Polar Science 30 (2021) 100640

Contents lists available at ScienceDirect

Polar Science

journal homepage: http://www.elsevier.com/locate/polar

Role of polar vortex weakening in cold events in central Asia during late winter

Seong-Joong Kim [*], Hye-Sun Choi

Division of Atmospheric Sciences, Korea Polar Research Institute, Incheon, Republic of Korea

ARTICLE INFO

Keywords:
Central Asia
Late winter
Cold events
Polar vortex
Siberian high

ABSTRACT

The cause of cold events over central Asia was investigated. Since 1958, surface air temperature (SAT) has gradually increased over central Asia, but SAT has shown very strong multidecadal fluctuations, with cooling dominant in the 1960s–1970s and recent decades but warming dominant in the 1990s. SAT in February in central Asia has decreased by more than 7 °C compared to that in normal years. Analysis indicates that cold events over central Asia are related to the weakening of the polar vortex, which is indicated by the increase in polar cap height (PCH) and weaker zonal-mean zonal winds. The increase in PCH begins in January in the stratosphere and propagates down to the troposphere in February; it is well reflected in the weakening of zonal-mean zonal winds in the stratosphere in January, which extends to the troposphere in February. The January increase in PCH anomaly is associated with surface conditions in the Arctic region, especially the Barents–Kara seas, where sea level pressure increases substantially in January; high pressure then expands to the southeastern (downstream) branch of the Siberian high in February, bringing cold eastern Siberian air to central Asia.

1. Introduction

Over the past several decades, climate change in the Arctic has been amplified, and surface temperature increases higher by 2 times global mean (Blunden and Arndt, 2019; IPCC, 2019; Cohen et al., 2020). The greater Arctic warming is linked to accelerated ice sheet and glacial melting over Greenland and a decline in Arctic sea ice (IPCC, 2019). By contrast, cold events are more common in winter in Eurasia and North America (Woo et al., 2012; Cohen et al., 2014; Horton et al., 2015; Johnson et al., 2018; Kim et al., 2019). Some of the most typical examples of mid-latitude cold surges despite recent Arctic warming occurred in 2009/2010 winter and January 2016 over Europe, North America, Eurasia (Cohen et al., 2020), and early January 2021 in east Asia. Cold surges accompanied by heavy snowfall have resulted in severe damage and the associated economic impact.

Many studies have suggested that the more frequent cold events in recent decades are associated with Arctic warming (Francis and Vavrus, 2012; Cohen et al., 2014; Kim et al., 2014; Mori et al., 2014, 2019; Kug et al., 2015; Overland et al., 2016) or are of tropical origin (Lee et al., 2015). Others have suggested that the role of the Arctic in recent cold anomalies over the Northern Hemisphere is unclear owing to the larger internal variability of the system (Barnes and Screen, 2015; Sun et al., 2015; Blackport et al., 2019). Models of the linkage between Arctic warming and mid-latitude weather and climate have been compared, but the model results regarding the influence of Arctic amplification (AA) on mid-latitude weather in winter diverge (Cohen et al., 2020). Previous studies suggested that to understand the impacts of Arctic changes on mid-latitude weather, we need a deeper understanding of the fundamental dynamics of atmospheric circulation, such as the meandering and oscillation of the jet stream (Cohen et al., 2014; Overland et al., 2015, 2016).

AA affects central Asian weather via two pathways, one through the troposphere and the other through the stratosphere (Cohen et al., 2014; Overland et al., 2016). Unlike North America, where the reinforcement of troughs and ridges over the troposphere is critical in determining local weather, the Siberian high is an important medium that transfers signals from the Arctic to Eurasia. The Siberian high can be strengthened by the development of snow cover (Cohen et al., 2014), which enhances radiative cooling owing to the higher albedo and the associated reduction in shortwave radiative heat fluxes (Gong et al., 2003). In recent years, the Siberian high has tended to become more intense after unprecedented low pressure in the 1990s following a weakening trend from the 1970s to the 1980s, which was associated with an increase in Eurasian snow cover (Jeong et al., 2011). The Siberian high is also

* Corresponding author. 26 Songdomiraero, Incheon, 21990, Republic of Korea.
E-mail addresses: seongjkim@kopri.re.kr, seongjkim@kopri.re.kr (S.-J. Kim).

https://doi.org/10.1016/j.polar.2021.100640
Received 3 September 2020; Received in revised form 12 January 2021; Accepted 18 January 2021
Available online 27 January 2021
1873-9652/

strengthened by the reduction in Arctic sea ice, especially in the Barents–Kara seas (BKS) via blocking development over the Ural Mountains, enhancing the existing Siberian high (Overland et al., 2015).

In addition to the tropospheric pathway, Arctic warming influences Eurasia through the stratosphere, mainly in late winter (Kim et al., 2014; Nakamura et al., 2015). The rapid increase in snow over Siberia in October activates stratospheric planetary waves and initiates stratospheric warming with a higher height anomaly that propagates to the surface during late winter (Lü et al., 2008; Fletcher et al., 2009; Peings et al., 2012). The increase in snow over the Tibetan plateau increases the activity of planetary waves, resulting in a negative phase of the Arctic Oscillation (Lü et al., 2008) and pushing the polar vortex farther south (Cohen et al., 2014). In addition to snow over Siberia, upward propagation of planetary waves is also activated by delayed sea-ice freeze-up in the BKS in early winter, which is associated with increased turbulent heat release from the ocean to the atmosphere (Kim et al., 2014; Nakamura et al., 2015). The upward propagation of planetary waves leads to adiabatic warming in the stratosphere at high latitudes (Limpasuvan et al., 2004) and weakens the polar vortex.

In this paper, we examine the characteristics of cold air outbreaks over central Asia, especially those in late winter associated with the weakening of the polar vortex in the stratosphere. There have been numerous studies on the effects of AA or delayed freeze-up of sea-ice on mid-latitude weather via the troposphere, as mentioned above. In this study, we diagnose cold events over central Asia in terms of changes in the polar vortex in the stratosphere in late winter. We first examine the degree of surface temperature change and select specific cold events to determine the causes of cold events over central Asia.

2. Data and methods

The data used in this study are from National Center for Environmental Prediction/National Center for Atmospheric Research reanalysis for temperature, geopotential height, zonal-mean zonal winds, and sea level pressure (SLP) from January 1, 1958 to March 2016 (Kalnay et al., 1996). The daily climatological variables calculated on the basis of 1981–2010 data are smoothed by a 31-day running mean. All anomaly fields in this study are defined in terms of departures from these climatological means.

We first analyze the temperature trends over Eurasia and the time variation of surface air temperature (SAT) over central Asia between 40°N and 60°N and 70°E and 120°E. Second, we produce the times of cold events over central Asia. Third, we estimate the standard deviations of the domain-averaged SAT using time series and define cold events as SAT anomalies more than 1 standard deviation (2.4 °C) below the climatological mean temperature. Finally, composite analyses of the meteorological variables during cold events, i.e. when SAT anomalies are below 1 standard deviation, are carried out to establish the relationship between the polar vortex strength, according to the polar cap height (PCH) and zonal-mean zonal wind anomalies, and the SAT over central Asia, according to sea level pressure anomalies. Student's *t*-test was done to check the statistical significance of all analyses. In this study, "late winter" refers to the values for February, unless otherwise noted.

3. Results and discussion

3.1. Surface air temperature trend

Fig. 1 shows the SAT trend for February over Eurasia from 1958 to 2016. The maximum warming rate is more than 2 °C per decade from offshore in the Barents Sea to near the Svalbard Islands. A secondary maximum warming trend occurs in the Kara Sea. Over Eurasia, the warming trend is not uniform. From the Ural Mountains to Lake Baikal and eastern Asia, the warming trend is slightly greater than that in the rest of the region, and the trend is statistically significant. In other regions, the warming trend is small, and a slight cooling trend even appears over eastern Siberia, although it is not statistically significant.

Greater warming over the Arctic compared to other areas has been reported in many studies (Pithan and Mauritsen, 2014; Goosse et al., 2018; Stuecker et al., 2018). Observational records show that the Arctic is warming twice as rapidly, and this greater Arctic warming is referred to as AA (Overland et al., 2016). In fact, the AA or polar amplification, which could be a more suitable term for past and future changes,

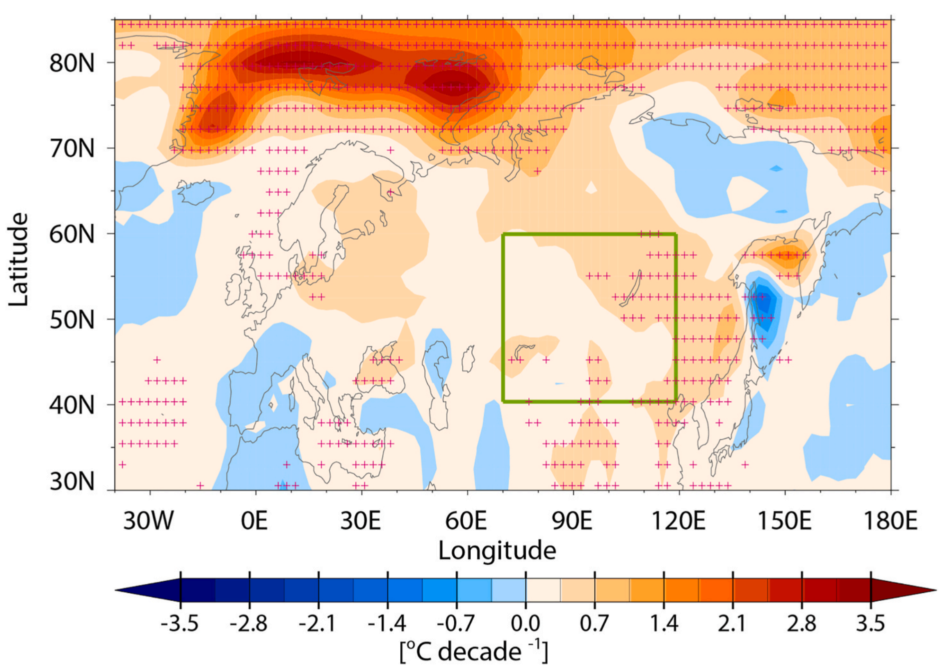

Fig. 1. SAT trend over Eurasia in February from 1958 to 2016. Crosses represent locations where the SAT change is significant at the 95% confidence level. Green box indicates central Asian domain of 40°N–60°N/70°E−120°E. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

describes larger surface temperature responses at both poles than the rest of the world owing to a change in external forcing, as shown in earlier studies (e.g., Manabe et al., 1991). Note that in the Southern Hemisphere, substantial warming is currently occurring only over the western part, but little warming is occurring in the eastern part owing to the internal mode of variability (Jun et al., 2020). AA is largest in winter and smallest in summer (Serreze and Barry, 2011; Walsh, 2014).

Many hypotheses have been suggested to explain the increased Arctic warming compared to that at lower latitudes (see Goosse et al., 2018 for a review). It has been suggested that AA might be due mainly to surface albedo feedback associated with the high albedo of snow and ice in polar regions (e.g., Screen and Simmonds, 2010), but several other hypotheses have been suggested, such as northward heat transport via the lower troposphere (Graversen et al., 2008), temperature feedback [i.e., more heat is radiated to space at low latitudes than in polar regions owing to higher surface temperature in low latitudes (Pithan and Mauritsen, 2014)], and lapse rate feedback associated with the more stable stratification in polar regions than lower latitudes, where vertical mixing by turbulence is much stronger than at high latitudes (Graversen et al., 2014; Stuecker et al., 2018). AA is also attributed in part to increases in water vapor and clouds and changes in vegetation, but their relative roles in AA are controversial, and further quantification is needed. Kim et al. (2017) suggested that AA could be driven by Atlantic storms, which introduce considerable heat and moisture into the Arctic through the northern North Atlantic Ocean. AA is obvious in the Eurasian sector during February.

Fig. 2 shows the time variation of SAT for February averaged over the central Asian domain, which is represented as a green rectangle in Fig. 1. The SAT over central Asia shows multidecadal fluctuations. For example, from the 1960s–1980s, the SAT over central Asia shows more years of low temperature anomalies larger than 1 standard deviation (±2.42 °C), but in the 1990s, SAT indicates warmer years overall. The monthly average temperature is more than 1 standard deviation above normal in all years. In the 2000s, again, the SAT over central Asia shows more frequent cold events. This result is consistent with an earlier finding by Woo et al. (2012) of stronger and longer-lasting cold surges in northeast Asia during the 1980s and 2000s than in the 1990s. They related the decadal fluctuation of cold surges to the phase shifts of the Arctic Oscillation, where the negative phase was dominant in the 1980s and 2000s, and the positive phase was dominant in the 1990s. Mori et al. (2019) also reported interannual fluctuations in surface temperature over Eurasia associated with sea ice fluctuations in the BKS. Because of the interdecadal fluctuations of SAT over central Asia, the slight increasing trend overall is not statistically significant at the 95% confidence level, although it is significant at the 90% level. Overall, the SAT over central Asia in February increased gradually with time, but there are more years with cold events from the 1960s-to the 1980s and in the 2000s than in the 1990s.

Fig. 3 shows the spatial distribution of the SAT anomaly over Eurasia for years with cold events in central Asia when the SAT is more than 1 standard deviation below normal, as indicated by blue dots in Fig. 2. A total of 14 years fell in this category, and Fig. 3 shows a composite of these cold years. As expected from the time series, SAT is more than 7 °C lower than that in normal years over central Asia, especially northwest of Lake Baikal. In the cold year composite, the cold anomaly is statistically significant at the 95% confidence level. Significantly cold events also occurred over eastern Asia. The reason is that the Siberian high brings cold air to this area as part of its downstream circulation, as shown later. Interestingly, SAT is higher in the BKS during the months in which cold events occur over central Asia. This pattern is similar to the warm Arctic and cold Eurasia (WACE) pattern, the second mode of empirical orthogonal function analysis of SAT (Mori et al., 2014, 2019). The amplitude of the WACE pattern exhibits multi-decadal fluctuations; the Eurasian SAT shows stronger contrast between the BKS and central Siberia in 1931–1955 and 1981–2013, whereas the contrast is weaker in 1901–1930 and 1956–1980 (Sung et al., 2018). Mori et al. (2019) claimed that approximately 44% of the WACE is reflected in sea ice loss in the BKS, but the remote influence of Arctic sea ice loss on the mid-latitudes remains highly controversial (McCusker et al., 2016; Screen et al., 2018; Blackport et al., 2019; Blackport and Screen, 2020), and the SAT responses to Arctic sea ice loss in numerical experiments differed (Cohen et al., 2020).

3.2. Relationship with polar vortex and surface circulation

To investigate the relationship between changes in the polar vortex and cold events over central Asia, we examined the composite geopotential height anomaly averaged for high latitudes (65°N to 90°N) and normalized by its standard deviation, which is referred to as the PCH anomaly. The PCH anomaly is commonly used to measure the strength of the polar vortex (Charlton and Polvani, 2007; Kim et al., 2014; Choi et al., 2019, 2020). Fig. 4 shows the composite PCH anomaly from November to March for cold events over central Asia. During these events, the PCH shows positive anomalies in January and February, which are statistically significant at the 95% confidence level. Beginning in mid-January, the higher height anomaly in the stratosphere propagates down, appearing in the troposphere in February, although the positive height anomaly is not statistically significant in the stratosphere. Note, however, that it is significant in the troposphere from late January to early March. By contrast, the negative higher height anomaly is dominant from November to mid-December, indicating a strengthening of the westerly jet, as shown below.

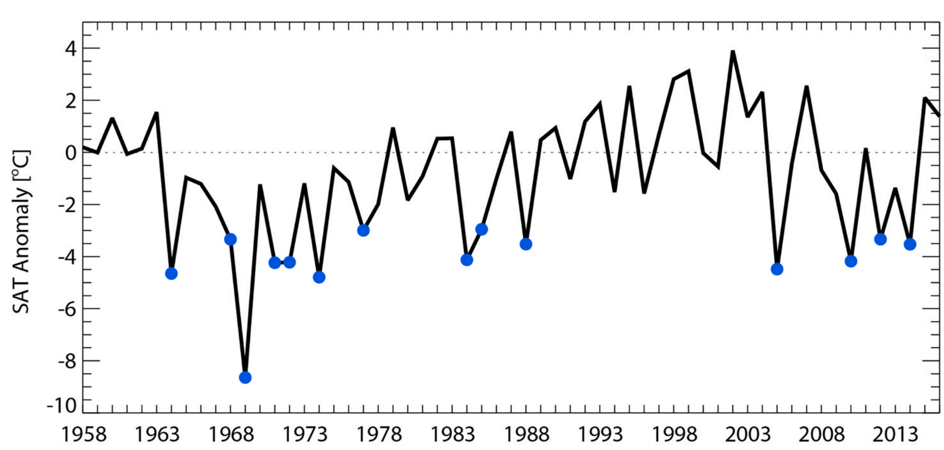

Fig. 2. Time series of SAT over central Asia (40°N–60°N/70°E−120°E, green box in Fig. 1). Blue dots show cold years with low-temperature anomalies larger than 1 standard deviation. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

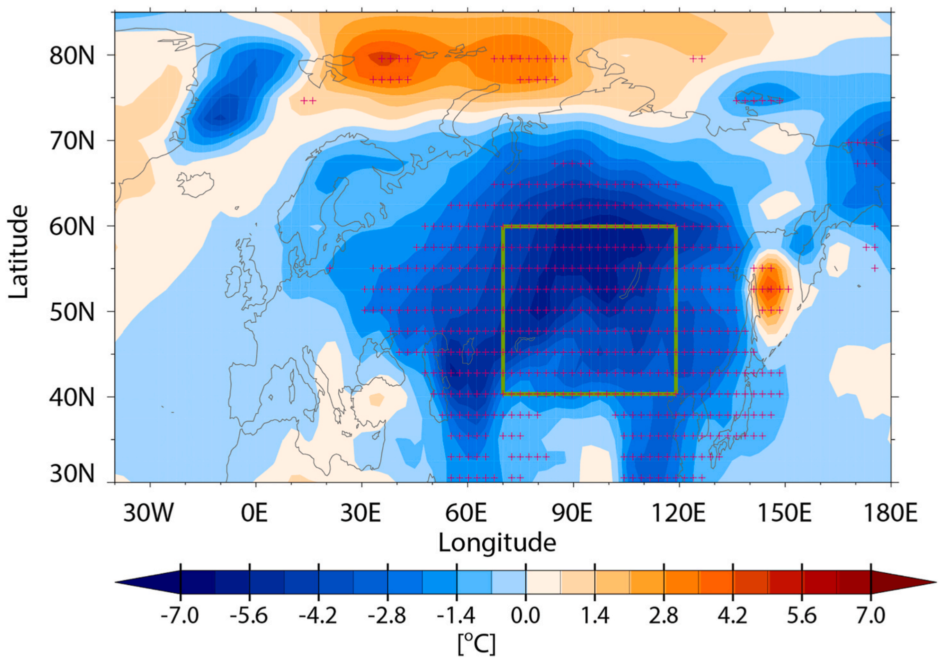

Fig. 3. Spatial distribution of SAT anomaly over central Asia for SAT reduction of more than 1 standard deviation (−2.4 °C, blue dots in Fig. 2). Crosses indicate SAT differences that are significant at the 95% confidence level. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

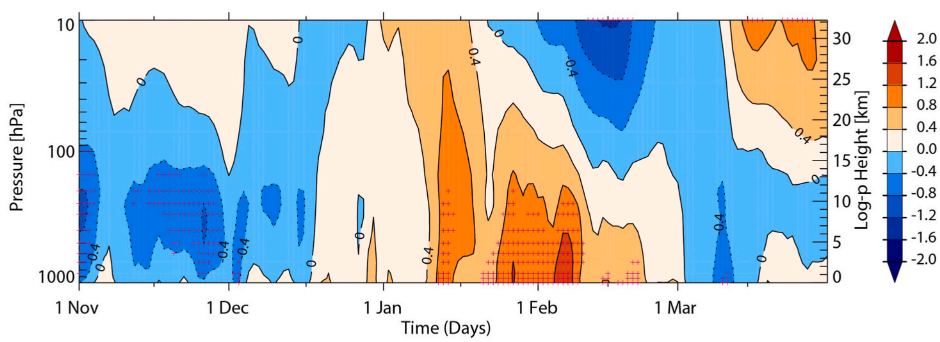

Fig. 4. Composite PCH anomaly for cold years over central Asia. Crosses indicate locations where the PCH change is significant at the 95% confidence level.

The change in PCH anomaly is well reflected in the change in zonal-mean zonal winds. Fig. 5 displays vertical cross sections of the zonal-mean zonal wind anomalies (shading) for cold event years over central Asia with monthly climatology (contours). In the climatology, the subtropical jet at approximately 30°N and 200 hPa and the polar night jet at 60°N and 10 hPa are visible. As expected from the composite PCH anomaly, in November, the zonal-mean zonal winds are stronger at the latitudes of the polar night jet, which is associated with a decrease in pressure over high latitudes relative to mid-latitudes. Note, however, that the increase in the zonal-mean zonal wind anomaly is not significant. In December, the zonal winds weaken slightly at high latitudes, whereas the zonal winds decrease more substantially on the northern rim of the subtropical jet compared to those in November. The former change is statistically insignificant, but the latter is significant. In January, the weakening of the composite zonal-mean zonal winds expands farther to high latitudes and upper levels, mainly at the location of the polar night jet. In February, the weakening of the zonal-mean zonal wind is quite substantial at approximately 60°N from the surface to the middle stratosphere. In the troposphere, the weakening is statistically significant, which is consistent with the significant increase in PCH in Fig. 4. In February, the zonal-mean zonal wind becomes stronger at subtropical jet latitudes.

Then, how does the weakening of the polar jet affect the SAT reduction over central Asia? Fig. 6 shows the distribution of the mean SLP anomaly (shading) for cold months and the monthly climatology (contours) over Eurasia. The Siberian high pressure is above 1030 hPa at 90°E and 50°N. In November and December, the SLP weakens slightly from the Arctic to southern Siberia, and the decrease is statistically significant, especially in December. Geopotential height starts to increase in stratosphere from December from the Arctic to around 50°N (not shown). From January, on the other hand, a substantial increase in SLP is found over the Arctic, especially in the BKS. The increase in SLP in January, which is consistent with the increase in PCH at the surface in Fig. 4, reaches the northeastern part of the Siberian high. In February, the SLP becomes even stronger, with maxima at the BKS and along the Ural Mountains; a positive SLP anomaly occurs across the Arctic latitudes. The strengthening of the SLP anomaly expands southward to approximately 35°N. The statistically significant strengthening of the SLP is especially large over the eastern rim of the Siberian high at approximately 120°E, i.e., along the downstream circulation branch that brings cold east Siberian air to central and eastern Asia, lowering SAT, as shown in Fig. 3.

Overall, the cold events over central Asia in February are related to the strengthening of the Siberian high, which expands from January in

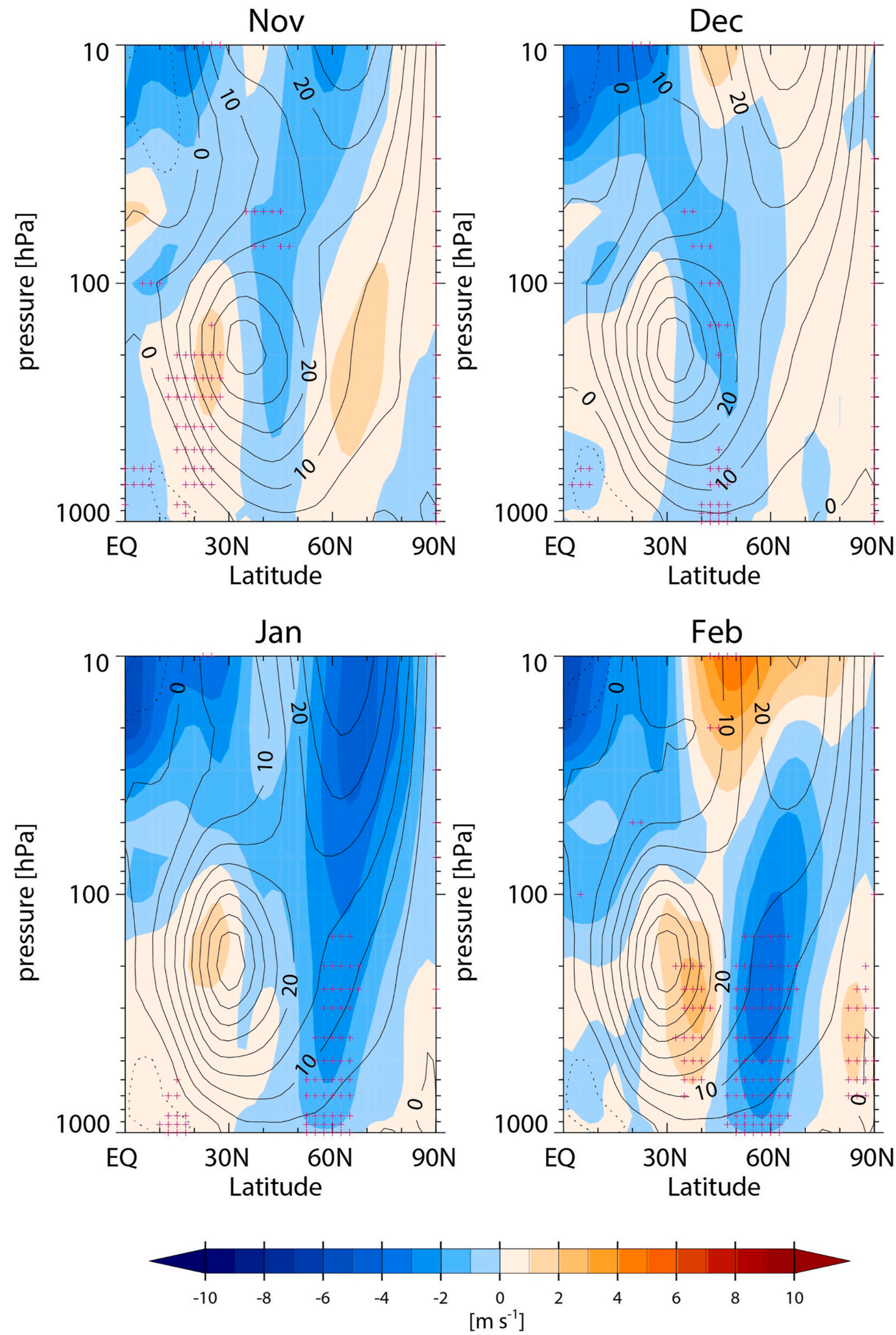

Fig. 5. Vertical cross sections of zonal-mean zonal wind climatology (contours) and anomaly for cold years over central Asia (shading). Crosses indicate locations where the zonal-mean zonal wind change is significant at the 95% confidence level.

the BKS and Ural Mountains. The increase in the Siberian high is consistent with the weakening of the zonal-mean zonal winds over high latitudes associated with the increase in PCH, which propagates down to the troposphere from the stratosphere in January.

3.3. Caveat

Several studies have reported that the warm SAT over the BKS is related to cold events over Eurasia (e.g., Kim et al., 2014; Kug et al., 2015; Mori et al., 2014, 2019). The reduction in sea ice over the BKS could contribute to the cooling over Eurasia via propagation of Rossby wave trains excited by diabatic heating (Honda et al., 2009) or via propagation of planetary waves to the stratosphere, which results in features such as sudden stratospheric warming by braking of the existing jet and subsequent poleward residual circulation that produces warming at high latitudes and an increase in geopotential height (Kim et al., 2014; Nakamura et al., 2015). Note, however, that some numerical experiments did not reproduce cooling over Eurasia in response to a reduction in sea ice over the BKS (Sun et al., 2015; McCusker et al., 2016; Cohen et al., 2020). The reason for the different responses to the reduction in BKS sea ice might be that the responses are smaller than the internal variability or that there is a missing mechanism in the stratosphere, because a high-top model reproduced the observed features better than a low-top model (Cohen et al., 2020). Overland et al. (2016) suggested

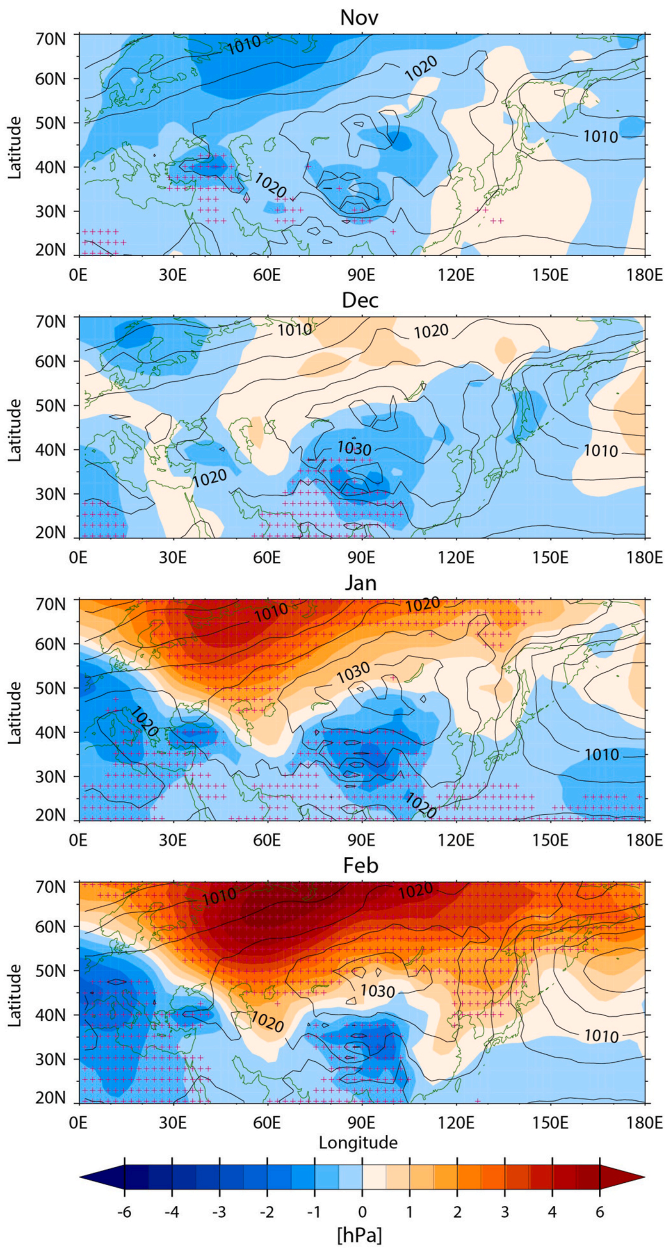

Fig. 6. SLP climatology (contours) and anomaly for cold years over central Asia (shading). Crosses indicate locations where the SLP change is significant at the 95% confidence level.

that intermittent shifts in atmospheric state might be responsible for these differing results of numerical sensitivity studies. These intermittent events are not well captured in monthly or seasonal averages.

Previous studies have suggested that sea ice reduction in the BKS and Chukchi Sea plays a role in the initiation of anticyclonic circulation anomalies, which subsequently produce cold anomalies over Eurasia and North America, respectively. However, Blackport et al. (2019) suggested that cold winters in mid-latitudes are driven not by the decrease in Arctic sea ice, but by atmospheric circulation, indicating that an increase in heat transport to the BKS drives sea ice reduction, not vice versa. Whatever the reason, the warming over the BKS seems to be quite important in driving cold events over central Asia. Guan et al. (2020) also suggested that the downward heat fluxes induced by atmospheric circulation result in sea ice reduction over the Chukchi–Bering seas, which subsequently supports the development of anticyclonic circulation over Alaska, causing cold events over North America. He et al. (2020) suggested that Eurasian cold anomalies are more frequent during deep Arctic warming, which depends on poleward energy and moisture transport, than during shallow warming resulting from sea ice loss over the BKS, indicating that internal variability and not sea ice loss is the main driver of Eurasian cold events. As mentioned above, whether the cold events over Eurasia are a response to changes in external forcing such as greenhouse gas increases and associated sea ice reduction or internal variability such as changes in atmospheric circulation remains controversial and requires further investigation using numerical models, although models have limited ability to reproduce the observed features.

4. Summary and conclusion

Cold events over central Asia in February are related to the weakening of the polar vortex, which is indicated by an increase in the PCH anomaly in the stratosphere from January. The higher PCH anomaly propagates down to the troposphere from January to February, eventually producing a cold anomaly over central Asia by enhancing the Siberian high. The strengthening of the Siberian high begins in January in the Arctic, especially the BKS and Ural Mountains. This result indicates that the increase in SAT over the BKS might be related to the increase in SLP there in January and expand to the entire region of the Siberian high.

In conclusion, the cooling over central Asia in late winter, defined here as February, depends strongly on the weakening of the polar vortex and associated strengthening of the Siberian high, which is related to the increase in geopotential height at high northern latitudes. The increase in the PCH anomaly propagates down to the troposphere from the stratosphere in January.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This study was supported by the KPOPS Project of the Korea Polar Research Institute (PE21010). We would like to thank Editage (www.editage.co.kr) for English language editing.

References

Barnes, E.A., Screen, J.A., 2015. The impact of Arctic warming on the midlatitude jet-stream: can it? Has it? Will it? WIREs Clim. Change 6, 277–286. https://doi.org/10.1002/wcc.337.

Blackport, R., Screen, J.A., van der Wiel, K., Bintanja, R., 2019. Minimal influence of reduced Arctic sea ice on coincident cold winters in mid-latitudes. Nat. Clim. Change 9, 697–704.

Blackport, R., Screen, J.A., 2020. Insignificant effect of Arctic amplification on the Amplitude of midlatitude atmospheric waves. Sci. Adv. 6, eaay2880.

Blunden, J., Arndt, D.S., 2019. State of the climate in 2018. Bull. Am. Meteorol. Soc. 100, Si–S306. https://doi.org/10.1175/2019BAMSStateoftheClimate.1.

Charlton, A.J., Polvani, L.M., 2007. A new look at stratospheric sudden warmings. Part I: climatology and Modeling Benchmarks. J. Clim. 20, 449–469. https://doi.org/10.1175/JCLI3996.1.

Choi, H., Kim, B.M., Choi, W., 2019. Type classification of sudden stratospheric warming based on pre- and postwarming periods. J. Clim. 32, 2349–2367. https://doi.org/10.1175/JCLI-D-18-0223.1.

Choi, H., Choi, W., Kim, S.-J., Kim, B.-M., 2020. Negative NAO favors the occurrence of SSW events evolving from displacement type to split type. Atmos. Sci. Lett. https://doi.org/10.1002/asl.953.

Cohen, J., et al., 2014. Recent Arctic amplification and extreme mid-latitude weather. Nat. Geosci. 7, 627–637.

Cohen, J., et al., 2020. Divergent consensuses on Arctic amplification influence on midlatitude severe winter weather. Nat. Clim. Change 10, 20–29.

Fletcher, C.G., Hardiman, S.C., Kushner, P.J., Cohen, J., 2009. The dynamical response to snow cover perturbations in a large ensemble of Atmospheric GCM Integrations. J. Clim. 22, 1208–1222.

Francis, J.A., Vavrus, S.J., 2012. Evidence linking Arctic amplification to extreme weather in mid-latitudes. Geophys. Res. Lett. 39, L06801. https://doi.org/10.1029/2012GL051000.

Gong, G., Entekhabi, D., Cohen, J., 2003. Modeled northern hemisphere winter climate response to realistic Siberian snow anomalies. J. Clim. 16, 3917–3931.

Goosse, H., et al., 2018. Quantifying climate feedbacks in polar regions. Nat. Commun. 9.

Graversen, R.G., Mauritsen, T., Tjernström, M., Källén, E., Svensson, G., 2008. Vertical structure of recent Arctic warming. Nature 451, 53–56.

Graversen, R.G., Langen, P.L., Mauritsen, T., 2014. Polar amplification in CCSM4: contributions from the lapse rate and surface albedo feedbacks. J. Clim. 27, 4433–4450.

Guan, W., Jiang, X., Ren, X., Chen, G., Ding, Q., 2020. Role of atmospheric variability in driving the "warm-arctic, cold-continent" pattern over the North America sector and sea ice variability over the Chukchi-Bering Sea. Geophys. Res. Lett. 47 https://doi.org/10.1029/2020GL088599 e2020GL088599.

He, S., Xu, X., Furevik, T., Gao, Y., 2020. Eurasian cooling linked to the vertical distribution of Arctic warming. Geophys. Res. Lett. 47, e2020GL087212 https://doi.org/10.1029/2020GL087212.

Honda, M., Inoue, J., Yamane, S., 2009. Influence of low Arctic sea-ice minima on anomalously cold Eurasian winters. Geophys. Res. Lett. 36,, L08707. https://doi.org/10.1029/2008GL037079.

Horton, D.E., Johnson, N.C., Singh, D., Swain, D.L., Rajaratnam, B., Diffenbaugh, N.S., 2015. Contribution of changes in atmospheric circulation patterns to extreme temperature trends. Nature 522, 465–469.

IPCC, 2019. Summary for policymakers. In: Pörtner, H.-O., Roberts, D.C., Masson-Delmotte, V., Zhai, P., Tignor, M., Poloczanska, E., Mintenbeck, K., Alegría, A., Nicolai, M., Okem, A., Petzold, J., Rama, B., Weyer, N.M. (Eds.), IPCC Special Report on the Ocean and Cryosphere in a Changing Climate.

Jeong, J.H., Ou, T., Linderholm, H.W., Kim, B.-M., Kim, S.-J., Kug, J.-S., Chen, D., 2011. Recent recovery of the Siberian high intensity. J. Geophys. Res. 116,, D23102. https://doi.org/10.1029/2011JD015904.

Johnson, N.C., Xie, S.P., Kosaka, Y., Li, X., 2018. Increasing occurrence of cold and warm extremes during the recent global warming slowdown. Nat. Commun. 9, 1724.

Jun, S.Y., Kim, J.H., Choi, J., Kim, S.J., Kim, B.M., An, S.I., 2020. The internal origin of the west-east asymmetry of Antarctic climate change. Sci. Adv. 6, eaaz1490.

Kim, B.M., Son, S.W., Min, S.K., Jeong, J.H., Kim, S.J., Zhang, X., Shim, T., Yoon, J.H., 2014. Weakening of the stratospheric polar vortex by Arctic sea-ice loss. Nat. Commun. 5, 4646. https://doi.org/10.1038/ncomms5646.

Kim, S.-J., Kim, B.-M., Ukita, J., 2019. How is recent Arctic warming impacting East Asian weather? Eos 100. https://doi.org/10.1029/2019EO129517.

Kalnay, E., et al., 1996. The NCEP/NCAR 40-year reanalysis project. Bull. Am. Meteorol. Soc. 77, 437–471.. https://doi.org/10.1175/1520-0477(1996)077<0437:TNYRP>2.0.CO;2.

Kim, B.M., Hong, J.Y., Jun, S.Y., Zhang, X., Kwon, H.-T., Kim, S.J., Kim, J.H., Kim, S.W., Kim, H.K., 2017. Major cause of unprecedented Arctic warming in January 2016: critical role of an Atlantic windstorm. Sci. Rep. 7, 40051.

Kug, J.-S., Jeong, J.-H., Jang, Y.-S., Kim, B.-M., Folland, C.K., Min, S.-K., Son, S.-W., 2015. Two distinct influences of Arctic warming on cold winters over North America and East Asia. Nat. Geosci. 8, 759–762. https://doi.org/10.1038/ngeo2517.

Lee, M.Y., Hong, C.C., Hsu, H.H., 2015. Compounding effects of warm sea surface temperature and reduced sea ice on the extreme circulation over the extratropical North Pacific and North America during the 2013-2014 boreal winter. Geophys. Res. Lett. 42, 1612–1618. https://doi.org/10.1002/2014GL062956.

Limpasuvan, V., Thompson, D.W.J., Hartmann, D.L., 2004. The life cycle of the Northern Hemisphere sudden stratospheric warmings. J. Clim. 17, 2584–2596.

Lü, J.-M., Ju, J.-H., Kim, S.-J., Ren, J.-Z., Zhu, Y.-X., 2008. Arctic oscillation and the autumn/winter snow depth over the Tibetan Plateau. J. Geophys. Res. 113, D14117. https://doi.org/10.1029/2007JD009567.

Manabe, S., Stouffer, R.J., Spelman, M.J., Bryan, K., 1991. Transient responses of a coupled ocean-atmosphere model to gradual changes of atmospheric CO2. Part I: annual mean response. J. Clim. 4, 785–818.

McCusker, K.E., Fyfe, J.C., Sigmond, M., 2016. Twenty-five winters of unexpected Eurasian cooling unlikely due to Arctic sea-ice loss. Nat. Geosci. 9, 838–842.

Mori, M., Watanabe, M., Shiogama, H., Inoue, J., Kimoto, M., 2014. Robust Arctic sea-ice influence on the frequent Eurasian cold winters in past decades. Nat. Geosci. 7, 869–873.

Mori, M., Kosaka, Y., Watanabe, M., Nakamura, H., Kimoto, M., 2019. A reconciled estimate of the influence of Arctic sea-ice loss on recent Eurasian cooling. Nat. Clim. Change 9, 123–129.

Nakamura, T., Yamazaki, K., Iwamoto, K., Honda, M., Miyoshi, Y., Ogawa, Y., Ukita, J., 2015. A negative phase shift of the winter AO/NAO due to the recent Arctic sea-ice reduction in late autumn. J. Geophys. Res. Atmos. 120, 3209–3227.

Overland, J.E., Francis, J.A., Hall, R., Hanna, E., Kim, S.-J., Vihma, T., 2015. The melting Arctic and mid-latitude weather patterns: are they connected? J. Clim. 28, 7917–7932.

Overland, J.E., Dethloff, K., Francis, J.A., Hall, R.J., Hanna, E., Kim, S.-J., Screen, J.A., Shepherd, T.G., Vihma, T., 2016. Nonlinear response of mid-latitude weather to the changing Arctic. Nat. Clim. Change 6, 992–999.

Peings, Y., Saint-Martin, D., Douville, H., 2012. A numerical sensitivity study of the influence of Siberian snow on the Northern Annular Mode. J. Clim. 25, 592–607.

Pithan, F., Mauritsen, T., 2014. Arctic amplification dominated by temperature feedbacks in contemporary climate models. Nat. Geosci. 7, 181–184.

Screen, J.A., Simmonds, I., 2010. The central role of diminishing sea ice in recent Arctic temperature amplification. Nature 464, 1334–1337.

Screen, J.A., Deser, C., Smith, D.M., Zhang, X., Blackport, R., Kushner, P.J., Oudar, T., McCusker, K.E., Sun, L., 2018. Consistency and discrepancy in the atmospheric response to Arctic sea-ice loss across climate models. Nat. Geosci. 11, 155–163.

Serreze, M.C., Barry, R.G., 2011. Processes and impacts of Arctic amplification: a research synthesis. Global Planet. Change 77, 85–96.

Stuecker, M.F., et al., 2018. Polar amplification dominated by local forcing and feedbacks. Nat. Clim. Change 8, 1076–1081.

Sun, L., Deser, C., Tomas, R.A., 2015. Mechanisms of stratospheric and tropospheric circulation response to projected Arctic sea ice loss. J. Clim. 28, 7824–7845.

Sung, M.-K., Kim, S.-H., Kim, B.-M., Choi, Y.-S., 2018. Interdecadal variability of the warm arctic and cold Eurasia pattern and its North Atlantic origin. J. Clim. 31, 5793–5810.

Walsh, J.E., 2014. Intensified warming of the Arctic: causes and impacts on middle latitudes. Global Planet. Change 117, 52–63. https://doi.org/10.1016/j.gloplacha.2014.03.003.

Woo, S.-H., Kim, B.-M., Jeong, J.-H., Kim, S.-J., Lim, G.-H., 2012. 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). J. Geophys. Res. 117,, D18117. https://doi.org/10.1029/2011JD016929.