# Interdecadal Variability of the East Asian Winter Monsoon and Its Possible Links to Global Climate Change

DING Yihui[1*] (丁一汇), LIU Yanju[1] (柳艳菊), LIANG Sujie[2] (梁苏洁), MA Xiaoqing[3] (马晓青), ZHANG Yingxian[1] (张颖娴), SI Dong[1] (司 东), LIANG Ping[4] (梁 萍), SONG Yafang[1] (宋亚芳), and ZHANG Jin[1] (张 锦)

1 *National Climate Center, China Meteorological Administration, Beijing* 100081

2 *Tianjin Climate Center, Tianjin* 300074

3 *Beijing Meteorological Bureau, Beijing* 100089

4 *Shanghai Climate Center, Shanghai* 200030

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**ABSTRACT**

This paper presents a concise summary of the studies on interdecadal variability of the East Asian winter monsoon (EAWM) from three main perspectives. (1) The EAWM has been significantly affected by global climate change. Winter temperature in China has experienced three stages of variations from the beginning of the 1950s: a cold period (from the beginning of the 1950s to the early or mid 1980s), a warm period (from the early or mid 1980s to the early 2000s), and a hiatus period in recent 10 years (starting from 1998). The strength of the EAWM has also varied in three stages: a stronger winter monsoon period (1950 to 1986/87), a weaker period (1986/87 to 2004/05), and a strengthening period (from 2005). (2) Corresponding to the interdecadal variations of the EAWM, the East Asian atmospheric circulation, winter temperature of China, and the occurrence of cold waves over China have all exhibited coherent interdecadal variability. The upper-level zonal circulation was stronger, the mid-tropospheric trough over East Asia was deeper with stronger downdrafts behind the trough, and the Siberian high was stronger during the cold period than during the warm period. (3) The interdecadal variations of the EAWM seem closely related to major modes of variability in the atmospheric circulation and the Pacific sea surface temperature. When the Northern Hemisphere annular mode/Arctic Oscillation and the Pacific decadal oscillation were in negative (positive) phase, the EAWM was stronger (weaker), leading to colder (warmer) temperatures in China. In addition, the negative (positive) phase of the Atlantic multi decadal oscillation coincided with relatively cold (warm) temperatures and stronger (weaker) EAWMs. It is thus inferred that the interdecadal variations in the ocean may be one of the most important natural factors influencing long-term variability in the EAWM, although global warming may have also played a significant role in weakening the EAWM.

**Key words:** East Asian winter monsoon, interdecadal variability, Northern Hemisphere annular mode, Arctic Oscillation, Pacific decadal oscillation, Atlantic multidecadal oscillation, global climate change

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## 1. Introduction

The East Asian winter monsoon (EAWM) is an important component of the climate system in East Asia, and has significant impacts on weather and climate anomalies in China and the entire East Asian region during winter. Originated from the Siberian high, the EAWM is characterized by a sudden estab-

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*Corresponding author: dingyh@cma.gov.cn.

lishment, a rapid southward movement, and strong winds. Variations in the intensity of the EAWM influence not only the weather in China and neighboring regions, but also droughts and tropical cyclogenesis in and around Indonesia, Australia, and the southern part of Malaysia (Liang et al., 1990; Zhu et al., 1990; Shi, 1996). A strong EAWM provides favorable climatic conditions for cold air outbreaks in northern China, Japan, Korea, and other nearby areas, and increases the likelihood of disastrous winter weather (such as frost damage, cold waves, heavy snowfall, and spring duststorms) in East Asia (Krishnamurti, 1979; Chang and Lau, 1982; Ding and Krishnamurti, 1987; Ding, 1994; Guo, 1994; Zhang et al., 1997; Wu and Liang, 2000; Huang et al., 2007a; Gu et al., 2008; Wang et al., 2009a; Wen et al., 2009; Sun et al., 2010; Wang et al., 2011; Li and Wang, 2012).

The EAWM is a multi-scale phenomenon (Jin and Sun, 1996; Xu et al., 1999; Chan and Li, 2004; Pei and Li, 2007; Wei and Li, 2009). First, the EAWM varies on intraseasonal timescales. Frequent cold air outbreaks result in cold waves penetrating southward into China and cause severe winter weather (such as extremely low temperatures and/or blizzards). Intraseasonal oscillations in the strength of the EAWM are strongest at periods of 30–60 days (quasi-40-day variability) and 10–20 days (quasi-2-week variability) (Lau and Lau, 1984; Pan and Zhou, 1985; Li, 1989c; Yang and Zhu, 1989; Lu, 1994; Chan and Li, 2004). The strong cold waves of 2004 and 2005 were prime examples of the influence of 10–20-day low-frequency variability of the EAWM. The 10–20-day low-frequency signals propagate separately over the northern and southern Tibetan Plateau before coupling together while going around the Tibetan Plateau, leading to large-scale cold wave outbreaks (Ma et al., 2008).

Second, the EAWM varies on interannual timescales, with strong variability on quasi-2-, 4-, and 4–7-yr (or 5–8-yr) timescales (Guo, 1994; Mu and Li, 1999; Xu et al., 1999; Chen et al., 2000; Li et al., 2001; Chan and Li, 2004; Pei and Li, 2007; Huang et al., 2007b; Yan et al., 2009; Huang et al., 2012). The El Niño–Southern Oscillation (ENSO) plays a significant role in the interannual variability of the global atmospheric circulation. Over the last decade, a number of studies have revealed the strong influence of ENSO on the EAWM (Li, 1989a, b, c; Zhang et al., 1996; Bueh and Ji, 1999; Mu and Li, 1999; Wang et al., 2000; Li et al., 2001; Chen, 2002; Chen et al., 2003; Huang et al., 2003; Wang et al., 2003; He et al., 2008; Zhang et al., 2008). The EAWM is generally weaker during strong El Niño events and stronger during strong La Niña events. El Niño conditions trigger an anomalous anticyclone over the western Pacific and anomalous southerly winds in the lower troposphere, while La Niña triggers an anomalous cyclone over the western Pacific and anomalous northerly winds in the lower troposphere in its western periphery, thus affecting the heat transport to South China (Chang and Lau, 1980; Tomita and Yasunari, 1996; Zhang et al., 1996; Ji et al., 1997; Wang et al., 2000; Wang and Zhang, 2002). The EAWM possesses different modes in the northern and southern parts of East Asia. The northern East Asian cold winter mode appears when the East Asian trough moves westward and the pressure in central Siberia deepens. By contrast, the southern East Asian cold winter mode is associated with a deepening East Asian trough and higher pressures over Mongolia. The northern cold winter mode is closely related to the northeastern Siberian high and sea surface temperatures (SST) over the Atlantic and Indian oceans, while the southern cold winter mode is closely related to the development of La Niña and reduced snow cover over northeastern Siberia (Chen et al., 2014). Wang et al. (2010) and Wu et al. (2011) identified a third mode of the EAWM. Although this third mode only accounted for 8.7% of the variance, it played an important role in generating abnormally high snow and frost in southern China during 2007 and 2008. This mode manifests as an increase in surface pressure over northeastern East Asia and central Siberia, as well as a westward movement and intensification of the western Pacific subtropical high.

Third, the EAWM varies on decadal and interdecadal timescales, particularly the 9–10-, 20–30-, and 40-yr timescales. Although the derived results depend on the index used, most available indices measuring the strength of the EAWM show that the EAWM has weakened since the mid 1980s (Xu et al., 1999; Wu and Wang, 2002; Yan et al., 2003; Chan and Li, 2004; Pei and Li, 2007; Shi et al., 2007; Zhu, 2008; Wang et al., 2010; He and Wang, 2012; He, 2013; Wang and Fan, 2013). This period represents the most pronounced weakening of the EAWM over the past 100 years (i.e., the strongest warming in winter temperatures over East Asia). The weakening of the EAWM since the mid 1980s may be attributable to a shift in the dominant mode of the Arctic Oscillation (AO) from viewpoint of the atmospheric circulation (He and Wang, 2012). Recent studies have also shown that decadal variations in SST might alter the relationship between ENSO and the EAWM (Wang et al., 2008; Ding et al., 2010), suggesting that the relationship between winter temperature over China and ENSO may be important but complicated. The influence of ENSO on the EAWM is relatively weak during positive phases of the Pacific decadal oscillation (PDO) and relatively strong during negative phases of the PDO. Likely, the PDO is closely related to the EAWM, and may be considered as a bridge between air-sea interaction in the midlatitude Pacific and that in the tropical Pacific (Zhou et al., 2007). PDO variability corresponds well to simultaneous "seesaw" changes in the Aleutian low and Mongolian high, which result in zonal land-sea pressure differences that might significantly affect the intensity of the EAWM (Zhu and Yang, 2003; Yang et al., 2004; Zhou et al., 2007; Li et al., 2011).

The reduced rate of global warming during recent years has stimulated renewed interest in the relationships between anthropogenic climate change and natural climate variability. This renewed interest has included increased attention to interdecadal variability of the EAWM. Liang et al. (2014) studied interdecadal variations in winter temperature and the regional circulation over mainland China between 1960 and 2013. They reported strong interdecadal fluctuations superimposed on an overall warming trend in winter temperature, which could be divided into three stages: a cold period, a warm period, and a hiatus period. These interdecadal changes in winter temperature are consistent with interdecadal variations in the EAWM. The present paper will therefore focus on the results from recent studies on interdecadal variability of the EAWM with the aim to provide a more systematic understanding of the features and physical mechanisms of this interdecadal variability and its relationships with global climate change. The remainder of this paper consists of four sections. Section 2 details the climatic background state. Section 3 describes interdecadal variations in the EAWM. Section 4 presents possible explanations for these interdecadal variations. Finally, Section 5 provides a synthesis and summary.

## 2. Climatic background: Impact of Global climate change

The global monsoon system is an important component of the climate system. Changes in the climate system due to changes in climate forcing will significantly affect the global monsoon system. This is particularly true for the enormous Asian monsoon system, which is driven primarily by the land-sea thermal contrast. Figure 1a shows annual global mean temperature anomalies from 1850 to 2013. The global average temperature clearly rose during this period. This warming trend was not monotonic, and included multiple scale fluctuations. For example, the time series since 1900 has included two cold phases (1900s–1920s and 1950s–1970s) and two warm phases (1930s–1940s and 1980s–1990s), suggesting a typical period of 40 yr. Global temperature observations became much more reliable around the 1950s (the shaded area represents the uncertainty range). The 60-yr period covered by these more reliable measurements included a cold period, a warm period, and a period of slowed warming (often called the "global warming hiatus") (Easterling and Wehner, 2009; Kerr, 2009; Knight et al., 2009). The effects of global warming are also apparent in the time series of annual mean surface temperature averaged over China from 1901 to 2012 (Fig. 1b). Application of a low-frequency filter to this latter time series again reveals two cold periods and two warm periods superimposed on a general warming trend. Relative to the global mean time series, the second cold period had a longer duration over China (the 1950s–mid 1980s rather than 1950s–1970s) and the second warm

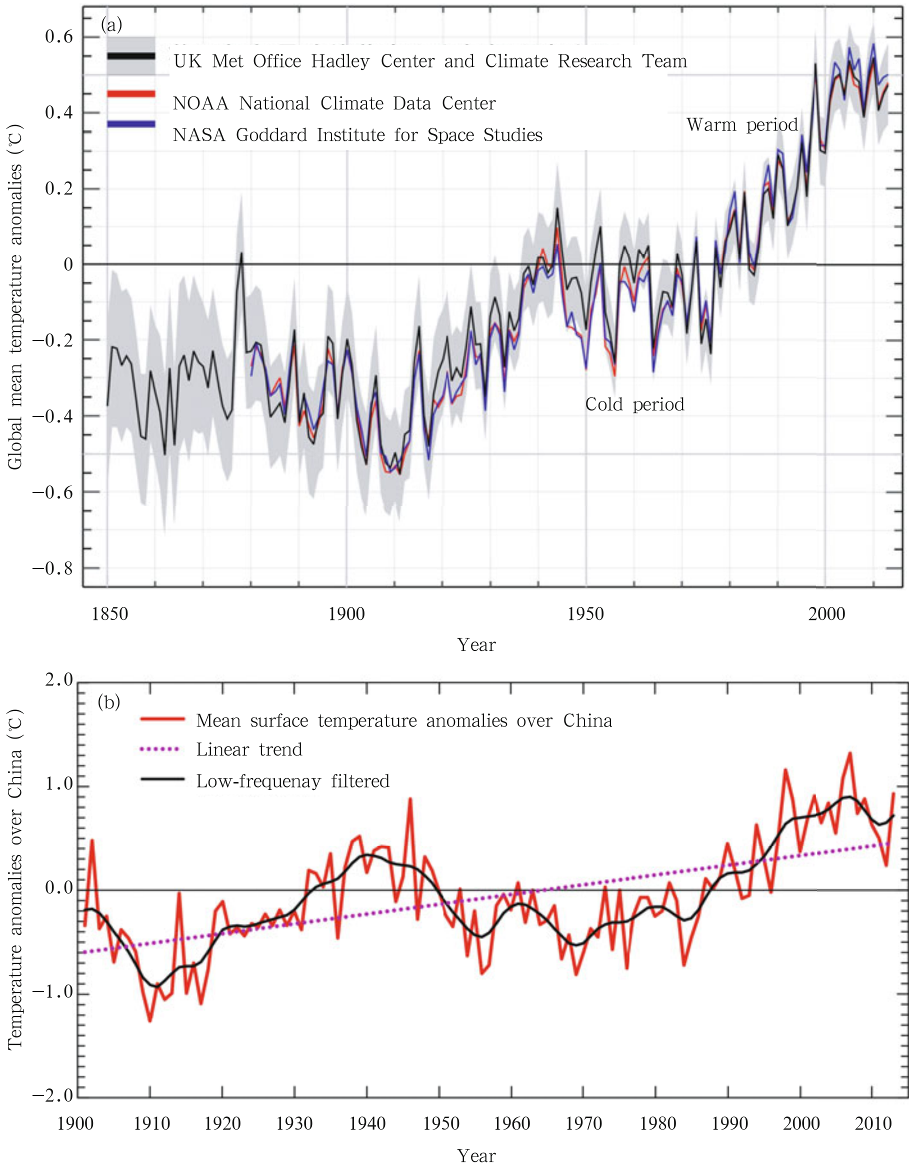


**Fig. 1.** Annual surface temperature anomalies (℃) averaged over (a) the entire globe for 1850–2013 (from the World Meteorological Organization Statement on the Status of the Global Climate in 2013, http://www.wmo.int) and (b) China for 1901–2013 (from China Climate Change Monitoring Bulletin 2013). The global mean anomalies are calculated relative to the 1961–1990 mean, while those over China are calculated relative to the 1971–2000 mean.

period also lasted slightly longer (to the mid 2000s rather than the late 1990s).

Wang and Chen (2014) showed significant negative anomalies in low-pass filtered winter temperature over East Asia before 1987 and after 2008 using a variety of datasets (Fig. 2). Although the temperature anomalies through most of the early 2000s were not negative, they were generally quite close to zero. These results indicate that changes in winter temperature over East Asia were closely related to changes in global mean temperature, even if they were not exactly simultaneous (winter temperature over East Asia lagged behind global mean temperature by approximately 5 yr). Regional responses to climate forcing can be very heterogeneous under global warming. Global temperature changes affect regional circulation patterns, which in turn affect regional temperatures, so the regional response may lag behind the global

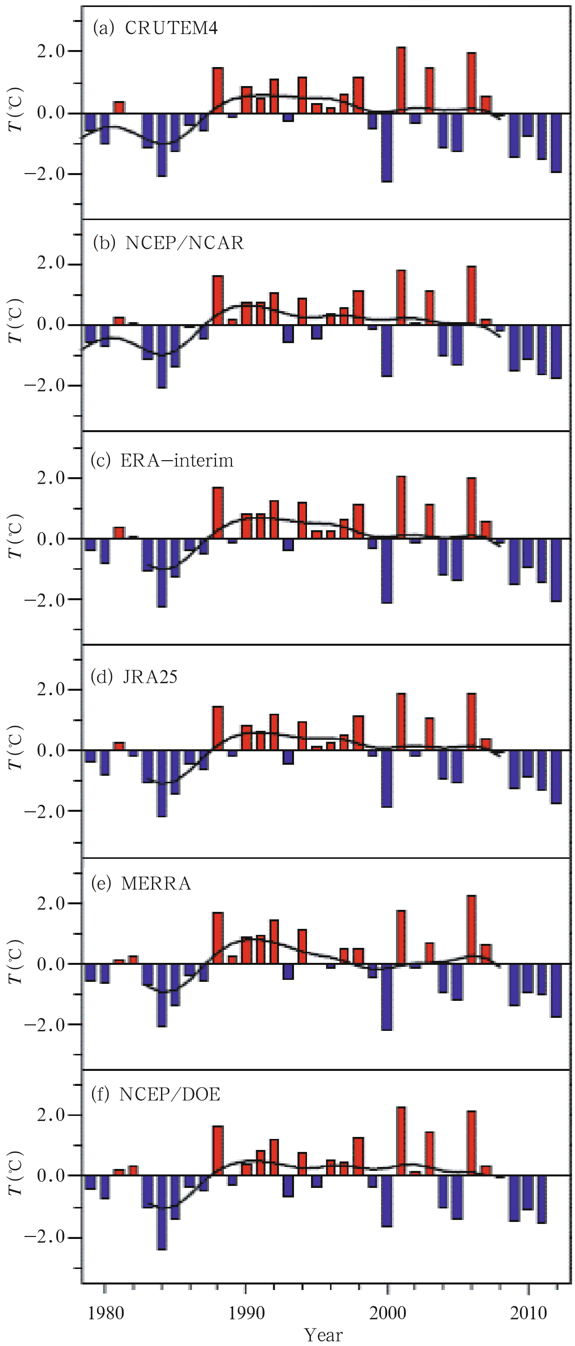


**Fig. 2.** Winter mean surface air temperature anomalies (℃) averaged over East Asia (20°–60°N, 100°–140°E) based on a variety of datasets. The black solid lines denote a 9-yr low-pass-filtered time series with the Lanczos filter. [From Wang and Chen, 2014]

response.

The time series of average winter (December–February) temperature over China over 100 yr (1901–2012) has the same two cold and warm phases as the time series of annual mean temperature (Tang et al., 2012). In addition, despite the recent reduction in the rate of warming in annual mean temperature, the winter temperature averaged over China has remained at high level (Fig. 3a). By contrast, the winter air temperature over Northeast China has declined over the past 10 years (Fig. 3b), suggesting that the stagnation of global warming over the past 10–15 years has been most pronounced over Northeast China. Decreases in winter temperatures have also been observed over northern Xinjiang and Inner Mongolia. These changes in global temperature and temperature over China affect land-sea thermal contrast and the winter atmospheric circulation, which both influence the EAWM. It is therefore necessary to analyze interdecadal variability of SST to gain an insight into their link.

Several recent studies have focused on interdecadal variations in the East Asian summer monsoon (Ding, 2007; Ding et al., 2013). The most pronounced variations occur on 60–80-yr timescales, and may reflect long-term oscillations in global air-sea interactions. The East Asian summer monsoon also varies on 44- and 22-yr periods.

SSTs in the large ocean basins experienced two periods of strong decadal warming during the 20th century. The first occurred in the late 1970s, when decadal-scale warming of SSTs reached 0.4–0.6°C in central and eastern equatorial Pacific (roughly equivalent to the warming associated with a standard El Niño event). Strong cold anomalies in North Pacific during this same period were associated with weather and climate anomalies throughout the world (Ding, 2013). The second warming, which occurred before 1997/98, was most pronounced in the North Atlantic and Indian oceans. SSTs in the central and eastern tropical Pacific have declined during the 15 years after 1998, indicative of a negative phase of the PDO (Tollefson, 2014). The PDO, which has a significant impact on the East Asian monsoon, caused warming in the central and eastern tropical Pacific from the late 1970s through 1998 followed by cooling after 1998. This cooling period has now lasted for 10–15 yr. Assuming a 40-yr periodic oscillation, the warming as-

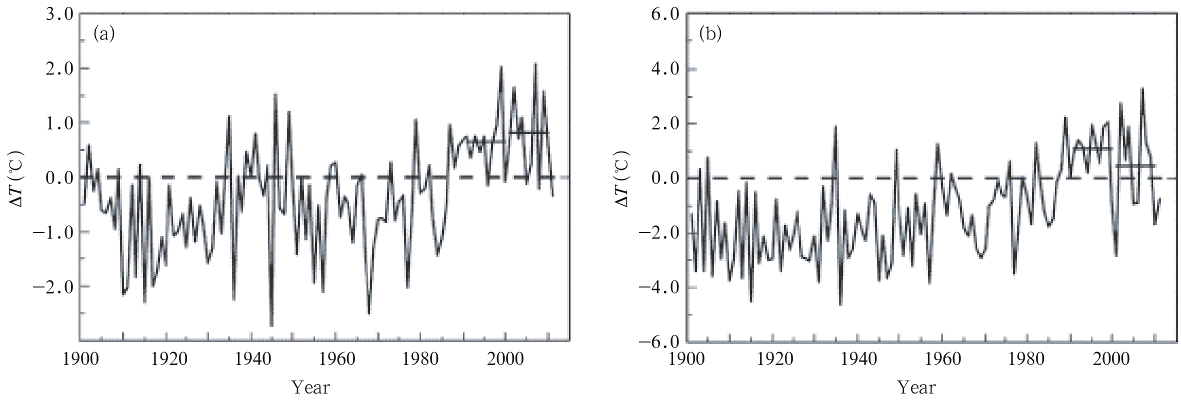


**Fig. 3.** Winter temperature anomalies (℃) averaged over (a) China and (b) Northeast China. Anomalies are calculated relative to the 1971–2000 mean. Short solid lines show decadal mean anomalies during 1991–2000 and 2001–2010. [From Tang et al., 2012]

sociated with the positive phase of the PDO may not return before 2020.

These interdecadal variations in SST over North Pacific have significantly influenced the East Asian monsoon, and hence the climate and weather in China. Variability in North Pacific SSTs can induce changes not only in the strength of the summer monsoon and the "southern flood and northern drought" pattern of precipitation, but also in winter temperatures. These changes can also affect the strength and latitudinal position of the EAWM (Ding, 2007; Wang et al., 2008; Deng et al., 2009). Interdecadal variations in the EAWM are therefore likely a manifestation of interdecadal variations in SST over North Pacific. However, differences in the response time and scope of different components of the climate system can cause regional differences in the timing and other characteristics of interdecadal variations over East Asia and North Pacific.

## 3. Interdecadal variability of the EAWM

### *3.1 Variations of the winter monsoon over East Asia*

The EAWM has experienced remarkable interdecadal variations. The EAWM strengthened consistently from the 1950s through the 1970s, and then weakened substantially after the mid 1980s. Researchers both within China and abroad agree that the weakening of the EAWM and Siberian high during recent decades may be attributable to global warming. Shao and Li (2012) assessed 20 different indices of the EAWM defined before 2009. Their results showed that changes and trends in the strength of the EAWM and related atmospheric circulation anomalies over East Asia are generally consistent among various indices based on different aspects of the EAWM. Although the timing of interdecadal changes and occurrence of strong or weak years obtained by using different indices may not completely agree, most of the indices indicate that the EAWM has weakened since the mid 1980s and that this has been the most pronounced reduction in the strength of the EAWM during the past 100 years. This weakening period coincides with the most rapid warming of winter temperatures over East Asia, and is largely consistent with trends in global mean temperature (Xu et al., 1999; Wu and Wang, 2002; Pei and Li, 2007; Shi et al., 2007; Zhu, 2008; Wang et al., 2010; He and Wang, 2012; He, 2013; Wang and Fan, 2013).

The weakening of the EAWM after the mid 1980s appears to have ended, with observations indicating that the EAWM has strengthened during the early 2000s (Figs. 4 and 5). Winter temperatures over East Asia accordingly decreased, as described in the previous section (see Fig. 3). Interdecadal variations in the EAWM over the past 60 years can be divided into three periods: the period before the mid 1980s when the EAWM was relatively strong, the period from 1987 to 2004 when the EAWM was relatively weak, and

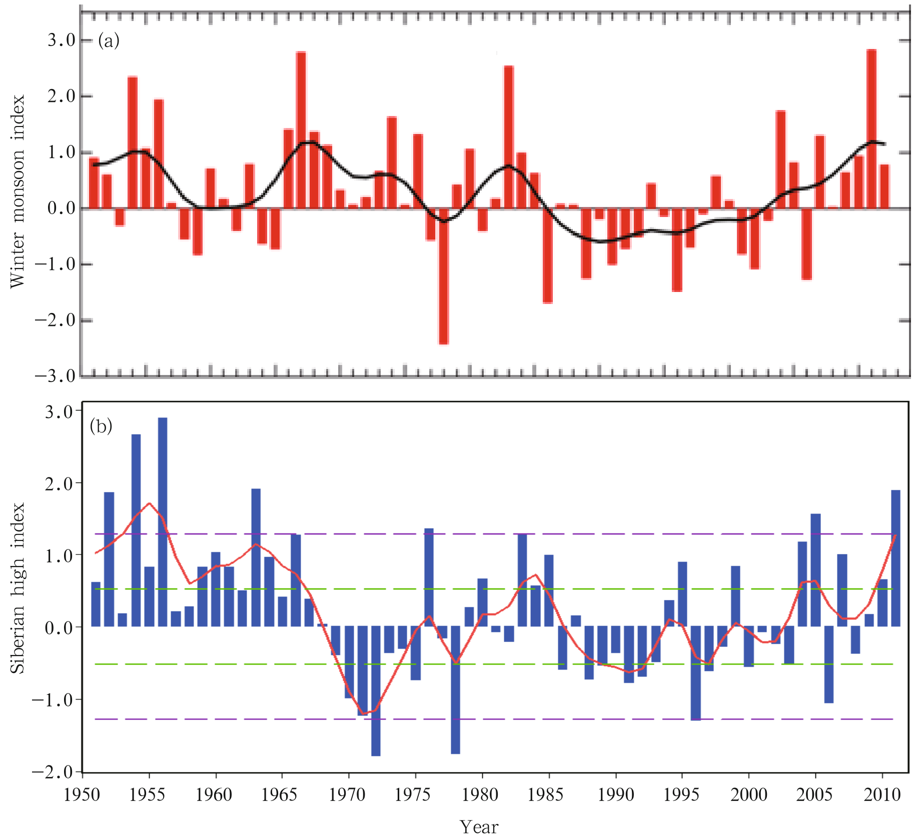


**Fig. 4.** Temporal variations of East Asian winter monsoon indices between winter 1950/51 and winter 2012/13 from (a) China Climate Change Monitoring Bulletin 2013 and (b) China Meteorological Administration (http://cmdp.ncc.cma.gov.cn/extreme/lowtemp.php?product= lowtemp_diag). The black solid line in (a) and the red solid line in (b) denote the Gaussian low-pass filtered time series.

the period since 2005 during which the EAWM has strengthened again (National Climate Center, 2013; Liang et al., 2014; Wang and Chen, 2014).

### *3.2 Variations of winter temperature in China*

The leading EOF mode of winter mean temperatures over China was a homogeneous warming with the maximum located north of 40°N (Fig. 6), suggesting stronger warming in the north than in the south (Kang et al., 2006; Liang et al., 2014). The standardized time coefficient of this leading EOF mode indicates a strong linear warming trend superimposed on interdecadal variability. These variations are particularly clear after a Gaussian low-pass filter is applied to the time series. Winter temperatures in China changed substantially in the mid 1980s, with the winter of 1986/87 as the approximate dividing line between cold and warm periods (Liu and Zheng, 2003; Song and Ji, 2005). The normalized time coefficient of the leading EOF was negative during the cold period (indicating colder winter temperatures throughout China) and positive during the warm period (indicating warmer winter temperatures throughout China). This normalized time coefficient has declined since the winter of 2006/07. This decline has coincided with decreases in temperature and increases in the frequent occurrence of freezing rain, snow, and cold spells during winter in China.

Several studies have further suggested that winter temperature in China has entered a new cold stage during recent years. Two recent studies have proposed that variability in winter temperatures over China can be divided into three stages (Liang et al., 2014; Wang and Chen, 2014). The cold period, when the EAWM was relatively strong, lasted from the win-

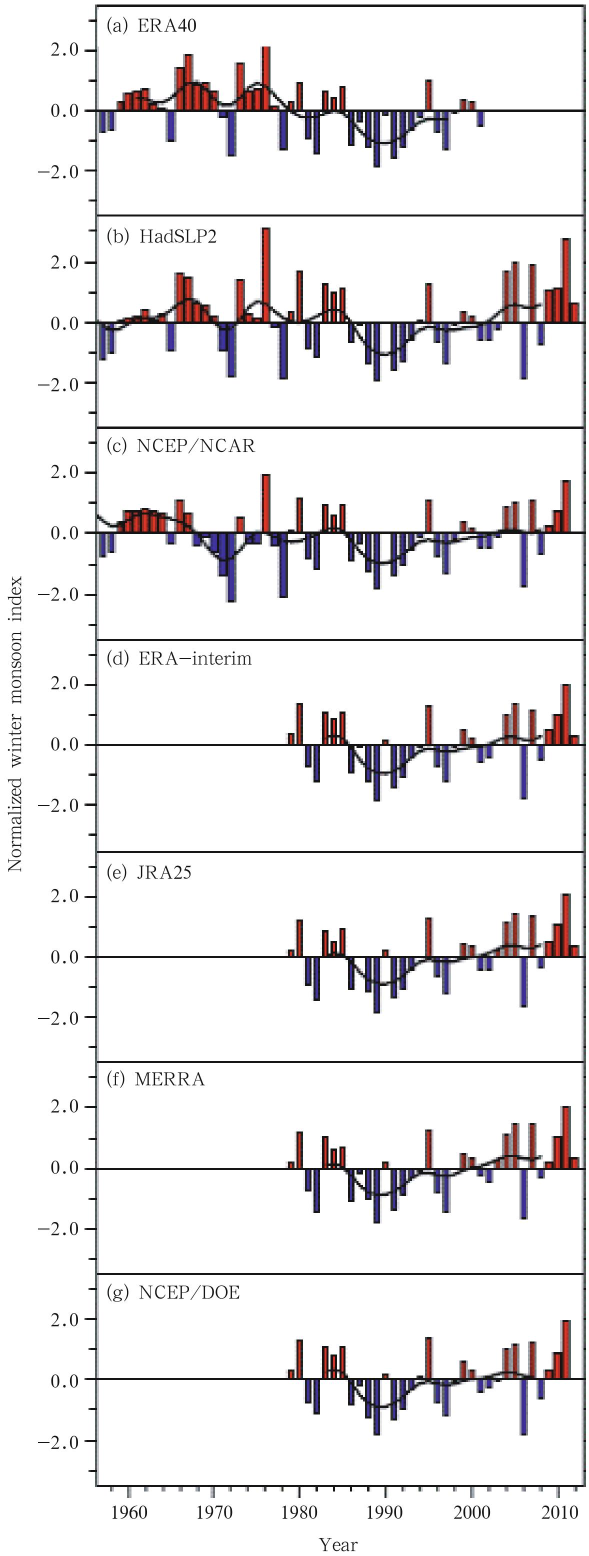


**Fig. 5.** Normalized winter-mean East Asian winter monsoon indices calculated by using a variety of datasets. The black solid lines show the 9-yr low-pass Lanczos filtered time series. [From Wang and Chen, 2014]

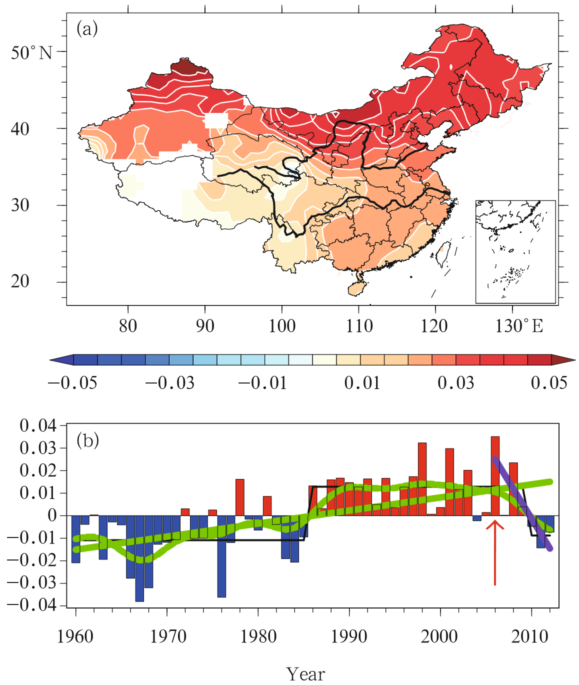


**Fig. 6.** (a) Spatial pattern and (b) normalized time coefficient of the leading EOF mode of winter-mean 2-m air temperature over mainland China between 1960/61 and 2012/13. The colored bars in (b) show the standardized anomaly, black solid line shows stepwise regime shifts in the mean detected by the sequential method, green solid line shows the linear trend, green dashed line shows the Gaussian low-pass filtered time series, purple solid line shows the linear trend between winter 2006/07 and winter 2012/13, and red arrow indicates the winter of 2006/07. [From Liang et al., 2014]

ter of 1960/61 to the winter of 1985/86. The warm period, when the EAWM was relatively weak, lasted from the winter of 1986/87 to the winter of 2005/06. The hiatus period, which has coincided with a strengthening of the EAWM, has lasted from the winter of 2006/07 through at least the winter of 2012/13 (Fig. 7). Most areas of China (with exception of the Tibetan Plateau) experienced colder temperatures during the cold period. The distribution of temperature anomalies during the warm period was exactly opposite, with warm temperatures over most of China (especially north of 35°N) and relatively cold temperatures over the Tibetan Plateau. The distribution of temperature anomalies during the hiatus period

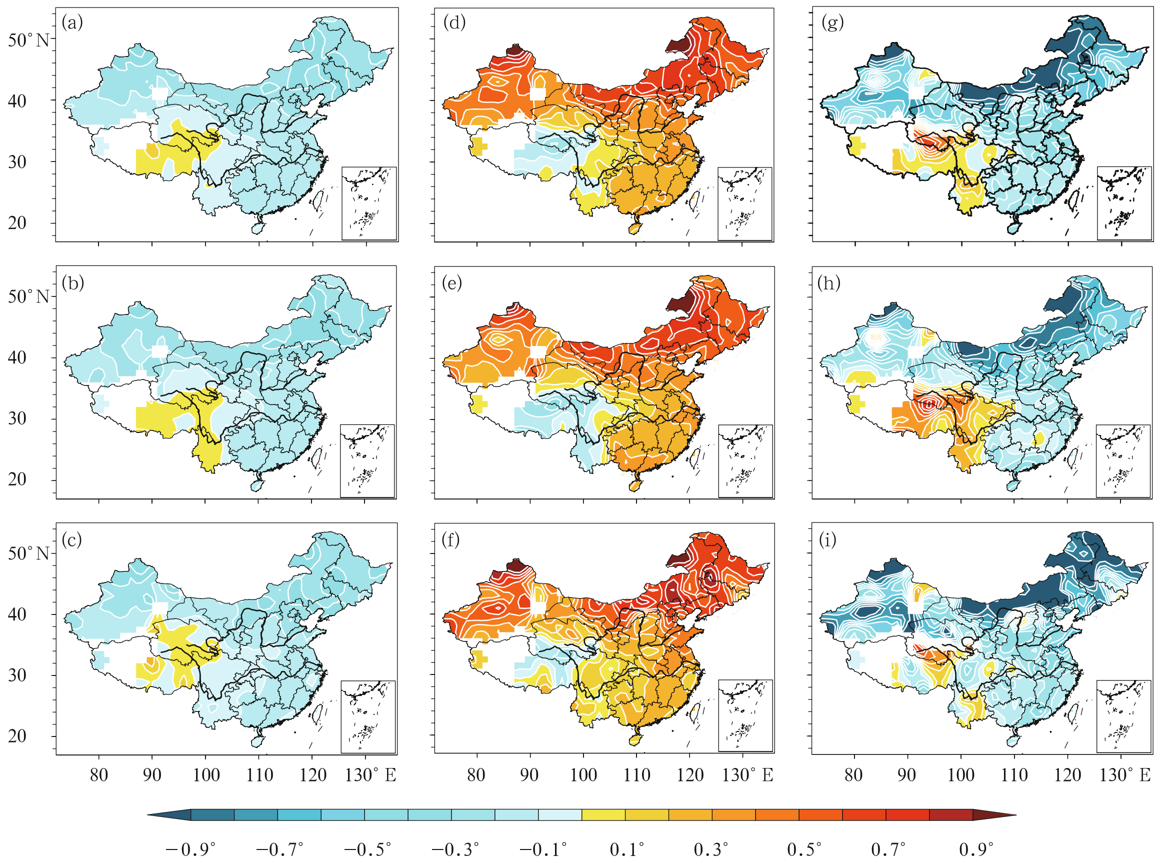


**Fig. 7.** Distributions of detrended winter mean anomalies (°C) in (a, d, g) daily temperature, (b, e, h) daily maximum temperature, and (c, f, i) daily minimum temperature during the (a–c) cold period, (d–f) warm period, and (g–i) hiatus period.

resembles that during the cold period, but the magnitude of the temperature decrease north of 35°N has been larger than that during the cold period, while the warming over the Tibetan Plateau has been much stronger than that during the cold period. The increase in the highest temperatures has been particularly remarkable. The strong cooling in winter over China during the hiatus period is consistent with the decadal changes in winter temperature presented by Tang et al. (2012) (Fig. 8). Although the overall temperature during the hiatus period was higher than that during the cold period, the detrended temperature anomalies indicate a stronger reduction in temperature during the hiatus period than during the cold period. This result highlights the mutual influences of anthropogenic warming and natural variability on winter climate over China. Detrended temperature anomalies over the Tibetan Plateau were very different from those over other areas of China during these three periods. The reasons for these differences need further investigations.

The long-term trend toward a weaker EAWM over the past 60 years has coincided with reductions in the intensity and frequency of cold waves in China. Cold waves happened frequently during the 1950s, with an average frequency of 5.4 cold waves in China per year. The frequency of cold waves declined slightly in the 1960s, and this reduction became more pronounced during the 1970s and 1980s. The occurrence frequency of extreme warm temperatures increased during this period, while the occurrence frequency of extreme cold temperatures decreased. These variations were consistent with the weakening trend of the EAWM since the 1980s, which numerous studies have attributed to global warming (Ding and Sikka, 2006; Wei, 2008; Chen et al., 2013). The EAWM has strengthened over

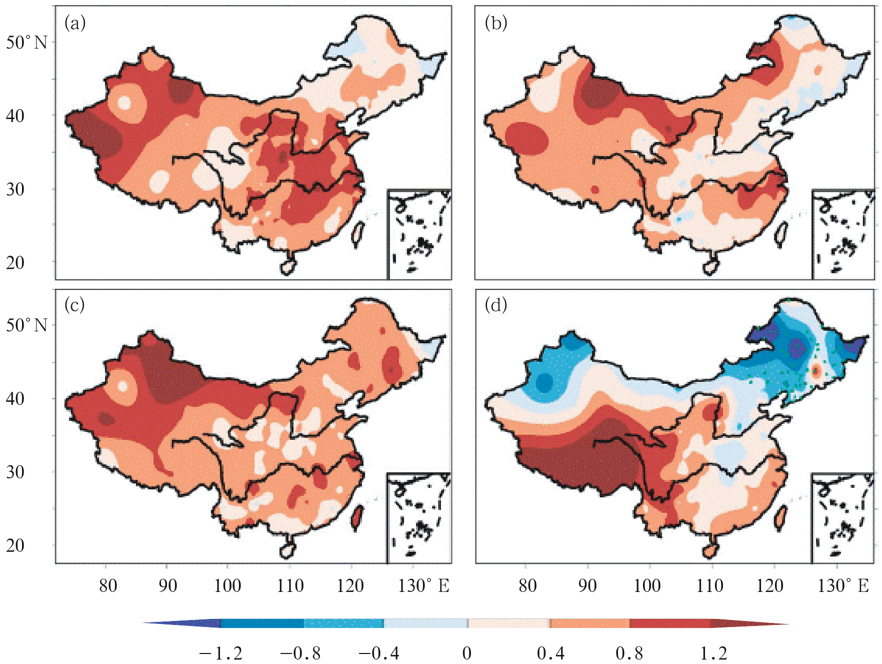


**Fig. 8.** Temperature changes over China from 1991–2000 to 2001–2010 during (a) spring, (b) summer, (c) autumn, and (d) winter. [From Tang et al., 2012]

the most recent 10–15 years; this strengthening has coincided with increases in both the frequency and intensity of cold waves.

### *3.3 Variations in the atmospheric circulation*

The cold Siberian high dominates the mid and high latitudes of the Asian continent during winter (Ding and Krishnamurti, 1987). Sea level pressure anomalies during the warm period were approximately opposite to those during the cold period, while those during the hiatus period were similar to those during the cold period (Figs. 9a–c). During the cold period, sea level pressure anomalies were positive over a large area north of 45°N and negative over most areas south of 45°N. The positive anomalies, which extended from Greenland to the Ural Mountains in northern Eurasia, favored stronger northerly winds over Eurasia and enhanced transport of cold air from high latitudes to mid and low latitudes. During the warm period, sea level pressure was relatively low over mid and high latitudes and relatively high over mid and low latitudes. China therefore experienced stronger transport of warm air from mid–low latitudes, which then led to warmer temperatures. The distribution of sea level pressure anomalies during the warm period reduced the strength of both the trough and the ridge that developed over East Asia during winter, indicating a significant reduction in the strength of the EAWM. During the hiatus period, a strong positive sea level pressure anomaly developed over Eurasia (from the East European Plain cross the West Siberian Plain to the Altai Mountains), significantly strengthening the Siberian high. These conditions were conducive for cold air intrusions into China, and led to significant fall in winter temperature.

The strength of the EAWM is also reflected in the intensity of the upper-level jet stream over East Asia (Jhun and Lee, 2004). The intensity of the upper-level jet averaged over the area 27.5°–37.5°N, 110°–170°E was stronger during the cold period and weaker during the warm period (Figs. 9d–e). By contrast, the intensity of the upper-level jet averaged over the area 50°–60°N, 80°–140°E was weaker during the cold period and stronger during the warm period. Both of these changes are consistent with a stronger EAWM during the cold period than during the warm period. The distribution of 300-hPa zonal wind anomalies during the hiatus period has many similarities with that

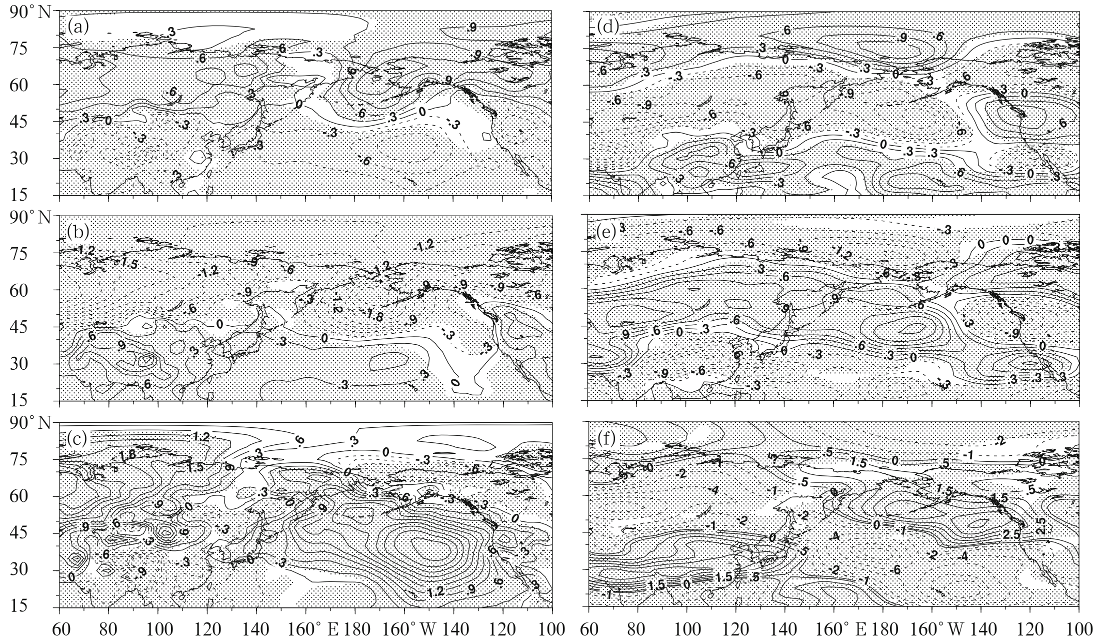


**Fig. 9.** Composite seasonal mean anomalies of sea level pressure (hPa) and 300-hPa zonal wind (m s$^{-1}$) during winter of the (a, d) cold period, (b, e) warm period, and (c, f) hiatus period. The grey stippling indicates statistical significance at the 95% confidence level. [Modified from Liang et al., 2014]

during the cold period, indicating a stronger EAWM; however, the distribution was oriented with northwest–southeast tilting rather than zonally (Fig. 9f). This indicates a northward shift in the EAWM system. The zonal wind anomalies during the cold, warm, and hiatus periods are consistent with variations in the Northern Hemisphere annular mode (NAM) and Arctic Oscillation (AO) and will be discussed further in the following section.

The East Asian major trough is an important component of the mid-tropospheric circulation in the wintertime Northern Hemisphere. The strength of this trough also reflects the strength of the EAWM. During the cold period, 500-hPa geopotential height anomalies were positive in the north and negative in the south (Fig. 10a). The positive anomalies were centered near the Ural Mountains and the Bering Strait, while the strongest negative anomalies over East Asia were located over North China, the Korean Peninsula, and southern Japan. The patterm of these anomalies strengthened the trough and ridge system over East Asia. The deepening of the trough was particularly pronounced. Downward motion over the Siberian area and the southward transport of cold air from high latitudes were both relatively strong, with northerly winds prevailing in the mid troposphere over mainland China. The anomalies in 500-hPa geopotential height during the warm period were opposite to those during the cold period, with negative anomalies in the north and positive anomalies in the south (Fig. 10b). This led to a more zonal circulation in mid and high latitudes, which inhibited the southward propagation of cold air from high latitudes. By contrast, the northward transport of warm air from low latitudes was relatively strong. These changes in temperature advection together led to warmer winter temperatures. During the hiatus period, the negative anomaly in 500-hPa geopotential height over Eurasia was located over the Lake Baikal and the region to its west, while the positive anomaly was located over North Pacific (Fig. 10c). Downward motion over the Siberian region was weaker during this period than during the cold period. The decrease in temperature and the increase in the occurrence frequency of cold waves during the hiatus period occurred mainly over northern areas. According to the quasi-geostrophic relation, changes in the

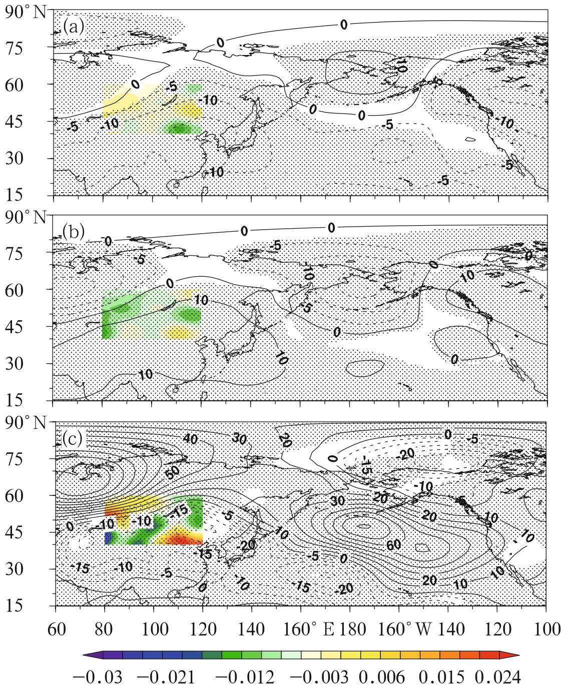

**Fig. 10.** Composite seasonal mean geopotential height (gpm) and vertical velocity (shaded; 0.01 Pa s$^{-1}$) anomalies at 500 hPa during winters of the (a) cold period, (b) warm period, and (c) hiatus period. The grey stippling indicates values significant at the 95% confidence level. [Modified from Liang et al., 2014]

geopotential height field are accompanied by changes in the wind field. The East Asian trough is therefore closely related to the EAWM, and these phenomena combine together to influence winter temperatures in China.

## 4. Reasons for interdecadal variations in the EAWM

Anomalies in the EAWM are associated with a complex circulation system that is composed of multiple components. Both anthropogenic warming and natural climate variability affect the strength and variability of the EAWM. Natural variability in the ocean can cause the development of atmospheric circulation anomalies via air-sea interactions, particularly the anomalies in fluxes of sensible and latent heat. These circulation anomalies affect the winter monsoon, and vice versa. Large-scale coupled atmosphere-ocean variability is therefore a very important factor in the development and variability of the EAWM.

Mainland China is adjacent to North Pacific, and is therefore profoundly influenced by SST anomalies in North Pacific. North Pacific SST experiences strong interdecadal variability (Fig. 11a$_1$), which is dominated by the PDO. The SST of North Pacific warmed substantially from the mid and late 1970s through the end of the 20th century, associated with both the positive phase of the PDO and global warming (Fig. 11a$_2$). The PDO changed to the negative phase during the winter of 2005 (Tollefson, 2014). Previous studies have indicated that interdecadal variations of SST in North Pacific substantially influence the East Asian monsoon and climate in China (Li and Xian, 2003; Wang et al., 2007; Wang et al., 2008). Figure 11b shows low-pass filtered time series of the EAWM index (Zhu, 2008) and the PDO index during winter. The EAWM index and the PDO index are negatively correlated (correlation coefficient –0.55) at the 99% confidence level. This correlation is consistent throughout China, and is particularly strong in northern China. Furthermore, the most significant correlation is with the daily minimum temperature in winter (figure omitted). On the interdecadal scale, the timing of the transition from negative to positive PDO (1978) led the shift in the EAWM (1987; see Section 2).

The EAWM index is also negatively correlated with the AO index. The AO influences the winter monsoon by altering the large-scale circulation pattern over Eurasia, the position and strength of the jet stream, and the strength of the Siberian high (Gong et al., 2002; Wu et al., 2004; Liang et al., 2014). The weakening of the EAWM since the mid 1980s may be associated with the simultaneous enhancement of the AO (He and Wang, 2012). Changes in the NAM have been associated with interannual and interdecadal variations of East Asian climate via their influences on quasi-stationary planetary waves, and can cause changes in the EAWM by influencing the strength of the Siberian high during winter (Wu and Huang, 1999; Gong et al., 2001; Chen and Kang, 2006). Wei and Li (2009) showed that the negative phase of the NAM/AO is associated with a weakening of the westerly jet, a deepening of the East Asian

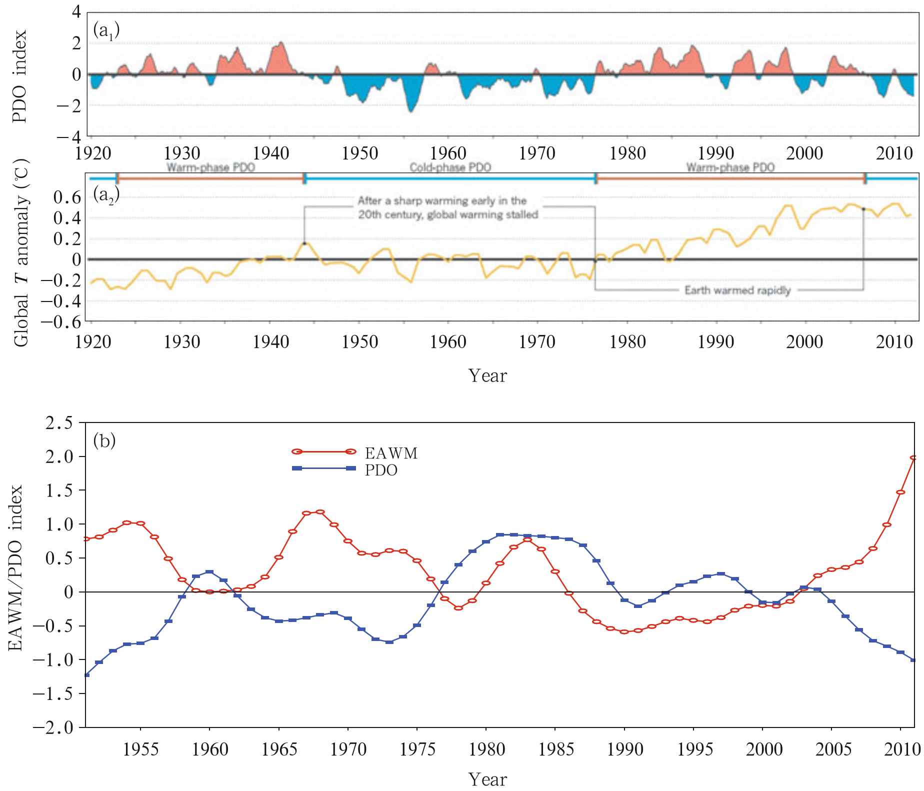


**Fig. 11.** Time series of ($a_1$) the PDO index and ($a_2$) annual global mean temperature anomalies (℃) relative to the 1961–1990 mean (from Tollefson, 2014), and (b) low-pass filtered East Asian winter monsoon index and winter PDO index.

trough, a strengthening of the downward motion behind the East Asian trough, and a strengthening of the Siberian high. The southeastward movement or extension of the Siberian high strengthens the EAWM and increases the occurrence frequency of cold air outbreaks in China. The positive phase of the NAM/AO is associated with the opposite distribution of circulation anomalies, and therefore warmer winter temperatures in China.

Liang et al. (2014) showed that the variance contributions of the NAM/AO were 8.01% on timescales of 15–25 yr and 21.16% on timescales of 40–60 yr, respectively. For comparison, the leading EOF mode of winter minimum temperature accounted for 1.44% of the variance on timescales of 15–25 yr and 21.16% of the variance on timescales of 40–60 yr. These results are consistent with those of Wallace (2000), who reported that the NAM/AO could explain around 30% of the warming signal in global mean temperature. The correlation coefficient between the mean winter NAM/AO index and the normalized time coefficient of the leading EOF of winter temperature in China was 0.75. This correlation coefficient remained relatively high (0.43) even when the 10-yr low-pass filter was not applied. Both correlation coefficients are significant at the 95% confidence level. The correlation coefficient between the PDO index and the leading EOF of winter temperature in China was 0.45 without the low-pass filter. Variations in the PDO index led variations in winter temperatures over China, with a maximum correlation coefficient (0.71) at a lead time of 6 yr. Decomposition indicates good agreement between the normalized time coefficient of the leading EOF of winter minimum temperature and the NAM/AO index in winter on timescales of 15–25 and 40–60 yr. The NAM/AO index slightly led the normalized time coefficient of the leading EOF on timescales of 15–25 yr during the cold period, while the two time series were nearly in phase during the warm period. After the winter of 2000, the normalized time coefficient of the leading EOF slightly led the NAM/AO index on 15–25-yr timescales. By contrast, the NAM/AO index slightly led the normalized time coefficient of the leading EOF on timescales of 40–60 yr, with relatively good agreement throughout the data record. The 40–60-yr NAM/AO index began to decline in 2000, while the 15–25-yr NAM/AO index shifted to a negative phase in 2006. Both time series indicate a transition to the negative phase of the NAM/AO between 2000 and 2005. This transition indicates a shift in the Northern Hemisphere circulation from a zonal circulation to a meridional one, with more frequent cold air outbreaks and lower winter temperatures in China. The normalized time coefficient of the leading EOF also declined around this time. This result further highlights the close relationships between the NAM/AO and winter temperatures in China on these two timescales. In other words, the NAM/AO substantially influenced winter temperatures in China on interdecadal timescales via its effects on the EAWM, particularly on timescales of 15–25 and 40–60 yr.

Studies have suggested that the PDO can modulate the correlation between ENSO and the atmospheric circulation, so the relationship between El Niño/La Niña events and winter temperature in China may not be linear. Different relationships between ENSO and the EAWM, and ENSO and winter temperature in China have been observed during different phases of the PDO (Wang et al., 2008). The correlation between ENSO and the EAWM was strong and negative when the PDO was in the negative phase before the mid 1970s. By contrast, there was no correlation between ENSO and the EAWM when the PDO was in the positive phase after the mid 1970s (Wang and Fan, 2013; Wang and He, 2013). The results of these studies indicate that the influence of ENSO on the EAWM is not stable, and is modulated by variations in North Pacific SST on decadal timescales. The shift to a positive PDO in 1978 may be an important reason behind the weak response of the atmospheric circulation over Asia to ENSO (Wang et al., 2008).

Liang et al. (2014) further investigated differences in the influences of ENSO and the AO on the EAWM under different phases of the PDO. Figure 12 shows that the interdecadal signals of the NAM/AO and the PDO were predominantly in the negative phase during the cold period and predominantly in the positive phase during the warm period. Both time series returned to the negative phase during the hiatus period. Both the PDO and the NAM/AO transformed to the negative phase at the start of this century, consistent with a drop in winter temperature over China (EOF1 and EOF2) and an increase in the frequency of cold ENSO (La Niña) events.

Further analysis indicates differences in the EAWM circulation under different combinations of

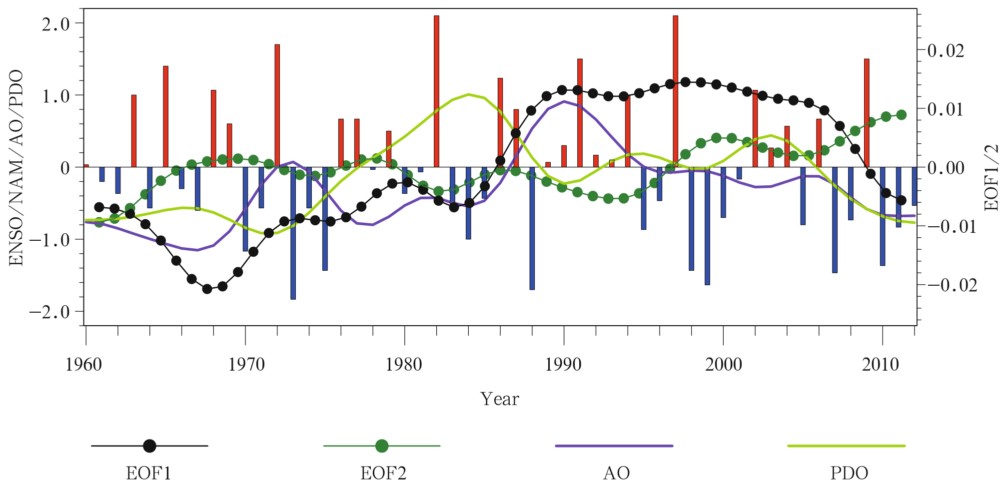


**Fig. 12.** Temporal variations of ENSO index (bars) and 11-yr running means of the NAM/AO index (purple solid line) and PDO index (light green solid line), and normalized time coefficients of the first (black line) and second (dark green line) EOF modes of winter mean temperature over mainland China (lines with filled circles). [From Liang et al., 2014]

NAM/AO and ENSO that can be modulated by the PDO (Liang et al., 2014). When the NAM/AO and ENSO were both in the positive phase, the East Asian circulation was characterized by anomalous southerly winds, a weaker East Asian trough, and warmer winter temperatures in China. By contrast, when both the NAM/AO and ENSO were in the negative phase, the East Asian circulation was characterized by anomalous northerly winds, a deeper East Asian trough, frequent southward cold air outbreaks, and colder winter temperatures in China. The atmospheric circulation pattern over Eurasia associated with interdecadal variations in the PDO and the NAM/AO was similar. Teleconnection patterns associated with interannual variability in the ocean mainly influenced the circulation over the eastern North Pacific and North America, with only small effects on the circulation over Eurasia (especially in mid and high latitudes). These results indicate that interdecadal variations in the circulation over Eurasia were mainly attributable to the PDO, while variations in the circulation over the eastern North Pacific and North America were mainly attributable to interannual signals (e.g., ENSO). Interdecadal variations in winter temperature over mainland China were primarily influenced by interdecadal variations in the NAM/AO and PDO, with the effects of ENSO manifested mainly in interannual north-south oscillations in winter temperature anomalies.

To summarize, the interdecadal variations of winter temperature in China were profoundly influenced by oscillations and variations in the atmospheric circulation and the SST distribution in North Pacific. Figure 13 shows a schematic diagram of the general features and flow patterns during the cold and warm periods. The NAM/AO was in the negative phase during the cold period. Upper-level zonal winds were relatively weak in mid and high latitudes, the East Asian trough was relatively deep, the Siberian high was relatively strong, and the 850-hPa meridional wind anomaly over China was northerly. SST in North Pacific was typical of the negative phase of the PDO, and an anomalous cyclone appeared at 850 hPa over the eastern part of the Philippines. These conditions increased the southward transport of cold air from high latitudes into China, and resulted in relatively cold winters. By contrast, the NAM/AO was in the positive phase during the warm period, with stronger upper-level zonal winds, weaker East Asian trough and Siberian high, and southerly anomaly at 850 hPa over China. The PDO was in the positive phase, with an anomalous anticyclone at 850 hPa over the eastern part of the Philippines. These conditions

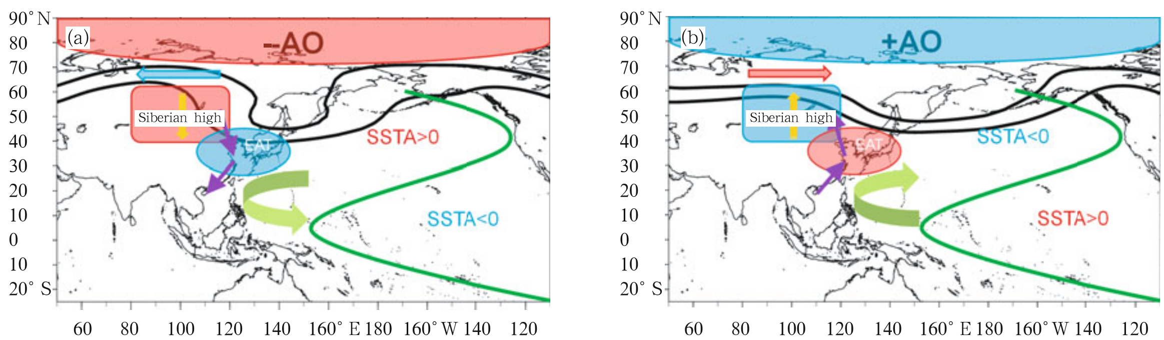


**Fig. 13.** Schematic diagrams depicting the characteristics and circulation patterns during (a) cold and (b) warm periods. The black thick lines represent the 5200-gpm (northern) and 5300-gpm (southern) contours of geopotential height. Shaded ellipses represent the East Asian trough, with red (blue) shading indicating higher (lower) geopotential height values relative to the climatological mean. Shaded boxes represent the Siberian high, with red (blue) indicating higher (lower) values relative to the climatology. The blue arrow in (a) and the red arrow in (b) indicate directions of the mean zonal wind anomalies. Purple arrows represent wind anomalies at 850 hPa. The yellow arrow represents anomalies in vertical velocity, with downward arrow indicating stronger downdrafts. The green contour separates positive SST anomalies from negative ones. The green curved arrow indicates the anomalous 850-hPa cyclone (anticyclone) during the cold (warm) period. Red (blue) shadings in the polar region indicate positive (negative) SLP anomalies corresponding to a negative (positive) NAM/AO index. [From Liang et al., 2014]

enhanced the northward transport of warm and moist air from low latitudes and inhibited the southward transport of cold air from high latitudes, and resulted in relatively warm winters in China.

The mean distribution of SST over the last 10–15 years (Fig. 14a) is consistent with the conceptual model of interdecadal variations in the EAWM presented in Fig. 13. In particular, the mean SST over the equatorial Pacific during the last 10–15 years was typical of La Niña, consistent with more La Niña events than El Niño events over the past 13 years (Fig. 14b). Meanwhile, the SST distribution in North Pacific was typical of the negative phase of the PDO, which favors a stronger EAWM and reduces warming over East Asia.

## 5. Conclusions and discussion

This paper has reviewed the studies on interdecadal variability of the EAWM conducted during recent years. The results of the research in this aspect can be summarized as follows.

(1) The EAWM has been significantly affected by global climate change. Winter temperature over China has experienced three stages since the beginning of the 1950s: a cold period (from the beginning of the 1950s to the early or mid 1980s), a warm period (from the early or mid 1980s to the early 2000s), and a hiatus period (from 1998 to the present). The EAWM has also varied in three stages. The winter monsoon was relatively strong before the winter of 1986/87, relatively weak from 1987/88 through 2004/05, and has strengthened since 2005.

(2) The atmospheric circulation over East Asia, the winter mean temperature, and the occurrence of cold waves in China have all experienced similar interdecadal variations. The upper-level zonal circulation was stronger, the mid-tropospheric trough over East Asia was deeper with stronger downdrafts behind the trough, and the Siberian high was stronger during the cold period than during the warm period. These changes resulted in a stronger EAWM with more frequent cold air outbreaks during the cold period and a weaker EAWM with less frequent cold air outbreaks during the warm period.

(3) Interdecadal variations in the EAWM appear to be closely related to interdecadal variations in the atmospheric circulation and the regional distribution of SST over the Pacific Ocean. The EAWM was stronger during negative phases of the NAM/AO and PDO, and weaker during positive phases of the NAM/AO and PDO. Winter temperatures over China were therefore colder during negative phases of the NAM/AO and PDO than during their positive phases.

The Atlantic multidecadal oscillation (AMO) may also have important effects on the EAWM. The negative phase of AMO corresponded to colder winter temperatures and a stronger winter monsoon, while the positive phase of AMO corresponded to warm winter temperatures and a weaker winter monsoon.

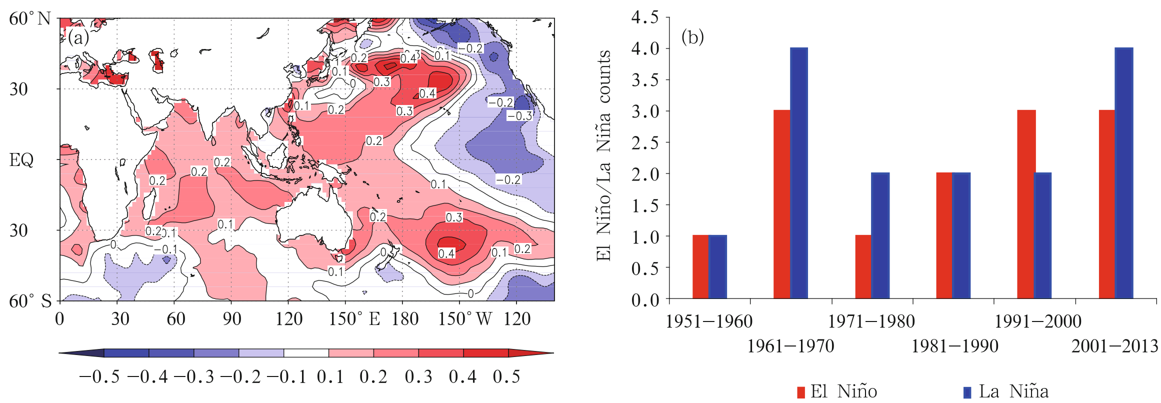


**Fig. 14.** (a) Distribution of mean winter sea surface temperature anomalies (℃) averaged over 2001–2012. (b) Decadal counts of El Niño and La Niña events between 1951 and 2013.

Thus, the AMO is strongly correlated with interdecadal variations in the East Asian monsoon. The AMO refers to quasi-periodic SST anomalies in the North Atlantic Ocean. This oscillation occurs on basin-wide spatial scales with a period of 65–80 yr (Kerr, 2009). Several studies have suggested that the positive (warm) phase of the AMO corresponds to a weaker EAWM and warm winter temperatures over most of China (Qu et al., 2006; Li and Bates, 2007; Yan et al., 2008; Li et al., 2009; Wang et al., 2009b). The significant warming of winter temperatures in China since the mid 1990s may be related to a combination of the warm phase of the AMO and global warming due to anthropogenic greenhouse gas emissions. The warming trend in winter temperatures over China slowed down with the advent of the negative (cold) phase of the AMO (Li and Bates, 2007; Li et al., 2009). Figure 15 shows the detrended time evolution of mean winter temperature over China and the AMO index during winter. The negative (cold) phase of the AMO corresponded to lower winter temperatures and stronger winter winds over China, while the positive (warm) phase corresponded to higher winter temperatures and weaker winter winds over China;

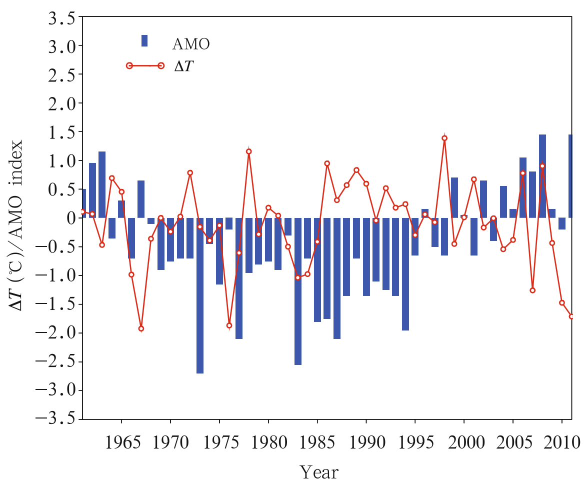


**Fig. 15.** Detrended time series of winter mean temperature anomalies (red line; ℃) and winter AMO index (blue bars; ℃) from 1961 to 2010. The AMO index is calculated as the SST anomaly averaged over North Atlantic (0°–60°N, 0°–80°W) by using the method proposed by Trenberth and Dennis (2006).

however, changes in the AMO and changes in winter temperatures over China were not completely in phase. Although the AMO exerts an important influence on winter temperature in China, its role relative to that of the PDO requires further investigations.

Interdecadal variations in the ocean may therefore be regarded as one of the most important natural factors influencing the variability of the EAWM on long timescales, although global warming may have also played a significant role in weakening the EAWM.

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