Decadal Features of Heavy Rainfall Events in Eastern China

CHEN Huopo[1,2,3] (陈活泼), SUN Jianqi[1,2*] (孙建奇), and FAN Ke[1] (范 可)

1 *Nansen-Zhu International Research Centre, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing* 100029

2 *Climate Change Research Center, Chinese Academy of Sciences, Beijing* 100029

3 *Graduate University of Chinese Academy of Sciences, Beijing* 100049

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ABSTRACT

Based on daily precipitation data, the spatial-temporal features of heavy rainfall events (HREs) during 1960–2009 are investigated. The results indicate that the HREs experienced strong decadal variability in the past 50 years, and the decadal features varied across regions. More HRE days are observed in the 1960s, 1980s, and 1990s over Northeast China (NEC); in the 1960s, 1970s, and 1990s over North China (NC); in the early 1960s, 1980s, and 2000s over the Huaihe River basin (HR); in the 1970s–1990s over the mid-lower reaches of the Yangtze River valley (YR); and in the 1970s and 1990s over South China (SC). These decadal changes of HRE days in eastern China are closely associated with the decadal variations of water content and stratification stability of the local atmosphere. The intensity of HREs in each sub-region is also characterized by strong decadal variability. The HRE intensity and frequency co-vary on the long-term trend, and show consistent variability over NEC, NC, and YR, but inconsistent variability over SC and HR. Further analysis of the relationships between the annual rainfall and HRE frequency as well as intensity indicates that the HRE frequency is the major contributor to the total rainfall variability in eastern China, while the HRE intensity shows only relative weak contribution.

Key words: heavy rainfall events, decadal variability, eastern China, atmosphere water content, stratification stability

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1. Introduction

More and more studies demonstrate that most of the deadly and destructive weather or climate hazards are caused by extreme events rather than the variation of mean climate (Karl and Easterling, 1999; Easterling et al., 2000). The society therefore has become more vulnerable to extreme weather and climate scenarios, such as flooding, drought, severe storm, and extreme heat or cold events (Kunkel et al., 1999; Wang et al., 2000). Given the increasing threat caused by global warming, the second assessment report (IPCC, 1995) raised a question: Has the climate become more variable or extreme? Since then, scientists and decision makers have paid more attention to extreme climate events.

Recently, a number of articles have indicated that the extreme climate events are indeed increasing at a faster rate relative to the mean climate change on the global scale (Karl and Knight, 1998; Alexander et al., 2006; Qian et al., 2007a). Since the mid 20th century, widespread increases have been observed in the frequency and intensity of extreme climate events, and the spatial extent of regions affected by these events has also been reported to increase, which is believed to be one of the consequences of global warming. On the other hand, the variability of extreme climate events shows strong regional features (Alexander et al., 2006; Sun et al., 2006). For example, the frequency of heavy rainfall events has been reported to increase in Japan,

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[*] Corresponding author: sunjq@mail.iap.ac.cn.

Australia, Europe, India, and USA (Iwashima and Yamamoto, 1993; Fowler and Hennessy, 1995), but decrease in the United Kingdom (Osborn et al., 2000). Detailed analysis on the regional variation of extreme events is therefore important for better understanding of the regional response to global warming.

Significant climate changes have been observed over China in the past half century. The Asian summer monsoon has weakened since the end of the 1970s (Wang, 2001, 2002; Han and Wang, 2007; Sun et al., 2008; Ding et al., 2009). Extreme climate events in China have also changed in connection with this weakening especially during the summer monsoon season (Wang and Zhou, 2005). Associated with these changes, the agricultural and economic losses in China are reported to have progressively increased for the last several decades, and more than 27.5% of the losses are caused by extreme precipitation events (Huang, 1999).

Due to the strong influence of extreme precipitation events, considerable efforts have been made to assess the spatial and temporal changes of extreme precipitation events over China using observed climatic records. The results show that the changes in extreme precipitation are more complicated than other extreme events in China (Zhai et al., 1999, 2005; Feng et al., 2007; Wang and Zhou, 2005; Wang et al., 2012). The occurrences of extreme precipitation events present an obvious increase in western China, the mid-lower reaches of the Yangtze River, and southeastern coastal region, but show downward trends in the regions of North China, Northeast China, and Southwest China (Yan and Yang, 2000; Zhai and Pan, 2003; Gong and Han, 2004; Bai et al., 2007; Qian et al., 2007b; Sun et al., 2007; Zhang et al., 2008; Wang and Yan, 2009). Further analysis shows that, for most regions, the intensity of light and heavy rains has increased slightly, but no significant change is found over the Yangtze River basin (Su et al., 2006; Qian et al., 2007b). These results have been well reviewed by Ren et al. (2010) and Wang et al. (2012).

Additionally, the patterns of trends in extreme precipitation events show distinct seasonal features (Wang and Zhou, 2005; Wang and Yan, 2009). For example, increasing trends are observed in the mid-lower reaches of the Yangtze River during both winter and summer, while decreasing trends occur in central and North China during both spring and autumn. Furthermore, Sun et al. (2010) investigated the spatial-temporal variability of intense snowfall events (ISEs) in China. They found four key regions of intense snowfall, i.e., eastern China, northern Xinjiang, eastern Tibetan Plateau, and northeastern China. Over the past 40 years, ISEs exhibited a decreasing trend for eastern China and an increasing trend for northern Xinjiang, eastern Tibetan Plateau, and northeastern China. Under global warming, the ISEs over southern China are projected to decrease continuously, while the ISEs over northern China would initially increase and then decrease (Sun et al., 2010).

Most of these studies focus on the investigation of the observed long-term trends in extreme precipitation events in China in order to better understand the regional response to global warming. Actually, besides the long-term trend, the extreme precipitation events in China are also characterized by decadal variability (Zhang et al., 2008; Chen et al., 2010). However, a comprehensive study about this feature in China has not been conducted so far. Further, Sun et al. (2011) revealed that the quasi-10-yr variability is one of the main decadal signals in extreme hot events in China in the past 50 years. Does this decadal signal exist in the heavy rainfall event? This needs an exploration. Therefore, this study aims to investigate the decadal characteristics of heavy rainfall events (HREs) in China in the past 50 years. Furthermore, possible mechanisms for these decadal changes are also explored.

2. Data and method

The observed daily precipitation data from 756 stations in China are obtained from the National Meteorological Information Center of the China Meteorological Administration and have been quality controlled. Although the data are available from January 1951 to December 2009, there are quite some missing data in the 1950s in most parts of China. Therefore, this study focuses on the period of 1960–2009. In this period, the stations missing more than 5% of days in the time series are further rejected. Consequently, there are 542 stations remained. Among these stations, 80 sites still have missing records and they are filled by climatological values so that all daily records are available for the period of 1960–2009.

Daily rain rates are generally classified into five grades of intensity, i.e., light rain ($\leqslant$ 10 mm day^{-1}), medium rain (10–25 mm day^{-1}), large rain (25–50 mm day^{-1}), heavy rain (50–100 mm day^{-1}), and extreme rain ($\geqslant$ 100 mm day^{-1}), in the operational prediction in China. The HREs in this study are defined as the rainfall events with daily rain rates exceeding 25 mm day^{-1}. According to this definition, there are almost no HREs that occurr over western China, thus the analysis in this study is confined to eastern China ($\geqslant$ 100°E). Additionally, the stations in eastern China with the HRE years less than 50% of the total analysis years are further removed. Finally, 433 stations are selected (Fig. 1a).

To investigate the relationship between the HRE frequency and intensity, the Kendall tau rank correlation (Kendall, 1938) is used.

Additionally, the precipitable water content, relative humidity, and air temperature at 500, 700, and 850 hPa for the period of 1960–2009 are also examined to explore the possible mechanisms of the decadal variability of HREs in eastern China. These data are obtained from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) monthly reanalysis dataset.

3. Climatological characteristics of HRE days

Figure 1a shows the spatial distribution of the annual mean HRE days for the period 1960–2009. The distribution of HRE days shows a similar spatial pattern to that of the annual mean precipitation (figure omitted), with more days in the lower reaches of the Yangtze River, South China, and some sites of the Sichuan basin, and fewer days over the north of eastern China, where the HRE occurrences for most stations are less than 5.0 day yr^{-1}.

The spatial distribution of the standard deviation of annual mean HRE days exhibits a similar feature to the HRE climatologic distribution (Fig. 1b). The large values are also located mainly over the south of eastern China, indicating strong variability of HRE days over these regions. Over most parts of northern China, the standard deviation values are relatively small, implying that the HRE variability of these regions is much weak.

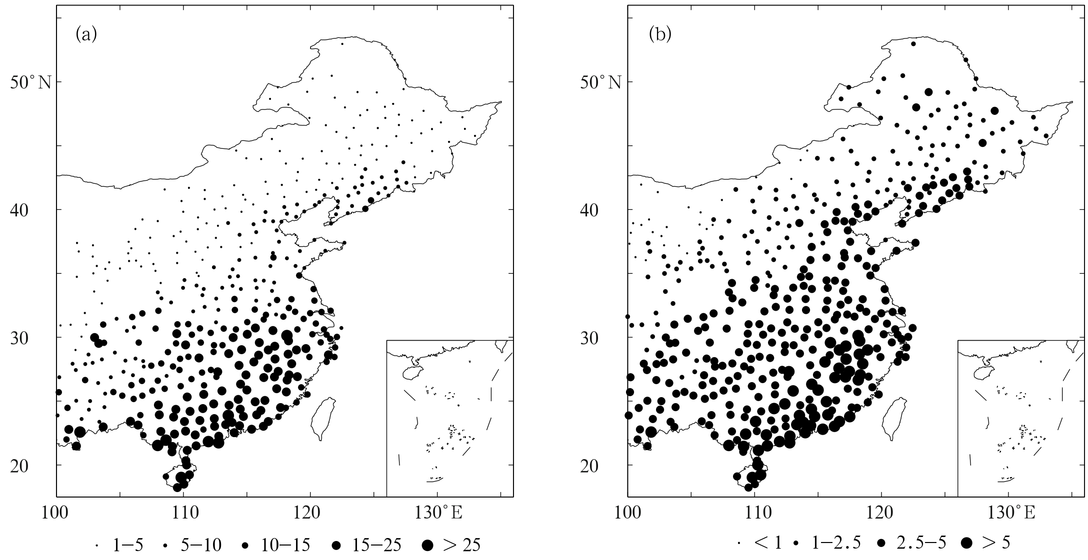

Fig. 1. Geographical distributions of (a) annual mean number of heavy rainfall days and (b) the corresponding standard deviation (day yr^{-1}) for the period 1960–2009.

4. Decadal characteristics of HRE days

Figure 2 displays the difference of HRE days between two adjacent decades for the period of 1960–2009, which is used to detect the decadal features of the HRE days in eastern China. Such decadal features have been well reflected in the extreme hot events in China (Sun et al., 2011). Obviously, significant changes of HRE days can be found over most parts of eastern China. Eastern China can be divided into five sub-regions in terms of HREs, i.e., Northeast China (NEC; ⩾40°N, ⩾120°E), North China (NC; 35°–42.5°N, 105°–120°E), the Huaihe River basin (HR; 32°–35°N, ⩾105°E), the mid-lower reaches of the Yangtze River (YR; 27°–32°N, ⩾105°E), and South China (SC; ⩽27°N, ⩾105°E). From the 1960s to 1970s, significant decreases of HRE days are observed over NEC, NC, and HR, while significant increases are over YR and SC. From the 1970s to 1980s, the HRE days in NC and SC decreased. Meanwhile, the HRE days over NEC, HR, and YR increased. The decadal change of the HRE days between the 1990s and 1980s displays an almost opposite spatial distribution against that between the 1980s and 1970s. Over the 2000s, most stations in eastern China are found with fewer HRE days than in the 1990s. The only region with increased

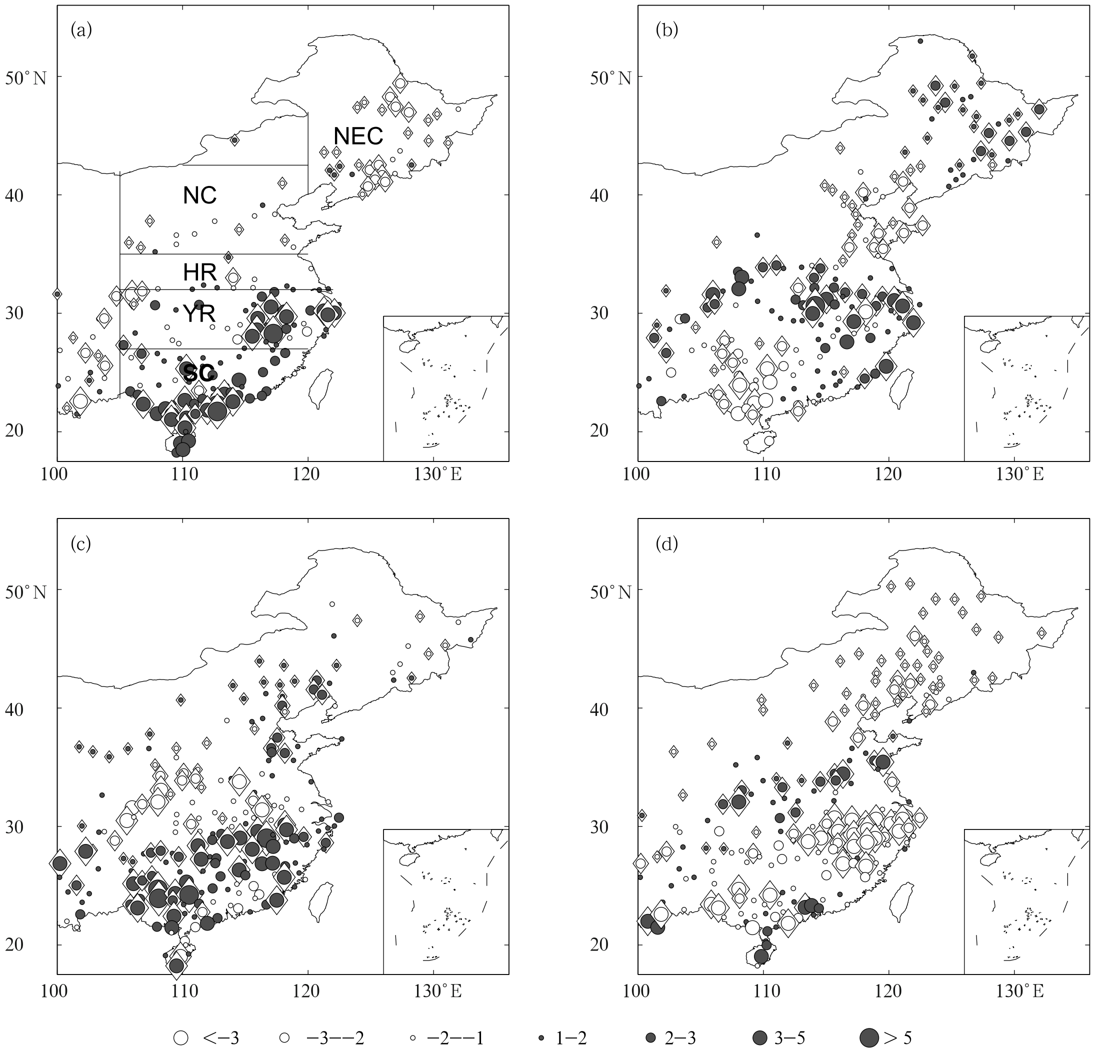

Fig. 2. Decadal changes of heavy rainfall days (day yr^{-1}) for the period 1960–2009. Mean difference between (a) the 1970s and 1960s, (b) 1980s and 1970s, (c) 1990s and 1980s, and (d) 2000s and 1990s. The symbol ◦ denotes decrease and • denotes increase, and ◊ means that the changes are significant at the 95% confidence level.

HRE days is the HR, which is closely associated with the northward shift of the rain belt in China from the end of the 1990s (Zhu et al., 2011).

The spatial distribution of the decadal HREs is highly consistent with that of the year-to-year HREs. In order to obtain the spatial distribution of the year-to-year HRE variability, rotated empirical orthogonal function (REOF) analysis is employed on the leading 20 EOFs (which explain about 66.9% of the total variance) of the normalized HRE frequency in the period of 1960–2009 in eastern China, and the first 5 leading modes of REOF (their explained variances are 8.7%, 6.7%, 4.6%, 4.4%, and 4.2%, respectively) are obtained. As shown in Fig. 3, there are 5 centers in eastern China for the HRE frequency in the past 50 years, which coincide with the 5 sub-regions.

The HRE frequency time series for the 5 sub-regions are displayed in Fig. 4. The HRE frequency for each sub-region is defined as the average of the HRE frequencies at all stations over the sub-region. We find that these five time series all show strong interannual variability that accounts for about 60% of the variance for all sub-regions. On the long term, less variance can be explained, but these indices exhibit large differences for different sub-regions. For the long-term trend, the HRE days show a decreasing trend over NEC in the past 50 years. This downward trend can also be observed over NC. The HRE days over the other three sub-regions all exhibit increasing trends. However, significant tests reveal that the long-term trends of these five time series are far from significant, indicating weak trends of HRE days in these sub-regions.

Different from the long-term trend, the 5 HRE frequency time series exhibit strong decadal variability in the past 50 years, which explains about 30% of the total variance. For NEC, high frequency of HRE is mainly concentrated in the 1960s, 1980s, and 1990s, but low frequency of HRE is in the 1970s and 2000s. More HRE days are observed over NC in the 1960s, 1970s, and 1990s, while fewer HRE days are found in the early 1980s and 2000s. The HRE days over HR

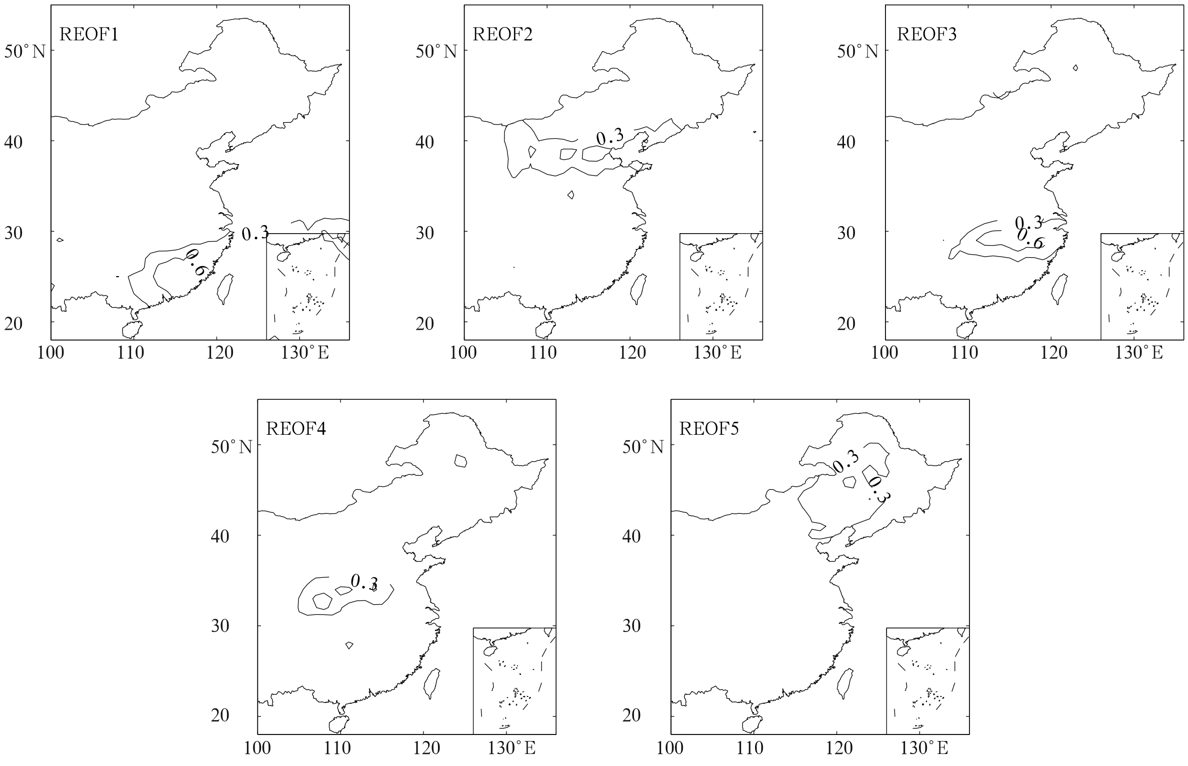

Fig. 3. The first 5 leading modes of the rotated empirical orthogonal function analysis on the leading 20 EOFs of the normalized HRE frequency in the period of 1960–2009 in eastern China.

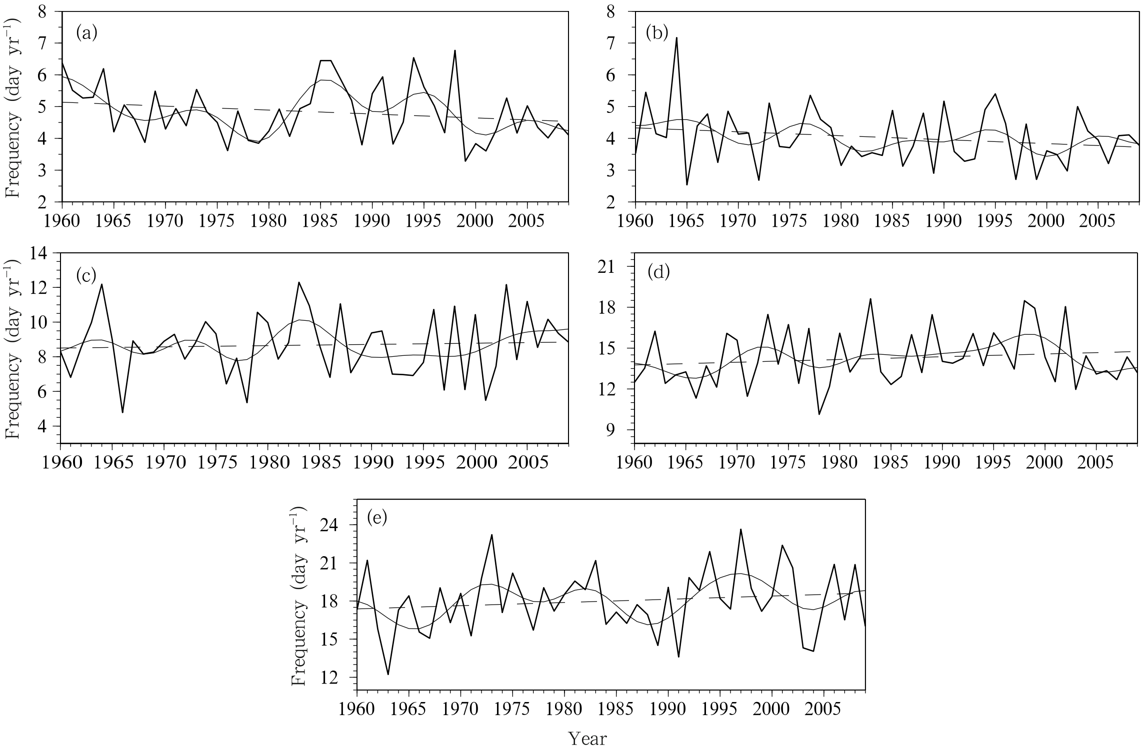

Fig. 4. HRE frequency time series (black line), their corresponding 9-yr low-pass filtered time series (gray line) and linear trends (dashed line) for (a) NEC, (b) NC, (c) HR, (d) YR, and (e) SC in the period of 1960–2009.

also show strong decadal variability, with more days in the early 1980s and 2000s, and fewer days in the 1970s and 1990s. For the YR region, the low frequency of HRE is mainly concentrated in the 1960s and 2000s, and high frequency in other periods. From Fig. 4e, it is seen that SC has more HRE days in the 1970s and 1990s, but fewer days in the 1960s, 1980s, and 2000s.

Above subjective analysis on these five sub-regions is further confirmed by the objective wavelet analysis. Since the long-term trend of the HRE in each sub-region is weak and this study mainly focuses on the HRE decadal characteristics, the linear trend for each time series has been removed prior to the wavelet analysis.

As shown in Fig. 5, the time series over the 5 sub-regions in eastern China all demonstrate that the HRE days present a significant interannual characteristic, especially for the HRE concentrated regions, i.e., SC, HR, and YR. In addition, all these five time series show significant decadal transitions. For NEC (Fig. 5a), three transition points of HRE days over the past 50 years are observed in 1966/1967, 1983/1984, and 1999/2000, respectively. All the three transitions are significant above the 95% confidence level (Table 1), indicative of three significant decadal changes of HRE days in the past 50 years. The largest decadal transition occurs around 1983/1984. The mean of HRE days in 1967–1983 is 4.5 days yr^{-1}, but it increases to 5.4 days yr^{-1} in 1984–1999. This climatic transition in the mid 1980s over NEC appears not only in HRE days, but also in other climatic variables, such as air temperature (Sun and Wang, 2006).

The decadal transition signal is much weaker in NC than in NEC (Fig. 5b). In the past 50 years, there are two decadal transitions around 1972/1973 and 1990/1991 in NC. However, only the transition in 1972/1973 is significant above the 95% confidence level.

The variability of HRE days in HR is much more complicated than in other regions (Fig. 5c). Before 1980, the HRE days are mainly characterized by variations on interannual scale, but a stable quasi-periodicity of 5–8 yr dominates after 1980. Two significant decadal transitions are observed in 1988/1989 and 2002/2003, i.e., HREs are more frequent in the 1980s and 2000s but less frequent in the 1990s. Some studies (e.g., Zhu et al., 2011) have reported strengthened ascending motion and increased air humidity in HR since 2000, which provides a beneficial background for the increase of HRE days in recent years.

The HRE days in the YR region during the past 50 years show two significant transitions in 1979/1980 and 2002/2003 (Fig. 5d). The first transition is closely connected with the weakening of East Asian summer monsoon (Wang, 2001), and the significant decrease of HRE days since 2002 can be mainly interpreted as the northward shift of the rain belt over eastern China (Zhu et al., 2011).

The strong interannual signal displays a stable 2–8-yr quasi-periodicity for SC in the past 50 years (Fig. 5e), which is different from other regions. In terms of decadal variability, four significant transitions are observed for the HRE days in SC: 1970/1971, 1983/1984, 1992/1993, and 2002/2003 (Table 1). The first two transitions can also be observed in the extreme hot events in this region and they are interpreted as the combined effect of the overlying geopotential height anomaly at the middle-to-upper levels and temperature advection by the meridional wind at the lower levels (Sun et al., 2011). Additionally, the mechanism of the transition in 1992/1993 has been well revealed by some previous studies (Ning and Qian, 2009; Wu et al., 2010). They reported that the increased HRE days after the early 1990s are closely associated with the strengthening of convection over SC, which is caused by the interdecadal changes of the latent heat flux over the South China Sea and the sensible heat flux over the Indo-China Peninsula. The last decadal transition of HRE days in 2002/2003 in SC is closely related to the northward shift of the rain belt over eastern China (Zhu et al., 2011).

Based on the above analysis, it is seen that all the 5 sub-regions over eastern China have experienced several significant decadal transitions of HRE days in

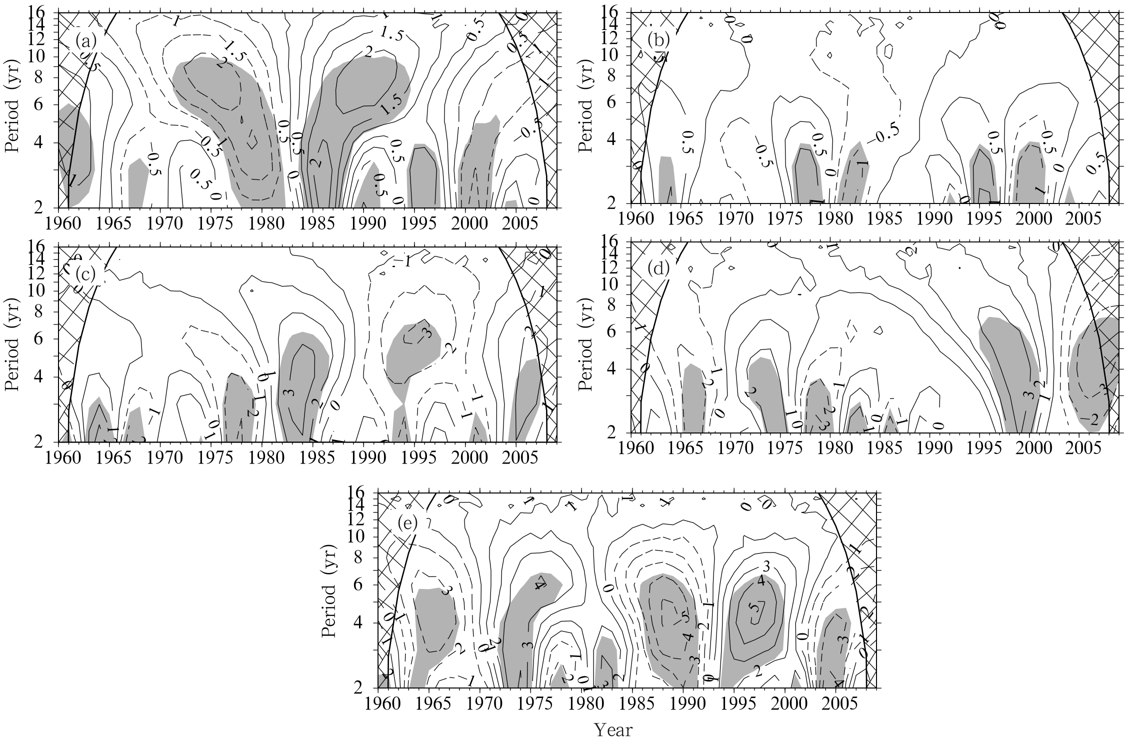

Fig. 5. The wavelet spectrum for the heavy rainfall days for each sub-region in 1960–2009 using the Mexican hat wavelet analysis (Torrence and Compo, 1998). (a) NEC, (b) NC, (c) HR, (d) YR, and (e) SC. Shadings represent regions passing the 99% significance level and the cross-hatched regions indicate the cone-of-influence.

Table 1. Decadal transition points of HRE frequency and intensity for each sub-region in eastern China during 1960–2009 based on the Mexican hat wavelet analysis

Region	Frequency	Intensity
NEC	1966/1967**, 1983/1984**, 1999/2000**	1966/1967**, 1987/1988**, 2000/2001**
NC	1972/1973**, 1990/1991*	1979/1980**, 1993/1994**, 2004/2005**
HR	1988/1989**, 2002/2003**	1984/1985*, 1994/1995**
YR	1979/1980**, 2002/2003**	1971/1972*, 1991/1992**
SC	1970/1971**, 1983/1984**, 1992/1993**, 2002/2003**	1974/1975**, 1992/1993**

** and * denote the differences between the two adjacent periods divided by the transition point are significant at the 95% and 90% confidence levels, respectively.

the past 50 years. Thus, it should be careful when investigating the regional response of HRE days to the global warming.

5. Decadal characteristics of the HRE intensity

Besides frequency, intensity is another important variable to characterize HREs. In this section, the temporal variability of HRE intensity over the five sub-regions is investigated. As shown in Fig. 6, the HRE intensity exhibits a decreasing trend in the north of eastern China (NEC and NC) and an increasing trend over the other regions (HR, YR, and SC). Such features are similar to the HRE frequency, indicating that on long term, the variability of HRE intensity is consistent with that of HRE frequency.

Over the five sub-regions, the HRE intensity also exhibits strong interannual and decadal variations as shown in Fig. 7. Comparing Fig. 7 with Fig. 5, we find that the wavelet of the HRE intensity shows some similarity in shape with that of the HRE frequency over NEC and NC on the decadal timescale. On the interannual timescale, the HRE intensity wavelet shows some similarity in shape with the frequency wavelet over NEC, NC, and YR. Over the other two regions, the wavelet shapes of the HRE frequency and intensity are significantly different. In addition, the transition

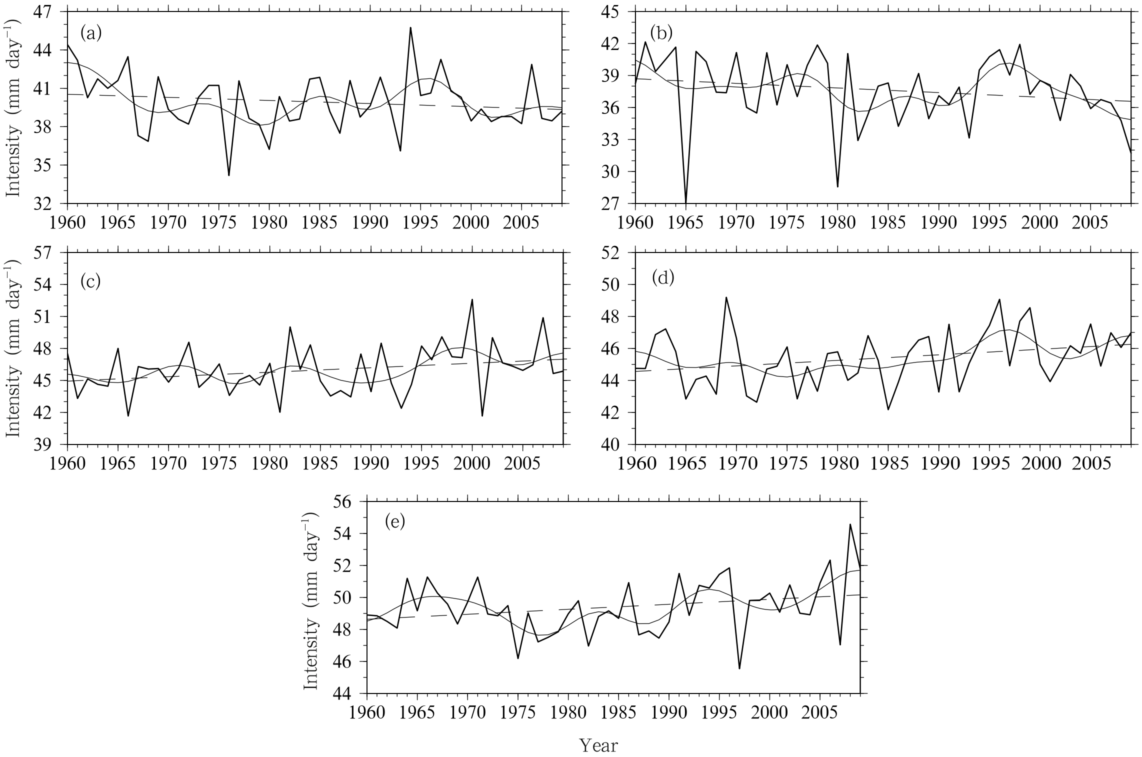

Fig. 6. As in Fig. 4, but for HRE intensity.

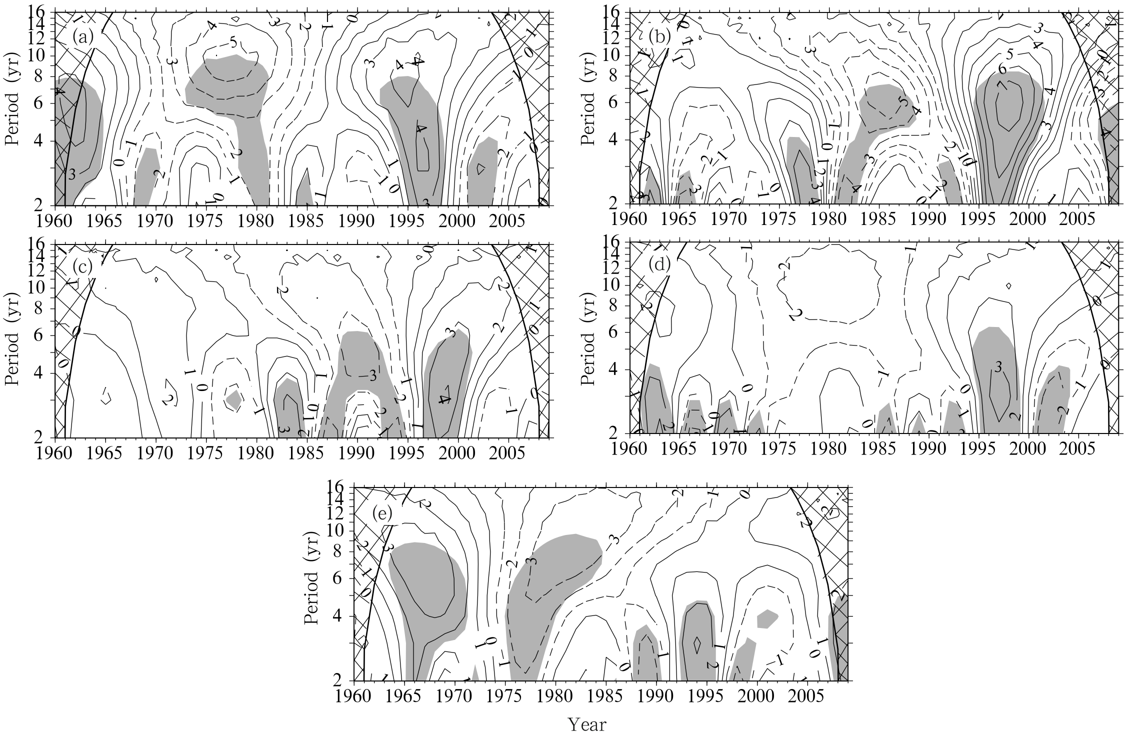

Fig. 7. As in Fig. 5, but for HRE intensity.

points of HRE intensity differ greatly with those of HRE days in these regions (Table 1). These results indicate that the HRE frequency and intensity co-vary to some extent over NEC, NC, and YR; however, over other regions, the variability of HRE frequency is independent of HRE intensity.

This deduction is further confirmed by the correlation results. For NEC, NC, and YR, the Kendall tau rank coefficients between the HRE frequency and intensity are 0.33, 0.46, and 0.30, respectively, all exceeding the 99% confidence level. However, for the regions of SC and HR, the correlation coefficients are only −0.03 and 0.18.

6. Connection between changes in HRE and annual rainfall

The variations of annual rainfall in China have been well investigated. Many studies demonstrate that a prominent interdecadal shift in rainfall pattern of eastern China happened in the late 1970s (Wang, 2001, 2002; Ding et al., 2009), with more rainfall in YR and less in NC since then. Meanwhile, in the recent years, another significant change in rainfall pattern in eastern China has occurred, with increased rainfall over HR and somewhat decreased rainfall over YR (Zhu et al., 2011). Besides, the summer rainfall over southern China also experiences a significant increase around 1992/1993 (Ding et al., 2008; Yao et al., 2008).

Our analysis indicates that the variability of HREs has a close relationship with annual rainfall in eastern China. Table 2 shows the rank correlation coefficients of annual rainfall with HRE days and intensity for the five sub-regions. It suggests that the HRE days are significantly correlated with annual rainfall in all the sub-regions, with all the coefficients larger than 0.77. As compared to the HRE frequency, the

Table 2. The Kendall tau rank correlation coefficients of annual rainfall with heavy rainfall frequency and intensity for each sub-region during 1960–2009

Region	HRE Frequency	HRE Intensity
NEC	0.77	0.32
NC	0.78	0.44
HR	0.82	0.25
YR	0.80	0.28
SC	0.88	0.02

connection between the annual rainfall and the HRE intensity is much weak, especially for SC (the correlation coefficient is only 0.02). These results imply that the change of HRE days is the major contributor to the variation of annual rainfall in all regions, but the HRE intensity shows a relatively weak contribution.

7. Discussion

The atmosphere water vapor content and stratification stability are two important divers for the occurrence of HREs (Chen et al., 2012). Thus, the investigation on these two factors is performed to further explore the possible mechanisms for the decadal variability of HREs over eastern China. Here, the atmosphere stratification stability is represented by the K index, a diagnostic factor for heavy rainfall, which shows an ability to depict the stability of atmosphere and is defined as

$$K = (T_{850} - T_{500}) + T_{\mathrm{d}850} - (T_{700} - T_{\mathrm{d}700}), \qquad (1)$$

where T is air temperature and T_{d} is dew point temperature estimated from relative humidity and the actual air temperature based on the Magnus-Tetens approximation (Lawrence, 2005). The first term on the right side of the equation represents temperature lapse rate, the second term represents the moisture condition at low level, and the third term reflects the saturation of atmosphere and the depth of moisture layer at middle level. The K index is thus an integrative indicator of atmosphere stability and the moisture condition. Large value of the K index generally favors more occurrences of HREs.

Analysis of the seasonal cycle of HREs for the 5 sub-regions indicates that, although the HREs occur from January to December, there are 61.4%–86.4% of HREs occurring from May to August (figure omitted). Thus, we will focus on this period in the following.

First, the relationships of the HRE index for each sub-region over eastern China with the precipitable water content and the K index are computed in the past 50 years. The correlations of HRE indices with precipitable water content indices averaged over NEC, NC, YR, and SC are 0.57, 0.48, 0.44, and 0.36, respectively, all significant at the 99% confidence level. The correlations with the averaged K indices in these 4 sub-regions are also significant at the 99% confidence level, with the values of 0.45, 0.39, 0.53, and 0.56, respectively. However, these relationships in the HR region are much weaker. This may be attributed to the small basin of the HR region, where there are only a few grids for the large-scale variables.

Next, the possible mechanisms for the decadal changes of HREs are investigated. Figure 8a shows the summer mean difference of the precipitable water content in the 1970s against the 1960s. It is found that the water vapor content significantly decreases in the north of eastern China (including NEC, NC, and HR), whereas significantly increases in YR and SC. Similar changes are observed with the K index (Fig. 9a), with significant decreases in NEC, NC, and HR, but increases in YR and SC. These changes are mainly responsible for the decadal changes of HREs in this period over eastern China. The decreases in water vapor content and K-index values in the north of eastern China provide unfavorable humid and dynamic conditions for the occurrence of HREs, so the HRE days are observed to significantly decrease in these regions (Fig. 2a). The increased HRE days in YR and SC are mainly attributed to the higher water vapor content and more unstable atmosphere stratification in these regions in the 1970s when compared to the 1960s. Additionally, the results of a 9-yr running T-test of the water vapor content and K index (Table 3) show that they both have experienced significant abrupt changes in NEC, NC, and SC, with the changes taking place in 1969, 1969, and 1972 for water vapor content and 1969, 1972, and 1970 for the K index, respectively. These abrupt changes in humidity and dynamic conditions can reasonably explain the abrupt transitions of HRE days in these regions (Table 1).

In the 1980s, the precipitable water content is observed to significantly increase in NEC when compared to the 1970s (Fig. 8b). Meanwhile, the atmosphere stratification in NEC becomes more unstable (Fig. 9b). The combined effect of these two factors is conducive to the occurrence of HREs in this region. Therefore, the HRE days in this region are found to significantly increase in this period relative to the

Table 3. Abrupt change years of precipitable water content and K index in NEC, NC, HR, YR, and SC regions in the past 50 years, based on the 9-yr running T-test

Regions	Water content	K index
NEC	1969**, 1983**, 2001*	1969**, 1980**, 2001**
NC	1969**, 1988**	1972**, 1990*
HR	1983**	1969**, 1983**, 1995**
YR	1975**, 2000**	2001**
SC	1972**, 2001**	1970**, 1984*, 1993*, 2001**

** and * denote the confidence level of 95% and 90%, respectively.

1970s (Fig. 2b). Furthermore, the water vapor content and K index in this period have also experienced a significant shift in 1980 and 1983, respectively. These shifts are the main contributors to the significant transition of HRE days in 1983/1984. The HRE days in HR and YR regions are also reported to increase, which is mainly attributed to the significant increase of water vapor content in this region, but not the K index as the latter shows no obvious change in this period. Over NC and SC, the water vapor content shows no obvious change and the K index shows a weak decrease. This decrease of K index over these regions is partly responsible for the reduction of HRE days in this period. This is further confirmed by the 9-yr running T-test of K index in SC. The K index has experienced a significant shift in 1984, which leads to the significant transition of HRE days in 1983/1984 in this region.

The differences of these two factors between the 1990s and 1980s (Figs. 8c and 9c) show that the K index significantly increases over eastern China, except for NEC, whereas the significant increase of water vapor content only dominates over NC. The weak changes of water vapor content and K-index values in NEC result in no obvious change of HRE days in this region. However, the HRE days in NC show a significant increase which mainly results from the combined effect of the significantly increased water vapor content

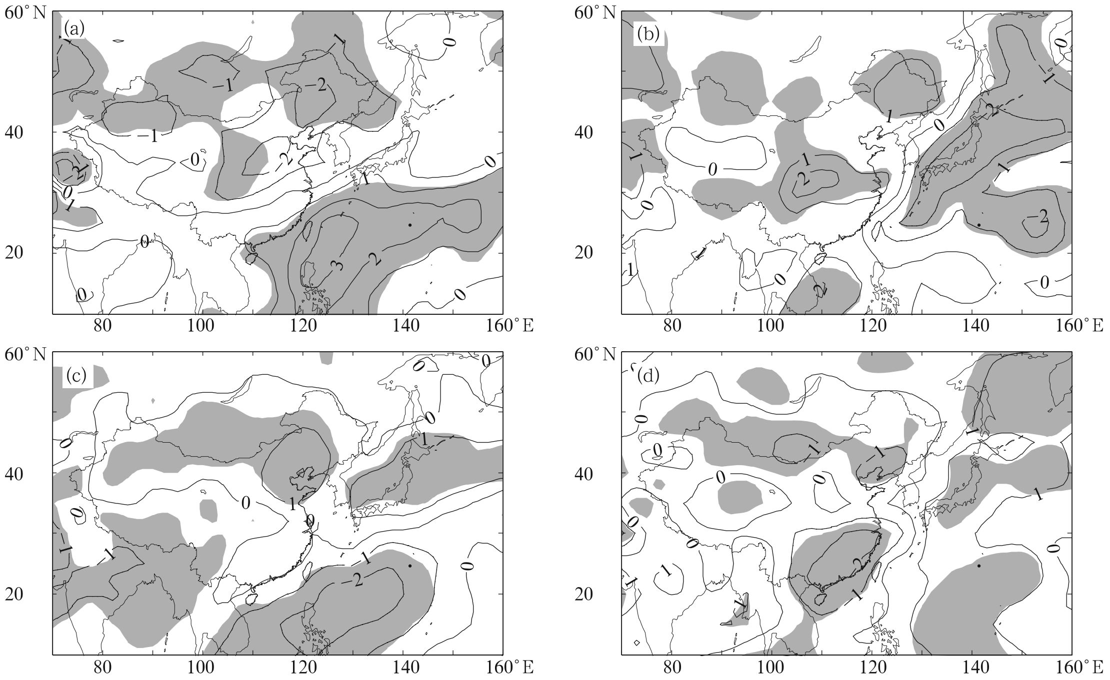

Fig. 8. Decadal changes of precipitable water content (kg m^{-2}) for the period 1960–2009. Mean difference between (a) the 1970s and 1960s, (b) 1980s and 1970s, (c) 1990s and 1980s, and (d) 2000s and 1990s. Shadings denote the changes significant at the 95% confidence level.

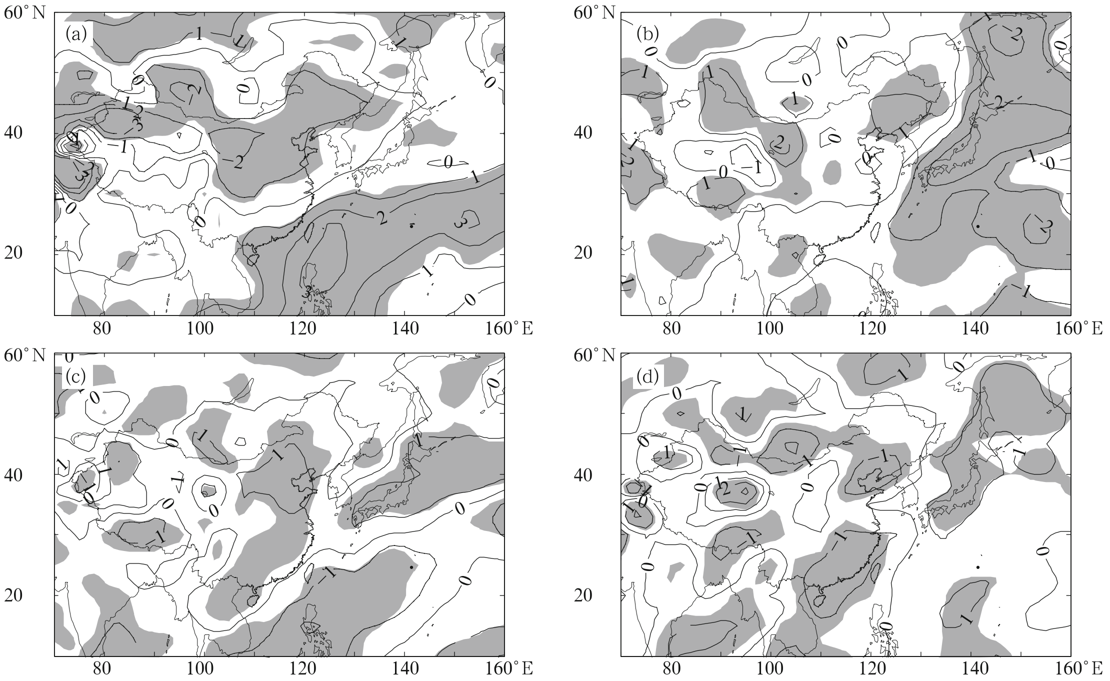

Fig. 9. As in Fig. 8, but for the *K* index (℃).

and K-index values. Additionally, the HRE days in this region have experienced a significant transition in 1990/1991, which is closely associated with the abrupt changes of water vapor content in 1988 and K index in 1990. Different from the results over the north of eastern China, the significant increases of HRE days in YR and SC are mainly attributed to the increase of K-index values in this period, while the changes of water vapor content offer no obvious contribution. Further, the K index in SC shows a significant shift in 1993 and this causes the significant transition of HRE days in 1992/1993 in this region.

In the 2000s (Figs. 8d and 9d), the precipitable water content and K index both significantly decrease over eastern China, except for the west of HR and the north of NEC, when compared with the results in the 1990s. Accordingly, the HRE days are reported to significantly decrease in these regions in the 2000s, in contrast to the HR region where the HRE days increase (Fig. 2d). Although the water vapor content and K index show no obvious change in the north of NEC, they both present a significant abrupt shift in 2001 in NEC, which is closely associated with the transition of HRE days in 1999/2000. Over the regions of YR and SC, the water vapor content is observed to experience a significant abrupt change in 2000 and 2001 respectively, and the K index in 2001. These shifts lead to the significant transition of HRE days in 2002/2003 in these two regions.

In conclusion, the variations of atmospheric water vapor content and stratification stability deeply influence the variability of HRE days on interannual and decadal scales over eastern China. In the north of eastern China (including NEC and NC), the decadal changes of HRE days are mainly attributed to the combined effect of the variations of local water vapor content and atmospheric stability. However, in the south of eastern China (including YR and SC), the atmospheric stability always plays a more important role in the decadal change of HRE days in the past 50 years, while the atmospheric water vapor content plays a less important role, with insignificant impact in the 1980s and significant impact in the other periods. Additionally, it should be pointed out that the decadal variations of HRE days in HR have not been well contributed by the local water vapor content and K index. This may result from the small area size of the HR region, which is not large enough to be resolved by the large-scale variables.

8. Conclusions

In this study, the long-term variability of the HRE frequency and intensity over eastern China is analyzed. It is found that the linear trends of the HREs are weak, while their decadal variability is significant. Based on the characteristics of the HRE interannual and decadal variations, eastern China is divided into five sub-regions, i.e., NEC, NC, HR, YR, and SC.

Over NEC, more HRE days are observed in the 1960s, 1980s, and 1990s, but fewer in the 1970s and 2000s. As compared to NEC, the decadal variability of HRE days over NC is much weaker, and there is only one significant transition in 1972/1973 in the past 50 years (1960–2009). The variability of HRE days in HR and YR regions shows almost opposite characteristics. More extreme days are observed in the early 1960s and 2000s in HR, but fewer in YR in the same periods. The decadal change of HRE days over SC is the strongest among the 5 sub-regions and there are 4 significant transitions in the past 50 years, which are 1970/1971, 1983/1984, 1992/1993, and 2002/2003, respectively. These significant decadal changes of HRE days in each sub-region imply that more attention should be paid when investigating the regional response of HREs to the global warming.

The HRE intensity also experiences significant decadal transitions in the past 50 years. On the long-term trend, the HRE intensity shows the same sign as the HRE frequency for each sub-region. However, there are obvious differences in their decadal and interannual variability. The transition points of HRE intensity totally differ from those of HRE days in each sub-region. The correlation analysis reveals that the HRE intensity and frequency co-vary over NEC, NC, and YR to some extent, but they have no connection over SC and HR, indicating the independence of HRE frequency from the HRE intensity over these regions.

Additionally, the HRE intensity has a weak correlation with annual rainfall in the north of eastern China, but no significant correlation with that in the south of eastern China, implying that there is no contribution of the HRE intensity to the variation of total rainfall over this region. However, very high correlation is observed between the variations of HRE days and annual rainfall at any timescale in eastern China, meaning that the change of the HRE days is the main contributor to the variation of annual rainfall in eastern China.

Furthermore, the possible mechanisms of the decadal variations of HRE days over eastern China are also explored. The results indicate that the atmospheric water vapor content and stratification stability are the two important factors that exert significant influences on the interannual and decadal variations of HRE days in the past 50 years. Over the NEC and NC regions, the decadal changes of HRE days mainly result from the combined effect of the changes of local atmospheric water vapor content and stratification stability. The significant transitions of HRE days in these regions have also been well connected with the significant abrupt changes in both of these two factors in the past 50 years. Different from the results in the north of eastern China, the atmospheric water vapor content and stratification stability show different performances in the decadal variations of HRE days in the regions of YR and SC. The atmospheric stability always plays an important role but the atmospheric water vapor content shows almost no influence on HRE days in 1980–1999.

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