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# Meridional seesaw-like distribution of the Meiyu rainfall over the Changjiang-Huaihe River Valley and characteristics in the anomalous climate years

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**Although Meiyu rainfall has its in-phase spatial variability over the Changjiang-Huaihe River Valley (CHRV) in most years, it is distributed in some years like a seesaw to the north and south of the Changjiang River, when the precipitation tends to be nearly normal throughout the valley, which would inevitably increase difficulties of making short-term prediction of the rainfall. For this reason, EOF analysis is made on 15 related stations' precipitation from June to July during 1951—2004, revealing that the EOF2 mode shows largely a north-south seesaw-like pattern, and thereby classifying Meiyu patterns into two types: "northern drought and southern flood (NDSF)" and "northern flood and southern drought (NFSD)". Afterwards, the authors investigated ocean-atmospheric characteristics when these two anomalous types occured using the NCEP reanalysis (version 1) and the extended reconstructed SSTs (version 2). The results show that in the NDSF years, the low-level frontal area and moisture convergence center lie more southward, accompanied by weaker subtropical summer monsoon over East Asia, with the western Pacific subtropical high and 200 hPa South Asia High being more southward. Both the Northern and Southern Hemisphere Annular Modes are stronger than normal in preceding February; SST is higher off China during boreal winter and spring and the opposite happens in the NFSD years. Also, this seesaw-form Meiyu rainfall distribution might be affected to some degree by the previous ENSO event.**

Meiyu, floods and droughts, spatial distribution, ocean-atmospheric singularities

Since the 1930s, numerous investigations have been made on the Meiyu rainfall as an essential component of the summer precipitation over the Changjiang-Huaihe River Valley (CHRV) because of the significance of the rainfall to summer floods and droughts therein[1−8]. Viewed overall, these studies placed more focuses on the droughts/floods throughout the valley as well as related factors. As a matter of fact, in addition to the drier or wetter than normal event all the valley over, there is probably a situation of being normal for the whole CHRV but with localized floods or droughts and there is occasion when the whole CHRV averaged is hit by floods (droughts) with parts under the effect of droughts (floods). Take the year of 1991 typically regarded as a wet year for an example[9−11], during which negative anomaly occurred to such areas as Jiujiang, Tunxi, Nanchang and Changsha south of the Yangtze River, of which Nanchang received minimum rainfall, with its negative anomaly reaching −228 mm. Consequently, the

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band to the south of the Yangtze River is believed to be drier than normal in 1991 in sharp contrast to the areas to the north. Wu et al.[12] revealed the droughts-floods coexistence phenomenon in the middle and lower reaches of the Yangtze River basin in years of normal summer monsoon, suggesting that in a year of normal summer monsoon, albeit the mean rainfall approaches a normal state for the valley, there is dryness in an interval of time and wetness in another. Now, whether the likelihood is available to the flood/drought co-existence on a spatial basis is our concern. That implies that for the nearly normal precipitation over the CHRV, drought and flood occur simultaneously, one to the south and the other to the north of the Yangtze River, a problem that seems to have been studied little, and is of great importance to the human activities there. And the localized inconsistency enhances the difficulties of short-range climate prediction of Meiyu precipitation. For this reason, an attempt is made to perform EOF analysis of the Meiyu rainfall field in June—July for the study valley in order to find out its abnormal space patterns as well as the typical years, with focus on the seesaw-like distribution of rainfall and the air-sea features in anomalous years.

## 1 Data and methods

In light of the classification of precipitation area given by Ting and Wang[13], we calculated the standard deviations of accumulative precipitation during the Meiyu period of Chinese 160 stations from 1951 to 2004, and selected the station of Anqing, which is of the largest variation in the CHRV, as the base point. We then made a one-point correlation map between the base point, Anqing, and Chinese 160 stations (Figure 1), where the shaded area with correlation coefficients exceeding 95% confidence level based on the Monte Carlo test is defined as the Meiyu region, and 15 stations evenly distributed to the east of 110°E were selected as the representative stations, and the EOF analysis of 54 a rainfall fields was conducted, leading to the first two dominant modes and their time coefficients, finding that the second mode shows north-south seesaw form that we are interested in. In order to investigate the simultaneous and previous (from December to May) characteristics of the air-sea background for this mode, monthly mean NCEP reanalysis version 1[14] at resolution of 2.5°×2.5° and extended reconstructed sea surface temperature (ERSST) version 2[15] (resolution being 2.0°×2.0°) provided by the National Oceanic and Atmospheric Administration (NOAA) are utilized.

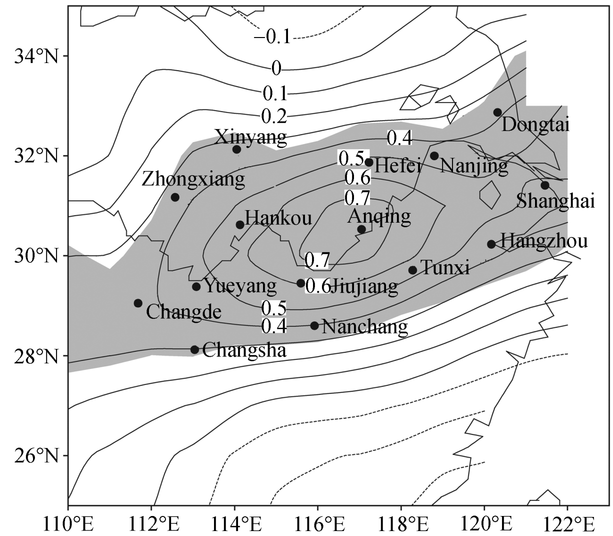


**Figure 1** One-point correlation of rainfall during the Meiyu period (from June to July) over the Changjiang-Huaihe River Valley (CHRV) with Anqing as the base point. Closed circles stand for the 15 representative stations. Values of the shaded area are taken at 95% confidence level on the basis of the Monte Carlo test.

## 2 North-south seesaw-like distribution of the Meiyu rainfall anomalies over the CHRV

Based on the EOF analysis, we find that the accumulated variance contribution ($V_h$) of the first 7 eigenvectors reaches 90% (Table 1). The EOF1-explained variance constitutes 51%, with in-phase spatial distribution throughout the valley, namely, the pattern of droughts or floods over the whole CHRV (figure not shown). The EOF2-explained variance is about 16%, characterized by a seesaw-like distribution with the Yangtze River as the division, centered at Dongtai and Changsha of maximal variability, separately, followed by spreading outward (Figure 2(a)). Figure 2(b) illustrates the time series, which shows significant interannual variability, with an about 25 a oscillation cycle but without distinct trends for the whole period.

In the following, we shall select the representative

**Table 1** Variance ($v_h$) and accumulated variance ($V_h$) explained by the first 7 EOFs of the Meiyu anomalies over the CHRV

| $h$ | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| $v_h$(%) | 51 | 16 | 8 | 5 | 4 | 4 | 3 |
| $V_h$(%) | 51 | 67 | 75 | 80 | 83 | 87 | 90 |

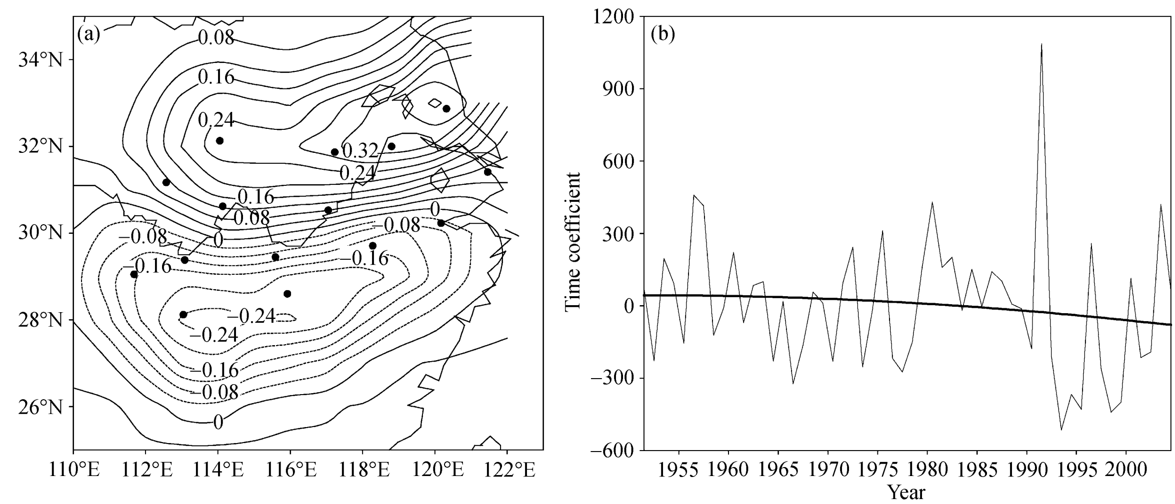


**Figure 2** Spatial distribution of EOF2 (a) and corresponding time series curve (b) from 1951 to 2004. Closed circles in (a) stand for the 15 representative stations. Thick solid line in (b) shows the trend of the time series variation.

years of the second mode by comparing the time series of the first two modes. Firstly, the years with the absolute value of normalized time series of the first two modes greater than 0.8 are picked out, respectively. Secondly, for the year with the values above 0.8 in both the modes, it would be chosen as the representative year of the mode with the bigger value, because when the absolute value of the normalized time series of EOF1 is greater than that of EOF2, the rainfall spatial distribution tends to be that of EOF1. In this way, we acquire the representative years of the second mode for flood and drought (Table 2). In order to verify the north-south-oriented seesaw of the Meiyu rainfall in these years, we calculate the 54 a standardized Meiyu rainfall of the 15 stations over the CHRV ($S_{15}$), 7 stations to the south ($S_{sth7}$) and 8 stations to the north ($S_{nth8}$) of the Yangtze River, separately. We define anomaly's absolute value smaller than 0.5 standard deviation (SD) as the criterion so that we have the years with normalized values between [−0.5, 0.5], and > 0.5 (<−0.5), which are defined as normal, and wetter (drier) than normal years, respectively.

Table 2 shows that for the abnormal years with a seesaw form distribution $S_{15}$ is less than 0.5 SD in most of the selected years except 1966, 1991 and 1993, indicating that the Meiyu precipitation over the CHRV is predominantly normal. Nevertheless, the sign of $S_{sth7}$ and $S_{nth8}$ is contrary, especially in 1957, 1991, 1993 and 1995, when one side (i.e. the southern or northern) is greater than 1 for absolute value of standardized rainfall. In the other years, at least one side ($S_{sth7}$ or $S_{nth8}$) has the value greater than 0.5, which means there is anomalous high or low in rainfall in the study area. In light of this, the selected years in Table 2 are justifiable.

**Table 2** The NDSF and NFSD years and their normalized Meiyu precipitation[a)]

| NDSF | | | | NFSD | | | |
|---|---|---|---|---|---|---|---|
| Year | $S_{15}$ | $S_{sth7}$ | $S_{nth8}$ | Year | $S_{15}$ | $S_{sth7}$ | $S_{nth8}$ |
| 1964 | −0.21 | 0.15 | −0.54 | 1956 | 0.14 | −0.62 | 0.92 |
| 1966 | −0.51 | −0.04 | −0.88 | 1957 | −0.27 | −1.01 | 0.60 |
| 1973 | 0.18 | 0.57 | −0.29 | 1960 | −0.49 | −0.80 | −0.03 |
| 1977 | 0.39 | 0.78 | −0.14 | 1975 | −0.07 | −0.68 | 0.61 |
| 1993 | 0.91 | 1.87 | −0.37 | 1991 | 1.34 | −0.53 | 3.02 |
| 1994 | −0.39 | 0.26 | −0.99 | 2003 | 0.22 | −0.36 | 0.79 |
| 1995 | 0.42 | 1.19 | −0.53 | | | | |

a) $S_{15}$, $S_{sth7}$ and $S_{nth8}$ denote the normalized rainfall of the 15 stations over the CHRV, 7 stations to the south and 8 stations to the north of the Yangtze River, respectively.

In the NDSF years, $S_{sth7}$ values are practically all positive except for 1966, by contrast to negative $S_{nth8}$, thereby manifesting that there is less rainfall in the north and more rainfall in the south. In 1966, $S_{15}$, $S_{sth7}$ and $S_{nth8}$ are all negative, and $S_{sth7}$ approaches to 0. In fact, there is considerably more rainfall at Changde, Changsha and Yueyang to the south of the Yangtze River, so that 1966 is thought to be an NDSF year. In 1993, besides, the total precipitation of the 15 stations is significantly more than normal, but the north receives less than mean rainfall in contrast to anomalously more than mean rainfall in the south, with the anomaly reaching 2 SD. As a result, this year is regarded as an NDSF type. In order to confirm the above results, we make a study on the composite rainfall anomalies of the NDSF years (figure not shown). It is obvious that the south of the Yangtze River displays positive anomalies, with the maximum at Yueyang, Nanchang and Changde where the rainfall anomalies exceed 120 mm. By contrast, the north of the Yangtze River is negative anomaly region, with the lowest down to −136 mm or thereabouts.

In the NFSD years, reversal happens with most anomalies being negative to the south in sharp contrast to positive values to the north (with exclusion of 1960), a situation that is entirely opposite to that of NDSF years. Taking the study valley as a whole, the absolute values of anomalies are less than 0.5 SD in 5 out of 6 years, which fall into normal-rainfall years. But in 1991 the anomalies are much bigger than 0.5 SD, indicative of a situation wetter than normal. The point has been mentioned in previous studies that paid little attention to the rainfall to the south that, in reality, is less than normal, particularly in Nanchang that receives rainfall by 228 mm less than normal such that 1991 should be put into the NFSD kind. Albeit in 1960 the standardized values of the three cases ($S_{15}$, $S_{\mathrm{nth8}}$ and $S_{\mathrm{sth7}}$) are all lower than zero (that to the north approaches zero), Hefei and Zhongxiang areas received considerably more rainfall, thus denoted as an NFSD year. Likewise, as the above discussed, the Meiyu rainfall is normal over the whole CHRV in most of the selected years, but the composite map of anomalies for NFSD years (figure not shown) shows that Changsha area to the south experiencing most severe drought has negative anomaly lower than −160 mm in comparison to the positive anomaly in excess of 230 mm in Dongtai to the north of the Yangtze River.

To sum up, CHRV Meiyu rainfall distribution is characterized by meridional heterogeneity in some years with the typical years of NDSF being 1964, 1966, 1973, 1977, 1993, 1994 and 1995, and those of NFSD being 1956, 1957, 1960, 1975, 1991 and 2003. It can be seen therefrom that there are no representative years of rainfall anomalies in the 1980s, which suggests that this mode might have interdecadal variability. We can also find that in the aforementioned years, NFSD is a lot stronger than NDSF, nevertheless the Meiyu rainfall is close to the normal in most of the study periods for the whole CHRV.

## 3 Simultaneous atmospheric features in the years of meridional asymmetry of the Meiyu distribution

Since the Meiyu front results from meeting of warm and cold air masses[16], the location of rainbelt may be associated with the strength of the air masses. The composite temperature anomaly field at 1000 hPa (figure not shown) shows that in the NFSD years, the south of the Yangtze River is covered by positive anomalies as opposed to the northern segment, which means that both the warm and air masses are very strong, with the 0-isopleth anomaly line in the north, indicating that the Meiyu front might be more northward of normal in the low level. While in the NDSF years, these air masses are stronger as well, only with the 0-line in the south, indicating that the Meiyu front is more southward of mean.

The Meiyu rainfall occurs when the Asian summer monsoon advances northward into the CHRV[17], so that the Meiyu anomaly might be intimately related to that of the monsoon. The composite difference of 850 hPa winds (NDSF minus NFSD (figures not shown)) shows that the subtropical East Asia is covered by pronounced differences in northeasterly winds, manifesting that the East Asian subtropical monsoon might be quite different in the intensity between the years of meridional asymmetry in that southwesterly is weaker for NDSF and stronger for NFSD. Besides, over the subtropical western Pacific is cyclonic circulation from differences, indicating that the western Pacific subtropical high might be weaker in NDSF than in NFSD years.

Figure 3(a) illustrates the composite differences in 850 hPa moisture transport. As for the composite differences in 850 hPa winds, over East Asia is a large area of salient northeasterly vapor transport. This means that the water vapor transported northward is much weaker in NDSF than in NFSD years, a condition that may be triggered chiefly by the intensity of westerly moisture transport, with smaller differences in vapor transfer by easterlies on the south side of the subtropical high, a result which is in agreement with that of Zhuo et al.[18]. Furthermore, the map of vapor flux divergences shows that in the abnormal years, the intensity of vapor convergence cores is comparable except their positions. We find that the moisture converges to the south of 30°N for NDSF (not shown) and near 30°N for NFSD cases (Figure 3(b)).

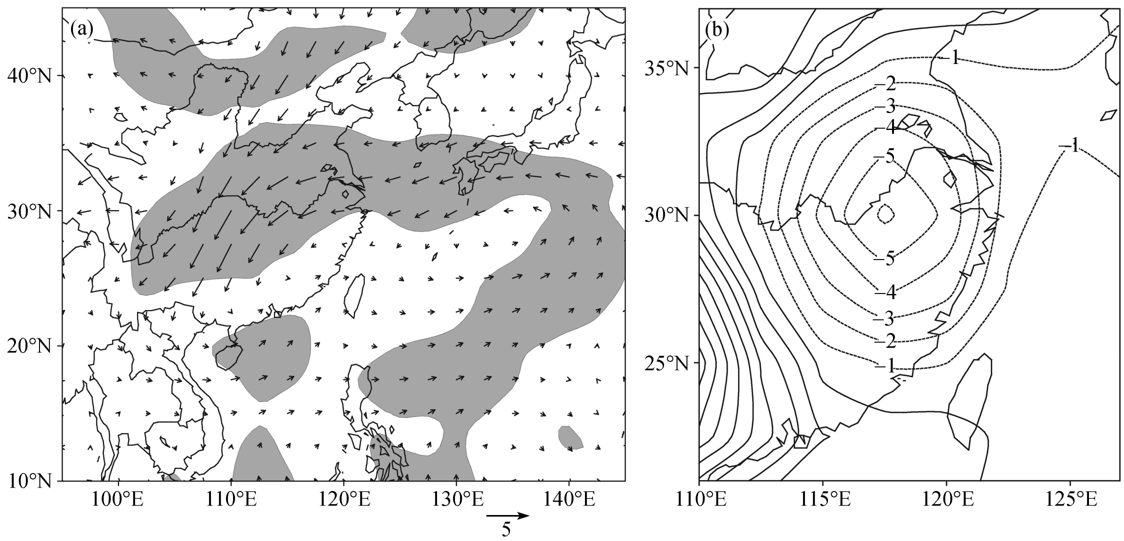


**Figure 3** (a) The composite difference in 850 hPa moisture transport during the Meiyu period from June to July (NDSF minus NFSD). Unit is $g \cdot cm^{-1} \cdot s^{-1}$. The shaded areas exceed 95% confidence level based on the *t*-test. (b) The composite 850 hPa water vapor flux divergence for NFSD. Unit is $10^{-8}$ $g \cdot cm^{-2} \cdot s^{-1}$.

Previous studies suggest that the geopotential height field at 500 hPa shows its anomalies in response to the happening of drought or flood in the CHRV[19], with the composite anomalies shown in Figure 4. In the NDSF years (Figure 4(a)), from low to high latitudes over the east Eurasia is "+ – + –" anomaly wave train, indicating that the western Pacific subtropical high is more southward and the blocking situation over the Okhotsk sea is stronger. While in the NFSD years (Figure 4(b)), anomaly wave train is "– + – +" from low to high latitudes over the east Eurasia, which means the western Pacific subtropical high is located more northward but the Okhotsk blocking high remains strong.

The Meiyu rainfall is intimately related to the South Asia High[16]. From the composite map of the geopotential height anomaly at 200 hPa for NDSF (Figure 5), we can see that the northern polar region is covered by negative anomalies, indicating that the height field is lower and the polar cyclone is stronger than normal. At high latitudes, over the Eurasian continent is largely negative anomalies, while in middle and low latitudes, west of 90°E is an area of mainly positive anomalies, corresponding to higher geopotential height, and we see that to the east of 90°E, the height field is lower (higher) to the north (south) of 20°N, denoting that the South Asia High is situated more westward and southward.

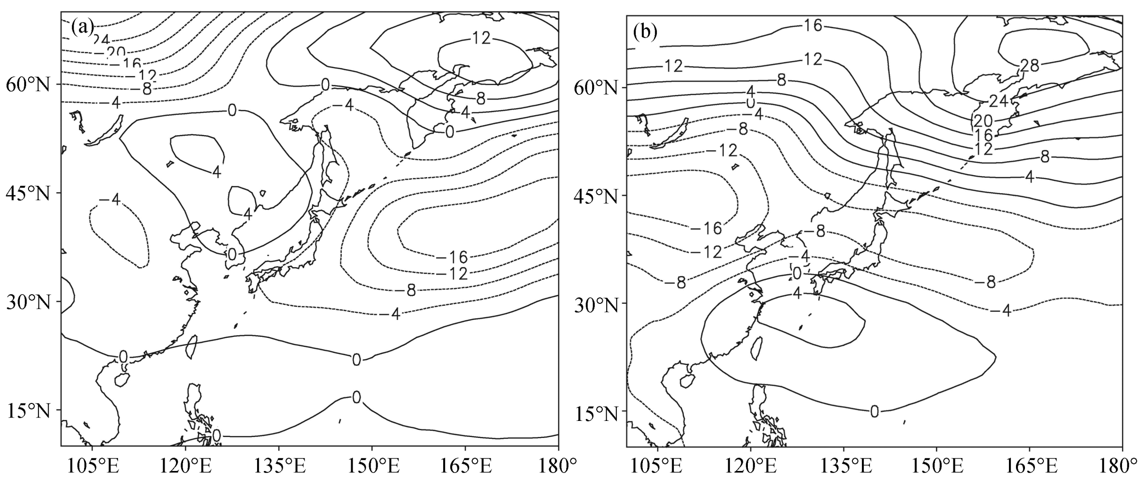


**Figure 4** The composite anomalies of 500 hPa geopotential height in the NDSF years (a) and the NFSD years (b) during the Meiyu period from June to July.

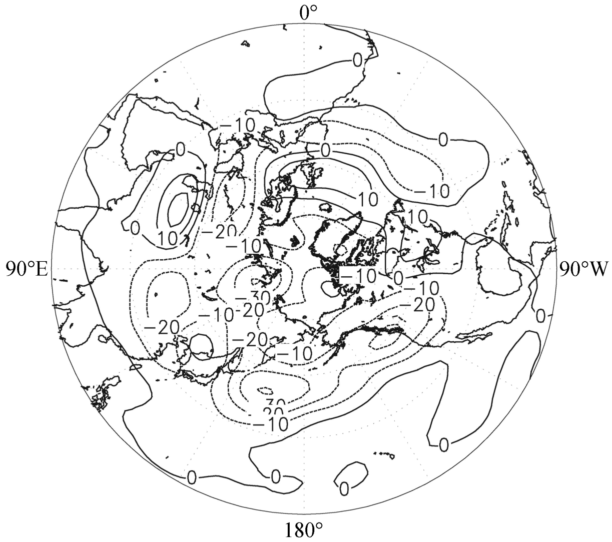


**Figure 5** The composite 200 hPa geopotential height anomaly for NDSF during the Meiyu period from June to July. Unit is gpm.

Reversal happens for NFSD (figure not shown), namely, the polar cyclone is weaker and the South Asia High is located more eastward and northward.

The above analyses of the temperature, wind, moisture transport and geopotential height fields during the Meiyu period from June to July suggest that the atmospheric features differ greatly between the NDSF and NFSD years. For NDSF (NFSD), the Meiyu front and water vapor convergence center lie more southward (northward) in the low level and the subtropical summer monsoon over East China is weaker (stronger), accompanied by the more southward (northward) western Pacific subtropical high and high-level South Asia High.

## 4 Previous ocean-atmospheric characteristics in the years of meridional asymmetry of the Meiyu rainfall

Figure 2 shows that EOF2 positive (negative) time coefficients respond to more (less) rainfall to the north (south) of the Yangtze River, and the bigger the absolute values of the coefficients, the more severe the dryness or dryness in the south and north distributed as a seesaw-like manner. As a result, the EOF2 normalized time series is defined as "meridional asymmetry index (MAI)" to depict the intensity of the meridional asymmetrical distribution of the Meiyu rainfall.

More and more investigations suggest that the Meiyu is closely associated with the atmospheric circulations in preceding boreal winter and spring[20−22], especially in February[19]. Correlations between the MAI and some circulation indices show that the meridional asymmetry of the Meiyu has good negative correlations with the boreal winter Northern Hemisphere Annular Mode (NAM), particularly in February, when the correlation coefficient reaches the maximum of −0.29. The correlation coefficients between the MAI and Southern Hemisphere Annular Mode (SAM) in preceding February and April are −0.3 and −0.23, respectively, exceeding the 95% confidence level based on the $t$-test. Figure 6 is the map of the correlations between the MAI and sea level pressure in February. For the mid- and low-latitudes, negative correlations are dominant, with the extreme values over the Pacific and Africa reaching −0.3 (Figure

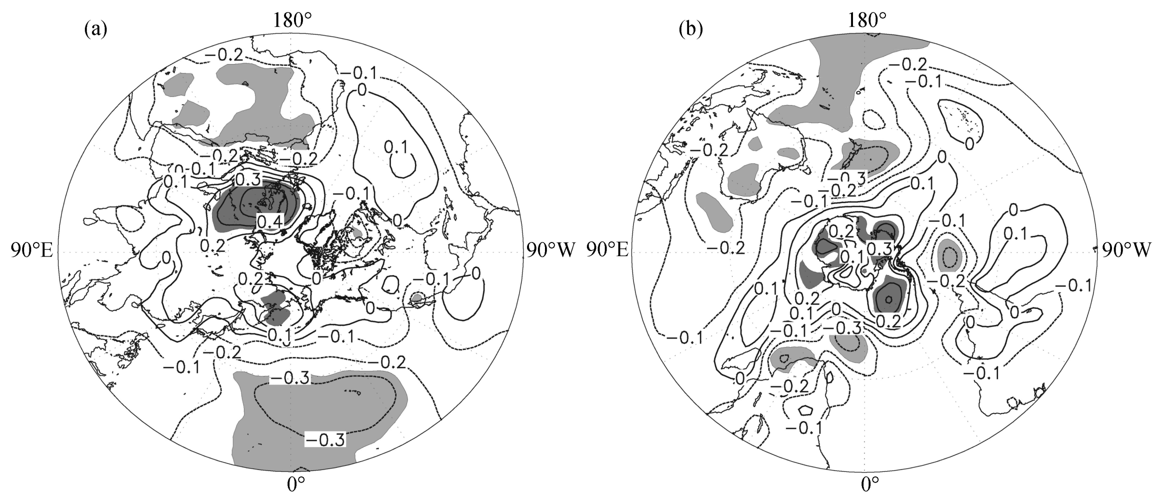


**Figure 6** Correlation coefficients between the MAI and sea level pressure in previous February. (a) Northern Hemisphere; (b) Southern Hemisphere. The shaded areas exceed the 95% confidence level based on the $t$-test.

6(a)). The high-latitude areas are under the control of positive correlations, the largest of which exceeds 0.4. This indicates that sea level pressures at low and high latitudes are out of phase for NDSF and NFSD, which demonstrate the correlations between the MAI and the NAM and SAM.

Previous studies indicate that not only sea surface temperature anomaly (SSTA) in tropics[23], but those in seas off China including the Kuroshio area[24−27] have great impacts on the Meiyu. The map of correlations between the MAI and previous SST shows that in boreal winter (Figure 7 (a)), the equatorial middle and eastern Pacific is a significantly negative area, indicating that the interannual variability of the meridional asymmetry of the Meiyu might be connected with ENSO in such a way that the warming phase of ENSO in boreal winter might be related to the Meiyu position southward of mean, indicative of rainfall deficit to the north of the Yangtze, and vice versa. Also, the low-latitude western Pacific is covered with negative correlations, and especially the South China Sea and Kuroshio area show salient negative correlations, indicating that the SSTA in these seas might have certain impacts on the meridional asymmetry of the Meiyu, namely, higher (lower) SST may lead to NDSF (NFSD). In previous boreal spring (Figure 7(b)), seas off China such as Bohai Sea, East China Sea and the northern South China Sea are significantly negative correlation areas, indicating that their positive SSTA might be associated with NDSF, and vice versa.

In summary, there are considerable differences in the preceding atmospheric circulation and SST between the NDSF and NFSD years. In the NDSF (NFSD) years, the NAM and SAM are intensified (weakened) in previous February, SST off China including Kuroshio area is higher (lower) in boreal winter and spring. Moreover, the meridional asymmetry of the Meiyu might be influenced by ENSO in the boreal winter.

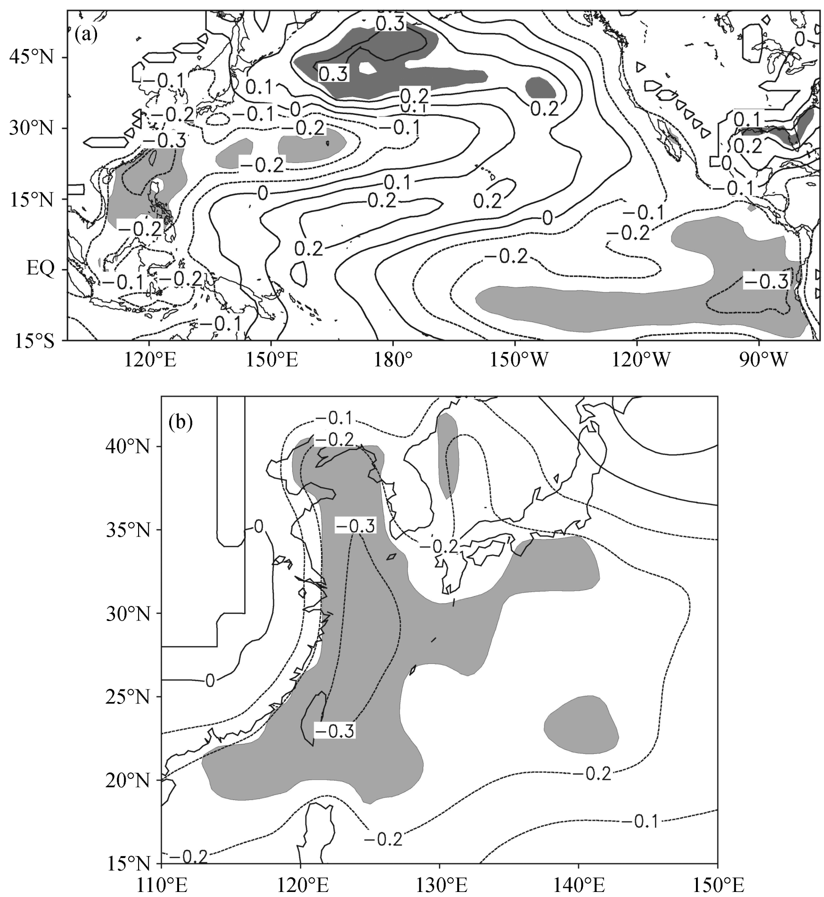


**Figure 7** Correlation coefficients between the MAI and SST in previous boreal winter (a) and spring (b). The shaded areas exceed the 95% confidence level based on the *t*-test.

## 5 Conclusions and discussion

CHRV rainfall anomalies are in phase in most of the years, but they are out of phase between regions to the north and south of the Yangtze in some years, whereto the previous studies pay little attention. We discover that the second mode takes a seesaw form distributed in a north-south direction through EOF analysis of the Meiyu rainfall anomalies during June—July, 1951—2004, so that the Meiyu patterns are classified into two types: NDSF and NFSD, with their representative years determined. Further analyses on these two types exhibit that the Meiyu rainfall over the whole CHRV is almost normal in most of these representative years. Hence our conclusions provide, in terms of space patterns, the supplement to the drought-flood coexistence in the middle and lower reaches of the Yangtze River by Wu et al.[12]. Then the composite and simple correlation methods are utilized to investigate the features of the contemporary and preceding air-sea background in the anomalous years, with the following results:

(ⅰ) For the NDSF years, the low-level frontal area and moisture convergence center are more southward, the subtropical summer monsoon over East Asia is weaker, the western Pacific subtropical anticyclone and the 200 hPa South Asia High are more southward and vice versa for the NFSD cases.

(ⅱ) For NDSF (NFSD) happening, the NAM and SAM are stronger (weaker) than normal in preceding February and SST is higher (lower) off China in boreal winter and spring, and the Meiyu rainband is more southward (northward) of normal. Additionally, the asymmetric distribution (EOF2) may be associated with the impacts of ENSO in the boreal winter.

How do the previous anomalous events influence the meridional asymmetry of the Meiyu rainfall? Yu et al.[28] simulated the impacts of the SSTA in the mid-latitude western Pacific on the subtropical high, discovering that the response of the 500 hPa atmospheric circulation to the Kuroshio marine heating lags 2–3 months, that is, if SST in the mid-latitude Kuroshio remained higher from March to May, then the 500 hPa subtropical high would be located more southward of mean in May through August. And the higher the SST is, the more southward the subtropical high will be, and vice versa. Liu et al.[29] suggested that radiative cooling over oceans would generate low-level anticyclonic circulations, and further influences the subtropical high. Based on the present analysis, we see that when seas off China including the Kuroshio area are warmer (cooler) during boreal winter and spring, atmospheric diabatic heating might be anomalously increased (decreased), thus generating cyclonic (anti-cyclonic) circulation in the middle and lower troposphere at subtropics, and providing unfavorable (favorable) condition for the northward progression of the subtropical high early in summer, leading to the fact that the 500 hPa subtropical high stays more southward (northward), and so does the Meiyu rainbelt. How on earth the SST off China exerts impact on the meridional asymmetrical feature of the Meiyu rainfall is a new meaningful topic, which needs further exploration.

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