Decadal variations of the East Asian winter monsoon in recent decades

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Abstract
Observational studies indicated that the East Asian winter monsoon (EAWM) showed significant decadal variations and experienced an interdecadal weakening in the mid-1980s. How did the EAWM evolve thereafter? In this study, we investigate the decadal variations of the EAWM in the past three decades using five reanalysis datasets and one observational dataset. In total, five members of EAWM system are examined. In the lower troposphere, the Siberian high intensity becomes stronger around 2005 in all five reanalysis datasets, whereas the Aleutian low strengthens in the mid-1990s and weakens in the mid-2000s. The two subsystems show opposing changes in the past two decades. In the middle troposphere, the intensity of the East Asian trough remains weakening in recent decades only with some short-time strengthening around the years of 1995 and 2010. In the upper troposphere, the EAWM index based on the meridional shear of the East Asian jet stream at the 300-hPa level shows a weak positive trend since the 1990s. It has decadal variations similar to those of the East Asian trough. In the context of these members’ changes, the low-level northerly wind index exhibits two cycles since the year 1980. This index increases in the mid-1980s, then decreases since the mid-1990s, and finally increases in the mid-2000s. Further analysis on the East Asian surface air temperature also reflects similar decadal variations. In summary, unlike the interdecadal shift in the mid-1980s, the EAWM members (i.e., the Siberian high, the Aleutian low, the low-level northwesterly wind, the East Asian trough and the East Asian jet stream) do not show consistent decadal variations over the past 30 years. The low-level members show more significant changes.

KEYWORDS
decadal variation, east Asian winter monsoon, inconsistent changes, reanalysis dataset

1 | INTRODUCTION

The East Asian winter monsoon (EAWM) is one of the most active atmospheric circulation systems in the boreal winter (Wang and Fan, 2013). Based on the previous studies, the EAWM has great impacts on the weather and climate over East Asia, including strong cold events and snowstorms (Wang et al., 2017; Zhou et al., 2017, 2018;
Wang and Zhou, 2018). For instance, the strengthened Siberian high-induced northerly cold advections and played an essential role in enhancing the snowfall events in central eastern China in January 2018 (Sun et al., 2019). These events caused substantial economic losses and deaths and bring great inconvenience to people’s daily lives. In addition, it also influences the weather and climate over remote regions. For instance, the anomalous daily lives. In addition, it also influences the weather and climate over remote regions. For instance, the anomalous

TABLE 1

| Name               | Definition                                           | Reference       |
|--------------------|------------------------------------------------------|-----------------|
| Siberian high index| SLP (40°–60° N, 70°–120° E)                         | Gong et al., 2001|
| Aleutian low index | SLP (30°–70° N, 155° E–130° W)                      | Wang and He, 2012|
| Low-level wind index | V, 850 hPa (20°–40° N, 100°–140° E)              | Yang et al., 2002|
| EAT index          | H, 500 hPa (30°–45° N, 125°–145° E)                | Sun and Li, 1997|
| EAWS index         | U, 300 hPa (27.5°–37.5° N, 110°–170° E) – (50°–60° N, 80°–140° E) | Jhun and Lee, 2004|

Abbreviations: H, geopotential height; U, zonal wind; V, meridional wind.

In this study, we thus examine the decadal variations of the whole EAWM system in recent decades using multiple datasets and different kinds of EAWM indices. The indices reflect evolution of different members of the EAWM system. The data and methods used here are briefly described in Section 2. Section 3 illustrates the decadal changes of the EAWM in detail. Section 4 presents some discussion and conclusions.

## 2 | DATA AND METHOD

In this study, the monthly atmospheric variables from five updating reanalysis datasets are used to examine changes in the EAWM in recent decades. They are the ERA-Interim (Dee et al., 2011), JRA-55 (Ebita et al., 2011), MERRA-2 (Gelaro et al., 2017), NCEP-DOE (Kanamitsu et al., 2002) and NCEP/NCAR (Kalnay et al., 1996) reanalysis datasets. In addition, the surface air temperature (SAT) from the CRUTEM4 dataset is also used here to illustrate the climatic impacts associated with the EAWM changes. Winter in this study denotes the means of December, January and February. The winter of 2019, for example, is calculated by averaging the months December 2018, January 2019 and February 2019.

To quantitatively investigate decadal variations of the EAWM system, five categories of EAWM indices are analyzed in this study (Table 1). All the indices are standardized with the reference period of 1981–2010. In the lower troposphere, the Siberian high index and Aleutian low index are defined as area-averaged SLP over the regions of 40°–60° N, 70°–120° E and 30°–70° N, 155° E–130° W,
respectively. A positive value of the Siberian high index denotes a stronger Siberian high. On the contrary, a positive value of the Aleutian low index denotes a weaker Aleutian low. The SLP gradient between these two sub-systems can induce northwesterly winds along the East Asian coast, and the low-level wind index is defined by area-averaged meridional winds over the region of 20°–40°N, 100°–140°E. A positive value of the low-level wind index denotes weaker northwesterly winds there. In the middle troposphere, the EAT locates around the Korean Peninsula and the Japan Islands. Thus, the area-averaged 500-hPa geopotential height over there (30°N–45°N, 125°E–145°E) is defined as the EAT index. A positive value of the EAT index means a shallower and weaker EAT. In the upper troposphere, the EAJS index is defined as the meridional shear of 300-hPa zonal wind between the regions of EAJS (27.5°–37.5°N, 110°–170°E) and its north (50°–60°N, 80°–140°E), and the positive value of the EAJS index suggests a stronger jet stream in the upper troposphere. Overall, these indices represent different components of the EAWM system. The 9-year low-pass Lanczos filtering method is applied to the indices to highlight the decadal variability of the EAWM.

3 | DEcadal Variation of the EAWM System

3.1 | Siberian high and Aleutian low

The Siberian high is an important component of the EAWM system. It plays a key role in controlling lower tropospheric circulation over the East Asian continent. A stronger (weaker) Siberian high is usually in favor of a strengthened (weakened) EAWM. As shown in Figure 1a, the Siberian high index shows obvious inter-decadal variations, especially for the 9-year low-pass filtered indices. The Siberian high indices enter into the negative phase around 1986. This inter-decadal weakening of the EAWM has been of concern and widely studied. Based on the five reanalysis datasets, the Siberian high indices return to the positive phase again in the mid-2000s. It suggests that the Siberian high intensified around the year 2005 and continued to the present time. Whether the intensification of the Siberian high is due to internal atmospheric variability or Arctic sea-ice loss remains controversial (Mori et al., 2019). Some modeling studies identified significant responses of mid-latitude climate conditions to Arctic sea-ice loss (e.g., Mori et al., 2014), while others could not (e.g., Ogawa et al., 2018).

The Aleutian low is a semipermanent atmospheric center of action over the Aleutian Islands, which is most intense in the boreal winter. Changes in the Aleutian low are closely related to the EAWM. A stronger/deeper Aleutian low gives rise to a larger land-sea pressure gradient and thus a stronger EAWM, and vice versa. As shown in Figure 1b, the Aleutian low indices turn to positive for a short time at the late 1980s. Thereafter, the indices shift to the negative value from the mid-1990s to the mid-2000s. Then, the Aleutian low index gets positive again, showing a weakened Aleutian low in the most recent decade. Many factors could be responsible for the Aleutian low variations, including atmospheric teleconnection patterns (e.g., Pacific–North America pattern and Arctic Oscillation; Overland et al., 1999), sea surface temperature variabilities (e.g., Pacific decadal oscillation; Mantua et al., 1997), Bering Sea ice cover variations (Li and Wang, 2013), and greenhouse warming (Gan et al., 2017). For example, the positive phase of Pacific decadal oscillation is correlated with a stronger Aleutian low, and vice versa (Mantua et al., 1997). Additionally, under the RCP8.5 scenario, the Aleutian low is projected to intensify and expand northward in the second half of the 21st century (Gan et al., 2017). The mechanisms for the recent weakening of the Aleutian low need further investigation.

Thus, both the Siberian high and Aleutian low experienced significant changes but with opposite signs in the past more than 10 years.
3.2 | EAT

The EAT is an important member of the EAWM system in the middle troposphere. A deeper/stronger EAT is conducive to an outbreak of cold air and stronger monsoon winds, and vice versa. The intensity of EAT is usually described by averaging 500-hPa geopotential heights near the Korean Peninsula, with positive anomalies meaning a weakened EAT (Sun and Li, 1997). As shown in Figure 2a, the EAT indices turn to positive in the mid-1980s in all five reanalysis datasets. The weakening period lasts until the present time, with only short-time intensifications in the mid-1990 and early-2010s. On the whole, EAT intensity does not show significant and stable re-amplification in the recent decades.

3.3 | EAJS

In the upper troposphere, the intensity of EAJS is highly correlated with the EAWM variability (Yang et al., 2002). A recent study, however, indicates that the relationship between the EAJS and the EAWM is nonstationary due to the meridional displacement of the EAJS (Song et al., 2019). Thus, we here adopt an EAJS index from Jhun and Lee (2004), which is defined as the meridional shear of 300-hPa zonal wind between the EAJS core region and its north. It is found that this EAJS index can account for the EAWM variability better (Figure S1). When the index is bigger (smaller), the cyclonic vorticity is enhanced (weakened) to the north of EAJS, which leads to stronger (weaker) EAT and cold surges over East Asia (Jhun and Lee, 2004). As shown in Figure 2b, the EAJS index exhibits significant changes in the mid-1980s, with an interdecadal weakening during the latter period. Then, a small recovery can be seen in the EAJS index from the mid-1990s. During this period, a stronger increase can be observed at the beginning of the 2010s. On the whole, the decadal variation of the EAJS is consistent with that of the EAT.

3.4 | Low-level wind

The northwesterly wind anomalies in the lower troposphere are highly correlated with variations of abovementioned EAWM subsystems. Under the condition that the Siberian high, the Aleutian low, the EAT and the EAJS are stronger, the northwesterly wind becomes stronger, and vice versa (Gao, 2007). During the period of 1986–1994, positive meridional wind anomalies are evident over the whole East Asian region from subtropics to the high-latitude, suggesting a weakened EAWM (Figure 3). These anomalies are mainly caused by the consistent weakening of the EAWM subsystems during this period. However, as mentioned in the above sections, the decadal variations of these circulation systems exhibit different evolutions in the following decades. Therefore, the lower-tropospheric winds also show different latitude changes over the East Asian regions. During the period from 1994 to the early 2000s, negative meridional wind anomalies are mainly located over eastern China, Korean Peninsula and Japan Islands, suggesting a strengthened EAWM circulation over the mid- and low-latitude regions. This low-latitude strengthening is possibly caused by the strengthened EAT during this period. Then, stronger negative meridional wind anomalies are evident over the high-latitudes of East Asia, north of 40°N, which are likely due to the increasing of the EAJS shear since the beginning of the 2000s. However, the EAWM circulation is weakened again from the mid-2000s, showing positive meridional wind anomalies over the East Asia. The decadal weakening of the Aleutian low is probably an important factor resulting in the recent weakened EAWM circulation. On the whole, EAWM circulation experienced two cycles since 1980 in all five datasets. It is stronger for the periods of 1980–1986 and 1994–2006, while weaker for the periods of 1986–1994 and 2006–2015. The low-level wind index well exhibits this decadal change of the EAWM circulation (Figure 4).
Many previous studies have investigated the relationship between the EAWM and SAT over East Asia. Guo (1994) indicated that both the Siberian high and the low-level winds play an important role in regulating winter SAT in China. Due to decadal changes of the EAWM subsystem, winter SAT over the East Asian continent also exhibits significant decadal variations. As shown in Figure 5, the negative zonal mean winter SAT anomalies are observed over the whole of East Asia before the year 1988. These anomalies could be due to the consistent strengthening.

**FIGURE 3** Latitude-time cross-section of winter 850-hPa meridional wind anomalies (unit: m s\(^{-1}\)) averaged over 100°E–145°E with relative to the period of 1981–2010. The data is 9-year low-pass filtered using the Lanczos filtering method. They are from the (a) ERA-interim, (b) JRA-55, (c) MERRA-2, (d) NCEP-DOE and (e) NCEP/NCAR reanalysis datasets, respectively. 

### 3.5 SAT

Many previous studies have investigated the relationship between the EAWM and SAT over East Asia. Guo (1994) indicated that both the Siberian high and the low-level winds play an important role in regulating winter SAT in
of the EAWM subsystems during this period. After that, positive SAT anomalies can be found over high-latitude or low-latitude East Asia regions until the year 2010. The strong warming occurs mainly north (south) of 40°N for the period of 1988–1998 (1998–2010). Though the low-level winds get stronger from the mid-1990s to the mid-2000s, the Siberian high intensity is relatively weaker than normal. It suggests that the Siberian high’s intensification is necessary for large-scale cooling over East Asia. After the year 2010, negative SAT anomalies can be observed north of 40°N. The cooling could be caused by the recovered Siberian high since 2005, and the stronger EAT and EAJS since 2010. However, the low-level monsoonal winds weakened during this period, which could partly explain why the cooling is limited over northern East Asia. Our result is consistent with a previous study (Wang et al., 2010) which separates winter SAT variations into the northern and southern modes by performing EOF analysis over the EAWM domain (0°–60°N, 100°–140°E). As shown in Figure S2, on the decadal timescale, the PC of EOF1 (i.e., the northern mode) and EOF2 (i.e., the southern mode) evolves similarly with the SAT anomalies north of 40°N and south of 40°N, respectively.

These two principle modes account for 67.8% of the total SAT variance. Overall, the decadal changes in SAT are signs of the EAWM variations to some extent. However, it should be noted that the SAT anomalies are also affected by many other factors.

4 | CONCLUSION AND DISCUSSION

In this study, we examine the decadal variations of the members of the EAWM system in recent decades using different kinds of EAWM indices. The results suggest that, in the lower-troposphere, the Siberian high intensifies in the mid-2000s in all five reanalysis datasets. In contrast, the Aleutian low becomes deeper in the mid-1990s but weakens again in the late-2000s. In the middle troposphere, the intensity of the EAT remains weak most years, but it demonstrates some short-time strengthening in the late 1990s and early 2010s. In the upper-troposphere, the intensity of the EAJS shows variation similar to that of the EAT. As a result, the low-level winds exhibit two-cycle variations since 1980. The winds weakened after the mid-1980s and mid-2000s respectively, while strengthened before the mid-1980s and during the period from the mid-1990s to the mid-2000s. Further analysis on the East Asian winter SAT suggests that the Siberian high, EAT, and EAJS all have important effects on the SAT. Low-level monsoon circulation mainly affects changes in the winter SAT over low- and mid-latitude East Asia.

In the context of global warming and the early 2000s’ hiatus, the EAWM shows more complex decadal variations in the past three decades. In contrast to the changes
in the 1980s, the members of the EAWM show, to some extent, inconsistent evolution in the recent decades. Particularly in the low-level troposphere, the intensities of the Siberian high and Aleutian low show opposite changes since the mid-2000s. These changes could have very different influences on the EAWM and, thereby, lead to relative complex decadal changes of the EAWM. Recently studies suggests that the tropical Pacific state is an important factor to influence the EAWM (Kim et al., 2016). At the same time, its impacts are modulated by the Pacific Decadal Oscillation (PDO) and the Atlantic Multidecadal Oscillation (AMO). Particularly in negative PDO phase, the relationship between the EAWM and tropical Pacific temperature and circulation is intensified (Kim et al., 2014, 2016). Thus, in the 21st century’s negative PDO phase, more influences from the tropical Pacific further increase the complexity of the EAWM.

Several previous studies have investigated the physical mechanism of the EAWM interdecadal weakening in the mid-1980s (see references in Miao et al., 2018). However, subsequent decadal changes of the EAWM and related mechanisms receive little attention. This study is mainly focused on the characteristics of decadal changes of the EAWM in the past three decades. The reasons or root causes require further investigation.

As clarified in Section 3.5, the winter SAT variations over East Asia are mainly affected by the atmospheric circulation changes. Referenced to Song et al. (2019), we further examined whether there exists changes in the relationship between the SAT and the EAWM factors. As shown in Figure S3, the SAT variation over northern East Asia (40°–55°N, 100°–145°E) is significantly correlated with the Siberian high, the EAT and the EAJS. However, their relationship is nonstationary, becoming weaker during the 1990s. It means that, the thermodynamic factors rather than dynamical factors could play a dominant role in the East Asian SAT variability during the 1990s, which requires further investigation in future studies. Similarly for the SAT variation over southern East Asia (20°–40°N, 100°–145°E), unstable relationship is also seen with the Siberian high, the EAT and EAJS (Figure S4). But, the SLP gradient (Shi et al., 1996) between the Siberian high and the Aleutian low is significantly correlated with it all the time. It indicates that the SLP gradient and it induced southward invasion of cold air plays an important role in regulating the southern East Asian SAT.

In this study, five categories of EAWM indices reflecting EAWM system members are analyzed separately. In fact, these members should be linked to each other. As shown in; Figure S5, the relationship between the low-level wind index and the Siberian high, the EAT, the EAJS is significant before the year 2000. However, it gets weaker after that time, which means that the EAWM sub-systems cannot individually account for the low-level wind variation. Instead, the SLP gradient between the Siberian high and Aleutian low is significantly correlated with the low-level wind index all the time, showing more important role of the zonal SLP gradient in regulating or shaping the East Asian winter climate. In addition, the Aleutian low index is weakly correlated with other members (e.g., the EAJS, the low-level wind; Figures S1 and S5). It suggests that the Aleutian low is relatively independent in the EAWM system, and it only works by modulating the zonal SLP gradient around East Asia.

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CONFLICT OF INTEREST
The authors declare no potential conflict of interest.

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