Multidecadal Fluctuation of the Wintertime Arctic Oscillation Pattern and Its Implication

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ABSTRACT

The multidecadal fluctuations in the patterns and teleconnections of the winter mean Arctic Oscillation (AO) are investigated based on observational and reanalysis datasets. Results show that the Atlantic center of the AO pattern remains unchanged throughout the period 1920–2010, whereas the Pacific center of the AO is strong during 1920–59 and 1986–2010 and weak during 1960–85. Consequently, the link between the AO and the surface air temperature over western North America is strong during 1920–59 and 1986–2010 and weak during 1960–85. The time-varying Pacific center of the AO motivates a revisit to the nature of the AO from the perspective of decadal change. It reveals that the North Pacific mode (NPM) and North Atlantic Oscillation (NAO) are the inherent regional atmospheric modes over the North Pacific and North Atlantic, respectively. Their patterns over the North Pacific and North Atlantic remain stable and change little with time during 1920–2010. The Atlantic center of the AO always resembles the NAO over the North Atlantic, but the Pacific center of the AO only resembles the NPM over the North Pacific when the NPM–NAO coupling is strong. These results suggest that the AO seems to be fundamentally rooted in the variability over the North Atlantic and that the annular structure of the AO very likely arises from the coupling of the atmospheric modes between the North Pacific and North Atlantic.

1. Introduction

The Arctic Oscillation (AO) proposed by Thompson and Wallace (1998) is defined as the first empirical orthogonal function (EOF) mode of the sea level pressure (SLP) in the extratropical Northern Hemisphere. It reflects a seesaw in the SLP field between the Arctic and midlatitudes. In this sense, the AO is also referred to as the northern annular mode (Thompson and Wallace 2001). Previous studies have demonstrated that the AO can strongly influence the global and regional climate through its teleconnections (e.g., Thompson and Wallace 2001; Gong et al. 2001; Chen and Kang 2006; Tan et al. 2008; Wang and Chen 2010; Chen et al. 2013). However, the physical significance of the mode, especially the Pacific center of the AO pattern, has been a matter of great debate since the AO was proposed (e.g., Deser 2000; Wallace 2000; Ambaum et al. 2001; Christiansen 2002; Rogers and McHugh 2002; Wallace and Thompson 2002; Feldstein and Franzke 2006; Itoh 2008). Thompson and Wallace

(1998) suggested that the AO is a fundamental mode of the climate variability that describes the seesaw of air masses between the Arctic and the midlatitudes. Deser (2000) found that among the three centers of the AO only the Arctic and Atlantic centers correlate strongly with each other, whereas the Pacific center is weakly correlated with the other two. Wallace and Thompson (2002) explained that the correlation between the Pacific and Atlantic centers becomes strong when the second EOF mode of the SLP is linearly removed from the original SLP field and that the AO is a reliable physical mode. In contrast, Ambaum et al. (2001) considered a three-point seesaw system representing three centers of action: the Arctic, Euro–Atlantic, and Pacific regions. They suspected that the North Pacific variability, together with the North Atlantic Oscillation (NAO), constitutes the AO and that the Pacific center of the AO may be produced from the North Pacific variability. In fact, the discussion about the nature of the AO still continues even in recent years (e.g., Itoh 2008; Sun and Tan 2013).

From another aspect, some studies found that the spatial structure of the AO is nonstationary and that the

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Pacific center of the AO cannot be observed very often (e.g., Honda and Nakamura 2001; Castanheira and Graf 2003; Zhao and Moore 2009; Sun and Tan 2013; Shi and Nakamura 2014; Dai and Tan 2017). For example, Honda and Nakamura (2001) pointed out that the amplitude of the Pacific AO pattern is linked to the Aleutian low and the Icelandic low seesaw (AIS) pattern in late winter (February–March) during 1973–94. During the twentieth century, the leading mode of SLP variability over the Northern Hemisphere is remarkably different in different phases of the AIS (Shi and Nakamura 2014). Besides, the Pacific center of the AO pattern can also be modulated significantly by the stratospheric polar vortex. It is strong and clear when the stratospheric polar vortex is strong, and it is weak and unclear when the stratospheric polar vortex is weak (Castanheira and Graf 2003; Sun and Tan 2013; Tan et al. 2015). These results indicate that the spatial structure of the AO pattern is variable under different conditions.

The above studies show the nonstationary feature of the spatial structure of the AO pattern, but their results were obtained under certain specific conditions (e.g., the extreme phases of the AIS pattern or the strength of the stratospheric polar vortex). However, it remains unknown how the wintertime AO pattern itself changes with time. It is also not clear whether the teleconnection of the wintertime AO changed during the twentieth century. Therefore, in this study we will investigate the possible changes in the pattern and teleconnections of the wintertime AO based on long-term observational and reanalysis data. Moreover, we will revisit the discussion on the nature of the AO from the perspective of the decadal changes of the wintertime AO pattern. The rest of the paper is organized as follows: section 2 describes the data and methods. Section 3 presents the observational evidence for the time-varying pattern and teleconnections of the wintertime AO during the twentieth century. Section 4 revisits the discussion of the nature of the AO from perspective of decadal change. Finally, a summary is presented in section 5.

2. Data and methods

The monthly mean SLP (HadSLP2r) and surface air temperature (SAT) anomalies data (HadCRUT4) are from the Met Office Hadley Centre (Allan and Ansell 2006; Jones et al. 2012). The horizontal resolution of HadSLP2r and HadCRUT4 is $5^\circ \times 5^\circ$, and the temporal coverage of the two datasets is from 1850 to the present. To verify the robustness of the results, the monthly mean SLP and SAT data from two reanalysis datasets are also employed. One is the Twentieth Century

Reanalysis dataset, version 2c (20CR-V2c), provided by the National Oceanic and Atmospheric Administration/Earth System Research Laboratory Physical Sciences Division (NOAA/ESRL PSD), which has $2^\circ \times 2^\circ$ horizontal resolution and spans from 1851 to the near present (Compo et al. 2011; Giese et al. 2016). The other is the monthly mean ERA-20C dataset provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) (Poli et al. 2016), which covers the period from 1900 to 2010 at the same horizontal resolution of $2^\circ \times 2^\circ$.

Considering the AO is the strongest and most active in boreal winter (Thompson and Wallace 2000), this study focus on the winter (December–February) mean AO. Following Thompson and Wallace (1998), the wintertime AO index is defined as the principal component (PC) of the first EOF mode of the winter mean SLP variability in the extratropical Northern Hemisphere (20° – 90° N). In addition to the AO, several other wintertime regional modes were also used in this study. One is the dominant atmospheric mode over the North Atlantic, referred to as the NAO (Hurrell 1995), and the other is the dominant atmospheric mode over the North Pacific, referred to as the North Pacific mode (NPM; Gong et al. 2017). These two regional modes are defined as the first EOF modes of the winter mean SLP anomalies over the North Atlantic (20° – 80° N, 90° W– 40° E) and the North Pacific (20° – 65° N, 120° E– 120° W), respectively. The corresponding PCs are defined as the NAO and NPM indices (Hurrell et al. 2003; Gong et al. 2017), respectively. In previous studies, several indices such as the Pacific–North America (PNA) pattern index (Wallace and Gutzler 1981) and the North Pacific index (Trenberth and Hurrell 1994) have been proposed to represent the variability of the wintertime North Pacific circulation. Here, we selected the EOF method to define the dominant mode of the wintertime North Pacific variations to keep consistency with the definition used for the NAO. The correlation coefficient between the winter mean NPM index and the PNA (North Pacific) index is -0.92 (0.99) during 1920–2010. This suggests that the NPM defined in this study represents almost the same variability described in the other definitions mentioned in the above references. Considering the many abbreviations that are used in this paper, Table 1 is included to summarize all abbreviations used in this study.

Few observations exist before 1920, which causes a large spread among the different datasets (Smoliak and Wallace 2015; Wegmann et al. 2017; Wang et al. 2017), and the ERA-20C dataset is available to 2010 (Compo et al. 2011); therefore, the time period 1920–2010 is employed in this study, constituting 91 winters from

TABLE 1. Abbreviations used in the text.

Abbreviation	Explanation
ACI	Arctic center intensity index, the area-averaged SLP anomalies over the Arctic (55° – 90° N, 0° – 360°) obtained by regressing winter mean SLP onto a simultaneous index
ACI _{AO}	ACI for AO obtained using AO index
AIS	Aleutian low and the Icelandic low seesaw
AO	Arctic Oscillation, the first EOF mode of the winter mean SLP over the extratropical Northern Hemisphere (20° – 90° N, 0° – 360°)
EOF	Empirical orthogonal function
NACI	North Atlantic center intensity index, the area-averaged SLP anomalies over the North Atlantic (20° – 55° N, 80° W– 40° E, denoted by the red box in Fig. 7a) obtained by regressing winter mean SLP onto a simultaneous index
NACI _{AO}	NACI for AO obtained using AO index
NACI _{NAO}	NACI for NAO obtained using NAO index
NAO	North Atlantic Oscillation, the first EOF mode of the winter mean SLP over the North Atlantic (20° – 80° N, 90° W– 40° E)
NPCI	North Pacific center intensity index, the area-averaged SLP anomalies over the North Pacific (25° – 60° N, 150° E– 120° W, denoted by the red box in Fig. 5a) obtained by regressing winter mean SLP onto a simultaneous index
NPCI _{AO}	NPCI for AO obtained using AO index
NPCI _{NPM}	NPCI for NPM obtained using NPM index
NPM	North Pacific mode, the first EOF mode of the winter mean SLP over the North Pacific (20° – 65° N, 120° E– 120° W)
PC	Principal component
PNA	Pacific–North America
$r_{AO,WNAT}$	Correlation coefficient between the AO and WNAT indices
$r_{NAO,NPM}$	Correlation coefficient between the NAO and NPM indices
$r_{NPM,WNAT}$	Correlation coefficient between the NPM and WNAT indices
SAT	Surface air temperature
SE1	The first strong epoch for NPCI _{AO} (1937–59)
SE2	The second strong epoch for NPCI _{AO} (1986–2008)
SLP	Sea level pressure
WE	The weak epoch for NPCI _{AO} (1963–85)
WNAT	Western North American temperature index, the area-averaged winter mean SAT over western North America (30° – 60° N, 110° – 135° W, denoted by the red boxes in Figs. 4j–l)

1920 to 2010. Here, the winter 1920 refers to the 1919/20 winter, and the winter means are calculated by averaging the monthly mean data of December, January, and February. The two-tailed Student's t test is adopted to evaluate the confidence level of linear correlation and regression.

3. Observed evidence for the time-varying patterns and teleconnections of the AO during the winters of 1920–2010

a. Pattern and teleconnections of the AO obtained from the winters of 1920–2010

Figure 1a shows the EOF1 mode of the wintertime SLP anomalies over the extratropical Northern Hemisphere (20° – 90° N) derived from the HadSLP2r dataset for 1920–2010. The normalized time series of the corresponding PC is shown in Fig. 1d (red line). The EOF1 pattern explains 31.9% of the total variance and can be clearly separated from the other eigenvalues based on the criterion proposed by North et al. (1982). The EOF1 pattern (Fig. 1a) is characterized by a seesaw in the SLP anomalies between the Arctic and the Northern Hemispheric midlatitudes. An anomalous low SLP center is

located in the Arctic region, and two anomalous high SLP centers are observed over the North Pacific and North Atlantic. To check the dependence of the results on datasets, the SLP data from the 20CR-V2c and ERA-20C datasets were also analyzed. The EOF1 pattern obtained from 20CR-V2c (ERA-20C) accounts for 29.2% (30.9%) of the total variance, which is comparable to that of HadSLP2r (31.9%). The wintertime AO pattern in 20CR-V2c and ERA-20C (Figs. 1b,c) both resemble the wintertime AO pattern derived from HadSLP2r (Fig. 1a), with a spatial correlation coefficient of 0.99 between them. The corresponding PCs from 20CR-V2c and ERA-20C are also highly correlated to the PCs from HadSLP2r, and the temporal correlation coefficients of both exceed 0.98 (Fig. 1d). These results suggest that the wintertime AO variability during 1920–2010 is consistent among the three datasets.

The climate anomaly over the Northern Hemisphere, especially in the SAT, is tightly linked to the AO variability (e.g., Thompson and Wallace 2001). Figure 1e displays the SAT anomalies over the Northern Hemisphere regressed onto the normalized wintertime AO index in the HadSLP2r dataset. It shows that the positive AO corresponds to significant warming over northern

FIG. 1. The winter (December–February) mean AO pattern obtained via regressing the winter mean SLP onto the normalized PC time series of the first EOF mode of the SLP anomalies over the extratropical Northern Hemisphere (20° – 90° N) during 1920–2010 in the (a) HadSLP2r, (b) 20CR-V2c, and (c) ERA-20C datasets. (d) The normalized PC time series [i.e., AO indices used in (a)–(c)]. (e)–(g) As in (a)–(c), but for the winter mean SAT [the HadCRUT4 dataset is used in (e)]. Dots in (a)–(c) and (e)–(g) indicate the 99% and 90% confidence level based on a two-tailed Student's *t* test, respectively.

Eurasia and southeastern North America and significant cooling over northern Africa and western and northeastern North America. The above signals are also apparent and consistent in the 20CR-V2c and ERA-20C datasets (Figs. 1f,g). These results suggest that the pattern and teleconnections of the wintertime AO are consistent between the observations and reanalysis datasets during 1920–2010.

b. Time-varying AO pattern during the winters of 1920–2010

Previous studies found that the spatial structure of the AO is not stationary under certain specific conditions

(Honda and Nakamura 2001; Castanheira and Graf 2003; Zhao and Moore 2009; Sun and Tan 2013; Shi and Nakamura 2014; Dai and Tan 2017). In this section, we investigate whether the wintertime AO pattern itself is variable during the different periods of 1920–2010. To clarify the variability of the wintertime AO pattern itself during 1920–2010, we calculate the standard deviation of the sliding AO pattern during 1920–2010 with a 23-yr window (Fig. 2). This is done in two steps. First, we regress the winter mean AO index onto SLP in 23-yr sliding windows during 1920–2010 (i.e., in the winters of 1920–42, 1921–43, ..., 1988–2010). Here, the AO index in each sliding window is extracted from the AO index in

Uncertainty of AO pattern

FIG. 2. (a) The AO pattern as in Fig. 1a (contours) overlaid with the standard deviation of the sliding AO pattern with a 23-yr sliding window during the winters of 1920–2010 (shading) based on SLP from the HadSLP2r dataset. See section 3b for details. (b),(c) As in (a), but based on SLP from the 20CR-V2c and ERA-20C datasets, respectively.

Fig. 1d. A total of 69 AO patterns will be obtained in this step. Second, we calculate the standard deviation among these 69 AO patterns to get the standard deviation of the sliding AO pattern. The choice of the 23-yr window is somewhat arbitrary because the window of approximately 20 years is often used to investigate decadal changes (e.g., Wang et al. 2010; Shi and Nakamura 2014). We also tested windows with other widths (e.g., 21, 25, and 31 years), and the main results remain almost unchanged (figures not shown).

The maxima of the standard deviation of the sliding AO patterns are mainly located over the North Pacific in all three datasets (Fig. 2), and they almost overlap with the Pacific center of the AO pattern derived during 1920–2010 (Figs. 1a–c, 2). This suggests that the intensity of the Pacific center of the wintertime AO has large variability during 1920–2010. In contrast, the variability of the Atlantic center in the wintertime AO pattern is much weaker compared with the Pacific center. It suggests that the Atlantic center of the wintertime AO pattern remains relatively invariant during 1920–2010. Although the amplitudes of the variability of the wintertime AO pattern in HadSLP2r (Fig. 2a) are overall weaker than those in 20CR-V2c and ERA-20C (Figs. 2b,c), plausibly because of the low horizontal resolution in HadSLP2r, their patterns resemble each other and are consistent among the three datasets. These results suggest that the Pacific center of the wintertime AO pattern has strong decadal changes during 1920–2010.

To analyze the changes in the intensity of the three AO centers in more detail, the North Pacific center intensity index (NPCI), the North Atlantic center intensity index (NACI), and the Arctic center intensity

index (ACI) are defined to represent the intensities of the three centers in the wintertime AO pattern. They are defined as the area-averaged AO-related SLP anomalies (i.e., the SLP anomalies regressed onto the wintertime AO index) over the North Pacific (25° – 60° N, 150° E– 120° W), the North Atlantic (20° – 55° N, 80° W– 40° E), and the Arctic (55° – 90° N, 0° – 360°) and are denoted as NPCI_{AO} , NACI_{AO} , and ACI_{AO} , respectively. Figure 3 displays the sliding intensity of the three indices with the 23-yr window during the winters of 1920–2010. The variability of the wintertime AO pattern is weaker in HadSLP2r than in the other two datasets, so the results from HadSLP2r use the right-hand y axis with a smaller scale in Fig. 3 for easy comparison with the other two datasets. It reveals that the NPCI_{AO} experiences significant multidecadal fluctuations in all datasets (Fig. 3a). The amplitude of the NPCI_{AO} is large before the 1950s, and it decreases rapidly afterward and reaches a minimum around 1974. After that, it increases slowly in the 1990s (Fig. 3a). This feature, which is consistent among the three datasets, confirms that the multidecadal fluctuations of NPCI_{AO} are robust during 1920–2010. The minimum of the NPCI_{AO} is 0.2 (0.5) hPa in the year 1974, which represents the 23-yr window for the winters of 1963–85 in HadSLP2r (20CR-V2c and ERA-20C), and the maxima before and after 1974 are around 1.2 (2.0) hPa and 0.9 (1.5) hPa in the years 1948 and 1997, which represents the 23-yr window for the winters of 1937–59 and 1986–2008, respectively, in HadSLP2r (20CR-V2c and ERA-20C). Compared with the large variability in the strength of the Pacific center of the AO pattern (i.e., NPCI_{AO}), the strength of the North Atlantic and Arctic centers of the AO pattern

FIG. 3. (a) Sliding NPCI_{AO} (hPa) in a 23-yr sliding window during the winters of 1920–2010 in the 20CR-V2c and ERA-20C datasets (using left y axis) and the HadSLP2r dataset (using right y axis). See section 3b and Table 1 for details. (b),(c) As in (a), but for the NACI_{AO} and ACI_{AO}, respectively.

(i.e., NACI_{AO} and ACI_{AO}) remains relatively invariant (Figs. 3b,c). The NACI_{AO} and ACI_{AO} are always around 0.7 (1.2) hPa and -1.7 (-2.0) hPa, respectively, in HadSLP2r (20CR-V2c and ERA-20C) during the winters of 1920–2010. These results further confirm that the Pacific center of the AO experiences significant multidecadal changes, whereas the Atlantic and Arctic centers of the AO remain almost unchanged during the winters of 1920–2010.

c. Time-varying AO teleconnections during the winters of 1920–2010

Considering the large variability of the Pacific center in the AO pattern, the climate anomalies associated with the AO may also experience significant differences during the winters of 1920–2010. To investigate the possibility of changes in circulation and climate anomalies associated with the variability in the AO pattern,

three typical 23-yr periods with the smallest and largest NPCI_{AO} are singled out. One spans the winters of 1963–85, corresponding to the minimum of sliding NPCI_{AO} in 1974 (Fig. 3a), and the other two span the winters of 1937–59 and 1986–2008, corresponding to the maximum of sliding NPCI_{AO} in 1948 and 1997 before and after 1974 (Fig. 3a). For convenience, these three periods are marked as weak epoch (WE, 1963–85), strong epoch 1 (SE1, 1937–59), and strong epoch 2 (SE2, 1986–2008), respectively. Because the results among the different datasets are highly consistent (figures not shown), only the results based on the 20CR-V2c reanalysis dataset are shown in the following sections.

Figure 4 displays the anomalies of SLP, 500-hPa geopotential height, 700-hPa winds, and SAT regressed onto the winter mean AO index in the three epochs. Significant positive SLP anomalies are observed over the North Pacific in SE1 and SE2 (Figs. 4a,c), although the intensity of the SLP anomalies is somewhat weaker in SE2 than those in the SE1 (Fig. 4c). In contrast, the positive SLP anomalies over the North Pacific almost disappear in WE (Fig. 4b). Similar differences can be seen in the 500-hPa geopotential height field (Figs. 4d–f), which shows significant high pressure center over the North Pacific in SE1 and SE2 (Figs. 4d,f), but not in WE (Fig. 4e). The high pressure center over the North Pacific is equivalently barotropic and can also be seen in the 700-hPa wind field (Figs. 4g–i). A pronounced anticyclonic anomaly is observed in the lower troposphere over the North Pacific in SE1 and SE2 (Figs. 4g,i). The northerly anomalies of this anticyclone over western North America are favorable for advection of cold air from the high latitudes to the western coast of North America, thereby inducing cold anomalies over western North America (Figs. 4j,l). In contrast, the anticyclonic anomaly over the North Pacific is weak and almost invisible in WE (Fig. 4h). As a result, the cold advection and SAT anomalies over western North America are both weak in WE (Fig. 4k). These results suggest that accompanied with the time-varying amplitude of the Pacific center of AO pattern, the influences of the AO on the SAT over the Pacific–North American region also experience multidecadal changes.

4. Revisiting the nature of the AO from the perspective of decadal change

The results in section 3 indicate that the winter mean AO pattern defined as the leading EOF of SLP anomalies over the extratropical Northern Hemisphere is nonstationary and that its Pacific center experiences clear multidecadal fluctuations during 1920–2010. The resultant AO teleconnection (i.e., the relationship

between AO and the western North American SAT) also displays distinct differences between SE1/SE2 and WE (Fig. 4). In SE1, the AO-related climate anomalies over the Pacific–North American region quite resemble those related to the North Pacific variability (e.g., Johnson and Feldstein 2010; Franzke et al. 2011; Yuan et al. 2015). To confirm these similarities, several variables were regressed onto the NPM index during the winters of 1920–2010 to display the patterns associated with the dominant regional variability over the North Pacific (Fig. 5). It shows that the positive phase of the NPM index is featured with pronounced quasi-barotropic high pressure anomalies extending from surface to the middle troposphere over the North Pacific (Figs. 5a–c), which are quite similar to those related to the AO in SE1 and SE2 (Figs. 4a,c,d,f,g,i). The 500-hPa geopotential height field shows a typical PNA pattern (Fig. 5b), indicating that the NPM is almost equivalent to the PNA pattern (see discussions in section 2). Significant cold anomalies are observed over northwestern North America (Fig. 5d), likely attributed to cold advection by the northerly anomalies there (Fig. 5c).

On one hand, the high similarity between AO-related climate anomalies in SE1/SE2 (left and right columns in Fig. 4) and NPM-related climate anomalies (Fig. 5) is consistent with Quadrelli and Wallace (2004). On the other hand, this high similarity raises a question: Which is the fundamental mode of the climate variability over the North Pacific, the NPM or the AO? In some sense, the answer to this question is related to the physical nature of the AO especially regarding the Pacific center of the AO discussed by many previous studies (e.g., Deser 2000; Wallace 2000; Ambaum et al. 2001; Rogers and McHugh 2002; Wallace and Thompson 2002; Feldstein and Franzke 2006; Itoh 2008). In this section, we will try to address this question from the perspective of decadal changes.

a. The NPM as the fundamental mode over the North Pacific

To answer the question whether the NPM or the AO is the fundamental mode of climate variability over the North Pacific, the possible multidecadal changes of the NPM pattern are examined during the winters of 1920–2010. Figure 6 shows the intensity of the NPM-related Pacific center in a 23-yr sliding window, marked as NPCI_{NPM} . Similar to the NPCI_{AO} used in section 3b, the NPCI_{NPM} is defined as the area-averaged NPM-related SLP anomalies over the North Pacific (25° – 60°N , 150°E – 120°W). It reveals that unlike the time-varying NPCI_{AO} , the NPCI_{NPM} remains almost the same (approximately 2.3 hPa) during the entire 1920–2010 period (Fig. 6). Therefore, the Pacific center associated with the NPM

AO-regressed variables

SE1(1937-1959)

WE(1963-1985)

SE2(1986-2008)

FIG. 4. The winter mean SLP regressed on the simultaneous normalized AO index during (a) SE1 (1937–59), (b) WE (1963–85), and (c) SE2 (1986–2008) in the 20CR-V2c dataset. (d)–(f), (g)–(i), and (j)–(l) As in (a)–(c), but for 500-hPa geopotential height field, 700-hPa winds, and SAT, respectively. Shading intervals are 0.6 hPa in (a)–(c), 8 gpm in (d)–(f), and 0.3 K in (j)–(l). Dots in (a)–(f) and (j)–(l) indicate the 90% confidence level based on a two-tailed Student's t test. Vectors exceeding the 90% confidence level are shown in (g)–(i). Red boxes in (j)–(l) indicate the region to define WNAT.

NPM-regressed variables

FIG. 5. (a) The winter mean SLP regressed on the simultaneous normalized NPM index during 1920–2010 in the 20CR-V2c dataset. (b)–(d) As in (a), but for 500-hPa geopotential height field, 700-hPa winds, and SAT, respectively. Dots in (a), (b), and (d) indicate the 99% confidence level based on a two-tailed Student's *t* test. Vectors exceeding the 99% confidence level are shown in (c). The red box in (a) indicates the region to define NPCI.

pattern is stationary and does not have decadal changes. To further examine the possible decadal changes in the NPM-related climate anomalies over western North America, we define an index as the area-averaged winter mean SAT over western North America (30° – 60° N, 110° – 135° W), denoted as the WNAT index. The sliding correlation coefficient between the winter mean NPM index and WNAT index (marked as $r_{\text{NPM,WNAT}}$) remains around -0.8 during the entire 1920–2010 period. This result suggests that the SAT variability over western North America is always closely tied to the NPM during 1920–2010. This stable NPM–WNAT relation can be attributed to the invariant Pacific center associated with the NPM pattern (Fig. 6). Compared with the time-varying intensity of the AO-related Pacific center (Fig. 3a), the relatively invariant intensity of the

NPM-related Pacific center (Fig. 6) suggests that the NPM rather than the AO is more likely an inherent and fundamental mode of the atmosphere variability over the North Pacific in boreal winter.

b. The stable similarity between the AO and NAO

It was generally accepted that the wintertime AO and NAO are quite similar and somewhat difficult to distinguish during a specified period (e.g., Deser 2000; Rogers and McHugh 2002; Feldstein and Franzke 2006). Here we will check whether the similarity between AO and NAO has decadal changes during the winters of 1920–2010. Figure 7a shows the wintertime SLP pattern of NAO obtained by regressing the winter mean NAO index onto SLP over the extratropical Northern Hemisphere for the winters of 1920–2010. The NAO pattern,

FIG. 6. Sliding correlation coefficients between the winter mean NPM index and WNAT index (i.e., $r_{\text{NPM,WNAT}}$) with a 23-yr sliding window during the winters of 1920–2010 (black line) and the sliding North Pacific center intensity index of the NPM pattern (i.e., NPCI_{NPM}) with a 23-yr sliding window during the winters of 1920–2010 (red line). Data are from the 20CR-V2c dataset.

especially the dipole structure over the North Atlantic, closely resembles the AO pattern, and the Pacific center of the NAO is weaker than that in the AO pattern (Fig. 1b). The pattern correlation coefficient between the SLP patterns of AO and NAO is 0.96, implying that the wintertime AO and NAO may always remain similar during different epochs of 1920–2010.

To verify the above hypothesis, the sliding correlation coefficients with a 23-yr sliding window were calculated between the wintertime NAO and AO (Fig. 7b). It reveals that the temporal correlation coefficients between the NAO and AO indices almost always exceed 0.9 and that the pattern correlation coefficients between the sliding SLP patterns of AO and NAO over the extratropical Northern Hemisphere (20° – 90°N , 0° – 360°) almost always exceed 0.95 during the entire 1920–2010 period (Fig. 7b). This result confirms that the wintertime AO and NAO are indeed difficult to distinguish during 1920–2010, supporting previous studies (e.g., Rogers and McHugh 2002; Feldstein and Franzke 2006). In addition, the intensity of the Atlantic center of the NAO, which is defined as the area-averaged NAO-related SLP anomalies over the North Atlantic (20° – 55°N , 80°W – 40°E) and marked as NACI_{NAO} , remains almost unchanged during the entire 1920–2010 period (Fig. 7b). This result suggests that the NAO is very likely the inherent and fundamental mode of atmosphere variability over the North Atlantic in boreal winter.

Wallace (2000) suggested that the NAO and AO are different names for the same variability, not different patterns of variability. He also proposed that the difference between NAO and AO lies in whether the North Atlantic variability is interpreted as a regional pattern controlled by processes within the North Atlantic sector or as an annular mode whose strongest teleconnections are located over the North Atlantic sector. On one hand, our results presented in sections 4a and 4b confirm that the NPM and NAO are the

inherent and fundamental regional modes over the North Pacific and North Atlantic regions in view of their stationary pattern over the two regions, respectively. On the other hand, the time-invariant consistency between the AO and NAO (Fig. 7b) and the time-varying North Pacific center of the AO indicate that the AO seems to be fundamentally rooted in the variability not over the North Pacific, but over the North Atlantic. Moreover, the time-varying North Pacific center of the AO implies that the annular structure of the AO very likely arises from the coupling of the atmospheric modes between the North Pacific and North Atlantic.

c. The time-varying Pacific center of the AO and the North Pacific–North Atlantic coupling

To test the possible linkage between the annular structure of the AO and the coupling of the atmospheric modes between the North Pacific and North Atlantic, the correlation coefficient between the winter mean NAO and NPM indices ($r_{\text{NAO,NPM}}$) was employed to represent the strength of coupling between the North Pacific and North Atlantic (Gong et al. 2017). The correlation was calculated in a 23-yr sliding window to show its possible decadal change. It reveals that the temporal variations of the sliding $r_{\text{NAO,NPM}}$ are highly consistent with that of the intensity of the Pacific center of the AO as indicated by NPCI_{AO} (Fig. 8a). This result suggests that the Pacific center of the AO is strong (weak) when the NAO is closely (loosely) coupled to the NPM, and vice versa. Figure 8b further shows the scatter diagram between $r_{\text{NAO,NPM}}$ (x axis) and NPCI_{AO} (y axis), where each dot represents the value in each 23-yr sliding window. The linearly clustered dots and the high correlation coefficient between $r_{\text{NAO,NPM}}$ and NPCI_{AO} ($r = 0.9$) suggest that approximately 80% of the variance of the intensity of the Pacific center of the AO (i.e., NPCI_{AO}) is linked to the coupling between the leading regional

FIG. 7. (a) The winter mean SLP regressed on the simultaneous normalized NAO index during 1920–2010. (b) Sliding temporal correlation coefficient between the winter mean AO and NAO indices (i.e., $r_{AO,NAO}$) with a 23-yr sliding window (black solid line), sliding pattern correlation coefficient between the SLP patterns of AO and NAO (i.e., $pcc_{AO,NAO}$) over the extratropical Northern Hemisphere (20°–90°N, 0°–360°) with a 23-yr sliding window (black dot line), and the sliding North Atlantic center intensity index of the NAO pattern (i.e., $NACI_{NAO}$) with a 23-yr sliding window during the winters of 1920–2010. Dots in (a) indicate the 99% confidence level based on a two-tailed Student's t test. Data are from 20CR-V2c dataset. The red box in (a) indicates the region to define NACI.

modes over the North Atlantic and North Pacific (i.e., between NAO and NPM).

Section 3c shows that the relationship between the AO and the winter mean SAT over western North America, which can be measured by the correlation coefficient between the winter mean AO index and the WNAT index (i.e., $r_{AO,WNAT}$), changes with the intensity of the Pacific center of the AO (i.e., $NPCI_{AO}$). Here we further examine whether $r_{AO,WNAT}$ is linked to the coupling between NAO and NPM. Figure 8a shows the sliding $r_{AO,WNAT}$ with a 23-yr window, where the sign of $r_{AO,WNAT}$ is multiplied by -1 for easy comparison with other indices. Clear multidecadal change is observed in the sliding $r_{AO,WNAT}$ during 1920–2010, and its temporal evolution is highly consistent with that of $NPCI_{AO}$ and $r_{NAO,NPM}$. The scatter diagrams between

$r_{AO,WNAT}$ (y axis) and $NPCI_{AO}$ (x axis) (Fig. 8c) and between $r_{AO,WNAT}$ (y axis) and $r_{NAO,NPM}$ (x axis) (Fig. 8d) confirm the results in Fig. 8a. The linearly clustered dots and the high correlation coefficients between $r_{AO,WNAT}$ and $NPCI_{AO}$ ($r = 0.88$) and between $r_{AO,WNAT}$ and $r_{NAO,NPM}$ ($r = 0.87$) confirm that the relationship between the AO and the winter mean SAT over western North America also depends on the intensity of the Pacific center of the AO and the coupling between NAO and NPM.

5. Summary

In this study, the multidecadal fluctuations of the pattern and teleconnections of the AO are investigated during the winters of 1920–2010 based on observation

FIG. 8. (a) Sliding correlation coefficient between the winter mean AO and negative WNAT indices (i.e., $-r_{\text{AO,WNAT}}$) with a 23-yr window (blue line, using left y axis), sliding correlation coefficient between the winter mean NAO and NPM indices (i.e., $r_{\text{NAO,NPM}}$) with a 23-yr window (black line, using left y axis), and sliding NPCl_{AO} (hPa) in a 23-yr sliding window (red line, using right y axis). (b) Scatterplot of sliding $r_{\text{NAO,NPM}}$ (x axis) vs sliding NPCl_{AO} (y axis). (c), (d) As in (b), but for the sliding NPCl_{AO} (x axis) vs the sliding negative $r_{\text{AO,WNAT}}$ (y axis) and the sliding $r_{\text{NAO,NPM}}$ (x axis) vs the sliding negative $r_{\text{AO,WNAT}}$ (y axis), respectively. Data are from the 20CR-V2c dataset.

(HadSLP2r, HadCRU4) and reanalysis (20CR-V2c and ERA-20C) datasets. The intensity of the Pacific center of the wintertime AO pattern (NPCl_{AO}) in a 23-yr sliding window is shown to experience clear multi-decadal changes. The NPCl_{AO} is strong before the 1950s and weak afterward, reaching a minimum around 1974, and it recovers slowly in the 1990s. In contrast, the Atlantic center of the wintertime AO pattern (NACl_{AO}) remains almost unchanged during 1920–2010. Accompanied with the fluctuations of NPCl_{AO} , the relationship between the AO and the SAT over western North America ($r_{\text{AO,WNAT}}$) also changes. During epochs with a strong Pacific center of the AO, a pronounced anticyclonic center is observed over the North Pacific in the positive phases of AO. It facilitates strong cold advection over the western coast of North America, resulting in significant cold anomalies over western North

America. In contrast, during epochs with a weak Pacific center of the AO, the influences of the AO on the SAT over western North America are weak.

The time-varying Pacific center of the AO motivated a revisit to the nature of the AO from the perspective of decadal change. On one hand, it was revealed that the North Pacific center in the NPM pattern, the regional dominant atmospheric variability over the North Pacific, and the North Atlantic center in the NAO pattern, the regional dominant atmospheric variability over the North Atlantic, both remain invariant during 1920–2010, suggesting that the NPM and NAO are inherent and fundamental modes of the wintertime climate variability over the North Pacific and North Atlantic, respectively. On the other hand, it was revealed that the AO-related circulation patterns surrounding the North Pacific quite resemble those related to the NPM during SE1 and SE2

when the strong Pacific center of the AO is observed, but this similarity disappears during WE when the weak Pacific center of the AO is observed. In contrast, the AO-related circulation patterns surrounding the North Atlantic always resemble those related to the NAO. Moreover, it was found that the intensity of the Pacific center of the AO evolves almost in phase with the strength of coupling between the NPM and NAO. The Pacific center of the AO is strong (weak) when the NAO is closely (loosely) coupled to the NPM, and vice versa. These results suggest that the AO seems to be fundamentally rooted in the variability over the North Atlantic, a finding aligned with those of Ambaum et al. (2001) and Itoh (2008), and that the annular structure of the AO very likely arises from the coupling of the atmospheric modes between the North Pacific and North Atlantic.

The time-varying pattern of the AO might challenge the reliability and validity of using the AO to represent the leading climate variability over the extratropical Northern Hemisphere. Meanwhile, it might also provide a new criterion to test the proposed theories of the AO. Note that the results reported in this study are based on statistics of winter mean variables without examining associated dynamical processes. These phenomena need to be explained by some diagnostic and theoretical studies in the future. Last but not least, it is important to understand why the NPM–NAO coupling shows multidecadal fluctuations. A preliminary inspection suggests that it may be related to the phase of the Atlantic multidecadal oscillation (not shown), and this will be investigated in our future studies.

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