Decadal changes in surface air temperature variability and cold surge characteristics over northeast Asia and their relation with the Arctic Oscillation for the past three decades (1979–2011)

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[1] Decadal changes in surface air temperature (SAT) variability and cold surge characteristics over Northeast Asia during late winter (January–March) are analyzed for the past three decades. Power spectrum analysis of SAT reveals that the low-frequency variabilities with a period longer than 10 days are significantly enhanced, while the high-frequency variabilities with a period shorter than 10 days are weakened in the 1980s and 2000s. Moreover, cold surges were stronger and lasted longer during the 1980s and 2000s compared to those that occurred in the 1990s. Here, we propose that large-scale atmospheric conditions manifested by a different phase of the Arctic Oscillation (AO) provide preconditioning for a cold surge event, which showed a prominent decadal fluctuation. The more (less) frequent strong and long-lasting cold surge occurrences in the 1980s and 2000s (1990s) are preceded by the more dominant negative (positive) phase of the AO. Lag-composite analyses for cold surge events categorized by the AO phases indicate that stronger and longer-lasting cold air advection dominates at the lower-level, when upper-level wave train and coastal trough are developed over East Asia under the strong negative AO phase. These results suggest that the decadal changes in SAT variability and cold surge characteristics are strongly associated with the decadal changes in the phase distribution of the AO.

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1. Introduction

[2] Surface air temperature (SAT) over East Asia during the winter season is controlled by various factors in a wide range of spatial and temporal scales. In seasonal time scale, SAT variability is mainly dominated by the East Asia winter monsoon (EAWM) system, which consists of Siberian high, Aleutian low, East Asian upper-level troughs, the mid-latitude jet stream, and local Hadley circulation [*Chang and Lau*, 1980; *Ding and Krishnamurti*, 1987; *Jhun and Lee*, 2004; *Wu et al.*, 2006; *Kim and Roh*, 2010]. The Arctic Oscillation (AO) is also known to have a strong influence on the seasonal or sub-seasonal mean SAT over the Eurasian continent [*Thompson and Wallace*, 1998; *Rigor et al.*, 2000]. *Gong et al.* [2001] pointed out the significant correlation between AO and mean sea level pressure over Siberian region, that is a key component of the EAWM. Besides the direct impact of AO on the EAWM, some other previous studies noted the development of upper-level East Asian coastal trough which is associated with the low-level cold air advection toward East Asia in negative phase of AO [*Wu and Wang*, 2002; *Takaya and Nakamura*, 2005].

[3] Cold surge is the most energetic and hazardous sub-seasonal SAT variability over East Asia in winter season [*Chang and Lau*, 1980; *Compo et al.*, 1999; *Jhun and Lee*, 2004]. Previous studies suggested that cold surge is influenced by large-scale teleconnection induced by the El Nino/Southern Oscillation (ENSO) [*Zhang et al.*, 1997; *Chen et al.*, 2004], and the Madden and Julian Oscillation (MJO) [*Madden and Julian*, 1972; *Jeong et al.*, 2005; *Kim et al.*, 2006]. In particular, AO is strongly associated with the cold surge over East Asia [*Jeong and Ho*, 2005; *Lu and Chang*, 2009; *Park et al.*, 2011b]. For example, *Gong and Ho* [2004] and *Jeong and Ho* [2005] suggested that the intensification of Siberian high, deepening of East Asian

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coastal trough and enhancement of the East Asian jet stream associated with the negative phase of monthly AO provides favorable conditions for the occurrence of cold surges. *Park et al.* [2011b] classified cold surges into wave train type and blocking types, and found that the blocking type cold surges tend to occur more frequently during the negative phase of monthly AO, with stronger amplitude and longer duration than the wave train type.

[4] As described above, the influence of AO on the cold surge characteristics mostly has been investigated in the seasonal and inter-annual timescale using monthly data set. Although some previous studies noted the cold SAT over East Asia induced by downstream pattern related with North Atlantic Oscillation (NAO) in sub-monthly scale [*Joung and Hitchman*, 1982; *Sung et al.*, 2010], the linkage between AO and cold surge has not been fully discussed. The cold surge is mainly a sub-monthly variability, and AO also shows a large variance in this time scale. Therefore, examination on the relation between AO and cold surge in sub-monthly scale can be important.

[5] In addition to the association between AO and cold surge in sub-monthly scale, understanding of their relation in decadal scale is also important. In recent decade, many East Asian countries have suffered successive occurrences of extreme cold winter which is characterized by long-lasting cold surges and anomalously low temperatures [*Park et al.*, 2008; *Hong and Li*, 2009; *Cohen et al.*, 2009, 2010; *Wang and Chen*, 2010]. The change of atmospheric circulation related with AO is also detected in recent decade [*Zhang et al.*, 2008; *Ohashi and Tanaka*, 2010]. These two features suggest the possible link of decadal change in cold surge characteristics over East Asia with AO. Previous studies reported that seasonal mean SAT and pressure anomalies over East Asia show a prominent decadal variation in association with the decadal changes in the AO and EAWM in the late 1980s [*Watanabe and Nitta*, 1999; *Wu et al.*, 2006; *Miyazaki and Yasunari*, 2008]. Besides the studies on the decadal variation of EAWM, *Hong et al.* [2008] addressed the decadal relationship between the 7-year running mean of cold surge frequency in Taiwan and NAO. Even though there have been some studies on the variation of cold surges frequency and EAWM in decadal scale, the decadal changes of cold surge in terms of duration and strength have not been fully investigated. Moreover, the relationship between these decadal changes in cold surge characteristics and AO has not been discussed in previous studies. In this study, we examine the decadal changes in cold surge characteristics (quantitative duration and strength) over Northeast Asia for the past three decades (1979–2011), and its related atmospheric circulation features. We also examine the decadal change of AO variability and phase distribution in sub-monthly scale, and how these changes are associated with the decadal changes in cold surge characteristics.

[6] In section 2, we present the data used in this study and the definition of cold surges. The changes in SAT variability and cold surge characteristics over Northeast Asia during winter of the past three decades are described in section 3.1. In section 3.2, we show that decadal change in AO variability and the relationship between AO and SAT conditions before cold surge occurrence. The decadal changes in the dominant daily AO phase are compared with the decadal changes in cold surge characteristics in section 3.3. Finally, we show that changes in atmospheric circulations are related to cold surge characteristics depending on the AO phase.

2. Data and Methods

[7] Daily mean winter SAT from the ERA-interim re-analysis data set [*Dee et al.*, 2011] was used to estimate the day-to-day variability and to define cold surge occurrences over Northeast Asia (35°N–45°N, 120°E–130°E) for the period of 1979–2011. The daily mean geopotential height (Z), and zonal and meridional wind data were also utilized to examine large-scale circulation features associated with changes in cold surge characteristics over the three most recent decades (1979–2011). In addition, daily AO index, which is produced by projecting the daily mean 1000-hPa height anomalies onto the AO loading, is used to examine the relationship between the AO and the change in cold surge characteristics. The AO loading is defined by the leading EOF (Empirical Orthogonal Function) pattern for monthly 1000-hPa height anomalies poleward 20°N in the Northern Hemisphere. This AO index is available on the Website of the National Oceanic and Atmospheric Administration (NOAA) climate prediction center.

[8] In this study, we examine SAT variability and cold surge characteristics over Northeast Asia. Many previous studies have examined the circulation and SAT variability related to the East Asian winter monsoon at various time scales [*Chang and Lau*, 1980; *Ding and Krishnamurti*, 1987; *Jhun and Lee*, 2004]. These studies mainly focused on the entirety of East Asia or China. However, some recent studies have reported that SAT variability and cold surges over Northeast Asia may be sensitive to large-scale variabilities such as the AO and variability of the East Asian coastal trough at the upper-level [*Wu and Wang*, 2002; *Takaya and Nakamura*, 2005; *Park et al.*, 2011b]. Therefore, in this study, the decadal change in SAT and cold surge characteristics over Northeast Asia and their linkage with the AO are examined.

[9] A cold surge occurrence is defined based on previous studies [*Zhang et al.*, 1997; *Jeong and Ho*, 2005; *Park et al.*, 2011b]. First, a surface anticyclone over the region of 90–115°E, 35–55°N (southeast of Siberia) should be identified prior to cold surge occurrence. The center of this surface anticyclone is found following the methodology of *Zhang and Wang* [1997], i.e., a grid point with the maximum Z at 1000 hPa compared with eight surrounding grid cells. In addition, the magnitude of mean sea level pressure (MSLP) of this anticyclone center must be greater than 1030 hPa. Second, based on *Jeong and Ho* [2005], the daily mean SAT averaged over northeast China (40°N–45°N, 120°E–125°E) or the Korean Peninsula (35°N–40°N, 125°E–130°E) should decrease more than 1.5 standard deviations of the SAT anomaly for 1979–2011, within 2 days. Moreover, the daily mean SAT should be below the long-term climatological mean value. The termination of the cold surge is defined as when the daily mean SAT recovers to the climatological mean value. When a new cold surge occurs before the termination of the previous cold surge, we regard the two surges as a single event. According to these criteria, 155 cold surge events were detected for the 33 years (1979–2011) of this study, which corresponds to 1.56 cases per month; this is comparable to the frequency of East Asian cold surges

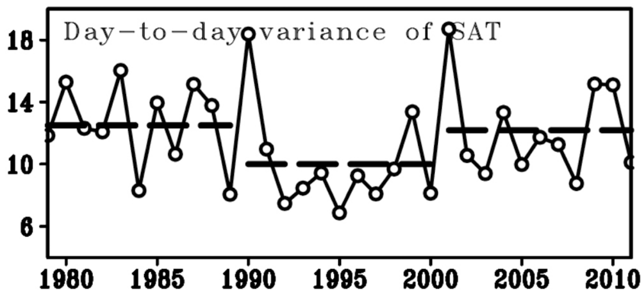

Figure 1. Winter day-to-day variance of surface air temperature (SAT) averaged over Northeast Asia from 1979–2011. The dashed lines indicate mean variances in the 1980s, 1990s, and 2000s.

obtained by previous studies: 1.85 per month according to *Zhang et al.* [1997], or 1.40 per month according to *Jeong and Ho* [2005].

[10] Power spectrum analysis was applied to examine the variability of daily winter SAT over Northeast Asia for the last three decades. Large-scale atmospheric conditions associated with cold surges according to the AO phase were analyzed by lag composite analysis before and after cold surge occurrence.

3. Results

3.1. Decadal Changes in SAT Variability and Cold Surge Characteristics

[11] In this section, we describe the decadal changes in SAT variability at a sub-seasonal timescale and cold surge characteristics over Northeast Asia for the winter season. In general, natural climate variability does not necessarily follow the typical calendar-defined decades as are used in this study. In addition, it is very difficult to pinpoint the changing point of decadal climate variability with precision. In the case of decadal variability of the EAWM, some previous studies have suggested that the SAT and circulation in East Asia vary prominently at the decadal time scale in relation with EAWM change 1980s [*Watanabe and Nitta*, 1999; *Wu et al.*, 2006; *Miyazaki and Yasunari*, 2008]. However, decadal changing points in the studies differ from each other. Moreover, it is not appropriate to directly apply the decadal changing points generated by previous studies to our research, as the timescale and area of variability are different. Instead of resorting to a particular definition of regime change, we divide the recent 33 years to three calendar-defined decades of 1979–1989, 1990–2000, and 2001–2011 (hereafter referred to as the 1980s, 1990s and 2000s, respectively). Nevertheless, we will show that decadal changes in SAT variability are reasonably captured on these calendar-defined decades and that the detected changes in this study are sufficient to elucidate the decadal change for various aspects of EAWM variability (i.e., AO, SAT, and atmospheric circulation).

[12] Figure 1 shows the time series of day-to-day variance of SAT averaged over Northeast Asia for 1979–2011. Decadal fluctuation of SAT day-to-day variance is remarkable for the 1980s, 1990s and 2000s. The SAT variances in eight years are less than 10°C in the 1990s, contrasting with occurring in one and three years in the 1980s and 2000s, respectively. On the other hand, variances larger than 12°C are observed frequently in the 1980s and 2000s, contrasting with occurring only in one year in the 1990s. The mean variance in the 1980s and 2000s is also distinctly larger than the 1990s. This decadal shift from mean day-to-day variance of the total analysis period satisfies the statistical significance at a 95% confidence level. To investigate the periodicity that was dominant in leading to this change, we analyzed the power spectrum of SAT for each decade separately (Figure 2). The enhancement of the power of relatively low-frequency variability with periods of 10–20 days and a weakening of the power of high frequency with periods of 5–10 day periods (typical synoptic scale variability range) were detected for the 1980s and 2000s. Conversely, in the 1990s, the power of high-frequency variability with periods of 5–10 days is dominant, while statistically significant powers are not detected in the 10–20 days period.

[13] Since cold surges are major intraseasonal variability in the EAWM and SAT variability is closely related to cold surge events [*Park et al.*, 2011a], the decadal change in SAT variability may imply a contribution from the change in cold surge characteristics during the three decades. In order to examine the relationship, we estimated the contribution of cold surge on variability of SAT for the three decades (Table 1). The cold surge period (384, 350, and 415 days in the 1980s, 1990s, and 2000s, respectively) occupies about 35–42% of the total analysis period in each decade, while the SAT variance for the cold surge period in each decade explains 46.7, 54.6, and 52.0% of total SAT variance in the 1980s, 1990s, and 2000s, respectively. Further, 29.0% of SAT variance increase in the 1980s and 45.9% in the 2000s compared to the 1990s is associated with the variance increase during the cold surge period. These results indicate that the decadal change in SAT variability may be related to the change in cold surge characteristics such as occurrence, strength, and duration.

[14] It is found that the frequency of cold surge occurrence was similar for three decades: 50, 52, and 53 times in the 1980s, 1990s, and 2000s, respectively. However, duration and intensity of cold surges showed considerable differences between the three decades. Figure 3 shows the number of cold surge occurrences categorized by duration and intensity for the 1980s (black), 1990s (light gray) and 2000s (dark gray). Cold surge events lasting longer than 4 days occurred more often in the 1980s (30 times, 60.0%) and 2000s (30 times, 56.6%) than in the 1990s (19 times, 36.5%), while those lasting less than 4 days occurred less often in the 1980s (20 times, 40.0%) and 2000s (23 times, 43.4%) than in the 1990s (33 times, 64.5%). The mean durations of cold surges for the three periods were 7.30, 5.19, and 6.58 days in the 1980s, 1990s and 2000s, respectively. In addition to the longer duration, the cold surge intensity, defined as the SAT on the cold surge occurrence day, was stronger in the 1980s and 2000s (Figure 3b). In the 1990s, 44.2% (23 times) of cold surge occurrences exhibited intensities below −3°C, in contrast to 64.0% (32 times) and 54.7% (29 times) in the 1980s and 2000s, respectively. The mean SATs on cold surge occurrence days for each decade were −4.06, −3.32 and −3.70°C in the 1980s, 1990s, and 2000s, respectively. To summarize, cold surges lasted longer and were stronger during the 1980s and 2000s than the 1990s.

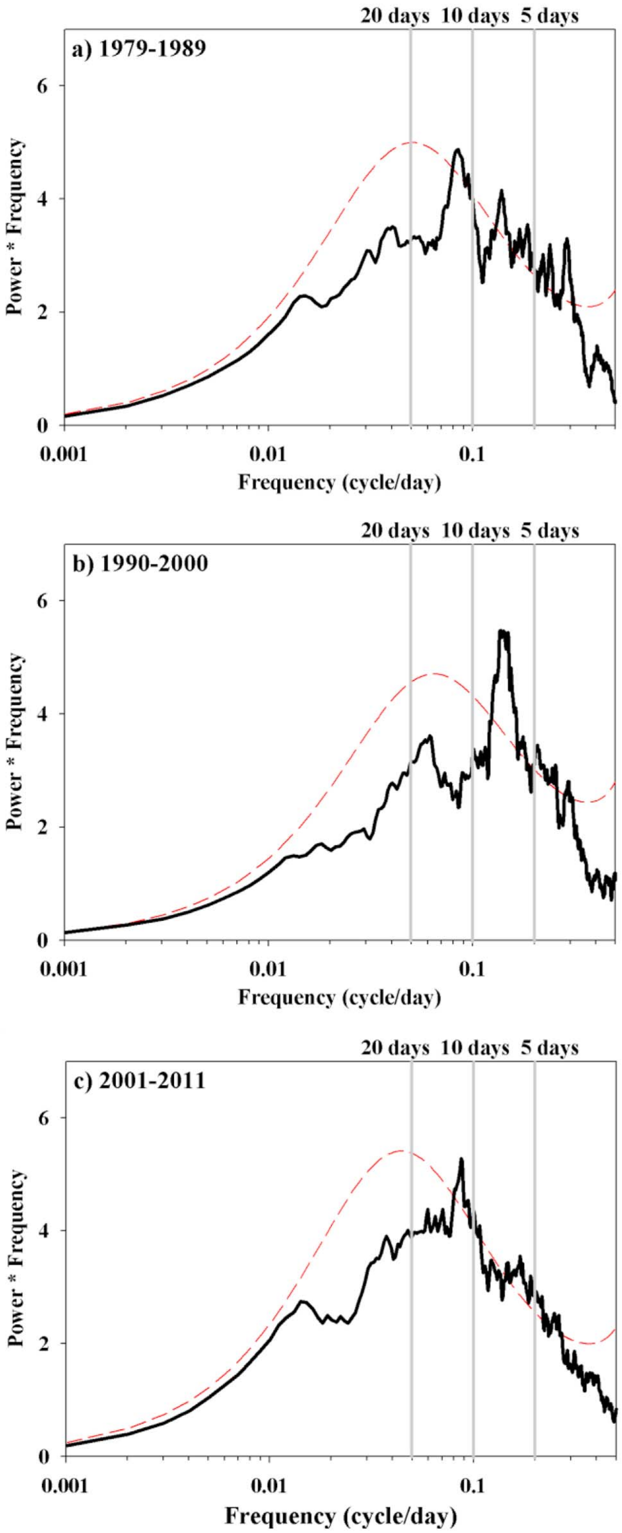

Figure 2. Power spectra of daily mean winter SAT averaged over Northeast Asia in (a) 1979–1989, (b) 1990–2000, and (c) 2001–2011. The thin dashed curve in each figure represents the 95% confidence level. Three gray vertical lines indicate (from left to right) 20, 10, and 5 days.

Table 1. Cold Surge Period, Total Variance of SAT, and the Variance Explained by the Variance of SAT During the Cold Surge Period for Each Decade

	CS Period (days)	Variance for CS Period (°C)	Total Variance (°C)
1980s	384	5.75	12.30
1990s	350	4.67	8.56
2000s	415	6.33	12.18

3.2. Decadal Changes in Large-Scale Circulation Related With Cold Surge

[15] In order to investigate the changes in atmospheric conditions associated with changes in cold surge characteristics for the recent three decades, we conducted lag-composite analyses of atmospheric circulation and SAT before and after cold surges in Northeast Asia in the 1980s, 1990s, and 2000s. Figures 4 and 5 show the composite anomalies of Z at 300 hPa (upper-level) and 850 hPa (lower-level) from 6 days before the occurrence of cold surges to 6 days after occurrences in each decade, respectively. Also, Figure 6

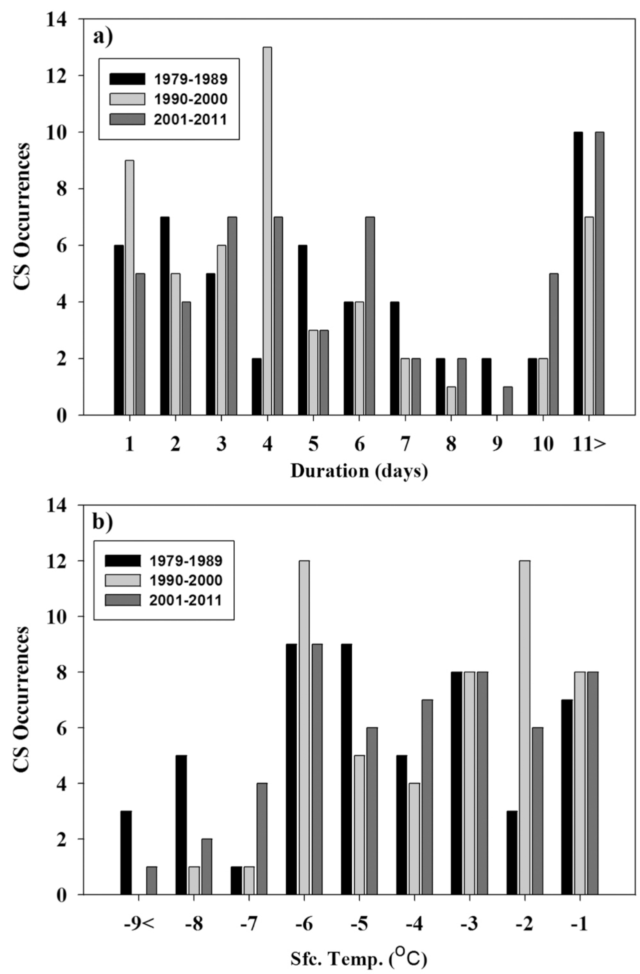

Figure 3. The number of cold surge occurrences classified by (a) duration and (b) SAT anomaly on the cold surge starting day.

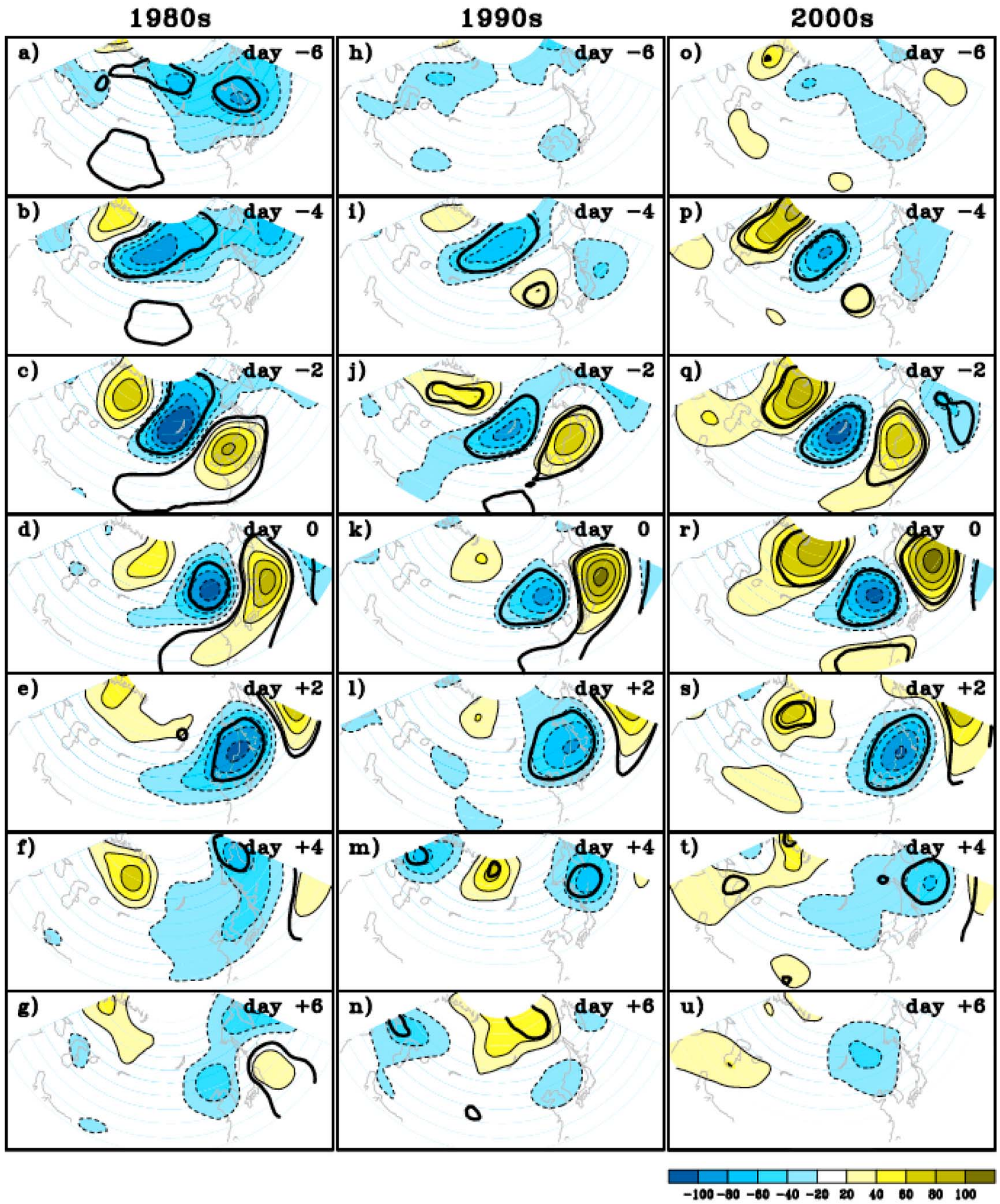

Figure 4. Composite maps of geopotential height (m) at 300 hPa (thin contour and shading with an interval of 20 m) before and after (−6 to +6 days) cold surges occurrence in Northeast Asia for the winter period during the (a–g) 1980s, (h–n) 1990s and (o–u) 2000s. The thick black lines represent the area satisfied the 95% confidence level.

represents the composite of SAT and wind at 850 hPa during the same time lag as Z composite.

[16] The circulation pattern at the upper-level shows similar wave trains in each of the three decades emanating southeastward from the Ural Mountains to Northeast Asia during 4 days before cold surge occurrences (Figure 4). The upper-level wave trains accompany lower-level Z anomalies that are approximately 90° out of phase against the upper-level Z fields until cold surge occurrence day (day 0) in Northeast Asia (Figure 5). This is a typical circulation feature observed during the developing phases of quasi-geostrophic and baroclinic waves [*Zhang et al.*, 1997; *Chen*, 2002; *Jeong and Ho*, 2005; *Park et al.*, 2011b]. Although upper-level wave trains prior to cold surges are common features in each of the three decades, those in the 1980s and 2000s are more prominent in terms of structure and strength (Figure 4). Moreover, the lower-level circulation in the 1980s and 2000s is also as remarkable as the features of upper-level circulation (Figure 5). In particular, the intensities of upper- and lower-level anticyclone anomalies over the

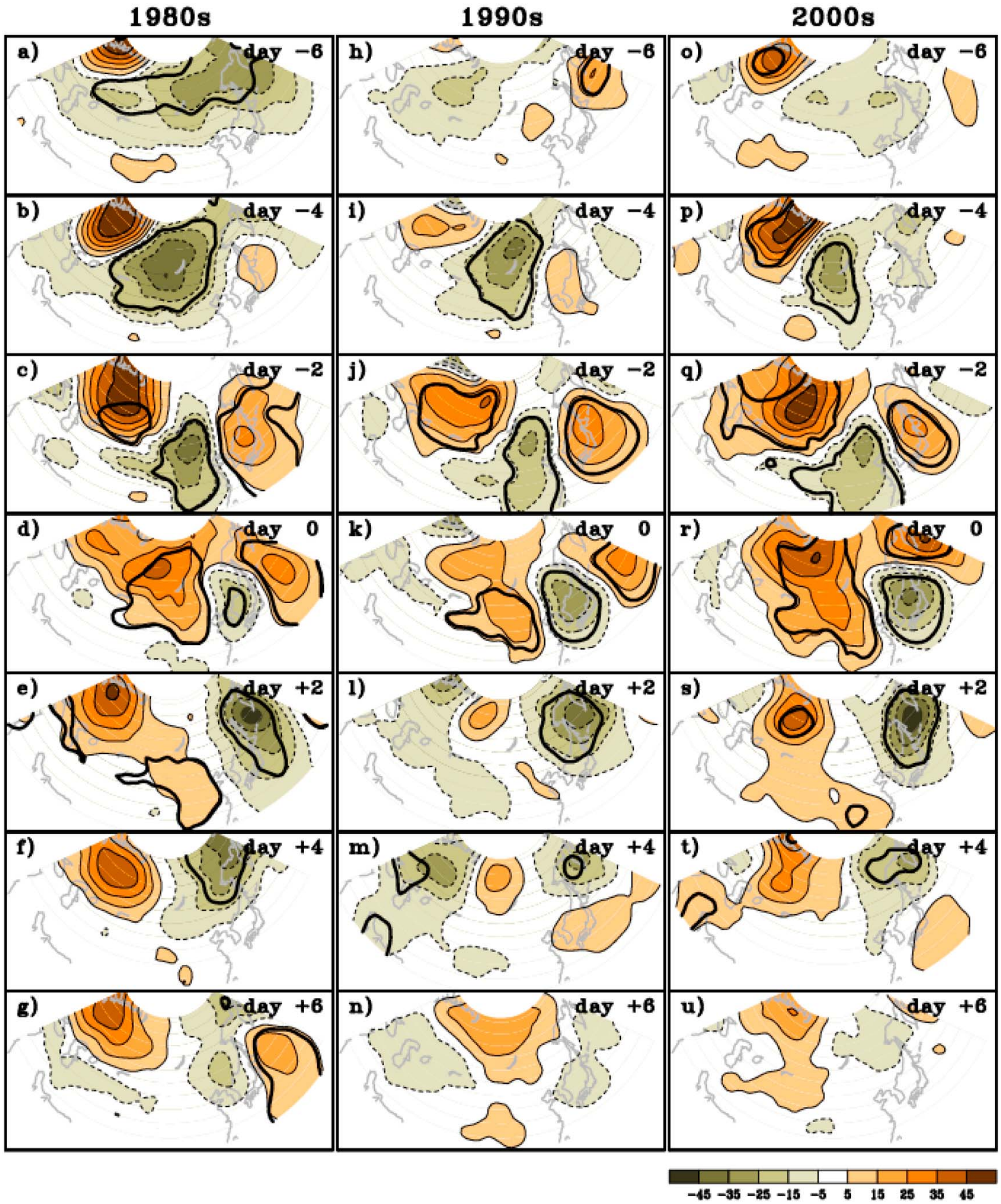

Figure 5. Composite maps of geopotential height (m) at 850 hPa (thin contour and shading with an interval of 10 m) before and after (−6 to +6 days) cold surges occurrence in Northeast Asia for the winter period during the (a–g) 1980s, (h–n) 1990s and (o–u) 2000s. The thick black lines represent the 95% confidence level.

Ural Mountains in the beginning of cold surge development (day −2 and −4) are stronger in the 1980s and 2000s than the 1990s. In addition, the upper-level cyclone anomalies over Northeast Asia and lower-level anticyclone anomalies centered over Siberia at day −2 are intense for the 1980s and 2000s. After cold surge occurrence, although upper-level wave trains decay in all of the three decades, upper-level cyclone anomalies over East Asian coast are developed. These upper-level cyclone anomalies are stronger in the 1980s and 2000s than those in the 1990s. The lower-level cyclone anomalies over Northeast Asia persist until day +4 after cold surge occurrence in the 1980s and 2000s. On the other hand, in the 1990s, the lower-level cyclone anomalies decay quickly over Northeast Asia and the anticyclone anomaly emerges over Siberia in day +4 and expands to North China in day +6.

[17] Near surface level (Figure 6), strong cold anomalies appear over Siberia at −4 days in all of the three decades

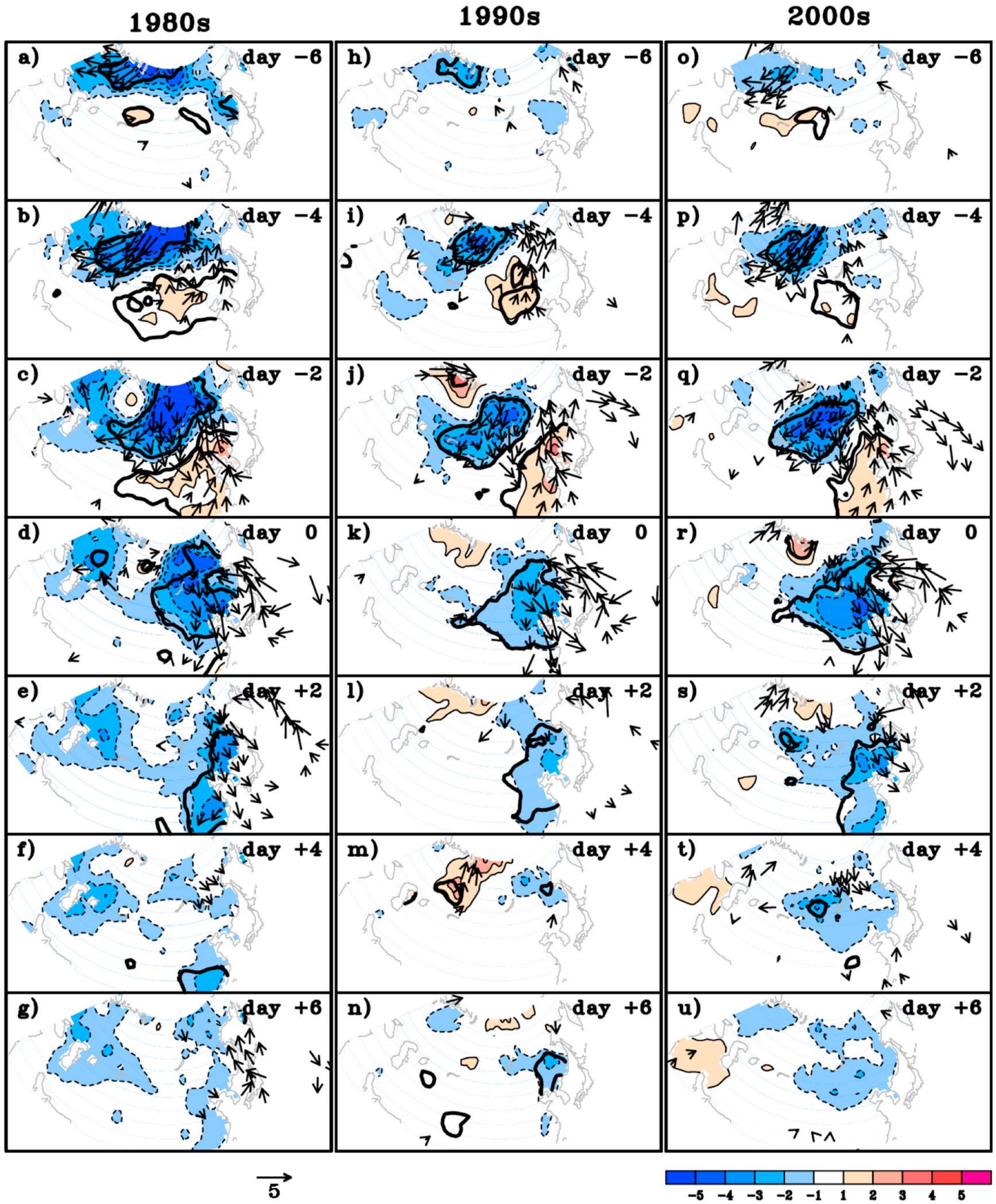

Figure 6. Composite maps of SAT anomaly (°C) and wind anomaly (m/s) at 850 hPa before and after (−6 to +6 days) cold surges occurrence in Northeast Asia for the winter period during the (a–g) 1980s, (h–n) 1990s and (o–u) 2000s. The thick black lines represent the area satisfied the 95% confidence level.

because of cold air advection by northerly winds between the eastern edge of anticyclone anomalies and western edges of cyclonic anomalies at the lower-level. These cold anomalies migrate southeastward to Northeast Asia until day 0, and are associated with the evolution of lower-level circulation anomalies coupled with upper-level wave trains. It is noted that anomalous lower-level circulation over Northeast Asia and cold air advection in the 1980s and 2000s were much stronger on the day of cold surge occurrence and persist longer thereafter compared to those in the 1990s. These stronger cold air advection and cold anomalies are consistent with the frequent occurrence of stronger cold surge events in the 1980s and 2000s, as seen in Figure 3. During the decaying phase of the cold surge, in the 1990s, the SAT anomaly over Northeast Asia returns to the climatological level in day +4 (Figure 6m), associated with the weakening of the anomalous lower-level circulation over the East Asian coast (Figure 4m). On the other hand, in the 1980s and 2000s, this cold anomaly persists longer, until day +6, over Northeast Asia. These features result from the

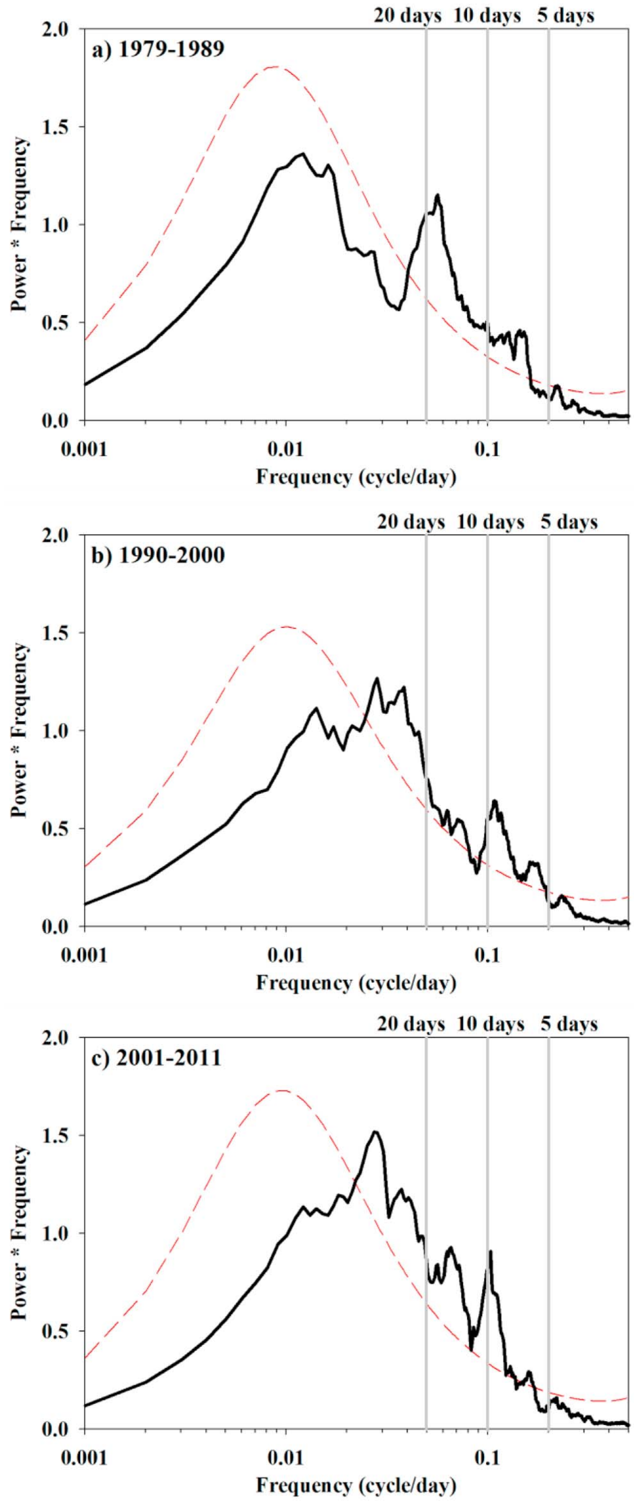

Figure 7. Power spectra of daily AO index in (a) 1979–1989, (b) 1990–2000, and (c) 2001–2011. The thin dashed curve in each figure represents the 95% confidence level. Three gray vertical lines indicate (from left to right) 20, 10, and 5 days.

anomalous lower-level northerly wind related to cyclone anomalies over the East Asian coast, which also persisted until day +6. The upper-level cyclone anomaly over the East Asian coast after cold surge occurrence plays a role in intensifying the climatological coastal trough. The deepened coastal trough is related dynamically with the intensification of northerly wind toward the East Asia area at the lower-level [*Chang and Lau*, 1982; *Joung and Hitchman*, 1982; *Lau and Lau*, 1984; *Boyle*, 1986]. As a result, the increase in stronger and longer-persisting cold surges for the 1980s and 2000s compared to the 1990s is associated with changes in large-scale circulation anomalies that are more favorable to the intensification of cold surges.

3.3. Decadal Change in AO Characteristics and Its Relationship to SAT Associated With Cold Surge

[18] Some previous studies have suggested that there has been prominent decadal change in the AO [*Overland et al.*, 1999; *Zhang et al.*, 2008; *Ohashi and Tanaka*, 2010], and that decadal change in SAT variability over East Asia is related to the AO [*Miyazaki and Yasunari*, 2008]. These results from previous studies are seemingly associated with the decadal changes in SAT variability and cold surge characteristics suggested in previous subsections. Therefore, we examined a possible linkage between the AO and SAT related to cold surges for the last three decades in more detail.

[19] Figure 7 shows the power spectrum of daily AO indices for each decade. Daily AO variabilities also fluctuate at the decadal scale. In the 1980s, the power of AO variability with periods of 10–20 days is much stronger. However, in the 1990s, the power of the 5–10 day period is enhanced and the power of the 10–20 day period is highly suppressed. In the 2000s, the power of the 10–20 day period is obviously more enhanced compared to during the 1990s, although strong power near the 10 day period does appear.

[20] The reason why the AO frequency fluctuates at the decadal time scale may be based on decadal changes in the dominant phase of the daily AO index (Figure 8a). In the 1980s and 2000s, the negative phase of the AO occurs more often at the daily scale, while the positive phase occurs more in the 1990s. Since the negative AO phase is linked to the weakening of the zonal mean westerly and slow phase propagation of overall the midlatitude weather system, the decadal change in the AO variability (Figure 7) related to decadal change in the dominant AO phase seems to be quite reasonable.

[21] Such AO decadal fluctuations may be related to the decadal modulation of the East Asian cold surges and SAT variabilities, because the AO is one of the critical components that affect cold surges [*Jeong et al.*, 2005; *Park et al.*, 2011b]. Even though the AO is basically zonally symmetric, it also has a significant zonally asymmetric component. This non-zonal component is more conspicuous at the upper-level [*Thompson and Wallace*, 1998] compared to the features depicted at the surface. If the local center of the AO over the Pacific sector extends upstream, it significantly influences the East Asian coastal trough [*Thompson and Wallace*, 1998]. Further, the role of the deepening upper-level trough on the intensification of Siberian High and cold air advection toward East Asia was well reported within the literature [*Ding and Krishnamurti*, 1987; *Zhang et al.*, 1997; *Gong et al.*, 2001; *Wang et al.*, 2009, 2010]. Based on these studies, in order to examine the linkage between the AO and cold surges over Northeast Asia, we compared anomalous SAT observed for a week before cold surge occurrences (Figures 9a–9c) with AO-related SAT change (Figures 9d–9i). The importance of preconditioning during a week before cold surge occurrence

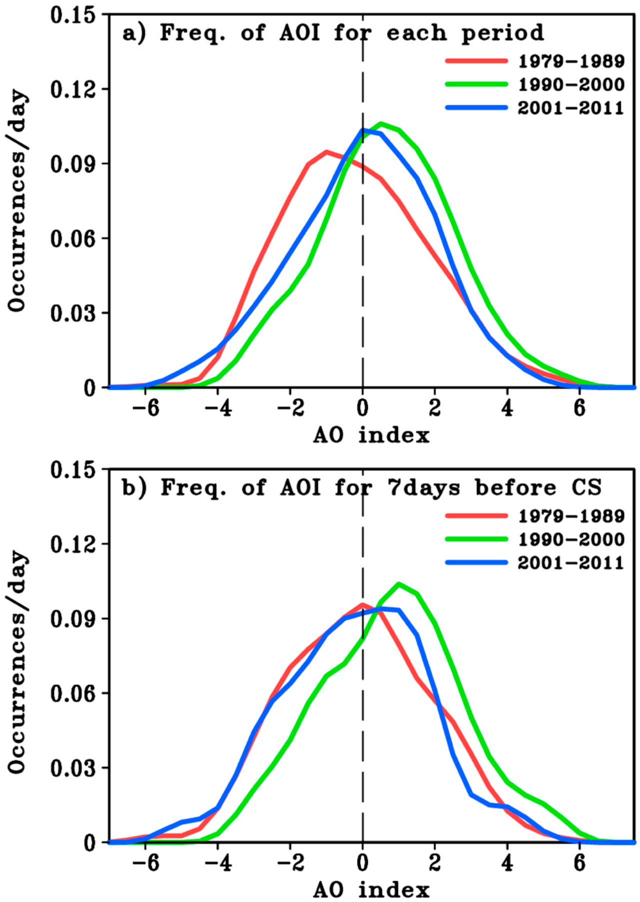

Figure 8. (a) Frequencies of the daily AO index for the 1980s (red), 1990s (green), and 2000s (blue) and (b) frequencies of the daily AO index for a week before cold surge occurrence in each decade.

over East Asia is suggested in previous studies. *Joung and Hitchman* [1982] suggested that cold air outbreaks over East Asia are related with the cyclone and anticyclone pair propagated from the western North Atlantic for 6–7 days before outbreak day. *Sung et al.* [2010] also showed that the significant surface anomalies (pressure and temperature) downstream of the negative NAO induce significant cold advection over East Asia after a week from NAO onset. Figure 9 shows the composite SAT for a week before cold surge occurrence (Figures 9a–9c) and in the positive (Figures 9d–9f) and negative (Figures 9g–9i) phases of the AO. Prior to cold surge occurrences, cold anomalies exist over central Siberia, indicating the strengthening of the Siberian High (Figures 9a–9c). This feature appears commonly in the three decades, but the amplitude of the SAT anomaly is distinctly stronger in the 1980s and 2000s than the 1990s. The cold anomalies elongate from Europe to East Asia and cover a larger area of the Eurasian continent in the 1980s and 2000s. Conversely, in the 1990s, they are confined within the central part of the Eurasian continent. The cold anomalies in the Eurasian continent are stronger in the 1980s than the 2000s. In the 2000s, the salient feature is the stronger positive SAT anomalies over the Arctic Ocean and Greenland. This pattern in the 2000s seems to be related to recent warming in the Arctic and constitutes a typical feature called the 'Warm Arctic Cold Continent' pattern [*Overland and Wang*, 2010]. Anomalously cold Siberian SATs in the 1980s and 2000s is favorable for strong cold surge occurrences over East Asia. These results are consistent with the stronger cold surges observed to occur frequently in the 1980s and 2000s.

[22] In the positive AO phase, warm SAT anomalies elongated over Europe to East Asia, while strong cold anomalies appear over Greenland (Figures 9d–9f). These features commonly appeared in the three decades, although the amplitude of warm SAT anomalies are larger in 1990s and 2000s than 1980s, and cold anomalies over Greenland are more prominent in the 1980s and 1990s. On the other hand, in the negative AO phase (Figures 9g–9i), SAT anomaly composites for the 1980s and 2000s are remarkably different from those of the 1990s over the Eurasian continent. While cold anomalies in the 1980s and 2000s elongate over Europe to East Asia, in the 1990s, negative SAT anomalies are confined over Europe, Northern Siberia and Kazakhstan. The amplitudes of cold anomalies over Europe in the 1990s are also much weaker than the 1980s and 2000s. SAT pattern for a week before cold surge occurrences (Figures 9a–9c) appears to be quite similar to those in the negative phase of the AO in all of the three decades. This indicates that the negative AO phase is strongly related with preconditions of SAT before cold surge occurrence. These implications are also supported by previous studies in which the circulation pattern downstream induces cold advection over East Asia after developing in the negative phase of the NAO [*Sung et al.*, 2010]. Further, because cold surges are able to occur in both phases of the AO, all SATs related to both phases of the AO are reflected in the mean SAT patterns before cold surge occurrence (Figures 9a–9c). Therefore, this result implies that the dominant phase of the AO before cold surge occurrences in each decade is important in decadal change in cold surge characteristics.

3.4. Decadal Change in Cold Surge Characteristics Related With AO Phase

[23] To clarify the relationship between the AO phase and cold surge characteristics, the frequencies of the daily AO index for a week before cold surge occurrences in the three decades are investigated, as atmospheric conditions related to the AO before cold surge occurrence are able to affect its characteristics [*Joung and Hitchman*, 1982; *Sung et al.*, 2010]. Figure 8b shows the frequency distribution of the daily AO index for a week before cold surge occurrence in each decade. The AO index is standardized by total cold surge in each decade for equivalent comparison. In the 1980s, the maximum frequency of the AO index appears near zero and the negative phase of the AO exists more frequently before cold surge occurrence. However, in the 1990s, the maximum frequency is shifted to the positive phase of the AO, which also becomes more frequent. In 2000s, although the maximum frequency of the AO slightly shifted to the positive phase, the negative AO index appears more frequently than the positive phase. In particular, extreme negative phases of the AO (less than −4) are more frequent. For example, the extreme negative AO events that occurred in 2001, 2004, 2006, and 2010 led to long and strong cold surges. These results could imply that the decadal change in the phase distribution of the AO is related

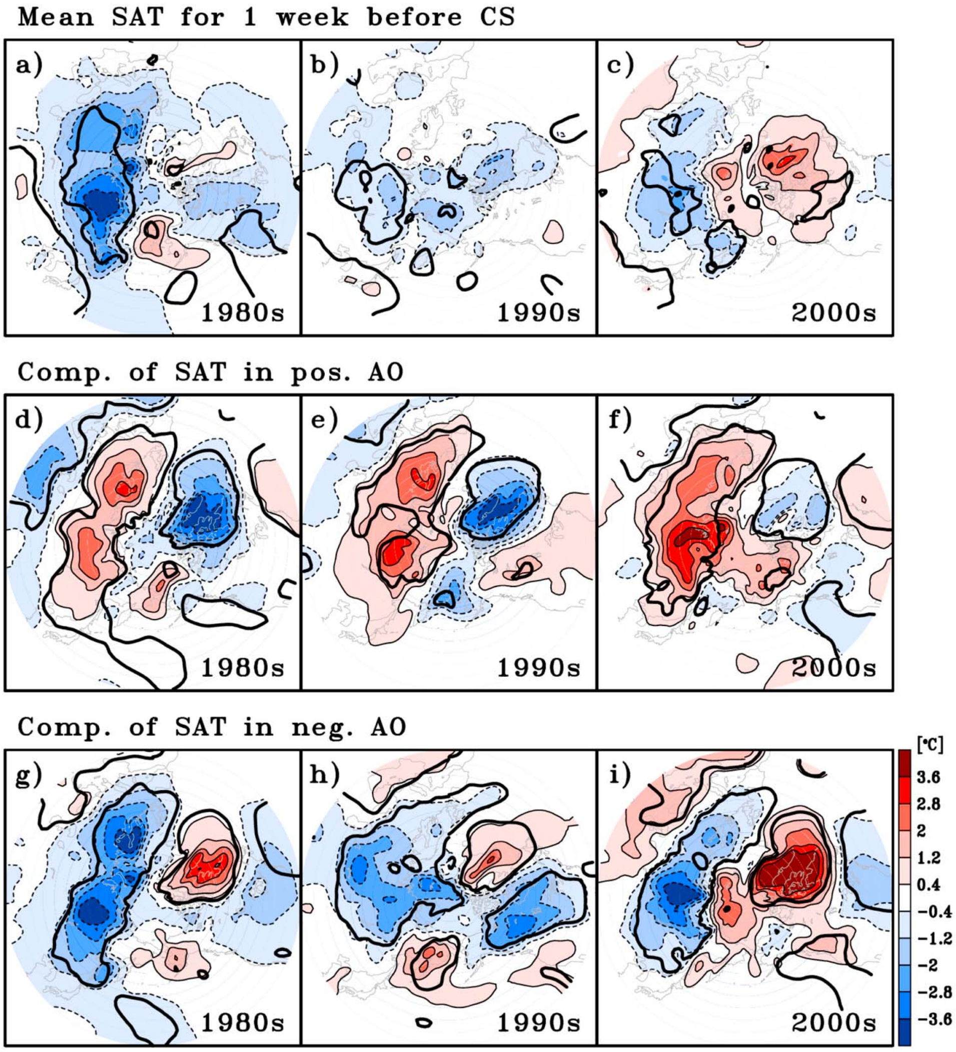

Figure 9. Composite SAT (contour and shading) anomalies for a week before cold surge occurrences for (a) the 1980s, (b) the 1990s, and (c) the 2000s. Composite SAT anomalies in the positive phase of the daily AO for (d) the 1980s, (e) the 1990s, and (f) the 2000s, and in the negative phase for (g) the 1980s, (h) the 1990s, and (i) the 2000s. The thick black lines represent the area satisfied the 95% confidence level.

to the change in cold surge characteristics over Northeast Asia.

[24] In order to examine how many cold surges occurred under the positive and negative phases of the AO, the number of cold surge occurrences is categorized by the phase of the AO index averaged for a week before cold surge occurrence. Table 2 shows the occurrences, mean duration, and strength of cold surges in each decade according to AO phase for the three decades. Cold surge events in the 1980s (58.0%) and 2000s (54.7%) occur more frequently in the negative phase of the AO than in the positive phase, while in 1990s more cold surge events (61.5%) appear in the positive phase. Mean duration (strength) of cold surges with negative AO phase preconditioning is shown to be longer (stronger) than positive preconditioning in all of the three decades. The result is consistent with the AO-cold surge relationship found by *Jeong and Ho* [2005]. These features are more remarkable in strong negative and positive phases of the AO (Table 3). Strong negative and positive phases of the AO in each decade are categorized based on the values of the mean AO index for a week before a cold surge, and are classified as being greater than −0.5 sigma and less than +0.5 sigma, respectively. Cold surges in the 1980s (63.6%) and 2000s (61.3%) also occur more frequently in strong negative phases of the AO than in strong positive phases, while in 1990s more cold surges (68.6%) appear in positive AO conditions. Further, the mean duration and strength in a strong negative

Table 2. Cold Surge Statistics for Each Decade in the Negative (Positive) Phase of the AO Index

Periods	Number	Mean Duration	Mean Strength
1980s	29(21)	8.48(5.67)	−4.31(−3.71)
1990s	20(32)	5.60(4.94)	−3.83(−3.00)
2000s	28(25)	8.44(4.36)	−3.94(−3.00)

Table 3. Cold Surge Statistics for Each Decade for Strong (Less Than −0.5 Standard Deviations of the Daily AO Index) Negative and Strong (Greater Than +0.5 Standard Deviations of the Daily AO Index) Positive Phases of the AO Index

	Number	Mean Duration	Mean Strength
1980s	21(12)	7.95(6.17)	−4.23(−3.61)
1990s	11(24)	5.18(5.00)	−3.37(−2.73)
2000s	19(12)	8.60(5.75)	−4.03(−2.68)

phase of the AO are longer and stronger than in the positive phase, as seen in Table 2. These results indicate that mean duration and strength of total cold surge events in each decade are strongly associated with the number of cold surges with preconditioning of negative and positive AO phases in each decade, and also that decadal change in cold surge characteristics is strongly related with the decadal change in dominant AO phase distribution before cold surge occurrence.

[25] To examine the differences of large-scale circulation associated with the differences of cold surge characteristics according to phase of the AO, we conducted lag-composite analyses of atmospheric circulation and SAT before and after cold surge occurrences for each phase of the AO separately. Figures 10–12 show the composite anomalies of Z (at 300 hPa and 850 hPa), SAT and wind (at 850 hPa) from 6 days before the occurrence of cold surges to 6 days after occurrences. The cold surge events in positive and negative phases of the AO are categorized based on criteria of strong negative and positive AO phases shown in Table 3. The 48

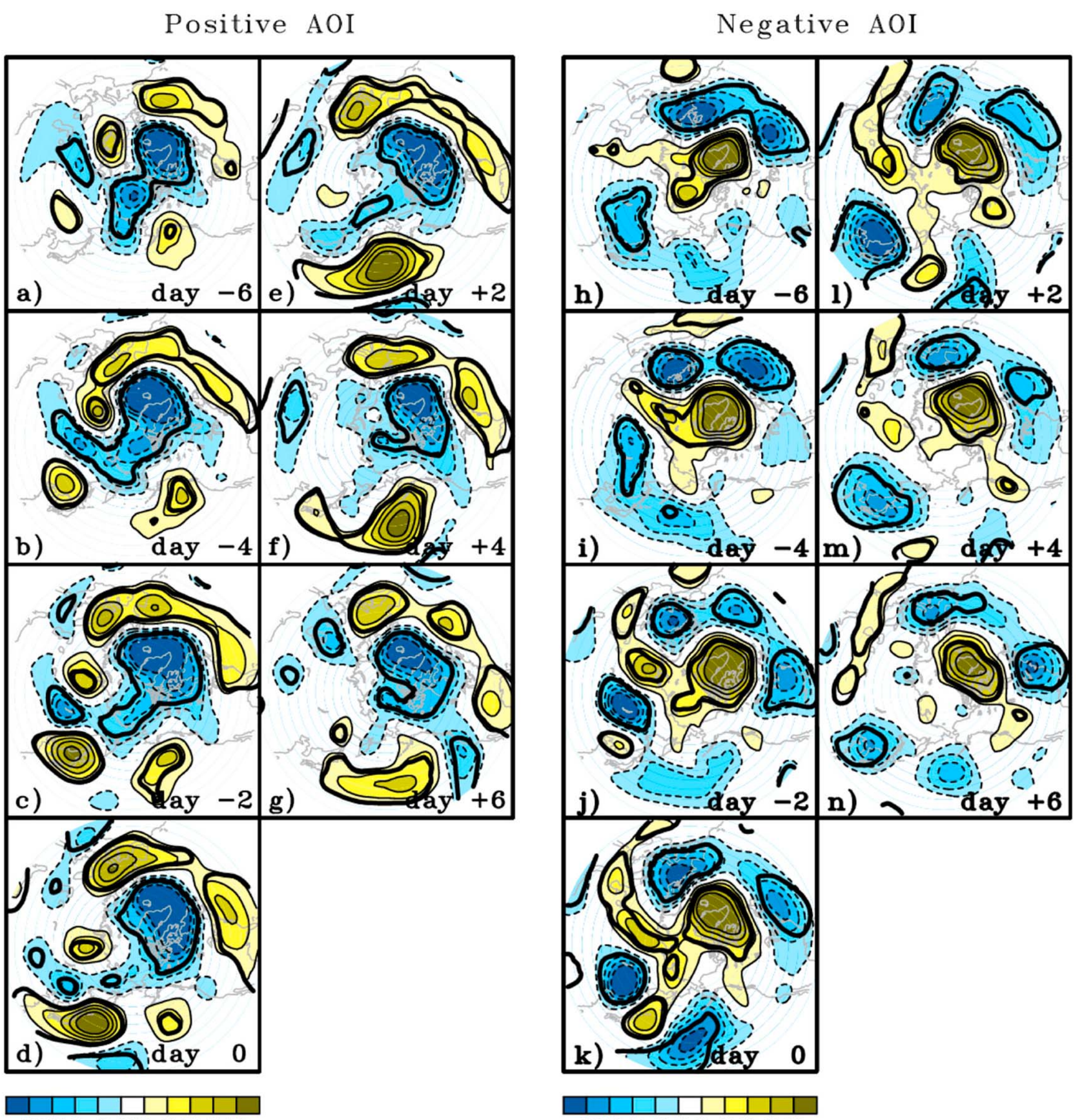

Figure 10. Composite maps of geopotential height anomaly (m) at 300 hPa (thin contour and shading with an interval of 20 m) before and after (−6 to +6 days) cold surge occurrences over the northern hemisphere in the (a–g) positive and (h–n) negative phase of the AO. The thick black lines represent the area satisfied the 95% confidence level.

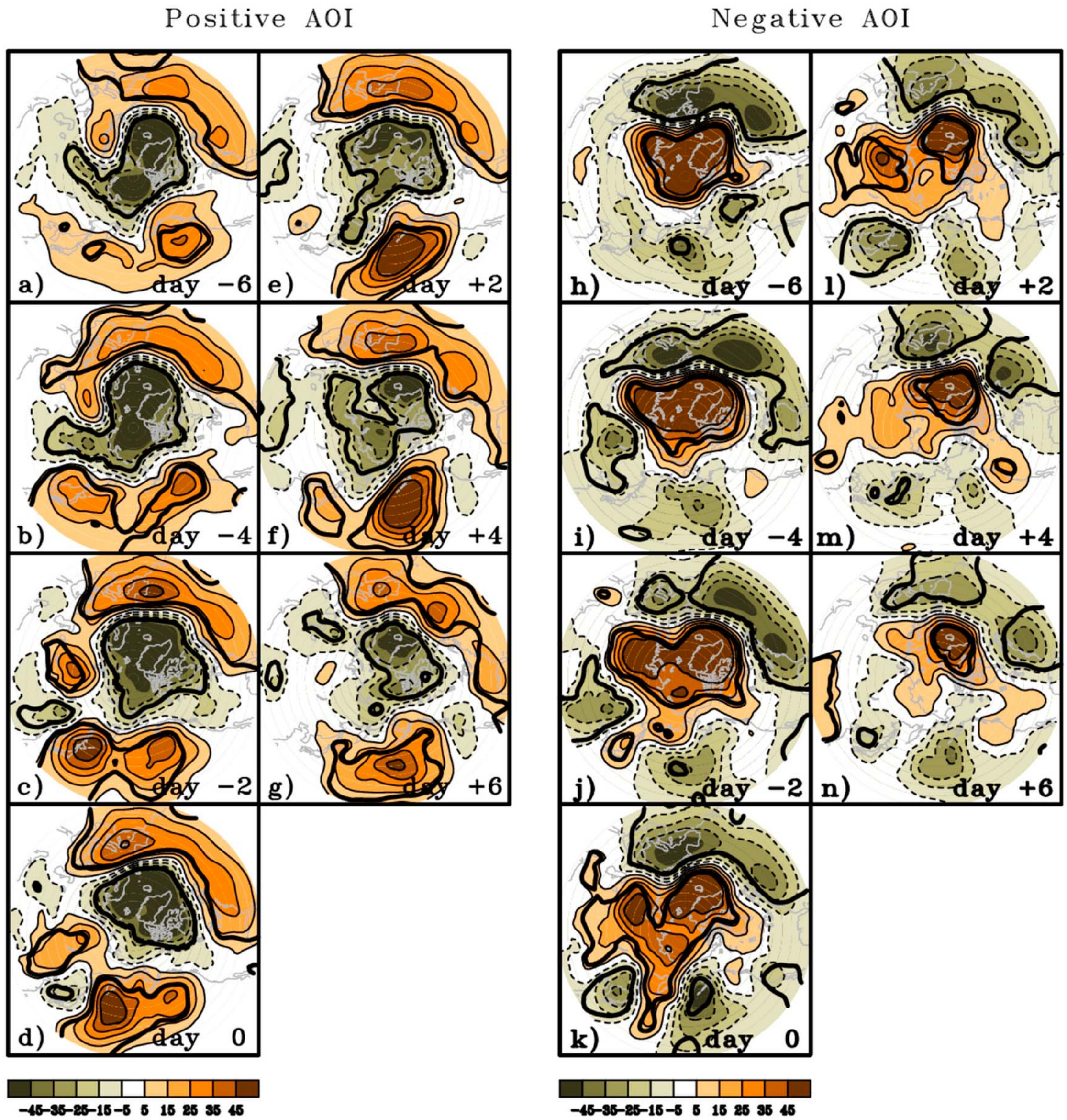

Figure 11. Composite maps of geopotential height anomaly (m) at 850 hPa (thin contour and shading with an interval of 10 m) before and after (−6 to +6 days) cold surge occurrences over the northern hemisphere in the (a–g) positive and (h–n) negative phase of the AO. The thick black lines s represent the area satisfied the 95% confidence level.

and 51 cold surge events in positive and negative phases of the AO are selected, respectively.

[26] The circulation composite fields at the lower-level (Figure 11) for the cold surge period are projected well onto the typical spatial pattern of negative and positive AO phases. For both phases of the AO, the wave trains in the upper-level (Z field in 300 hPa) emanating southeastward from the Ural Mountains to Northeast Asia before cold surge occurrences (Figure 10) are observed clearly. Although upper-level wave trains prior to cold surges are common features in both phases of the AO, there are remarkable differences. In day −2, while a strong positive Z anomaly appears over the East Asian coast in the wave pattern of the positive AO phase, a negative and positive Z anomaly pair over the Ural Mountains and Siberia in the negative AO phase is much stronger. After cold surge occurrence, upper-level cyclone anomalies over the East Asian coast decay quickly from day +2 in the positive phase of the AO and positive Z anomalies extend from the Pacific, while in the negative phase of the AO, negative Z anomalies become strong in day +2 and sustain until day +6 after cold surge occurrence. These upper-level features in the negative AO phase intensify the East Asian coastal trough and are favorable conditions to induce the cold air advection by northerly wind toward East Asia [*Chang and Lau*, 1982; *Joung and Hitchman*, 1982; *Lau and Lau*, 1984; *Boyle*, 1986]. The lower-level circulation field (Figure 11) shows more prominent anticyclone-cyclone pairs in the negative phase of the AO than the positive phase. In particular, the intensities of cyclone anomalies centered over the Korean Peninsula and Japan in day 0 are

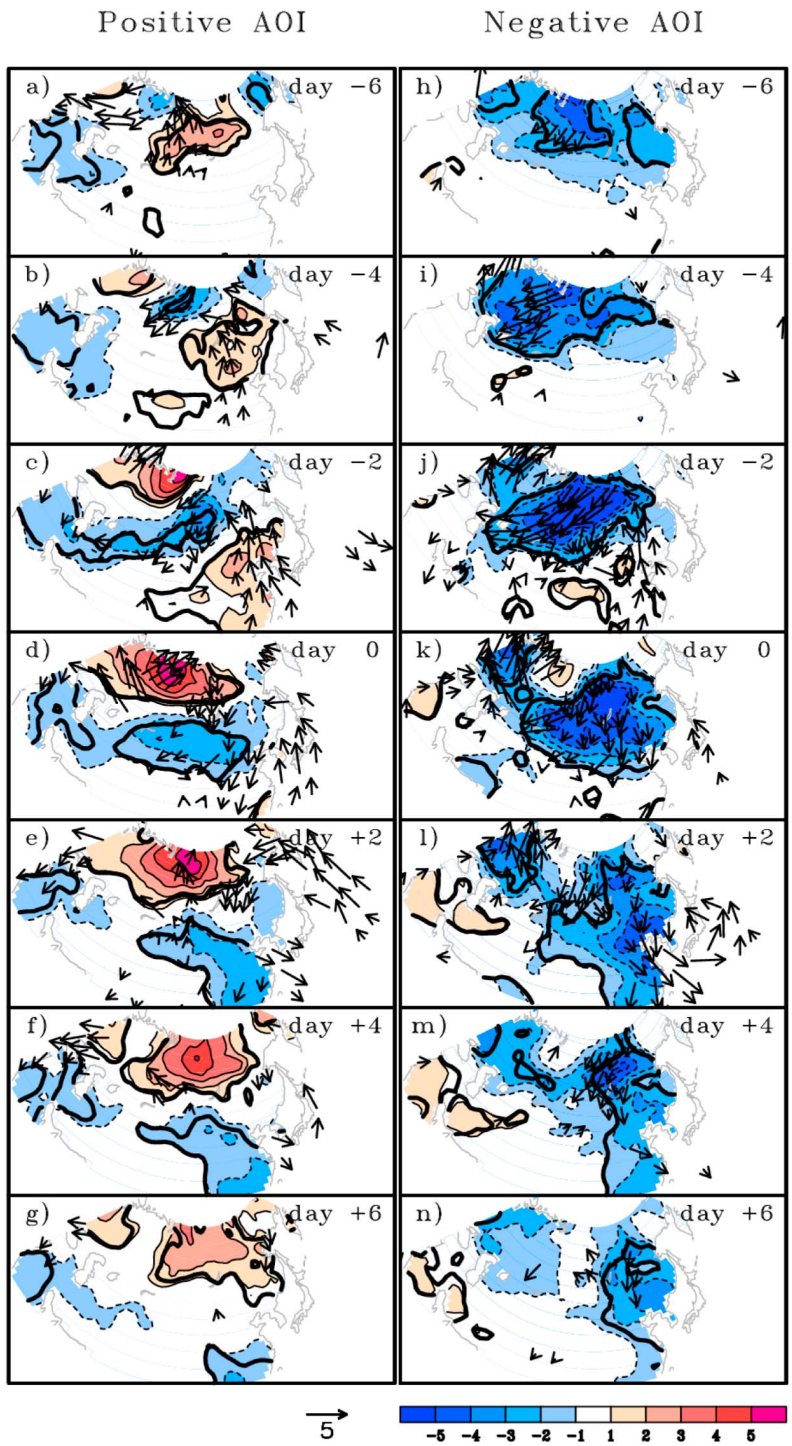

Figure 12. Composite maps of SAT anomaly (thin contour and shading with an interval of 1°C) and wind anomaly (m/s) at 850 hPa before and after (−6 to +6 days) cold surge occurrences over the East Asian domain in the (a–g) positive and (h–n) negative phase of the AO. The thick black line represents the 95% confidence level.

stronger and larger in the negative phase of the AO than the positive phase. These patterns in the lower-level induce strong northerly winds and cold air advection toward Northeast Asia during cold surge occurrence and lead to stronger cold surges in the negative phase of the AO than the positive phase (Figures 12d and 12k). After cold surge occurrence, lower-level positive (negative) Z anomalies over Siberia (East Asian coast) in the negative AO phase are long-lasting until day +4, while they almost disappear in day +2 of the positive phase. These lower-level circulation features in the negative phase of the AO contribute to the northerly wind and cold air advection toward Northeast Asia and contribute to strongly maintain the cold anomaly until day +6 (Figure 12n). On the other hand, in the positive phase of the AO, northerly wind and cold advection is already weak in day +2 (Figure 12e). Therefore, the cold anomaly over Northeast Asia returns to the climatological level at day +2 and is immediately followed by a warm anomaly in Siberia.

[27] These circulation and SAT features related to cold surges in the negative phase of the AO, such as strong upper-level wave trains over Eurasia before cold surge occurrence, long-lasting upper- and lower-level cyclone anomalies over the East Asian coast, are similar to those related to cold surges in the 1980s and 2000s. These results indicate that the stronger and longer-persisting cold surge characteristics in the 1980s and 2000s compared to the 1990s is strongly connected with large scale circulation, which are possibly associated with the negative phase of the AO. Further, the atmospheric preconditions related with the negative AO phase before cold surge occurrence are more favorable to the intensification and long-lasting nature of cold surges. These implications are supported by a previous study that suggested that cold surge events during the negative phase of the AO are stronger and last longer than those during the positive phase [*Park et al.*, 2011b].

4. Summary and Discussion

[28] The present study examined decadal changes in SAT variability and cold surge characteristics over Northeast Asia for the most recent three decades. The power of low-frequency variability (periods of 10–20 days) of SAT over Northeast Asia was enhanced and the power of high-frequency variability was weakened during winter in the 1980s and 2000s. The enhanced low-frequency variability of SAT during the winter season was found to be related to more frequent occurrences of stronger and longer-lasting cold surges in the 1980s and 2000s.

[29] The decadal change in SAT variability and cold surge characteristics is strongly related with a change in the dominant AO phase in each decade. Power spectrum analysis of the daily AO index shows that in the 1980s and 2000s the power of the 10–20 day period is stronger than that of the 5–10 day period. In contrast, in the 1990s, the power of the 5–10 day period is enhanced while the power of the 10–20 day period is weakened. Moreover, cold surges were stronger and lasted longer during the 1980s and 2000s compared to those that occurred in the 1990s.The pattern of composite SAT before cold surge occurrence in each decade is well projected in the SAT composite in negative phase of the AO. Further, the negative phase of the AO is detected for a week before cold surge occurrence more often in the 1980s and 2000s, while the positive phase is dominant in the 1990s. In addition, lag-composite analysis of cold surge events in positive and negative phases of the AO (categorized by AO index averaged for a week before cold surge occurrence) revealed that stronger and longer cold air advection from Siberia to Northeast Asia (associated with the intense upper-level cyclonic anomaly over the East Asian coast) in the negative phase of the AO. These circulation and SAT features related to cold surges in the negative phase of the AO are similar to those related to cold surges in the 1980s and 2000s. These results imply that the change in atmospheric conditions before cold surge occurrence associated with the phase of the AO is directly related to the change in cold surge characteristics over Northeast Asia, and that decadal change in cold surge characteristics was strongly influenced by the decadal change in the dominant AO phase.

[30] The decadal changes in SAT variability and cold surge characteristics presented in this study are associated to findings from previous studies on the long-term variability of the East Asian winter monsoon. *Miyazaki and Yasunari* [2008] found that the principal mode of SAT in winter related to the AO shows decadal oscillation, and signaled changes in 1988 and 1997. In particular, the shift of the significant mean state in the 500-hPa circulation field was detected by *Watanabe and Nitta* [1999]. These previous results support our findings that the decadal change in cold surge characteristics is strongly related with the decadal change in atmospheric circulation, such as the East Asian trough associated with the AO, for cold surge events. However, *Wu et al.* [2006] argued that although the winter mode of the East Asia winter monsoon is associated with the deepening of the East Asian trough at the inter-annual time scale, this mode does not show a close relationship with either the NAO or the AO. Nevertheless, our results show the tight relationship between cold surge characteristics and the AO at the decadal time scale.

[31] East Asian cold surges in most previous studies are defined using criteria involving a sudden SAT drop over inland China or Hong Kong [*Zhang et al.*, 1997; *Chen et al.*, 2004; *Jeong and Ho*, 2005]. *Compo et al.* [1999], *Kiladis et al.* [1994], and *Meehl et al.* [1996] also focus more on the cold surges which propagate more directly southward (sudden SAT drop in Hong Kong) affecting and interacting with the circulation in the Tropics, such as the convection over the western Pacific and the evolution of the MJO from the Indian Ocean to the western Pacific. On the other hand, our definition essentially includes more cold surges propagating southeastward and eastward (Northeast Asia) in addition to the southward cold surges. Therefore, the AO, which is related strongly to the East Asian coastal trough and SAT over Northeast Asia [*Thompson and Wallace*, 1998; *Wu and Wang*, 2002], is able to influence directly the evolution of cold surges propagating to Northeast Asia. This suggests that cold surges categorized by their trajectory are able to represent the different characteristics in cold surge evolution and the interaction with other variabilities.

[32] Moreover, we presume that there exists a phase asymmetry relationship between atmospheric conditions related to the AO and preconditioning of cold surge occurrence. SAT composite patterns for a week before cold surge occurrences are similar to SATs related to the negative phase of the AO in all three decades, although dominant AO phases prior to cold surge occurrences differ among each other. In particular, in the 1990s, positive SAT anomalies are strong over Europe and Siberia, and cold surges occurred frequently in the positive phase of the AO. However, preconditioning prior to cold surges show similar patterns as SATs related to the negative AO phase. These features enable us to make interpretations with respect to the phase asymmetric effect of the AO in cold surge preconditions. Our presumption is supported by a previous study that noted the asymmetric impact on the East Asia winter monsoon according to the phase of the NAO [*Sung et al.*, 2010].

[33] We showed the decadal change in cold surge characteristics for the recent three decades and its possible linkage to atmospheric circulation related to the AO phase. In particular, the intensification of the East Asian coastal trough during cold surge events in the negative phase of the AO is strongly related with cold surge characteristics. However, the specific mechanism and causality between the negative phase of the AO and the East Asian coastal trough have not been discussed. Despite this limitation, our results will be helpful for understanding changes in the East Asian winter monsoon system over recent decades. Moreover, our results regarding the importance of AO preconditioning for a week prior to a cold surge occurrence will contribute to forecast weather conditions during the winter season in East Asia.

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