Effects of AO on the interdecadal oscillating relationship between the ENSO and East Asian winter monsoon

Dong Chen1,2 | Jianqi Sun1,2,3 | Ya Gao1,2

1Nansen-Zhu International Research Centre, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China
2Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters/International Joint Laboratory on Climate and Environment Change, Nanjing University of Information Science & Technology, Nanjing, China
3University of Chinese Academy of Sciences, Beijing, China

Correspondence
Dong Chen, Nansen-Zhu International Research Centre, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China.
Email: chend@mail.iap.ac.cn

Funding information
National Natural Science Foundation of China, Grant/Award Numbers: 41421004, 41705066, 41875110; the National Key Research and Development Program of China, Grant/Award Number: 2017YFA0603802

Abstract
Based on the Twentieth Century Reanalysis version 2 datasets (1871–2010), this article first analyzes the relationships of the Arctic Oscillation (AO) and the El Niño-Southern Oscillation (ENSO) with the East Asian winter monsoon (EAWM) and further investigates the changes in the relationships between the ENSO (AO) and EAWM before and after removing the AO (ENSO) signal. As revealed by previous studies, an interdecadal oscillating relationship is found between the ENSO and EAWM. This oscillation disappears when the AO signal is removed; however, the ENSO–EAWM relationship has exhibited a stable and significant negative correlation over the past 140 years. In contrast, the oscillating relationship (with a period of approximately 60 years) between the AO and EAWM shows little differences when the ENSO signal is removed. Further analysis reveals the main reasons for the strengthening of the ENSO–EAWM relationship by removing the AO signal. The results show that after removing the AO signal, the ENSO-induced anomalous sinking branch of the Walker circulation over the western Pacific shifts northwestward, and the ENSO-related anomalous anticyclone in the northern part of the western Pacific strengthens. Such circulation anomalies are conducive to the establishment of the East Asia–North Pacific teleconnection, which is favourable for the ENSO–EAWM relationship. The above results reveal that there is an interdecadal oscillation in the AO–EAWM relationship and the ENSO–EAWM relationship may be relatively stable, the interdecadal oscillation only occurs under the influence of the AO. These results may improve the use of ENSO for predicting the EAWM on seasonal time scale in the future.

KEYWORDS
Arctic oscillation, east Asian winter monsoon, ENSO, interdecadal oscillation

1 | INTRODUCTION

The East Asian winter monsoon (EAWM) is the most active circulation system in East Asia during the boreal winter, and it consists of the Siberian high (SH), the East Asian trough (EAT) and the East Asian jet stream (EAJ). The main features in the lower levels are the northerlies or northwesterlies, and the annual variability of the EAWM exerts a significant impact on the occurrence of disastrous weather in East Asia. The cold northerly or...
north-westerly air from polar regions often brings cold surges and heavy snowfall to East Asia (Ding, 1990; Chang et al., 2006; Li & Wang, 2012), which causes significant social impacts and economic losses in East Asian countries (Wang et al., 2011). Considering the important impacts of the EAWM on climate change in East Asia, many studies have focused on improving the seasonal and annual prediction ability for the EAWM (Sohn et al., 2011; Yang & Lu, 2014; Zhu & Li, 2017). Among various predictors for the EAWM (Ao & Sun, 2016a,b; Liu et al., 2017; Park et al., 2011; Sun & Wang, 2013), the El Niño–Southern Oscillation (ENSO; Rasmusson & Carpenter, 1982) and the Arctic Oscillation (AO; Thompson & Wallace, 1998, 2000) are considered as the two most important factors (Gong et al., 2001; He & Wang, 2013a; Li & Yang, 2010; Li, 1990; Park et al., 2011; Wang et al., 2000).

The prediction ability for the EAWM on the interseasonal time scale has been significantly improved with these two important factors taken into account (Yang & Jiang, 2014). Early research mainly concentrated on the interannual relationships of the ENSO or AO with the EAWM. The positive phases of AO and ENSO warm events have been found to generally correspond to the weakening of the EAWM, while the opposite conditions correspond to a strengthening EAWM (Chen et al., 2015; Chen, 2002; Gong et al., 2001; Li, 1990; Wang et al., 2000; Zhang et al., 1996). However, less attention has been paid to the interdecadal variations in existing interannual relationships. Using data with a longer time scale, studies have found that the ENSO–EAWM relationship is not stable and shows significant interdecadal variations (Wang & He, 2012; Wang et al., 2008; Zhou et al., 2007). A periodical oscillation has been observed in the interannual variations of the ENSO and the EAWM, and it has the main period of approximately 60 years (Chen et al., 2016; Chen et al., 2018; He & Wang, 2013b). Meanwhile, the AO–EAWM relationship has also been characterized by an interdecadal oscillation (Chen et al., 2016; Chen et al., 2018; Liu et al., 2017) with a period of approximately 60 years. Chen et al. (2018) revealed that the AO and ENSO alternately affect the EAWM. When the AO has a significant relationship with the EAWM, a weak ENSO–EAWM relationship is observed. In contrast, when the ENSO–EAWM relationship becomes significant, the influence of the AO on the EAWM decreases. These observations show that the oscillating relationship among AO, ENSO and EAWM may be modulated by the phase transitions in the North Pacific interdecadal mode—Pacific Multidecadal Oscillation (PMO). Knowledge of this kind of interdecadal change allows us to consider the influence of the AO or ENSO on the EAWM under different interdecadal backgrounds.

Li et al. (2014) have revealed the significant strengthening in the AO–ENSO relationship in January since the 1990s. The main characteristic of the AO–ENSO relationship is that an early-onset AO event will have a certain impact on late-onset ENSO events, and this effect has a strong seasonal dependence (Chen et al., 2013, 2014). For the same period, the AO and ENSO are relatively independent especially in winter (Liu et al., 2004; Wang & Sun, 2009), but they also can affect global climate change through the joint effect of low latitude and high latitude climate systems (Greatbatch & Jung, 2007; Zhu & Wang, 2016).

Therefore, will this relationship affect the interdecadal oscillating relationships of the AO and ENSO with the EAWM? If so, how important are the AO and ENSO? Which mode is the most dominant? To this end, this article attempts to answer the above questions mainly from the interactions of the AO and ENSO with the EAWM. In addition, their relationships and influence on each other at the interdecadal scale will also be analysed. We have investigated whether the interdecadal oscillating relationships among the AO, ENSO and the EAWM would change after removing the influence of the ENSO (AO) from the relationship between the AO (ENSO) and EAWM. For climate predictions at time scales ranging from seasonal to annual, a large problem is that the predictability of the climate systems (such as the AO) in the middle and high latitudes is poor while that of the tropical climate systems is much higher (Liu & Wang, 2015). The ENSO is the most predictable climate signal at the time scales from months to seasons (Tang et al., 2018), and if it can be used to predict the strength of EAWM at any time, the seasonal predictability of EAWM can be greatly improved. Therefore, the relationships among the AO, ENSO and EAWM and their relative importance have been investigated in this article. The results aim to provide deeper insights into the mechanism of EAWM and facilitate seasonal predictions.

The rest of this article is organized as follows. The data and methods are described in Section 2. The change in the relationship between the ENSO (AO) and the EAWM before and after removing the AO (ENSO) signal as well as the possible reasons for this change are discussed in Section 3. A summary and a discussion are provided in Section 4.

### 2 | DATA AND METHODS

The monthly geopotential height, horizontal wind and specific humidity data derived from the Twentieth Century Reanalysis Dataset Version 2c during 1871–2010, with a horizontal resolution of 2° by 2°, are provided by the National Oceanic and Atmospheric Administration (NOAA; Compo et al., 2011). The monthly mean sea level pressure (SLP) data (1871–2010) are acquired from the
Hadley Centre website (at http://hadobs.metoffice.com/hadslp2/), with a horizontal resolution of 5° by 5° (Allan & Ansell, 2006). The monthly mean sea surface temperature (SST) data are obtained from the NOAA Extended Reconstructed Sea Surface Temperature dataset version 5 (1871–2010) (Huang et al., 2017) and the NOAA Extended Reconstructed Sea Surface Temperature dataset version 3b (Smith et al., 2008).

The methods used in this study include linear correlation, regression analysis, composite analysis and a 23-year sliding window correlation. To obtain the interannual variability of the data, an 11-year high-pass filter based on the theory of fast Fourier transform (FFT) is applied in this work. For the removal of a signal (e.g. ENSO, AO and the global warming) from a variable, assuming that the relationship between the signal and variable is linear, then the method from Chen et al. (2015, 2018) is adopted for the removal. The formula is as follows:

\[
x = x^* - Z \times \text{cov}(x^*, Z) / \text{var}(Z),
\]

where \(x^*\) is the original variable, \(Z\) is the time series of the signal, \(\text{cov}(\xi^*, Z)\) is the temporal covariance between \(\xi^*\) and \(Z\), \(\text{var}(Z)\) denotes the variance of \(Z\), and \(\xi\) is the newly formed variable, where the signal covariant of \(\xi^*\) with \(Z\) are removed from \(\xi^*\). The statistical significance of the differences in this work is determined via the Monte Carlo test.

The coinciding positive or negative rates (R) are calculated as follows:

\[
R = N_c / N \times 100%,
\]

where \(N\) is the total number of years and \(N_c\) represents the number of years in which the predicted results are consistent with the observation data regarding the positive or negative rates.

The EAWM index is defined as the negative area-averaged 500 hPa geopotential height in winter within the domain of 25°–45°N and 110°–145°E (Wang & He, 2012; Wang et al., 2009). The ENSO event is represented by the Niño3.4 index, which is defined as the area-averaged winter SST anomaly (SSTA) in the Niño3.4 region (5°S–5°N, 120°–170°W). The AO index is defined as the principal component of the leading mode of the empirical orthogonal function (EOF) analysis on the standardized winter SLP poleward of 20°N (Thompson & Wallace, 1998).

3 | RESULTS

To analyse the changes in the relationships of the AO and ENSO with the EAWM after removing their respective influences, the interannual signals of the three indexes are obtained through 11-year high-pass filtering. Then, the 23-year running correlations of the AO and ENSO with the EAWM are calculated. Figure 1a presents the relationships between the ENSO and EAWM before and after removing the AO signal, while Figure 1b shows the relationships between the AO and EAWM before and after removing the ENSO signal. The results show that the AO and ENSO have significant interdecadal oscillation relationships with the EAWM before removing their respective influences. And these results are consistent with those of previous studies (Chen et al., 2018; Liu et al., 2017). From Figure 1a, when the AO signal is taken into account, there is a significant interdecadal oscillation in the ENSO–EAWM relationship. However, when the AO signal is removed, that oscillation relationship would disappear over the past 140 years, and significant negative correlations are observed. According to Figure 1b, the interdecadal oscillation in the interannual relationship between AO and EAWM is not affected by ENSO. Regardless of whether or not the ENSO signal is removed, an interdecadal oscillation exists in the AO–EAWM relationship. Therefore, in later analyses, the main focus will be on the reasons for the change in the ENSO–EAWM relationship after the AO signal is removed.

According to the interdecadal oscillation periods in the relationships of the AO and ENSO with the EAWM, the past 140 years (1871–2010) have been divided into five periods: 1871–1897, 1898–1922, 1923–1948, 1949–1978 and 1979–2003. During 1898–1922 and 1949–1978, the ENSO–EAWM relationship is significant regardless of whether the AO signal is removed or not; Therefore, this article does not perform much analysis on these two periods. The subsequent analyses will be concentrated on the other three periods in which the ENSO–EAWM relationship is not significant before the AO signal is removed, and a discussion will be further conducted on the possible reasons why the relationship becomes significant after the AO signal is removed.

Chen et al. (2018) have noted that when the EAT deepens, the relationship between the EAWM and SSTs in both the tropical Indian Ocean and the western Pacific strengthens. Because the tropical western Pacific and central-eastern Pacific are linked by the Walker circulation (Chang et al., 2004; Weng et al., 2007; Yuan & Yang, 2012), the linkage between the EAWM and SSTs is facilitated in the equatorial central and eastern Pacific regions (He & Wang, 2013b; Kumar et al., 1999). Therefore, the variations in the relationship between the EAWM and SSTs are investigated. Figure 2 shows the relationships between the EAWM and SST during the periods of 1871–1897, 1923–1948 and 1979–2003. Figure 2a–f show
that when the AO signal is removed, the relationships between the EAWM and SSTs in the tropical Indian Ocean, the tropical western Pacific and the tropical eastern Pacific are significantly strengthened. The strength of the EAWM can affect the surface wind in the western Pacific and the tropical Indian Ocean, leading to the changes in the heat flux (Wu, 2016) and ultimately affecting the SSTAs in the region by the wind-evaporation-SST effect (Xie, 2004). Therefore, in Figure 2d–f, only the changes of SSTs in Northwest Pacific and Indian Ocean are related to the changes of the EAWM, while the changes of SST in the equatorial central and eastern Pacific are not directly caused by the EAWM. This is mainly attributed to the linkage between the Walker circulation and the Southern Oscillation (SO), which is reflected in the collaborative relationship with the variations of SSTs in Northwest Pacific. Figure 2g–2i show that the ENSO–EAWM relationship is significantly strengthened after the removal of the AO signal. Meanwhile, all the different patterns indicate a significant ENSO-type SST distribution.

To further verify the strengthening of the relationship between EAWM and the tropical atmospheric circulation, the relationship between the EAWM index and the 500 hPa geopotential height has also been investigated (Figure 3). The relationship between the EAWM and the geopotential height over the tropical Indian Ocean and the tropical Pacific Ocean is significantly strengthened, while the connection between the EAWM and the geopotential height over the eastern Pacific in mid-latitudes is weakened. In contrast, the relationship between the EAWM index and the 500 hPa geopotential height exhibits different spatial distribution characteristics before the removal of the AO signal, which is strong over the eastern Pacific at mid-latitudes and weak over the tropical regions.

In addition to the relationship between the EAWM and the tropical atmospheric circulation, the impact of the SSTs in the equatorial central and eastern Pacific on the atmospheric circulation in the western Pacific is another important factor affecting the relationship between the Asian Monsoon system and ENSO (He &
Wang, 2013b; Kumar et al., 1999). According to previous studies (He & Wang, 2013b), warm ENSO events will lead to the weakening of the Walker circulation. The anomalous sinking branch in the Walker circulation will be located over the East Asia, the western Pacific and other places and two anomalous anticyclones will be formed over the Philippine Sea and the Kuroshio extension region in the western Pacific. Wang et al. (2000) have emphasized that the Philippine anticyclone is a key system linking the ENSO with the EAWM. However, He and Wang (2013b) studied the interdecadal oscillation in the ENSO–EAWM relationship based on datasets with longer time series and noted that the Kuroshio extension anticyclone may be more important than the Philippine anticyclone for linking the ENSO with EAWM. When the anomalous sinking branch of the Walker circulation moves south-eastward, the Philippine anticyclone still exists while the anticyclone in the northern Kuroshio

**FIGURE 2** Distribution of the correlation coefficients between SST and the EAWM index during three different periods: (a) 1871–1897, (b) 1923–1948 and (c) 1979–2003. (d–f) Similar to (a–c) but for the distribution of correlation coefficients between SST and the EAWM index without the AO signal. The white stippling indicates the regions where the correlation coefficients exceed the 95% confidence level. (g–i) Differences between (d–f) and (a–c), with the white stippling showing the regions where the differences of correlation coefficients exceed the 90% confidence level

**FIGURE 3** Same as Figure 2, but for the EAWM index and the 500 hPa geopotential height
extension area disappears. Meanwhile, there is a significant weakening in the ENSO–EAWM relationship. In contrast, when the anomalous sinking branch of the Walker circulation moves north-westward, an anticyclone in the Kuroshio extension area appears, and the ENSO–EAWM relationship would be strengthened.

Therefore, further studies have also been carried out on the changes in the ENSO-related anomalous sinking branch and the two anomalous anticyclones in the western Pacific after the removal of the AO. The differences show that the relationship between ENSO and SSTs in the Indian Ocean and the western Pacific Ocean is strengthened after removing the AO signal (figure omitted). Furthermore, from the velocity potential (200 hPa) associated with the Niño3.4 index (Figure 4), when the AO signal is removed, the ascending branch related to ENSO over the western Pacific moves north-westward substantially. At this time, the relationship between ENSO and the circulations in the East Asia region is significantly strengthened. The results at lower levels (850 hPa) are consistent with those in the upper levels, which facilitates the establishment of the link between

**FIGURE 4** Same as Figure 2, but for the Niño3.4 index and the 200 hPa velocity potential

**FIGURE 5** Shading and stippling are the same as that described in Figure 4 but for the Niño3.4 index and 850 hPa geopotential height. The vectors indicate the Niño3.4 index and the 850 hPa horizontal wind
the ENSO and EAWM. With the movement of the western Pacific ascending branch, the corresponding changes in the geopotential height and horizontal wind have also been analysed. Figure 5 show that there are two anticyclonic anomalies in the western Pacific region when a warm ENSO event occurs, with one located near the tropical Philippines and the other located northward at mid-latitudes, regardless of removing (Figure 5d–f) or retaining the AO signal (Figure 5a–c). The differences (Figure 5g–i) reveal that after removing the AO signal, the anticyclone in the north is significantly increased, while the anticyclone in the south is weakened. That is, the anticyclone in the north is indeed more important for the establishment of the ENSO–EAWM relationship, which is also confirmed by the results of He and Wang (2013b).

In summary, the role of the AO in the ENSO–EAWM relationship has been analysed. It has been found that there is a significant interdecadal oscillation in the ENSO–EAWM relationship when the AO signal is not removed. After the removal of the AO signal, the interdecadal oscillation relationship between the ENSO and EAWM disappears and their relationship becomes stable. For the three periods when the ENSO–EAWM relationship was shown to be not significant in previous studies are emphatically analysed. The differences in the relationships before and after the removal of the AO signal are compared, and the reasons why the ENSO–EAWM relationship strengthens after removing the AO signal are also discussed.

The results show that there are three main reasons for the strengthening in the ENSO–EAWM relationship after removing the AO signal. First, after removing the AO signal, the relationship between the EAWM and the atmospheric circulation over the mid-latitude Pacific Ocean weakens, whereas over the tropical western Pacific and Indian Ocean strengthens significantly, as characterized by the deepening of the monsoon trough. As the SSTs in the tropical western Pacific and Indian Ocean are closely linked with those in the equatorial eastern Pacific through the Walker circulation, this situation is conducive to the establishment of the link between the ENSO and EAWM. Second, previous studies (He & Wang, 2013b; Kumar et al., 1999) have noted that the changes in the location of ENSO-related anomalous sinking branches in the western Pacific are crucial to the relationships between ENSO and the East Asian monsoon system. Further research in this article finds that when the AO signal is removed, the anomalous sinking branches in the Northwest Pacific associated with the ENSO move north-westward, which facilitates the establishment of the link between the ENSO and the East Asian monsoon system. In addition, the strengthening of the anomalous anticyclones in the northern region of the Northwest Pacific Ocean is another important factor in strengthening the ENSO–EAWM relationship. When the ENSO-related SSTs change, the Walker circulation will undergo substantial adjustments. When warm ENSO
The coinciding positive or negative rates (the bold percentage value) for the Niño3.4-fitted EAWM index and EAWM index in three periods and for specific years. Niño3.4 and rmAO-Niño3.4 represent the original Niño3.4 index and the Niño3.4 index without the AO signal, respectively.

| Period     | Niño3.4 (Nc) | rmAO_Niño3.4 (Nc) |
|------------|--------------|-------------------|
| 1871–1897  | 59.3% (16/27 years) | 74.1% (20/27 years) |
| 1923–1948  | 61.5% (16/26 years) | 73.1% (19/26 years) |
| 1979–2003  | 64.0% (16/25 years) | 72.0% (18/25 years) |

Events occur, abnormal sinking branches will appear over the Northwest Pacific Ocean. Study in this article reveals that, this abnormal sinking branch will move north-westward, which will strengthen the abnormal anticyclone in the north; thus, the anomalous northerlies along the western side of the anticyclone would further influence the variation in the winter monsoon along the coast of East Asia.

The significance of this article is as follows. Previous studies have shown that the AO and ENSO represent the main modes at high and low latitudes, respectively, and could alternately affect the EAWM. When the AO–EAWM relationship strengthens, the AO–ENSO relationship is not significant. However, when the EAWM–ENSO relationship strengthens, the relationship between AO and the atmospheric circulation at high latitudes would decrease. According to this study, the ENSO–EAWM relationship may be largely stable, and the interdecadal oscillation shown in this relationship may be affected by the AO. In other words, the AO may be the dominant factor in the interdecadal oscillation relationships of the AO and ENSO with the EAWM. Previous studies have found that the ENSO–EAWM relationship is unstable. Therefore, when the ENSO–EAWM relationship is poor, the ENSO cannot be used as a predictor for the strength of the EAWM. Since the ENSO is still the most predictable climate signal at the time scales from months to seasonal predictability after the AO signal is removed.

Investigations have also been conducted on the sliding window correlation between the AO and ENSO over the past 140 years, and significant correlations are only observed in a few periods, indicating that they are usually independent of each other (figure omitted). For the two relatively independent factors, why does removing the AO signal lead to such a change in the ENSO and EAWM-related circulations, which ultimately leads to a significant strengthening of their relationship? According to Chen et al. (2018), the AO–EAWM relationship becomes significant only when the centre of the AO appears in the North Pacific Ocean, and the ENSO–EAWM relationship weakens thereafter. Therefore, whether the centre of the AO existing over the North Pacific Ocean may be a key factor. When this system exists, the relationship between the EAWM and zonal circulation is strong while the meridional influence is weak. In contrast, the ENSO has a strong influence on the polar direction but a weak influence on the zonal direction, such as in the tropical western Pacific region. Therefore, the influence of the AO centre over the North Pacific disappears after the AO signal is removed, which could strengthen the meridional influence of the EAWM and the latitudinal influence of ENSO, eventually leading to the strengthening of ENSO–EAWM relationship. However, how the AO affects the ENSO–EAWM relationship requires further study and will be explored in our future work.

ACKNOWLEDGEMENTS
This work was supported by the National Key Research and Development Program of China (Grant No. 2017YFA0603802), and the National Natural Science Foundation of China (Grant No. 41705066, 41875110 and 41421004).
REFERENCES
Ao, J. and Sun, J. (2016a) The impact of boreal autumn SST anomalies over the South Pacific on boreal winter precipitation over East Asia. *Advances in Atmospheric Sciences*, 33(5), 644–655. https://doi.org/10.1007/s00376-015-5067-x.
Ao, J. and Sun, J. (2016b) Decadal change in factors affecting winter precipitation over eastern China. *Climate Dynamics*, 46, 111–121.
Allan, R. and Ansell, T. (2006) A new globally complete monthly historical gridded mean sea level pressure dataset (HadSLP2): 1850–2004. *Journal of Climate*, 19, 5816–5842.
Chang, C., Wang, Z. and Hendon, H. (2006) The Asian winter monsoon. In: Wang, B. (Ed.) *The Asian Monsoon*. Cham: Springer Press, pp. 89–127.
Chang, C.P., Wang, Z., Ju, J. and Li, T. (2004) On the relationship between western maritime continent monsoon rainfall andenso during northern winter. *Journal of Climate*, 17(3), 665–672.
Chen, D., Wang, H., Sun, J. and Gao, Y. (2018) Pacific multidecadal oscillation modulates the effect of Arctic oscillation and El Niño southern oscillation on the east Asian winter monsoon. *International Journal of Climatology*, 38(6), 2808–2818.
Chen, D., Wang, H.J., Liu, J.P. and Li, G.P. (2015) Why the spring North Pacific oscillation is a predictor of typhoon activity over the Western North Pacific. *International Journal of Climatology*, 35(11), 3353–3361.
Chen, D., Wang, H.J., Yang, S. and Gao, Y. (2016) A multidecadal oscillation in the northeastern Pacific. *Atmospheric and Oceanic Science Letters*, 9(4), 315–326. https://doi.org/10.1080/16742834.2016.1194716.
Chen, S., Chen, W., Yu, B. and Graf, H.F. (2013) Modulation of the seasonal footprinting mechanism by the boreal spring Arctic oscillation. *Geophysical Research Letters*, 40(24), 6384–6389.
Chen, S., Yu, B. and Chen, W. (2014) An analysis on the physical process of the influence of AO on ENSO. *Climate Dynamics*, 42(3–4), 973–989.
Chen, W. (2002) Impacts of El Niño and La Niña on the cycle of the east Asian winter and summer monsoon. *Chinese Journal of Atmospheric Sciences*, 26, 595–610 (in Chinese).
Cheng, Y., Tang, Y. and Chen, D. (2011) Relationship between predictability and forecast skill of ENSO on various time scales. *Journal of Geophysical Research*, 116, C12006.
Compo, G.P., Whittaker, J.S., Sardeshmukh, P.D., Matsui, N., Allan, R.J., Yin, X., Gleason, B.E., Vose, R.S., Rutledge, G., Bessemsoum, P., Brönnimann, S., Brunet, M., Crouthamel, R.L., Grant, A.N., Groisman, P.Y., Jones, P.D., Kruk, M.C., Kruger, A.C., Marshall, G.J., Maugeri, M., Mok, H.Y., Nordli, Ø., Ross, T.F., Trigo, R.M., Wang, X.L., Woodruff, S.D. and Worley, S.J. (2011) The twentieth century reanalysis project. *Quarterly Journal of the Royal Meteorological Society*, 137, 1–28.
Ding, Y.H. (1990) Build-up, air-mass transformation and propagation of Siberian high and its relations to cold surge in East Asia. *Meteorology and Atmospheric Physics*, 44, 281–292.
Gong, D.Y. Wang, S.W. and Zhu, J.H. (2001) East Asian winter monsoon and Arctic oscillation. *Geophysical Research Letters*, 28(10), 2073–2076.
Greatbatch, R. and Jung, T. (2007) Local versus tropical Diabatic heating and the winter North Atlantic oscillation. *Journal of Climate*, 20, 2058–2075.
He, S. and Wang, H. (2013a) Impact of the November/December Arctic oscillation on the following January temperature in East Asia. *Journal of Geophysical Research-Atmospheres*, 118(23), 12–981.
He, S. and Wang, H. (2013b) Oscillating relationship between the east Asian winter monsoon and ENSO. *Journal of Climate*, 26(24), 9819–9838.
Huang, B., Thorne, P.W. and al, e. (2017) Extended Reconstructed Sea surface temperature version 5 (ERSSTv5), upgrades, validations, and intercomparisons. *Journal of Climate*, 30, 8179–8205. https://doi.org/10.1175/JCLI-D-16-0836.1.
Kumar, K.K., Rajagopalan, B. and Cane, M.A. (1999) On the weakening relationship between the Indian monsoon and ENSO. *Science*, 284, 2156–2159.
Li, C.Y. (1990) Interaction between anomalous winter monsoon in East Asia and El Nino events. *Advances in Atmospheric Sciences*, 7, 36–46.
Li, F. and Wang, H.J. (2012) Predictability of the east Asian winter monsoon interannual variability as indicated by the DEMETER CGCM3. *Advances in Atmospheric Sciences*, 29, 441–454.
Li, F., Wang, H.J. and Liu, J.P. (2014) The strengthening relationship between Arctic oscillation and ENSO after the mid-1990s. *International Journal of Climatology*, 34, 2515–2521.
Li, Y. and Yang, S. (2010) A dynamical index for the east Asian winter monsoon. *Journal of Climate*, 23(15), 4255–4262.
Liu, J., Curry, J.A. and Martinson, D.G. (2004) Interpretation of recent Antarctic Sea ice variability. *Geophysical Research Letters*, 31(2), L02205.
Liu, S. and Wang, H.J. (2015) Seasonal prediction systems based on CCSM3 and their evaluation. *International Journal of Climatology*, 35(15), 4681–4694.
Liu, Y., He, S., Li, F., Wang, H.J. and Zhu, Y. (2017) Interdecadal change between the Arctic oscillation and east Asian climate during 1900–2015 winters. *International Journal of Climatology*, 37(14), 4791–4802.
Park, T.W., Ho, C.H. and Yang, S. (2011) Relationship between the Arctic oscillation and cold surges over East Asia. *Journal of Climate*, 24(1), 68–83.
Rasmusson, E.M. and Carpenter, T.H. (1982) Variations in tropical sea surface temperature and surface wind fields associated with the southern oscillation/El Niño. *Monthly Weather Review*, 110(5), 354–384.
Smith, T.M., Reynolds, R.W., Peterson, T.C. and Lawrimore, J. (2008) Improvements to NOAA’s historical merged land-ocean surface temperature analysis (1880–2006). *Journal of Climate*, 21, 2283–2296.
Sohn, S.J., Tam, C.Y. and Park, C.K. (2011) Leading modes of east Asian winter climate variability and their predictability: An assessment of the APCC multi-model ensemble. *Journal of the meteorological Society of Japan Series II*, 89(5), 455–474.
Sun, B. and Wang, H. (2013) Larger variability, better predictability? *International Journal of Climatology*, 33(10), 2341–2351.
Tang, Y., Zhang, R., Liu, T., Duan, W., Yang, D., Zheng, F., Ren, H., Lian, T., Gao, C., Chen, D. and Mu, M. (2018) Progress in ENSO prediction and predictability study. *National Science Review*, 5(6), 826–839.

Thompson, D.W. and Wallace, J.M. (1998) The Arctic oscillation signature in the wintertime geopotential height and temperature fields. *Geophysical Research Letters*, 25(9), 1297–1300.

Thompson, D.W. and Wallace, J.M. (2000) Annular modes in the extratropical circulation. Part I: Month-to-month variability. *Journal of Climate*, 13, 1000–1016.

Wang, B., Wu, R. and Fu, X. (2000) Pacific-east Asian teleconnection: How does ENSO affect east Asian climate? *Journal of Climate*, 13, 1517–1536.

Wang, H.J. and He, S.P. (2012) Weakening relationship between east Asian winter monsoon and ENSO after mid-1970s. *Chinese Science Bulletin*, 57(27), 3535–3540.

Wang, H.J. and Sun, J.Q. (2009) Variability of Northeast China river break-up date. *Advances in Atmospheric Sciences*, 26(4), 701–706.

Wang, H.J., Yu, E.T. and Yang, S. (2011) An exceptionally heavy snowfall in Northeast China: Large-scale circulation anomalies and hindcast of the NCAR WRF model. *Meteorology and Atmospheric Physics*, 113, 11–25.

Wang, L., Chen, W. and Huang, R.H. (2008) Interdecadal modulation of PDO on the impact of ENSO on the east Asian winter monsoon. *Geophysical Research Letters*, 35(20), 1–4.

Wang, L., Chen, W., Zhou, W. and Huang, R. (2009) Interannual variations of east Asian trough axis at 500 hPa and its association with the east Asian winter monsoon pathway. *Journal of Climate*, 22, 600–614.

Weng, H., Ashok, K., Behera, S.K. and Rao, S.A. (2007) Impacts of recent El Niño Modoki on dry/wet conditions in the Pacific rim during boreal summer. *Climate Dynamics*, 29, 113–129. https://doi.org/10.1007/s00382-007-0234-0.

Wu, R. (2016) Coupled intraseasonal variations in the east Asian winter monsoon and the South China Sea–western North Pacific SST in boreal winter. *Climate Dynamics*, 47(7–8), 2039–2057.

Xie, S.P. (2004) The shape of continents, air-sea interaction, and the rising branch of the Hadley circulation. In: Diaz, H.F. and Bradley, R.S. (Eds.) *The Hadley Circulation: Present, past and future*. Dordrecht: Springer, pp. 121–152.

Yang, S. and Jiang, X. (2014) Prediction of eastern and Central Pacific ENSO events and their impacts on east Asian climate by the NCEP climate forecast system. *Journal of Climate*, 27(12), 4451–4472.

Yang, S.H. and Lu, R. (2014) Predictability of the East Asian winter monsoon indices by the coupled models of ENSEMBLES. *Advances in Atmospheric Sciences*, 31(6), 1279–1292.

Yuan, Y. and Yang, S. (2012) Impacts of different types of El Niño on east Asian climate: Focus on ENSO cycles. *Journal of Climate*, 25, 7702–7722. https://doi.org/10.1175/JCLI-D-11-00576.1.

Zhang, R., Sumi, A. and Kimoto, M. (1996) Impact of El Niño on the east Asian monsoon: a diagnostic study of the ’86/87 and ’91/92 events. *Journal of the Meteorological Society of Japan*, 74, 49–62.

Zhou, W., Wang, X., Zhou, T.J., Li, C. and Chan, J.C.L. (2007) Interdecadal variability of the relationship between the East Asian winter monsoon and ENSO. *Meteorology and Atmospheric Physics*, 98, 283–293.

Zhu, Y. and Wang, T. (2016) The relationship between the Arctic oscillation and ENSO as simulated by CCSM4. *Atmospheric and Oceanic Science Letters*, 9, 198–203.

Zhu, Z. and Li, T. (2017) Statistical extended-range forecast of winter surface air temperature and extremely cold days over China. *Quarterly Journal of the Royal Meteorological Society*, 143(704), 1528–1538.

How to cite this article: Chen D, Sun J, Gao Y. Effects of AO on the interdecadal oscillating relationship between the ENSO and East Asian winter monsoon. *Int J Climatol*. 2020;40: 4374–4383. https://doi.org/10.1002/joc.6459