no matter in the interannual or interdecadal variations, indicating the August APO is an effective signal for predicting autumn CEC precipitation.

The APO is considered to be one of the key factors affecting the Asian–Pacific climate (e.g., Zhao et al. 2007; Zhou

Table 2 Index's rate between the CECPI and different indices at different levels

	APOI	Niño3.4Jul	Niño4Aug	APOI&Niño3.4Jul&Niño4Aug
Excellent rate	36.70%	26.70%	33.30%	60.00%
Excellent&Good rate	56.70%	50.00%	50.00%	73.30%

et al. 2010; Liu et al. 2017). Although the relationship between the preceding APO and autumn precipitation in CEC was revealed, there are still many issues that need further discussion. For instance, does the preceding APO have an impact on the precipitation elsewhere (such as Southeast Asia, the Indian peninsula, and Australia)? If so, how do the fluctuations in atmospheric circulation correspond to changes in precipitation? Furthermore, the surface air temperature is also considered to be an important meteorological factor affecting human productive activities. Therefore, the influence of the preceding APO on the surface air temperature needs to be further explored. Such efforts will help to improve our understanding of the interaction between the APO and the Asian–Pacific climate changes.

Acknowledgments This research was jointly funded by the National Natural Science Foundation of China (41775072, 91537214), 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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