Relationship between the Arctic Oscillation and Cold Surges over East Asia

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ABSTRACT

The present study reveals the changes in the characteristics of cold surges over East Asia associated with the Arctic Oscillation (AO). Based on circulation features, cold surges are grouped into two general types: wave train and blocking types. The blocking type of cold surge tends to occur during negative AO periods, that is, the AO-related polarity of the blocking type. However, the wave train type is observed during both positive and negative AO periods, although the wave train features associated with negative AO are relatively weaker. The cold surges during negative AO are stronger than those during positive AO in terms of both amplitude and duration. The cold surges during positive AO in which the extent of effect is confined to inland China passes through East Asia quickly because of weaker Siberian high and Aleutian low, leading to short duration of these cold surges. In contrast, the cold surge during negative AO, characterized by a well-organized anticyclone–cyclone couplet with high pressure over continental East Asia and low pressure over Japan, brings continuous cold air into the entire East Asian region for more than one week with long-lasting cold advection. It is also found that the tracks of the cold surges during negative AO tend to occur more frequently over Korea and Japan and less frequently over China, compared with those during positive AO. The tracks are related to a west–east dipole structure of the ratio of rain conversion to snow according to AO phase, resulting in freezing precipitation or snowfall events over inland China (Korea and Japan) are likely to occur more frequently during the positive (negative) AO periods.

1. Introduction

The wintertime East Asian cold surges, especially those associated with intensified Siberian high, exert tremendous societal and economic impacts on East Asian countries. Cold surges lead to abrupt temperature drops with prevailing northerly winds related to strong cold advection along the edge of the Siberian high. Approximately 10 cold surges sweep across East Asia each winter (Chen et al. 2004). They often cause heavy freezing precipitation and snowfall over East Asia (Boyle and Chen 1987; Ding 1994; Chen 2002; Jeong et al. 2008) and modulate the convective activity over the South China Sea (Chan and Li 2004). On rare occasions, they even induce climate anomalies over remote regions including North America (Cohen et al. 2001; Yang et al. 2002).

The Siberian high, a semipermanent pressure system during winter, is known as a cold core and a high pressure system. It is maintained by large-scale subsidence and strong radiative cooling (Ding and Krishnamurti 1987). A sudden migration of the high pressure toward East Asia reinforces local cold weather to a severe cold surge accompanied by a rapid temperature drop over a broad region. Accordingly, the amplification of the Siberian high is recognized as an essential factor for the generation and maintenance of cold surges (Zhang et al. 1997; Gong and Ho 2002; Takaya and Nakamura 2005a). Favorable conditions for the occurrence of cold surges are observed when the high pressure reaches certain intensity and the upper-tropospheric disturbances over the Eurasian continent grow into a wave train (i.e., a periodic trough–ridge pattern) over Lake Baikal. The southeastward propagation of the upper-tropospheric wave train deepens the tropospheric trough near the
eastern seaboard of East Asia, which leads to a northwesterly flow that brings cold air from the main “reservoir” over the Eurasian continent (Zhang et al. 1997). As a result, the northwesterly flow expands the preexisting cold anomalies over Siberia (Joung and Hitchman 1982; Lau and Lau 1984; Chen 2002) and amplifies the surface cold anomalies, which in turn induce anomalous anticyclonic circulation that accelerates the northwesterly flow and the wave train. The interactions between the upper-level wave train and the preexisting cold anomalies over Siberia intensify the Siberian high to generate cold surges in East Asia (Takaya and Nakamura 2005a).

Besides the general discussion of the cold surges caused by wave trains as described above, some studies have suggested that some cold surges are distinctive from the wave train type. For example, Takaya and Nakamura (2005b) documented two different origins of the intra-seasonal amplification of the Siberian high: a wave train from the Atlantic and a blocking from the Pacific. In fact, the two origins lead to different types of cold air outbreaks over East Asia. Park et al. (2008) reported that the expansions of the Siberian high and the subsequent cold surges are caused by a wave train across the Eurasian continent and a blocking from the North Pacific, respectively. The wave train type and the blocking type have different mechanisms. The former is a growing baroclinic wave, whereas the latter is a dipole pattern related to slowly retrogressing blockings.

Previous studies have also addressed the influences of large-scale climate phenomena such as the Arctic Oscillation (AO; Thompson and Wallace 1998), El Niño–Southern Oscillation (ENSO), and Madden–Julian oscillation (MJO; Madden and Julian 1972) on the cold surges over East Asia. When AO is negative, a combination of increase in the monthly mean and daily variability of the Siberian high, deepening of the east coastal trough, and enhancement of the East Asian jet stream provides favorable conditions for the occurrence of cold surges (Gong and Ho 2004; Jeong and Ho 2005). Zhang et al. (1997) and Chen et al. (2004) showed that the number of cold surges is influenced by the northerly flow over the South China Sea and the wave train over the North Pacific, which are modulated by ENSO. As noted by Jeong et al. (2005), the changes in large-scale extratropical circulation induced by MJO, of which the convection center is located over the tropical Indian Ocean, strengthen the amplitude of cold surges over East Asia. While ENSO and MJO indirectly modulate the occurrence of cold surges, AO has a direct influence on cold surges through the changes in mid- and high-latitude atmospheric circulation systems including the Siberian high, upper-level trough, and westerly jet stream. Consequently, the changes in atmospheric circulation associated with AO phases may also influence the outbreak mechanisms and properties of cold surges as well as the number of occurrence. However, few studies have been conducted to investigate the relationship between AO phases and cold surges, by which the present study is motivated.

We first investigate the general features of cold surges over East Asia and then examine the characteristics and properties of these cold surges such as their occurrence, development, duration, tracks, and related large-scale circulation patterns. Next, we investigate the connections of the cold surges with AO phases. Both statistical analysis and dynamical interpretation are applied in this study.

Section 2 describes datasets and analysis techniques, which include the procedures to determine cold surges and calculate wave activity flux and cold surge tracks. The general features of cold surges are described in section 3, which is followed by a detailed discussion of the changes in the characteristics of cold surges with respect to AO phases in section 4. The findings and limitations of this study and the potential issues for further analysis are summarized and discussed in section 5.

2. Data and analysis methods

2a. Data

To analyze the characteristics of cold surges, we apply the daily-mean surface air temperature (SAT) and precipitation data from 103 stations in China and 13 stations in Korea. These data are obtained from the China Meteorological Administration and the Korea Meteorological Administration, respectively (see Fig. 1). We also use the 6-hourly, daily, and monthly mean temperatures, geopotential height (Z), horizontal and vertical winds, and sea level pressure (SLP) from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis (Kalnay et al. 1996). Daily and monthly means are applied to analyze the atmospheric circulation related to cold surges and AO, and 6-hourly means are used as the input data of a model to determine cold surge tracks. Our analyses are carried out for 52 winters (November–March) from 1954/55 to 2005/06, considered the availability and confidence of data, especially SAT.

This study also applies the AO index from the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center (CPC) Web site (available online at http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/ao.shtml#forecast). It is used to reveal the changes in cold surges and atmospheric circulation with
respect to AO phases. The AO index is defined as the time series of the first empirical orthogonal function mode of monthly SLP anomalies poleward of 20°N (Thompson and Wallace 1998).

b. Definition of cold surges

An abrupt drop of SAT and an expansion of the Siberian high are important features of the cold surges over East Asia. To depict these features, previous studies have proposed various synoptic criteria to identify cold surges (Zhang et al. 1997; Chen et al. 2002, 2004; Jeong and Ho 2005). In this study, the dates of the occurrence of cold surges were defined based on the methodology of Zhang et al. (1997) and Jeong and Ho (2005), with slight modifications and additional criteria described as follows.

The expansion of the Siberian high to southern Siberia is related to a cold surge occurrence (Zhang et al. 1997). We defined the region of southern Siberia as indicated in Fig. 1 (35°–55°N, 90°–115°E) as a domain of the Siberian high. We identified the days of strong Siberian high when the magnitude of SLP and relative vorticity in the center of the surface anticyclone over the Siberian high domain exceeds 1035 hPa and $-1.0 \times 10^{-5}$ s$^{-1}$, respectively. As seen in the figure, this domain was located in the southeast of the maximum climatological SLP where an expansion of the high is often accompanied by cold surges. The center of the surface anticyclone was defined as the grid point where 1000-hPa $Z$ is larger than the values of the 8 surrounding grid points (Zhang and Wang 1997).

We focused on the systematic cold surges with synoptic-scale features like the expansion of the Siberian high and upper-level circulation. Accordingly, small-scale cold weather caused by local effects such as a radiative cooling, which is not accompanied by large-scale synoptic features, should be excluded. We should detect cold surges that occur at several surrounding stations. Thus, we divided the 116 stations into $5^\circ \times 5^\circ$ grid boxes and calculated the SAT values averaged over these boxes (Fig. 1). We also considered a second criterion: both the day-to-day drop of SAT and the SAT anomaly should exceed 1.5$\sigma$ ($\sigma$ is the standard deviation of SAT during the 52 winters) in more than one grid box. Our criterion with regard to SAT anomalies would exclude some cold events whose temperature was not sufficiently low. So, our method contains additional criterion to that of Zhang et al. (1997) and Jeong and Ho (2005), which considered only the day-to-day SAT drop in defining cold surges. Before applying the supplemental criterion, 544 cold surges were detected during the 52 winters from 1954/55 to 2005/06. However, only 332 cold surges among 544 were selected by the supplemental criterion related to SAT anomalies and used for the present analysis.

In addition, the domain of the Siberian high used in this study is larger than that used by Zhang et al. (1997) and Jeong and Ho (2005). These previous studies focused on central and southern China, but the domain of our analysis covers Korea, southern Japan, and a larger part of China. Thus, we were able to detect both blocking and wave train cold surges effectively.

c. Wave activity flux

We adopted the stationary wave activity flux introduced by Plumb (1985) to diagnose the three-dimensional propagation of stationary waves in association with cold surges. Following Plumb (1985), the stationary wave activity flux ($F_s$) is derived as

$$F_s = p \cos \phi \left\{ \frac{u'^2}{2\Omega \sin \phi} - \frac{1}{2} \frac{\partial (u' \Phi')}{\partial \lambda} + \frac{1}{2} \frac{\partial (u' \Phi')}{\partial \lambda} \right\}. \quad (1)$$

In Eq. (1), the prime denotes the value obtained by removing the zonal average at each latitude and height, $p$ is pressure, $(u, v)$ represents zonal and meridional winds, $\Phi$ is geopotential height, $T$ is temperature, $\Omega$ is the earth’s rotation rate, $a = (6.37 \times 10^6$ m) is the earth’s radius, and $(\phi, \lambda)$ is the latitude and longitude. Here $S$ is the static stability, which is defined as

$$S = \frac{\partial T}{\partial z} + \frac{\kappa T}{H}. \quad (2)$$
where the caret indicates the area average over the Northern Hemisphere, \( \kappa = 287 \text{ J K}^{-1} \text{ kg}^{-1}/1004 \text{ J K}^{-1} \text{ kg}^{-1} \)
 is the ratio of gas constant to specific heat at constant pressure, and \( H = 8000 \text{ m} \)
 is the constant-scale height. In this study, anomalous wave activity fluxes were computed by anomalies of atmospheric fields for two days before and after the occurrence of cold surges.

\[ \frac{dX}{dt} = \hat{X}[X(t)], \]  

where \( t \) represents time, \( X \) is the position vector, and \( \hat{X} \) is the wind velocity vector. This equation is solved using the constant acceleration scheme (Petterssen 1940, 221–223) expressed by

\[ X(t_i) = X(t_0) + \frac{1}{2} (\Delta t) [\hat{X}(t_0) + \hat{X}(t_i)]. \]  

In Eq. (4), \( \Delta t \) is time interval and the subscript specifies the step number. The solution to the equation is obtained by the following iteration:

\[ X^1(t_1) \approx X(t_0) + (\Delta t) \hat{X}(t_0) \]
\[ X^2(t_1) \approx X(t_0) + \frac{1}{2} (\Delta t) [\hat{X}(t_0) + \hat{X}^1(t_1)] \]
\[ \vdots \]
\[ X^i(t_1) \approx X(t_0) + \frac{1}{2} (\Delta t) [\hat{X}(t_0) + \hat{X}^{i-1}(t_1)]. \]  

where the superscripts indicate the iteration number. When the difference in trajectory positions between two subsequent iterations is less than a specific value, the iteration process is terminated and a trajectory is determined. A detailed description of the model is given in Stohl (1998) and Stohl and Seibert (1998) (the source code and documentation are available online at http://zardoz.nilu.no/~andreas/flextra.html).

The FLEXTRA requires four three-dimensional meteorological fields: the two horizontal wind components, the vertical motion, and temperature. To determine the cold surge tracks, the initial location of the cold surge and 6-hourly mean reanalysis data are used as inputs of the model. The initial location is defined as the longitude and latitude of the \( 5^\circ \times 5^\circ \) grid box in which the SAT drop is maximum on the occurrence date of the cold surge. Using these data, the FLEXTRA yields backward tracks for 5 days before, and forward tracks for 4 days after the cold surge occurrence, which are combined into one cold surge track.

3. General features of cold surges over East Asia

As mentioned above, the atmospheric circulation patterns related to cold surges over East Asia have been investigated by many studies (e.g., Lau and Lau 1984; Boyle 1986; Boyle and Chen 1987; Zhang et al. 1997; Chen et al. 2002; Jeong and Ho 2005; Park et al. 2008). Before ascertaining the impact of AO on the properties of cold surges, we summarize the general features of cold surges to provide a background for later analysis.

Figure 2 depicts the patterns of SLP, SAT, 500-hPa Z, and 300-hPa zonal wind, as well as their anomalies, averaged for the 332 cold surges selected. Since cold surges are the most significant transient disturbances embedded within the East Asian winter monsoon (Zhang et al. 1997), the large-scale circulation features shown in the figure are largely analogous to those of strong winter monsoons (see Figs. 1 and 6 in Jhun and Lee 2004; also see Li and Yang 2010). An exception occurs in the connection of cold surges to the upper-level synoptic wave train as shown in the anomaly fields of 500-hPa Z and 300-hPa zonal wind. The SLP field is characterized by an amplification of the Siberian high and the Aleutian low (Fig. 2a). The centers of the Siberian high and the Aleutian low are above 1040 hPa and below 1004 hPa, respectively, and they are associated with significant cold advection. (The boxes in Figs. 1 and 2a represent the areas used to define the cold surges, in which the value of SLP reaches maximum.) The anomalous SLP values form an anticyclone–cyclone couplet with high pressure over the center of the Siberian high and low pressure over Japan near the southwest edge of the Aleutian low, both exerting a dominant cold northerly flow (Lau and Lau 1984). An intrusion of cold flow toward East Asia decreases SAT and increases the meridional SAT gradient over a broad region (Fig. 2b). Widespread cold anomalies are also found in Fig. 2b, over both East Asia and northeastern Eurasia near 60°N. Figures 2c,d show
a deepened tropospheric trough near the eastern seaboard of East Asia and an enhanced East Asian jet stream, respectively. Anomalies of 500-hPa $Z$ and 300-hPa zonal wind exhibit wave train features in which anomalous cyclone (tropospheric trough) and strong zonal winds are located over East Asia. In Jhun and Lee (2004), 500-hPa $Z$ and 300-hPa zonal wind anomalies related to strong winter monsoons did not show the upper-level synoptic wave, but exhibited a widespread trough and strong jet stream over East Asia and the North Pacific. These atmospheric circulation features are related to strong baroclinicity conditions and lead to strong cold advection that causes cold surges (Boyle 1986).

To further manifest the mechanism of the cold surges initiated and developed by the upper-level wave train, Fig. 3 shows composite anomalies to depict the time evolutions of $Z$ at 300 hPa and 850 hPa, vertical cross sections of $Z$ and potential temperature, and temperature and horizontal wind at 850 hPa averaged for the 332 cold surges. Significant fluctuations of ridge, trough, and ridge are alternately situated around the Ural Mountains (50°–75°N, 50°–90°E), Lake Baikal (45°–65°N, 90°–120°E), and Korea–Japan (30°–45°N, 120°–140°E) on day −2 relative to the occurrence date of cold surges (Fig. 3a). The ridge–trough–ridge pattern, implying a wave train across the Eurasian continent, aligns in a northwest–southeast direction across East Asia. The upper-tropospheric wave train appears to propagate southeastward (Figs. 3a–c). The anticyclone–cyclone couplet over Siberia and East Asia is also found at the lower troposphere on day 0, which also exhibits a southeastward propagation. At the lower troposphere, the anticyclone progresses from Siberia to southern China along the propagation of the wave train, linked to an expansion of the Siberian high toward East Asia. The $Z$ feature at the upper troposphere shifts slightly westward compared to that at the lower troposphere. Westward tilting with height is the obvious structure in the vertical cross section of $Z$ along the waveguided line (Figs. 3d–f). Throughout the troposphere (i.e., below 300 hPa), troughs and ridges tilt westward with height, and warm and cold cores have opposite tilts. The $Z$ and potential temperature patterns show a phase difference. Overall, the tilted warming-ridge and cooling-trough structure characterizes the baroclinic growth system of extratropical cyclones, which intensify upper-level troughs and ridges (Holton 2004, 146–147). On day +2, the baroclinicity of the wave train weakens slightly. The $Z$ patterns of both upper and lower troposphere
over Lake Baikal show a nearly in-phase feature and the vertical cross section exhibits equivalent barotropic structure (Figs. 3c,f).

Figures 3g–i depict the flows induced by lower-tropospheric $Z$ patterns and the related temperature anomalies at 850 hPa. A strong northerly flow is formed by the anticyclone–cyclone couplet noted in Fig. 3b and is closely linked to the occurrence of cold surges (Fig. 3h). Interestingly, the temperature pattern matches well with the 300-hPa $Z$ pattern shown in Figs. 3a–c. In the developing baroclinic wave systems, upper-tropospheric troughs are located over the west of the lower-level low pressures because of the westward tilting of $Z$. Thus, cold advection also lies to the west of low pressures at the lower troposphere. Consequently, cold surges break out and are maintained by the expansion of the Siberian high through an interaction between the upper-level trough and the lower-level cold advection, which intensifies and expands the existing cold anomalies over the Siberian region in the growing baroclinic wave systems (Takaya and Nakamura 2005a; Jeong et al. 2006).

4. Relationship between cold surges and AO

To examine the relationship between cold surges and AO phases, we selected the months of positive and negative AO when the values of AO index were greater than $+1\sigma$ and less than $-1\sigma$, respectively, among a total of 260 months in 52 winters. Based on this criterion, 40 positive and 42 negative AO months were identified. We then categorized the 332 cold surges with respect to AO phases. Among all the cold surges, 241, 31, and 60 cold

![Fig. 3. Composite anomalies of (a)–(c) geopotential height at 300 hPa (contours; in intervals of 20 m, significant values at the 95% confidence level are represented by thick lines) and 850 hPa (shadings; significant values at the 95% confidence level are represented by gray dots), (d)–(f) vertical cross sections of geopotential height (contours; in intervals of 20 m) and potential temperature (shadings) along thick red lines in (a)–(c), and (g)–(i) temperature (shadings; significant values at the 95% confidence level are represented by gray dots) and winds (vectors) at 850 hPa during day $-2$ to day $+2$ relative to all cold surge occurrences for the entire analysis period.](image-url)
surges occurred during neutral, positive, and negative AO periods, respectively. This result, which shows more frequent cold surges during negative AO than during positive AO, is in agreement with the result of Jeong and Ho (2005).

Figure 4 shows the composite patterns of anomalies of $Z$ at 300 and 850 hPa, vertical cross sections of $Z$ and potential temperature, and 850-hPa temperature and horizontal wind for the 31 cold surges during positive AO. The general features relevant to wave train bear a resemblance to those shown in Fig. 3 in spite of several disparities. The upper-tropospheric ridge–trough–ridge pattern in a northwest–southeast direction from central Russia to Japan is found with a westward tilt relative to the pattern at the lower troposphere. It moves southeastward toward East Asia with an expansion of the Siberian high (Figs. 4a–c). The vertical structure (Figs. 4d–f) clearly displays a growing baroclinic wave system with a westward tilt of $Z$ and an eastward tilt of potential temperature in the troposphere, similar to the features shown in Figs. 3d–f. The in-phase and equivalent barotropic structure over Lake Baikal on day +2 presented in Figs. 4e,f is also similar to the structure shown in Figs. 3c,f, respectively. However, the features of cold surges for positive AO can be distinguished from those of the typical cold surges in terms of some properties. There are significant negative $Z$ anomalies over the polar region at both the upper and lower troposphere (Figs. 4a–c) and in the stratosphere (Figs. 4d–f), which are associated with monthly mean features during positive AO. Significant positive $Z$ anomalies at the lower troposphere over the North Pacific are also found. The large-scale SLP pattern during positive AO weakens the Siberian high and the Aleutian low (Thompson and Wallace 1998), which is linked to a weakening of the anticyclone–cyclone couplet with a high near the Siberian high and a low near the southwestern edge of the Aleutian low (Figs. 4a–c). In particular, the negative $Z$ anomalies at 850 hPa over Japan in Fig. 4b are weaker than those in Fig. 3b. By these circulation patterns, the amplitude of the cold anomaly

Fig. 4. As in Fig. 3, but for cold surge occurrences during positive AO.
over East Asia is smaller than that shown in Figs. 3g–i and the cold advection is associated with anomalous northwesterly flow (Figs. 4g–i), instead of anomalous northerly flow. Because the anomalous cyclone over Japan is particularly weak, this northwesterly flow induced by the only anomalous anticyclone related to the Siberian high becomes dominant (Figs. 4b,h). In spite of the differences, the cold surges during positive AO appear to be the similar circulation features to those of the common cold surges over East Asia.

Similarly, the mean patterns of various anomaly fields averaged for the 60 cold surges during negative AO are presented in Fig. 5. Strong positive and negative Z anomalies are found near the subarctic region and over East Asia, respectively, on day $-2$ (Fig. 5a). The positive anomalies (i.e., blockings) are nearly barotropic and stationary during the occurrence and development stages of cold surges, whereas the negative anomalies (i.e., troughs) show a baroclinic structure of westward tilt with height and propagate slowly southeastward (Figs. 5a–c). Coinciding with the positive–negative dipole anomalies in the meridional direction that constitute blockings and troughs, the unusual southward expansion of the Siberian high is clearly shown in Fig. 5b. It is noted that, in Figs. 5a–c, the expanded Siberian high forms a strong anticyclone–cyclone couplet with a negative Z anomaly over Korea and Japan. The anticyclone–cyclone couplet causes a prevailing northeasterly flow over the entire East Asian seaboard along the couplet (Figs. 5g–i). In contrast to those during positive AO, the cold surges during negative AO are more intense because of the strong couplet structure, and thus widespread and severe cold anomalies over East Asia are evident (Figs. 5g–i).

In the vertical structure of the blocking cold surges along the dipole anomalies, maximum and minimum Z anomalies are found at approximately 20 hPa (i.e., midstratosphere) and 300 hPa (i.e., the tropopause), respectively (Figs. 5d–f). During the occurrence and development stages of cold surges, stratospheric signals related to the blocking centered at the midstratosphere propagate downward into
the troposphere, while the trough centered at the tropopause is amplified. The influence of this downward propagation of blocking related to negative AO suggests a stratospheric modulation of the tropospheric circulation by the downward propagation of AO signals, consistent with the result of Baldwin and Dunkerton (1999).

Interestingly, a wave train is observed in Figs. 5a–c as well as in Figs. 4a–c, though it is somehow weak due to the occurrence of blocking, suggesting that the cold surges of wave train type can occur for both positive and negative AO. Thus, the occurrence of wave train type is not biased toward a specific AO phase, while the AO-related polarity of the blocking type is evident.

The composite patterns discussed above indicate that the circulation features of cold surges according to AO phases are sensitive to the formation and development of blocking during negative AO. To evaluate the major wave activity of the circulation features during each AO phase, we calculate the stationary wave activity flux introduced by Plumb (1985). Figure 6 displays the anomalous Z and horizontal component of the stationary wave activity flux at 300 hPa. For the cold surges during positive AO, strong wave activity propagates into East Asia across the ridge–trough patterns (Figs. 6a–c). On day −2, the wave packet ranges from northern Eurasia to Korea and Japan. On day 0 and day +2, a large flux
passes through East Asia to the North Pacific. For negative AO, no apparent wave activity propagates to East Asia, although a propagation from the blocking ridge to the trough over Lake Baikal associated with a weak wave train is observed on day $-2$ (Fig. 6d). In Figs. 6e,f, the wave activity flux is confined to the blocking ridge without traversing from the ridge to the trough and there is no apparent wave packet propagation except for a weak wave flux over East Asia and the North Pacific.

To further clarify the foregoing characteristics of cold surges with respect to AO phases, we summarize the statistical values for the occurrence dates of cold surges in Table 1. The maximum SLP over the Siberian high domain averaged over all cases is 1045.31 hPa, larger than the value for positive AO (1043.69 hPa) but smaller than the value for negative AO (1046.52 hPa). Thus, the amplitude of the daily Siberian high associated with cold surges depends on the phase of AO. As seen from the table, the day-to-day SAT drop, the SAT anomaly, and the amplitude of the Siberian high exhibit strong relationships with AO phases. However, while the SAT anomaly changes with AO phase more significantly, ranging from $-1.60^{\circ}$C to $-2.20^{\circ}$C and being significant at the 95% confidence level, the relationship between the SAT drop and AO phase seems less significant, with a range of SAT drop of about $0.18^{\circ}$C. Because the monthly SAT anomaly is relatively high during positive AO (Thompson and Wallace 1998), the cold advection associated with an anticyclone of modest intensity can decrease the temperature considerably. On the other hand, during negative AO, temperature does not drop substantially in the background, which is already cold, and the differences in temperature are confined within a narrow limit. Thus, as expected from the composite results shown in Figs. 4 and 5, the cold surges during negative (positive) AO are relatively stronger (weaker) than the normal cold surges.

The robust dependence of the amplitude of cold surges on AO is clearly supported by Fig. 7, which shows distributions of the maximum SLP, the day-to-day SAT drop, and the SAT anomalies for 31 cold surges during positive AO and 60 during negative AO. All distribution statistics (i.e., maximum, mean, median, and minimum values, and 95%, 75%, 25%, and 5% tails) are dependent on AO phases. The distribution of maximum SLP exhibits a larger variability, ranging from 1035 to 1060 hPa, during negative AO than during positive AO. These features are in agreement with the result of Jeong and Ho (2005), showing that the day-to-day variability of the Siberian high increases (decreases) during negative (positive) AO. It should be pointed out that there are several warm anomalies for the cold surges during positive AO (Fig. 7b). Because the SAT is averaged over all stations in East Asia and the cold surges are defined at specific $5^\circ \times 5^\circ$ grid boxes, the warm SAT anomalies indicate that the cold surges during positive AO are apt to occur in the small restricted regions used in the definition, which is in contrast to the situation during negative AO.

The statistics related to the directions of lower-tropospheric winds associated with cold surges are also shown in Table 1. Here, an angle of $0^{\circ}$ indicates northerly flow. Cold surges are generally induced by northerly flow (angle of $354.52^{\circ}$), in a combination of a small negative zonal wind anomaly ($-0.23$ m s$^{-1}$) and a large negative meridional-wind anomaly ($-2.39$ m s$^{-1}$). Northerly flow that brings cold air to East Asia is essential for the occurrence of cold surges, but the role of zonal wind in cold surge occurrence depends on the phase of AO.

The cold surges during negative AO are associated with northeasterly flow (angle of $339.07^{\circ}$) because of the relatively strong easterly wind ($-0.89$ m s$^{-1}$). During positive AO, a positive zonal wind anomaly ($0.38$ m s$^{-1}$) gives rise to cold surges through northwesterly flow (angle of $12.07^{\circ}$). The magnitude of wind velocity also depends on the phase of AO. Because of strong winds, cold surges related to negative AO are more intense, supporting the discussions in previous

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**Table 1. Statistical values for occurrence dates of cold surges with respect to AO phases.**

<table>
<thead>
<tr>
<th>No. of cold surges</th>
<th>$SLP_{\text{max}}$ (hPa)$^a$</th>
<th>$dT$ ($^{\circ}$C)$^b$</th>
<th>$T'$ ($^{\circ}$C)$^b$</th>
<th>$u_{w650}$ (m s$^{-1}$)$^c$</th>
<th>$v_{w650}$ (m s$^{-1}$)$^c$</th>
<th>Wind direction ($^{\circ}$)$^d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>All months</td>
<td>332</td>
<td>1045.31</td>
<td>$-2.10$</td>
<td>$-1.55$</td>
<td>$-0.23$</td>
<td>$-2.39$</td>
</tr>
<tr>
<td>Positive AO months</td>
<td>31</td>
<td>1043.69</td>
<td>$-2.02$</td>
<td>$-1.06$</td>
<td>0.38</td>
<td>$-1.79$</td>
</tr>
<tr>
<td>Negative AO months</td>
<td>60</td>
<td>1046.52</td>
<td>$-2.20$</td>
<td>$-2.20$</td>
<td>$-0.89$</td>
<td>$-2.32$</td>
</tr>
<tr>
<td>Differences$^d$</td>
<td>29</td>
<td>2.83$^f$</td>
<td>$-0.18$</td>
<td>$-1.14$</td>
<td>$-1.27$</td>
<td>$-0.53$</td>
</tr>
</tbody>
</table>

$^a$ Maximum values in the region of $35^{\circ}-55^{\circ}$N and $90^{\circ}-115^{\circ}$E.

$^b$ Values averaged over 116 stations in China and Korea.

$^c$ Values averaged over $42.5^{\circ}-50^{\circ}$N and $105^{\circ}-130^{\circ}$E.

$^d$ Values during negative AO months minus those during positive AO months.

$^f$ Significant values at the 99% confidence level.

$^d$ Significant values at the 95% confidence level.
paragraphs. To further elucidate the dependence of wind directions on AO phases, we classify wind directions into 12 groups with 30° intervals, with probability distributions presented in Fig. 8. The maximum probability of cold surges is found in the northwest (in northwesterly wind) during positive AO and the northeast (in northeasterly wind) during negative AO. A difference in the shape of probability distributions between the two AO phases is also apparent.

Duration is another factor that characterizes cold surges. Zhang et al. (1997) revealed that strong cold surges last approximately 2 days longer than normal events. To understand the dependence of cold surge duration on AO phases, we construct composite patterns of anomalous $Z$ at 300 and 850 hPa and temperature and wind at 850 hPa, averaged from +4 to +6 days after cold surge occurrence (Fig. 9). For the cold surges during positive AO, there is no apparent feature associated with the upper-tropospheric wave train observed in Figs. 4a–c. Instead, a pattern with negative $Z$ anomalies over the subarctic region and positive $Z$ anomalies over the North Pacific is observed throughout the troposphere (Fig. 9a), which is reminiscent of the monthly $Z$ pattern for positive AO. On the other hand, for the cold surges during negative AO, the dipole anomalies constituting blockings and troughs shown in Fig. 9b are analogous to those shown in Figs. 5a–c. They remain over East Asia approximately 5 days after the occurrence of cold surges. This difference in cold surge duration between the wave train type and the blocking type suggests a different influence on the temperature and wind fields. Figure 9c shows that, during positive AO, central-northern China, Korea, and Japan are not affected by cold surges and cold anomalies are found only over southern China because of the absence of cold advection. As shown in Fig. 9d, however, all of East Asia is under the influence of cold surges during negative AO, with strong cold advection induced by the dipole anomalies. Therefore, the blocking cold surges during negative AO have a longer duration and exert a larger influence on the temperature and winds over East Asia because of the longer-lasting blocking and cold advection, in contrast to the cold surges during positive AO.

It is also important to analyze the tracks of cold surges because they are closely linked to substantial damage in the regions that the cold surges pass through. Here, cold surge tracks are defined as the paths of the cold core computed by three-dimensional winds using a Lagrangian trajectory model. Cold surge tracks may be affected by circulation patterns associated with different cold surge

**Fig. 7.** Distributions of (a) maximum SLP and (b) a drop in SAT and anomalous SAT for occurrence dates of cold surges during positive and negative AO. The SAT is the averaged value over 116 stations in China and Korea.

**Fig. 8.** Probability distributions of wind directions at 850 hPa averaged over 42.5°–50°N and 105°–130°E for occurrence dates of cold surges during positive (thick solid lines) and negative (dashed lines) AO.

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types, with respect to AO phases. Figures 10a–c show the cold surge tracks during all, positive, and negative AO months, respectively. Figure 10a indicates that cold surges mostly originate from the Eurasian continent and terminate over two distinct regions: the northwestern Pacific and the Philippine Sea. More cold surges seem to pass over the east of Lake Baikal and travel to the southeast of Japan during negative AO than during positive AO. However, cautions should be applied when distinguishing the overall geographical preferences of cold surge tracks between Figs. 10b,c, because different numbers of cold surges are analyzed between the two AO phases.

We further examine the passage frequency of cold surges, which is computed by dividing the number of cold surge passages in each 5° × 5° grid box by the total number of cold surges. We conduct the analysis for all cold surges (i.e., 332), the cold surges during positive AO (i.e., 31), and the cold surges during negative AO (i.e., 60). The passage frequency implies the probability density of cold surge tracks that do not contain information about the number of cold surge occurrence [see Ho et al. (2004) for the example of tropical cyclone passages]. Figure 10d shows that, climatologically, the passage frequency of cold surges is concentrated in their mean track, extending from Lake Baikal to coastal China, and high densities are observed over the northwestern Pacific and west of the Philippines where tracks usually end. During positive AO (Fig. 10e), the passage frequency of cold surges is not systematically different from the climatology, since the circulation pattern associated with cold surges during positive AO is similar to that associated with common cold surges. In contrast, the passage frequency during negative AO (Fig. 10f) is remarkably different from climatology. It increases from the north of Korea to the south of Japan but decreases over inland China, with a statistical significance at the 95% confidence level. The considerable dipole pattern and the eastward shift of cold surges are attributable to the blocking and the northeasterly flow as shown in Fig. 5.

The distinctive characteristics of cold surges and their relationship to AO phases may be linked to variations
in precipitation, besides temperature, over East Asia (Thompson and Wallace 2001; Li et al. 2005; Wen et al. 2009). Since the influence of cold temperature anomalies on precipitation is not independent of cold surges, the negative temperature anomalies related to cold surges can further alter water precipitation into snow or freezing rain and lead to severe weather events over large regions. It is thus expected that the changes in large-scale circulation related to AO affect not only the geographical distribution of snow or freezing rain, with different distinctive properties of cold surges. As shown in Fig. 11, in which equivalent snowfall is defined as the precipitation amount when daily SAT is <1°C as in Wen et al. (2009), changes in precipitation and snow are related to AO phases. The precipitation accumulated during the 4 days after cold surge occurrence during positive AO is larger than that during negative AO over entire East Asia except west of Korea (Fig. 11a), which is consistent with the result of Wen et al. (2009).
Accordingly, there is more snowfall during positive AO (Fig. 11b). However, the ratio of snowfall to precipitation exhibits an obvious dipole pattern (Fig. 11c), with positive values west of 120°E and negative values east of 120°E, reminiscent of the anomalies of cold surge tracks (see Fig. 10f). Thus, there is a large probability of freezing precipitation or snow occurrence over west (east) of 120°E during positive (negative) AO. This result suggests that the high possibility for modest precipitation to develop into a severe snowstorm depends on the changes in cold surge characteristics with respect to the phase of AO.

In short, because of evident polarities of the blocking related to AO phases, the cold surges of blocking type seem to prefer the negative AO phase while the wave train type is less sensitive to AO phases. Thompson and Wallace (2001) showed that high-latitude blocking occurs much more frequently over the North Pacific during negative AO. Because of these frequent blocking outbreaks, cold surges during negative AO tend to be induced by subarctic blocking over the North Pacific.

5. Summary and discussion

In spite of the limited work such as Jeong and Ho (2005), previous studies of the East Asian cold surges and AO have mostly investigated the phenomena separately, instead of depicting their relationship. In this study, we have analyzed the characteristics of the cold surges over East Asia with respect to positive and negative AO phases. An evident AO-related polarity is found for the cold surges of blocking type, which indicates frequent occurrence of blocking cold surges during negative AO periods. The cold surges of wave train type are observed in both positive and negative AO phases. Different AO phases are accompanied by distinctive characteristics of cold surges in terms of intensity, frequency, duration, and tracks. The 31 cold surges examined for positive AO are fundamentally characterized by upper-tropospheric wave train developed as growing baroclinic waves, similar to the features shown for the typical cold surges of 332 cases. The cold surges are modulated by northwesterly cold advection. Because of an undeveloped anticyclone–cyclone couplet and their short duration, the cold surges are relatively weak in terms of the amplitude of the Siberian highs, day-to-day temperature drop, and temperature anomalies. During negative AO, however, the patterns averaged for 60 cold surges exhibit mainly blocking-type features with an apparent north–south-oriented dipole in height anomalies (i.e., blocking and trough), although a weak wave train feature is also observed. The dominant northeasterly cold advection along the blocking and the trough of the dipole lead to unusually strong cold surges. A well-organized anticyclone–cyclone couplet and long-lasting cold advection also favor strong cold surges during negative AO, compared to positive AO. The cold surges during negative AO are also stronger than the cold surges during neutral AO. Cold surges during negative AO tend to shift eastward to Korea and Japan, although this feature is not evident.

FIG. 11. Differences in (a) precipitation, (b) equivalent snow, and (c) ratio (equivalent snow over precipitation), accumulated from day 0 to day +4 relative to occurrence of cold surges between positive and negative AO.
during positive AO. In addition, because of the shift in the tracks of blocking cold surges, the regions over inland China (Korea and Japan) during positive (negative) AO tend to undergo freezing precipitation or heavy snowfall.

An analysis of the composite patterns of cold surges with respect to AO phases indicates that the changes in large-scale circulation associated with AO alter the background flow and induce different characteristics of cold surges, suggesting a possibility of predicting the occurrence and characteristics of cold surges using large-scale climate variability such as AO. However, several limitations should be considered before the current result is applied to operational prediction of cold surges.

First, because there are no biased circulation anomalies of the wave train type toward a specific AO phase, the cold surges of wave train type are apt to occur in both positive and negative AO phases. As shown in Figs. 5a and 6d, the upper-tropospheric wave train is also seen in the blocking cold surges during negative AO. This may complicate the interpretation and weaken the reliability of the results. Thus, we apply a clustering analysis to further classify cold surges into the two groups. About 80% of the total 332 cold surges are classified into the wave train type, leading to the emergence of wave train cold surges during both positive AO and negative AO. Moreover, the AO-related polarity of cold surges is evident in the blocking type but less significant in the wave train type (figure not shown). That is, the dependence of cold surges on AO phases may correspond to only the polarity of blocking cold surges related negative AO. A more detailed analysis is beyond the scope of the present study and should be performed in further research.

Second, although we have shown a dependence of the characteristics of cold surges on AO phases, the causal relationship between cold surges and AO has not been discussed thoroughly. High-latitude blocking occurrences over the North Pacific during negative AO are more frequent than those during positive AO (Thompson and Wallace 2001), and circulation anomalies during negative AO may be associated with the blocking type of cold surges. However, there is no clear evidence that a negative AO enhances the occurrence of blocking related to the cold surges over the Far East. On the other hand, the blocking type may contribute to the emergence of negative AO phase in monthly averaged circulation because the strong blocking type lasts for more than a week (Fig. 9). To elucidate the causality between the occurrence of blocking-type cold surges and negative AO phase, one should consider the two-way interaction between transient synoptic eddies and low-frequency flow, which plays an important role in constituting and sustaining low-frequency flow and further controlling synoptic eddy activity (Lau 1988; Cai and Mak 1990; Qin and Robinson 1992; Limpasuwan and Hartmann 1999; Cai et al. 2007; Kug and Jin 2009). While cold surges can be modulated by synoptic eddy activity, AO is one of the low-frequency patterns mentioned above. Thus, the interaction between the two seems to be closely connected with the aforementioned mechanisms. It will be necessary to conduct a further in-depth study of the interaction between the day-to-day variability in cold surges and the month-to-month variations in AO.

In spite of the above limitations, this analysis is probably among the earliest to document the relationship between the characteristics of cold surges and AO, which is helpful for better understanding cold surge occurrences. Furthermore, a combination of this analysis with the studies on AO predictability using stratospheric initial conditions and memories (Baldwin et al. 2003; Charlton et al. 2003) and on model ensemble simulations (Tang et al. 2007) could be useful for extended-range (e.g., beyond 10 days) forecasts of cold surges.

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REFERENCES


