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The northward shift of Meiyu rain belt and its possible association with rainfall intensity changes and the Pacific-Japan pattern

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ABSTRACT

The meridional location change of Meiyu rain belt and its relationship with the rainfall intensity and circulation background changes for the period 1958–2009 are examined using daily rainfall datasets from 756 stations in China, the 6-h ERA-Interim reanalyses, CRU monthly temperature and daily outgoing long-wave radiation (OLR) data from the US National Oceanic and Atmospheric Administration (NOAA). The results indicate that the Meiyu rain belt experienced a northward shift in the late 1990s in response to global warming. Moreover, the intensity of interannual and day-to-day variability of rainfall within Meiyu period has been increasing in the warming climate. The amplification of the variability within Meiyu period over the northern Yangtze-Huai River Valley (YHRV) is much larger than that of the southern YHRV. The large difference in the trends of variance within the Meiyu period between these two regions induces a spatial varying for different rainfall categories in terms of intensity. More significant positive trends in heavy and extreme heavy rainfall occur over northern YHRV compared with southern YHRV, which is a crucial indicator of changes in the rain band, despite the observation of an increase in heavy and very heavy rain events and a decrease in weak events throughout the entire YHRV. A composite of the atmospheric circulation indicates that intense northward horizontal transport and the convergence of water vapor fluxes are the immediate causes of the rain band shift. Besides, through forcing a northward extended convection over the tropics, the Pacific-Japan (P-J) pattern induces a northward expansion of western Pacific Subtropical High, leading to intensified convergence and enhanced rainfall over Northern YHRV.

1. Introduction

Extensive observations have yielded evidence of changes in precipitation with global warming (Giorgi, 2002; Gu and Adler, 2013; Wentz et al., 2007). On the global scale, precipitation tends to increase with warming, whereas the situation

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is more complicated and exhibits inconsistent changes on a regional scale (IPCC, 2007; Lee et al., 2013; Trenberth et al., 2003; Zhang and Zhou, 2011; Zhu et al., 2014). Due to the influence of the Asian summer monsoon, the Yangtze-Huai River Valley (YHRV) of China is vulnerable to floods. Nearly 40% of the floods in this region occur during the Meiyu season (Li, 1996). Research on changes in the spatial distribution of the Meiyu over the YHRV represents a novel scientific challenge with significant societal and economic implications.

Previous studies (Gong and Ho, 2002; Wang, 2001; Xu, 2007; Yu et al., 2004) have suggested that the Meiyu rain band underwent a significant interdecadal shift in the late 1970s, with increased rainfall and the occurrence of 'south wet north drought' pattern. However, as the climate rapidly warms, the rainbelt pattern is tending to become more complex and diverse (Chen et al., 2007; Hu and Ding, 2009; Hu et al., 2010; Li et al., 2016). Specifically, high-intensity rain (Ding et al., 2007; Xu, 2007) and atypical Meiyu rainfall are occurring more frequently (Liang et al., 2009). In the 1990s, heavy rain and flood events frequently occurred in the areas south of the Yangtze River. However, since 2000, Meiyu rainfall and floods have become increasingly concentrated in the Huai River Basin; floods are occurring nearly twice as often as the climatological average (Chen et al., 2007). Huang et al. (2010) examined the linear trends of different durations of continuous rainfall during the Meiyu period and found that long-duration rainfall has become significantly less since 2000, whereas 2-day and 3-to-4-day continuous rainfall events have become more. Previous studies indicate that the intensity of extreme precipitation is showing an increasing tendency (Kusunoki and Mizuta, 2008; Wang and Zhai, 2008). These complicated changes make it difficult to predict rainfall during the YHRV flood season.

Understanding the mechanism of the changes in Meiyu property is a prerequisite for improving the seasonal prediction over Meiyu region. Recently, the possible causes of the Meiyu rain belt shift have been investigated from the perspective of atmospheric circulation in East Asia (Si et al., 2010). Researchers speculate that the subtropical westerly jet over East Asia has shifted northward and that the East Asian tropical Hadley cell has expanded poleward because of the expansion of the subtropics; thus, the Meiyu rain belt has also shifted northward. The migration of the Meiyu rain belt may be also associated with the principal weather systems (Hu and Ding, 2009). However, the influence factors of the Meiyu rainfall are complicated and the underlying mechanism remains unclear, and the previous studies, despite their scientific significance, have not considered how changes in rainfall composition affect the distribution of the Meiyu rain belt. Thus, further research is necessary to gain an insightful understanding of the trends of the Meiyu phenomena and to provide a scientific basis for the development of climate change policies.

In this study, we first examine the changes of the Meiyu rain belt (Section 3) and establish relationships between these changes and rainfall composition. The various intensities of rainfall are presented in Section 4. In Section 5, we discuss the possible causes of the Meiyu rain belt changes. Finally, a summary and discussion are presented in Section 6.

2. Datasets and methods

2.1. Datasets

Daily rain gauge observations recorded at 756 stations in China from 1958 to 2009 were provided by the National Meteorological Information Center of the China Meteorological Administration (CMA).

For each station, the rainfall data for various periods throughout each year were aggregated based on the Meiyu periods (17 June to 11 July) defined by Sun (2014). The tropical cyclone (TC) rainfall within the YHRV during each Meiyu season was extracted using the objective synoptic analysis technique (OSAT) proposed by Ren et al. (2007) and Liu et al. (2013) and was subsequently subtracted from the data to eliminate the influence of the TC rainfall.

A monthly temperature time series (TS) was extracted from the CRU TS3.21 dataset provided by the Climate Research Unit (CRU) at the University of East Anglia. Previous versions of the CRU TS dataset have been widely applied in scientific research on global warming (Folland et al., 2001). In this study, we used the v3.21 temperature data from 1958 to 2012 in a climate background analysis of the changes in the Meiyu rain belt and rainfall composition.

Daily atmospheric circulation data were derived from the 6-hourly ERA-Interim reanalysis datasets (Dee et al., 2011) provided by the European Centre for Medium-Range Weather Forecasts (ECMWF), which span a 31-year period from 1979 to 2009. Daily gridded interpolated outgoing long-wave radiation (OLR) data were obtained from the US National Oceanic and Atmospheric Administration (NOAA). The resolutions of these two datasets are $2.5^\circ \times 2.5^\circ$ and $1^\circ \times 1^\circ$ latitude/longitude, respectively.

2.2. Methods

A total of 604 stations throughout the country were chosen under the constraint of at least 90% daily data availability during the flood season [May to August (MJJA)] from 1958 to 2009 to minimize temporal inconsistencies; of these stations, 77 stations throughout the YHRV (28°–34°N, 110°–112°E) were selected for use as Meiyu rains monitoring stations in this study (Fig. 1).

Composition analysis, a rotated empirical orthogonal function (REOF) and empirical orthogonal function (EOF) analysis, accumulated anomaly analysis, Mann-Kendall analysis, and regression analysis were applied to explore the shift in the

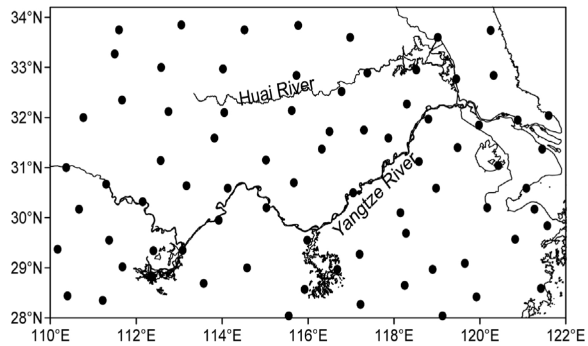

Fig. 1. The locations of the 77 selected stations throughout the Yangtze-Huai River Valley (YHRV) in China.

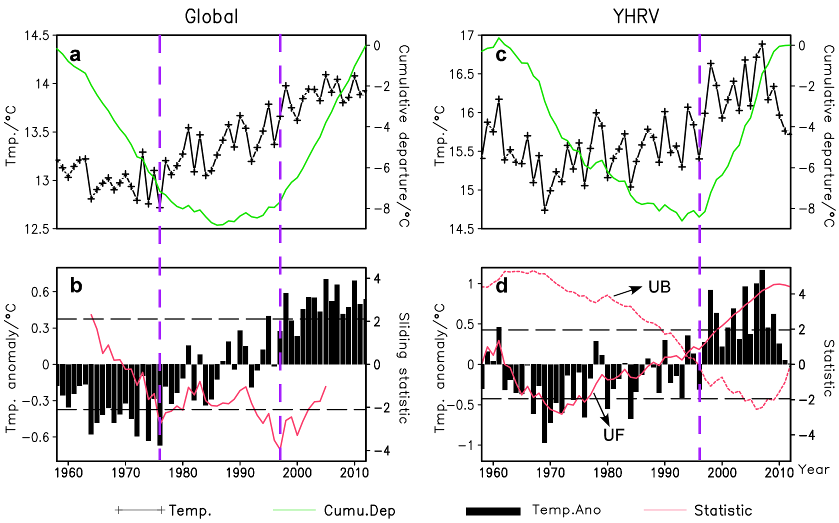

Fig. 2. Annual mean global and YHRV air temperatures (a, c; black solid lines with cross marks; °C) and the corresponding anomalies (b, d; bars; °C) and cumulative anomalies (green lines; °C) during the 1958–2009 period. The results of the moving T-test technique and the Mann-Kendall rank statistics are represented by the red curves in (b) and (d), respectively. Thick vertical dashed line denotes the decadal change points. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Meiyu rainfall belt and its possible causes. In addition, the percentile method (Bonsal et al., 2001) was used to identify rain categories.

3. Changes in the distribution of Meiyu rainfall phenomena

Previous studies (IPCC, 2007; Wu et al., 2011) indicate that the global temperature has exhibited a continuous rise over the last 50 years, with a marked inter-decadal change in the late 1970s. As seen from Fig. 2a and c, an increasing trend is observed in the annual mean air temperature over the YHRV, consistent with the change in the global temperature during the 1958–2012 period. An abrupt change in the global mean temperature occurred after the late 1990s (Fig. 2a,b), whereas an accumulated anomaly analysis (Fig. 2c) and the Mann-Kendall statistic (Fig. 2d) reveal an abrupt change in temperature around 1995 and a significant warming after 2000 in the YHRV, which indicates that the remarkable inter-decadal change in warming in the YHRV lagged behind that in the global temperature. To facilitate a comprehensive analysis of the change in the Meiyu rainfall distribution against the broader background of climate warming, in the following discussions, we refer to the time periods before 1979, from 1980 to 1999, and after 1999 as the cool period, the transitional period and the warm period, respectively.

Climatological Meiyu-season rainfall (averaged over the 1958–2009 period) is concentrated in the middle and lower reaches of the Yangtze River and to its south. The rainband, with a local maximum of approximately 390 mm per Meiyu season, lies nearly parallel to the Yangtze River (Fig. 3a). During the cool and transitional periods (figures not shown), the location and shape of the observed rainbelt correspond well to the climatological pattern; however, the amounts of rainfall are less and more than the mean, respectively. Specifically, the rainfall to the south of the Yangtze River was distinctly higher than normal during the transitional period. Compared with the earlier periods, the spatial distribution of the Meiyu rainfall in the warm period (Fig. 3b,c) is quite different: the leading rain zone is shifted northward to the Huai River Basin. Anomalous

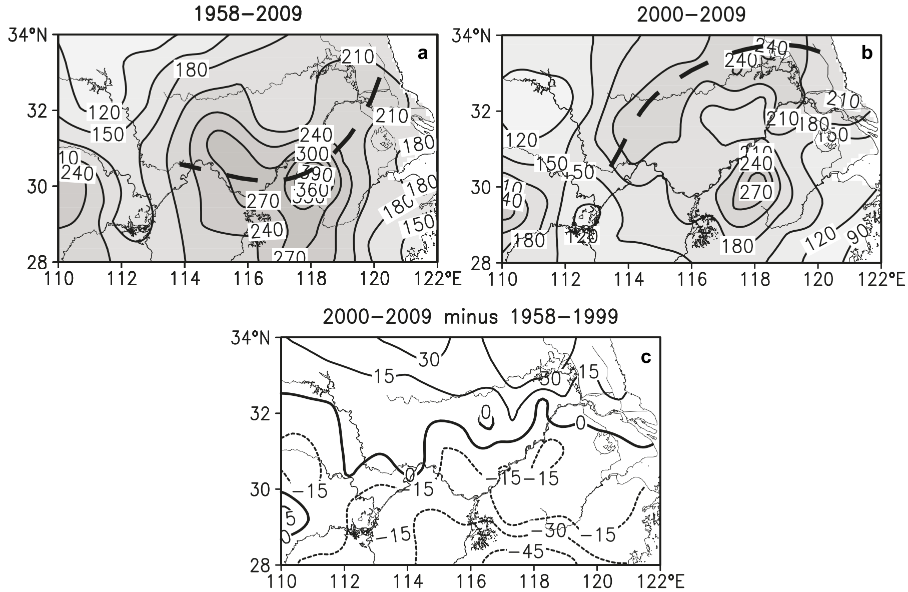

Fig. 3. The rainfall pattern during Meiyu season (June 17-July 11) for: (a) the climatological mean from 1958 to 2009, (b) the warm period from 2000 to 2009, and (c) the difference using 2000–2009 mean minus 1958–1999 mean (Values are in units of mm per Meiyu season; the thick dashed lines in a, b represent the maximum rain band.).

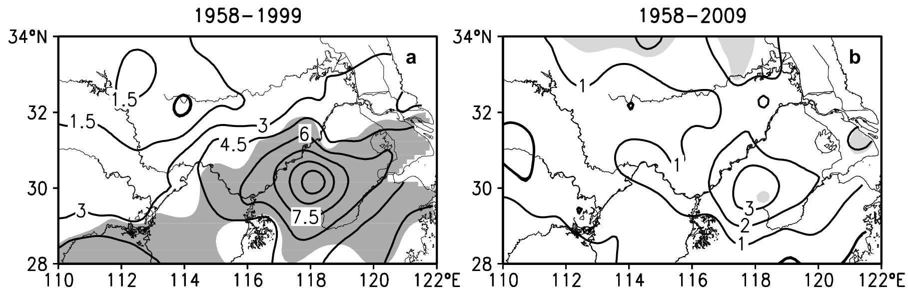

Fig. 4. Distributions of the linear trends in precipitation during the Meiyu period for (a) 1958–1999 and (b) 1958–2009 (values are in units of mm/yr; light and dark shaded areas are statistically significant at the 90% and 95% confidence levels, respectively).

rainfall also shows a 10% or greater increase with respect to the mean, whereas the rainfall to the south of the Yangtze River is decreased by 20% at a confidence level exceeding 95%(figures not shown). Before 2000, a consistent upward trend was apparent over the entire region, particularly in areas of the southern Yangtze River Valley (Fig. 4a). With the extension of the study period to include the data from 1999 to 2009 (Fig. 4a,b), the trend coefficients over the entire YHRV are obviously decreased, though they still show positive values. Moreover, the area with a remarkable increasing trend shifts from the southern YHRV to the central and northern YHRV, indicating that the precipitation has decreased rapidly in the southern Yangtze River Valley but has increased in the northern part of the region. We applied a REOF analysis to the normalized Meiyu rainfall data. The first and second REOF modes, which account for 26.4% and 25.7% of the total variance, respectively, are statistically distinct from the remaining eigenvectors in accordance with the rule defined by North et al. (1982). The regions of high loading corresponding to these first two modes are bounded by the Yangtze River, which essentially overlaps with the latitude line at 31°N (figures not shown). For simplicity, in this paper, we use the latitude of 31°N as a boundary line to divide the YHRV into southern and northern regions. Fig. 5a and b displays the standardized average rainfall series in the southern and northern Yangtze River regions, respectively. The two series exhibits coherent trends before early 1990s but opposite trends afterwards. Particularly after 2000, the southern rainfall series shows a notable increase but the northern series decreases rapidly. These changes further emphasize the northward shift of the Meiyu rain belt after 2000, which is consistent with the findings of recent studies (Hu and Ding, 2009; Si et al., 2010).

Against the background of the rising global air temperature, the amounts of Meiyu rainfall occurring in the southern and northern YHRV exhibit some interdecadal variability with no significant long-term trend (Fig. 5a,b). However, the 11-year moving standard deviations of the Meiyu rainfall show a significant increasing trend (at the 0.01 significance level) during 1958–2009 period (Fig. 6c), which indicates an increase in the interannual variability. The increase in the standard deviation during the 1990s was significantly stronger than that during the 2000s in the northern YHRV because Meiyu rainfall was persistently excessive after 2000, which resulted in an insignificantly year to year variability. In the southern region, by

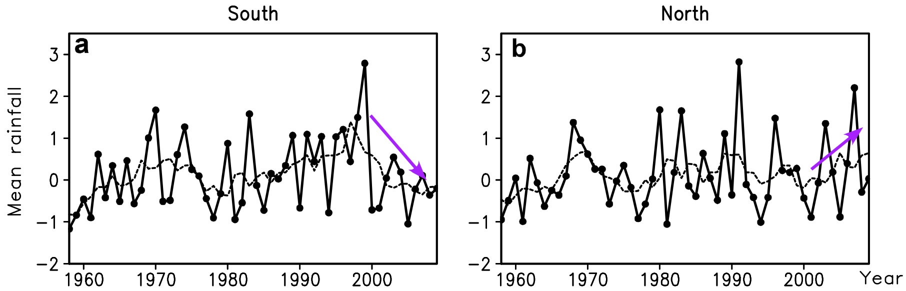

Fig. 5. The normalized rainfall in the (a) southern and (b) northern YHRV as divided by the latitude line at 31°N for 1958–2009 (the dashed lines represent 5-year running mean values).

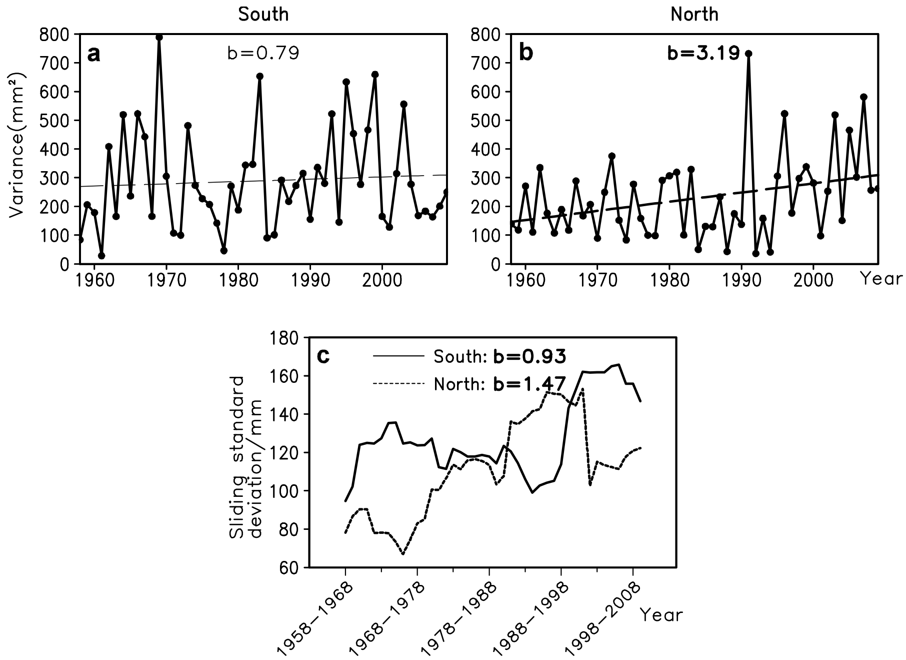

Fig. 6. Temporal variations (1958–2009) in the variance of daily rainfall during the Meiyu period over the (a) southern and (b) northern YHRV, together with their linear trends (dashed lines), as well as (c) the 11-year moving standard deviations of the Meiyu rainfall for the southern (solid line) and northern (dashed line) YHRV. The b values represent trend coefficients, and bold-faced text indicates a trend that is statistically significant at the 90% (a, b) or 99% (c) confidence level according to a *t* test.

contrast, the interannual variability showed an abrupt increase in the late 1990s. The temporal variations (1958–2009) in the variance of daily rainfall during the Meiyu season averaged over these two regions are also presented in Fig. 6a,b, and both show increasing trends, which are consistent with the warming trends in the global and YHRV annual mean temperatures. However, the increase in the variance over the northern part of the region is stronger compared with that over the southern part; in particular, since the mid 1990s, the mean variance of the daily rainfall during the Meiyu period has been above the previous maximum.

A trend in rainfall variance is related to a trend in the availability of atmospheric moisture content (Trenberth et al., 2005), as governed by the Clausius-Clapeyron (C—C) equation, which corresponds to a change of approximately 7% for each 1 °C change in temperature (Trenberth, 1998; Wentz et al., 2007). The trend in the availability of atmospheric moisture content, in turn, is due to the gradual warming of the air temperature (Trenberth et al., 2003). Goswami et al. (2006) showed that the long-term increase in daily rainfall variance that has been observed over central India during the summer monsoon season is likely due to the warming of the sea surface temperature in the tropical Indian Ocean and the associated increase water vapor. In China, upward trends in the amounts of precipitable water in all seasons and in the annual mean from 1970 to 1990 have been revealed by Zhai and Eskridge (1997), and subsequent analyses by Trenberth et al. (2005) and Ross and Elliott (2001) further verified these results. Durre et al. (2009) found that the total column density of water vapor in the atmosphere has increased by approximately 0.45 mm/decade (1973–2006) over the land in the Northern Hemisphere. These observed increased water vapor affect both the greenhouse effect, by providing positive feedback for climate change, and the hydrological cycle, by making more atmopheric moisture available to all precipitation systems. Therefore, these effects have

Table 1
The thresholds for various rainfall intensity categories averaged over the YHRV during the Meiyu season.

Category	1	2	3	4	5	6	7	8	9	10	11
Percentile(%)	<10	10–20	20–30	30–40	40–50	50–60	60–70	70–80	80–90	90–95	>95
Threshold (mm/day)	<0.3	0.4–0.7	0.8–1.5	1.6–2.9	3.0–5.0	5.1–8.4	8.5–13.5	13.6–21.9	22.0–38.0	38.1–54.5	>54.5

ramifications for precipitation, driving changes in precipitation amounts and rates. However, it is unlikely that such changes in moisture will be uniform, although the air temperature is increasing at a similar rate almost everywhere (Trenberth et al., 2003). On the one hand, because of the nonlinear dependence on temperature described by the C—C equation, a larger absolute increase in moisture occurs at lower latitudes despite a larger increase in temperature at higher latitudes. On the other hand, atmospheric dynamics modify the atmospheric moisture content through preferential regional convergence and subsidence (Trenberth, 2011). Accordingly, despite similar trends of increase (figures not shown) in the air temperatures over the southern and northern YHRV, there is a considerable difference in the trends of daily rainfall variability between the two regions.

4. Relationship between the northward shift of the Meiyu rain belt and rainfall in various intensity categories

In the previous section, it was demonstrated that with rising temperature, the consequent increase in water vapor causes the daily rainfall variance during the Meiyu period to intensify, which inevitably manifests as variations in the frequency and intensity of rainfall (Trenberth et al., 2003). According to the percentile method (Bonsal et al., 2001), eleven categories of rainfall (Table 1) during the Meiyu period were identified. Then, we analyzed the trends for each rainfall category and their influence on the shift in the Meiyu rain belt in terms of the frequency of occurrence (FOC), the amounts of rainfall and thresholds to define the intensity of rainfall.

To facilitate the assessment of the variations in the FOCs of rainfall in various intensity categories in the most recent decade (the warm period) compared with those in the cool and transitional periods, it is advantageous to separately construct the frequency distributions of rainfall of various intensities at all stations throughout the southern (39 stations) and northern (38 stations) regions of the YHRV (Fig. 7) during the Meiyu season for three periods of equal length: 1970–1979, 1990–1999 and 2000–2009. From 1970–1979 to 1990–1999, the numbers of rain events in the three highest intensity categories (9th–11th) over the southern YHRV increased, whereas the number of all rain events except very heavy rain events (11th category, rainfall exceeding the 95th percentile; hereafter, $R \geq R95p$) over the northern YHRV decreased. After 2000, increases in the FOCs of events of the three highest categories (9th–11th) occurred only over the northern YHRV, and the FOCs of rain events in the four lowest cateories and of all rain events decreased over both the northern and southern regions.

In fact, the FOCs of rain events in the two highest categories (10th–11th) have been rising by 10% per decade (with a confidence level exceeding 90%) in the northern YHRV since 1958, whereas those in the southern region were initially rising by only 5% per decade (not a significant increase) and later entered a downturn, decreasing by 20% on average after 2000 (Fig. 8a,b). The growth rate of the FOC of rain events in the 9th category in the northern region is also larger than that in the southern region (Fig. 8c,d). Regarding rain events in the moderate categories, the trends of change in the FOCs are barely perceptible. Fig. 8e and f shows negative trends in the light categories (1st–4th) over the two regions and significant declines in the lightest rain events (1st, rainfall in the lowest 10th percentile; hereafter, $R < R10p$). The FOCs of rain events in the 2nd–4th categories in the northern region exhibit more significant decreasing trends than those in the southern region, which seems to indicate that the variance in light rain events has played a negative role in the northward shift of the Meiyu rain belt; however, in terms of rainfall amout, a larger absolute decrease is seen in the southern region (figures not shown). These findings illustrate that light and moderate rain events have less impact on the overall distribution of rainfall, whereas the rain events in the heavier categories have an important effect on the spatial distribution of Meiyu rainfall, as indicated

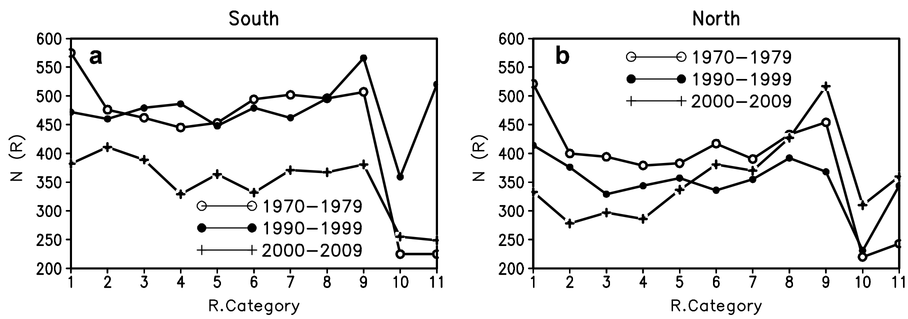

Fig. 7. The numbers (*N*) of rain events of various intensities over the (a) southern and (b) northern YHRV during the Meiyu season for three periods: 1970–1979, 1990–1999 and 2000–2009.

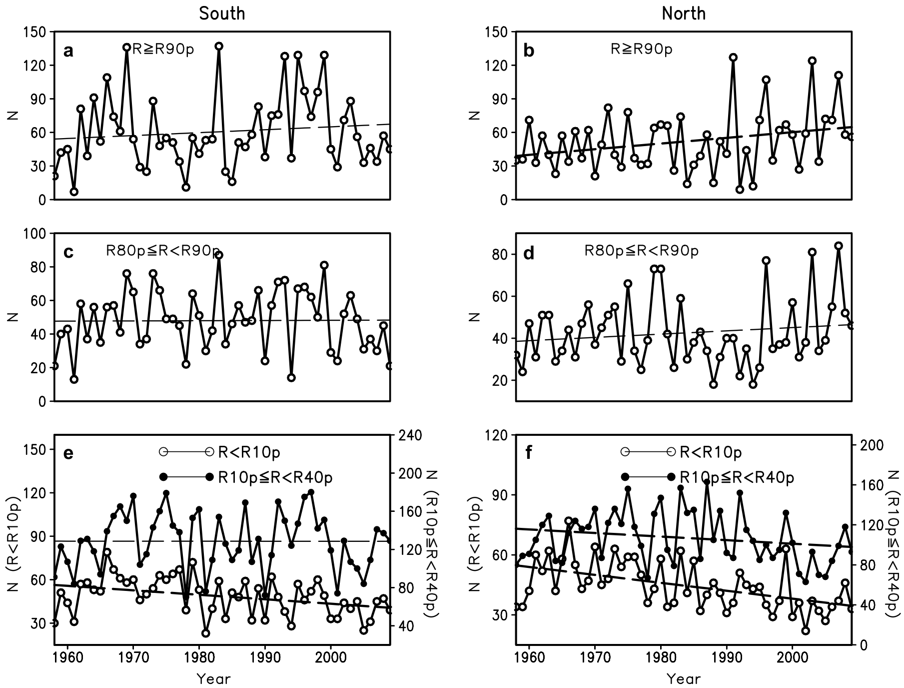

Fig. 8. Temporal variations (1958–2009) in the numbers (*N*) of rain events in heavy intensity categories (a, b: R ≥ R90p, c, d: R80p ≤ R < R90p) and light intensity categories (e, f: R<R10p and R10p ≤ R<R40p) over the southern and northern YHRV during the Meiyu season, together with their linear trends (dashed lines). R ≥ R90p denotes daily rainfall exceeding the 90th percentile. A bold-faced line indicates a trend that is statistically significant at the 90% confidence level according to a *t* test.

by the fact that their FOCs are significantly correlated with the Meiyu rainfall (with a correlation coefficient of more than 0.53).

We next examine changes in the intensity of heavy rainfall as derived from threshold changes. For each station, the daily rainfall for May to August of each year were first ranked in ascending order and then used to calculate the values corresponding to each percentile. The magnitudes of the 80th–99th percentiles represent the intensity of heavy rainfall in a given year because more than 90% of the rain events in those percentiles over all studied years occurred during the Meiyu season, and thus, the yearly variations in these thresholds represent the changes in the intensity of heavy rainfall. Larger thresholds for the 80th to 99th percentiles over the southern YHRV compared with those in the northern region are clearly evident in Fig. 9a,c, and these findings are consistent with the climatic distribution of the Meiyu rainfall. Importantly, however, these thresholds also show increasing trends over both regions, with a larger increase over the northern YHRV. For instance, the increase in the threshold from the heaviest rainfall over the northern YHRV, from approximately 48 mm/day in the early 1960s to approximately 60 mm/day, is equal to quadruple the increment observed in the southern region (from 55 mm/day to 58 mm/day). Furthermore, the average intensity thresholds for the 90th to 99th percentiles (Fig. 9b,d) show a 1.9 mm/day per decade increase over the 52-year period that is significant at the 90% confidence level in the northern region, whereas no significant increase is apparent in the southern YHRV.

The above findings indicate increases in the FOCs and intensities of rain events in heavy categories (9th–11th) and decreases in light categories (1st–4th) with the warming of the climate throughout the entire YHRV. These findings are consistent with model projections (Karl and Knight, 1998; Trenberth et al., 2003) and observations in other areas (Goswami et al., 2006). A comparison of the rainfall in the southern and northern YHRV reveals that the FOCs and intensities of the two heaviest categories of rain events (R ≥ R90p) have shown a significant increasing tendency in areas north of the Yangtze River, whereas a barely noticeable increase has occurred to the south of the river. Moreover, the rainfall amounts of these heavy rain events are significantly correlated with the total Meiyu rainfall (with a correlation coefficient of more than 0.9), and their contribution to the total Meiyu rainfall is as high as 33–50.7%. Thus, the larger increase in rainfall events in heavy intensity categories over the northern region, especially the two heaviest intensity categories, has had an important impact on the northward shift of the Meiyu rain belt.

5. Changes in atmospheric circulation associated with the northward shift of the Meiyu rain belt

Because the movement of the Meiyu rain belt has occurred predominantly over the last two or three decades, and the ERA-Interim reanalysis data exhibits high homogeneity when satellite data was collected since 1979, this section focuses on the period of 1979–2009. Consistent with the observed changes in the rainfall during the Meiyu period (Fig. 3c), the

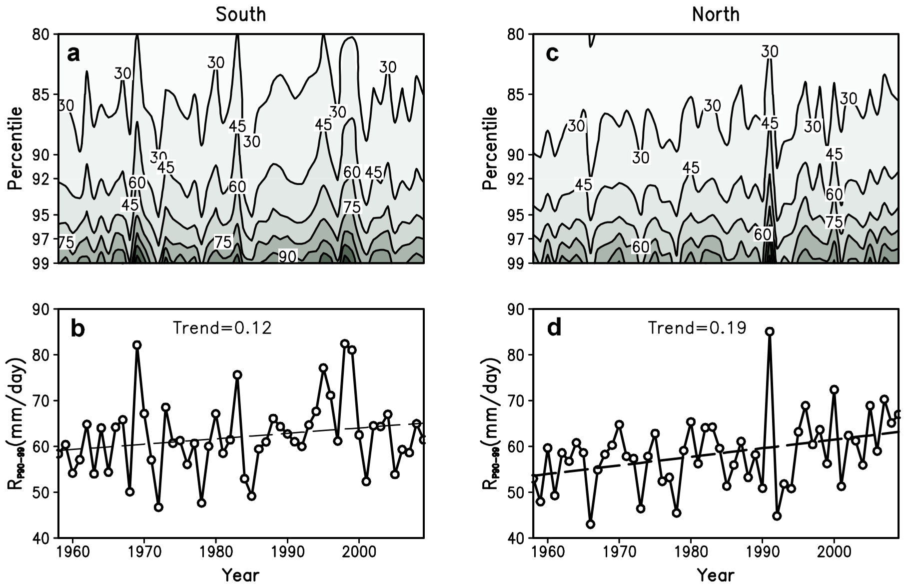

Fig. 9. Temporal variations (1958–2009) in (a, c) the 80th to 99th percentiles of rainfall events during the flood season (May to August) and (b, d) the mean rainfall amounts for the 90th to 99th percentiles of rainfall events in the southern and northern YHRV. The contours in (a, c) represent rain intensity in units of mm/day. The dashed lines in (b, d) represent linear trends, and a bold-faced line indicates a trend that is statistically significant at the 90% confidence level according to a *t* test.

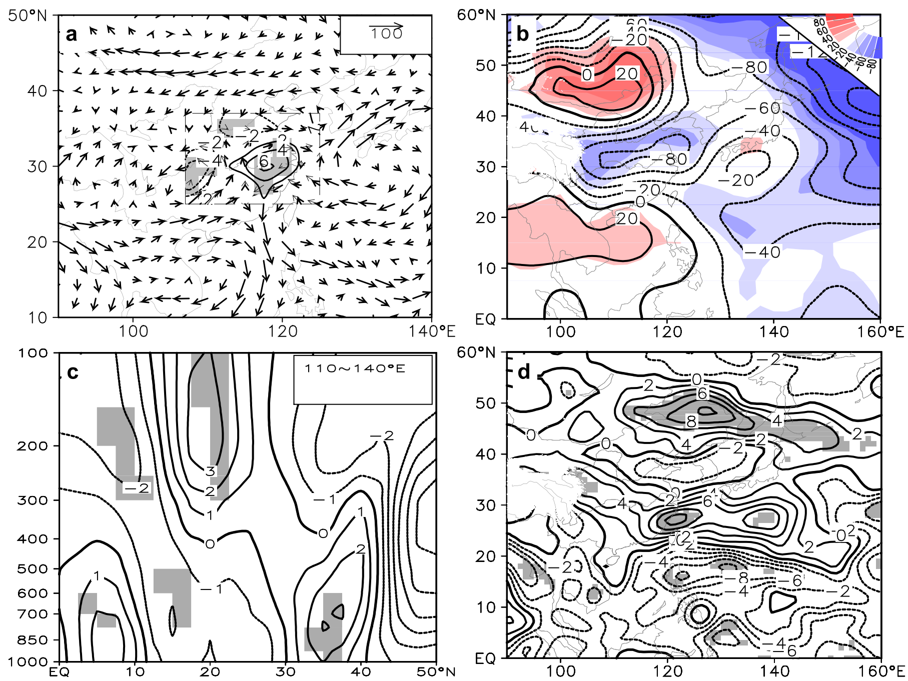

Fig. 10. Differences in patterns observed over time during the Meiyu period (2000–2009 minus 1979–1999): (a) vertically integrated (from the surface to 300 hPa) water vapor fluxes (arrows; kg/(m s)) and their divergences (contours; 10^{-5} kg/(m^2 s), (b) sea level pressures (SLPs) (contours; hPa) and geopotential heights (shaded regions; gpm) at 850 hPa, (c) meridional sections of vorticity along 110–140°E (10^{-6} s^{-1}), and (d) OLR (W/m^2). The shaded areas in (c, d) are statistically significant at the 90% confidence level according to a *t* test.

divergence of water vapor fluxes exhibits a negative trend that is centered to the north of the Yangtze River and a positive trend that is centered to the south of the river (Fig. 10a). The former can be interpreted as the interaction of the enhanced cyclonic circulation in the vicinity of the Bohai Sea with the increased water vapor flux from the northern Bay of Bengal (BOB), from the Indochina Peninsula to the north of the Yangtze River). By contrast, the increased flux has been attributed to an enhancement of the southwest monsoon resulting from a north-south barometric gradient, which is formed by an increase in pressure in the South China Sea (SCS), strengthening the western WPSH, and a marked reduction in pressure

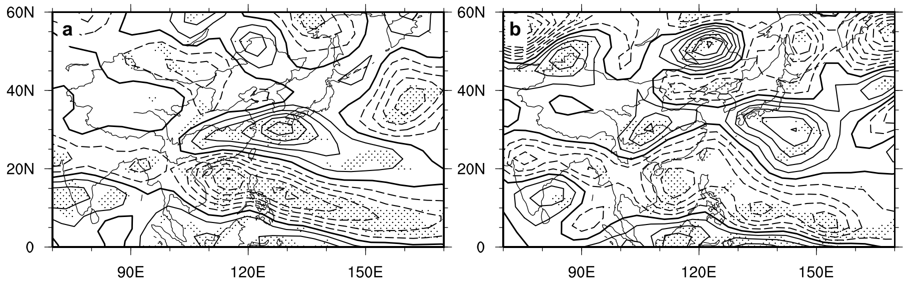

Fig. 11. Pacific-Japan (P-J) teleconnection patterns during the Meiyu season (a) from 1979 to 1999 and (b) from 2000 to 2009. Solid (dashed) lines indicate regressed positive (negative) anomalies of 850-hPa relative vorticity (units: 10^{-6} s^{-1}). The contour interval is 0.5. Heavy solid lines denote a value of zero. The shaded areas are statistically significant at the 90% confidence level according to a *t* test.

that is centered on the northern YHRV at the middle latitudes (Fig. 10b). The latter is due to the westward expansion of the WPSH, which decreases the northward transport of water vapor over the SCS.

In Fig. 10b, the lower tropospheric circulation features meridional dipoles between the low latitudes (10°–30°N) and middle latitudes (30°–40°N). The corresponding vorticity changes show similar wave-like characteristics (figures not shown) that exhibit a distinct tilt with height (Fig. 10d). These features characterize the Pacific-Japan (P-J) teleconnection pattern, which provides a crucial connection between the tropics and the middle latitudes. The prevalence of the P-J pattern during the Meiyu period was identified based on an empirical orthogonal function (EOF) analysis, following Kosaka and Nakamura's study (2010). An EOF analysis was applied to anomalies of 850-hPa vorticity over the East Asia-Pacific region [0°–60°N, 100°–160°E] during the Meiyu periods from 1979 to 2009. The first EOF mode (EOF1) explains 12.5% of the total variance and is therefore well separated based on the criteria proposed by North et al. (1982). Then, anomalies of 850-hPa vorticity for 1979–1999 and 2000–2009 were regressed onto the corresponding principal component (PC1) time series. The results of both analyses are characterized by distinct meridional wave trains of zonally elongated vorticity anomalies, which are characteristic P-J patterns (Kosaka and Nakamura, 2006, 2010; Kosaka et al., 2013). PC1 is defined as the P-J pattern index. It exhibits positive correlations with the average rainfall amounts over the southern and northern YHRV, with correlation coefficients of 0.58 and 0.34, respectively. These results indicate a link between the changes in the rainfall over the YHRV and the P-J pattern. Above-normal precipitation during the Meiyu period corresponds to the positive phase of the P-J teleconnection, which exhibits a tripole pattern with positive, negative and positive vorticity anomalies clearly located in the region south of the Philippines, the region of the South China Sea (SCS) and Philippine Sea, and the region containing the YHRV in China and southern Japan, respectively, whereas below-normal precipitation corresponds to the negative phase of the P-J pattern. A comparison between Fig. 11a and b reveals that the P-J pattern was displaced poleward between 1979–1999 and 2000–2009; the uppermost boundary of the phenomenon, which corresponds to the northern margin of the negative vorticity anomaly extending from the SCS to the Philippine Sea, has been pushed northward by 5 ° in latitude, whereas the positive anomaly area to the north of the negative anomaly has shrunk to the north of the Yangtze River. It is thus suggested that, as shown in Fig. 10b and c, the differences in vorticity and pressure can be divided into two regions at approximately 30°N. A concrete comparison of values (Fig. 11a,b) reveals that the magnitude of the negative vorticity anomaly has decreased, indicating a weakening of anticyclonic perturbation and an enhancement in cyclonic perturbation. Correspondingly, the OLR in the vicinity of the Philippines is obviously decreased (Fig. 10d), which reflects an enhancement in convective activity. The negative anomaly OLR maximum is located at approximately 16°N, which is some distance north from the climatological location of the western Pacific ITCZ (8–12°N). Apparently, the western Pacific ITCZ is tending to strengthen and extend northward. Conversely, the OLR is positive along 20–30°N, the northern marginal zone of the WPSH, and convection has decreased. This implies that the WPSH has also strengthened and shifted northward.

Additionally, previous studies (Lu, 2001; Lu and Dong, 2001; Wakabayashi and Kawamura, 2004) have found that the P-J pattern can effect a westward extension or eastward retreat of the North Pacific high. Fig. 10d shows that the OLR has slightly increased over the SCS. Such a change, which is contrary to that in the Philippine Sea, can induce enhanced anticyclonic circulation (Fig. 10a and b) and an anomalous westward extension of the WPSH, which, in turn, could lead to the above changes in the water vapor fluxes.

As described above, the P-J pattern has extended poleward since 2000, which may have induced anomalous westward and northward extensions of the WPSH, thereby strengthening convective activity over the northern YHRV and in the vicinity of the Bohai Sea while suppressing that over the region to the south of the Yangtze River. These effects may have led to intense convection and an increase in precipitation over the region to the north of the Yangtze River, ultimately inducing the observed changes to the Meiyu rain belt.

6. Summary and discussion

We have illustrated the northward shift of the Meiyu rain belt during the late 1990s based on daily rainfall datasets (after the elimination of TC rainfall) from 77 stations in the YHRV using the improved definition of the onset and termination dates of the regional Meiyu period proposed by Sun (Sun, 2014). The relationship between the changes in the Meiyu rain belt over China and the intensity of rainfall as well as the possible causes of these changes during 1958–2009 were preliminarily examined. The average Meiyu rainfall amounts over the northern and southern YHRV show no significantly long-term trends with climate warming, although some interdecadal variability is evident. However, the interannual variability of the Meiyu rainfall has been increasing during 1958–2009. And an evident uptrend in day-to-day variability within the Meiyu period also can be seen with the feature that the increasing in the northern is stronger than that in the southern. Such an increase in variability inevitably manifests as variations in the frequency and intensity of rainfall. Over the past 52 years, the FOCs and intensities of rain events in heavy intensity categories ($R \geq R80p$) have tended to increase, whereas events in weak categories ($R < R40p$) have exhibited a decreasing trend in both the southern and northern YHRV under climate warming. However, the more significant positive trends in heavy rainfall ($R \geq R90p$) over the northern YHRV compared with the southern YHRV have exerted an important effect on the northward shift of the Meiyu rain belt.

The possible causes of the Meiyu rain belt migration were examined in terms of changes in atmospheric circulation. Since 2000, the northward intensification of the horizontal transport and convergence of water vapor fluxes have caused rainfall to become increasingly concentrated in the northern YHRV. The P-J pattern, a wave-like circulation pattern emanating from the tropics toward the extratropical regions of East Asia and the Northern Pacific, was displaced poleward between 1979–1999 and 2000–2009. This induced intense convergence of water vapor and convection over the northern YHRV via the enhancement and northward expansion of convection over the western Pacific ITCZ and areas to its north, forcing the WPSH to expand northward and westward.

The rainfall distribution during the Meiyu is complex, particularly because of the changes in rainfall associated with climate warming. Thus, further studies of the influence of the atmospheric internal variability on rainfall distribution are needed. Why does the water vapor transport channel change? Will the relative contributions of wind fields and water vapor to the horizontal water vapor flux change with climate warming? These questions will be addressed in future research.

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