

Article ID: 1006-8775(2026)01-0055-18

Anomalous Characteristics and Mechanisms of Autumn Rain in Western China: A Synergistic Analysis of Upper and Lower Atmospheric Circulation Influences

LI Yi-nuo (李一诺)^{1,2}, LI Yue-qing (李跃清)³, XIANG Shuo-yu (向朔育)⁴, FAN Xu-yan (范旭燕)⁵

(1. Tianjin Meteorological Information Center, Tianjin 300074 China; 2. Chinese Academy of Meteorological Sciences, Beijing 100081 China; 3. Institute of Plateau Meteorology, China Meteorological Administration, Chengdu 610213 China;

4. Sichuan Meteorological Disaster Prevention Technology Center, Chengdu 610072 China; 5. Institute of Shannxi Province, Xi'an 710000 China)

Abstract: Autumn rain in western China (ARWC) is a unique and significant precipitation phenomenon that occurs during the summer-to-winter transition of the atmospheric circulation. Using the fifth generation of global climate and weather reanalysis data from the European Centre for Medium-Range Weather Forecasts and CN05.1 grid precipitation data, this study examined the anomalous characteristics and mechanisms of ARWC by combining the synergistic effect of the westerly jet and meridional wind. Over the past 60 years, ARWC has exhibited significant interdecadal and interannual variations, as well as a north-south seesaw pattern. The westerly jet index (meridional wind index) exhibited a negative (positive) correlation with precipitation in the northern autumn rain zone (NARZ), and a positive (negative) correlation with precipitation in the southern autumn rain zone (SARZ). The coupling of a weak meridional southerly wind with a southward westerly jet and a strong meridional southerly wind with a northward westerly jet are the two primary modes that synergistically influence the ARWC. These synergistic effects cause significant atmospheric changes throughout the troposphere. The contrasting circulation structure, temperature advection, vertical motion, and water vapor flux contributed to the opposite precipitation anomalies observed in the NARZ and SARZ. A new comprehensive index that reflects the coupled synergistic effect is proposed to characterize the anomalous changes in ARWC. This study improves the understanding of the anomalous characteristics and mechanisms of ARWC.

Key words: precipitation; synergistic effects; westerly jet; lower-level meridional wind

CLC number: P462.4

Document code: A

Citation: Li, Y. N., Y. Q. Li, S. Y. Xiang, and X. Y. Fan, 2026: Anomalous Characteristics and Mechanisms of Autumn Rain in Western China: A Synergistic Analysis of Upper and Lower Atmospheric Circulation Influences. *J. Trop. Meteor.*, **32**, 55–72, <https://doi.org/10.3724/j.1006-8775.2025.055>.

1 INTRODUCTION

Owing to significant contrasting differences in thermal properties between land and sea, most areas of China, located in the eastern part of the Eurasian continent and bordering the Pacific Ocean to the east, experience a pronounced precipitation peak in summer. However, in western China, autumn rain is second only to that in summer (Chen et al. 2010), leading to a bimodal precipitation climatic distribution in summer and autumn (Hui 2016). Autumn precipitation, characterized by its duration and overcast condition, may be less intense and destructive than summer precipitation, but its impact should not be underestimated, considering its far-reaching effects on water conservancy, agriculture, transportation, and other sectors, and even the phe-

nomenon of autumn flooding can occur. Therefore, studying the autumn rain in western China (ARWC) has important scientific significance and application value.

In the middle of the 20th century, Gao et al. (1958) noticed the phenomenon of ARWC and conducted initial investigations on its location, onset, and cessation dates, along with the associated atmospheric circulation systems. Crucial studies on interannual and interdecadal variations in ARWC have been conducted since the 21st century, yielding important findings with regard to the characteristics, evolution, mechanisms, impacts, and forecasts of ARWC. Key highlights include findings of significant interannual differences, “positive-negative-positive” interdecadal variations, and the 4–8-year cycle (Liu et al. 2012; Luo et al. 2013; Wang et al. 2015; Wang et al. 2019; Xu et al. 2020; Zhang et al. 2019). Additionally, it has been pointed out that the atmospheric circulation system at low, middle, and high latitudes, tropical sea surface temperature forcing, and the Tibetan Plateau have distinct impacts on ARWC. For instance, Niu et al. (2008) observed a correlation between the ridge of the western Pacific subtropical high and autumn precipitation, and Ding et al. (2008) pointed out the influence of the South China Sea and the Bay of Bengal monsoon on ARWC. Qi et al. (2020) found that the broad Lake Baikal–Lake Balkhash trough, the strong westward-

Received 2024-07-03; **Revised** 2025-04-14; **Accepted** 2025-07-03

Funding: National Natural Science Foundation of China (42030611), Second Tibetan Plateau Scientific Expedition and Research (STEP) Program (2019QZKK0103)

Biography: LI Yi-nuo, Assistant Engineer, primarily undertaking research on synoptic climatology.

Corresponding author: LI Yue-qing, e-mail: yueqingli@163.com

extending subtropical high, and the deep India-Burma trough facilitate the transport of cold and warm air, resulting in intense autumn rainfall. [Zhu et al. \(2020\)](#) used the European Centre–Hamburg Atmospheric General Circulation Model 4.6 and the Advanced Research version of Weather Research and Forecasting model to demonstrate that ARWC is primarily associated with the horizontal trough between two high-pressure systems in East Asia. The east-west thermal contrast of the North Pacific Ocean surface can also affect water vapor transport by triggering a Rossby wave train, thereby affecting the abundance of autumn rainfall ([Wei et al. 2018](#)). [Hu et al. \(2018\)](#) emphasized that the El Niño–Southern Oscillation has an important effect on ARWC and further differentiated between the central Pacific El Niño event and the eastern Pacific El Niño event. Based on various types of influencing factors, monitoring and diagnostic indices, as well as forecasting technology, ARWC models have been established ([Bai et al. 2004](#); [Wei et al. 2019](#); [Wu et al. 2020](#)).

Previous studies have examined atmospheric circulation characteristics and major weather influence systems at high and low levels based on the relationship between ARWC formation and the persistent convergence of cold and warm air, and initially explored their interactions and integrated effects. However, the relative relationship between the integrated effect of multiple systems and factors driving the evolution of ARWC, including the location, intensity, morphology, and other characteristics of the dominant cold and warm air circulation systems, remains to be analyzed in detail. Because the coupling of atmospheric circulation at different levels has important, large-scale regional impacts on weather and climate ([Chen et al. 2021](#); [Guo and Zhu 2022](#); [Song et al. 2022](#); [Yao et al. 2017](#)), understanding the diverse interactions between the upper and lower circulation systems within the complex terrain of the Tibetan Plateau is crucial for comprehending how they influence ARWC.

We thus comprehensively analyzed the spatial and temporal distributions of ARWC. In addition, we investigated the specific impacts of the westerly jet and low-level meridional wind circulation on the ARWC. Through combining observational studies, physical diagnoses, and comprehensive analyses, we propose an anomalous mechanism for the evolution of ARWC and have developed a conceptual model that accounts for the combined effects of these factors. By achieving a holistic understanding of the ARWC, we can enhance our ability to effectively predict and manage this phenomenon.

2 DATA AND METHODS

2.1 Data

We used precipitation data from the CN05.1 grid dataset with a resolution of $0.25^\circ \times 0.25^\circ$, processed by the anomaly approach based on daily observation data collected from more than 2400 national base,

benchmarks, and ordinary stations ([Wu et al. 2013](#)).

The atmospheric circulation data used were reanalysis data of the fifth generation of global climate and weather from the European Centre for Medium-Range Weather Forecasts (ERA5) ([Hersbach et al. 2020](#)), including geopotential height, temperature, specific humidity, horizontal velocity, vertical velocity, and other elements. The resolution was $0.25^\circ \times 0.25^\circ$, and 23 layers in the vertical direction of 1000–200 hPa were selected.

The selected study period for precipitation and circulation spanned from September to October, from 1962 to 2021, totaling 60 years.

2.2 Methods

The methods applied in this study included cumulative anomalies, (partial) correlation analysis, composite analysis, multiple regression analysis, empirical orthogonal function (EOF) analysis, T-N wave flux dynamic diagnosis, and other analytical methods.

When focusing on the characteristics of interannual variation, the corresponding variables were preprocessed using a 9-year highpass filter with a Butterworth digital filter to eliminate interdecadal trends.

In addition, t-tests, F-tests, and North tests were used to assess the statistical significance of the variables.

3 CLIMATIC STATE OF AUTUMN RAIN IN WESTERN CHINA

3.1 Spatial distribution of autumn rain in western China

Based on existing relevant studies, it is reasonable to select (25° – 39° N, 100° – 114° E) as the overall key zone of ARWC, namely the autumn rain zone (ARZ, mainly including Hubei Province, Hunan Province, Chongqing City, Sichuan Province, Guizhou Province, Shaanxi Province, Gansu Province, and Ningxia Hui Autonomous Region) defined in this paper. To analyze the spatiotemporal distribution of ARWC, EOF was employed for area-weighted standardized anomaly precipitation in September and October from 1962 to 2021. The use of area weighting was aimed at reducing the influence of area differences between latitudes on the analysis results, as the focus of this study was not the effect of geographical area.

[Figure 1](#) illustrates the spatial and temporal distribution of ARWC, revealing that the explanatory variance of the first mode was substantial, accounting for 25.80%. It passes the North test ([North et al. 1982](#)), which is significantly different from the second mode and can effectively explain the overall situation of ARWC.

In general, the first mode of precipitation showed a reverse north-south variation. The boundary between the positive and negative regions exhibited a V-shaped non-latitudinal distribution. Notably, within the same latitude, the spatial load values were opposite between eastern and western Sichuan Province, a phenomenon that may be attributed to the distinct topographical elevation differences between the Sichuan Plateau and the basin. The absolute value of the central anomaly in the northern

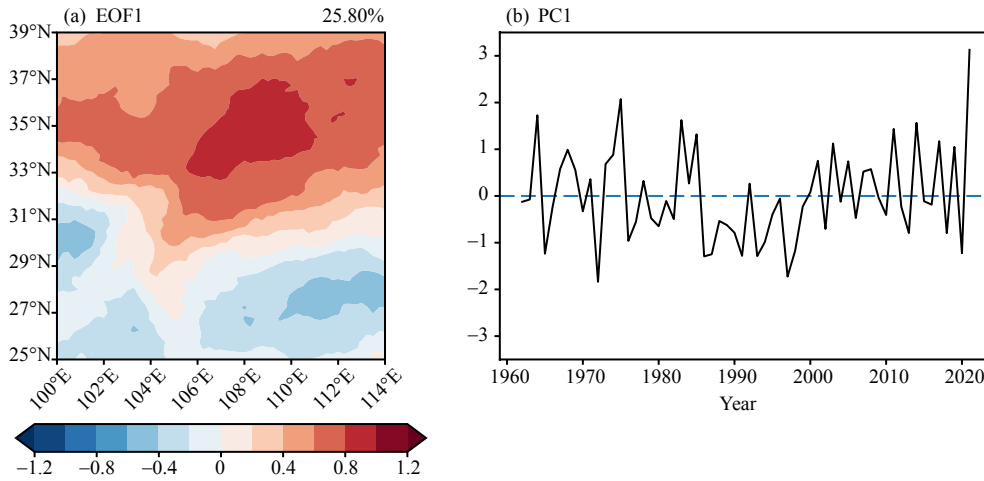


Figure 1. (a) Spatial distribution and (b) time coefficient of standardized anomaly precipitation by EOF analysis.

positive zone was significantly higher than that in the southern negative zone. In addition, the positive region exhibited a wider spatial extent (Fig. 1a). Regarding temporal variations, there were substantial differences in precipitation (Fig. 1b). The temporal evolution of ARWC is further analyzed below.

3.2 The temporal evolution of autumn rain in western China

Figure 2 depicts the temporal variation in the average daily precipitation within the ARZ in September and October from 1962 to 2021. The curve exhibits a pattern of upward and downward undulations, indicating significant variations of the ARWC at both decadal and annual scales.

The 9-year moving mean curve unravels three distinct phases of “more-less-more” of ARWC over the past 60 years. Precipitation in the third stage was greater than that in the first stage. ARWC has entered a stronger interdecadal period after being weak for more than 20 years, which is consistent with the results of existing studies, and is related to atmospheric circulation and water vapor transport, which are more conducive to precipitation (Xu et al. 2020). The cumulative anomaly results showed abrupt changes of ARWC in 1985 and 2010. In addition, the slide *t*-test results confirmed that interdecadal changes did occur (Fig. A1).

In contrast, ARWC also exhibits interannual variability. The 60-year average precipitation was 2.78 mm d^{-1} . The maximum daily precipitation occurred in 1983, reaching approximately 3.78 mm d^{-1} , whereas the minimum occurred in 1998, at approximately 1.90 mm d^{-1} . Remarkably, the ratio between these extremes was nearly two-fold. Moreover, even within the same high or low rainfall phase, variability in precipitation persisted among different years, confirming the continuing significance of interannual variability alongside interdecadal effects.

The characteristics of the interdecadal variability of ARWC and its influencing factors have been discussed (Bai et al. 2004; Fang et al. 2008; Liu et al. 2012; Wang et al. 2019; Zhang et al. 2019); thus, the focus will be on the interannual variability in ARWC below.

3.3 Precipitation index

To characterize the regional climate differences in ARZ and to exclude the influence of interdecadal variability, the time coefficient in Section 3.1 was standardized and highpass-filtered to obtain the following precipitation index (PREI) of ARWC:

$$\text{PREI} = \text{Filter}[\text{Std}(\text{PC1})] \quad (1)$$

In Eq. (1), PC1 represents the first-time coefficient of

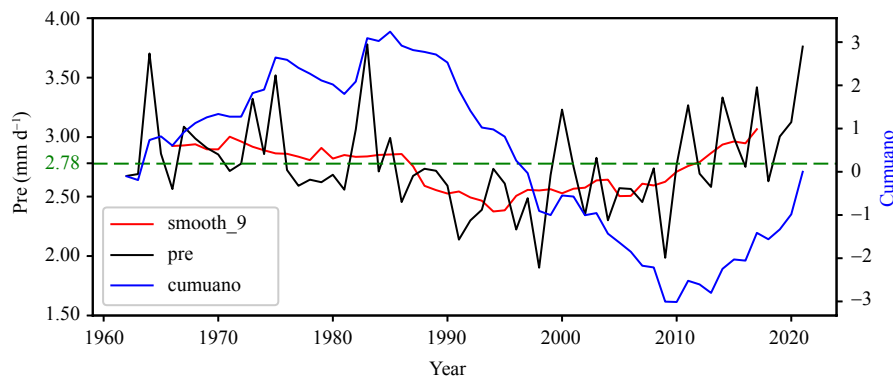


Figure 2. Temporal variation of average daily precipitation in ARZ (the black line represents raw data, the red line represents 9-year moving average, the blue line represents cumulative anomaly, and the green dashed line represents the average of 60 years).

EOF decomposition to the standardized precipitation anomaly in the ARZ, “Std” stands for the standardization of the variables, and “Filter” stands for the 9-year highpass filtering. When the index was high (low), it indicated more (less) precipitation in the northern autumn rain zone (NARZ) and less (more) in the southern autumn rain zone (SARZ) than in the climatological pattern.

Applying the “0.6 standard deviation” principle, 12 years with high PREI (1964, 1968, 1975, 1983, 1985, 1992, 1996, 2001, 2003, 2011, 2014, 2017) and 13 years with low PREI (1965, 1972, 1976, 1982, 1986, 1987, 1997, 2002, 2006, 2010, 2013, 2018, 2020) were identified, and the distribution of precipitation anomaly percentages in high and low-PREI years was calculated, which again confirmed the physical implications of PREI (Fig. A2).

4 RELATIONSHIP BETWEEN AUTUMN RAIN IN WESTERN CHINA AND HIGH-LEVEL WESTERLY JET

Following the method of objectively describing westerly jets based on EOF (Wei et al. 2017; Zhao et al. 2014), we investigated the relationship between the ARWC and the high-level westerly jet.

By performing EOF analysis on the anomalous zonal wind field at 200 hPa in the region of 25°–55°N, 75°–125°E, two main modes representing anomalous changes in the westerly jet were obtained. Because the first and second modes accounted for 46.31% and 24.06% of the explained variance, respectively, the cumulative variance contribution reached 70.37%, indicating that the first two

modes can reflect the main characteristics of the zonal wind anomaly at 200 hPa in this region. Fig. 3a shows that EOF1 exhibited an opposite north-south phase distribution, with the zero line located between 30° and 35°N. This “seesaw” pattern reflects the north-south oscillation of the jet. When PC1 was high (low), the westerlies on the south side of the jet strengthened (weakened), and the westerlies on the north side weakened (strengthened). Therefore, the positive and negative values of PC1 reflect the southward or northward swinging of the jet axis. In contrast, EOF2 showed a prominently large center near 35°N, which aligned with the average climatic position of the jet center, reflecting the change in jet intensity (Fig. 3c). Consequently, the corresponding time coefficient PC2 served as an indicator of jet intensity, and the greater (lower) the PC2 value, the stronger (weaker) the jet intensity and the higher (lower) the jet wind speed.

By selecting the standardized PC1 greater than 0.6 or less than −0.6 as anomalous years, we identify a total of 14-year with negative PC1 anomalies (i.e., 1964, 1970, 1974, 1975, 1981, 1983, 1985, 1989, 1999, 2007, 2016, 2017, 2020, 2021) and 14 years with positive PC1 anomalies (i.e., 1965, 1966, 1972, 1976, 1979, 1986, 1990, 1991, 1993, 1997, 2002, 2006, 2012, 2018).

Further analysis of the T-N wave activity flux revealed anomalous Rossby wave transport from Europe to East Asia via Siberia, and an anomalous distribution of the geostrophic stream function was observed along the direction of this fluctuation transport. During years with high PC1 values, the meridional component of the T-N

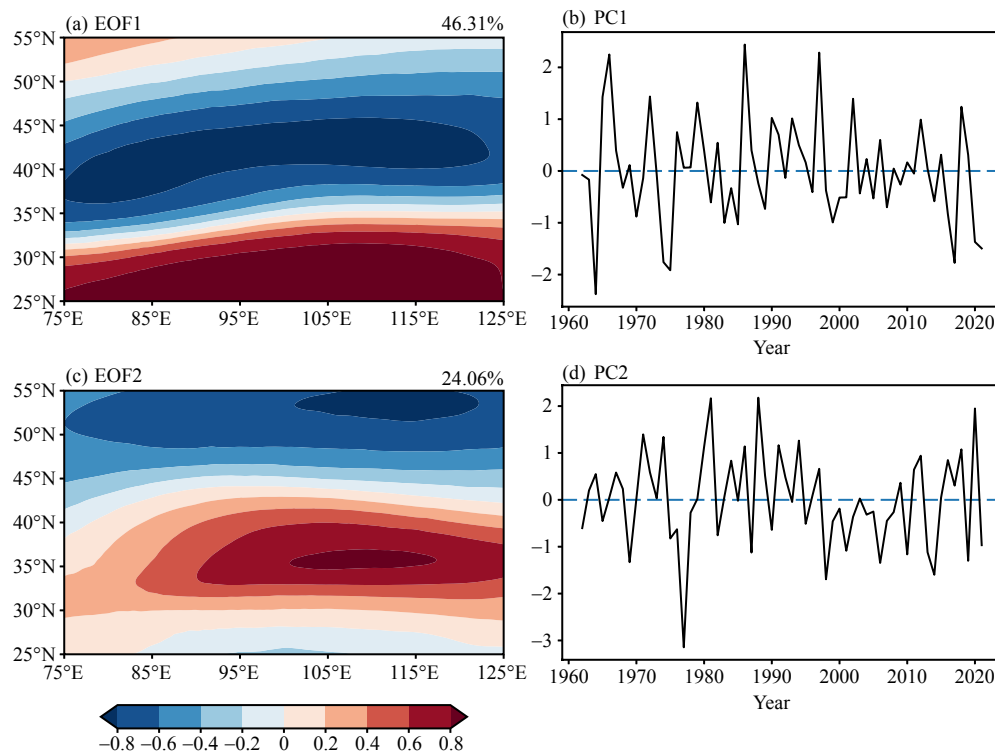


Figure 3. Spatial distribution of zonal wind anomalies by EOF at 200 hPa (a) first mode, (c) second mode, and (b, d) their respective time coefficients.

wave flux was larger, facilitating the dispersion of fluctuation energy to the south. This condition was conducive to a westerly jet shifting southward, especially west of 125°E, as illustrated in Figs. A3a and A3c. Conversely, during periods with low PC1, the meridional component of the T-N flux reduced, resulting in a more northern transport of fluctuation energy. This led to a northward shift of the westerly jet, as shown in Figs. A3b and A3c.

The relationship between the jet and ARWC is explored in the following section. Given the significant interdecadal variability characteristics of the ARWC, a 9-year highpass filtering process was applied to PC and precipitation. Subsequently, correlation analysis confirmed a strong correlation (Fig. A4).

As shown in Fig. A4a, there was a negative correlation between standardized PC1 and precipitation in the NARZ. The correlation coefficient in some regions reached -0.6 , with most regions surpassing 95% significance level, indicating a close association between the location of the jet and the amount of rainfall in NARZ. Similarly, a positive correlation was observed in the SARZ, and the correlation coefficient in some regions exceeded 0.5 , suggesting that the location of the jet was closely related to the amount of rainfall in the SARZ. It is worth noting that the correlation between the north or south of the ARZ and the jet differed, and this inverse correlation corresponded to the north-south distribution characteristics of ARWC. The physical mechanism behind these findings can be preliminarily explained as follows: when the 200 hPa jet axis passes over the ARZ, according to the theory of secondary circulation (Sun et al. 1987), the inlet area of the jet stimulates direct thermal circulation, and the southern and northern sides exhibit ascending and descending movements, respectively, which then impact regional precipitation. When the jet moves southward, abnormal rising (sinking) movements occur to the south (north) of the ARZ, which creates (un) favorable dynamic conditions for precipitation. Conversely, when the jet shifts to the northern area, the opposite is true. Thus, it is evident that standardized PC1 can reflect changes in ARWC.

Figure A4b illustrates the correlation distribution between the standardized PC2 and ARWC during the same period. It can be seen that the correlation is markedly weaker than that of PC1, with most of the correlations between -0.1 and 0.1 . The spatial distributions exhibited less coherence and lacked clear regularity, with only a relatively small area passing the significance test. This indicates that the influence on the ARWC is mainly manifested by the location of the jet, whereas the influence of the intensity is secondary and more localized. In comparison to the changes in jet intensity, changes in location cause fundamental alterations in the atmospheric dynamic-thermal structure on a much larger scale, leading to a significant anomalous precipitation change. As a matter of fact, the positional change of the jet, as the first mode with the largest variance contribution of the EOF

decomposition, reflects the primary features of the westerly jet and should be the main focus. In the following section, the 9-year highpass-filtered normalized westerly jet position index (standardized PC1) is denoted as the westerly jet index (WI) to further analyze the specific physical processes and influence mechanisms between the westerly jet and ARWC.

$$WI = \text{Filter}[\text{Std}(\text{PC1})] \quad (2)$$

In Eq. (2), PC1 represents the first time coefficient of EOF decomposition to the zonal wind anomaly at 200 hPa in the range of (25°–55°N and 75°–125°E). When the WI value was high (low), the westerly jet moved south (north).

5 RELATIONSHIP BETWEEN AUTUMN RAIN IN WESTERN CHINA AND LOW-LEVEL MERIDIONAL WIND CIRCULATION

In addition to the influence of the upper-level circulation on ARWC, the impact of the lower-level circulation was also significant. The specific effects are examined below.

First, the correlation between PREI and the meridional wind field at 850 hPa was calculated, which led to the analysis of the key meridional wind region affecting ARWC. As depicted in Fig. 4a, the precipitation abundance was closely related to the meridional wind field, particularly the meridional wind from the Pacific Ocean at low latitudes to the eastern part of China, reflecting the interconnection between low-level meridional wind circulation and ARWC. In contrast, the correlation between the Indian Ocean wind field and PREI was relatively small and failed to pass the significance test in most cases.

The different distribution of the 850 hPa wind fields in the high- and low-PREI years was calculated and is shown in Fig. 4b. It can be seen that when the precipitation anomaly is more in the north and less in the south (high PREI), there are easterly anomalies in the equatorial Pacific Ocean to the East China Sea. Additionally, southerly anomalies prevail in eastern China, whereas abnormal anticyclonic circulation is observed in the middle and low latitudes of the Pacific Ocean, which is conducive to the transport of warm and humid water vapor from the tropical ocean surface to the NARZ, resulting in excessive rainfall. The opposite pattern emerged when the precipitation anomaly was less in the north and more in the south (low PREI).

Based on the information provided in Figs. 4a and 4b, the standardized series of mean meridional winds at 850 hPa (25°–35°N, 105°–130°E) and (9°–19°N, 131°–143°E) after applying a 9-year of highpass filter was selected as the meridional wind index (MI), which is considered to represent the significant impact of low-level meridional wind circulation on ARWC. A higher MI value indicated a stronger southerly wind speed within the critical zone, reflecting a more intense low-level meridional wind circulation and an increase in water vapor transport from low latitudes. Therefore, MI is an ideal index with obvious

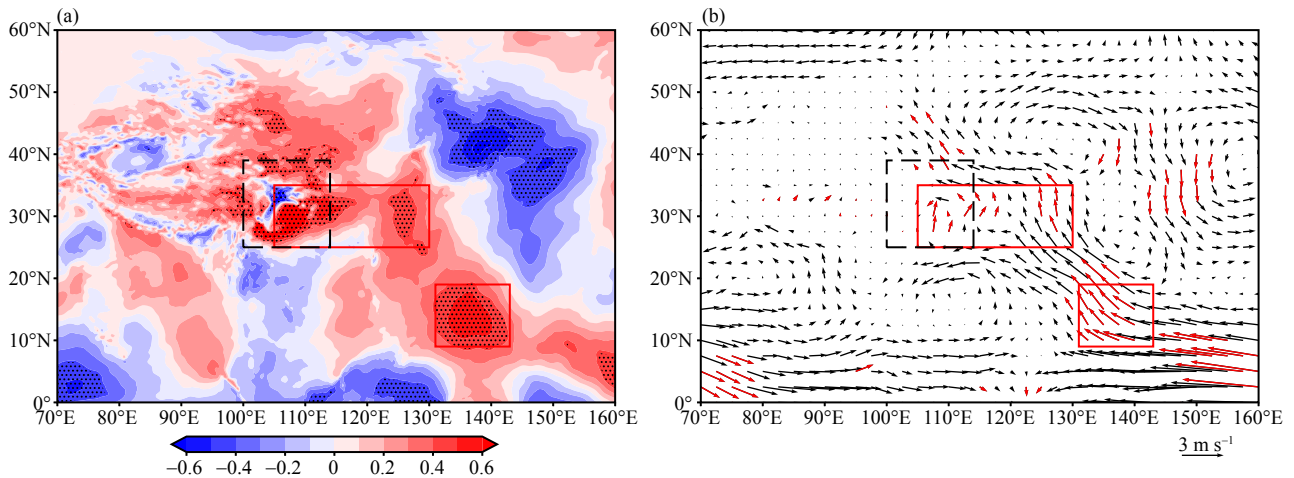


Figure 4. (a) Correlation between PREI and meridional wind after 9-year highpass filtering at 850 hPa (shaded area). The dots indicate that it passed the significance test at the 99.9% level. (b) Difference distribution of the wind fields at 850 hPa in high- and low-PREI years. Red arrows indicate significance at the 99% level. The black dashed box indicates ARZ, and the red solid box indicates the key region of meridional wind, the same hereinafter.

physical significance and a notable relationship with precipitation.

$$MI = \text{Filter} \left\{ \text{Std} \left[\frac{\bar{V}_{(25^{\circ}-35^{\circ}\text{N}, 105^{\circ}-130^{\circ}\text{E})} + \bar{V}_{(9^{\circ}-19^{\circ}\text{N}, 131^{\circ}-143^{\circ}\text{E})}}{2} \right] \right\} \quad (3)$$

Figure A5 shows the positive correlation between precipitation in NARZ and MI; the correlation coefficient of some regions exceeded 0.6, with the majority passing the significance test at the 95% level. Similarly, there was a negative correlation between precipitation in the SARZ and MI, and the correlation coefficient of some regions reached -0.5 , with several also passing the 95% significance test. It is worth noting that precipitation in the NARZ and SARZ is inversely correlated with low-level meridional wind, which is consistent with the north-south distribution of ARWC and the correlation between the westerly jet and ARWC. The physical mechanism can be preliminarily explained as follows: a strengthened low-level meridional southerly wind extending northward enhances water vapor transport to the NARZ, leading to increased precipitation in the NARZ, but decreased precipitation in the SARZ. This highlights that the MI can also reflect the regional characteristics of ARWC.

6 SYNERGISTIC INFLUENCE OF WESTERLY JET AND MERIDIONAL WIND CIRCULATION ON AUTUMN RAIN IN WESTERN CHINA

6.1 Relationship between the westerly jet index and meridional wind index

The influences of the upper westerly jet and lower meridional wind circulation on ARWC were discussed above. As a matter of fact, they are closely related to each other as important systems of atmospheric circulation at different latitudes and altitudes. The strong negative correlation coefficient between WI and MI was -0.72 , passing the significance of 99.9% (Fig. 5). When the westerly jet in the upper troposphere shifts southward, it typically corresponds to weak meridional circulation at a lower level. Conversely, when a westerly jet shifts northward, this often corresponds to a strong meridional circulation. This also aligns with the correlation differences between WI, MI, and ARWC.

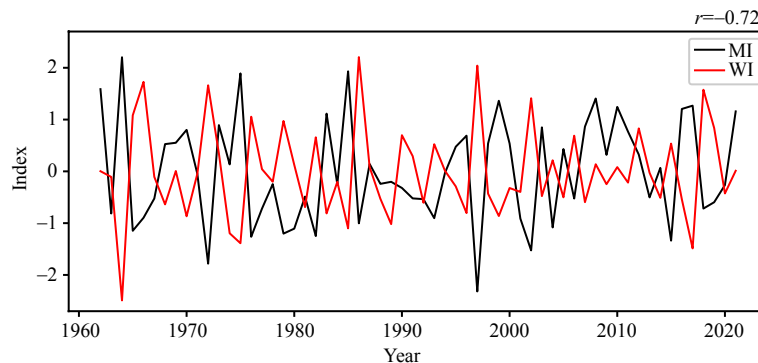


Figure 5. Time series of WI and MI.

The results of the correlation analysis (Table 1) further confirmed the synergistic effects of the westerly jet and meridional wind. Although the correlation coefficient of WI and PREI was -0.65 (passing the 99.9% significance test), the partial correlation between WI and PREI without the effect of meridional wind was -0.39 (passing the 99% significance test). By contrast, the correlation coefficient between MI and PREI was 0.60 (passing the 99.9% significance test), the partial correlation with westerly influence removed is 0.25 , less than half of the original correlation, passing only 90% significance test. This further confirms that westerly and meridional winds are intrinsically linked and have a close synergistic effect on ARWC. In addition, the original correlation and partial correlation between WI and PREI

Table 1. The (partial) correlation coefficient of WI, MI, and PREI. Significance levels are denoted as follows: *** ($p < 0.001$), ** ($p < 0.01$), and * ($p < 0.1$).

Correlation	WI	MI
PREI	-0.65^{***}	0.60^{***}
PREI (partial)	-0.39^{**}	0.25^*
MI	-0.72^{***}	—

were stronger than those of MI, indicating that the upper westerly jet had a relatively stronger influence on ARWC.

Therefore, the following is a preliminary examination of the coupled behavior between the upper-level westerly jet and the lower-level meridional wind. WI, MI, geopotential height, and horizontal wind fields showed significant associations. Both indices exhibited correlations with anomalously large-scale anticyclonic systems and anomalous geopotential heights in the mid-troposphere across regions spanning eastern China to Democratic People's Republic of Korea, Japan, and the Pacific Ocean (Fig. 6).

Anomalous anticyclones tend to occur around the regions of 20° – 50° N, 100° – 150° E at 500 hPa when the WI is low (high WI value). This association encompassed the influence of low-level meridional winds, as shown in Fig. 6a. However, upon removing the influence of the low-level meridional wind, this anticyclone was significantly weakened (Fig. 6c). This suggests that low-level meridional wind primarily contributes to the formation of anomalous anticyclones at mid-latitudes of 500 hPa and regulates the north-south movement of the westerly jet by accelerating easterly winds on its southern side and

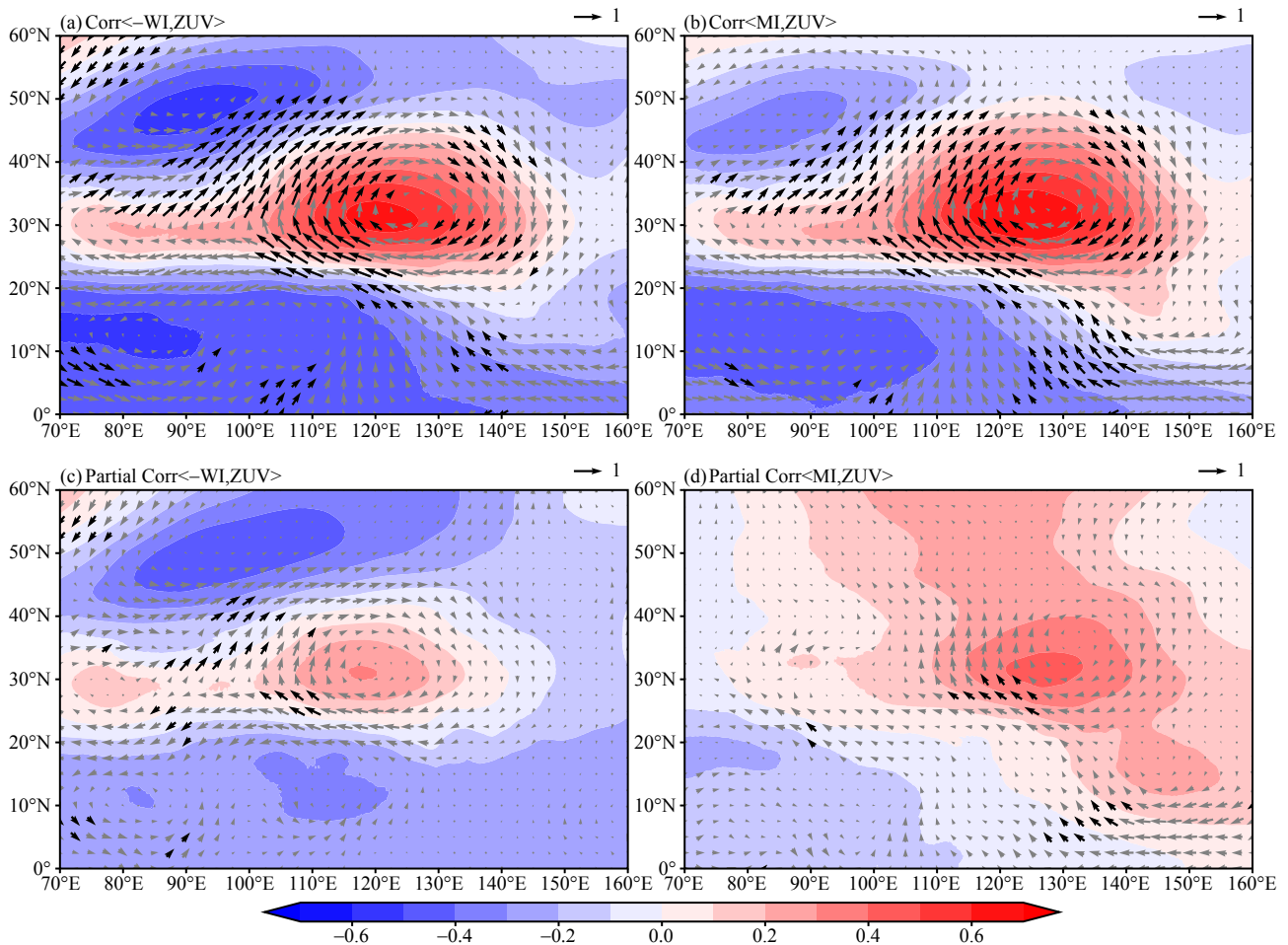


Figure 6. The correlation between (a) WI and (b) MI with geopotential height (shadow) and horizontal wind field (vector) at 500 hPa, and (c) and (d) are partially correlated (for ease of comparison, the WI is taken as the opposite). The black arrow indicates that it passed the 95% significance test.

westerly winds on its northern side.

When the MI, which encompasses the influence of the westerly jet, is high, it tends to cause a decrease in the geopotential height near Lake Balkhash–Lake Baikal at high latitudes and an increase in the geopotential height in East Asia at mid-latitudes. This pattern was associated with the presence of an anomalous air pressure gradient in the north-south direction (Fig. 6b). However, after removing the influence of the upper-level westerly jet, the difference in the geopotential height between 20°–40°N and 40°–60°N diminished, as shown in Fig. 6d. This indicates that the westerly jet primarily regulates changes in low-level meridional wind circulation by influencing positive geopotential height anomalies in the mid-latitude East Asian region and negative geopotential height anomalies in the high-latitude Lake Balkhash and Lake Baikal regions. Consequently, the southerly wind intensified under the influence of a favorable pressure gradient force.

Taken together, the westerly jet at 200 hPa and meridional wind circulation at 850 hPa were interconnected through the presence of anticyclones and corresponding positive potential height anomalies near the East Asian region (20°–50°N, 100°–150°E), as well as negative potential height anomalies near Lake Balkhash–Lake Baikal. This linkage extends vertically from 850 to 200 hPa, exhibiting a deep vertical distribution structure (figure omitted), with the 500 hPa level being particularly prominent.

Hence, the 60-year from 1962 to 2021 are classified into different types according to the WI and MI criteria (Table 2). Initially, using ± 0.6 as threshold, they are categorized into four coupling modes: low MI-high WI (mlwh), high MI-low WI (mhlw), high MI-high WI (mhwh), and low MI-low WI (mlwl). Because of the negative correlation between WI and MI, mlwh and mhlw are the dominant modes, and the mhwh and mlwl modes are not present under this criterion. However, to comprehensively analyze the potential coupling forms between westerly jet and meridional wind, mhwh, mlwl were obtained with the relaxed judgment criterion ± 0.3 as a threshold. Furthermore, four coupling types were used, i.e., mhwn, mlwn, mnwh, mnwl, as one index being in a high or low anomaly state, and the other being normal, i.e.,

greater than 0.6 for the high anomaly, less than -0.6 for the less anomaly, between 0.6 and -0.6 for the normal state.

6.2 Distribution characteristics of precipitation in different westerly jet-meridional wind configurations

The composition of precipitation anomalies in years characterized by reverse coupling synergy between the westerly jet and meridional wind (Figs. 7a and 7b) reveals that when MI is low and WI is high, namely weak meridional wind-southward westerly jet (mlwh: 1965, 1966, 1972, 1976, 1979, 1982, 1986, 1997, 2002, 2018, totaling 10 years), there is a negative precipitation anomaly in the NARZ and a positive anomaly in the SARZ. When MI is high, and WI is low, that is, a strong meridional wind-northward westerly jet (mhlw: 1964, 1970, 1975, 1983, 1985, 1996, 1999, 2017, totaling 8 years), the precipitation in the ARZ exhibits a positive anomaly in the north and a negative anomaly in the south. Notably, there was a strong correspondence between these years and the anomalous years of the PREI. When MI and WI were both high (mhwh: 1973, 2012), positive and negative precipitation anomalies appeared alternately in the ARZ (Fig. 7c). In both-low years (mlwl: 1981, 1992, 2001), the precipitation anomaly appeared to have a positive-negative distribution in the northwest-southeast direction; however, most regions failed the significance test (Fig. 7d). Because of the opposite effects of the westerly jet and meridional wind on ARWC, their effects offset each other in phase, resulting in an atypical anomalous distribution of precipitation. Such synergistic coupling anomalies rarely occur in the climatic states. When the westerly jet and meridional wind were neither in phase nor antiphase, the precipitation anomaly pattern of ARWC tended to be relatively uneven, and a few regions passed the significance test, indicating that when only one of the WI and MI was stronger or weaker, the other remained normal, and the influence on the configuration of ARWC was complex, unequal, and less statistically significant (Figs. 7e–7h).

6.3 Synergistic mechanism of the westerly jet and meridional wind

In the following section, the different physical mechanisms of precipitation distribution are explored under the synergistic action of a westerly jet and meridional wind.

Table 2. The configuration year of different coupling modes of the westerly jet and meridional wind, the threshold values for mhwh and mlwl are 0.3, whereas those for the other modes are 0.6.

Different configurations	Year
mlwh	1965, 1966, 1972, 1976, 1979, 1982, 1986, 1997, 2002, 2018
mhlw	1964, 1970, 1975, 1983, 1985, 1996, 1999, 2017
mhwh	1973, 2012
mlwl	1981, 1992, 2001
mhwn	1962, 1973, 2003, 2007, 2008, 2010, 2011, 2016, 2021
mlwn	1963, 1977, 1980, 1993, 2001, 2004, 2015
mnwh	1990, 2006, 2012, 2019
mnwl	1968, 1974, 1981, 1989, 1992

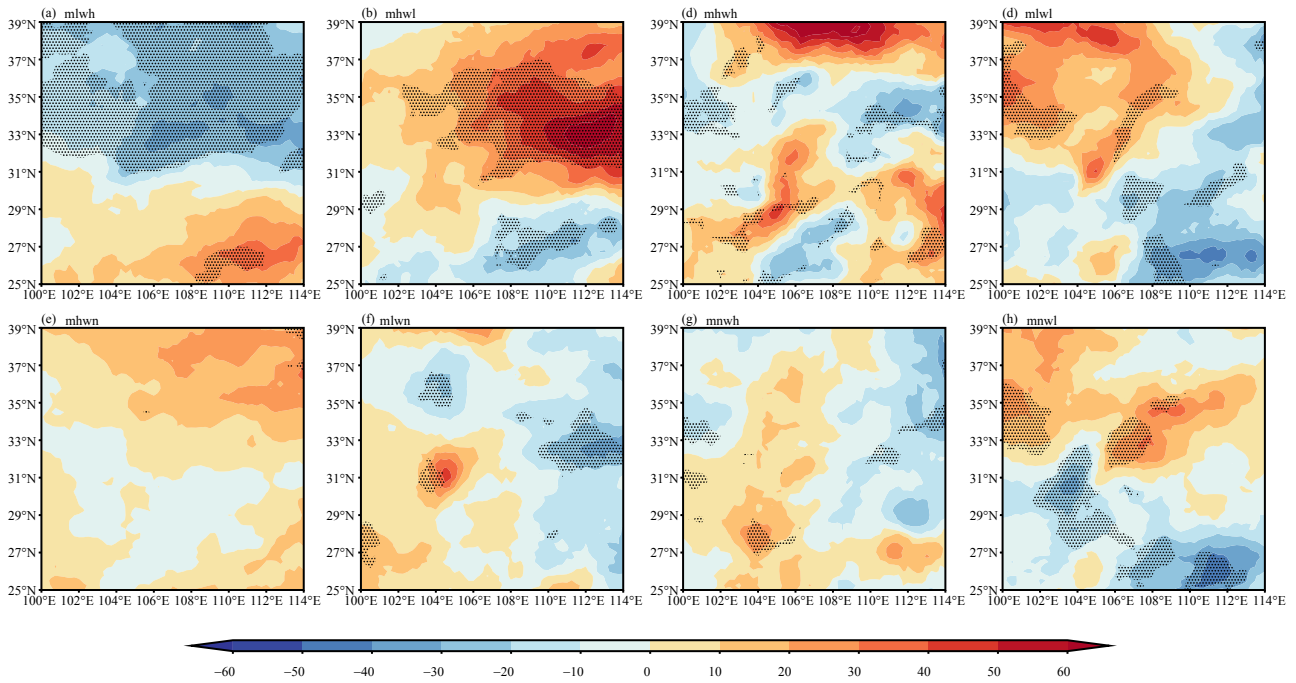


Figure 7. Composition distribution of precipitation anomaly (units: %) in (a) mlwh; (b) mhw; (c) mhw; (d) mlw; (e) mhwn; (f) mlwn; (g) mnwh; and (h) mnw year (the dot indicates that it passed the 95% significance test).

In an mlwh year, geopotential height anomaly displays a positive and negative distribution from west to east at 700 hPa and below, a positive-negative-positive “sandwich” distribution from north to south at 500 hPa, and the distribution at 200 hPa is positive in the north and negative in the south. The geopotential height anomaly gradually increases from the lower to the upper troposphere. The atmosphere in the overall vertical direction was in a barotropic state, particularly to the east. The distribution in the mhw years showed the opposite trend (Fig. 8). The results show that for the coupling of a strong meridional wind-northward westerly jet and a weak meridional wind-southward westerly jet, the East Asian region has a significant overall atmospheric response, and the three-dimensional large-scale circulation exhibits remarkably opposite anomalous characteristics, which results in the opposite anomaly distribution of the ARWC. When WI is in a normal state, the lower troposphere distribution in years of high or low MI is roughly the same as that when the westerly jet and meridional wind are reversely coupled. When MI was in a normal state, the upper tropospheric distribution in high or low WI years was consistent with the reverse coupling of WI and MI (figure omitted). These findings suggest that low-level meridional winds mainly cause the geopotential height anomalies in the lower troposphere, whereas the westerly jet mainly causes anomalies in the upper troposphere. When the two systems cooperate, they simultaneously cause a distribution of geopotential height anomalies in different layers, which is related to the fact that the westerly jets and meridional wind systems are mainly at different heights in the troposphere.

In the mlwh year, the geopotential height field at

middle and high latitudes exhibits pronounced meridionality (Fig. 9), and there is an abnormally low trough from the Sihot Mountains in southern Russia to the Sea of Japan, the Korean Peninsula, and the East China Sea; the position of the western Pacific subtropical high is more east than the climatology. From high to low latitudes, there is a pattern of positive-negative-positive geopotential height deviations. A positive anomaly center at high latitudes appeared between Lake Balkhash and Lake Baikal (45°–55°N, 75°–105°E), whereas the center of the negative anomaly was situated near the Korean Peninsula and southern Japan (30°–40°N, 120°–140°E). In the mhw year, the distribution of the high-latitude geopotential height field was relatively flat, without an obvious abnormal trough along the East Asian coast. The western Pacific subtropical high, represented by 5880 gpm, was further west. These results show that for the coupling of the strong meridional wind-northward westerly jet and weak meridional wind-southward westerly jet, the large-scale circulation in the middle troposphere also exhibits remarkable anomalous characteristics of the opposite distribution, which results in the opposite anomaly distribution of the ARWC.

Figure 10 shows the vertical velocity distribution. In the mlwh year (Fig. 10a), there was a negative vertical velocity anomaly in the NARZ at 500 hPa, indicating an abnormal downward movement, whereas a positive vertical velocity anomaly occurred in the SARZ, which represented an abnormal upward movement. The vertical velocity anomaly profile (Fig. 10c) showed anomalous subsidence in the NARZ throughout the layer from 200 hPa downward, whereas an abnormal upward movement occurred in the entire layer of the SARZ. The

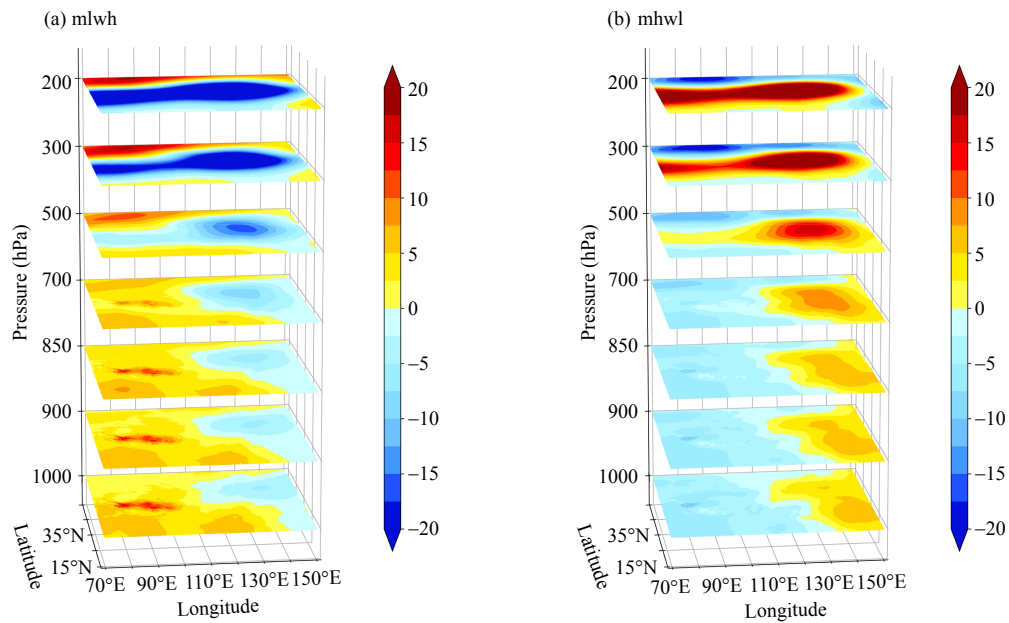


Figure 8. Composite vertical distribution of geopotential height anomalies (shaded area, units: gpm) in (a) mlwh and (b) mhw1 years.

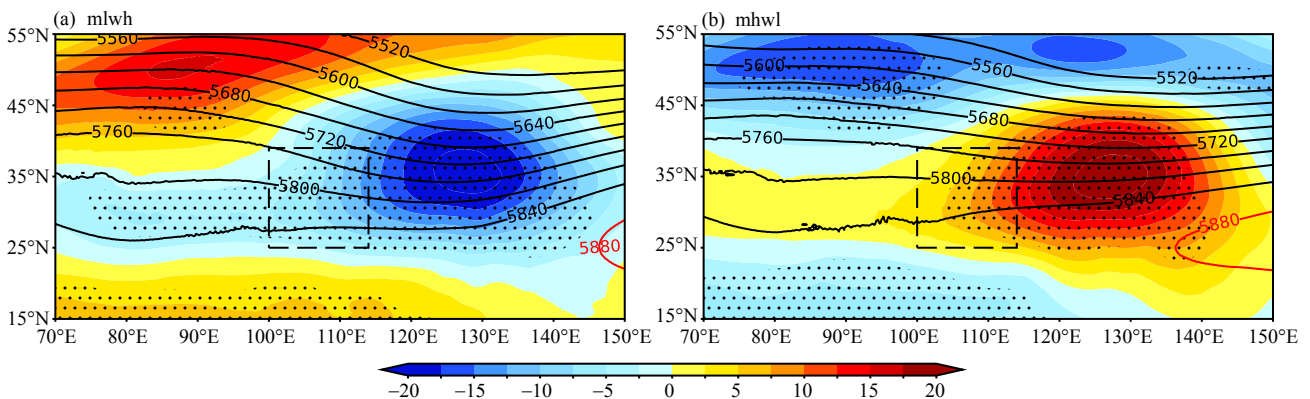


Figure 9. Composite distribution of geopotential height (contour lines, units: gpm) and anomalies (shaded) at 500 hPa in (a) mlwh and (b) mhw1 year. The dots indicate significance at the 95% level.

magnitude of the vertical velocity anomaly increased with height, and the anomaly in the upper troposphere was more pronounced. In contrast, in the mhw1 year (Fig. 10b), there was a positive vertical velocity anomaly in the NARZ at 500 hPa, indicating abnormal upward movement. Conversely, a negative vertical velocity anomaly was observed in the SARZ, which represented abnormal subsidence motion. The velocity anomaly profile (Fig. 10d) shows an abnormal upward movement in the NARZ in the entire layer, whereas an abnormal subsidence movement occurred in the SARZ. However, when the WI and MI were not in a reverse or consistent state, such as in mhw1, mlwn, mnwh, and mnw1, the abnormal state of vertical motion was not as prominent (figure omitted). This suggests that the reverse coupling of WI and MI is the most prominent state that triggers the vertical motion anomaly of the entire layer, and the joint action of the westerly jet and meridional wind causes opposite abnormal dynamic conditions to appear in the NARZ and SARZ,

producing the opposite precipitation anomaly.

In the mlwh year, a negative temperature advection anomaly indicating abnormal cold advection was observed in the NARZ. According to the ω equation, $-\omega$ is positively correlated with $-\mathbf{v} \cdot \nabla T$. Therefore, in the cold advection region, subsidence movement occurred. The abnormal warm advection anomaly in the SARZ led to upward movement. In contrast, in the mhw1 year, unusual warm advection and an upward movement are observed in NARZ, whereas an unusual cold advection in the SARZ caused an abnormal downward movement. The temperature advection anomaly at the upper level was significantly greater than that at the lower level, and the positive and negative anomaly distribution at 200 and 500 hPa was evident, whereas the temperature advection anomaly at 850 hPa was more sporadic and smaller, corresponding to the gradual decrease in the vertical velocity anomaly from the upper to the lower level (Fig. 11).

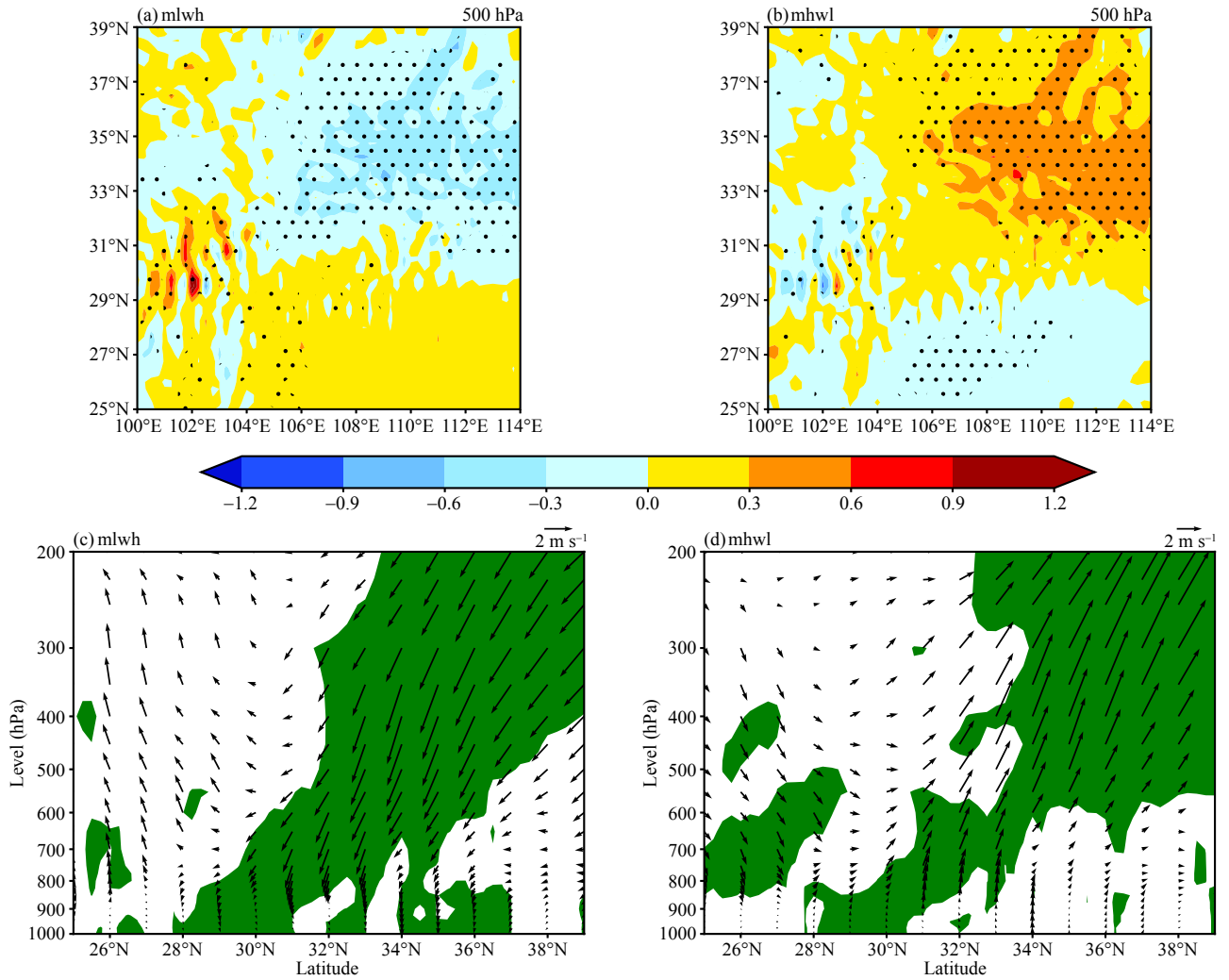


Figure 10. Composite distribution of vertical velocity anomalies at 500 hPa (shaded, units: 10^{-2} m s^{-1}) in (a) mlwh and (b) mhw1 year. The dots indicate significance at the 95% level. Composite profile distribution of average velocity anomalies within the region of $100^{\circ}\text{--}114^{\circ}\text{E}$ (arrows, vertical velocity magnified by 10^3) in (c) mlwh and (d) mhw1 year. The green shaded area represents significance at the 95% level.

The water vapor conditions integrated from surface to 200 hPa (Fig. 12) show that in the mlwh year, an abnormal cyclonic circulation in the Pacific Ocean resulted in a decrease in overall water vapor transport to the ARZ. There was an abnormal divergence of the water vapor flux in the NARZ and an abnormal convergence of the water vapor flux in the SARZ, which resulted in less precipitation in the north and more precipitation in the south. In contrast, in an mhw1 year, the abnormal anticyclonic circulation in the Pacific Ocean steers more tropical warm and moist water vapor into the ARZ, leading to an abnormal convergence of water vapor flux in the NARZ and an abnormal divergence of water vapor flux in the SARZ, resulting in different precipitation anomalies in the NARZ and SARZ. The joint action of the westerly jet and meridional wind causes opposite net water vapor inflow or outflow in the NARZ and SARZ, producing opposite precipitation anomalies.

6.4 Westerly jet-meridional wind comprehensive index

Considering the synergistic effect of the westerly jet

and meridional wind on the amount of ARWC, a novel comprehensive index, denoted as CI, was formulated by combining WI and MI to effectively characterize ARWC. Using multiple linear regression, WI and MI were used to fit PREI, and the following CI was derived; the regression equation passed the significance test of 99.9%:

$$\text{CI} = -0.4308\text{WI} + 0.2370\text{MI} - 0.0375 \quad (4)$$

The correlation coefficient between CI and PREI was 0.68, which was higher than that of individual WI or MI, indicating that the ability to reflect ARWC was improved by combining the effects of the westerly jet and meridional wind. The correlation coefficient between WI and PREI was slightly higher than that between WI and MI; the former was negative, whereas the latter was positive (Table 1), which was also reflected in the coefficients in Eq. (4).

Figure 13 shows the scatter densities of CI, WI, MI, and PREI. It can be seen that in comparison with WI or MI, CI has a closer relationship with a higher congruence

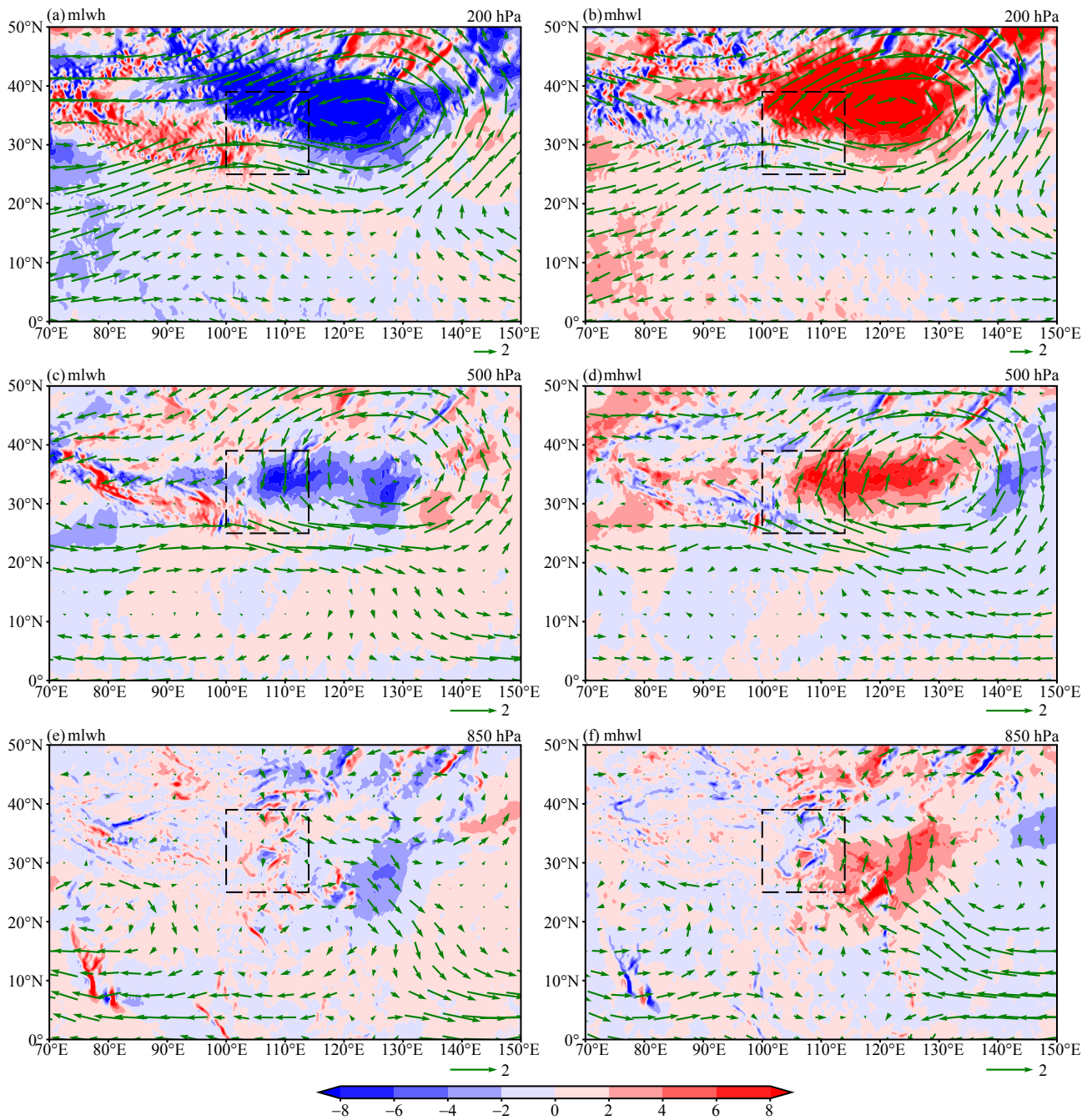


Figure 11. Composite distribution of temperature advection (shaded area, units: 10^{-6} K s^{-1}) and wind fields (vectors, units: m s^{-1}) anomalies at (a, b) 200 hPa, (c, d) 500 hPa, and (e, f) 850 hPa in (a, c, e) mlwh and (b, d, f) mhw1 years.

rate with PREI. This positive correspondence was predominantly observed in the first and third quadrants of the scatterplot, with a notable concentration along the line congruent with PREI, accompanied by a reduced occurrence of outliers. This finding suggests that the integration of the westerly jet and meridional wind offers a more accurate representation of ARWC.

In addition, the correlation distribution between CI and ARWC (Fig. 14) shows that the correlation between CI and ARWC in the NARZ and SARZ was opposite, which corresponds to the characteristics of different abnormal distributions of rainfall in the NARZ and

SARZ. The correlation and significance were better than those of WI or MI alone. This further verified the important influence of the synergistic coupling effect of the westerly jet and meridional wind on ARWC.

7 CONCLUSION AND DISCUSSION

Owing to the distinct monsoon climatological characteristics in most regions of China, summer precipitation constitutes the majority of the annual precipitation. However, a unique autumn precipitation pattern also exists in the western parts of the country. Prolonged autumn rain can profoundly affect daily life,

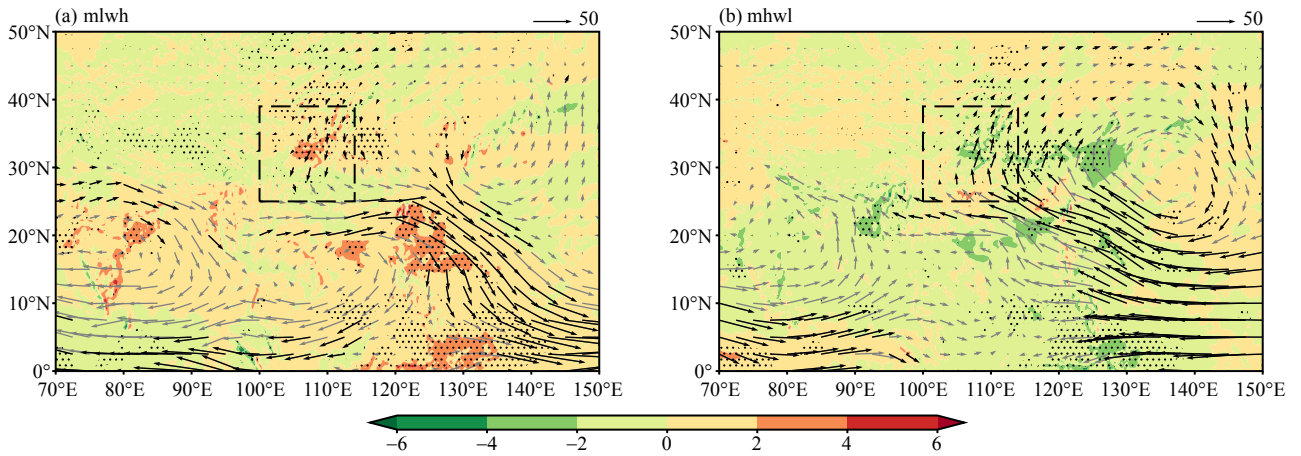


Figure 12. Composite distribution of vertically integrated water vapor flux anomalies from the surface to 200 hPa (vectors, units: $\text{kg s}^{-1} \text{m}^{-1}$, black arrows indicate significant test at 90% significance level) and water vapor flux divergence (shaded, units: $10^{-5} \text{kg s}^{-1} \text{m}^{-2}$, dots indicate significant test at 90% significance level) anomalies in (a) mlwh and (b) mhw years.

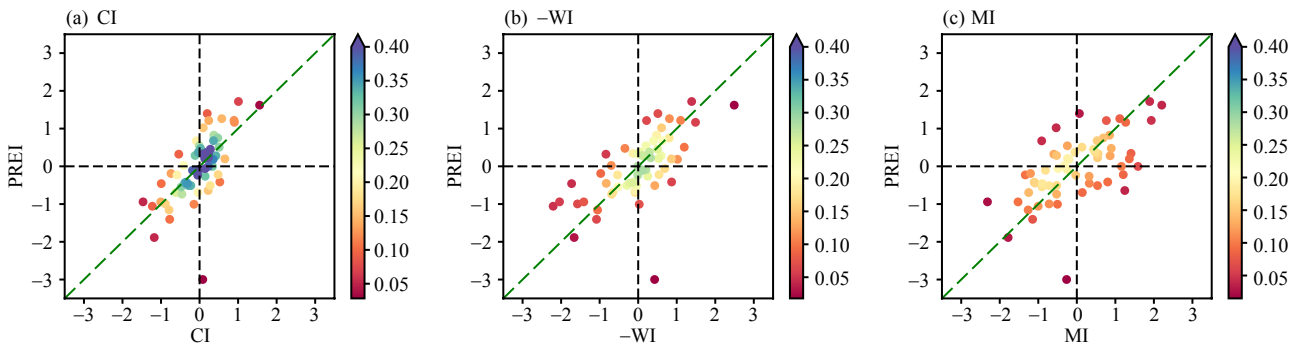


Figure 13. Scatter distribution density of CI (a), $-WI$ (b) (for ease of comparison, the WI is taken as the opposite), MI (c), and PREI. The color bar indicates the density of scattered points.

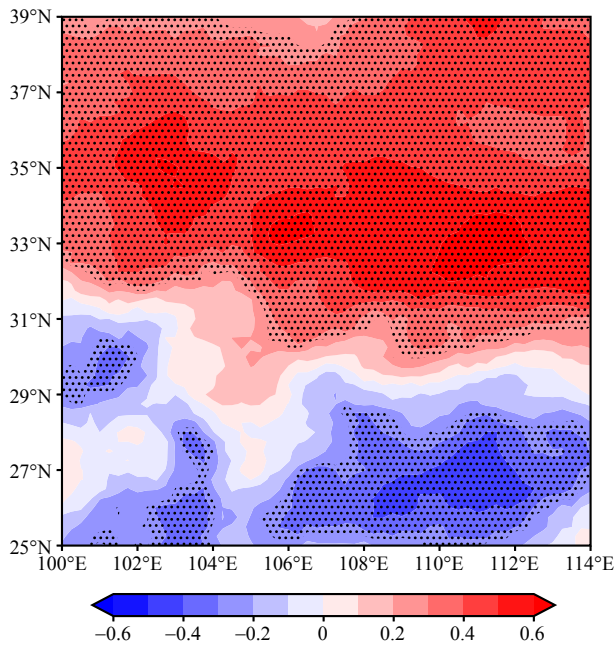


Figure 14. Correlation between CI and precipitation after 9-year highpass filtering (shaded area; dot marks indicate passing 95% significance test).

economic activities, and transportation. ARWC is a crucial meteorological phenomenon that is intimately linked to the economy, society, and overall well-being of the nation.

Focusing on the scientific problem of ARWC, based on the ERA5 reanalysis data and CN05.1 grid precipitation data in September and October from 1962 to 2021, we examined the characteristics of ARWC under the synergistic effect of the coupling of the westerly jet and meridional wind, as well as their interrelationships and physical mechanisms, and drew the following main conclusions.

(1) Precipitation in the ARZ is characterized by significant regional climatic differences. The northern and southern regions showed an inverse anomaly distribution, and the boundary between the positive and negative regions was V-shaped. Over the past six decades, the ARWC has undergone three stages: increasing, decreasing, and increasing, and sudden trend changes occurred in 1985 and 2010.

(2) ARWC is intimately intertwined with a westerly jet, particularly the north-south oscillation of its position. When the position of the westerly jet shifted southward (northward), the precipitation in the NARZ was more barren (abundant), and the precipitation in the SARZ was

more abundant (barren), reflecting the direct influence of the upper atmospheric circulation system at middle to high latitudes on the ARWC. The north-south oscillation of the westerly jet can be attributed to the southward transmission of energy from the teleconnection wave train in Eurasia. Specifically, the larger meridional component of the T-N wave flux carried more fluctuating energy dispersed to the south, thereby contributing to the southward displacement of the westerly jet position.

(3) There is a significant relationship between ARWC and meridional wind circulation within key regions at 850 hPa, specifically between (25°–35°N, 105°–130°E), as well as (9°–19°N, 131°–143°E). Strong (weak) mean meridional southerly wind circulation in these crucial zones was correlated with high (low) precipitation levels in the NARZ and low (high) levels in the SARZ. This pattern highlights the direct impact of the low-level atmospheric circulation system at low and mid latitudes on the ARWC.

(4) There was a significant negative correlation between the westerly jet and meridional wind, indicating an inherent coupling relationship. This coupling of wind fields in the high and low layers leads to abnormal responses in atmospheric circulation, which is a key physical mechanism driving ARWC. From 1962 to 2021, two predominant reverse coupling modes of the westerly jet and meridional wind have been identified: weak meridional wind-southward westerly jet (mlwh) and strong meridional wind-northward westerly jet (mhw). These coupling forms significantly affect ARWC by inducing a significant three-dimensional thermodynamic abnormal response across the atmospheric circulation. When a weak southerly wind coincided with a southward westerly jet, the atmospheric circulation at 500 hPa exhibited large meridionality at mid-high latitudes. This was accompanied by a positive-negative-negative geopotential height anomaly from high to low latitudes. The position of the western Pacific subtropical high is more eastern than the climatological norms. In the NARZ (SARZ), abnormal cold (warm) advection occurred along with downward (upward) movement and a large amount of net water vapor outflow (inflow), which caused less (more) precipitation. However, during periods of strong southerly winds and northward westerly jets, and vice versa.

(5) After elucidating that the synergistic effect of wind fields at different levels influences ARWC, we propose a new CI, integrating WI and MI. This index captures the synergistic effect of the westerly jet and meridional wind, offering a more accurate characterization of the ARWC than either WI or MI alone. The correlation between the CI and precipitation in the ARZ significantly improved. Notably, the CI exhibited opposite correlations with precipitation in the NARZ and SARZ, highlighting distinct anomaly patterns in these regions. The CI, with its clear physical basis and practical applicability, enhances our ability to predict abnormal changes in ARWC and

offers significant application value.

This study introduces an innovative approach to address the limitations of current research on ARWC by integrating the combined effects of the upper-level westerly jet and lower-level meridional wind circulation. It reveals the three-dimensional atmospheric dynamics, thermodynamic structures, and physical processes that influence the ARWC, driven by the synergistic coupling between the upper and lower atmospheric circulations. Furthermore, this research introduces a new comprehensive index to quantify anomalous changes in ARWC, offering significant contributions to both the scientific understanding and practical forecasting of the ARWC. Nevertheless, recognized challenges remain that warrant further investigation and enhancement in future research.

This research acknowledges the intricate and varied interconnections between the upper and lower atmospheric layers at high and low latitudes, characterized by multiscale, nonlinear features. While the primary focus is on anomalies in large-scale circulation and their dynamic-thermal impacts, future research should also consider the potential effects of atmospheric energy, momentum transfer, and conversion on interactions across different scales. Dynamic diagnosis, numerical simulation, and theoretical research offer promising methods for further analysis.

Furthermore, while this study primarily addressed the impacts of large-scale westerly jet and meridional wind circulations, it is essential to recognize the significant influence of the complex terrain of the Tibetan Plateau on ARWC. Specifically, the anomalous activities of plateau weather systems, including variations in the frequency, organization, and diversity of their climatic regimes, play a crucial role. For instance, the interactions between small- and medium-scale atmospheric systems, such as the plateau low vortex and southwestern low vortex, merit detailed investigation. These relationships underscore the complexity of atmospheric dynamics over the plateau, highlighting the need for further research on ARWC.

REFERENCES

- Bai, H. Z., and W. J. Dong, 2004: Climate features and formation causes of autumn rain over southwest China. *Plateau Meteorol.*, **23**, 884–889, <https://doi.org/10.3321/j.issn:1000-0534.2004.06.022>. (in Chinese)
- Chen, S. Y., S. Lin, and K. Z. Guo, 2010: Relationship between precipitation anomaly in September of western China and 700 hPa wind field in East Asia. *Plateau Meteorol.*, **29**, 1501–1506. (in Chinese)
- Chen, J., W. Huang, S. Feng, Q. Zhang, X. Kuang, J. Chen, and F. Chen, 2021: The modulation of westerlies-monsoon interaction on climate over the monsoon boundary zone in East Asia. *Int. J. Climatol.*, **41**, E3049–E3064, <https://doi.org/10.1002/joc.6903>.
- Ding, Y. H., and Z. Y. Wang, 2008: A study of rainy seasons in China. *Meteorol. Atmos. Phys.*, **100**, 121–138, <https://doi.org/10.1007/s00703-008-0299-2>.

- Fang, J., J. Z. Hou, J. L. Tao, M. J. Li, and A. J. Bai, 2008: An analysis of climate characteristic of rainfall in Qinling in autumn. *J. Meteorol. Sci.*, **28**, 415–420. (in Chinese)
- Gao, Y. X., and Q. Y. Guo, 1958: On the autumn raining area in China. *Acta. Meteorol. Sin.*, **29**, 264–273. (in Chinese)
- Guo, L., and C. W. Zhu, 2022: Coupling mode of westerly-monsoonal flow over the Tibetan Plateau and its seasonal variation. *Chin. J. Atmos. Sci.*, **46**, 1017–1029, <https://doi.org/10.3878/j.issn.1006-9895.2204.21260>. (in Chinese)
- Hersbach, H., and Coauthors, 2020: The ERA5 global reanalysis. *Q. J. R. Meteorol. Soc.*, **146**, 1999–2049, <https://doi.org/10.1002/qj.3803>.
- Hu, H. B., Q. G. Wu, and Z. P. Wu, 2018: Influences of two types of El Niño event on the Northwest Pacific and tropical Indian Ocean SST anomalies. *J. Oceanol. Limnol.*, **36**, 33–47, <https://doi.org/10.1007/s00343-018-6296-5>.
- Hui, Y., 2016: A synoptic climatology of the bimodal precipitation in West China, Ph.D. thesis, Institute of Earth Environment, University of Chinese Academy of Sciences, 104 pp. (in Chinese)
- Liu, Y. J., L. Sun, C. H. Sun, Z. Y. Wang, Y. J. Wang, and Y. Yuan, 2012: Analysis of anomalies of autumn rain in West China in 2011 and its possible mechanism. *Meteorol. Mon.*, **38**, 456–463. (in Chinese)
- Luo, X., D. L. Li, and H. Wang, 2013: New evolution features of autumn rainfall in West China and its responses to atmospheric circulation. *Plateau Meteorol.*, **32**, 1019–1031. (in Chinese)
- Niu, N., and J. P. Li, 2008: Interannual variability of autumn precipitation over South China and its relation to atmospheric circulation and SST anomalies. *Adv. Atmos. Sci.*, **25**, 117–125, <https://doi.org/10.1007/s00376-008-0117-2>.
- North, G. R., T. L. Bell, R. F. Cahalan, and F. J. Moeng, 1982: Sampling errors in the estimation of empirical orthogonal functions. *Mon. Weather Rev.*, **110**, 699–706, [https://doi.org/10.1175/1520-0493\(1982\)110<0699:SEITEO>2.0.CO;2](https://doi.org/10.1175/1520-0493(1982)110<0699:SEITEO>2.0.CO;2).
- Qi, D. M., C. Y. Zhou, Y. Q. Li, and Z. X. Sun, 2020: Analysis of autumn rainy and sunless characteristics and its mechanism in Sichuan in 2017. *Meteorol. Mon.*, **46**, 37–49, <https://doi.org/10.7519/j.issn.1000-0526.2020.01.004>. (in Chinese)
- Sun, Z. P., Y. Z. Liu, and Y. H. Ding, 1987: On secondary circulation in synoptic scale systems. *Chin. J. Atmos. Sci.*, **11**, 88–99. (in Chinese)
- Song, C. Y., J. Wang, Y. J. Liu, L. Zhang, Y. H. Ding, Q. P. Li, X. Y. Shen, Y. L. Song, and Y. P. Yan, 2022: Toward role of westerly-monsoon interplay in linking interannual variations of late spring precipitation over the southeastern Tibetan Plateau. *Atmos. Sci. Lett.*, **23**, e1074, <https://doi.org/10.1002/asl.1074>.
- Wang, L., W. Chen, W. Zhou, and G. Huang, 2015: Tele-connected influence of tropical Northwest Pacific sea surface temperature on interannual variability of autumn precipitation in Southwest China. *Climate Dyn.*, **45**, 2527–2539, <https://doi.org/10.1007/s00382-015-2490-8>.
- Wang, Z. Y., and B. T. Zhou, 2019: Observed decadal transition in trend of autumn rainfall over Central China in the late 1990s. *J. Climate*, **32**, 1395–1409, <https://doi.org/10.1175/JCLI-D-18-0112.1>.
- Wei, T., S. P. He, Q. Yan, W. Dong, and X. Wen, 2018: Decadal shift in West China autumn precipitation and its association with sea surface temperature. *J. Geophys. Res.-Atmos.*, **123**, 835–847, <https://doi.org/10.1002/2017JD027092>.
- Wei, T., W. L. Song, W. J. Dong, Z. Ke, L. Sun, and X. Wen, 2019: A skilful prediction scheme for West China autumn precipitation. *Theor. Appl. Climatol.*, **135**, 183–192, <https://doi.org/10.1007/s00704-017-2363-7>.
- Wei, W., R. H. Zhang, M. Wen, and S. Yang, 2017: Relationship between the Asian westerly jet stream and summer rainfall over central Asia and North China: Roles of the Indian Monsoon and the south Asian high. *J. Climate*, **30**, 537–552, <https://doi.org/10.1175/JCLI-D-15-0814.1>.
- Wu, J., and X. J. Gao, 2013: A gridded daily observation dataset over China region and comparison with the other datasets. *Chin. J. Geophys.*, **56**, 1102–1111, <https://doi.org/10.6038/cjg20130406>. (in Chinese)
- Wu, Y., H. Y. Tang, Y. Liu, X. Y. Dong, and Q. Guo, 2020: Application of statistical downscaling model to autumn rainfall forecasting over southwest China. *Meteorol. Mon.*, **46**, 1555–1564. (in Chinese)
- Xu, M., B. Zhou, and Z. Cheng, 2020: Preliminary analysis on the interdecadal increase of autumn rainfall in western China since 2010. *Trans. Atmos. Sci.*, **43**, 568–576, <https://doi.org/10.13878/j.cnki.dqkxxb.20191227002>. (in Chinese)
- Yao, T. D., S. L. Pu, M. G. Shen, J. Gao, W. Yang, G. Q. Zhang, Y. B. Lei, Y. Gao, L. P. Zhu, B. Q. Xu, W. S. Yu, and S. H. Li, 2017: Chained impacts on modern environment of interaction between westerlies and Indian monsoon on Tibetan Plateau. *Bull. Chin. Acad. Sci.*, **32**, 976–984, <https://doi.org/10.16418/j.issn.1000-3045.2017.09.007>.
- Zhang, C., Z. Y. Wang, B. T. Zhou, Y. Li, H. Tang, and B. Xiang, 2019: Trends in autumn rain of West China from 1961 to 2014. *Theor. Appl. Climatol.*, **135**, 533–544, <https://doi.org/10.1007/s00704-017-2361-9>.
- Zhao, Y., M. Z. Wang, A. N. Huang, H. Li, W. Huo, and Q. Yang, 2014: Relationships between the West Asian subtropical westerly jet and summer precipitation in northern Xinjiang. *Theor. Appl. Climatol.*, **116**, 403–411, <https://doi.org/10.1007/s00704-013-0948-3>.
- Zhu, Z. W., R. Lu, H. P. Yan, W. Li, T. Li, and J. He, 2020: Dynamic origin of the interannual variability of West China autumn rainfall. *J. Climate*, **33**, 9643–9652, <https://doi.org/10.1175/JCLI-D-20-0097.1>.

Citation: Li, Y. N., Y. Q. Li, S. Y. Xiang, and X. Y. Fan, 2026: Anomalous Characteristics and Mechanisms of Autumn Rain in Western China: A Synergistic Analysis of Upper and Lower Atmospheric Circulation Influences. *J. Trop. Meteor.*, **32**, 55–72, <https://doi.org/10.3724/j.1006-8775.2025.055>.

APPENDIX

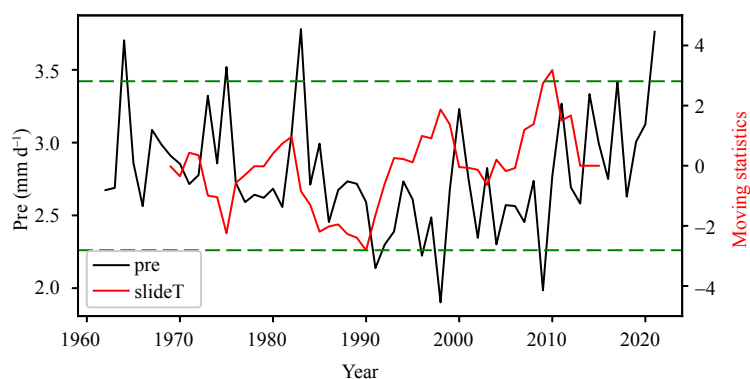


Figure A1. Temporal variation of average daily precipitation and sliding-T statistic curve in ARZ (the black line represents regional average precipitation, the red line represents sliding-T statistic, and the green dashed line represents the critical value at 99% significance level).

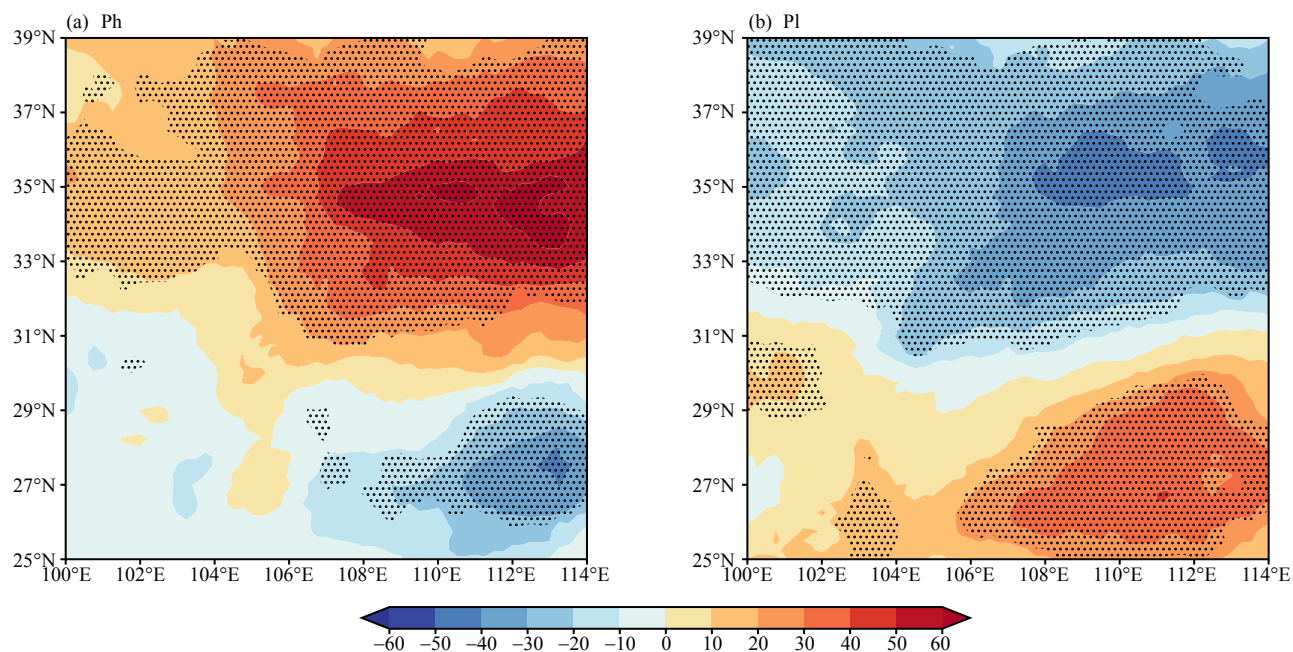


Figure A2. Composite distribution of precipitation anomaly percentage (units: %) in (a) high PREI and (b) low-PREI years (dot indicates passing 95% significance test).

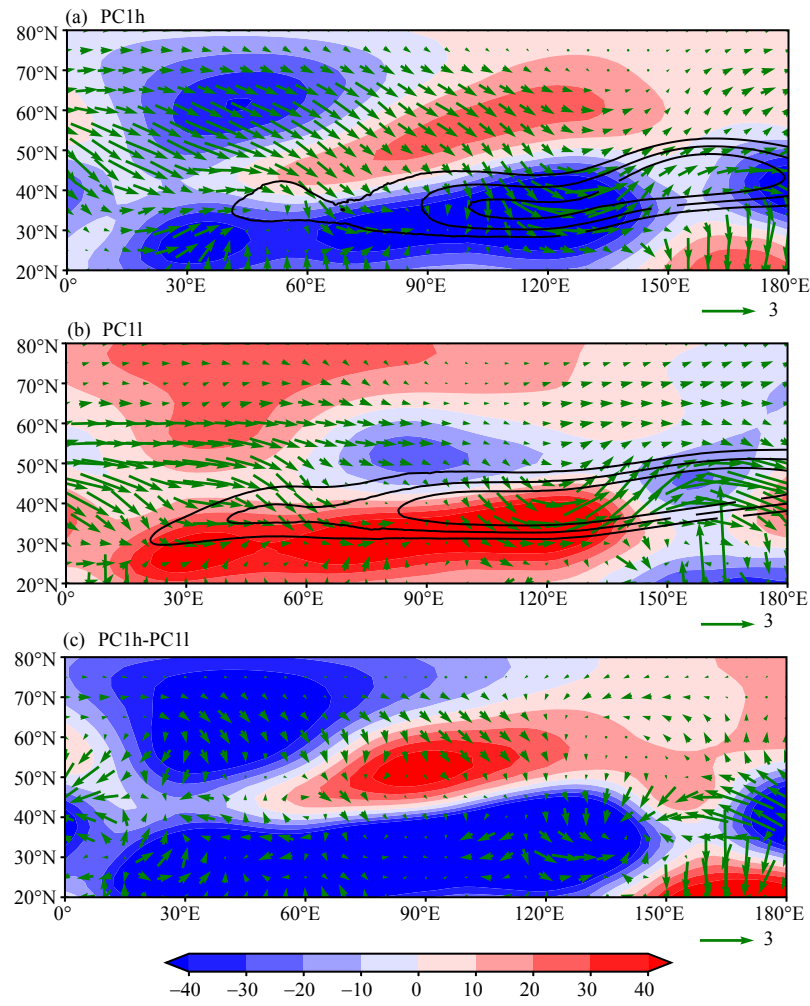


Figure A3. (a) PC1 positive anomaly years, (b) PC1 negative anomaly years of stream function (shaded, units: 10^5 m) and T-N wave activity flux (vector, units: $\text{m}^2 \text{s}^{-2}$) at 200 hPa, and (c) the difference. Black contours in (a) and (b) represent jets with zonal wind greater than 24, 30, and 36 m s^{-1} .

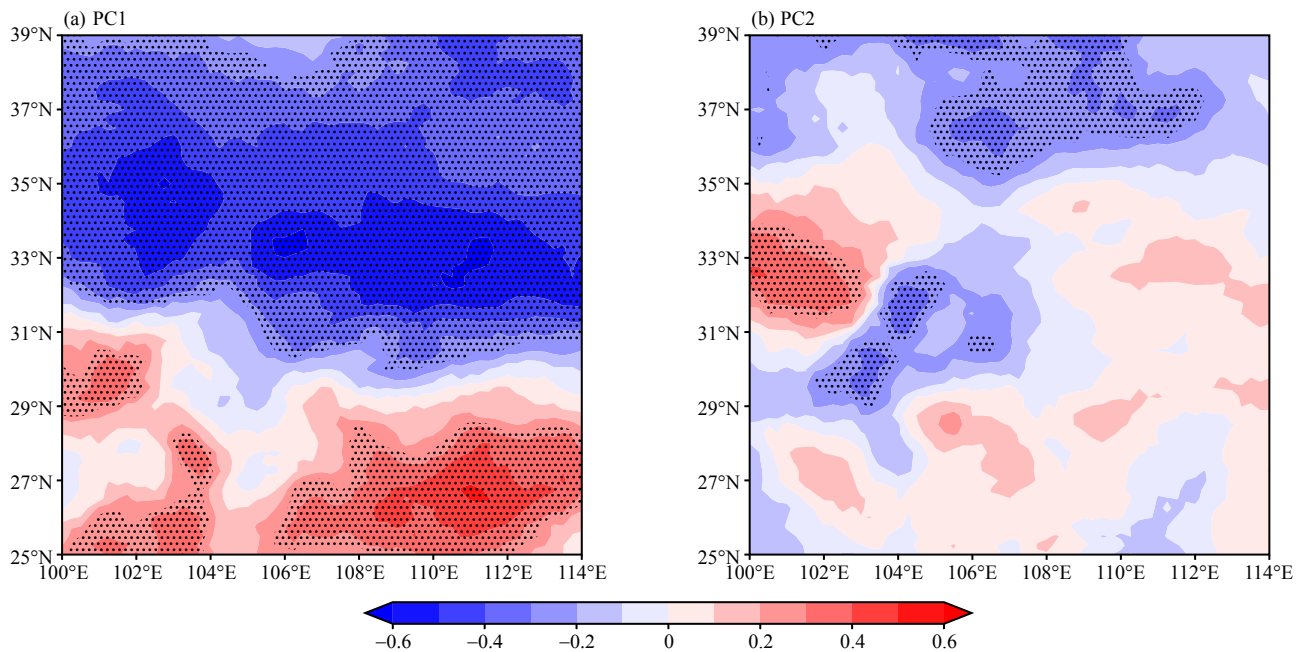


Figure A4. Correlation between standardized westerly (a) PC1, (b) PC2 and precipitation after 9-year highpass filtering (shaded area; dot marks indicate passing 95% significance test).

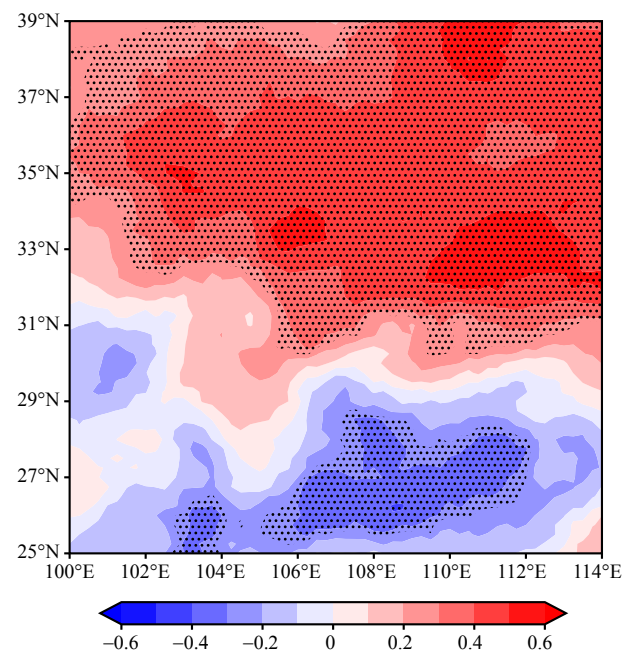


Figure A5. Same as Fig. A4, but for MI.