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Research Article

The Relationship between the Atmospheric Heat Source over Tibetan Plateau and the Westerly-Monsoon Evolution in August and Its Physical Mechanism

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In this study, the relationship between the East Asian subtropical westerly jet (EASWJ) and the East Asian summer monsoon (EASM) (westerly monsoon) and the correlation with the atmospheric heat source (AHS) on the Tibetan plateau (TP), especially the possible connection of the sudden enhancement of the correlation in August were analyzed. The results show that there is a significant correlation between the EASWJ and the EASM from June to October in terms of both intra-annual variability and interannual fluctuations, and the correlation between the AHS over TP and the EASWJ and the EASM during the same period is significantly enhanced in August. The synthetic analysis indicated that when the AHS was strong, a positive anomaly of a horizontal temperature gradient appeared over TP, which was conducive to the southward shift of the high-altitude temperature gradient center, resulting in the southward position of the axis of the 200 hPa westerly jet, and an upward and downward inclined westerly anomaly zone appeared from the south slope of TP to the main body and its north slope. Meanwhile, the East Asia–Pacific (EAP) teleconnection pattern with a negative phase appeared at 500 hPa, and TP to western Japan was located in the negative value area of the wave train. The AHS was conducive to the enhancement of the EAP negative phase, which was not conducive to the further northward transportation of water vapor by the EASM. On the contrary, when the AHS on TP was weak, the position of the westerly jet was northward and the EAP positive phase enhanced, contributing to the further northward transport of water vapor from the EASM.

1. Introduction

The westerlies and the monsoon circulation system are two important components of the global atmospheric circulation [1], and the low-level monsoon activity and the upper-level wind system changes are not isolated from each other; they are a whole, but only in the low-level and upper-level performance characteristics are they different [2]. Many works have studied the relationship between the East Asian subtropical westerly jet (EASWJ) and East Asian summer monsoon (EASM) from different perspectives, such as the meridional displacement of the EASWJ and the seasonal transition [3], the onset of the EASM [4, 5] and Meiyu in East Asia [6], and the north margin of the EASM [7]. Lu et al. [8] pointed out that the EASWJ may be the key linkage between the EASM and the Indian monsoon. Zuo et al. [1] found through numerical simulation that the westerlies and monsoon precipitation are driven by the subtropical divergence sources in both hemispheres, and the summer monsoon weakens the westerlies in the northern hemisphere. Yao et al. [9] showed that two major circulations, the westerlies and the Indian monsoon, are the decisive factors controlling climate and environmental changes on the Tibetan Plateau (TP). Chen et al. [10] found that the EASM and the EASWJ have synergistic effects on precipitation at the edge of the monsoon.

TP and its atmospheric heat source (AHS) effects play an important role in the weather and climate of East Asia and the global [11]. Numerous studies demonstrated that the weather and climatic systems such as the South Asian high [12], the TP vortices [13, 14], and the subtropical high [15] were affected by the AHS of the TP. Moreover, the abnormal activities of the EASM and the EASWJ are also more or less regulated by the AHS of TP. Some studies indicate that when the AHS of TP is strong in spring, the onset of the EASM is often late. In summer, the eastern rain belt of China is abnormally distributed as "negative-positive-negative," and the precipitation in the middle and lower reaches of the Yangtze River is abnormally high [16–19]. And when the AHS of TP is relatively strong, the EASWJ on the north side of TP is strengthened, and the EASWJ is located to the north. In addition, the AHS of TP also guides the east-west movement of the EASWJ center [20–23].

It should be pointed out that although previous studies have noticed the correlation between EASWJ and EASM, the physical mechanism of the synchronous changes is not very clear, and many works mainly study the effects of TP thermal effects on EASM and EASWJ separately, while the analysis between the AHS of TP and EASWJ and EASM (westerly-monsoon) is still less and needs to be further strengthened. Therefore, starting from the evolution of the AHS of the TP and the westerly monsoon, the changes of their relationship in summer and the role of the AHS of the TP are studied to further enhance the scientific understanding of the physical mechanism for the coordinated change of the westerly-monsoon under the influence of the AHS.

2. Data and Methods

2.1. Data. NCEP/NCAR reanalysis I daily and monthly data for 1981 to 2020 were used, including the variables such as pressure, air temperature, wind, relative humidity, and vertical velocity, with a spatial resolution of $2.5^\circ \times 2.5^\circ$, and the NCAR monthly OLR (outgoing longwave radiation) data for the same period, with a spatial resolution of $2.5^\circ \times 2.5^\circ$.

2.2. Methods. The calculation method of the AHS is chosen Yanai et al. [24] proposed the inverse algorithm with the following calculation equation:

$$Q_1 = \left[\frac{\partial T}{\partial t} + V \bullet \nabla T + \left(\frac{P}{Ps}\right)^k \omega \frac{\partial \theta}{\partial P}\right], < Q_1 > = \frac{1}{g}\int_{Po}^{Ps} Q_1 dp, \tag{1}$$

where Q_1 is the atmospheric apparent heat source for each layer (unit, $K \bullet d^{-1}$), $<Q_1>$ denotes the entire vertical integral atmospheric apparent heat source (unit, $W \bullet m^{-2}$), T is the temperature, V is the horizontal wind speed, P_s is the 100 hPa atmospheric pressure, P_o is the surface air pressure, $k = R/c_p$, $R = 8.314$ ($J \bullet mol^{-1} \bullet K^{-1}$), ω is the vertical velocity($Pa \bullet s^{-1}$) of P coordinate system, and θ is the potential temperature (K).

Referring to the method of Kuang and Zhang [25], the average value of the latitude where the maximum westerlies are located in the range (70–120°E, 30–50°N) at 200 hPa is defined as the axial index of EASWJ, which can accurately reflect the north-south variation of the location of EASWJ and has a better correspondence with EASM.

Using the EASM index defined by Wang and Fan [26]; it is the difference between the mean values of 850 hPa latitudinal winds in region I (5–15°N, 90–130°E) and region II (22.5–32.5°N, 110–140°E). The index has a clear interannual variability and is a good indicator of the tripolar type monsoon precipitation in summer in China. When the EASM index is strong (weak), the summer rain belt in China tends to have a spatial anomaly distribution of "positive-negative-positive" "(negative-positive-negative)," with the most significant anomaly in the middle and lower reaches of the Yangtze River.

3. Results and Discussion

3.1. Relationship between the Atmospheric Heat Source of the TP and the Westerly-Monsoon. Under the climatic mean conditions, the EASM has a very consistent intra-annual trend with the EASWJ. The intensity of the EASM first strengthens and then weakens, with the strongest in August. At the same time, the position of the EASWJ axis moves northward and then southward, with the northernmost position also being reached in August. The correlation coefficient between the EASM index and the EASWJ index in August from 1981 to 2020 was 0.35, which exceeded the 95% confidence level.

Figure 1(a) shows the spatial distribution of the average summer AHS for the whole layer of TP from 1981 to 2020. It can be seen that most of the regions are positive, and large centers of heat source are observed in the southeast. In addition, based on the correlation distribution of the August EASWJ index and the EASM index with the AHS of TP (Figures 1(b)–1(c)), the significant negative correlation zone is also located in the southeastern part of TP. Therefore, this region is the key region to reflect the relationship between the AHS and the EASM and the EASWJ. And the AHS index of TP is defined as the regional average of the whole layer in the key area (87.5–105°E, 27.5–35°N).

It can be seen from Figure 2 that the correlation coefficients between the AHS index and the EASWJ index for the same period from June to October are mainly negative, among which, in August and September are strongly negative correlations, with the strongest correlation coefficient −0.43 in August, exceeding the 99% confidence level. The contemporaneous correlations between the AHS index and the EASM index from June to October varied widely from month to month, with insignificant positive correlations in June, September, and October and insignificant negative correlations in July, but the correlation coefficient reaches −0.65 in August, exceeding the 99% confidence level.

The location of the EASWJ gradually moves northward from June to August and southward from August to October, which is the result of seasonal transformation. The negative correlation between the AHS and the location of the EASWJ cannot change its general trend. Although the AHS is strongest in July, the EASWJ is also in the stage of accelerating northward movement, so the impact of the AHS

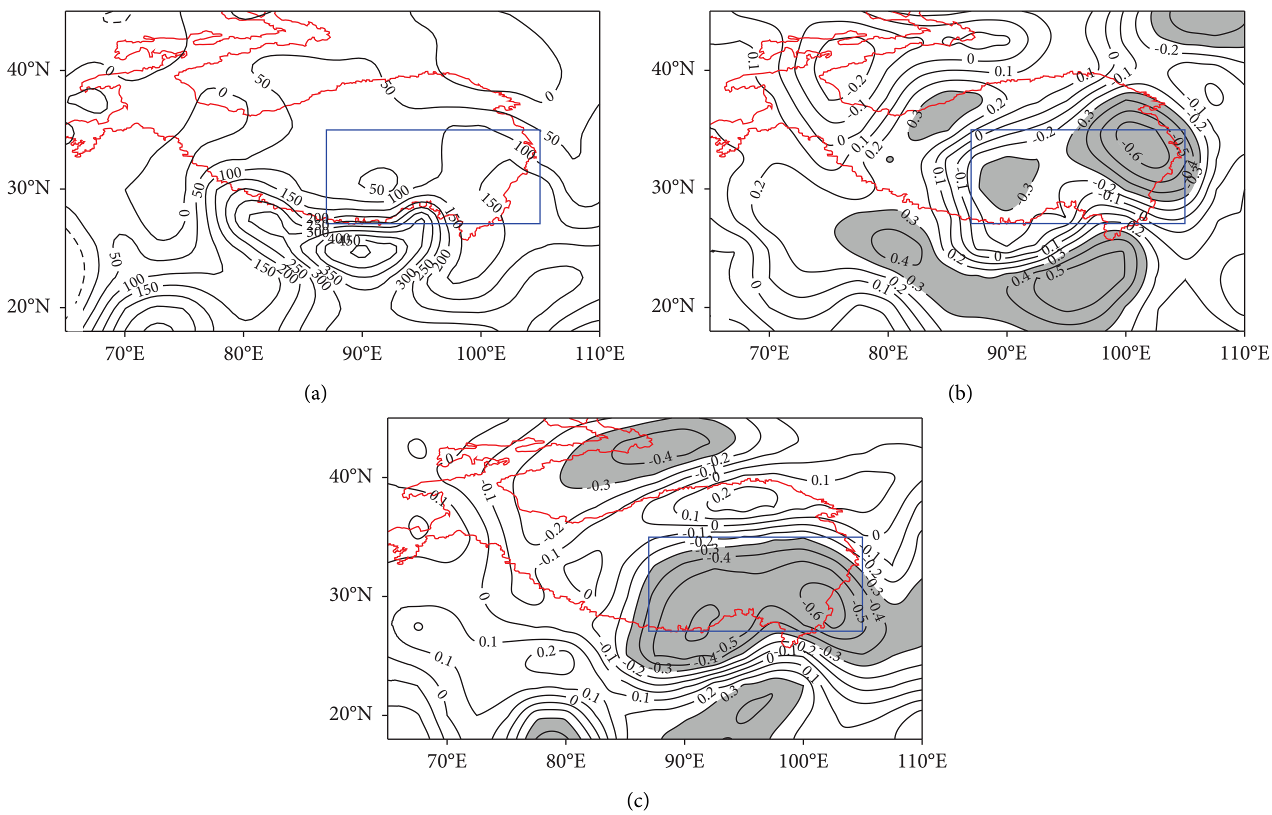

Figure 1: Spatial distribution of average atmospheric heat source of the whole layer in summer 1981–2020 (a) unit: w/m^2 and the corresponding correlation coefficient between the EASWJ index (b) and the EASM index (c) with heat source (blue area: 87.5–105°E, 27.5–35°N).

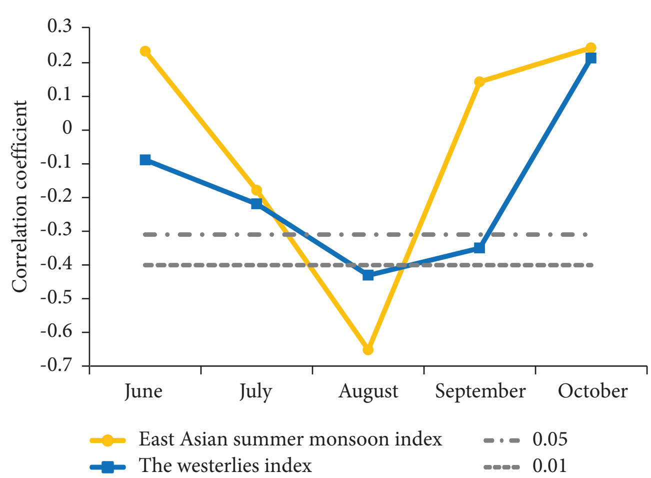

Figure 2: The monthly corresponding correlation coefficient between the AHS index of TP and the EASWJ index and the EASM index from 1981 to 2020 (dotted line is confidence level).

on it is not prominent. In August, the EASWJ starts to retreat southward. Although the AHS is weaker than that in July, it is still strong, and the influence of the AHS on the EASWJ was consistent with its change trend. So, the effect of the AHS became stronger. The intensity of the AHS decreases significantly after September, and its influence on the EASWJ also weakens. A similar relationship exists between the AHS and the EASM.

3.2. Mechanism of the Westerly-Monsoon Variation Influenced by AHS. The above analysis indicates that the EASM and the EASWJ from June to October have a significant isotropic variation relationship, and the AHS of TP in August has a significant inverse phase relationship with the EASM, while the AHS in August–September has a significant inverse phase relationship with the EASWJ. In particular, the AHS over TP in August is closely related to the

EASM and the EASWJ, respectively. So, how does the AHS, which is an important external forcing in summer, affect the changes of the EASM and the EASWJ through strong correlations in August? In the following, further analysis is investigated.

3.2.1. Characteristics of the AHS Anomalies over TP. Based on the close relationship between the westerly-monsoon variation and the AHS over TP, the yearly variation of the AHS index, the EASWJ index, and the EASM index in August from 1981 to 2020 is given in Figure 3, and each index is standardized separately for comparison purposes. Thus, it is seen that the August EASWJ index is well synchronized with the EASM index in terms of interannual fluctuations and interdecadal variability from 1981 to 2020, while the AHS is in the opposite trend of variability with both. Here, the simultaneous positive and negative anomalous years of the three indices were selected with 0.5 times the standard deviation as the cutoff value to obtain four strong AHS (weak westerly-monsoon) years (1988, 1998, 2008, and 2014) and four weak AHS (strong westerly-monsoon) years (1984, 1997, 2006, and 2016).

According to the three indices of synchronous anomalous years selected above, synthetic analysis was used to obtain the composite difference fields for the strong AHS (weak westerly-monsoon) and weak AHS (strong westerly-monsoon) years in August (Figure 4). It can be seen that the northern part of TP is a weak AHS negative anomaly, while most other areas are positive anomalies, with a positive anomaly maximum center in the southeast. Therefore, the southeast of TP is the key area of AHS anomaly.

3.2.2. Influence of AHS over TP on the EASWJ. The same synthetic analysis of three indices for the typical synoptic anomalies of 200 hPa latitudinal winds shows that there are obvious differences in the strength and especially the location of the EASWJ in the strong AHS (weak westerly-monsoon) and weak AHS (strong westerly-monsoon) years. The difference fields (Figure 5) show that a clear "positive-negative-positive-negative" latitudinal distribution of anomalous wave trains from low to high latitude for 200 hPa winds in the Philippine Islands, the South Central Peninsula, the TP-Bohai Sea, and the southern part of Lake Baikal.

Because 97.5°E is at the center of the EASWJ and is also located in the large value area of the AHS anomaly, a synthetic analysis of the height-latitude section along 97.5°E for zonal wind was further conducted to study the characteristics of the EASWJ anomaly in the whole atmosphere (Figure 6). It can be seen that the whole atmospheric wind field from low latitude to high latitude exhibits an obvious "negative-positive-negative" vertical distribution anomaly wave train, and there is a westerly anomaly belt from the south slope of TP to the main body and the north slope, with an anomaly center at 200 hPa and 500 hPa, respectively.

Next, a synthetic analysis of the height-latitude section along 97.5°E for the atmospheric meridional temperature gradient index in the strong AHS (weak westerly-monsoon) and weak AHS (strong westerly-monsoon) years is given

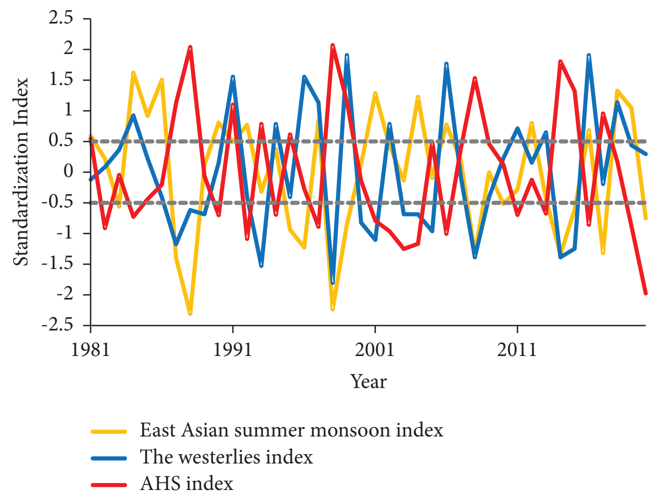

Figure 3: Variation of the EASWJ index, EASM index, and the AHS index of TP in August from 1981 to 2020.

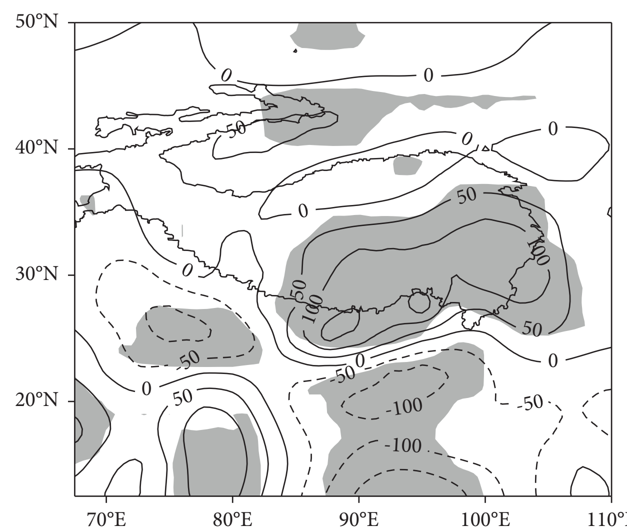

Figure 4: Difference synthetic field of <Q1> of strong AHS/weak westerly-monsoon year and weak AHS/strong westerly-monsoon year (shadow indicates passing 95% reliability test, unit: w/m^2).

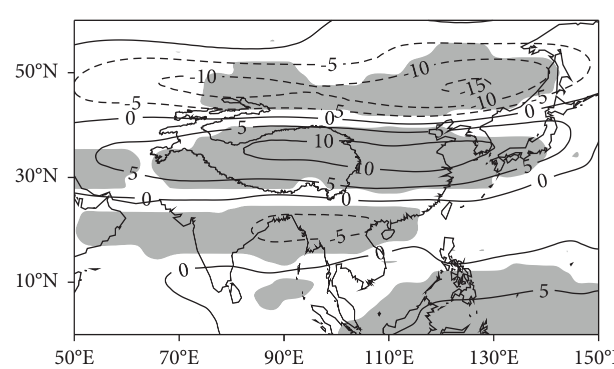

Figure 5: Difference synthetic field of 200 hPa zonal wind of strong AHS/weak westerly-monsoon year and weak AHS/strong westerly-monsoon year (shadow indicates passing 95% reliability test, unit: m/s).

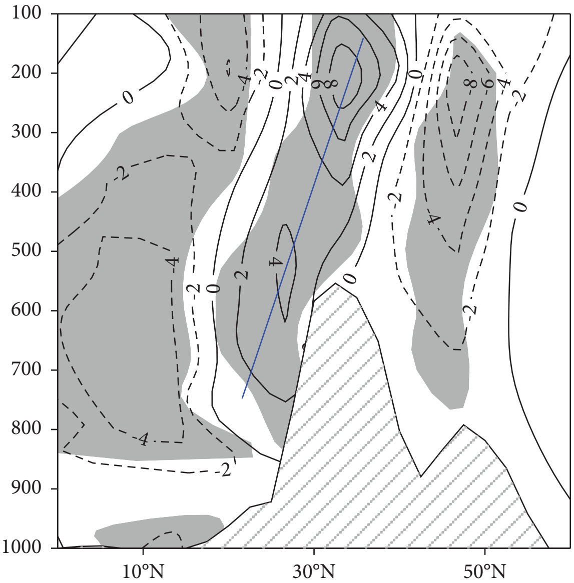

Figure 6: Difference synthetic field of the height-latitude section of zonal wind along 97.5°E of strong AHS/weak westerly-monsoon year and weak AHS/strong westerly-monsoon year (unit: m/s, shadow indicates passing 95% reliability significance test, slashes area represent terrain).

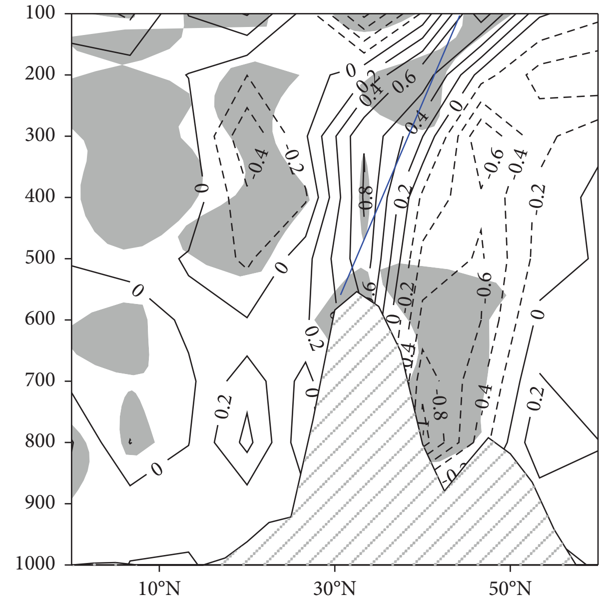

Figure 7: Difference synthetic field of the height-latitude section of temperature gradient along 97.5°C of strong AHS/weak westerly-monsoon year and weak AHS/strong westerly-monsoon year (unit: °C, shadow indicates passing 95% reliability significance test, slashes area represent terrain).

(Figure 7). It can be seen that when the strength of the AHS over TP changes, the atmospheric temperature gradient also has obvious distribution differences. And the large value center of the temperature gradient at 300 hPa shifts to lower latitudes when the AHS is strong. In other words, the strong AHS of TP can cause the southward shift of the large value area of the temperature gradient. According to the thermal wind principle, the center of the large value of the westerly jet is located over the maximum temperature gradient, so the strong AHS causes the southward shift of the westerly jet position.

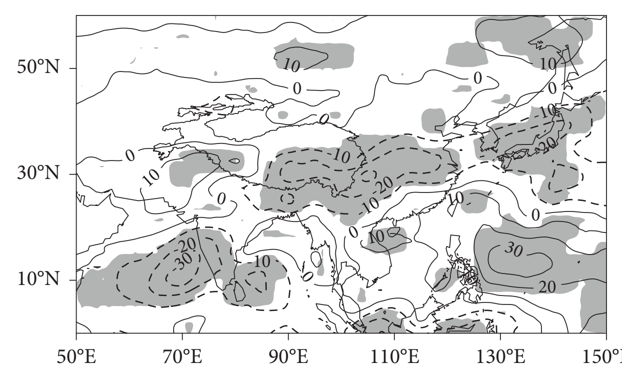

Figure 8: Difference synthetic field of OLR of strong AHS/weak westerly-monsoon year and weak AHS/strong westerly-monsoon year (unit: w/m^2, shadow indicates passing 95% reliability test).

3.2.3. Influence of AHS over TP on the EASM. OLR is an important component observed by satellites to characterize the radiative balance of the earth-atmosphere system, which can reflect the large-scale atmospheric vertical circulation and is widely used in the analysis of atmospheric convective activity [27, 28]. The synthetic analysis of OLR using the same method as above shows that the distribution of OLR anomalies in the years with strong AHS (weak westerly-monsoon) and the years with weak AHS (strong westerly-monsoon) are also significantly different. The difference field (Figure 8) shows clearly that the strong convective activity is in the southeastern part of TP, the Arabian Sea-Bay of Bengal, and Yangtze River basin to southern Japan, but it is suppressed in the eastern Philippines.

The 500 hPa height field reveals that there is a clear difference in the variation of the western Pacific subtropical high between the strong AHS (weak westerly-monsoon) and weak AHS (strong westerly monsoon) years. The difference synthesis field (Figure 9) shows that the anomalous wave train with "positive-negative-positive" latitudinal distribution from low latitude to high latitude appears in the northern Philippines, TP to the Bohai, and Sea of Okhotsk to Western Siberia, that is, the negative phase of East Asia–Pacific (EAP). From the main body of TP to western Japan, it is in the negative value region; that is, when the AHS is relatively strong, it is conducive to the enhancement of the negative phase of the EAP. And many studies have pointed out that the negative phase of the EAP is not conducive to the further northward advance of the EASM, thus producing anomalously high precipitation in the Yangtze and Huaihe River basins in China [29]. This is consistent with the study of Huang and Sun [30], who found that when convective activity in the Philippine region is enhanced (weakened), the position of the western Pacific subtropical high tends to be northward (southward), and precipitation is less (more) in the Yangtze-Huaihe River valley and more (less) in the Yellow River basin in China.

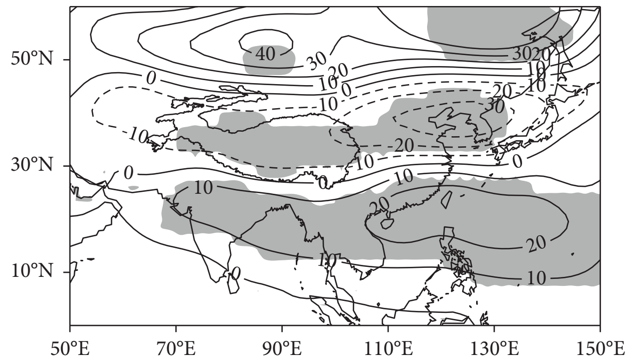

Figure 9: Difference synthetic field of 500 hPa height field of strong AHS/weak westerly-monsoon year and weak AHS/strong westerly-monsoon year (unit: gpm, shadow indicates passing 95% reliability test).

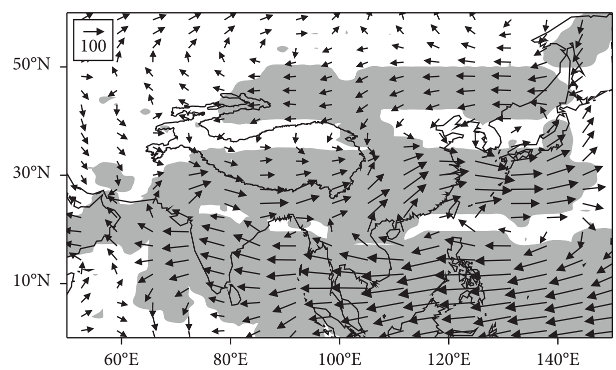

Figure 10: Difference synthetic field of water vapor transport flux from 1000 to 100 hPa of strong AHS/weak westerly-monsoon year and weak AHS/strong westerly-monsoon year (unit: $kg\,s^{-1}m^{-1}$, shadow indicates passing 95% reliability test).

The whole layer water vapor flux (Figure 10) further indicates that there is an anticyclonic water vapor transport anomaly from South China to the Philippines, where water vapor is transported from the South Central Peninsula to the Yangtze River basin with a clear water vapor convergence feature. This indicates that the anomalous anticyclonic water vapor transport in the northeast of the Philippines is not conducive to the further transport of water vapor from the south to the north by the EASM when the AHS is strong.

4. Conclusion

(1) There are correlations between the EASWJ and the EASM both in terms of intra- and interannual variability. The EASWJ moves northward and then southward from June to October each year, reaching its northernmost position in August; the EASM strengthens and then weakens during the same period, and strength is the strongest in August. Meanwhile, the correlations between the AHS over TP and the EASWJ and the EASM in June-October, although varying greatly from month to month, are significant, and the most negative correlation is for the AHS with both in August.

(2) The AHS over TP in August has a close correspondence with the westerly-monsoon variation. The EASWJ is well synchronized with the EASM in both interannual and interdecadal variability from 1981 to 2020, while the AHS is in obvious opposite variation to both. The center of the anomalously large value of the AHS occurred in the southeastern part of TP in both strong AHS (weak westerly-monsoon) years (1988, 1998, 2008, and 2014) and weak AHS (strong westerly-monsoon) years (1984, 1997, 2006, and 2016).

(3) Anomalies of the AHS over TP in August can affect the north-south shift of the axis of the EASWJ. When the AHS of TP is strong, the horizontal temperature gradient on the south side of TP, over it and the north side of it will have a “negative-positive-negative” anomalous distribution, resulting in the large value area of the horizontal temperature gradient in the high altitude shifting southward, thus making the high altitude westerly jet axis positioned southward, and a vertical inclined strong westerly jet belt appear from the south slope of TP to over TP. When the AHS of TP is weak, the opposite happens, resulting in the westerly jet axis positioned northward.

(4) The anomalies of the AHS of TP in August also affect the changes in the advance and retreat of the EASM at the same time. When the AHS of TP is strong, the convective activity over the southeastern part of TP can enhance the negative phase of the EAP teleconnection, which is not conducive to the northward advance of the EASM. On the contrary, when the AHS is weak, it can enhance the positive phase of the EAP teleconnection, which is conducive to the strengthening and promotion of the EASM.

Although the close relationship between the AHS on TP and the EASWJ and the EASM, especially the important influence of the AHS on the activities of the EASWJ and the EASM in August is revealed, this is only a preliminary result. And a more in-depth and systematic analysis is needed to investigate how the AHS on TP affects the EASWJ and the EASM activities and thus leads to the variation of atmospheric circulation system such as subtropical high in East Asia and its weather-climate anomaly mechanism. In addition, some studies have pointed out that the anomaly of the westerly-monsoon system also has a significant impact on the amount of summer precipitation on the Tibetan Plateau [31–33] and precipitation can directly affect the AHS of TP by the release of latent heat [34, 35]. Therefore, there may be a feedback mechanism between the westerly-monsoon and the AHS of TP, and the interaction between them is also very worthy of in-depth study.

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.

Authors' Contributions

C. W. conducted the conceptualization and methodology and wrote the manuscript. Y. L. provided guidance throughout the meteorological analysis.

Acknowledgments

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