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Arctic warming and its influence on East Asian winter cold events: a brief recap

Seong-Joong KIM* & Baek-Min KIM

Korea Polar Research Institute, 26 Songdomirae-ro, Yeonsu-gu, Incheon, #406-840, Republic of Korea

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Abstract The rate of warming of Arctic surface temperature is about 2–3 times faster than the global mean surface warming. Increases of ice albedo feedback and water vapor as well as moisture intrusion from outside the Arctic all have major roles in this phenomenon. In contrast to this rapid Arctic warming, in recent decades, stronger cold air outbreaks have occurred more frequently during winter in East Asia than were recorded in the 1990s, resulting in severe socioeconomic impacts. A number of related studies have claimed the increased frequency of these stronger cold air outbreaks is linked to the amplified warming in the Arctic through complicated mechanisms. As there are time lags between the observed Arctic warming and East Asian cold weather response at various scales, understanding the entire chain of processes from the Arctic to East Asia has importance for forecasting winter weather in East Asia. There are two pathways linking Arctic warming with East Asian cold weather events. One is the synoptic-scale pathway in the lower troposphere via strengthening of the Siberian High initiated by Ural blocking. The other is the planetary-scale path through the stratosphere via activation of planetary waves and downward propagation, which weakens the polar vortex. This study briefly reviews the current understanding of the linkage mechanisms between Arctic warming and East Asian winter cold weather.

Keywords **Arctic warming, East Asia cold surge, linkage process, synoptic response, planetary response**

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1 Introduction

Since the start of industrialization, the global mean temperature has increased by over 1°C and the rate of warming has increased toward the present (Hansen et al., 2010). The fastest warming is occurring over the Arctic, where the temperature is increasing at a rate 2–3 times greater than in other regions (Overland et al., 2016). In contrast to this amplified Arctic warming, over recent decades, anomalous cold air outbreaks have occurred more frequently over mid-latitude areas, especially in East Asia in winter (Woo et al., 2012). In January 2016, a cold spell affected East Asian countries despite the overall warm weather during autumn and winter. For example, at Jeju Island in South Korea, a cold surge was accompanied by heavy snow that caused the Jeju International Airport to shut down for a week, affecting many tourists. In December 2009, an even stronger cold surge hit many parts of a number of East Asian countries, bringing extreme heavy snowfall to northwestern China and South Korea, which resulted in serious economic consequences. From December 2012 to January 2013, the temperatures in China were the lowest recorded over the previous 28 winters; in December 2005, record breaking heavy snowfall occurred over Japan, and in January and February 2008, freezing rain occurred over southern China (Wu et al., 2017, 2013).

Numerous related studies have suggested the cold anomalies that have occurred in East Asia and mid-latitude areas in recent winters have been linked to amplified Arctic warming and Arctic sea ice decline. Using numerical

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* Corresponding author, E-mail: seongjkim@kopri.re.kr

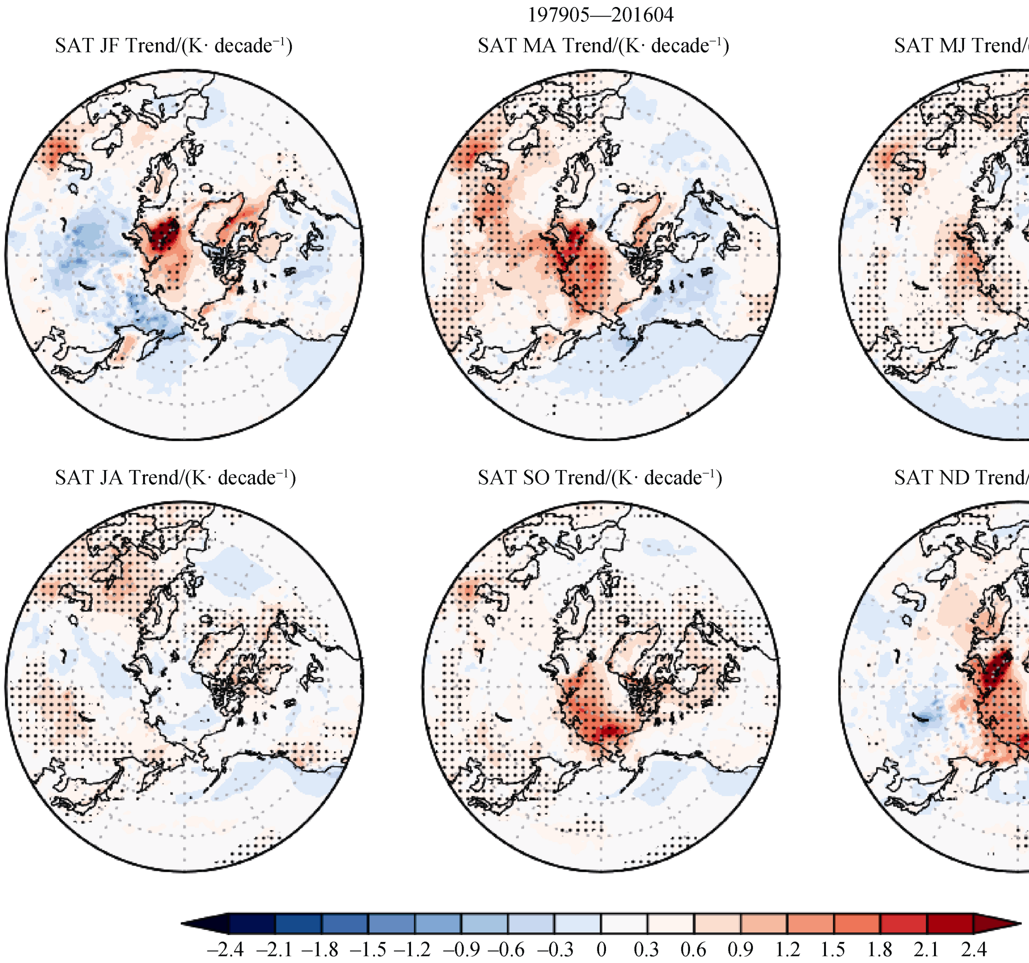
models, some studies have examined the climatic response to reduced sea ice cover over the Arctic to mimic warm periods in a paleoclimate perspective and obtained cold anomalies in the Northern Hemisphere (NH) mid-latitudes (Raymo et al., 1990; Royer et al., 1990; Newson, 1973). Through composite analysis and numerical experimentation involving reduced sea ice extent over the Arctic, many studies have simulated the lower temperature anomalies found in the NH mid-latitudes, especially over Eurasia (Zhang et al., 2016; Kug et al., 2015; Nakamura et al., 2015; Kim et al., 2014; Mori et al., 2014; Peings et al., 2014; Francis and Vavrus, 2012; Petoukhov and Semenov, 2010; Honda et al., 2009). However, other studies have suggested the Arctic's influence on the recent NH cold anomalies is uncertain because of the large internal variability of the system (Barnes and Screen, 2015; Sun et al., 2015; Wallace et al., 2014; Barnes, 2013), or because the mid-latitude cold air outbreaks originate from the tropics (Lee et al., 2015; Hartmann, 2015). Recently, some studies have been conducted to try to establish the reasons for such different responses when using the same numerical model with different initial and boundary conditions and between different numerical models (Francis et al., 2017; Overland et al., 2016). Several reviews have been published regarding the linkage between Arctic climate change and the weather and climate of the NH mid-latitudes (Cohen et al., 2016; Gao et al., 2015; Overland et al., 2015; Vihma, 2014; Walsh, 2014); however, the linkage mechanism remains highly uncertain and controversial (Screen, 2017).

Research has been conducted on East Asian cold surge events that originate from the Pacific side (e.g., Park et al., 2008); however, the focus of this study was on the teleconnection from the Atlantic sector of the Arctic Ocean. The steps linking amplified Arctic warming or the decline of Arctic sea ice extent to cold anomalies over the NH mid-latitudes are considered complex (Overland et al., 2016). The occurrence of cold anomalies over the NH mid-latitudes is due to slower propagation of Rossby waves in response to a reduced meridional pressure gradient resulting from the increase of air pressure over the Arctic following amplified warming (Francis and Vavrus, 2012). Even though the linkage mechanism between the Arctic and the NH mid-latitudes remains uncertain and controversial, the connection between the Arctic and East Asia is comparatively robust (Cohen et al., 2014). This study had two primary objectives: to update some recent developments regarding the linkage mechanisms and to elucidate further current understanding of the pathways linking Arctic warming or Arctic sea ice decline to East Asian winter cold events.

2 Arctic amplification and East Asian cold anomaly

The Arctic is covered by snow and ice with high albedo, which means it is vulnerable to changes in external forcings, e.g., increased atmospheric carbon dioxide. Observational records show the increase in Arctic temperature is faster than in other regions of the world by at least a factor of two (Overland et al., 2016) and that the Arctic warming is more pronounced in winter (Walsh, 2014). Figure 1 shows the trends of NH surface air temperature during 1979–2016. Except for the summer months, the warming trend is more pronounced in the Arctic than at lower latitudes. The greatest Arctic warming occurs in winter over the Barents Sea, while in autumn and spring, the greatest warming occurs in the European sector of the Arctic Ocean. The marked Arctic warming in autumn and winter, and the comparatively lower warming in summer, are well-known and well-documented features (Serreze et al., 2011).

The preferential warming of the Arctic in comparison with the remainder of the globe is referred to as "Arctic amplification," after recognition of the phenomenon by Arrhenius (1986). Arctic amplification is caused by several feedback mechanisms associated with ice, temperature, water vapor, and clouds. Among these feedback mechanisms, the ice albedo feedback is considered dominant (Screen and Simmonds, 2010; Solomon et al., 2007; Serreze and Francis, 2006). As the snow and ice that cover the Arctic have higher albedo (0.7–0.8) than either oceans (0.1) or bare land (0.3–0.4), greater quantities of shortwave radiation can be absorbed wherever the sea ice or land ice has disappeared (Taylor et al., 2013; Crook et al., 2011). Secondarily, increases in both water vapor and clouds due to an enhanced greenhouse effect represent additional important contributors to Arctic amplification (Graversen and Wang, 2009). Changes in oceanic and atmospheric heat transport are also known to have roles in increasing the Arctic temperature (Spielhagen et al., 2011). Global warming could modulate the vertical structure of temperature over the Arctic, contributing to Arctic amplification via a change in lapse rate (Bintanja et al., 2012). A recent study has suggested the most important factor in Arctic amplification is not the surface albedo feedback but the temperature feedback. This is partly associated with the lower temperature of the Arctic in comparison with lower latitudes that allows less emission of blackbody radiation, and partly due to the peculiar nature of the vertical temperature profile of the polar region (Pithan and Mauritsen, 2014). Aside from local feedback mechanisms, some recent studies have focused on the contribution of direct energy input from outside the Arctic through moisture intrusion (Graversen and Burtu, 2016; Woods and Caballero, 2016; Park et al., 2015a; Park et al., 2015b). Increased Atlantic windstorm entry into the Arctic region introduces enormous quantities of heat to the Arctic, which can establish a blocking condition that could help sustain heat transport from the North Atlantic to the Arctic (Kim et al., 2017; Rinke et al., 2017). Despite the various potential causes of Arctic amplification, the amplified temperature response to increased concentrations of greenhouse gases is unequivocal.



SAT JF Trend/(K· decade^{-1})

SAT MA Trend/(K· decade^{-1})

SAT MJ Trend/(K· decade^{-1})

SAT JA Trend/(K· decade^{-1})

SAT SO Trend/(K· decade^{-1})

SAT ND Trend/(K· decade^{-1})

Figure 1 Geographic distribution of surface air temperature (SAT) trend during 1979–2016 averaged for every two months. Regions marked by dots are significant at the 95% confidence level based on a two-sided significance test. JF: January–February; MA: March–April; MJ: May–June; JA: July–August; SO: September–October; ND: November–December.

In contrast to the marked trend of Arctic warming over the recent several decades, a slight cold anomaly has been detected over Siberia and East Asia in the winter months (Figure 1). This cold anomaly has become more pronounced toward the present over Asia, and since 2000, the lowest minimum temperature has been decreasing, while the numbers of icing days and cold winter months have increased (Cohen et al., 2014). Figure 2 displays the monthly mean surface temperature anomalies for December 2009 and January 2016 when there were severe cold air outbreaks over East Asia. In both years, marked warming occurred over the Arctic, while substantially lower surface temperature anomalies were evident in East Asia.

In association with Arctic amplification, the extent of Arctic sea ice has been shrinking rapidly. Since the commencement of measurement of Arctic sea ice extent in 1979, using satellite-borne microwave sensors, Arctic sea ice has been found to be declining in all months and declining at a much faster rate toward the present (Serreze and Strove, 2015; Serreze et al., 2009)(Figure 3). In winter months, the trend of diminishment of sea ice is smaller than in summer months. The largest reduction in sea ice occurs in the Chukchi Sea during September–October, while in winter, the greatest decline occurs in the Barents and Kara seas (B-K). As described later, sea ice reduction in the B-K is important in driving anomalous circulation and planetary wave propagation. Since 2002, the September sea ice extent has shown drastic reduction (Strove et al., 2012). For example, in the early 1980s, the sea ice extent was 7.80 million km^2, whereas it had shrunk to 4.22 million km^2 by September 2007. The minimum sea ice extent recorded in September 2007 was broken in September 2012, when it dropped to 3.44 million km^2, i.e., less than half that of the early 1980s.

Arctic amplification influences the amount of snow around the Arctic Ocean. Since the 1980s, spring snow cover extent has declined sharply by 1.1%–3.4% per decade and in June the trend of snow cover decrease is even larger than spring at 11.7% per decade (Stocker et al., 2013). However, in winter over Eurasia, increased snow accumulation has been reported (Bulygina et al., 2009). For example, Jeong et al. (2011) showed that during 1967–1990, snow cover over Siberia and East Asia had a negative trend in October and November, whereas during 1991–2009, it

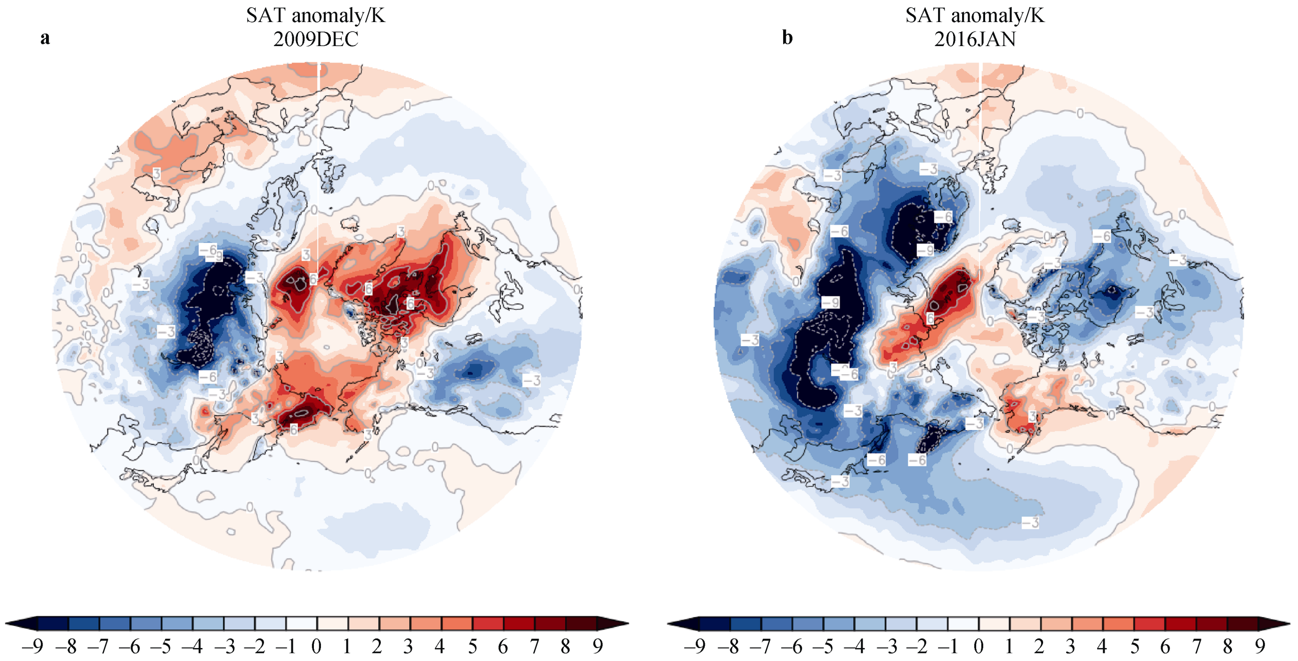


Figure 2 Surface air temperature (SAT) anomaly in December 2009 (**a**) and January 2016 (**b**, based on ERA-Interim reanalysis data).

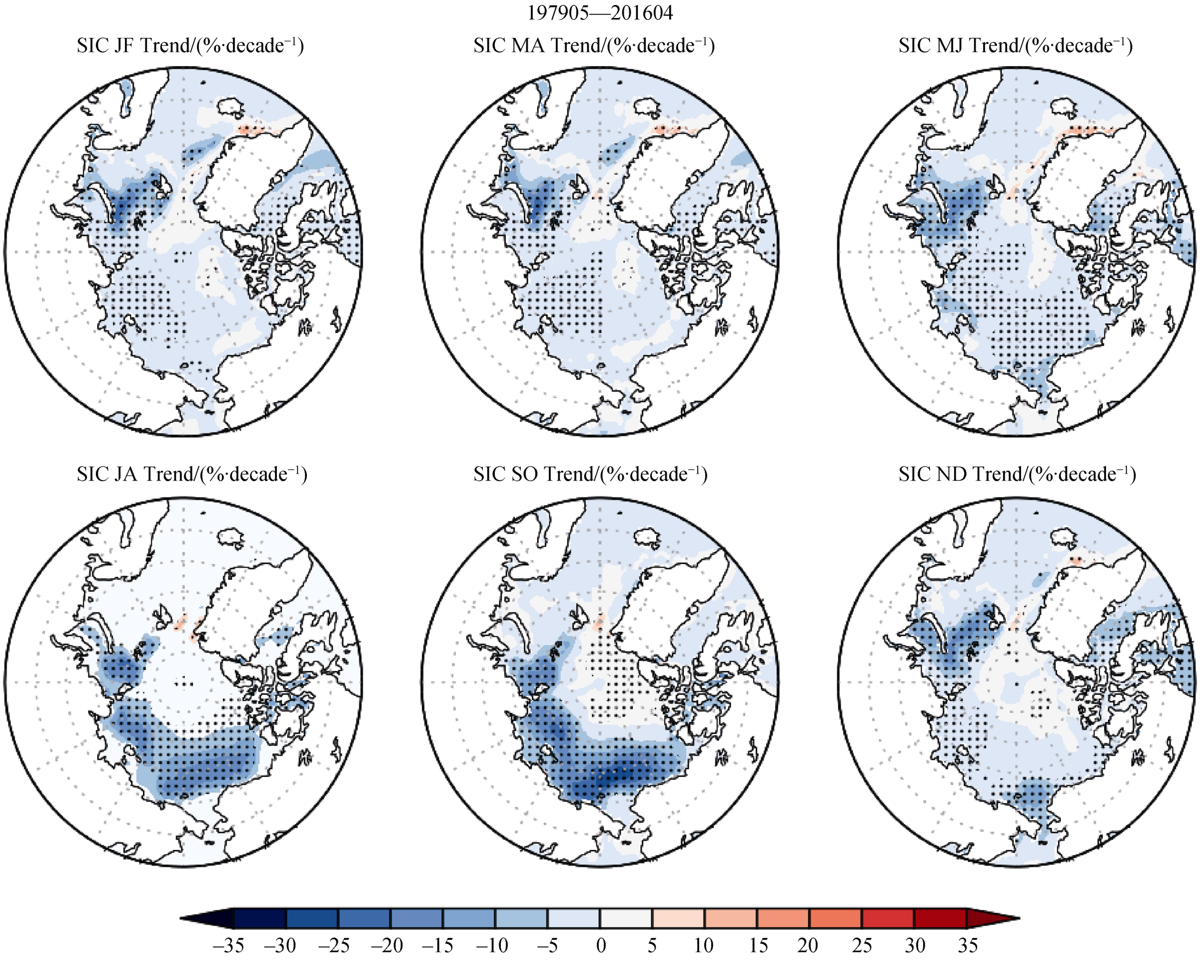


Figure 3 Geographic distribution of Arctic sea ice cover trend during 1979–2016. Regions marked by dots are significant at the 95% confidence level based on a two-sided significance test. JF: January–February; MA: March–April; MJ: May–June; JA: July–August; SO: September–October; ND: November–December.

had an increasing trend, strengthening the intensity of the Siberian High from the 1990s to the present. As addressed later, an increase in snow over Siberia is important in modulating the local Siberian High and wave propagation, even though the source of the snow over Siberia remains unclear. One possible source is the Arctic Ocean. As mentioned above, in September, Arctic sea ice extent reaches its minimum, and it has been disappearing more drastically in recent years. Based on analysis of observational data and through numerical simulations, some studies have suggested that an increase in open areas in the Arctic could provide greater quantities of moisture for transport to neighboring regions, including Siberia during autumn and winter (Wegman et al., 2015; Liu et al., 2012; Ghatak et al., 2012).

3 Arctic warming influence on East Asian winter cold events

As stated in the introduction, many previous studies have shown that mid-latitude cold anomalies might be linked to amplified Arctic warming or Arctic sea ice decline. Two pathways linking the signal of Arctic warming to East Asian cold anomalies are discussed in the following.

3.1 Influence through the troposphere

Excessive snow cover over Siberia in October tends to enhance the magnitude of the preexisting Siberian High within a couple of weeks, in association with increases in both radiative cooling and albedo (Cohen et al., 2014; Cohen and Entekhabi, 1999). By prescribing snow over Siberia in the NASA GISS model, Cohen (1991) obtained substantial reduction in surface temperature associated with a reduction in shortwave radiation. Using the MPI ECHAM 3 model, Gong et al. (2003) prescribed snow depth over Siberia in autumn and winter, which generated a substantial increase in albedo, especially in autumn. The increase in albedo was directly reflected in a surface temperature drop of up to 5°C, which enhanced the local Siberian High by more than 5 hPa. Thus, increasing snow over Siberia tends to strengthen the Siberian High and generate cold surges over East Asia (Jeong et al., 2011).

The Siberian High is also strengthened by reduction of the Arctic sea ice extent, especially in the B-K. Arctic sea ice extent reaches its minimum in September. Freezing recommences from October, and by the end of November, almost the entire Arctic is covered by ice. Freezing occurs last over the Atlantic sector of the Arctic Ocean because of the influx of warm Atlantic water via the Gulf Stream and the North Atlantic extension, whose northward shift leads to lower sea ice extent in the B-K (King et al., 2016; Schlichtholz, 2016; Nakanowatari et al., 2014; Sato et al., 2014). Strong windstorms in the North Atlantic introduce enormous quantities of heat and moisture into the Arctic, which contribute to sea ice reduction (Kim et al., 2017). As the atmosphere cools to well below freezing toward late autumn and early winter, lower than average sea ice extent in the B-K results in a marked thermal contrast between the atmosphere and the ocean, which allows the release of huge amounts of turbulent (latent and sensible) heat into the atmosphere (Screen and Simmonds, 2010). This release of turbulent heat provides conditions favorable for the development of either tropospheric Rossby waves emanating horizontally and vertically from the B-K and the Ural Mountains (Honda et al., 2009) or Ural blocking (Luo et al., 2017; Yao et al., 2017). Anticyclonic pressure anomalies usually dominate from the surface to the upper troposphere over the B-K and the Ural Mountains after an initial transient phase. After a couple of days, an upper-level wave train is developed, displaying synoptic-scale ridges and troughs over the Eurasian continent, which enhances the preexisting lower-level Siberian High (Overland et al., 2016, 2015; Mori et al., 2014; Park et al., 2011, 2008; Takaya and Nakamura, 2005). It should be noted that the preexisting Siberian High is initiated and strengthened by radiative cooling and adiabatic mass change (Ding, 1990; Ding and Krishnamurti, 1987). With time, the center of the Siberian High propagates southeastward, and as the Siberian High becomes stronger, the East Asian trough in the western North Pacific is strengthened (Overland et al., 2016, 2015; Park et al., 2011). Through the passage between the strengthened Siberian High and the deepened East Asian trough, cold air is brought to Northeast China, the Korean Peninsula, Japan, and sometimes the northern Philippines.

3.2 Influence through the stratosphere

In addition to synoptic-scale disturbances that modulate the Siberian High, thermal forcing established by the rapidly increased snow cover over Siberia in October enhances planetary-scale wave propagation into the troposphere within about 2 weeks and into the stratosphere within one month. This leads to warming and an associated higher height anomaly over the high northern latitudes that can persist for several months and last until February, and from mid-winter, this higher height anomaly propagates down to the surface (Liu et al., 2012; Peings et al., 2012; Fletcher et al., 2009; Gong et al., 2003). The higher height anomaly at high latitudes driven by excessive snow cover over Siberia is consistent with the negative phase of the Arctic Oscillation (AO), Northern Annular Mode, or weaker polar vortex. There have been many studies on the relation between the extensive snow over Siberia and its influence on the AO into the negative phase (Allen and Zender, 2011; Cohen and Entekhabi, 1999). The higher height anomaly over high northern latitudes weakens the polar vortex and pushes the jet further southward, leading to mid-latitude cooling (Cohen et al., 2014).

The reduction of sea ice extent in the B-K has consequences similar to excessive snow over Siberia. The enhanced release of turbulent heat from the ocean to the atmosphere, driven by of lower than average sea ice extent in the B-K during November–December, establishes conditions favorable for enhanced propagation of planetary-waves into the stratosphere via constructive linear interference processes (Nakamura et al., 2015; Kim et al., 2014). Upward propagation of planetary waves deposits energy in the preexisting westerly flow and the Coriolis force, which induces a poleward residual circulation that requires sinking motion at the pole for mass balance, leading to adiabatic warming (Limpasuven et al., 2004), offsets the decelerated westerly. Therefore, the stratospheric polar vortex weakens and sometimes, in extreme cases, a sudden stratospheric warming event occurs with wind reversal.

A warmer polar stratosphere leads to a higher height anomaly in the high northern latitudes, and its signal tends to propagate down to the surface within a couple of months, setting the phase of the AO as negative or weakening the polar vortex (Mitchell et al., 2013; Limpasuven et al., 2004; Baldwin et al., 2001) (Figure 4a). It should be noted that in Figure 4b, the positive polar cap height confined to the lower stratosphere and troposphere is almost coincident with the downward signal during the middle of January. Three downward propagation mechanisms have been suggested (Hartmann et al., 2000). First, interaction between the planetary waves and zonal-mean zonal winds could influence the troposphere (Holton and Mass, 1976). Second, it can be shown using the potential vorticity inversion technique that a well-defined potential vorticity anomaly in the stratosphere could directly influence the tropopause height and tropospheric circulations (Kim et al., 2009; Hartly et al, 1998). Finally, mass redistribution in the lower stratosphere could influence the surface pressure (Baldwin and Dunkerton, 1999). Figure 4 shows typical examples of sudden stratospheric warming events in 2009 and 2016, when surface cold anomaly events occurred in East Asia, as shown in Figure 2. In 2009, upward propagation of planetary waves and associated sudden stratospheric warming occurred from November, whereas in 2016, it occurred suddenly during early January.

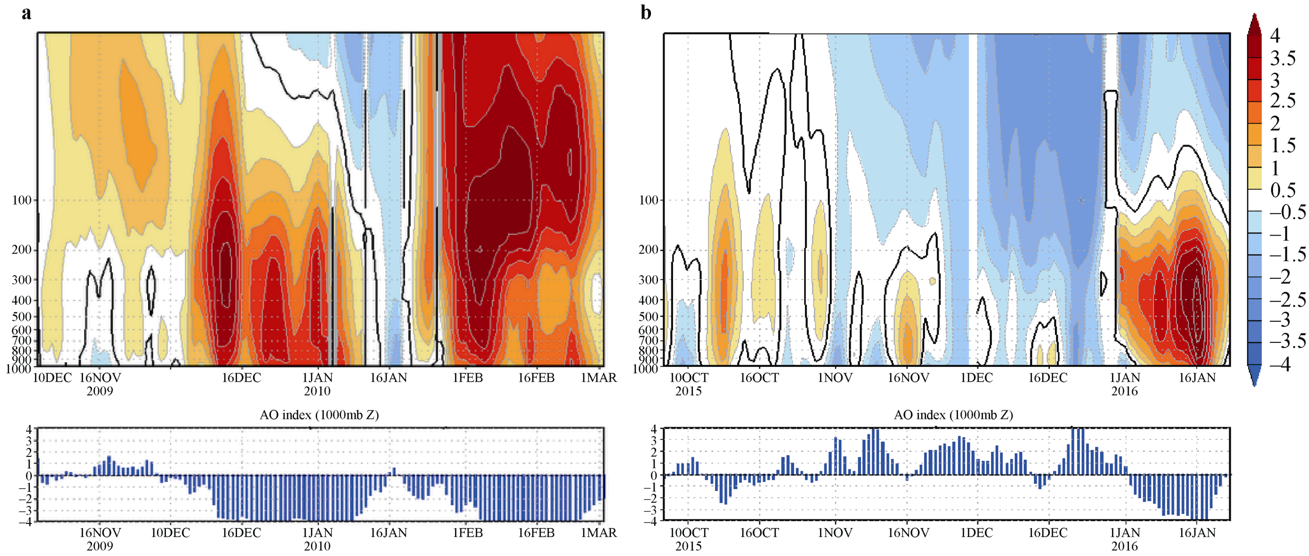


Figure 4 Vertical cross section of normalized geopotential height anomaly (65°N–90°N) (upper panels) and Arctic Oscillation indices (lower panels) for 2009/2010 winter (**a**) and 2015/2016 winter (**b**, figures obtained from the Climate Prediction Center, NOAA).

A weaker polar vortex pushes the jet further southward, leading to mid-latitude cooling (Cohen et al., 2014). Based on analysis of observational data and through numerical model simulations, many previous studies have suggested that reduction of Arctic sea ice leads the AO phase to become negative (Overland et al., 2015; Vihma, 2014; Walsh, 2014; Cohen et al., 2014). When the AO is in negative phase, cold surges occur more frequently than during the positive AO phase (Park et al., 2011). Under a negative AO phase, cold air is driven by a circulation anomaly initiated from the Arctic: one branch of the cold air that originates from the B-K blows toward eastern parts of Europe, while the other branch blows toward East Asia via Siberia (Gong et al., 2007). In comparison with the situation under a positive AO phase, the air transported from the Arctic toward East Asia is much colder and it tends to remain longer in East Asia after the cold surge event (Woo et al., 2012). An anticyclonic anomaly in the lower and upper troposphere is prominent over the B-K and the Ural Mountains during the developing stage of a negative AO phase, whereas a cyclonic anomaly is present over the Arctic under a positive AO case (Park et al., 2011). In Figure 4, prominent negative AO indices are evident when there is downward propagation, e.g., December 2009 and January 2016, and these are coincident with the cold anomaly over East Asia, as shown earlier (Figure 2).

4 Summary and discussion

Although many studies have suggested that Arctic sea ice reduction could lead to weakening of the polar vortex, caution must be exercised because some studies have obtained different responses (Sun et al., 2015). Furthermore, a large part of the mid-latitude temperature variability can be ascribed to natural variability, which is essentially chaotic rather than a reflection of a forced signal such as Arctic warming linked to sea ice loss (Barnes and Screen, 2015). Other studies have shown that the signal is derived from the tropics rather than high-latitude areas (Lee et al., 2015; Hartmann, 2015). Further comprehensive studies comprising analysis of observational data and numerical model simulations are required to obtain common and robust signals linking Arctic warming to East Asian cold weather events.

The relative roles of snow cover over Siberia and of sea ice extent over the B-K on the Siberian High and the eventual occurrence of cold surges over East Asia are case dependent, i.e., their effects are different at different times. October snow cover anomalies have impacts on the AO during middle and late winter, while reduced sea ice extent in the B-K in November plays a role in the development of atmosphere circulation anomalies during November and December with secondary influence in late January and February (Furtado et al., 2016). Sea ice in the B-K is an important external driver of the mid-latitude circulation, while Eurasian snow cover has an effect in modulating sea level pressure in Asia, although its exact role in the AO remains unclear (Kretschmer et al., 2016). Currently, it is not easy to quantify their contributions to East Asian cold surges and their relative roles need to be clarified further in future study.

The effects of reduced sea ice extent and excessive snow cover are not reflected linearly in the occurrence of cold air events because many other factors are involved in modulating the local Siberian High and the East Asian trough. Arctic warming also modulates the phase of the Pacific Decadal Oscillation, which subsequently influences the western coast of North America (Sung et al., 2016). A recent study suggested that reduced sea ice extent in the Atlantic sector of the Arctic, together with a negative phase of the Atlantic multidecadal oscillation, increases Ural blocking and enhances snow over Eurasia, resulting in “Warm Arctic and Cold Eurasia” events (Li et al., 2018). However, cold events have occurred more frequently since 2000 when the Atlantic multidecadal oscillation has been in positive phase. Therefore, the relationship between the Atlantic multidecadal oscillation and Arctic sea ice extent needs to be clarified in future work.

Another problem to be resolved is the coupling between the troposphere and stratosphere, which has importance in the warm Arctic–cold continents response (Wu et al., 2016). Planetary waves are sometimes confined within the troposphere, whereas at other times, they reach the stratosphere and levels beyond. From the stratosphere, their higher-height anomaly signals propagate downward in late winter and sometimes reach the surface, leading to a negative AO phase; however, they also often only reach the lower troposphere without influencing the AO phase. The factors controlling the levels of upward and downward propagation are not yet fully understood and these features should be examined further to help elucidate the entire linkage processes.

A full description of the dynamics of the AO was not presented here because it has been covered in many previous studies, e.g., Thompson and Wallace (2000). Downward propagation of the higher-height anomaly from the stratosphere to the surface occurs within a timescale of about 3 weeks (Baldwin and Dunkerton, 1999). However, the dynamical explanation of this downward propagation remains unclear and it remains to be clarified in future studies.

To summarize, excessive snow cover over Siberia in early autumn and reduced sea ice extent in the B-K in late autumn both provide conditions favorable for synoptic-scale enhancement of the Siberian High within a couple of days. This sometimes activates the propagation of planetary waves to the upper troposphere or the stratosphere, weakening the polar vortex, the signal of which can persist for months or a season and propagate down to the lower troposphere or sometimes to the surface, leading to the occurrence of extreme cold weather events over East Asia. In conclusion, we are at the incipient stage of distinguishing some signal of the Arctic influence on East Asia from the noise and of elucidating the process linking Arctic warming and East Asian cold surges in winter. By deepening our understanding of the relative roles of known predictors, such as increased snow cover over Siberia and reduced sea ice extent in the B-K, on synoptic-scale weather disturbances in East Asia under the background of planetary-scale modulation of the polar vortex or storm tracks, we could improve subseasonal–seasonal-scale winter weather prediction in East Asia.

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