Interdecadal variability of the large-scale extreme hot event frequency over the middle and lower reaches of the Yangtze River basin and its related atmospheric patterns

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\textbf{ABSTRACT}

Based on daily maximum temperature data from Chinese weather stations for the period 1960–2013, the characteristics of the interdecadal variability of large-scale extreme hot event (EHE) frequency over the middle and lower reaches of the Yangtze River basin (MLYR) are analyzed. It is found that the frequency of large-scale EHE over the MLYR experiences two significant interdecadal changes, around the early 1970s and early 2000s, having a more–less–more variability shape during the past half century. Furthermore, the EHE frequency interdecadal variability–related atmospheric circulation patterns are diagnosed. The results indicate the western Pacific subtropical high could not be the dominant atmospheric circulation associated with the interdecadal variability of the large-scale EHE frequency over the MLYR. In contrast, the dominant teleconnection pattern over the Eurasian continent, which is represented by the second empirical orthogonal function mode of the 200 hPa geopotential height, is closely related to the interdecadal variability of the EHE frequency over the MLYR. The results of this study deepen our understanding of the variability of the EHE frequency over the MLYR and its possible mechanism.

\textbf{1. Introduction}

According to IPCC AR5 (IPCC 2013), temperatures have increased globally since the early twentieth century. Climate extremes have changed significantly because of global warming. In addition, a number of studies have shown that climate extremes have a larger response to climate change than mean climate (Alexander et al. 2012; Easterling et al. 2000; Karl and Easterling 1999; Karl and Knight 1985; Katz and Brown 1992; Plummer et al. 1999). Therefore, an increasing amount of attention has been paid to extreme climate variability and its possible mechanisms.

An extreme hot event (EHE) is a type of climate extreme in China that has a serious impact on human society and the natural environment. Thus, EHEs have been emphasized in previous studies (Ren, Feng, and Yan 2010; Yin, Yin, and Zhang 2013; Zhai and Pan 2003). It has been found that EHEs in China show distinct regional characteristics. According to the long-term trend, EHEs have increased in recent decades in northern parts of China and some areas in western China (Ding, Qian, and Yan 2009; Zhai and Pan 2003), but decreased in central China (Zhai and Pan 2003). There is no significant trend of EHE frequency in the Yangtze River basin region over the period 1960–2002 (Su, Jiang, and Jin 2006). According to the decadal variability, more EHEs are observed within southern China in the 1960s and 1980s, and within central China in the 1960s and 1990s; in addition, EHEs show a significant increase over northern China mainly after the late 1990s (Sun, Wang, and Yuan 2011).
The occurrence of EHEs is closely related to various factors. For example, the anomalous geopotential height at the middle and upper levels is an important atmospheric factor that influences the occurrence of EHEs in China (Li et al. 2015; Sun, Wang, and Yuan 2011). For central and southern China, besides the geopotential height anomaly, the temperature advection at the lower level is also an important atmospheric factor influencing EHEs (Sun, Wang, and Yuan 2011). Sun (2014) pointed out that the upper-level westerly is an important atmospheric factor influencing the occurrence of EHEs in the Jianghuai region. Li, Wang, and Yan (2012) indicated that the synergistic variation of extreme high temperature and extreme precipitation in eastern China has a close relationship with the East Asian summer monsoon circulation. In addition, Sun et al. (2014) showed that the increase in EHEs in eastern China from 1955 to 2013 is also attributable to the anthropogenic emissions of greenhouse gases.

In China, the MLYR is a special region with a developed economy and high population and production. In addition, the MLYR is also a core region for EHEs in China, with higher frequency and greater variability (Sun, Wang, and Yuan 2011). Variations of EHEs have a profound impact on the MLYR region. Therefore, studying EHEs in the MLYR has important scientific significance and also provides input for disaster prevention and mitigation.

Previous studies have focused mainly on the interannual variation and case studies of EHEs over the MLYR, as well as the possible underlying mechanism (Li et al. 2015; Peng et al. 2005; Sun et al. 2014; Wang, Zhou, and Chen 2013; Wang et al. 2013; Yang and Li 2005). The western Pacific subtropical high (WPSH) is considered an important atmospheric circulation pattern for EHEs over southern China. When the WPSH enhances, anticyclonic anomalies over the Yellow Sea and the Korean Peninsula will result in more EHEs in eastern China (Ding, Qian, and Yan 2009; You et al. 2011). In a case study, Yang and Li (2005) suggested that the anomalous high temperature in South China during the summer of 2003 was mainly due to the extreme intensity and westward extension of the WPSH. Besides the WPSH, Sun (2014) has indicated that the upper-level westerly is another important factor influencing the occurrence of EHEs in the Jianghuai region. Compared to the interannual variability, the interdecadal variation and its possible mechanism for large-scale EHEs in the MLYR in recent decades is not clear. Thus, in this study, the decadal variability of large-scale EHE frequency over the MLYR is investigated, and the atmospheric pattern associated with the decadal variability of EHE frequency is then explored. The results of this study will deepen our understanding of the decadal variability of EHE frequency over the MLYR and its possible underlying mechanism.

2. Data and method
In order to investigate the variability of EHEs, we use a homogenized temperature data-set for China (Li et al. 2016), which includes homogenized daily maximum temperature series from 753 stations in China spanning from 1960 to 2013. Here, the MLYR is defined as the region covering (25°–35°N, 105°–125°E), and there are 266 stations in this region.

In order to diagnose the atmospheric circulation associated with EHE frequency variability, the monthly reanalysis data from the Japan Meteorological Agency (JRA-55) are used. The data are available with a horizontal resolution of 1.25° × 1.25°. Additionally, to explore the temperature and atmospheric circulation over a long time period, the National Oceanic and Atmospheric Administration–Cooperative Institute for Research in Environmental Sciences (NOAA–Cires) twentieth Century Reanalysis V2c data (Compo et al. 2011) and NASA Goddard Institute for Space Studies (Giss) analysis of global surface air temperature data (GISTEMP Team 2016; Hansen et al. 2010) are also used. The NOAA–Cires twentieth Century Reanalysis V2c data are available at a resolution of 2°. The Giss global surface air temperature data are available at a resolution of 2°.

According to the definition from the National Meteorological Center, an EHE is defined as a day when the daily maximum temperature is equal to or greater than 35 °C. Different from previous studies mentioned in the introduction to this paper, and in order to remove the impact from a single station or few stations, here, the large-scale EHE frequency is studied with the goal of obtaining the general variability features of EHEs over the MLYR. A large-scale EHE is defined as a day with maximum temperature equal to or greater than 35 °C over more than one third of stations in the MLYR. Figure 1(a) shows the monthly frequencies of large-scale EHEs over the MLYR. The figure suggests that MLYR large-scale EHEs mainly occur in July and August. In this study, summer is therefore defined as the mean of July and August.

3. Results
3.1. Interdecadal variability of large-scale EHE frequency over the MLYR
Figure 1(b) shows the detrended anomalous large-scale EHE frequency over the MLYR during the period 1960–2013, which depicts a more–less–more variational shape during the past half century. To investigate the interdecadal change of the large-scale EHE frequency, Figure 1(c) shows the ten-year moving t-test result for the detrended large-scale EHE frequency over the MLYR during 1960–2013. The figure suggests that the EHE frequency over the MLYR experiences two significant decadal changes.
Over the periods before the early 1970s and after the early 2000s, the EHE frequencies are above normal, and over the period between the early 1970s and the early 2000s, the EHE frequency is below normal. Mexican wavelet analysis shows a consistent result with the ten-year moving t-test (figure not shown), further confirming the two interdecadal changes of large-scale EHE over the MLYR. Therefore, based on Figure 1(c), the period of 1960–2013 is divided into three sub-periods: Period-1 (1960–72), Period-2 (1973–2000), and Period-3 (2001–13). The averaged EHE frequency over the three sub-periods are 19, 12, and 22 days, respectively. The differences in the EHE frequencies between Period-2 and Period-1 and between Period-2 and Period-3 are both within the 99% confidence level, based on the t-test. Therefore, large-scale EHEs in the MLYR have experienced a more–less–more interdecadal variation over the past half century.

Figure 1(d) shows the spatial distribution of the EHE frequency interdecadal differences between the high-frequency periods (Period-1 and Period-3) and the low-frequency period (Period-2). The figure suggests that almost all stations over the MLYR experience more EHEs over Period-1 and Period-3 compared to Period-2. In addition, most of the stations show a significant increase of EHEs. These results indicate that such interdecadal change is a general feature of large-scale EHEs over the MLYR.

3.2. Atmospheric circulations associated with the interdecadal variability of the large-scale EHE frequency over the MLYR

The WPSH is generally considered an important atmospheric circulation pattern for the EHE interannual variability over eastern China (Shi, Ding, and Cui 2009; Wang,
We investigate whether the WPSPH is the main circulation factor for the interdecadal variability of large-scale EHEs over the MLYR. The interdecadal difference in summer mean 500 hPa geopotential height between the high EHE frequency periods and the low EHE frequency period is calculated. Figure 2(a) suggests that...
there is nearly no significant signal over the WPSH region, except for a small area over the North Pacific east of 150°E. These results indicate that the variations of the WPSH and EHE frequency over the MLYR are inconsistent on an interdecadal timescale. Therefore, the WPSH cloud may not be the main atmospheric circulation factor for the interdecadal variation of large-scale EHE frequency over the MLYR.

Some previous studies have indicated that the anomalies of geopotential height at the upper level play an important role in the variability of temperatures and EHEs (Li et al. 2015; Sun, Wang, and Yuan 2008, 2011). Therefore, in order to diagnose the atmospheric factor for the EHE frequency variation over the MLYR, the interdecadal difference in summer mean 200 hPa geopotential height between the high EHE frequency periods and the low EHE frequency period is displayed in Figure 2(b). In contrast to the weak signal at the middle level, there is a significant signal at the upper level. The interdecadal difference in the upper-level geopotential height shows a zonal wave train–like pattern over the Eurasian continent. This wave train–like pattern is closely related to the circumglobal teleconnection (CGT) revealed in previous studies (Ding and Wang 2005; Lu, Oh, and Kim 2002). A significant correlation between EHEs over southeastern China and the CGT has been noted on the interannual timescale (Wang et al. 2013). Here, we find that this teleconnection pattern is highly related to the variation of large-scale EHEs over the MLYR on the interdecadal timescale.

According to Figure 2(b), a teleconnection pattern index is defined as the normalized 200 hPa geopotential height averaged over East Asia (30°–45°N, 90°–110°E) (the boxed area shown in Figure 2(b)). Figure 2(c) shows the 200 hPa geopotential height and wind regressed on the teleconnection pattern index. The figure depicts a zonal wave train–like pattern over the Eurasian continent, which is similar to the wave train–like pattern in Figure 2(b). Therefore, the teleconnection pattern index is defined reasonably, which can be used to investigate the variation of the teleconnection pattern over the Eurasian continent.

The correlation coefficient between the EHE frequency and the teleconnection pattern index is 0.46, at the 99% confidence level. If the interdecadal variation is obtained using the 15-year running mean, the correlation coefficient between the two can reach 0.92, confirming the covariation of the EHE frequency and teleconnection pattern on the interdecadal timescale.

The above analysis indicates the upper-level teleconnection pattern is closely related to the EHE frequency interdecadal variation over the MLYR. We then want to see whether or not the teleconnection pattern is a dominant mode. To answer this question, empirical orthogonal function (EOF) analysis is applied to the detrended 200 hPa geopotential height over the Eurasian continent (10°–65°N, 0°–130°E). The second EOF mode (EOF2) accounts for 14.4% of the total variance. The 200 hPa geopotential height and wind regressed on the principal component time series of EOF2 (PC2) are shown in Figure 2(d), and a zonal wave train–like pattern can also be seen over the Eurasian continent. The spatial correlation between Figures 2(c) and (d) is 0.75, at the 99% confidence level. In addition, PC2 is highly correlated with the teleconnection pattern index; the coefficient between them is 0.62 on the year-to-year timescale, at the 99% confidence level. On the interdecadal timescale, based on the 15-year running mean method, the correlation coefficient between PC2 and the teleconnection pattern index is 0.92. The correlation between PC2 and the EHE frequency is also high; the coefficient is 0.39 on the year-to-year timescale, and 0.92 on the interdecadal timescale, both at the 99% confidence level. This result indicates there is a close correlation between the Eurasian continent’s upper-level dominant atmospheric mode and the MLYR’s large-scale EHE variability on the interdecadal timescale.

To further investigate the temporal evolution of the EHE frequency, WPSH, and PC2, on the decadal timescale, Figure 3(b) depicts the three normalized 15-year running mean indices. We calculate the correlation distribution of the 500 hPa geopotential height with the MLYR EHE frequency on the year-to-year variability. The figure displays a significant signal over the MLYR region (Figure 3(a)). The result is consistent with previous studies (e.g., Peng et al. 2005), which have shown the WPSH affects EHEs over southern China via its western extension, controlling the region. Thus, here, the averaged 500 hPa geopotential height over the MLYR is defined as the WPSH index. In Figure 3(b), PC2 shows a consistent variability with the EHE frequency. If the linear trends are removed, the variations of PC2 and MLYR are more consistent. In contrast, the interdecadal variation of the WPSH is different from that of the large-scale EHE frequency over the MLYR. In particular, during the period before the early 1970s, there are more EHEs over the MLYR; however, the WPSH is weakened. The index analysis confirms the change in the upper-level dominant teleconnection pattern over the Eurasian continent is closely related to the EHE frequency interdecadal change over the MLYR, while the WPSH cannot be the major factor for the MLYR’s EHE variation on the interdecadal timescale, consistent with the result in Figure 2.

In order to further analyze the linkage of the physical processes between PC2 and the large-scale EHEs over the MLYR, the PC2-related 200 hPa zonal wind, the 200 hPa divergence, the 200–500 hPa averaged omega, and the middle and low cloud cover are regressed. Li et al. (2015) showed the upper-level westerly jet has an effect on EHEs in the Jianghuai region. The effect of the upper-level westerly is even larger than the effect of the WPSH (Sun 2014).
East Asia. Against such a background, there is an upper-level convergence over the MLYR (Figure 4(b)). Based on mass balance, the upper-level convergence can result in downward motion over the MLYR, and is consistent with the positive signal of the 200–500 hPa average omega anomalies in Figure 4(c). According to the positive-phase upper-level teleconnection, the downward motion does not benefit cloud formation, and results in less middle and low cloud cover over the MLYR (Figure 4(d)), and less cloud cover is favorable for solar radiation reaching the ground and consequently raising the temperature. These atmospheric changes are all favorable for the occurrence of EHEs over the MLYR.

4. Summary and discussion

Based on analysis of the summer large-scale EHE frequency over the MLYR during 1960–2013, it is found that the large-scale summer EHE frequency over the MLYR has significant interdecadal variability. There are more large-scale EHEs over the MLYR before the early 1970s and after the early 2000s, and fewer between the two periods.

Some studies have suggested that the WPSH is an important factor for EHEs over the MLYR on the interannual and synoptic scale (Peng et al. 2005; Shi, Ding, and Cui 2009;
Wang, Zhou, and Chen 2013; Yang and Li 2005); however, the atmospheric circulation analysis in this study indicates that the WPSH can not be the major factor responsible for the interdecadal variation of EHE frequency over the MLYR. In contrast, the dominant teleconnection pattern over the Eurasian continent at the upper level has a highly consistent variability with the EHE frequency over the MLYR. When the teleconnection is in a positive phase, it results in a weakened upper-level westerly jet over East Asia, upper-level convergence, downward motion, and less cloud cover over the MLYR. All these changes are favorable for solar radiation reaching the ground, and thus rising temperatures. Such atmospheric changes favor more EHEs over the MLYR.

The above result of a close relationship between the Eurasian continent's upper-level teleconnection and the MLYR's large-scale EHE frequency is based on an analysis of data over the past half century. The result is also confirmed by long-term data. Specifically, the teleconnection pattern index is calculated using the NOAA-CIRES twentieth Century Reanalysis data over the period 1900–2014. Because there are no century-scale daily temperature data over China, the monthly mean data are used as a proxy for the EHE variability. Here, the summer mean surface temperature (MST) index over MLYR (25°–35°N, 105°–125°E) is calculated using the GISS data. Over the period 1960–2013, the correlation coefficient on the year-to-year timescale between the MLYR's large-scale EHE frequency and the MST index is 0.75, and on the interdecadal timescale it is 0.95, both at the 99% confidence level. Therefore, it is reasonable to use the MST index to represent the large-scale EHE frequency over the MLYR. Figure 5 shows the normalized 15-year running mean of the detrended MST index and teleconnection pattern index. The figure suggests that these two indices show a consistent variability on the interdecadal timescale, with a correlation coefficient of 0.92. Although there is quantitative uncertainty in analyzing data over the first half of the twentieth century, the qualitative aspect of the result is reliable. The long-term data analysis further confirms there is a close relationship between the variability of large-scale EHE frequency over the MLYR region and the upper-level teleconnection pattern over the Eurasian continent on the interdecadal timescale.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was jointly supported by the National Natural Science Foundation of China [grant number 41421004], [grant number 41522503]; and the External Cooperation Program of the Bureau of International Co-operation, Chinese Academy of Sciences [grant number 134111KYSB20150016].

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