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The East Asian winter monsoon: re-amplification in the mid-2000s

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Abstract Based on several reanalysis and observational datasets, this study demonstrates that the East Asian winter monsoon (EAWM) recovered from its weak epoch and re-amplified in the mid-2000s. Accordingly, East Asia has experienced more cold winters and significant negative surface air temperature anomalies during the recent strong EAWM epoch spanning the period 2004–2012. The associated cooling was mainly located over inland northern East Asia with a west–east orientation. The cooling generally coincided with negative winter temperature trends in eastern Eurasia in the last two decades, possibly contributing to the observed regional cooling trend when the global mean temperature is still trending up. Enhanced wintertime blocking activity around the Ural mountain region and diminished Arctic sea ice concentration in the previous September are suggested to be the responsible internal atmospheric process and external driver for the recent re-amplification of the EAWM, respectively.

Keywords East Asian winter monsoon · Blocking · Sea ice · Global warming · Trend

1 Introduction

The East Asian winter monsoon (EAWM), which is of great significance to East Asia's weather and climate, is a distinct and active component of the global circulation system [1, 2]. Accompanied by clear changes in both external forcing and internal atmospheric dynamic processes, the EAWM entered a decadal weak phase in the late 1980s [3–5]. The resulting increase in surface air temperature contributed to the global warming trend and explains, to some extent, the greater-than-average warming trends over East Asia reported by the Intergovernmental Panel on Climate Change [6].

Although the global annual mean temperature is still trending upward, widespread cooling trends have been observed in recent years across large stretches of the mid-latitude Northern Hemisphere, including East Asia, during the boreal winter in recent years [7–9]. For example, Wu et al. [9] reported a cooling trend over central Siberia over the last two decades, and the trend was confirmed by two subsequent studies using independent datasets [7, 8]. Concurrently, the Siberian High experienced a salient recovery [9, 10], particularly after 2003 [9]. Moreover, severe cold spells and damaging snowstorms were frequently observed over East Asia during the recent winters such as 2004 [11], 2005 [12], 2007 [13], and 2009 [14]. These cold spells were far more frequent and prevalent than those that occurred before the mid-2000s. A natural question is whether the EAWM recovered from its decadal weak phase. If so, what are the characteristics and possible causes of the re-amplification? These issues are investigated in this paper.

2 Data and methods

The monthly mean datasets used in this study are listed in Table 1. We focus on winter means that are constructed by averaging the monthly means of December, January, and February (DJF). Most of the data cover the most recent months, including the winter of 2012. Here, 2012 refers to the boreal 2012/13 winter. The index proposed by Wang

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Table 1 Datasets used in this study

	Resolution	Period of record
ERA40 reanalysis	2.5° × 2.5°	1957.9–2002.8
NCEP/DOE reanalysis	2.5° × 2.5°	1979.1–2012.12
NCEP/NCAR reanalysis	2.5° × 2.5°	1948.1–2013.2
ERA-Interim reanalysis	1.25° × 1.25°	1979.1–2013.2
JRA25 reanalysis	2.5° × 2.5°	1979.1–2013.2
MERRA reanalysis	2/3° × 0.5°	1979.1–2013.2
HadSLP2	5° × 5°	1850.1–2013.2
CRUTEM4	5° × 5°	1850.1–2013.2
HadISST	1° × 1°	1870.1–2013.2

and Chen [15] is employed to describe the strength of the EAWM, which can delineate both the circulation and surface air temperature features associated with the EAWM. The definition of this index is

$$I_{\mathrm{EAWM}} = (2 \times \mathrm{SLP}_1^* - \mathrm{SLP}_2^* - \mathrm{SLP}_3^*)/2, \qquad (1)$$

where SLP_1^*, SLP_2^*, and SLP_3^* indicate the normalized area-averaged winter mean sea level pressure (SLP) over Siberia (40°–60°N, 70°–120°E), the North Pacific (30°–50°N, 140°E–170°W), and the Maritime Continent (20°S–10°N, 110°–160°E), respectively. In addition to the monthly mean datasets, the daily mean data are used to detect blocking events, following the definition and algorithm proposed by Barriopedro et al. [16]. In this study, the climatology mean is defined as the average for the period spanning 1971–2000 (for the ERA40 dataset) and as the average for the period spanning 1981–2010 otherwise.

3 Re-amplification of the EAWM

Figure 1 illustrates the normalized EAWM indices and their decadal components based on seven reanalysis and observational datasets. Positive index denotes a strong EAWM, i.e., below-normal surface air temperature over East Asia. The EAWM is shown to be in the strong epoch from the early 1960s to the mid-1980s (Fig. 1a, b) and in the weak epoch from the mid-1980s to the early 2000s (Fig. 1a–g), consistent with previous studies [3–5]. We notice that the EAWM variability revealed by the NCEP/NCAR data is somewhat different from that revealed by the ERA40 and HadSLP2 data before 1976 (Fig. 1a–c; Table 2). This discrepancy can be attributed to the biases of the NCEP/NCAR dataset over East Asia for the period before the late 1970s [17]. Our analysis confirms this bias and suggests that despite the biased results before 1976, the EAWM variability in the NCEP/NCAR data agrees quite well with the variability in the ERA40 and HadSLP2 data for the period after 1976 (Table 2).

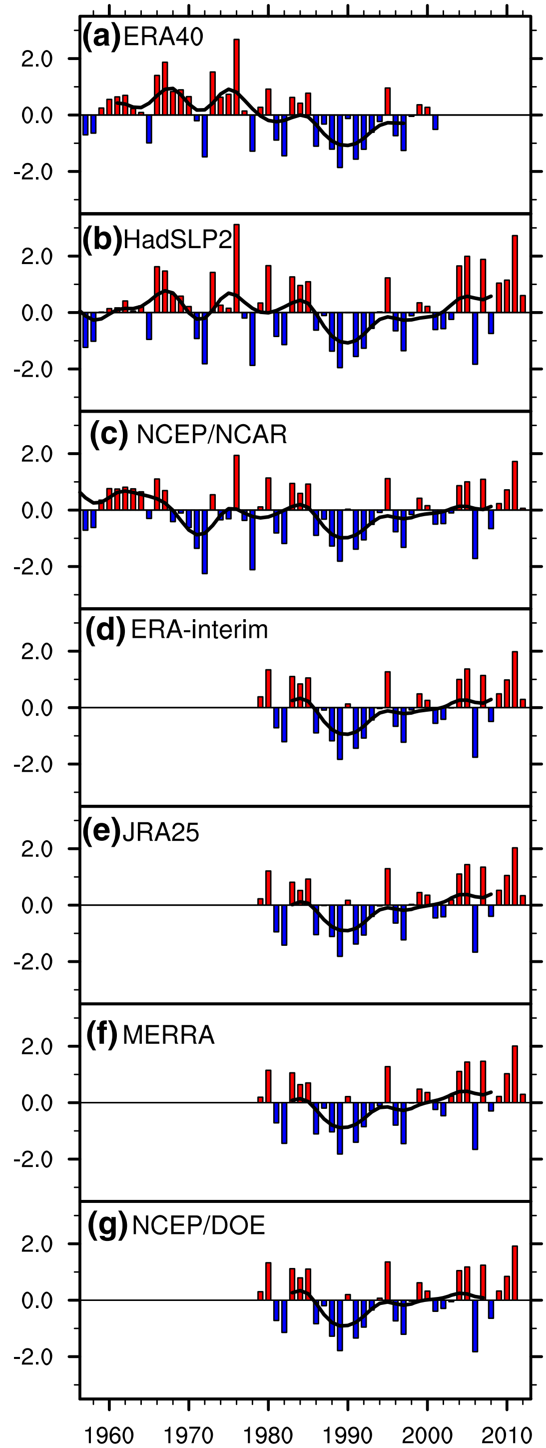


Fig. 1 Normalized winter mean EAWM index (*bar*) based on **a** ERA40, **b** HadSLP2, **c** NCEP/NCAR, **d** ERA-interim, **e** JRA25, **f** MERRA, and **g** NCEP/DOE datasets for the periods **a** 1957–2001, **b**, **c** 1957–2012, **d–f** 1979–2012, and **g** 1979–2011. The *lines* indicate 9-year low-pass components using the Lanczos filter

After the extreme negative values that are centered around 1990, the decadal component of the EAWM index recovers gradually, starting in the mid-1990s (Fig. 1a–g).

Table 2 Correlation coefficients of the EAWM index among different datasets for the periods 1957–1975 (left column) and 1976–2001 (right column)

	HadSLP2	ERA40
NCEP/NCAR	0.75/0.98	0.68/0.96
ERA40	0.96/0.98	

All of the correlation coefficients exceed 99.9 % confidence level based on Student's *t* test

The decadal component of the EAWM index then turns positive in the early 2000s in all of the datasets that contain temporal coverage until recent years (Fig. 1b–g). Especially when we look at the period 2004–2012, seven out of the nine winters experienced a strong EAWM. Moreover, the strength of the EAWM in recent years is even stronger than that before the late 1980s (Fig. 1), in spite of the continuous global warming trend. These results are highly consistent among various datasets, and suggest that the EAWM is likely to begin a strong epoch in recent years.

To further substantiate this interpretation, the winter mean surface air temperature averaged over East Asia (20°–60°N, 100°–140°E) is shown from 1979 to 2012 (Fig. 2). This temperature series reveals that the low-frequency component of the East Asian winter temperature is below-normal before 1987 and after 2008, and is above normal in between. Although the temperature series does not turn negative in the early 2000s, as does the EAWM index, it is only slightly above zero in the early and mid-2000s. Again, we examine the period 2004–2012. Seven out of the nine winters featured colder-than-normal conditions over East Asia (Fig. 2a–e), which is exactly in agreement with the results revealed by the EAWM index (Fig. 1b–f). Therefore, both the negative regional temperature anomalies and the high frequency of cold winters confirm that the EAWM did re-amplify and entered a strong epoch in recent years.

4 Possible causes

Now, the question is what are the spatial characteristics and possible causes of the recent re-amplification of the EAWM? In the following sections, the period 2004–2012 is referred to as the *recent* strong EAWM epoch and is compared with the *previous* strong EAWM epoch of 1976–1987. Figure 3 shows the spatial pattern of temperature and circulation anomalies associated with the previous and recent strong EAWM epochs. In the previous strong epoch, significant cooling was mainly observed along the coast of East Asia, with a magnitude of approximately −1 °C (Fig. 3a). Northwestern Europe, southeast North America, and the central North Pacific also

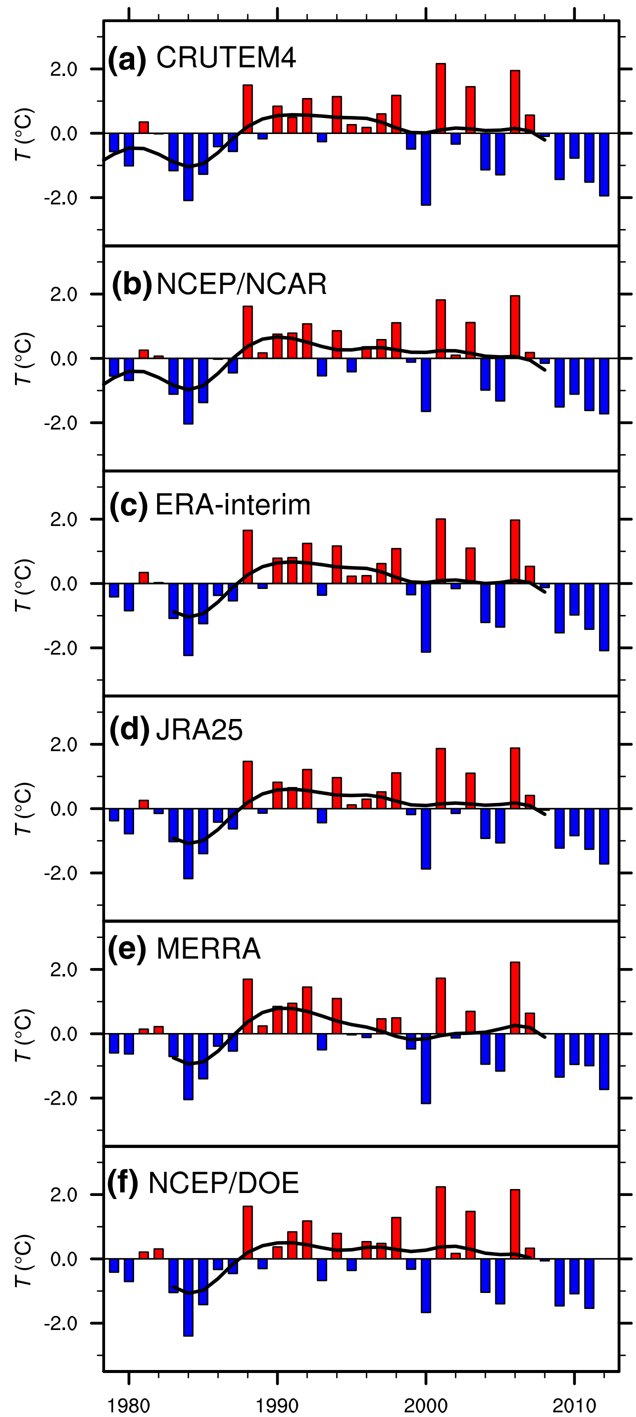
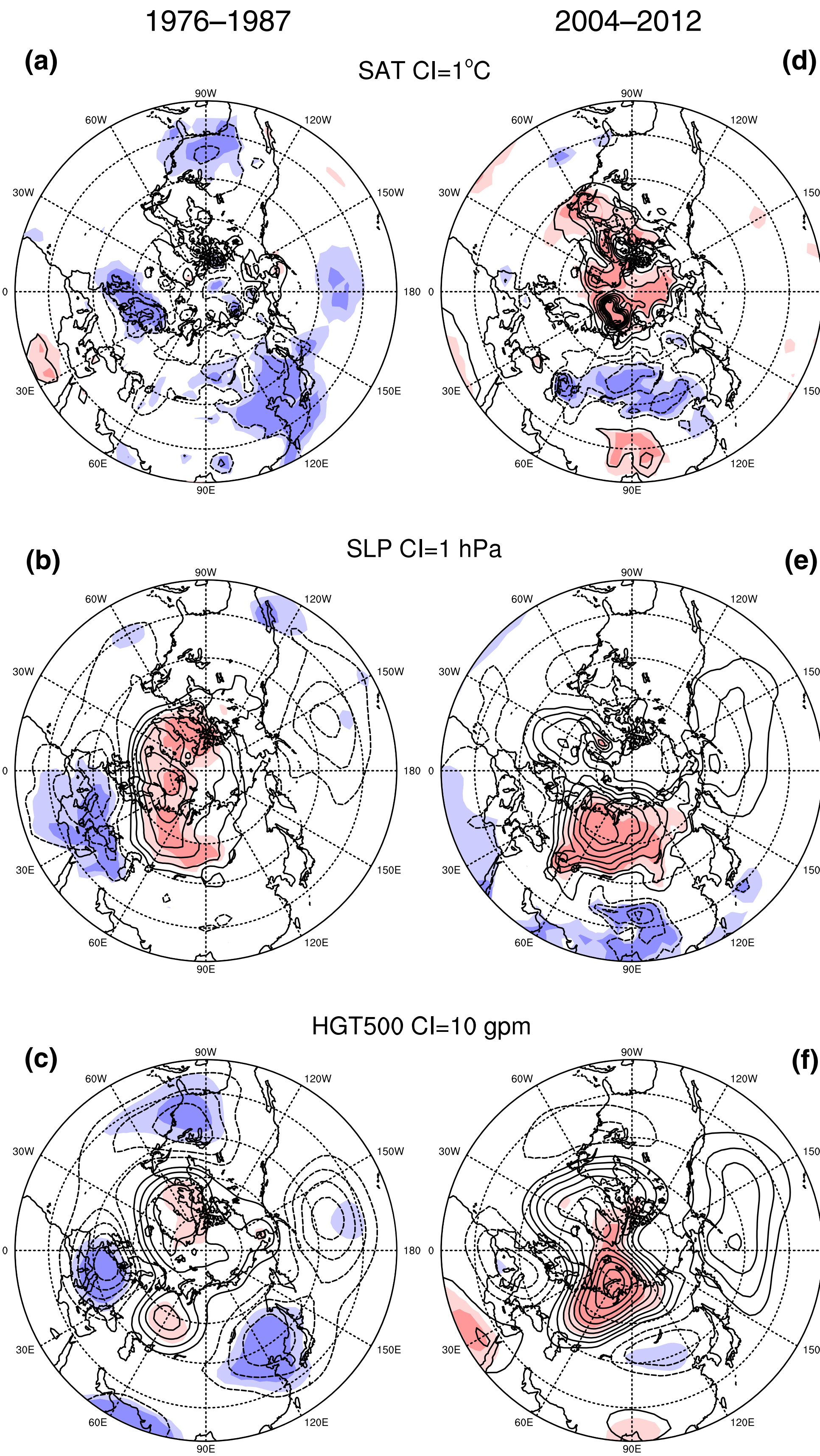


Fig. 2 Winter mean surface air temperature anomalies averaged over East Asia (20°–60°N, 100°–140°E) (*bar*, unit: °C) based on **a** CRUTEM4, **b** NCEP/NCAR, **c** ERA-interim, **d** JRA25, **e** MERRA, and **f** NCEP/DOE datasets for the periods **a**–**e** 1979–2012 and **f** 1979–2011. The *lines* indicate 9-year low-pass components using the Lanczos filter

experienced significant cooling, while no significant warming was observed in the extra-tropical Northern Hemisphere (Fig. 3a). This temperature pattern and the


1976–1987
2004–2012
(a)
SAT CI=1°C
(d)
(b)
SLP CI=1 hPa
(e)
HGT500 CI=10 gpm
(c)
(f)
90W
60W
120W
30W
150W
0
180
30E
150E
60E
120E
90E

◀**Fig. 3** Composite anomalies of winter mean **a** surface air temperature, **b** sea level pressure, and **c** 500 hPa geopotential height for the previous strong EAWM epoch 1976–1987 based on the NCEP/NCAR reanalysis dataset. **d–f** are the same as **a–c**, except for the recent strong EAWM epoch 2004–2012. The composite is performed with respect to the weak EAWM epoch 1988–2003. Contour intervals are 1 °C in **a** and **d**, 1 hPa in **b** and **e**, and 10 gpm in **c** and **f**. *Light and dark shading* indicates 95 % and 99 % confidence levels, respectively

related circulations (Fig. 3b, c) resemble those associated with the Northern annular mode (NAM [18]). In fact, the previous strong epoch can be accounted for by the negative phase of NAM [3, 5] and the associated planetary wave activities [3]. During the recent strong epoch, in contrast, the cooling is mainly oriented west–east and is confined over inland northern East Asia (Fig. 3d). The magnitude of cooling exceeds −3 °C and is stronger than cooling in the previous strong epoch. In addition, two significant warming regions are observed over the Arctic and the Tibetan Plateau (Fig. 3d). The different temperature patterns between Fig. 3a and d implies that the recent strong EAWM epoch is not likely associated with the NAM.

Previous studies suggest that the variations of the EAWM are closely related to the blocking activity around the Ural mountain region (hereafter referred to as Ural blocking), with more (less) frequent Ural blocking facilitating stronger (weaker) EAWM [19–21]. This relationship was particularly pronounced in recent decades [21]. Moreover, an inspection of the geopotential height field indicates that the barotropic high-pressure center around the Ural mountain region is the most significant and consistent signal throughout the troposphere (Fig. 3e, f). This result suggests that enhanced Ural blocking is likely the key factor of the recent strong EAWM epoch.

Figure 4a shows the number of blocking days [16] over the Ural region (50°–80°E) for the winters 1976–2012. The Ural blocking frequency experiences a clear decrease around 1985 and an increase around 2002 (Fig. 4a), which is generally consistent with the decadal variations of the EAWM index (Fig. 1) and East Asian temperature (Fig. 2). An inspection of the longitudinal distribution of blocking frequency further confirms this result. The Ural mountain region (e.g., the area around 60°E) experienced more blocking days in the recent and previous strong EAWM epochs and fewer blocking days in the weak EAWM epoch (Fig. 4b), supporting the analysis of the winter mean circulation (Fig. 3e, f). Although a similar change can be observed over the Pacific sector (e.g., around 180°), its magnitude is small (Fig. 4b). The changes in blocking days are large over the Atlantic sector, but they are not consistent during the recent and previous strong epochs. These results, therefore, suggest that the recent strong EAWM epoch should be attributed to higher blocking frequency

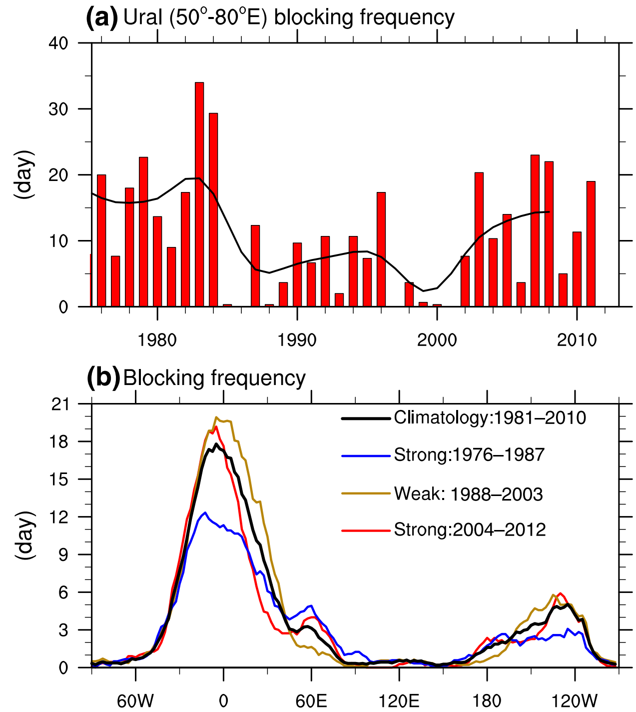


Fig. 4 **a** Winter mean blocking frequency over the Ural mountain region (50°–80°E) for the period 1976–2012. **b** Winter mean blocking frequency for the climatology, the strong EAWM epochs 1976–1987 and 2004–2012, and the weak EAWM epoch 1988–2003. The *line* in **a** indicates a 9-year low-pass component using the Lanczos filter. The results are based on the NCEP/NCAR reanalysis dataset

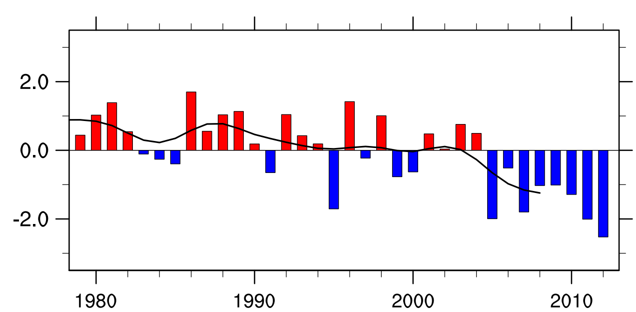


Fig. 5 The normalized area-averaged Arctic sea ice concentration over the Kara-Laptev Sea (76.5°–83.5°N, 60.5°–149.5°E) for the Septembers 1979–2012. The *line* indicates a 9-year low-pass component using the Lanczos filter

and the associated high-pressure center around the Ural mountain region.

5 Summary and discussion

Based on comprehensive reanalysis and observational datasets, this study identifies the recent amplification of the EAWM. During the recent strong epoch of 2004–2012, frequent cold winters and significant negative surface air temperature anomalies were observed over East Asia. The decadal cooling, the magnitude of which exceeded −3 °C, was mainly located over inland northern East Asia and had a west–east orientation. These characteristics are in contrast to the previous strong epoch of 1976–1987, when the cooling was oriented more north–south along the East Asian coast and had a magnitude of approximately −1 °C. Further analysis indicates that the recent strong EAWM epoch is a result of enhanced blocking activity and an associated positive geopotential height anomaly around the Ural mountain region.

It is interesting to note such significant decadal cooling over East Asia when the global mean temperature is simultaneously rising. Moreover, the region experiencing this cooling generally coincides with that of the negative winter temperature trend over the eastern Eurasian continent in recent decades (e.g., Fig. 6e of [9], Fig. 3b of [7]), implying that the recent strong EAWM epoch may have contributed to the negative trend. In contrast, the cooling trends over Europe and southeast North America [7] are not likely associated with the decadal variations of temperature due to the lack of signal in Fig. 3d. Therefore, our results may imply some active influences of the EAWM on the regional temperature trend pattern.

It should be noted that the changes in Ural blocking are only part of the story of the recent amplification of the EAWM because the low-frequency variability in the climate system is generally associated with atmospheric external forcing. For example, Wu et al. [22] revealed for the first time that less (more) wintertime sea ice over the Kara and Barents seas would cause strong (weak) EAWM by modulating East Asian cold wave activities. Below-normal autumn (especially September) Arctic sea ice is also suggested as an important driver and potential predictor of excessive wintertime snowfalls and cold spells over the mid-latitude Northern Hemisphere on the inter-annual timescales [9, 23–25] through modulating the cyclone tracks [25] or exciting stationary Rossby waves [23]. We analyzed several atmospheric external factors associated with the recent strong EAWM epoch, including sea ice, snow cover, and sea surface temperature, and found that the Arctic sea ice concentration is likely responsible for the recent strong EAWM epoch.

Figure 5 shows the normalized area-averaged Arctic sea ice concentration (SIC) over the Kara-Laptev Sea (76.5°–83.5°N, 60.5°–149.5°E, [9]) for the Septembers of 1979–2012. The low-frequency component of the SIC series turns negative in 2004, which is coincident with the start of the recent strong EAWM epoch. Moreover, the spatial patterns of both the surface air temperature and the sea level pressure over East Asia in our analysis (Fig. 3d, e) resemble those associated with diminished Arctic SIC (e.g., Fig. 2a, c of [24]), further indicating the possible role of the Arctic SIC in the recent strong EAWM epoch. Nevertheless, it is noteworthy that the surface air temperature anomalies associated with the Arctic SIC extend to Europe and North America (Fig. 2c of [24]), whereas those associated with the recent strong EAWM epoch are confined to East Asia (Fig. 3d). These discrepancies suggest that the processes through which the Arctic SIC influences the climate may be different on inter-annual and decadal timescales. The complexity of the involved mechanism is an interesting issue and deserves further study.

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