Potential Impacts of the Arctic on Interannual and Interdecadal Summer Precipitation over China

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ABSTRACT
After the end of the 1970s, there has been a tendency for enhanced summer precipitation over south China and the Yangtze River valley and drought over north China and northeastern China. Coincidently, Arctic ice concentration has decreased since the late 1970s, with a larger reduction in summer than spring. However, the Arctic warming is more significant in spring than summer, suggesting that spring Arctic conditions could be more important in their remote impacts. This study investigates the potential impacts of the Arctic on summer precipitation in China. The leading spatial patterns and time coefficients of the unfiltered, interannual, and interdecadal precipitation (1960–2008) modes were analyzed and compared using empirical orthogonal function (EOF) analysis, which shows that the first three EOFs can capture the principal precipitation patterns (northern, central, and southern patterns) over eastern China. Regression of the Arctic spring and summer temperature onto the time coefficients of the leading interannual and interdecadal precipitation modes shows that interdecadal summer precipitation in China is related to the Arctic spring warming but that the relationship with Arctic summer temperature is weak. Moreover, no notable relationships were found between the first three modes of interannual precipitation and Arctic spring or summer temperatures. Finally, correlations between summer precipitation and the Arctic Oscillation (AO) index from January to August were investigated, which indicate that summer precipitation in China correlates with AO only to some extent. Overall, this study suggests important relationships between the Arctic spring temperature and summer precipitation over China at the interdecadal time scale.

1. Introduction
After the abrupt climate shift near the end of the 1970s (Hu 1997; Weng et al. 1999; Chen and Wu 2000; Wang 2001; Zhang et al. 2004; Ho et al. 2005), precipitation over eastern China went through a significant adjustment. While north and northeast China have suffered from severe and persistent droughts, the Yangtze River valley and south China have experienced more heavy rainfall and floods events (Weng et al. 1999; Lau and Weng 2001; Hu et al. 2003; Yang and Lau 2004; Ding et al. 2007; Zhou et al. 2009a). These changes were related to reduced northward moisture transport and convergence as the East Asian summer monsoon weakened.

The change of precipitation pattern over eastern China has been explained using relationship between sea surface temperature (SST) (e.g., ENSO) and the East Asian summer monsoon (Yang and Lau 1998; Weng et al. 1999; Chang et al. 2000a,b; R.-G. Wu and B. Wang 2002; Wang et al. 2003b; Yang and Lau 2004; Zhou et al. 2011). The influence of ENSO on the East Asia summer monsoon is different at different stages of the ENSO cycle. While the first mode of interannual precipitation associated with the Asian–Australian monsoon generally coincides with the onset of El Niño, the second mode of interannual precipitation is a response to La Niña forcing at its decaying stage, which were verified using 11 atmospheric general circulation models (AGCMs) by Zhou et al.
(2009b). ENSO also plays a major role in the summers following the mature phases of El Niño events (Zhang et al. 1999; Gong and Wang 1999; Lu 2005). For example, the severe flood over the Yangtze River valley in 1998 is associated with the biennial tendency of basin-scale SST during the transition from El Niño to La Niña in 1997–98 (Lau and Weng 2001). Besides its impacts at interannual time scale, Yang and Lau (2004) found that the upward trend of springtime precipitation over southeastern China and downward trend of summertime precipitation over northern China are attributable to the warming trend of the ENSO-like mode. Also, the recent frequent summer floods over central-eastern China have been linked to the warming trend of SSTs over the warm pool and Indian Ocean (Hu et al. 2003; Chen et al. 2006; B. Wu et al. 2009). The interannual variability of East Asian–Southeast Asian summer monsoon is also strongly tied to the sea surface temperature anomaly (SSTA) in the Sea of Japan, the East China Sea, and the South China Sea (Lau et al. 2000). However, using the Southern Oscillation index as a predictor of the monsoon, Webster and Yang (1992) noted that, although the simultaneous correlation between the Southern Oscillation index and the monsoon is high, limited correlations were found over the South Asian region in summer. Moreover, Wang et al. (2003b) suggested that the warm SSTA in the Indian and western Pacific Oceans are a result of the anomalous monsoons to a large extent. Thus, the atmosphere–warm ocean interaction may significantly modify the impacts of remote El Niño forcing and should be regarded as one of the physical factors that determine the variation of the Asian–Australian monsoon.

The interdecadal relationship between ENSO, the North Pacific mode, the Indian Ocean, and the tropical and South Atlantic Ocean and the summer climate anomalies in China have been studied using observations, reanalysis, and models (Hu 1997; Weng et al. 1999; Chen and Wu 2000; Chang et al. 2000a,b; Lau et al. 2000; Wang 2001; Gong and Ho 2002; Yang and Lau 2004; Zhang et al. 2004; Ho et al. 2005; Chen et al. 2006; Zhu et al. 2007; Wang et al. 2008; Zhou et al. 2011). Rainfall in south China and the Yangtze River valley may be influenced by the decadal or long-term SST variability. Additionally, the observed prolonged drought over northern China and increasing flooding over the Yangtze River valley since the 1950s may be associated with a long-term warming trend in the tropical Indian Ocean and western Pacific Ocean (Lau and Weng 2001). Wang and Ding (2006) found an overall weakening of global land precipitation over the last 56 yr, primarily due to the weakening of summer monsoon in the Northern Hemisphere, in particular the African and Asian monsoon (Zhou et al. 2008b). Based on a set of AGCM simulations forced by historical SSTs, Zhou et al. (2008a) suggest that the decreasing tendency of global land monsoon rainfall was mainly caused by the warming trend over the central–eastern Pacific and the western tropical Indian Ocean. The western Pacific subtropical high is closely related to the Asian climate. Previous examination of changes in the subtropical high found a westward extension since the late 1970s, which has contributed to the interdecadal transition of East Asian climate. Zhou et al. (2009c) suggest that the change of the subtropical high is partly due to atmospheric response to the observed Indian Ocean–western Pacific warming. Using a suite of numerical experiments, Wu et al. (2010) revealed that the anomalous anticyclone over the western North Pacific is maintained by the combined effects of the local forcing of the negative SSTA in the western North Pacific and the remote forcing from the Indian Ocean basin mode. Li et al. (2010) analyzed ensemble simulations of two AGCMs forced by observed SSTs. The results demonstrated that the recent warming of tropical oceans has played a significant role in the weakening of summer monsoon circulation over East Asia during recent decades.

The increases of Tibetan Plateau snow cover and snow depth have also been shown by diagnostic studies and numerical simulations to delay the onset and weaken the intensity of the summer monsoon over East Asia (Chen and Wu 2000; Qian et al. 2003; Wu and Qian 2003; Zhang et al. 2004; Zhao et al. 2007; Liu and Wang 2011). The close association between summer rainfall in eastern China and winter snow cover over the Tibetan Plateau is apparent not only at interannual but also at interdecadal time scales (Chen and Wu 2000). The spring/summer atmospheric heating over the Tibetan Plateau has significantly weakened since the late 1970s. This weakening due to the increased snowmelt can reduce the land–sea thermal contrast over the Asian monsoon region, leading to weakening of the Asian summer monsoon (Ding et al. 2007, 2009). As the northward moisture transport in East Asia is weakened, north China receives less precipitation and more moisture converges over the Yangtze River valley and south China, causing increases in flood events (Ding et al. 2009). Corresponding to the increase of snow cover depth, there is a significant decrease of the June 500-hPa geopotential height from the Tibetan Plateau to the western North Pacific. Meanwhile, the anomalous northeasterlies extending from Japan through the east coast of China to central-eastern China also weaken the East Asian summer monsoon, leading to a decrease of surface air temperature and rainfall in the Yangtze and Huai Rivers and an increase of rainfall in southeastern China (Zhao et al. 2007).
More recently, the relationships between the Asian summer monsoon anomalies and the Arctic have become active research topics. However, our understanding of the causes and effects of the anomalies is far from complete. A few papers have investigated the influence of the Arctic ice concentration (B.-Y. Wu et al. 2009a,b) and the Arctic Oscillation (AO) on the East Asian summer monsoon (Gong and Ho 2003; Gong et al. 2011) or winter monsoon (Gong et al. 2001; B.-Y. Wu and J. Wang 2002; Chen and Kang 2006). Spring sea ice concentration and Chinese summer rainfall exhibit a coherent interannual variability, and both went through two apparent interdecadal transitions that occurred in the late 1970s and early 1990s (B.-Y. Wu et al. 2009a). B.-Y. Wu et al. (2009a) also showed that the summer Arctic dipole anomaly has a closer relationship with the summer rainfall over China than the AO. However, Gong et al. (2011) showed that the AO effects on the summer precipitation are important over China. They suggested that, following a stronger positive spring AO, positive precipitation anomalies develop over a broad region south of 30°N stretching from southern China to the western Pacific while negative precipitation anomalies appear in the lower valley of the Yangtze River and southern Japan. Despite these efforts, most studies of Asian monsoon variations have focused on the impacts of the tropical conditions (such as ENSO) at the interannual (Wang et al. 2001; R.-G. Wu and B. Wang 2002) or interdecadal (Ho et al. 2005; Ding et al. 2007, 2009; Wang et al. 2008) time scales separately. An integral analysis and comparison of the unfiltered precipitation, interannual, and interdecadal components is still lacking.

What are the impacts of the Arctic warming on the leading modes of interannual and interdecadal precipitation in China? When and at what scale is precipitation influenced by the variation in Arctic temperature? These questions motivate the present study. In this study, eastern China (105°E–120°E) is divided into three regions: north China is defined between 33° and 42°N, the Yangtze River valley is between 27° and 33°N, and south China is located between 20° and 27°N (Fig. 1). Section 2 describes the data used in the present study. Section 3 examines the ice concentration and temperature variation over the Arctic during boreal spring and summer. Section 4 displays the leading empirical orthogonal function modes (EOFs) of the summer unfiltered (natural variation and no filtering), interannual, and interdecadal precipitation over China. The leading-mode contributions of interannual and interdecadal precipitation components to the unfiltered precipitation are examined and assessed. The relationships between the leading modes of interannual and interdecadal summer precipitation and Arctic temperature variations are investigated in section 5. Section 6 explores the correlation between AO and the unfiltered, interannual, and interdecadal summer precipitation over China. Finally, conclusions and a discussion are presented in section 7.

2. Data

Monthly precipitation is derived from the National Meteorological Information Center in China, which includes observations from 743 stations. However, only 532 stations with continuous observations from 1960 to 2008 are used in this study. The distribution of stations is shown in Fig. 1.

Global ice concentration data are from the British Atmospheric Data Centre (BADC; http://badc.nerc.ac.uk/view/badc.nerc.ac.uk). The data are provided by the Hadley Centre (Met Office), which contain global 1° monthly-mean ice coverage data from 1870 to 2010. Ice concentrations are given as percentage of grid box covered with ice.

The Twentieth Century Reanalysis (20CR) data are downloaded from the National Oceanic and Atmospheric Administration (NOAA)/Office of Oceanic and Atmospheric Research (OAR)/Earth Systems Research Laboratory (ESRL) Physical Sciences Division (PSD), Boulder, Colorado, through their website (at http://www.esrl.noaa.gov/psd/) (Compo et al. 2006, 2011; Whitaker et al. 2004). The 20CR contains objectively analyzed four-dimensional data on a 2.0° latitude × 2.0° longitude global grid (180° × 91; 90.0°N–90.0°S, 0.0°–358.0°E). Monthly values are from January 1871 to December 2008. Monthly air temperature at sigma level 0.995 and 1000 hPa and ice concentration data of 20CR are used in the present study.

AO index data are from the National Weather Service (NWS) Climate Prediction Center (CPC) website
To identify the leading teleconnection patterns in the atmospheric circulation, empirical orthogonal function analysis was applied to the monthly-mean 1000-hPa height anomalies poleward of 20°N for the Northern Hemisphere. Monthly AO indices are constructed by projecting the monthly-mean 1000-hPa height anomalies onto the leading EOF mode. The time series is normalized by the standard deviation of the monthly index (1979–2000 base period).

3. Variations of sea ice concentration and temperature over the Arctic

Comparison of the ice concentration provided by the Hadley Centre (Met Office) from 1870 to 2010 (Fig. 2) and the ice concentration of 20CR from 1871 to 2008 (not shown) shows that ice concentration exhibits similar variation tendency over the Arctic in spring (Fig. 2a) and summer (Fig. 2b), respectively. The ice concentration has decreased since the beginning of the 1970s for both spring and summer. Furthermore, the ice concentration has decreased more in summer than in spring because the chance of above freezing summer temperature is more, and ice–albedo feedback likely also plays a role.

Could the significant decrease of Arctic ice concentration since the beginning of the 1970s (spring and summer) have induced or interacted with the abrupt climate shift over the Asian monsoon regions near the end of the 1970s? As noted earlier, the Asian summer monsoon circulation became weaker after this transition. The overall increase of precipitation intensity in southern China (which includes part of the Yangtze River valley and south China) started in the late 1970s and peaked in the middle of the 1990s (Lei et al. 2011). Coincidentally, since the late 1970s, an interdecadal climate regime shift has occurred in the North Pacific SST and sea level pressure fields (e.g., Nitta and Yamada 1989; Trenberth and Hurrell 1994; Graham 1994). However, using an AGCM, Han and Wang (2007) showed that the significant interdecadal variation of the East Asian summer monsoon that occurred around the end of the 1970s cannot be explained by the evolution of global SST or sea ice concentration distribution. On the contrary, Li et al. (2010) show that model results suggest that recent warming in the tropics, especially the warming associated with the tropical interdecadal variability centered over the central and eastern Pacific, is a major cause of the weakening of the summer monsoon and the associated rainfall changes over East Asia since the 1970s. However, as Li et al. (2010) pointed out, a successful model simulation that reproduces the monsoon circulation is not necessarily followed by a successful reproduction of rainfall anomalies. Therefore, modeling studies linking different aspects of SST or large-scale circulation anomalies to monsoon precipitation have not yet
produced a robust understanding of interannual and interdecadal precipitation variability. Overall, the East Asian summer monsoon abrupt shifts must be triggered by variations of external (e.g., geographic and orbital; defined by Wang et al. 2003a) and/or internal (the coupled atmosphere–ocean–land system; Wang et al. 2003a) forcings or interactions.

To examine possible relationships between Arctic climate and the Asian monsoon, the variations of Arctic air temperature were analyzed at sigma level 0.995 (Fig. 3) and 1000 hPa (not shown). Results showed that the variations of near-surface temperature are different from that of the ice concentration (Fig. 2) over the Arctic in that the temperature variations are more conspicuous in spring (Fig. 3a) than in summer (Fig. 3b), while the opposite is true for ice concentration. The much smaller warming trend during summer can be explained by the increased ice melt, which absorbs heat and reduces the temperature near the surface. The warm anomalies rise above a positive standard deviation (1.38°C) in springs after the late 1970s. Because the atmosphere should respond to the thermal forcing reflected by the anomalous near-surface temperature related to the Arctic ice rather than the Arctic ice itself and the Arctic spring warming anomaly is conspicuous, we investigate the possible linkages between the significant temperature variations over the Arctic in spring and climate variations in the subtropical and midlatitude regions, including the Asian monsoon regions.

4. Leading modes of the unfiltered, interannual, and interdecadal components of summer precipitation over China

The East Asian monsoon precipitation varies over a wide range of spatial and temporal scales. It is possible that variations at different scales are related to different impact factors or mechanisms, which may interact in significant ways. In other words, the primary features of the unfiltered precipitation (natural variation of precipitation) cannot be perfectly explained by the spatial pattern or temporal evolution of overfiltered precipitation at either interannual or interdecadal time scales. This motivated us to identify the dominant patterns of precipitation variation over China using EOFs derived from interannual or interdecadal scales and also comparing them with the leading modes of unfiltered precipitation. The summer precipitation patterns over China are commonly known to be dominated by three spatial patterns (Xu et al. 1999), the northern pattern, central pattern, and southern pattern. Thus, we analyzed
the first three modes in order to confirm whether the EOF analysis could capture the principal modes during 1960–2008. In addition, heavy economy losses due to flood and drought mainly happened in eastern China during flooding seasons. Thus, we focus on studying the summer precipitation over the eastern regions and use precipitation anomaly (i.e., departures from the 1960–2008 summer mean) to perform the EOF analysis in the present study. Using percentage of rainfall departure will result in larger signals from regions such as northwestern China where the mean precipitation amount is relatively low.

In this section, the time coefficients of EOFs were scaled by their standard deviations in the temporal domain. The corresponding eigenvectors (spatial patterns) were then multiplied by their standard deviations (Weng et al. 1999). The spatial patterns corresponding to the positive time coefficients are described below.

a. The leading modes of unfiltered summer precipitation over China

EOF analysis of the summer precipitation (unfiltered) from 1960 to 2008 was performed to extract the first three EOFs over China. Applying the rule of thumb (North et al. 1982) to carry out a significance test, we found that EOF1 and EOF2 as well as EOF2 and EOF3 are well separated but EOF3 and EOF4 cannot be distinguished clearly. Therefore, only the first two modes of EOFs pass the rule-of-thumb significance test. However, EOF3 possesses physical meaning and has been used in operational seasonal forecast in China. Therefore, the spatial patterns and time coefficients of the first three EOFs are analyzed and presented in Figs. 4 and 5, respectively.

The spatial pattern of EOF1 shows major negative and positive anomalies over central and southern east China (Fig. 4a), which is the often-mentioned dipole structure and similar to the traditional southern pattern of precipitation (indicating the location of mainly positive anomalous precipitation). The positive anomalies of precipitation cover south China, while negative anomalies of precipitation are between the Yellow River and the Yangtze River. Although the time coefficient of EOF1 shows obvious interdecadal variability, interannual variability is also apparent (Fig. 5a). The first leading mode explains about 15% of the total precipitation variance. The spatial pattern of EOF1 is very similar to the spatial pattern of EOF2 by Zhou and Yu (2005). The differences between the present study and that by Zhou and Yu (2005) may be related to the use of the departure of summer precipitation (1960–2008) in the present study and the percentage of summer rainfall anomaly (1951–99) by Zhou and Yu (2005).

The spatial pattern of EOF2 displays maximum positive anomalies between the middle and lower reaches of the Yangtze River valley and northern south China (Fig. 4b), which is similar to the traditional central pattern of precipitation, somewhat southward relative to the traditional one. The time coefficient shows intensified precipitation during the mid1990s (Fig. 5b). The second leading EOF mode accounts for 11% of the total precipitation variance.

The spatial pattern of EOF3 mainly shows major positive anomalies around northeast and north China (Fig. 4c), which is similar to the traditional northern pattern of precipitation. Negative anomalies are found over most of central and south China. This mode explains about 8% of the total variance. The time coefficient tends to transition gradually from more positive to more
negative values during 1960–2008 (Fig. 5c). This mode can be used to illustrate the drought conditions that happened over north China and northeast China during the recent 20 yr.

Although the spatial patterns of EOF1, EOF2, and EOF3 resemble the precipitation patterns over China previously analyzed by Weng et al. (1999), they differ somewhat from the result of Xu et al. (1999) and Zhao et al. (2008). Most notably, the order of the spatial patterns of EOF1, EOF2, EOF3, and EOF4 is different between the present study and those described by Xu et al. (1999), Zhou and Yu (2005), and Zhao et al. (2008). That is, the variances explained by the leading modes are different between this study and Zhao et al. (2008), who used precipitation data from 1880 to 1950 (59 observation stations). Moreover, different approaches used in carrying out the EOF analysis of precipitation data [e.g., using departure from 1960 to 2008 in the present study versus the percentage of rainfall departure from 1951 to 1999 in Zhou and Yu (2005), as discussed above] may also result in differences in the EOF patterns and variances explained. Furthermore, we experimented with EOF analyses using precipitation data from 1956 to 2010 with a total of 350 continuous observation stations and found that the first five leading spatial modes and time coefficients and their variances are almost identical to the EOF results from 532 observation stations during 1960–2008. We also used 379 observation stations only over the eastern part of China (i.e., east of 105°E) and found that the first five leading modes remained the same as the EOF results of the 532 observation stations from 1960 to 2008 with the variances increased by only about 1% in the first two modes and

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**Fig. 5.** The time coefficients of the first three EOFs for unfiltered precipitation variation (black bar), (a) EOF1, (b) EOF2, and (c) EOF3. The solid curves (open circle lines) are 9-point running averaged by one time (two times). The solid (open circle) lines are multiplied by 3 (5) in order to recuperate the loss by 9-point running average and show clearly the variation tendency.
even smaller changes for the third, fourth, and fifth modes. The order of the leading EOFs modes stays the same. Thus, we confirmed that limited differences in observation stations or time periods cannot lead to large differences in the order of the EOFs. We speculate further that the discrepancy is related to the interdecadal variability of precipitation too, which may be forced by some interdecadal-scale impact factors.

The first three modes together explain only about 34% of the total variance. This indicates the challenge of predicting summer precipitation over China, and prediction schemes based on information of the leading modes alone may not be effective.

b. The leading modes of interannual and interdecadal precipitation components over China

To study the leading EOFs of interannual and interdecadal precipitation components and their contribution to the leading modes based on the unfiltered precipitation, a one-dimensional Gaussian low-pass filter is applied to the precipitation data. We used the time scale of 9 yr as the threshold. Variation with time scales less than 9 yr is considered interannual and that more than 9 yr is called interdecadal, although the latter includes both interdecadal and ultra-low-frequency variation. The use of the Gaussian low-pass filter rather than bandpass filter to separate interannual and interdecadal variability is more effective for interdecadal signals to emerge based on a relatively short record of 49 yr. Analysis of the leading spatial modes based on bandpass temporal filtering using the recurrence method (Murakami 1979; Ding 1993) to isolate the 10–23-yr or 9–36-yr variation yielded very similar results compared to the use of the 9-yr low-pass filter, except that the energy is notably reduced (not shown). In addition, although only interannual and interdecadal EOF1 are distinguishable from EOF2 according to the rule of thumb (North et al. 1982), the first three modes are shown in the present study in order to compare the leading modes of interannual and interdecadal precipitation with those of unfiltered precipitation, which are used in operational short-term climate prediction.

The spatial pattern of interannual EOF1 shows a clear dipole pattern between the middle and lower reaches of the Yangtze River valley and south China (Fig. 6a1). This mode accounts for about 15% of interannual precipitation variance. The interdecadal EOF1 shows anomalous precipitation mainly over southern China extending to the middle and lower reaches of the Yangtze River (Fig. 6a2), while other regions are near normal, except for some small areas in north China and northeast China that are out of phase relative to the southern region. This first leading mode explains about 33% of interdecadal precipitation variance and suggests that some interdecadal factors can induce excessive precipitation over the southern region. The first mode of interdecadal precipitation is similar to Ding et al. (2007). From the spatial pattern and time coefficient of interannual and interdecadal precipitation EOF1 (Fig. 6a1, a2 and Fig. 7a), we found that excessive precipitation over south China in recent years is attributed to interdecadal influences or the conjunctive impacts of interannual and interdecadal factors. However, the interannual mode dictates the dipole pattern of unfiltered precipitation between the Yangtze River valley and south China.

The interannual EOF2 shows excessive precipitation over most of eastern China, except the southeastern coast and the Huai River valley (Fig. 6b1). It explains about 11% of interannual precipitation variance. The interdecadal EOF2 shows the central pattern of precipitation over eastern China (Fig. 6b2). Excessive precipitation areas located over the middle and lower reaches of the Yangtze River valley occur simultaneously with reduced precipitation over south China and the lower reach of the Yellow River. The second mode accounts for about 16% of interdecadal precipitation variance. Also, the second mode of interdecadal precipitation is similar to that of Ding et al. (2007). Comparison of the spatial pattern and time evolution of interannual and interdecadal EOF2 (Fig. 6b1, b2 and Fig. 7b) indicates that some interdecadal factors had favored excessive precipitation over the Yangtze River valley and reduced precipitation over the north to the Huai River from the late 1970s to the early 2000s. For some years, both interannual and interdecadal factors contribute to the precipitation pattern.

The interannual EOF3 (Fig. 6c1) shows an opposite phase relationship between south China and north China. It accounts for about 8% of interannual precipitation variance. This dipole pattern of EOF3 is somewhat similar to that of the interannual EOF1, except that the dividing line of the dipole pattern for EOF3 is located farther north over the Huai River compared to the junction between the Yangtze River valley and south China for EOF1. The interdecadal EOF3 shows reduced precipitation between the Yellow River and Yangtze River (Fig. 6c2) and excessive precipitation over southern and northern China. The interdecadal EOF3 explains 12% of interdecadal precipitation variance. The spatial patterns and time coefficients of interannual and interdecadal precipitation EOF3 (Fig. 6c1, c2 and Fig. 7c) show that scarce precipitation or drought over north China is related to both interannual and interdecadal factors for the recent decades. For some years, the interannual factors play a pivotal role, but for other years interdecadal factors have more important contributions.
5. Relationship between spring/summer Arctic temperature and the leading modes of interannual and interdecadal precipitation components over China

EOF analyses based on the unfiltered, interannual, and interdecadal precipitation components show that the contributions of interannual and interdecadal precipitation to the unfiltered precipitation exhibit notable differences. What factors influence the interannual and interdecadal precipitation? In the present study, we focus on the potential impact of the Arctic low-level temperature and investigate the relationships between the leading modes of interannual and interdecadal precipitation and the low-level temperature (1000 hPa) over the boreal middle to high latitudes and the Arctic. Regions with statistical significance exceeding 95% confidence levels are noted (absolute value of correlation coefficient greater than 0.27 based on 49 samples from 1960 to 2008 and 0.29 after using a t test to perform a significance test).

Fig. 6. The spatial patterns of the first three EOFs for interannual precipitation variability at 532 stations during 1960–2008, (a1) EOF1 (15% of the total interannual precipitation variance), (b1) EOF2 (11% of the total interannual precipitation variance), and (c1) EOF3 (8% of the total interannual precipitation variance), and for interdecadal summer precipitation variability, (a2) EOF1 (33% of the total interdecadal precipitation variance), (b2) EOF2 (16% of the total interdecadal precipitation variance), and (c2) EOF3 (12% of the total interdecadal precipitation variance). The interval of contours is 20 mm per summer. The zero contours are not drawn in each plot to improve clarity.
First, regressions of the spring and summer 1000-hPa temperature over the middle to high latitudes and the Arctic (50°–90°N) onto the time coefficients of the first three interannual EOFs are analyzed (Fig. 8). The most noteworthy correlation is found over the middle to high latitudes of Asia (Fig. 8b1). High anticorrelations and low regressed spring temperatures are found across the West Siberian Plain and the Sea of Okhotsk for the second interannual precipitation mode. This suggests that warmer spring temperature from the West Siberian Plain to the Sea of Okhotsk correlates with less precipitation over the Yangtze River valley and northeast China and more precipitation in the Huai River and southeastern coast in the summer at an interannual time scale. However, the spring and summer temperatures over the Arctic are not accompanied by notable correlations with any leading modes of interannual precipitation in China.

Next, regressions of the spring and summer 1000-hPa temperature over the middle to high latitudes and the Arctic onto the time coefficients of the first three interdecadal precipitation EOFs are investigated (Fig. 9). The results indicate some distinct differences from the interannual time scale. Pronounced correlations over the Arctic exist for every leading interdecadal precipitation mode in spring (Fig. 9a1,b1 and c1).

With reference to the time coefficient of interdecadal precipitation EOF1, high correlations and strong positive regressed temperature values are notable over the Arctic (Fig. 9a1), suggesting that the higher spring temperature in the Arctic corresponds with more interdecadal precipitation from south China to the southern part of the Yangtze River valley (cf. Fig. 9a1 and Fig. 6a2). However, the first interdecadal precipitation mode is less related to the summer temperature over the Arctic but instead is more related to summer temperature in the boreal mid–high-latitude regions from Sweden and the Denmark Strait to Hudson Bay and Lake Baikal (Fig. 9a2). This suggests a difference in the time lag of Arctic versus middle to high latitudes influence on the East Asian summer monsoon. Moreover, it may be related to
Fig. 8. Regressed anomalous temperature at 1000 hPa in (left) spring and (right) summer. The regressions are made with reference to the corresponding time coefficients of the interannual precipitation (a) EOF1, (b) EOF2, and (c) EOF3. The contour interval is 0.2. The shadings exceed the 95% confidence level ($\pm 0.27$, $\pm 0.29$ after using $t$ test).
FIG. 9. As in Fig. 8, but the regressions onto the time coefficients of the interdecadal precipitation variability EOF1, EOF2, and EOF3.
the more noteworthy warming over the Arctic in spring than summer (Fig. 3), which provides stronger anomalous surface forcing to impact other regions.

Regressions on the time coefficient of interdecadal precipitation EOF2 show high correlations and strong positive temperature values over parts of the Arctic and the middle to high latitudes of the boreal Western Hemisphere in spring (Fig. 9b1). This illustrates that higher spring temperature over the Arctic and the middle to high latitudes of the Western Hemisphere is correlated with more (less) precipitation over the Yangtze River valley (the lower reach of the Yellow River and south China) on an interdecadal time scale (Fig. 6b2). However, summer Arctic temperature is not closely related to the second interdecadal precipitation mode (Fig. 9b2).

For temperature regressions on the time coefficient of the interdecadal precipitation EOF3, high anticorrelations and low regressed temperature values are located over the center of the Arctic (Fig. 9c1). That is, when spring temperature over the Arctic is higher, there is less (more) precipitation over most of eastern China (the regions between the Yangtze River and Yellow River). The above regression analyses suggest that the summer drought of north China and northeast China that happened in the recent decades may be partly related to the enhanced spring Arctic temperature. Figure 9c2 shows that interdecadal summer precipitation is less related to the summer Arctic temperature, except for the obvious anticorrelations and low regressed temperatures in the boreal middle to high latitudes from Sweden to Baffin Island (Fig. 9c, right). In other words, the increases of both spring Arctic temperature and summer boreal mid–high-latitude temperature contribute to the interdecadal precipitation EOF3 (Fig. 6c2).

6. Correlations between AO index and summer precipitation over China

Besides Arctic spring temperature, AO may also exert an influence on summer precipitation over China through remote effects. Time series of monthly AO index were obtained online (from http://www.cpc.ncep.noaa.gov/products/), which was constructed by projecting the monthly-mean 1000-hPa height anomalies onto the leading EOF mode. The time series were normalized by the standard deviation of the monthly indices (1979–2000). The AO has been described as “a seesaw pattern” in which atmospheric pressure at the polar and middle latitudes fluctuates between positive and negative phases.

Operational short-term climate prediction has made use of the relationship between spring AO and Asian summer monsoon derived from previous studies (e.g., Gong and Ho 2003; Gong et al. 2011) to predict summer precipitation pattern in China. However, this has not led to the expected improvements in prediction skill. To investigate this issue, correlations of the AO index from January to August with the unfiltered, interannual (not shown), and interdecadal (not shown) summer precipitation were examined over China. Regions with statistical significance exceeding the 95% confidence level are highlighted (absolute value of the correlation coefficient is greater than 0.27 based on 49 degrees of freedom from 1960 to 2008 and 0.29 after t test).

Obvious correlations between January AO index and summer precipitation are found over some central and western parts of China (Fig. 10a; the shaded regions are above 95% confidence level). Namely, larger AO index in January often corresponds to more summer precipitation over those areas. Figure 10b shows the positive correlation between the February AO with summer precipitation over the southern area of the lower Yangtze River valley, with an evident east–west belt structure. The positive correlation belt area is mainly contributed by the interdecadal precipitation or precipitation of an even longer time scale. The belt structure becomes narrow because of interannual precipitation (not shown here).

Significant positive correlations between the March AO index and precipitation are located along the northwest loop of the Yellow River (Fig. 10c) while negative correlations are found over the lower reach of Yangtze River valley. The two regions with notable correlation are primarily due to the relationship between interannual precipitation and the AO index. The negative correlations between the April AO index and precipitation are mainly centered over the western and southern loop areas of the Yellow River (Fig. 10d), which originates from the relationship between AO and both interannual and interdecadal precipitation.

The May AO index is not closely related to precipitation in the majority of China, except for a small negative correlation over the southern part to the lower reaches of the Yangtze River (Fig. 10e), which is mainly due to the relationship between interannual precipitation and AO. It is somewhat similar to but also different from that of Gong and Ho (2003), who showed that May AO has the closest connection to summer monsoon rainfall over the lower of the Yangtze River valley. The discrepancy may be related to differences in the data and analysis method. Gong and Ho (2003) obtained their rainfall data from 10 stations along the Yangtze River and southern Japan for 1900–98. All data were high-pass filtered before the analysis to highlight interannual variability. With one standard deviation above the mean AO index, there is about 20–40-mm decrease in precipitation over the region extending from the Yangtze River valley to southern Japan and 10–30-mm increase over southern China (Gong and Ho 2003).
In the present study, our correlation analyses were performed using monthly AO index and the unfiltered, interannual, and interdecadal precipitation data from 532 stations. Our precipitation data cover a larger spatial extent (Fig. 1) but include only 1960–2008.

Negative and positive correlations with a high confidence level are found between the June AO index and summer precipitation that cover parts of central China and both the western loop and parts of south China (Fig. 10f), respectively, showing a positive–negative–positive spatial structure from south to north China. The correlation pattern is due to both interannual and interdecadal precipitation, but the interannual component plays a dominant role. For July and August, the AO index is not closely correlated with summer precipitation over China (not shown).

From the above analysis of correlations between summer precipitation and the AO index from January to August, we showed that summer precipitation over China is related to the AO to some extent. Overall,
regions with the notable connection between summer precipitation and AO are primarily over the western loop areas of the Yellow River (for March, April, and June AO index) and along the Yangtze River valley or the lower reaches of the Yangtze River (for February, March, and June AO index).

7. Conclusions and discussion

With the 20CR temperature data from NOAA/OAR/ESRL PSD, ice concentration from the British Atmospheric Data Centre (BADC), AO index data from CPC/NWS, and monthly precipitation from the National Meteorological Information Center of China, we investigated the variations of ice concentration and near-surface temperature over the Arctic; the leading EOF modes of the unfiltered, interannual, and interdecadal precipitation components over China; and the relationship between the leading modes of interannual and interdecadal precipitation and Arctic temperature in spring and summer. Finally, correlations between the AO index from January to August and the unfiltered, interannual, and interdecadal summer precipitation were examined. The key findings are summarized below.

1) Ice concentration over the Arctic has decreased since the 1970s and the changes are more significant in summer than spring. However, the Arctic warming is more significant in spring than in summer. This suggests that the spring thermal and thermodynamical conditions over the Arctic can produce stronger anomalous surface forcing to trigger or interact with climate in other regions, such as the Asian monsoon regions, and motivated our use of Arctic temperature rather than ice concentration to understand the potential influence of Arctic conditions on the East Asian summer monsoon precipitation.

2) The spatial pattern of the unfiltered precipitation EOF1 shows the dipole pattern with positive precipitation anomalies over south China and negative anomalies between the Yellow River and the Yangtze River. The spatial pattern of EOF2 displays maximum positive anomalies over the middle and lower reaches of the Yangtze River valley and northern south China. The spatial pattern of EOF3 mainly shows major positive anomalies over north China and northeast China and negative anomalies over central and south China. The three leading modes only explain about 34% of the total precipitation variance.

3) Using a threshold of 9 yr to define interannual versus interdecadal time scales, the spatial pattern of interannual EOF1 shows a clear dipole pattern between the middle and lower reaches of Yangtze River valley and south China. However, the interdecadal EOF1 shows anomalous precipitation mainly over southern China, extending to the middle and lower reaches of the Yangtze River. During the 1990s, excessive precipitation and even flood over south China are attributed to interdecadal influences or the conjunctive impacts of interannual and interdecadal factors.

4) Based on regression analysis, we found that the first three modes of the interannual precipitation are not closely related to the spring and summer temperatures over the Arctic. However, the interdecadal precipitation EOF1, EOF2, and EOF3 are clearly connected with the Arctic spring temperature variation. The first two are a positive relationship while the third is the opposite. Regression analysis showed that the summer flood over the Yangtze River valley and south China and drought over north China and northeast China in the recent decades are partly related to the spring Arctic warming. On the contrary, the first three interdecadal precipitation modes are not closely related to the summer Arctic temperature.

5) Correlation analyses between summer precipitation and AO index from January to August showed that summer precipitation over China is related to the AO to some extent. Regions with notable connection are primarily over the western loop areas of the Yellow River (positive correlation for March and June AO index and negative correlation for April AO index) and
along the Yangtze River valley or the lower reaches of the Yangtze River (positive correlation for February AO index and negative correlation for March and June AO index).

A previous study (Ho et al. 2005) showed that a large amount of interdecadal variability could be accounted for by less than 20% of the total number of rainy events in the heavy to extremely heavy categories (≥~25 mm day$^{-1}$) across most of eastern China. The present study showed that interdecadal precipitation variability over China may partly be attributed to the Arctic warming in spring. For example, the unfiltered precipitation EOF1 for 1960–75, which is before the abrupt climate shift, can explain 16% of the total variance. However, the unfiltered precipitation EOF1 for 1990–2005, which is after the abrupt climate shift, can account for 22% of the total variance, although the first spatial patterns of the EOFs for 1960–75 and 1990–2005 are similar to that for 1960–2008 to a large extent. This suggests that the influence of the spring Arctic warming on the first mode of the unfiltered precipitation is becoming more significant from 1960–75 to 1990–2005. Based on this study and comparison with previous studies, we speculate that the interdecadal factors may exert an important influence on precipitation by modulating the leading-mode variance. However, not all the interdecadal precipitation variance can be explained by the Arctic warming.

Overall, this study showed a close relationship between the leading modes of interdecadal summer precipitation and the Arctic spring temperature. The spring Arctic warming and the associated sea ice concentration reduction can result in precipitation increase (decrease) over the Yangtze River valley and southeast China (north China). This finding is similar to the study by Zhao et al. (2004) on the relationship between sea ice extent in the North Pacific and summer precipitation in China. However, B.-Y. Wu et al. (2009a) indicated that, although spring Arctic sea ice concentration and Chinese summer rainfall exhibit coherent interannual and interdecadal variability, their relationship is more important on interannual time scales than interdecadal time scales. Their conclusion seems to contradict our results. Possible reasons may be related to the use of different variables and approaches. B.-Y. Wu et al. (2009a) regressed the summer 500-hPa height anomalies on the spring sea ice concentration in the leading singular value decomposition, which was performed between summer precipitation over China and spring sea ice concentration over Northern Hemisphere at interdecadal and interannual time scales. Their results show that the ratios of the accumulated variance of summer 500-hPa height variations induced by interannual variability of spring Arctic sea ice concentration to the accumulated total variance of 500-hPa height variation are obviously greater than that induced by interdecadal variability to the total variance. Our results are based on the regressed Arctic 1000-hPa temperature on the time coefficients of the leading interannual and interdecadal precipitation EOFs (two variables), while their results are based on relationships among three variables (precipitation, ice concentration, and 500-hPa height).

Differences between our results and previous works can also arise because of differences in how precipitation data are filtered and what precipitation data are used. When overly filtered precipitation or other variables are analyzed, some important information may be lost and the filtered precipitation may only account for a small fraction of the unfiltered. Therefore, the present study indicates that the conclusions using overly filtered data may not be directly applicable to short-term operational prediction. Furthermore, as multiscale interactions may grow or cancel one another, studies focused on limited temporal scale may improve understanding of climate phenomena, but they may be limited in direct usefulness for climate prediction. In addition, individual station precipitation data with limited temporal or spatial coverage may not well represent regional phenomena because of spatial and temporal discontinuities of precipitation. Hence, correlation analyses may be sensitive to the selected observation stations to some extent. This may partly explain the differences between the present correlation analyses of precipitation and the AO index with previous studies. The potential changes of East Asian summer monsoon associated with global warming are of great scientific and societal importance, because the monsoon determines the salient features of the East Asian climate (Zhou et al. 2009a). In the present study, notable relationships between the spring Arctic low-level temperature and the leading modes of interdecadal summer precipitation have been revealed. This suggests that the spring Arctic temperature increase (thermal condition) since the 1970s could be a trigger factor for the summer precipitation enhancement (reduction) over the Yangtze River valley and south China (north China and northeast China) in the recent decades, due to some dynamics and/or thermodynamics adjustment between the Arctic and Asian monsoon regions. In other words, the thermal balance between the Arctic and the subtropical and middle latitudes has been perturbed because the spring temperature has increased more over the Arctic (70°–90°N, 0°–360°E) than the Asian monsoon regions (20°–50°N, 60°–150°E) (not shown). Moreover, the change in the temperature gradient between the Arctic and the Asian monsoon regions is more significant in spring than in summer (not shown). Therefore, a natural adjustment to attain a new balance may influence the summer precipitation over China. Understanding the
mechanisms and time scales of the adjustment, which may involve both atmospheric and oceanic heat transport, may have important implications to predicting interdecadal summer precipitation contribution to the unfiltered precipitation in China.

Observations show that precipitation variability between north China and the Yangtze River valley often has an opposite phase; for example, when north China has precipitation deficit, the Yangtze River valley usually has excessive precipitation and vice versa (Wang et al. 2005; Zhou et al. 2009a). Moreover, the trend of rainfall derived from data representing a limited length of time (e.g., 50 yr) should be considered cautiously, because it is possible that the trend may actually reflect a natural phase transition in the multidecadal variability (Zhou et al. 2009a). Even if the precipitation signal were just a natural phase transition during the recent 49 yr (1960–2008), it is still very important to investigate the antecedent impact on the precipitation variation by the underlying surface forcing because the summer monsoon precipitation over eastern China cannot be effectively predicted with statistical or dynamical methods up until now. As both anthropogenic forcing and natural variability can influence the East Asian monsoon in various ways, a key challenge is to better delineate different local and remote forcing mechanisms responsible for the climate shift since the late 1970s to constrain future projections of East Asian summer monsoon precipitation, which has impacts on a large population. While this study has focused primarily on finding potential linkages between Arctic and high-latitude climatic anomalies and precipitation in China, future work will examine large-scale circulation anomalies and dynamical and thermodynamical mechanisms for the remote influence of the Arctic conditions on the East Asian summer monsoon.

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