Inter-decadal variation of the summer precipitation in East China and its association with decreasing Asian summer monsoon. Part I: Observed evidences

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ABSTRACT: In recent two decades, North and Northeast China have suffered from severe and persistent droughts while the Yangtze River basin and South China have undergone much more significant heavy rainfall/floods events. This long-term change in the summer precipitation and associated large-scale monsoon circulation features have been examined by using the new dataset of 740 surface stations for recent 54 years (1951–2004) and about 123-yr (1880–2002) records of precipitation in East China. The following new findings have been highlighted: (1) One dominating mode of the inter-decadal variability of the summer precipitation in China is the near-80-yr oscillation. Other modes of 12-yr and 30–40-yr oscillations also play an important role in affecting regional inter-decadal variability. (2) In recent 54 years, the spatial pattern of the inter-decadal variability of summer precipitation in China is mainly structured with two meridional modes: the dipole pattern and the positive-negative-positive (“+−+” pattern). In this period, a regime transition of meridional precipitation mode from “+−+” pattern to dipole pattern has been completed. In the process of southward movement of much precipitation zone, two abrupt climate changing points that occurred in 1978 and 1992, respectively, were identified. (3) Accompanying the afore-described precipitation changes, the East Asian summer monsoon have experienced significant weakening, with northward moisture transport and convergence by the East Asian summer monsoon greatly weakened, thus leading to much deficient moisture supply for precipitation in North China. (4) The significant weakening of the component of the tropical upper-level easterly jet (TEJ) has made a dominating contribution to the weakening of the Asian summer monsoon system. The cooling in the high troposphere at mid- and high latitudes and the possible warming at low latitude in the Asian region is likely to be responsible for the inter-decadal weakening of the TEJ. Copyright © 2007 Royal Meteorological Society

KEY WORDS inter-decadal variability; precipitation in China; summer monsoon; large-scale circulation; moisture transport

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1. Introduction

In recent years, numerous investigators have studied the decadal and inter-decadal variability of precipitation in China as well as in East Asia (Zhai et al., 1999; Huang et al., 1999; Chang et al., 2000; Zhou and Huang, 2003; Ding and Sun, 2003; Zhang et al., 2003; Sun and Chen, 2003; Yang and Lau, 2004; Ha et al., 2005). It has been found that the inter-decadal variability of the summer precipitation in China for the past 50 years is very significant, with two major characteristic features identified: (1) occurrence of prolonged droughts in North China and, at the same time, marked flooding conditions in the Yangtze River basin and South China in the period from the end of the 1970s to the beginning of the 21st century, and (2) the rainfall regime has undergone an obvious abrupt shift or jump in the mid- and late 1970s. This precipitation regime shift is in good coincidence with a significant abrupt climate change or jump which has been extensively observed in other regions over the world as well as for other variables.

On the other hand, several studies have indicated that the Asian summer monsoon has become weaker after the end of the 1970s (e.g. Wang, 2001). In connection with this change, the summer rainfall decreased over the lower reaches of the Yellow River and the Huaihe River (central and southern North China), while the summer precipitation has increased over the lower and middle reaches of the Yangtze River. Wu (2005) has also found that the Indian summer monsoon circulation underwent two weakening processes in the last 50 years, with the first one occurring in the mid-1960s and the second one in the late 1970s. The latter weakening process is in good agreement with the precipitation regime shift in East China as described above.

However, it is not clear yet how the weakening of the Asian (especially the East Asian) summer monsoon affects the significant southward shift of precipitation patterns in East China. Furthermore, the reason why the inter-decadal weakening of the Asian summer monsoon occurred remains an open question. Until now, several
different physical explanations have been put forward to explain this unique shift of the precipitation pattern in East China. The first one invokes the inter-annual and inter-decadal variations of the sea surface temperature in the Pacific and Indian Oceans (Ju and Slingo, 1995; Hu, 1997; Weng et al., 1999; Chang et al., 2000). Recently, Yang and Lau (2004) have indicated that both the inter-annual and inter-decadal variations of precipitation in China can be explained by the same mode of sea surface temperature (SST). They have statistically obtained that a high negative relationship between the tropical central and eastern Pacific SSTs and the northern China precipitation had been confirmed, while over central eastern China, the inter-annual variation of precipitation is positively correlated with a north-south dipole mode of SST anomalies over the western North Pacific, the tropical Indian ocean and warm pool. In the last two decades, there have been apparent increases of warm events compared to cold events and a lowering of the sea level pressure in the tropical Pacific. This change may be due to a general warming of mean SSTs or the occurrence of an in-phase relationship among the long-term trend, decadal and inter-annual variability (Weng et al., 1999). So, Yang and Lau (2004) have attributed the downward trend of summertime precipitation over northern China to the warming trend of the El Nino southern oscillation (ENSO)-like mode, and the recent frequent summer floods over central eastern China to be linked to the warming trend of SSTs over the warm pool and the Indian Ocean.

Although the influence of SSTs and ENSO events on the Asian summer monsoon and the precipitation in China has been recognized, not all the variances of precipitation can be explained by SSTs. Other external forcing factors have been sought for to explain the variability of East China precipitation. Numerous investigators have statistically studied the snow-monsoon relationship with observational snow depth data and satellite-measured snow cover (Hahn and Shukla, 1976; Shankar-Rao et al., 1996; Kripalani and Kulkarni, 1999; Liu and Yanai, 2002). Their results have consistently shown that there generally exists an inverse snow-monsoon relationship, with excessive (deficient) Eurasian winter and spring snow cover anomaly followed by weak (strong) Indian monsoon rainfall. The effect of the Eurasian snow cover on the Indian monsoon has also been investigated by a number of numerical experiments based on general circulation models (Shukla, 1987; Barnett et al., 1988, 1989; Yasunari et al., 1991; Vernekar and Zhou, 1995). Most of the modelling results have documented the above statistical snow-monsoon relationship well and have further elucidated two dominant feedback mechanisms involved in the effect of the preceding winter and spring snow on the summer monsoon circulation and rainfall: the increase of surface albedo and soil hydrological effect of melting snow, which may change the surface and atmospheric temperature and soil moisture, thus leading to variations in the large-scale land–sea thermal contrast and the following summer monsoon (Liu and Yanai, 2002). Liu and Yanai (2002) have found a significant and stable inverse relationship between the Eurasian spring snow cover and the Eurasian land surface temperature anomaly. They argue that the shrinking or deficient Eurasian spring snow cover may be related to global warming, thus leading to intensification of the heating from the Eurasian land surface and subsequent strengthening of the Asian summer monsoon by increasing the thermal contrast between land and sea. Thus, it is very apparent that the long-term decrease of Eurasian winter and spring snow cannot be used to explain the weakening of the Asian summer monsoon and there should be other significant external forces at work for causing the Asian summer monsoon to decrease in intensity.

In contrast to the decreasing trend of the Eurasian winter and spring snow cover, the winter and spring snow cover, snow depth and number of snow days over the Tibetan Plateau (TP) have had an increasing trend during the last 45 years (1956–2000) (Li, 2002), with an abrupt increase occurring in the late 1970s (Liu et al., 2003; Zhang et al., 2004; Peng et al., 2005). Correlative relationship between the TP winter and spring snow and the Asian summer monsoon circulation and rainfall have been studied by a number of investigators with observed analyses (NCC, 1998; Qian et al., 2003; Wu and Qian, 2003; Liu et al., 2003; Zhang et al., 2004) and modelling simulations (Zwiers, 1993; Qian et al., 2003; Liu et al., 2004). Modelling results have shown the similar inverse relationship between excessive (deficient) TP winter and spring snow and a decreasing (increasing) intensity of the Asian summer monsoon (the South Asian and East Asian summer monsoon) through the snow-monsoon mechanism. At the same time, they have further obtained a positive (negative) correlative relationship between the preceding winter and spring snow over TP and summer rainfalls in the Yangtze River basin (North China). This correlative relationship has been used in the seasonal prediction of the National Climate Center of China as a useful climate signal (NCC, 1998), and considerable success has been achieved, particularly for the seasonal prediction of the prolonged, excessively heavy rainfall and unprecedented flooding event in 1998 over the Yangtze River basin which was preceded by extremely excessive winter and spring snow over the TP. Although the seasonal prediction using this correlative relationship is encouraging, some key issues may emerge. They include: (1) What is observed as evidence to show the dominating mode of the inter-decadal variability to modulate the anomalous long-term variation and the regime shift of the summer precipitation in East China? (2) Is there a coherent change in large-scale circulation features in the Asian region to correspond to the above inter-decadal variability of the summer precipitation in East China, especially the weakening of the Asian summer monsoon and its subsequent effect on significant shift of summer precipitation patterns in East Asia? (3) The Asian summer monsoon is driven by the land–sea thermal contrast, with the heating effect over the TP playing an important role. Are there any
evidences to show any decreasing trend of the TP heating intensity due to increasing TP winter and spring snow? If this decreasing trend does exist, how does it cause the weakening of the Asian summer monsoon and further the summer precipitation in East China? (4) In the context of the above chain of events, is the correlative relationship between the preceding winter and spring snow over TP and subsequent summer rainfalls in China a robust one with statistical significance and physical basis? Is the regime shift of summer precipitation in East China mainly a response to weakening in large-scale monsoon circulation systems in the Asian region? This study is intended to answer these questions. On this basis, we shall give a more plausible physical explanation of the inter-decadal variation of the summer precipitation in East China in the context of the weakening Asian (or East Asian) summer monsoon. This is the first part of our paper, and will mainly address issues (1) and (2). Issues (3) and (4) will be discussed in Part II. Part I is divided into six parts. Section 1 is the introduction. Section 2 describes the datasets and computational methods used in this study. Section 3 will discuss some new aspects of observed inter-decadal variation of the summer precipitation in East China. Section 4 will describe the inter-decadal variability of East Asian summer circulation features and associated moisture transport. Section 5 will observationally discuss the inter-decadal weakening of the Asian summer monsoon. Finally, a conclusion is given in Section 6.

2. Data and computational method

The daily precipitation dataset of 740 stations in China for the period 1951–2004 was used in this study. The quality control of this dataset was made by National Meteorological Center (NMC) of China Meteorological Administration (CMA). Out of 740 stations, 568 stations have a continuous record length of 43 years (1961–2004) and 160 stations have continuous 54-year records (1951–2004). The 123-year precipitation data (1880–2002) at 35 stations in East China with monthly and seasonal resolution are available from Prof. Shaowu Wang, University of Beijing (Wang et al., 2000). 35 stations are located east of 105°E. The precipitation records of 1880–1950 were produced by blending instrumental measurements and historical documentary records of various sources. In addition, the 121-year precipitation data (1885–2004) for the Meiyu season with daily temporal resolution at the five representative stations in the middle and lower basins of the Yangtze River (Shanghai, Nanjing, Wuhu, Jujiang and Wuhan) were also used here as the longest instrumental records of high temporal resolution precipitation. This dataset was provided by the National Climate Center of China, CMA. The CPC (Climate Prediction Center) Merged Analysis of Precipitation (CMAP, Xie and Arkin) dataset for 1979–2004 was used to obtain larger-scale (Asian – West-Pacific) precipitation distributions, NCEP-NCAR Reanalysis for 1948–2003 (Kalnay et al., 1996) and ECMWF ERA-40 Reanalysis datasets (Simmons and Gibson, 2000) were used to examine changes in large-scale circulation features and the Asian summer monsoon. In particular, these two datasets were used for the calculation of the monsoon index in the Asian monsoon region, but they produced somewhat different results.

The atmospheric heating and moisture divergence fields are estimated based on the atmospheric apparent heat source \( Q_1 \) and moisture sink \( Q_2 \) that are calculated with the following expressions by using daily observations (Yanai et al., 1973)

\[
Q_1 = C_P \left( \frac{\partial T}{\partial t} + \mathbf{v} \cdot \nabla T + \left( \frac{P}{P_0} \right)^k \frac{\partial \theta}{\partial p} \right)
\]

\[
Q_2 = -L \left( \frac{\partial q}{\partial t} + \mathbf{v} \cdot \nabla q + \omega \frac{\partial q}{\partial p} \right)
\]

Vertically integrating the above expressions from surface to 100 hPa for \( Q_1 \) and to 300 hPa for \( Q_2 \), respectively, one may obtain

\[
\langle Q_1 \rangle = \frac{1}{g} \int_{100}^{P_1} Q_1 dp = LP + Q_s + \langle QR \rangle
\]

\[
\langle Q_2 \rangle = \frac{1}{g} \int_{300}^{P_2} Q_2 dp = L(P - E_s)
\]

where \( k = R/c_p \), \( P \) is the atmospheric pressure, \( \theta \) is the potential temperature, \( q \) is the specific humidity, \( P \) is the precipitation rate, \( Q_s \) and \( E_s \) are surface sensible and latent heat fluxes respectively, and \( QR \) is the radiative heating (cooling) rate. \( P_1 \) is the surface pressure and \( \langle > \) represents vertical integration.

3. The inter-decadal variation of the summer precipitation in China

The change in the summer precipitation in East China, which is greatly affected by the East Asian summer monsoon, is very significant, with great inter-annual and inter-decadal variabilities as well as regional differences observed. Figure 1 presents the 123-year time series of summer (JJA) precipitation in three sub-regions (North China: 105–122°E, 34–43°N; the Yangtze River basin: 105–122°E, 28–34°N; South China: 105–122°E, 22–28°N) of East China. For North China (Figure 1(a)), significant above-normal precipitation occurred from the 1940s to the 1970s, while below-normal precipitation was observed from the 1890s to the 1930s and the 1980s to the 1990s (see the horizontal bars). In the last 54 years, the significantly decreasing trend has occurred mainly since the late 1970s. It seems that a 60–80-year oscillation exists with shorter inter-decadal variabilities superimposed upon it (see the smoothed bold solid line and inserted diagrams). For the middle and lower basins of the Yangtze River (Figure 1(b)), 20 and 30–40-year oscillations are very evident, with peak precipitation occurring in the 1910s, 1950s and 1990s. The decreasing trend in
the period from the mid-1950s to the late 1970s was observed while the increasing trend of precipitation is very obvious since the late 1970s. This evidence shows that the change in summer precipitation in North China and the Yangtze River Basin seems to assume nearly an opposite trend. A piecewise linear fitting method was applied to the above time series in order to examine trend changing points and changing trends in different periods (Tome and Miranda, 2004). It is interesting to note that the change in an out of phase trend during the past 50 years can be derived between North China and the Yangtze River Basin (Figure not shown). The above result is very clear from Figure 1(d) which represents the time series of the Meiyu season at five representative stations along the middle and lower basins of the Yangtze River. The Meiyu season spanning normally from mid-June to early July is the highest precipitation period in summer in this region. Figure 1(d) clearly shows near-80 and 30–40-year oscillations with the rainfall peak occurring in 1910–1920 and the 1990s, respectively. In addition, a much shorter period of the inter-decadal variability (~20 years) is also seen in Figure 1(d). In South China (Figure 1(c)), the 30 and 60–80-year oscillations may be seen, with precipitation peaks found in the 1880s, 1910s, the early 1930s, mid-1970s and the late 1990s, respectively. From the late 1970s to the early 1990s, a period of much-below-normal precipitation is observed, while since then an abrupt change to a much-above-normal period may be seen, which implies the existence of the 30-year oscillation.

In order to justify the reliability of the 123-year time series of summer precipitation derived from 35 stations,
Figure 1. (Continued).
point of the late 1970s was obtained. For the 121-year record in this region, another trend changing point possibly occurred between 1905 and 1924. Overall, for the period of the last 54 years there are three trend changing points of which the changing point of the late 1970s was a common one for all three sub-regions. This fact has indicated that a major regime shift of summer precipitation in the whole of East China did occur in the late 1970s while the other regime shift of 1992 occurred mainly in South China. This sudden change in summer rainfall characteristics in the late 1970s also occurred in Korea (Ho et al., 2003). Figure 2 clearly shows the spatial patterns of this inter-decadal variability in summer precipitation before and after the two changing points which are approximately defined as the years 1978 and 1992, respectively. For the period of 1951–1978 (Figure 2(a)), the main above-normal rainfall areas were located in North China and South China, respectively, whereas the below-normal rainfall area was located in central East China, especially in the middle and lower basins of the Yangtze River, showing the ‘+− ’ meridional pattern. Starting from the late 1970s, the main above-normal rainfall zone shifted to the central East China, while in North China and South China the rainfall decreased, with an extensive area of below-normal rainfall observed in North China and southern Northeast China (Figure 2(b)), showing the ‘−+− ’ meridional pattern or the negative phase of the ‘+− ’ meridional pattern. This southward shift of the summer rainfall pattern continued until a dipole-type rainfall pattern was established in the period 1993–2004 (Figure 2(c)). This slowly-varying, inter-decadal variability may be seen more clearly in Figure 3. Before the end of the 1970s, great positive departures of anomalous precipitation were observed mainly in North China. Then they moved southward down to the region of 28–34°N (The Yangtze-Huaihe River basins) and finally moved further to South China in the 1990s. This inter-decadal shift of the seasonal rainbelt shows the southward shift of the inter-decadal component of the summer precipitation with greater than 25-year periods, because the inter-decadal variability with periods less than 25 years were basically filtered out in producing this figure. Based on Figures 2 and 3, one can obtain the fact that the southward shift of the rainfall pattern in East China started from the late 1970s, as an abrupt climate change, then experienced a transition period in 1979–1992 and, through the second abrupt climate change in 1992, finally completed the regime shift of the summer rainfall in the period 1993–2004, i.e. the change from the precipitation pattern of so-called floods in the north and droughts in the south before 1978 to the reverse precipitation pattern of droughts in the north and floods in the south after 1978. It seems that this changing process took about 40 years, which mainly reflects the contribution of oscillations with longer periods, especially the near-80-year oscillation (Table I).

As a necessary requirement of the precipitation, the distribution of mean vertical velocity (\(\omega = \frac{dp}{dt}\)) in East China also assumed a reverse change corresponding to the above change in precipitation patterns (Figure 4). During the period 1951–1978, when North China had above-normal precipitation, the upward motion dominated the region to the north of 34°N, with the maximum located in North and Northeast China, while the downward motion was found in the Yangtze River basin (Figure 4(a)). In

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<th>Sub-region</th>
<th>A Periods (Unit: year)</th>
<th>B Periods (Unit: year)</th>
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<tr>
<td>South China</td>
<td>4, 14, 30, 80</td>
<td>2, 7, 30</td>
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<tr>
<td>Middle and lower basins of the Yangtze River</td>
<td>2, 7, 20, 40</td>
<td>2, 7, 14, 40</td>
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<tr>
<td>North China</td>
<td>3, 9, 18, 40, 80</td>
<td>3, 9, 18</td>
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<tr>
<td>5 stations of the Yangtze River basin (121 years)</td>
<td>2, 7, 12, 40, 80</td>
<td>2, 7, 12, 40</td>
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Remark: \(^a\) Denotes exceedance of 95% confidence level.

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<th>Methods</th>
<th>South China</th>
<th>Middle and Lower basins of the Yangtze River</th>
<th>North China</th>
<th>5 stations of the Yangtze River basin for Meiyu season</th>
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Remark: All trend changing points in the Table II exceed 95% confidence level.
South China, there was weak upward motion. Figure 4(b) shows the condition of the transition period (1979–1992) with downward motion and upward motion basically established in North China and the Yangtze River basin, respectively. The distribution of a reverse vertical velocity was fully established during the period 1993–2004 (Figure 4(c)). One may see strong downward motion in North and Northeast China, and strong upward motion in the Yangtze River basin and South China, respectively.

In order to compare the change in the spatial patterns of summer precipitation in East China with the corresponding climatological anomaly fields, the empirical orthogonal function (EOF) analysis was applied to the spatial fields of summer precipitation in China for 54 years (1951–2004). Figure 5 shows the first and second components of EOF of summer precipitation fields in China which were derived with the inter-annual variability filtered out by using the 9-year running average. Therefore, these principal component fields mainly reflect the characteristic features of the inter-decadal variability. The first EOF component of the summer precipitation field (EOF 1) assumes the dipole pattern (Figure 5(a) and (b)). It is a dominating mode of summer precipitation in East China, which accounts for 25.4% of total variance. Its time coefficient curve shows 12–18-year oscillation. Starting from 1992, the positive time coefficient implies above-normal precipitation in the Yangtze River basins and South China which is similar...
to the observed anomalous precipitation pattern shown in Figure 2(c). This mode is closely similar to the remote effect of El Nino events on summer precipitation in East China (Chang et al., 2000; Yang and Lau, 2004), which implies that the inter-decadal and inter-annual variability assume this same precipitation mode. The second component of EOF field (EOF 2) clearly demonstrates the precipitation pattern of positive (North China) – negative (the Yangtze River and Huaihe River basins) – positive (South China) departures (Figure 5(c)) in meridional direction. The time coefficient corresponding to this ‘+ − +’ precipitation pattern (Figure 5(d)) indicates that a major regime shift occurred in the late 1970s. Before this regime shift, the anomalous precipitation pattern is characterized by the ‘+ − +’ pattern (the positive phase) whereas afterwards it is basically characterized by
‘$-+-$’ precipitation pattern (the negative phase). This change in precipitation patterns is fully consistent with observed patterns displayed in Figure 2(a) and (b). This demonstrates that the second component should also be viewed as a dominating mode in the meridional structure of the summer precipitation in China, which accounts for 19.6% of total variance. The third EOF component displays positive departure along coastal regions and negative departure in western and central China, mainly reflecting the effect of tropical cyclones coming from the Western North Pacific (Figure not shown). Although this mode is also an important anomalous precipitation pattern, it is not associated with the inter-decadal variation of the major rainfall belt this paper addresses. The above comparison has evidently shown that the observed inter-decadal shift of the meridional precipitation mode in fact demonstrates the transition from EOF 2 mode to EOF 1 mode of summer precipitation fields.
4. Inter-decadal variability of the East Asian summer circulation features and associated moisture transport

Having examined changes in the large-scale low-level and upper-level wind fields in summer in the Asian region, it has been found that the most remarkable regime shift of wind patterns occurred in the East and Southeast Asian monsoon regions (Figure not shown). Therefore, the following analysis focusses first on the inter-decadal variability of the East Asian summer monsoon. In contrast to the South Asian summer monsoon, the East Asian summer monsoon has a significant meridional component (Ding, 1994). Its variation of strength is usually characterized by the v-component variations at 850 hPa, with great southerly winds (v > 0) representing strong summer monsoon. Figure 6 depicts the long-term variation of the 850 hPa v-component in the East Asian monsoon region. During the period 1951–1978, the East Asian summer monsoon was anomalously strong, with anomalous southerlies prevailing over most of the East Asian region. This strong southerly monsoonal condition favours more frequent occurrence of monsoon rainfalls in North and Northeast China. But this condition of strong East Asian summer monsoon abruptly changed since 1978 when the anomalous northerlies developed over East Asia. The major seasonal rainfall zone in East China started to shift southward corresponding to the above weakening of the East Asian summer monsoon (cf Figure 4). In North China, the East Asian summer monsoon represented by anomalous low-level southerly wind component (v) showed a significant reverse change in wind direction since 1978, i.e. from anomalous southerlies to anomalous northerlies, indicating the fact that

the intensity of the East Asian summer monsoon greatly weakened, with much less frequent visitation of southerly wind in North China. Corresponding to this change in monsoonal airflow the major rainfall zones in East Asia were also shifted to the Yangtze River basin and South China as well as Japan islands, called the Meiuy-Baiu region. In short, the above-described inter-decadal change in low-level meridional wind clearly shows the large-scale weakening of the East Asian summer monsoon.

The change in the East Asian summer monsoon will directly affect the moisture transport and supply for precipitation. Thus the vertically integrated (surface-300 hPa) moisture transport in the East Asian region for summer was estimated. Figure 7 clearly demonstrates the inter-decadal southward shift of significant meridional moisture transport and the convergence of moisture transport ($Q_2$) (the positive $Q_2$ represents the moisture convergence here by definition of the formula (2)). Before the mid-1970s, the strong northward moisture transport could reach North and Northeast China (Figure 7(a)). Later, this northward moisture transport abruptly decreased or nearly disappeared. $Q_2$ had a similar change (Figure 7(b)). During the period 1951–1978, significant moisture convergence was observed in North China (Figure 7(b)). During the period 1978–2004, the major moisture convergence was located in latitudinal range from the Yangtze River ($30^\circ$N) to the South China Sea (SCS), while in North China there was a great deficit of moisture supply (Figure 7(b), (c)). Figure 8(a) is the first component of EOF of the vertically integrated moisture transport vector in summer. It can be seen that strong northward moisture transport coming from the tropical Indian and
West Pacific oceans dominated the whole East Asian region (see the rectangular region in Figure 8(a)). The time coefficient curve indicates the change in sign occurring in the mid-and late 1970s (Figure 8(b)). Since then, dominating spatial mode was changed into anomalous southward moisture transport. In addition, the significant decrease of the northward moisture transport in mid-1960s is also marked. This trend-changing point has been identified in North China as seen in Table II.

Significant changes in the large-scale circulation situation at mid-and high latitudes in the Eurasian continent were also observed. In the period 1951–1978, when North China had above-normal precipitation, two ridges situated over the Ural mountain region and the Okhotsk Sea, respectively, and one major trough in between (around the Baikal Lake region) predominated over the extensive region to the north of 30°N (Figure not shown). This circulation situation is typical of the large-scale circulation pattern for much precipitation in North China (Ding, 1994). The pattern of departures of 500 hPa geopotential height also clearly demonstrated this so-called ‘+-’ zonal distribution, with the extensive region of great negative height departures being found in the Asian region of 40–50°N, 60–120°E (Figure 9(a)). Under this anomalous circulation condition, the cold air accompanied by synoptic disturbances can frequently invade North China and interact with anomalously strong summer monsoon, thus bringing about a large amount of precipitation through enhancement of upward motion (Figures 1(a) and 4(a)). But this circulation condition started to change in 1978, with this abnormal low pressure centre moving eastward and the gradual merging of
two abnormal high pressure centres in the mid-and high latitude of the Asian region (Figure 9(b)). This transition or adjustment of the large-scale circulation situation had been completed in the period of 1993–2004 when a reverse circulation pattern was formed in the Eurasian continent which is characterized by the ’−−+’ zonal distribution of the anomalous 500 hPa geopotential height, with the previous negative height departures in the Asian region of 40–55°N, 60–120°E being replaced by the positive height departures (Figure 9(c)). Under this circulation condition, North China was dominated by the anomalously stable high pressure ridge, thus causing strong downward motion (Figure 1(c) and 4(c)) and less frequent activity of cold air. These conditions may suppress the occurrence of precipitation in North China. The above-described circulation pattern is fully consistent with that for droughts in North China obtained by Zhang et al. (2003).

5. Inter-decadal weakening of the Asian summer monsoon

The monsoon index (WYI) developed by Webster and Yang (1992) is normally used to characterize the intensity of the Asian summer monsoon. The WYI is defined as the vertical shear of zonal winds at 850 and 200 hPa in the region of 0–20°N, 40–110°E. These two levels are selected mainly due to their respective representation of low-level monsoonal flow and high-level tropical easterly jet (TEJ) stream, two major components of the Asian summer monsoon system. However, the maximum intensity of the TEJ is located in the layer of...
150–100 hPa (Koteswaram, 1958; Tanaka, 1982) rather than at 200 hPa. In addition, the analysis of the vertical structure of divergence and vertical velocity fields in the Asian monsoon region shows that the 850 hPa level has a stronger coupling with 150 or 100 hPa level than 200 hPa level (Chen et al., 2006). So, we have calculated the WYI with the zonal wind at 150 hPa instead of 200 hPa (the thus-defined monsoon index is termed DHI). Figure 10 shows long-term variations of the WYI and DHI based on the NCEP/NCAR reanalysis dataset. It can be found that the intensity of the Asian summer monsoon represented by the DHI has had a more significant weakening trend than that represented by the WYI. Likewise, the Mann–Kendall Rank method is applied to check abrupt change points. For the DHI, two abrupt weakening with statistical significance occurred in the mid-and late 1970s and around 1991, respectively, which are in good agreement with abrupt changes in summer precipitation patterns in China (Figure not shown). For the WYI, two sets of reanalysis datasets (NCEP/NCAR and ERA-40) have not shown above two abrupt changes in the Asian summer monsoon, only with a weak weakening trend. Figure 11 clearly demonstrates significant differences in long-term variations of high-level easterlies between 200 hPa and the mean layer of 150–100 hPa. At 200 hPa, one cannot detect any significant abrupt change, while in the mean layer of 150–100 hPa an abrupt change in the mid-and late 1970s can be easily found, with negative anomalies of easterly wind switching to positive anomalies (easterly wind weakening). Since the early 1990s, positive anomalies became more obvious, indicating the second abrupt change or further weakening. The 850 hPa zonal wind in the region of the Asian summer monsoon (0°–20°N, 40°–110°E) has also shown a decreasing trend in the last 56 years (1948–2003). But its magnitude of coefficients of decreasing trend is much smaller (−0.38) than that at 150 hPa (−0.53), with an abrupt change occurring in the early 1980s, slightly later than the abrupt change in the layer of 150–100 hPa. Therefore, the main contribution to the abrupt weakening of the Asian summer monsoon around 1978 has come from the upper level wind field of the TEJ. From the above discussions, it can be concluded that the DHI not only indicates a more significant weakening trend of the Asian summer monsoon, but also can more clearly exhibit two abrupt changes than the WYI.

Recently, Wang and Ding (2006) have reported an overall weakening of the global land monsoon precipitation in the last 56 years (1948–2003), primarily due to the weakening of the summer monsoon precipitation in the Northern Hemisphere, which is quite consistent with the result shown in Figure 10.

Next, one naturally asks why the upper level easterlies of the TEJ have assumed the more significant interdecadal variability in the Asian summer monsoon system. Our analysis has revealed that changes in upper-level temperature fields in the Asian region play a key role. From Figure 12, it can be clearly seen that the thickness anomaly field between 100 and 500 hPa that represents the mean temperature field in the upper half of the troposphere also showed a reverse change, from significant anomalous warming over the Asian region in 1951–1978 (Figure 12(a)) to significant anomalous
cooling in 1992–2004 with the maximum located in North China (Figure 12(c)). The cause of the large-scale cooling in the high troposphere in the Asian region is not clear yet. The cooling of the atmosphere over the TP and its neighbourhood appears to play an important role (Figure 4 of Part II). Yu et al. (2004) also found the significant cooling in late spring in the high troposphere in the mid-and high latitudes of East Asia. In contrast, in the low latitudes, cooling is not evident; there might even be slight warming. Recently, Chen et al. (2002) observed strengthening of tropical general circulation and convection in the 1990s. As a result, the meridional temperature gradient in the high troposphere in the Asian monsoon region was reverse from the period 1951–1978.
to the period of 1993–2004. This inter-decadal reverse variation of the large-scale meridional temperature gradient in the high troposphere in the Asian region may explain the weakening of the tropical high-level easterly wind as displayed in Figure 11, because the anomalous westerly wind will enhance in the upper troposphere since 1992, based on the thermal wind relationship (Ding, 2007).

Finally, the correlative relationship between the Asian summer monsoon and the summer precipitation in China are examined from the statistical perspective. This relationship may be discussed separately for the Indian (South Asian) monsoon and the East Asian monsoon, with the latter usually represented by the SCS monsoon (including the central and southern parts of Indo-China Peninsula) (Lau et al., 2001). Figure 13(a) shows a significant positive correlation between the Indian summer monsoon characterized by the DHI monsoon index and rainfalls in North China from June–August. This result has been previously pointed out by Guo and Wang (1988), Kripalani and Kulkarni (2001) and recently Ding and Wang (2005). Our study has well documented their conclusions with much reasonable correlative patterns. Ding and Wang (2005) have explained this correlative relationship with a teleconnection mode excited by a large amount of summer monsoon precipitation in northern and northwestern part of the Indian subcontinent. When the Indian summer monsoon has weakened, so has the Indian precipitation in general, and the rainfall in North China should also decrease through the above teleconnection mode. This can be a possible cause for the observed decrease in the summer precipitation in North China.

On the contrary, in the Yangtze River basin and most of South China, there was a negative correlative relationship between the summer rainfall in these regions and the Indian summer monsoon. When the latter weakens, the precipitation in the Yangtze River basin and most of South China will increase. This implies that the increase in rainfalls in the Yangtze River basin and most of South China since the late 1970s was likely related to the significantly weakened Indian summer monsoon. If the WY1 monsoon index is used to represent the Indian summer monsoon, a similar, but slightly weaker, correlation pattern can be also obtained (Figure not shown).

The correlative relationship between the East Asian summer monsoon (or the SCS summer monsoon) and the summer precipitation in China shows two major features (Figure 13(b)): (1) significant negative correlation in the middle and lower basins of the Yangtze River and South China. This result indicates that during conditions of strong East Asian or SCS summer monsoon, less precipitation occurs in the Yangtze River basin and South China. For conditions of weak East Asian or SCS summer monsoon, the Yangtze River basin and South China will have much precipitation. (2) For North China, one may see weak positive correlation, indicating that much precipitation can be expected for conditions of strong East Asian or SCS summer monsoon and vice versa. The South China Sea monsoon experiment (SCSMEX) carried out in 1998 has also revealed a similar relationship between the SCS summer monsoon and the summer precipitation in China (Lau et al., 2001; Ding et al., 2004), with weak SCS monsoon corresponding to unusually abundant precipitation in the Yangtze River basin. The 1998 prolonged, excessively heavy rainfall event in the Yangtze River basin did occur under the weak SCS summer monsoon in which case the leading front of the East Asian or SCS summer monsoon can only reach the Yangtze River basin and frequently interacts with weather disturbances coming from mid-and high latitudes over there, while North China experienced deficient precipitation condition due to the failure of monsoon moisture transport to reach there. Based on the above discussions, it may be assumed that both the weakened Indian summer monsoon and East Asian summer monsoon possibly led to the southward shift of the major seasonal rain belt, causing the decrease in summer precipitation in North China, and the increase in the Yangtze River basin and most of South China during the last two decades.

6. Concluding remarks

On the basis of 54 and 123-year datasets in China, a study of the inter-decadal variability of the summer precipitation in East China was undertaken, with a special emphasis on the role of the Asian summer monsoon and its inter-decadal variation. The following conclusions have been drawn:

1. The dominating mode of the inter-decadal variability of the summer precipitation in China is the near-80-yr oscillation. Other modes of 12-yr, 20-yr and
30-40-yr oscillations also play an important role in modulating the regional inter-decadal variability. The spatial patterns of the inter-decadal variability are mainly demonstrated with the first and second EOF component, i.e. the meridional structure of positive-negative-positive (+ − +) pattern and the dipole pattern. In the last 54 years, the inter-decadal variability of the summer precipitation in East China is characterized by much precipitation in North and Northeast China during 1951–1978, rapid southward shift to the Yangtze River basin during 1978–1992 and further extension to South China during 1993–2004. In this process of the southward movement of the much-precipitation belt, there were two major regime shifts which occurred in 1978 and 1992, respectively. At the same time, the ‘+ − +’ meridional precipitation pattern in 1951–1978 has changed into the dipole pattern in 1993–2004. This transition took about 40 years, equivalent to a half period of a near-80-year oscillation.

2. Accompanying this inter-decadal variability of the summer precipitation in China, large-scale circulation features in the East Asian monsoon region experienced similar variations, including the change from anomalously strong summer monsoon flow in 1951–1978 to anomalously weak monsoon flow since 1978, the significant weakening of northward moisture transport and convergence by the East Asian summer monsoon since 1978, the southward shift of prevailing upward motion zone from North and Northeast China to the Yangtze River basin and South China, and the change from the warming centre in the high troposphere in the Asian region before 1978 to the cooling centre after 1978. On the other hand, the
anomalously strong low pressure trough prevailing before 1978 was replaced by anomalously strong high pressure in mid- and high latitudes in the Asian region after 1978, accompanied by significant intensification and westward extension of the West-Pacific subtropical high. These changes in large-scale circulation and thermodynamic and moisture fields in the Asian region were quite consistent with each other, reflecting the fact that the inter-decadal variability of the summer precipitation in China is not only a regional phenomenon, but also the consequence of significant changes in the Asian or East Asian climate system.

3. In the context of these changes in large-scale circulation patterns as well as thermodynamic and moisture conditions in the East Asian region, precipitation conditions also assumed fundamental changes in both North China and the Yangtze River basin – South China. In North China, deficient moisture supply and prevailing downward motion and prevailing anticyclonic circulation of high pressure are unfavourable for the occurrence of precipitation events, thus causing a decrease in summer precipitation and prolonged droughts since 1978. In contrast, strong upward motion and a large amount of moisture transport and convergence are favourable for the occurrence of precipitation in the Yangtze River basin and South China.

4. The weakening of the Asian summer monsoon, which is likely to be associated with cooling at mid- and high

Figure 9. Anomalous 500 hPa geopotential height fields in summer, averaged for 1951–1978 (a), for 1979–1992 (b) and for 1993–2004 (c). The positive and negative height anomaly is indicated with solid and dashed lines, respectively. Height anomalies were obtained relative to the climatological mean of 1971–2000. Plus and minus symbols denote centres of positive and negative height anomaly. Unit: gpm.
Figure 10. Time series of anomalous summer monsoon indices for WYI estimated by using NCEP Reanalysis dataset (a); and DHI estimated by using NCEP Reanalysis dataset (b). WYI = U850–U200. DHI = U850–U150 (see the text). Bold straight lines denote the linear regression trend. The non-smoothed curves are obtained with the 6-order polynomial fitting. Unit: m/s.
latitudes and warming at low latitudes in the Asian regions, especially the weakening of the East Asian summer monsoon, is a central problem to explain the inter-decadal variability of the summer precipitation in China. All the evidence presented in this paper indicates significant weakening of low-level monsoonal airflow and associated northward moisture transport since 1978, thus producing the greatly insufficient moisture supply and less frequent interaction with cold air coming from mid-and high latitudes in North China. On the contrary, weakened monsoonal airflow often visited or was stationary in the Yangtze River basin and South China. Thus, they can bring abundant moisture and rain-producing disturbances favourable...
for precipitation in these regions. Recently, numerous investigators have indicated a significant increase in total precipitation amount, and intensity and frequency of heavy rainfall events in these regions in the 1980s and 1990s (e.g. Zhai et al., 2005). Observations have also shown that flooding events have more frequently occurred since 1990, including prolonged heavy rainfall events in the flooding seasons of 1991, 1993, 1994, 1998, 1999 and 2003 in the Yangtze River Basin, and of 2005 and 2006 in South China.

Finally, it should be pointed out that these results have been obtained based on 54 and 123-year long datasets, with the former having a better coverage and observation accuracy. But, for the study of multi-decadal variability, they seem to have relatively short duration of records. In fact, the 54-year time period can only reflect a part of the inter-decadal variability with a longer period (e.g. near-80-year oscillation). The 123-year dataset is only used for East China, with a relatively poor geographical coverage. Efforts have been made to extend the length and area of instrumental observation records of precipitation back to the late 19th century (1880), including the western part of China, when China measured precipitation with rain gauges (Qin, 2005). But the quantity and quality of instrumental records of precipitation rapidly declined before 1951. The precipitation records for 1880–1899 and 1900–1950 only account for 22.6 and 69.0% of those
for the period of 1951–1998, respectively, with much lower reliability of measurements. Therefore, the unavailability of long precipitation records restricts the analysis of the full spectrum of the inter-decadal variability of summer precipitation for the whole of China. Wang et al. (1981) reconstructed the summer rainfall record for the last 500 years in China by merging various proxy and instrumental data, especially including historical documentary records. They also found that the 80-year period was a dominating one even for such a long period. In addition, they identified other inter-decadal modes of 100, 35, 33, and 11 years. These periods are very similar to those found in our study. Recently Wang et al. (2005) have further pointed out that precipitation variability between North China and the Yangtze River basin often had an opposite phase, e.g. while North China had more precipitation, the Yangtze River basin had less precipitation and vice versa. For example, for several decades after 1900 and in the 1980s, the precipitation of the Yangtze River basin was much above-normal while North China suffered from prolonged droughts. These results are very consistent with the analysis presented here. Therefore, it is possible that in the period from 1951 to 1978, the precipitation in North China was in the declining phase of the period of much precipitation, and since 1978, it rapidly shifted to the phase of less precipitation with the 1990s reaching the minimum. The reverse case was true for the Yangtze River basin. Recently, the studies made by Gong and Ho (2003) and Zhao et al. (2005) provide remarkable evidence to lend further support to the existence of the near 80-year period of the summer precipitation in China, based on the analysis of the index of the East Asian summer monsoon for 1873–2000. From their studies, it can be seen that from 1910 to 1970 there existed a phase of stronger East Asian summer monsoon intensity, with the 1930s and 1940s having maximum intensity. This phase more or less corresponded to the period of much precipitation in North China and less precipitation in the Yangtze River basin. Since the early 1970s, the index of the East Asian summer monsoon has turned into the phase of weaker monsoon intensity, with decreasing precipitation in North China observed. Before 1910, the decreasing or very low monsoon index is also evident. Therefore, the inter-decadal variability of near 80-year oscillation very likely exists based on various data sources. If this conclusion is correct, the natural forcing (including internal variability) could be a primary factor to modulate this quasi-80-year variability of precipitation. In Part II of this paper, the possible causes along this line will be discussed in detail.

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References

Figure 13. Correlative relationship of the Asian summer monsoon and precipitation in China: (a) simultaneous correlation between South Asian monsoon index (DHI) (0–20°N, 40–105°E) and East Asian rainfall from June–August. Shaded regions represent exceedance of the confidence level of 95%, and (b) same as (a), but for SCS monsoon index (105–120°E, 5–20°N). Shaded areas are regions greater than 95% confidence level.

OBSERVED INTER-DECADAL VARIATION OF THE SUMMER PRECIPITATION IN CHINA


