Variation in Summer Rainfall over the Yangtze River Region during Warming and Hiatus Periods

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Abstract: Variation in summer precipitation over the Yangtze River region during a global warming period (1976–1997) and a hiatus period (1998–2013) are investigated in this study. The results show that during the warming period, precipitation over both the Yangtze River region and South China shows an increasing trend, attributable to increasing ascending motion, a decreasing East Asian westerly jet (EAWJ), and a decreasing temperature gradient. During the hiatus period, the rainfall belt moves from the Yangtze River region to the Huang-Huai River region in association with the northward displacement of the EAWJ, attributable to the increasing trend in the temperature gradient at high latitudes. Empirical orthogonal function (EOF) analysis is one of the widely used methods in atmospheric science. It is also known as principal component analysis (PCA). The second EOF mode of summer precipitation can represent the variation in rainfall over the Yangtze River region. During the warming period, rainfall over the Yangtze River region is controlled by a dipole mode of water vapor transport, induced by SST cooling in the Maritime Continent, which can lead to a strong Pacific–Japan teleconnection; warming SST in the east-central tropical Pacific can also strengthen this pattern. During the hiatus period, the Pacific–Japan pattern is weak, and the water vapor transport pattern over the western subtropical Pacific changes from a dipole structure to a weak monopole structure.

Keywords: summer rainfall; southeastern China; global warming; warming hiatus

1. Introduction

Southeastern China has a large population and an advanced economy, and it also suffers from weather and climate disasters, such as extreme freezing rain and snow in winter and floods in summer. Precipitation variation in this region is worthy of more attention.

Different methods have been used to study climate change. For example, a least squares approach and the Kendall_tau significance test are usually used to calculate the linear trend of precipitation [1–3]. A T-test is usually applied to study the difference between two subperiods [4,5]. For analysing the extreme precipitation, statistical quantities such as the 90th or 95th percentile have been used as extreme indices in some studies [6–8] and a fixed intensity of precipitation (normally greater than 100 mm/day is defined as extreme precipitation in China) have also been used in some other studies [9]. Empirical orthogonal function (EOF) analysis is widely used to study the spatio-temporal patterns of precipitation[10–12]. In this study, the EOF analysis is applied to investigate the variations in rainfall over southeast China.

Variation in summer rainfall and water vapor transport over southeastern China is highly affected by the East Asian summer monsoon system, which is strongly modulated by variation in tropical sea surface temperature (SST), including SST anomalies in the tropical Indian Ocean, western tropical Pacific, and east-central tropical Pacific [13–16]. Gong and Ho [17] pointed out that the shift
in the summer rainfall pattern over eastern China is attributable mostly to variation in the western Pacific subtropical high (WPSH), which is modulated by changes in SST over the tropical Pacific.

Since the 1960s, the earth’s temperatures have undergone a rapid increase. However, the increase speed has been lower from 1998 to 2013 compared to preceding decades; this period is known as the hiatus [18,19]. Studies indicate that the global warming hiatus is part of natural climate variability and is contributed by sea surface temperature (SST) anomalies in the tropical Pacific [20]. During the hiatus, SSTs in the tropical Pacific are warmer in the western tropical Pacific and colder in the east-central tropical Pacific, which is similar to the SST anomalies during La Niña years. The long-lasting cooling in the east-central tropical Pacific corresponds to the negative phase of the Pacific Decadal Oscillation (PDO) starting at around 1998, and the associated changes in winds result in more heat sequestered in the deep ocean and less heat released into the atmosphere through changing currents, convection, and overturning in the ocean. The situation reverses during a positive PDO, which contributes to global warming [21].

Associated with global warming, increasing temperature trends occur at different rates over the land and ocean. The thermal contrast between the continents and adjacent oceans may have associated changes that lead to variation in atmospheric circulation and climate change, especially in monsoon regions. During global warming, in the summer season, cooling is found in the subtropics–extratropics near the Tibetan Plateau and its adjacent areas from 1960s to 1990s, which is contributed by excess snow over the Tibetan Plateau in the preceding spring, and warming in the surrounding oceans could reduce the thermal contrast between the land and the ocean, resulting in a weaker East Asian summer monsoon and leading to heavier precipitation over the YZ [22,23].

During the hiatus period, SST anomalies differ from those in the warming period, which may play an important role in climate change. Ueda et al.[24] compared summer rainfall anomalies between the hiatus period and the warming period and found that there is less rainfall in the middle and high latitudes of East Asia (EA) and more rainfall over the western Pacific (WP). They further investigated that the rainfall anomalies are contributed mostly by SST anomalies in the tropical Pacific, which intensify the convection and rainfall over the tropical WP and suppress rainfall in the middle and high latitudes of EA through atmospheric teleconnection during the warming period from 1999 to 2013.

So how do the summer rainfall pattern and related circulations vary under the background of global warming and during the warming hiatus? It seems that SST variation in the tropical ocean plays an important role in both changes in global temperature and summer rainfall variation. The influence of the tropical ocean on the summer rainfall pattern through modulating the related water vapor transport during the warming period (1976–1997) and the hiatus period (1998–2013) is worth further study.

Previous studies are mainly focused on the influence of global warming on the rainfall variations over China by analyzing the changes of temperature in atmosphere; in this study, we aim to further study the changes of rainfall as well as the related changes of atmospheric circulation during warming hiatus, and also discover the role of changes of temperature in the tropical ocean in those variations. This paper is arranged as follows. Section 2 describes the data used in this study. Section 3 describes the variation in summer rainfall over southeastern China and the associated anomalous atmospheric circulations during the warming and hiatus periods. In Section 4, the EOF patterns of summer rainfall and their associated water vapor transport during these two periods are studied and as the role of tropical ocean SSTs in rainfall variation was analyzed. The conclusion and a discussion are presented in section 5

2. Data and Method

a. Station data

Fifty-three years (1961–2013) of observed daily precipitation data obtained from the Climate Data Center, China Meteorological Administration (CMA) are used in this study. In total, 191 stations are used from June to August in southeastern China (17° N–35° N, 105° E–125° E)

b. Reanalysis data
Thirty-eight years (1976–2013) of reanalysis data obtained from the National Centers for Environmental Prediction (NCEP) are used in this study [25]. Monthly data from June to August are used to analyze the characters of atmosphere circulation include geopotential height, wind speed, air temperature, omega and so on. The horizontal resolution is $2.5^\circ \times 2.5^\circ$ latitude-longitude and 10 vertical levels are used from 1000 to 100 hPa.

The SST data used in this study are monthly data from the Extended Reconstructed Sea Surface Temperature (ERSST) version 4 dataset [26]. Summer period (June-August) from 1976–2013, and the resolution is $2^\circ \times 2^\circ$.

c. Empirical orthogonal function (EOF) analysis

The purpose of EOF is to decompose the value of a field into a space-time field. Lorenz [27] named the EOF method and used it in a forecasting project. Recently, EOF analysis has been frequently used to extract dominant modes of variability, such as the Arctic Oscillation (AO) [28,29], and Pacific Decadal Oscillation (PDO) [30].

The field to be analyzed is preprocessed to obtain an anomalous data matrix $X_{m \times n}$; then, the sample covariance matrix is defined by:

$$C_{m \times m} = \frac{1}{n} X \times X^T$$  \hspace{1cm} (1)

Matrix $C$ can be further decomposed as:

$$C_{m \times m} \times V_{m \times m} = V_{m \times m} \times \Lambda_{m \times m}$$  \hspace{1cm} (2)

Here, $V$ is the singular vector and $(\lambda_1, \lambda_2, ..., \lambda_n)$ are the singular values of the matrix.

$$\Lambda = \begin{bmatrix}
\lambda_1 & 0 & \ldots & 0 \\
0 & \lambda_2 & \ldots & 0 \\
\ldots & \ldots & \ldots & \ldots \\
0 & 0 & \ldots & \lambda_m
\end{bmatrix}$$  \hspace{1cm} (3)

The singular values are sorted in decreasing order, that is, $\lambda_1 \geq \lambda_2 \geq \ldots \geq \lambda_n \geq 0$. The singular vector corresponding to each singular value is called the EOF. For example, the singular vector corresponding to $\lambda_1$ is the first EOF mode, which is the first column of matrix $V$, that is, $EOF_1 = V(:,1)$, and so on, $EOF_n = V(:,n)$.

The principal component $PC$ can be calculated by projecting $EOF$ onto the original data matrix $X$, which yields the time coefficients corresponding to all spatial singular vectors, that is:

$$PC_{m \times n} = V^T_{m \times m} \times X_{m \times n}$$  \hspace{1cm} (4)

Here, each row of data in the $PC$ is the time coefficient corresponding to each singular vector. For example, $PC(1,:)$ is the time coefficient corresponding to EOF1.

In this way, the original data matrix $X$ can be decomposed into $EOF$ and $PC$ with space and time fields.

$$X = EOF \times PC$$  \hspace{1cm} (5)
In this study, the rainfall over southeastern China can be decomposed to two dominant spatial patterns named EOF1 and EOF2; PC1 and PC2 can explain the related temporal variations.

3. Variation in Summer Rainfall during the Warming and Hiatus Periods

   a. Variation in Summer Rainfall

   Anomalies of summer rainfall averaged over 110°–122° E relative to the climatological mean of 1971–2000 are shown in Figure 1. During the global warming period (1976–1997), rainfall over the Yangtze River region shows an increasing trend and over South China, the rainfall amount rapidly reaches a high value during the 1990s. During the hiatus period (1998–2013), rainfall over the Yangtze River region decreases, going from above normal to below normal, and rainfall over South China is relatively higher than in other periods, but also shows a slightly decrease. Furthermore, rainfall over the Huang-Huai River region increases during this period.

![](image)

**Figure 1.** Variation of summer (JJA) precipitation anomalies averaged over 110° E–122° E. The climatological mean is calculated from 1971 to 2000; the unit is mm.

The variation and trend of summer precipitation are shown in Figure 2. According to the Figure 1d in Leung et al. [31], rainfall in the Yangtze River region (25°–32.5° N, 115°–122° E) shows a significant increasing trend during 1960–2013, so this region is also selected in this study. Rainfall over the Yangtze River region is higher than normal during the 1990s, while it suffers an abrupt decrease in the early years of the 2000s; the linear trend of rainfall shows that the enhancement of summer rainfall is mostly a result of the increase in temperature during the global warming period. The variation in summer rainfall over South China (20°–25° N, 105°–120° E) shows that rainfall in this region was low during the 1980s, but it sharply increased at the beginning of the 1990s, and higher than normal precipitation remained in the 1990s and the early 2000s. The linear trend also shows an increase during the global warming period and a slight decrease during the hiatus period.
b. Circulation variation

Vertical velocity is necessary for precipitation; when vertical convection is strong, moisture can be transported into the upper level of the atmosphere, where it condenses to create precipitation. Figure 3 shows the climatological mean and trend of vertical velocity averaged from 110° E to 122.5° E in summer during the warming period and the hiatus period. During the warming period, an upward motion center is dominant over 20°–30° N, with the maximum increasing trend in the same region, indicating that the rainfall belt is located over the Yangtze River region and South China, and that the increase in rainfall is a result of the increase in vertical convection during this period. During the hiatus period, the mean vertical velocity is also located over the Yangtze River region and South China, but the trend of vertical motion shows a dominant upward motion north of the Yangtze River and a downward motion south of the Yangtze River, which indicates that the rainfall belt moves from south to north during this period.

Figure 2. Variation and trend of summer precipitation over (a) Yangtze River (25° N–32.5° N, 115° E–122° E) and (b) South China (20° N–25° N, 105° E–120° E) during different periods. The unit is mm.
Changes in 500 hPa geopotential height are also examined. Figure 4 shows that during the warming period, there is a positive trend center of geopotential height located over the continent and a negative trend center over the ocean at high latitudes. In this situation, a stable high pressure dominates North China, which leads to stronger descending motion there; in addition, the EASM cannot reach as far north, and water vapor transported by the monsoon winds accumulates over southern China, favoring an increase in precipitation in this region. During the warming period, a slightly decreasing trend is located over the Lake Baikal region and a slightly increasing trend is located over the ocean. In this situation, a deep trough is located in North China, which leads to more cold air transport into this region; when the cold air meets the warm and wet air transported by the EASM, more rainfall will occur over the Huang–Huai River region. The WPSH plays a very important
role in precipitation over eastern China. Northwestward movement of the WPSH is related to greater precipitation over eastern China [32]. If we compare the strength and location of the WPSH during these two periods, it can be found that the WPSH is stronger in the hiatus period, which indicates that water vapor transport along the west of the WPSH is stronger and can reach the Huang–Huai River region and create more precipitation there.

**Figure 4.** Same as Figure 3, but for geopotential height at 500 hPa; blue contours represent the values of 5860 and 5880 gpm.

The strength and location of the East Asian westerly jet (EAWJ) can also modulate the rainfall pattern over eastern China. When the EAWJ is relatively weak, interaction between the high latitudes and low latitudes will be stronger; more cold air from the north can be transported into southern
China, where it meets the wet and warm air there and leads to more precipitation. During the warming period, the EAWJ shows a decreasing trend, which results in a stronger mixing of cold and warm air and leads to an increase in rainfall (Figure 5a). Studies also observed that the north and south displacement of the EAWJ also has an influence on the rainfall pattern [33–35]. During the hiatus period, the EAWJ moves northward, accompanied by anomalous convergence over the middle and high latitudes and anomalous divergence over the lower latitudes in the upper level, which results in increasing upward motion in the Huang–Huai River region and downward motion in the Yangtze River region and causes the rainfall belt to shift from the Yangtze River region to the Huang–Huai River region during this period (Figure 5b).

Figure 5. Same as Figure 3, but for zonal wind at 200 hPa.
Variation in the strength and location of the EAWJ can be explained by the meridional temperature gradient in the middle to high troposphere. According to the thermal wind relationship, a weaker temperature gradient can result in weaker westerly winds in the upper troposphere. During the warming period, the temperature undergoes a significant increase at high latitudes and a significant decrease at low latitudes, resulting in a weaker temperature gradient and leading to a decrease in the strength of the EAWJ (Figure 6a). Moreover, the cooling temperature trend in the subtropics-extratropics over the continent is different from the general warming of the SSTs in the tropical Indian and western Pacific Oceans, which can reduce the meridional and zonal thermal contrasts between the continent and surrounding seas and lead to a weaker summer monsoon [22]. During the hiatus period, the maximum increasing center is located along 40°N, and there is a slight decreasing center and a slight increasing center to the north and south, indicating a stronger temperature gradient at high latitudes and a weaker temperature gradient at low latitudes. In this situation, the EAWJ moves northward during this period (Figure 6b).
4. Rainfall Pattern and Affecting Factors

a. EOF pattern

In order to study changes in the summer rainfall pattern during the warming period (1976–1997) and the hiatus period (1998–2013), empirical orthogonal function (EOF) analysis is applied to analyze the summer precipitation in southeast China, first from 1976 to 2013. The first two leading EOF modes as well as their related time series are shown in Figure 7. The EOF1 mode is characterized by a dipole pattern, with positive rainfall anomalies in South China and negative rainfall anomalies in the north. The related time series shows both the interannual and interdecadal variability of this pattern. Previous research has pointed out the phase shifts in the dipole pattern from negative to positive during 1993 are related to the weakening of the EASM. During the positive phase, the weak EASM transports less moisture northward to create precipitation [23,36].

The second leading mode (EOF2) shows a negative-positive-negative “- + -” pattern with a rainfall belt centered along the Yangtze River region and below-normal rainfall to the north and south. This pattern also shows decadal variation, with pronounced interannual variation before the late 1990s. Furthermore, the phase shifts from negative to positive during this period, which indicates an increase in summer rainfall over the Yangtze River region during this period. After the late 1990s, the variation of EOF2 is less dominant.
If we compare these two time series, it can be found that during the warming period, both the first and second EOF modes dominate, while during the hiatus period, summer rainfall shows a positive phase of EOF1 with above-normal rainfall in South China. To illustrate this more clearly, the years in which these two patterns are dominant are listed in Table 1. During the warming period, rainfall in South China and the Yangtze River region increases, as revealed by the phase change from negative to positive in both EOF1 and EOF2 during these years. During the hiatus period, the rainfall center is located mostly in South China, as revealed by the dominant positive phase of EOF1 during these years.

Table 1. Dominant positive and negative years of EOF patterns.

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<th></th>
<th>Dominant Years</th>
<th>Count</th>
</tr>
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The rainfall amount is highly affected by water vapor transport and supply, and Figure 8 shows the correlation between the integrated moisture transport and the temporal principal component of the first (PC1) and second (PC2) leading mode of summer precipitation over southeast China. The correlation with PC1 shows that associated with the positive phase of EOF1, there is strong cyclonic water vapor transport and moisture convergence over South China, which creates much precipitation in this region. This anomalous cyclonic pattern is driven by the anomalous wind field. Figure 8c shows the correlation between PC1 and 850 hPa wind and geopotential height. There is a dominant cyclonic circulation over South China, and the northeasterly wind in its west branch is associated with the weakened EASM. That is, when the EASM is weak, the moisture transported by the monsoon system cannot reach as far north, but concentrates in South China and creates more precipitation there. The negative relationship between the EASM and rainfall in South China has also been pointed out by Ding et al. [36] and Gong and Ho [37]. Colors in figure 8c present the relationships of 850 hPa geopotential height; only the correlation coefficients that passed the significant test are shown in this figure. The significant threshold is 0.271 in this case, while the correlation coefficient of the WPSH and PC1 is less than 0.15, which cannot pass the significant test, indicating that there is little relationship between the WPSH and the first EOF pattern of rainfall.
Figure 8. Correlation of water vapor transport (upper) and 850 hPa wind and geopotential height (lower) against PC1 (a) (c) and PC2 (b) (d).

The correlation with PC2 shows a dipole pattern; that is, when PC2 is positive, strong anomalous cyclonic water vapor transport is located over the Western North Pacific (WNP) and South China Sea (SCS). The western branch of this cyclone can bring large amounts of water vapor to the Yangtze River region, and the associated anticyclone is located north of the cyclone (Figure 8b). This coupling structure leads to moisture convergence over the Yangtze River region, creating more precipitation there, while anomalous moisture divergence over South China creates below-normal rainfall in this region. Moreover, south of the cyclone, a westerly moisture flow is located around 5° N–10° N; the direction of this flow is opposite that of the climatological moisture transport, indicating the weakening of water vapor transport by the South Asian summer monsoon flow. This dipole structure of water vapor transport is a result of the similar dipole structure in the 850 hPa anomalous horizontal wind field, with an anticyclone located in the WNP and SCS, and a cyclone to its north. The anomalous anticyclone is driven by the significant strengthening of the WPSH.

As mentioned in the last section, if we compare the PC values, it seems that both the EOF1 and EOF2 rainfall pattern can contribute to the rainfall anomalies during the warming period, while the EOF1 pattern is dominant during the hiatus period. To better illustrate this characteristic, EOF analysis is applied to summer rainfall during the global warming period (1976–1997) and the hiatus period (1998–2013). The reason for choosing 1997/1998 is that this is the year of climate variability...
transition, as in the phase change of PDO, and also the PC2 of water vapor transport shows strong variation before 1997 and weak variation after 1998 [38].

The distribution patterns of EOF1 and EOF2 during the warming period are similar to those of the EOFs for the whole period (1976–2013), with the rainfall belt located in South China for EOF1 and in the Yangtze River region for EOF2 (Figure 9). Both PC1 and PC2 show a phase shift from negative to positive, which indicates that the precipitation in South China and the Yangtze River region increases during the warming period. The associated water vapor transport is shown in Figure 10; similarly, the moisture convergence is a result of the anomalous cyclonic water vapor transport over South China for EOF1, and the dipole structure of the anomalous water vapor transport is responsible for the above-normal precipitation in the Yangtze River region. The related 850 hPa wind field and geopotential height show similar characteristics.

**Figure 9.** Same as Figure 7 but for the global warming period (1976–1997).
The rainfall pattern during the hiatus period is shown in Figure 11. The first EOF pattern is the dipole pattern, with positive rainfall anomalies over South China, and the related PC1 shows that the positive phase is dominant during the hiatus period. The associated moisture transport and circulation show a similar pattern compared to EOF1 of the warming period, with an anomalous cyclonic water vapor flux and wind field located over South China and providing more moisture in this region, but the cyclonic circulation is relatively weak, which is related to the slowed weakening of the EASM during this period.
The second EOF mode is characterized by a “+, −, −” pattern, with above-normal rainfall over the Yangtze River region and below-normal rainfall over South China and the Huang-Huai River region, but the strength of the negative rainfall is greater than in the warming period (Figure 11). According to PC2, this mode shifts from positive to negative, indicating that during the hiatus period, the rainfall belt shifts northward from the Yangtze River region to the Huang-Huai River region. The associated water vapor transport is very different from the mode during the warming period; unlike in the dipole mode, the weak anomalous cyclonic circulation located over the subtropical ocean plays a dominant role in providing moisture convergence over the Yangtze River region. A dominant negative phase of EOF2 indicates that during the hiatus period, there is cyclonic anomalous water vapor transport that carries more moisture to the Huang-Huai River region and leads to more precipitation there and less precipitation over the Yangtze River region. The associated anomalous wind field also shows the correlated cyclone, but the change in the WPSH is not remarkable (Figure 12).

Figure 11. Same as Figure 7.7, but for the hiatus period (1998–2013).
b. Modulation of the tropical ocean

As demonstrated in the last section, the first EOF pattern is controlled by similar anomalous cyclonic moisture transport during the warming period and the hiatus period, while the second EOF pattern of summer rainfall, which leads to the variation in rainfall over the Yangtze River region, is controlled by a strong dipole structure of water vapor transport during the warming period but a weak monopole structure of water vapor transport during the hiatus period. Focusing on the Yangtze River region, the following discussion addresses the possible factors responsible for the changes in the EOF2 pattern.

Because SSTs are the heat source for the atmosphere and play a very important role in atmospheric circulation, SST variation may be one of the factors affecting the anomalous water vapor transport. Table 2 lists the dominate positive and negative years of EOF2 during the warming and hiatus periods. The composite anomalies of SSTs are shown in Figure 13; during the warming period, the SSTs are higher in the Indian Ocean and east-central tropical Pacific, while lower SSTs appear in the Maritime Continent. Associated with SST anomalies, anomalous ascending motion appears over the east-central tropical Pacific and anomalous descending motion over the Maritime Continent, but the anomalous upward motion over the Indian Ocean is not that apparent (Figures are not shown).
Figure 13. Composite anomalies of SSTs of dominate positive and negative years of EOF2 during the warming period according to Table 2.

Table 2. Dominant positive and negative years of EOF2 during the warming and hiatus periods.

<table>
<thead>
<tr>
<th>EOF2</th>
<th>Positive</th>
<th>Negative</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hiatus Period</td>
<td>1999</td>
<td>2003 2005 2007</td>
</tr>
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Many studies have pointed out that anomalous ascending motion over the western tropical Pacific can induce anomalous descending motion to its north, in a teleconnection called the “Pacific-Japan pattern”[39,40], which can be clearly seen in Figure 13a. The anomalous meridional vertical circulation is clearer in the latitude-pressure cross section (Figure 14). An anomalous wave train persists along the meridional direction with alternative upward and downward anomalies. The two upward anomalies are located over 10° N and 35° N, and the two downward anomalies are located over 5° S and 25° N. The anomalous descending and ascending motions over the western subtropical Pacific are key contributors to the dipole mode of water vapor transport anomalies, with anomalous anticyclonic flow in the south and anomalous cyclonic flow in the north.
The warming SSTs in the east-central tropical Pacific can induce abnormal upward motion, which causes anomalous westerly winds to prevail along the tropical region in the lower atmosphere and anomalous easterly winds in the upper atmosphere, which weaken the Walker circulation (Figure 15). The winds converge in the upper level and diverge in the lower level over the Maritime Continent, maintaining the anomalous downward motion there. Accompanying the anomalous anticyclone over the Maritime Continent is an anomalous cyclone to its north, which further induces an anomalous anticyclone over the western subtropical Pacific and an anomalous cyclone over the Japan Sea.
Figure 15. Divergent components of the composite anomalies between positive and negative years of EOF2 in wind at 200 hPa (a) and 850 hPa (b) during the warming period.

The composite anomalies of omega at 500 hPa and the divergent winds at 850 hPa during the hiatus period are shown in Figure 16. There is an anomalous ascending motion over the Maritime Continent, which may contribute to the anomalous upward motion and anticyclone over the western subtropical Pacific, but compared with the structures of the warming period (Figure 13a), the Pacific–Japan pattern is not that robust. In addition, the anomalous circulation over the east-central tropical Pacific disappears, indicating that the Walker circulation may not play an important role during this period. These differences may lead to a weaker anomalous circulation and result in a weaker monopole mode of anticyclonic water vapor transport in the positive years of EOF2 during the hiatus period.
Figure 16. Composite anomalies of omega at 500 hPa (a) and divergent components of the wind at 850 hPa (b) between positive and negative years of EOF2 during the hiatus period.

The difference in SSTs during the hiatus period and warming period is shown in Figure 17. SSTs are cooler in the east-central tropical Pacific, which shows a La Niña-like pattern. As warmer SSTs in the east-central tropical Pacific are beneficial for maintaining the dipole mode of water vapor transport, the background of cooler SSTs in the hiatus period is unfavorable for this structure. Therefore, there tends to be a weaker water vapor supply and less rainfall over the YZ during the hiatus period.
Figure 17. SST anomaly between hiatus period (1998–2013) and warming period (1976–1997). The unit is °C.

5. Conclusion and Discussion

This study focuses on the variation in summer precipitation over Yangtze River region during a global warming period (1976–1997) and a hiatus period (1998–2013). During the warming period, rainfall over both the Yangtze River region and South China has an increasing trend. This increasing trend results mainly from the dominance of increasing ascending motion over this region and from variation in atmospheric circulation. The strengthened geopotential height over north China, the weakened EAWJ, and the weaker temperature gradient in the upper atmosphere, result in more precipitation over South China and the Yangtze River region. This result is consistent with the work of Ding et al. [36], who pointed out that increasing rainfall over South China and the weakening of the EASM have a negative relationship.

During the hiatus period, the rainfall belt tends to shift from the Yangtze River region to the Huang-Huai River region. During this period, the location of the EAWJ moves northward as a result of the increasing temperature gradient to its north and the decreasing temperature gradient to its south. The northward displacement of the EAWJ favors increasing ascending motion over the middle and high latitudes and increasing descending motion over the lower latitudes, leading to more precipitation over the Huang-Huai River region and below-normal precipitation in the Yangtze River region.

Results of the EOF analysis show that both a dipole and tripole mode of the summer rainfall pattern are dominant during the warming and hiatus periods. Rainfall over South China is mainly related to the first EOF mode, the phase change from negative to positive indicates more precipitation over South China during the warming period. The EOF1 pattern is controlled by an anomalous cyclonic circulation of water vapor transport associated with the weaker EASM.

However, rainfall over Yangtze River region is mostly related to the tripole mode, which shows different variations during the warming period and the hiatus period. During the warming period, the “−, +, −” rainfall pattern shifts from the negative phase to the positive phase and indicates an increasing amount of rainfall over Yangtze River region. Associated with this pattern, a strong dipole structure of water vapor transport is dominant over the western subtropical Pacific, with an anomalous anticyclone on the south side and an anomalous cyclone on the north side, and moisture transported by the anomalous circulation convergence over the Yangtze River region creates a lot of rainfall there. This structure is induced by the Pacific Japan teleconnection pattern originating from the Maritime Continent with cooler SSTs, which can create anomalous downward motion there, and
warming in the east-central tropical Pacific can contribute to this structure by reducing the Walker circulation. During the hiatus period, the rainfall pattern shifts from positive to negative, resulting in the rainfall belt shifting northward, and the associated anomalous water vapor transport is characterized by an anomalous weak anticyclone over the western subtropical Pacific. During this period, the Pacific Japan pattern is relatively weak, and the variation in SSTs in the east-central tropical Pacific does not play a role in this structure.

It should be noted that in this study, we discuss variations in the temperature gradient only in the upper atmosphere, which can contribute to changes in atmospheric circulation during the warming and hiatus periods, but the reason for these temperature changes is not discussed in this work. Studies have revealed that a reduction in snow cover may contribute to Arctic warming [41] and changes in oceanic circulation, and cloud cover can also play an important role in Arctic temperature amplification [42]. While excessive spring snow depth over southeastern Tibet may contribute to the cooling trend of temperatures over the midlatitudes, when there is excess snow cover, more solar radiation is needed to melt the snow, which cools the atmosphere [22,43]. In addition, this work discusses only the role of tropical SST anomalies that can influence water vapor transport and thus modulate rainfall variation, but why SSTs are undergoing these changes under the background of global warming and during the warming hiatus is still unclear. Nevertheless, changes in SSTs in other regions can also play an important role in summer rainfall variation, such as the Pacific Decadal Oscillation [5] and tropical Atlantic SST warming [44]. As ENSO matures in winter, it can modulate summer water vapor transport anomalies over the western subtropical Pacific in a quasi-4-year period [38]; the influence of ENSO on water vapor transport therefore needs further study.

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