Changing contribution rate of heavy rainfall to the rainy season precipitation in Northeast China and its possible causes

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A R T I C L E   I N F O

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A B S T R A C T

Based on the daily precipitation data from 208 meteorological stations in Northeast China, NCEP/NCAR re-analysis monthly mean wind, sea level pressure data and NOAA reconstructed monthly mean sea surface temperature (SST) data from 1961 to 2013, the contribution rate of heavy rainfall to the total rainfall (hereafter referred to as “heavy rainfall contribution rate” or HRCR) during the rainy season in Northeast China was investigated. The changing characteristics of HRCR in the context of global warming are analyzed. The relationship between the HRCR and the contemporaneous atmospheric general circulation and early SST anomaly was analyzed to understand the possible physical mechanism responsible for the changing HRCR before and after the warming. Results show that during the whole study period (1961–2013), no evident trend in the HRCR has been detected. However, during cold period (1961–1979), the HRCR showed a significantly declining trend, while during warm period (1981–2013), the HRCR does not exhibit any trend. During cold period, the anomalous North Pacific summer monsoon and March North Atlantic tripole SST are the main factors affecting the HRCR, while the West Pacific summer monsoon, the East Asian subtropical westerly jet and March North Pacific dipole SST are responsible for the HRCR in the warm period. In the cold period, due to the air-sea interaction, March Atlantic tripole SST can influence the North Pacific summer monsoon in the late July–August, in turn affecting the HRCR. In the warm period, March North Pacific dipole SST tends to cause anomalies in the West Pacific summer monsoon and the position of the East Asian subtropical westerly jet axis in the July–August through air-sea interaction, thereby affecting the HRCR. During 1961–1979, the weakening of the North Pacific summer monsoon might have been the primary cause of the significant decline in the trend of the HRCR in the cold period. In 1981–2013, the absence of significant trends of the West Pacific summer monsoon and subtropical westerly jet position might be the main reason for the lack of an obvious linear trend of HRCR in the warm period.

1. Introduction

East China locates in the typical monsoon climate zone, significantly affected by the advance and retreat of the East Asian monsoon, and the precipitation here has distinct phases and regional characteristics (Zhu, 1934). Many scholars have investigated the rainy seasons precipitation in different phases and regions, including precipitation in the pre-flood season in South China (Zheng et al., 2006), the Meiyu in the Yangtze-Huaihe River basin (Ding et al., 2007), autumn rains in West China (Bai and Dong, 2004), the rainy season rainfall in Southwest China (Yan et al., 2013), the rainy season precipitation in the northern part of China (Zhao, 1994), and that in Northeastern part of China (Fang et al., 2014, 2016; Gong et al., 2015b). These studies have greatly improved our understanding on climate characteristics in China.

Additionally, lots of researches have been performed to investigate the climate change under the background of the global warming (Zhao et al., 2010; He et al., 2016). It is found that the global warming has led to evident changes in the frequency and intensity of the extreme
weather events in many parts of the world (Tosnis, 1996; Pourtouhierkan and Rakshandehroo, 2014). Since the mid-1990s, with the increase in extreme climate change research, study on changes in the magnitude and types of precipitation has also increased. Yan and Yang (2000) reported that “drizzle” has decreased in China. Qian et al. (2007) showed that as the climate has warmed, the frequency of the light rain has declined significantly in China. Sun et al. (2007) found that the annual days of light rain events decreased in Northeast China during 1951–2002, but the intensity increased. Sun and Ao (2013) also suggested that as China’s regional winter temperature rises, China’s regional winter precipitation and extreme precipitation show a consistent increasing trend. Lu et al. (2016) studied the relative importance of precipitation frequency and intensity to the inter-annual variability of summer precipitation in China. Their results showed that the precipitation frequency and intensity primarily affect heavy and weak precipitation, respectively. Other scholars have conducted related research in this field (Wang and Zhai, 2008; Chen and Dai, 2009).

The above findings show that the study of precipitation volume is not equal to the study of precipitation intensity. At present, research on precipitation in China is primarily concentrated on the average rainfall or extreme precipitation events (Kunkel et al., 2013; Gong et al., 2015a; Jury, 2015; Ren et al., 2017; Zittis et al., 2017). However, analysis of the contribution rate of precipitation with different intensities is less common. The diagnostic analysis of the contribution rate of precipitation at various levels to total rainfall in the Northeast China rainy season can determine whether predictions of rainy-season precipitation should emphasize heavy or light precipitation. This determination can indicate the direction for rainy-season rainfall forecasts and has scientific value for disaster prevention and mitigation as well as for promoting economic development. The contribution rate of heavy rain precipitation to total rainfall in the Northeast China rainy season is the focus of the present study. The objective is to analyze the changing characteristics and genesis of heavy rain in the context of global warming to provide theoretical support for the prediction of the contribution rate of heavy precipitation in the Northeast China rainy season.

In addition, climate change under the background of the global warming is one of heated topics in climate research. Alexander et al. (2006) has pointed out that the global precipitation indices show a tendency toward wetter conditions throughout the 20th century. Similarly, Chen and Zhang (2016) suggested that the frequencies of the global extreme severe precipitation events and the extreme high temperature events increase under significant global warming during the last 112 years. As to China, the entire country was dominated by apparent increase of the frequency of extreme precipitation (Gu et al., 2016). These research findings indicate that heavy rainfall events are increasing with global warming, these variation characteristics should be used considered for HRCR prediction.

2. Data and methods

2.1. Data sources and research methods

The datasets used in this study include the observational daily precipitation data from 208 stations in Northeast China (three northeastern provinces and four cities in eastern Inner Mongolia) during 1961–2013, NCEP/NCAR reanalysis monthly mean wind field data, sea level pressure (SLP) data (Kalnay et al., 1996; http://www.esrl.noaa.gov/psd/), and the National Oceanic and Atmospheric Administration (NOAA)-reconstructed monthly mean sea surface temperature (SST) data (Huang et al., 2014; http://www.esrl.noaa.gov/psd/). The station data was provided by the National Meteorological Information Center of China, which is available at http://data.cma.cn. Fig. 1a shows the geographic location of the northeastern China, and the stations selected are shown in Fig. 1b.

The empirical orthogonal function (EOF) decomposition, Mann-Kendall test, correlation analysis, composite analysis, regression analysis and other statistical analysis methods are used in current study.

Mann-Kendall method has been widely used to check the abrupt point or trend of a given time series. For a time series \(x_1, x_2, \ldots, x_n\) we can calculate the statistical variable \(d_k\) as following:

\[
d_k = \sum_{i=1}^{k} P(2 \leq k \leq n)
\]

where \(P_i\) denotes the cumulative samples where \(x_i > x_j (1 \leq j \leq i)\).

Suppose that the original time series are random and independent, the mean and the variance of \(d_k\) can be calculated by:

\[
E[d_k] = \frac{k(k - 1)}{4}
\]

\[
\text{Var}[d_k] = \frac{k(k - 1)(2k + 5)}{72}(2 \leq k \leq n)
\]

Under the above assumption, the forward sequential statistic \(U_F\) (MK test based on the data) is calculated as:

\[
U_F = \frac{d_k - E[d_k]}{\sqrt{\text{Var}[d_k]}}
\]

where \(U_F\) satisfies the normal distribution and the null hypothesis can be rejected at the significance level of \(\alpha\), if \(|U_F| > U_{F_a} - \alpha/2\). Also, \(U_{F_a} - \alpha/2\) is the critical value of the standard normal distribution with a probability exceeding \(\alpha/2\). The backward sequential statistic \(U_B\) is calculated based on the adverse sequence of the data. When \(U_F\) and \(U_B\) curves intersect, the intersection point denotes the jumping (or turning) point. In other words, the sequential version of the Mann-Kendall is considered as an effectual way of locating the beginning year of trend.

2.2. Index definition

2.2.1. North Atlantic SST tripole index

The March North Atlantic SST tripole index for 1961–1979 was sourced from the projection index given by the National Climate Centre website, and the definition refers to http://ncc.cma.gov.cn.

2.2.2. North Pacific dipole index

The North Pacific dipole index is defined as the difference between the SST of the North Pacific in the region (165°E–140°W, 45°N–55°N) in March of 1981–2013 and that in the region (170°E–155°W, 25°N–37.5°N) at the same time.

2.2.3. North Pacific and West Pacific summer monsoon index

In this paper, the East Asian summer monsoon primarily reflects the difference in SLP. Therefore, the North Pacific summer monsoon index is characterized by the difference in mean SLP between the North Pacific (165°E–170°W, 50°N–65°N) and the Chinese mainland (90°E–110°E, 35°N–50°N) in July–August of 1961–1979. The West Pacific summer monsoon index is characterized by the difference in SLP between the West Pacific (125°E–140°E, 28°N–36°N) and Siberia to the north of Lake Baikal (90°E–120°E, 55°N–65°N) in July–August of 1981–2013.

2.2.4. East Asian subtropical westerly jet position index

The East Asian subtropical westerly jet position index is defined as the difference in mean 200-hPa zonal wind velocities between the (110°E–140°E, 45°N–55°N) area and (110°E–140°E, 28°N–38°N) area at the 200-hPa zonal wind field in July–August of 1981–2013 for standardization, the definition is similar to Yan et al. (2017). The larger (smaller) index indicates the East Asian subtropical westerly jet locates northward (southward).
2.3. Calculation of HRCR

Daily precipitation greater than or equal to 50 mm is considered as heavy rain. According to the previously defined objective identification standard of start and end dates of the Northeast China rainy season (Fang et al., 2014), annual total precipitation and the heavy rain and more intense rainfall in the Northeast China rainy season are calculated and divided by total precipitation in the Northeast China rainy season to obtain the contribution rate of annual heavy rain to total precipitation in the Northeast China rainy season in 1961–2013.

2.4. Division of the study periods

The European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis data were used to analyze the variation characteristics of global annual mean surface temperatures by Zhao et al. (2010). The results indicated that the global annual mean temperature anomaly is increasing each year; it was negative in the 1960s–1970s but positive in the 1980s–1990s, changing from negative to positive in 1980. Additionally, the total precipitation in the Northeast China rainy season showed an abrupt change in the early 1980s (figure omitted). Therefore, the period before global warming is defined in this study as 1961–1979 (cold period) and the period after global warming is defined as 1981–2013 (warm period). These definitions are used to analyze the changing characteristics and the geneses of the variation in HRCR in both periods.

2.5. Determination of the contemporaneous period of the northeast east rainy season

As the average start and end dates of the Northeast China summer rainy season are June 26 and August 31, respectively (Fang et al., 2014), i.e., because the rainy seasons are primarily concentrated in July and August, the contemporaneous period of the Northeast China rainy season was determined for July–August.

2.6. Method for defining anomalous SST years in key areas

Because of fewer years in the cold and warm periods, the three years with the maximum and minimum SST index are considered the abnormally high and low SST index years in this study. Among these, the years with a lower North Atlantic tripole index included 1972, 1971 and 1962, while the years with a higher tripole index included 1978, 1970 and 1977; the years with a higher North Pacific dipole index included 1996, 1997 and 2005, while the years with a lower dipole index included 1999, 2000 and 2002.

3. Results

3.1. Characteristics of HRCR change in the context of global warming

This study focuses on the HRCR to total rainfall in the Northeast China rainy season. The calculated contribution rate of precipitation events such as heavy rain and more intense events (greater than or equal to 50 mm) to the total rainfall of the Northeast China rainy season has a correlation coefficient of 0.52 with the total rainfall of the Northeast China rainy season in the last 53 years, passing the significance test with a confidence level of 0.01. However, the contribution rate of precipitation events such as moderate rain (greater than or equal to 25 mm and less than 50 mm) to the total rainfall of the rainy season has a correlation coefficient of 0.26 with the total rainfall of the Northeast China rainy season in the last 53 years, failing to pass the significance test with a confidence level of 0.05. These findings show that heavy rain and precipitation events of greater intensity have more significant contribution rates to the total rainfall of the Northeast China rainy season than heavy rain events. Therefore, the HRCR is the focus of the present study.

As viewed from the 11-year moving average curve shown in Fig. 2, from the 1960s to the late 1970s, the HRCR was on the decline, while in the early 1980s, an initially increasing and then decreasing trend is shown. Overall, the HRCR had no obvious trend from 1961 to 2013. However, in the cold and warm periods discussed in Section 2.4, the HRCR had obviously different trend (green line), i.e., a decline in the cold period (1961–1979) that passed the significance test but almost no trend during 1981–2013.

The EOF analysis was conducted on the HRCRs of 208 stations in Northeast China during 1961–2013. The variance contribution rate of the first mode is 57.1%, reflecting the primary change characteristics of the HRCR. However, the variance contribution rate of the second mode declined rapidly to only 2.8%. Therefore, this study focused on the first mode of the EOF of the HRCR. The inter-annual variability curve trend
(figure omitted) of the time series of the first mode is consistent with
the change curve of the HRCR, and both correlation coefficients are up
to 0.98. Thus, the subsequent analyses are all based on the causes of the
significant differences in the trends of the time series of the first mode
of the EOF of HRCR (hereafter referred to as t1) before and after global
warming.

3.2. Relationship between the HRCR and atmospheric circulation

To analyze the causes for the significant differences in the HRCR
trend before and after warming, it is necessary to clarify the con-
temporaneous circulation influence factor for the HRCR in the cold and
warm periods. The correlation analysis method is used to analyze the
relationship between t1 and the circulation fields at different levels.
Research indicates that the SLP field is closely related to t1 in the cold
period. Moreover, the SLP field and 200-hPa zonal wind field are clo-
sely related to t1 in the warm period.

3.2.1. Relationship with SLP

Fig. 3a and b show the distribution map of the correlation coefficient
between t1 in the cold and warm periods and the SLP field in
July–August. As shown in Fig. 3a, the relationship between t1 and the
July–August SLP field has a significantly positive correlation in the
North Pacific and a significantly negative correlation on the Chinese
mainland (in the circle). These trends show that the HRCR in the cold
period is closely related to the East Asian summer monsoon, which is
classified as the “North Pacific monsoon”). The case in which the North Pacific summer monsoon
is stronger (weaker) is (not) conducive to water vapor convergence in
Northeast China and advantageous to larger (smaller) HRCRs. As shown
in Fig. 3b, a significant positive correlation exists in southern Japan and
adjacent oceans, while a significant negative correlation exists in Si-
beria to the north of Lake Baikal (in the circle). These trends suggest
that the HRCR in the warm period is closely related to the East Asian
summer monsoon, which is characterized by pressure differences be-
tween the West Pacific and Siberia to the north of Lake Baikal (hereafter
referred to as the “West Pacific summer monsoon”). That is, the case in which the West Pacific summer monsoon is stronger (weaker) is (not) conducive to water vapor convergence in Northeast China and advantageous to larger (smaller) HRCRs. The 850-hPa wind field is also analyzed, the results show that HRCR has a close relationship with the south wind component over the southern part of northeastern China in both cold and warm period. The higher (lower) south wind component, the more advantageous to larger (smaller) HRCR it will be. It is indicated that the North Pacific summer monsoon and the West Pacific summer monsoon represented by low level air flow show similar results with that reflected by the SLP field.

3.2.2. Relationship with 200-hPa zonal wind

Fig. 4b shows that a significant positive correlation exists in the area centered at 125°E to the north of 40°N and a significant negative correlation exists in the area to the south of 40°N (in the circle). These trends indicate that the t1 in the warm period is closely related to the subtropical westerly jet position, i.e., the northward (southward) subtropical westerly jet position is advantageous to larger (smaller) HRCRs. The possible dynamic mechanism is that when the north subtropical westerly jet is northward, Northeast China is located to the south of the jet, and the divergence occurs in the upper air to the south of the jet. Meanwhile, the convergence in the lower air leads to a prevailing updraft, which is advantageous to the formation of strong precipitation. Thus, lower air convergence is beneficial to larger HRCRs, while the opposite case is beneficial to smaller HRCRs. The significant negative correlation between the t1 in the cold period and the 200-hPa zonal wind field shows a center at 120°E and 40°N. However, this correlation does not reflect the relationship between the HRCR and the subtropical westerly jet, so there is no significant correlation between the HRCR in the cold period and the subtropical westerly jet (Fig. 4a).

In summary, the HRCR is influenced by the North Pacific summer monsoon in the SLP field during the cold period. In the warm period, the HRCR is influenced by the West Pacific summer monsoon in the SLP field and the East Asian subtropical westerly jet position in the 200-hPa zonal wind field. Thus, the contemporaneous circulation system anomaly at the high and low level appears to be the direct cause of the HRCR anomaly in the cold and warm periods.

3.3. Relationship between HRCR and early SSTA

After clarifying the relationship between the HRCR in the cold and warm periods and the contemporaneous circulation factors, the relationship between the HRCR and early external forcing is analyzed. Similarly, the correlation analysis method is used to calculate the correlation between the t1 in the cold and warm periods and the early monthly global SST. The results indicate that the early March SST is closely correlated with the HRCR change in the cold and warm periods.

Fig. 5a and b show the distribution of the correlation coefficients between t1 in the cold and warm periods and the early March SST. Fig. 5a indicates that the first mode of the HRCR in the cold period presents a significant “positive-negative-positive” correlation distribution with the North Atlantic SST from north to south. This correlation situation is similar to that of the North Atlantic SST tripole pattern. As indicated by Fig. 5b, the first mode of the HRCR in the warm period presents a “north positive–south negative” distribution with the North Pacific SST. This distribution situation is the “North Pacific dipole.” It is possible considered that the March Atlantic tripole pattern and the March North Pacific dipole pattern may affect the HRCRs in the cold and warm periods, respectively, through the air-sea interaction.

3.4. Relationship between early SST, HRCR and atmospheric circulation

In Sections 3 and 4, the influence of the contemporaneous circulation system and the early (March) SST factor corresponding to the first mode of the HRCR in the cold and warm periods are discussed, respectively. This section discusses whether the March key-area SST anomalies in the cold and warm periods will influence the July–August circulation system anomaly. The composite analysis method is used to analyze the anomaly distribution characteristics of the July–August SLP field and the 200-hPa zonal wind field corresponding to the year with the March key-area SST anomaly. If the July–August circulation field characteristics obtained by the composite analysis are consistent with the contemporaneous circulation system influenced on the HRCR, i.e., consistent with Fig. 3 and Fig. 4, we can consider that the March key-area SST anomaly causes the July–August circulation system anomaly, thus affecting the HRCR.

3.4.1. July–August circulation corresponding to the year with a March Atlantic tripole index anomaly in the cold period

Fig. 6 shows the July–August SLP field composite map corresponding to the years with the March Atlantic tripole index anomaly. Fig. 6a indicates that in the years with the smaller index, the East Asia continent shows characteristics of the north (eastern Russia) SLP positive anomaly, the south (northern China) negative anomaly, and the positive anomaly adjacent to the Sea of Japan (three red-circle areas). This result is generally consistent with the distribution of the areas of significant correlation in Fig. 3, and only a slight difference exists in the key area. Fig. 6b shows that in the year with the higher index, the anomalies of the three key areas are opposite the year with the lower index. The difference map (figure omitted) also shows the distribution characteristics of the north positive anomaly, while the south negative anomaly in the East Asia continent passes the significance test, proving that the above regional difference has significant meaning in the years with lower and higher index values. Because the composite analysis result of Fig. 6 is consistent with the areas of significant correlation in Fig. 5a, the analysis indicates that a significant teleconnection wave train (figure omitted) exists in the correlation coefficient between the North Atlantic tripole index and the April–August mean 500-hPa geopotential height field from the Atlantic through the Polar Regions to East Asia. Therefore, the March Atlantic tripole index may cause the July–August SLP field anomaly in key areas of the East Asian continent through the upper air teleconnection wave train produced by air-sea interactions. Moreover, the anomalous SLP field will influence on the North Pacific summer monsoon intensity resulting in the HRCR anomaly. What's more, a preliminary study shows that a barotropic wave-train pattern occurring over the Atlantic-Eurasia region likely acts as a link between the East Asia summer monsoon and the North Atlantic tripole during summer (Zuo et al., 2013), so the North Atlantic tripole maybe influence the HRCR through the East Asia summer monsoon anomaly.

3.4.2. July–August circulation corresponding to the year with a March Pacific dipole index anomaly in the warm period

Fig. 7 shows the July–August SLP composite map corresponding to the years with a March North Pacific dipole index anomaly. Fig. 7a indicates that in the years with the higher index, the SLP in southern Japan and adjacent oceans (in the red circle) shows a positive anomaly, while a negative anomaly is shown in Siberia to the north of Lake Baikal. Such a distribution is consistent with the significant correlation area positions in Fig. 3b. Fig. 7b shows that in the year with the lower index, the SLP in the key area of southern Japan and adjacent oceans (in the red circle) shows a negative anomaly. This correlation presents an anti-phase correspondence with the SLP anomaly in Fig. 7a. In the difference map between Fig. 7a and b (figure omitted), the differences near the key area of southern Japan and adjacent oceans passed the significance test, indicating that in the years with the higher and lower index values, the difference in this key area has significance. Because the composite analysis results in Fig. 7 are consistent with the distribution of the significant correlation areas in Fig. 3b, the heating or cooling effect of the North Pacific dipole SST will have an influence on the SLP. That is, the air-sea interaction will cause the SLP field anomaly
in the July–August southern Japan and adjacent oceans. The March
North Pacific dipole may lead to an anomaly in sea-land pressure
differences, resulting in the anomaly in the West Pacific summer monsoon
intensity and thus causing the HRCR anomaly.

Fig. 8 shows that adjacent to the longitude of Northeast China and
its western areas, the 200-hPa zonal wind velocity shows a significant
positive anomaly to the north of 45°N and a negative anomaly to the
south of 45°N. This distribution corresponds to the northwesterly jet
position over Northeast China, which is advantageous to a larger HRCR.

Fig. 8b shows that adjacent to the longitude of Northeast China, the

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**Fig. 5.** Distribution map of the correlation coefficients between $t_1$ in the cold (a) and warm (b) periods and the early March SST field (dots indicate the correlation coefficient passing the significance test of 0.1 level).

**Fig. 6.** SLP field composite maps in the years with 3 lowest (a) and 3 highest (b) North Atlantic tripole index values (shaded areas indicate the SLP anomaly; unit: hPa).

**Fig. 7.** SLP field composite maps over the years with 3 lowest (a) and 3 highest (b) North Pacific dipole index values (shaded areas indicate the SLP anomaly; unit: hPa).
200-hPa zonal wind velocity shows a negative anomaly to the north of 35°N and a positive anomaly to the south of 35°N. This distribution corresponds to the southwesterly jet axis over Northeast China, which is advantageous to a smaller HRCR. This finding is consistent with the distribution of areas of significant correlation in Fig. 4b and reflects that the heating or cooling effect of the North Pacific dipole south-north anti-phase SST on the upstream upper air has an influence on the upper wind field anomaly. That is, the air-sea interaction causes the July–August 200-hPa zonal wind field anomaly. The March North Pacific dipole may lead to the anomaly in the south-north position of the East Asian subtropical westerly jet axis and thus cause the HRCR anomaly.

3.5. Direct causes of changes in HRCR trend in cold and warm periods

In this section, we focus on the trend of the influence of contemporaneous circulation on the HRCR in the cold and warm periods and analyzing the causes of the trend in the HRCR. Because the HRCR in the cold (warm) period is affected by the North (West) Pacific summer monsoon, the analysis is required to determine whether the trend of the North (West) Pacific summer monsoon index in the cold (warm) period is approaching that of the contribution rate. Fig. 9a shows the North Pacific summer monsoon index curve. The index presents a declining trend in 1961–1979, passing the significance test, and is consistent with the significant declining trend of the HRCR in the cold period. This result further supports the conclusion in Section 3.4.1 that the North Pacific summer monsoon is closely related to the HRCR. Moreover, the calculation can determine the correlation coefficient between the North Pacific summer monsoon index and the HRCR curve in the cold period, which was up to 0.58 in 1961–1979, passing the significance test with a confidence level of 0.01, but their correlation coefficient in 1981–2013 was 0.19, cannot pass the significance test. Therefore, the significant weakening of the North Pacific summer monsoon in 1961–1979 may be the direct cause of the significant declining trend of the HRCR in the cold period. Fig. 9b shows the West Pacific summer monsoon index curve in 1961–2013. The index presented a very weak upward trend from 1981 to 2013, which is inconsistent with the weak downward trend of the HRCR in the warm period. The explanation may be that the definition of the West Pacific summer monsoon index considers the SLP in Siberia to the north of Lake Baikal. This area has no real anti-phase correspondence in Fig. 7a and b, but the trends of the West Pacific summer monsoon index and the HRCR in the warming period are far from passing a significance test. Thus, both have almost no trend, which supports the conclusion in Section 3.4.2 that the West Pacific summer monsoon is closely related to the HRCR. Moreover, the calculation shows that the correlation coefficient between the West Pacific summer monsoon index and the HRCR curve in the warm period in 1961–1979 was 0.66, passing the significance test with a confidence level of 0.01, but their correlation coefficient in 1981–2013 was 0.14, cannot pass the significance test. Therefore, the weakly trend of storm rainfall in the warm period from 1981 to 2013 may be associated with the weakly trend of the West Pacific summer monsoon.

Additionally, because the HRCR in the warm period is influenced by the East Asian subtropical westerly jet axis position, an analysis is conducted on whether the trend of the East Asian subtropical westerly jet axis position index is approaching that of the contribution rate. Fig. 10 shows the East Asian subtropical westerly jet axis position index.
curve in 1961–2013. The East Asian subtropical westerly jet axis position index in 1981–2013 had almost no trend. The correlation coefficient between the East Asian subtropical westerly jet axis position index and the HRCR in 1981–2013 in the warm period was 0.50, passing the significance test with a confidence level of 0.01, but their correlation coefficient in 1961–1979 was −0.01, far from passing the significance test. Therefore, the absence of a trend of the HRCR in the warm period of 1981–2013 may be related to the weakly trend of the East Asian subtropical westerly jet axis position.

4. Conclusions and discussion

This study disclosed changing HRCR to total rainfall during rainy season in the Northeast China. The influence of anomalous atmospheric general circulation on the HRCR in cold and warm period together with related mechanism has been explored. The early external forcing factor of the HRCR is studied to prove that it can cause the anomaly in the contemporaneous circulation system through air-sea interaction, further resulting in the HRCR anomaly. Through this analysis, the following seven conclusions can be made.

(1) During the period of 1961–2013, there is no evident trend in the HRCR. However, the HRCR exhibits significant declining trend in the cold period.

(2) Regarding the contemporaneous circulation factor, the first mode of the EOF of the HRCR in the cold period is closely related to the North Pacific summer monsoon, when the North Pacific summer monsoon is stronger (weaker), the HRCR is larger (smaller). While in the warm period, the first mode of the EOF of the HRCR is closely related to the West Pacific summer monsoon and the East Asian subtropical westerly jet axis position, when the West Pacific summer monsoon is stronger (weaker), the HRCR is larger (smaller). Meanwhile, the East Asian subtropical westerly jet axis located northward (southward), which is advantageous to a larger (smaller) HRCR in the warm period.

(3) Regarding early external forcing, the EOF first modes of the HRCR in the cold and warm periods are affected by the early March Atlantic SST tripole pattern and the early March North Pacific dipole pattern.

(4) In the cold period, corresponding to the year with the anomaly in the March Atlantic tripole index, the late July–August East Asian SLP field distribution is consistent with the distribution of the contemporaneous circulation anomaly of the HRCR in the cold period. The March Atlantic tripole pattern may cause the anti-phase of the SLP fields in the July–August North Pacific and on the Chinese mainland (the anomaly in the North Pacific summer monsoon) through the teleconnection wave train produced by air-sea interaction, resulting in the HRCR anomaly.

(5) In the warm period, corresponding to the year with the anomaly in the March North Pacific dipole index, the distribution of the late July–August East Asian SLP field and the 200-hPa zonal wind field are consistent with the distribution of the contemporaneous circulation system anomaly of the HRCR in the warm period. The March North Pacific dipole pattern may cause the anomaly in the East Asian subtropical westerly jet axis positions of the July–August West Pacific summer monsoon and the 200-hPa zonal wind field through the upstream atmospheric heating or cooling effect, resulting in the HRCR anomaly.

(6) During the cold period (1961–1979), significant weakening of the North Pacific summer monsoon is likely responsible for the significantly declining of the HRCR. However, during the warm period (1981–2013), the West Pacific summer monsoon intensity had no obvious change, and the East Asian subtropical westerly jet position showed no significant south-north moving trend, which is the primary cause for no significant trend of the HRCR in the warm period.

In this study, a variety of statistical methods are used to investigate the possible reasons for the differences in the trend of the HRCR between the cold and warm period from two perspectives, i.e., the early external forcing factor and the contemporaneous circulation factor. Our study can provide a theoretical basis for predicting the HRCR of the total precipitation of the rainy season in Northeast China. Understanding the mechanisms influencing the early SST as an external forcing factor on the contemporaneous circulation system anomaly in the rainy season requires additional research based on numerical modeling, therefore, only the influence of the contemporaneous circulation system on the trend change in the HRCR before and after warming is considered in the present study.

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