A recent weakening of winter temperature association between Arctic and Asia

Bingyi Wu1,2,∗, Zhenkun Li3, Jennifer A Francis4 and Shuoyi Ding1

1 Department of Atmospheric and Oceanic Sciences/Institute of Atmospheric Sciences, Fudan University, Shanghai, People’s Republic of China
2 CMA-FDU Joint Laboratory of Marine Meteorology, Shanghai 200438, People’s Republic of China
3 Beijing MojiFengYun Technology Co., Ltd., Beijing, 100012, People’s Republic of China
4 Woodwell Climate Research Center, Falmouth, MA, United States of America
∗ Author to whom any correspondence should be addressed.
E-mail: bywu@fudan.edu.cn
Keywords: Asian winter temperature, phasic variation, Arctic–Asia linkage, Arctic sea ice loss
Supplementary material for this article is available online

Abstract
Arctic warming and its association with the mid-latitudes has been a hot topic over the past two decades. Although many studies have explored these issues, it is not clear how their linkage has changed over time. The results show that winter low tropospheric temperatures in Asia experienced two phases over the past two decades. Phase I (2007/2008–2012/2013) was characterized by a warm Arctic and cold Eurasia, and phase II by a warm Arctic and warm Eurasia (2013/2014–2018/2019). A strengthened association in winter temperature between the Arctic and Asia occurred during phase I, followed by a weakened linkage during phase II. Simulation experiments forced by observed Arctic sea ice variability largely reproduce observed patterns, suggesting that Arctic sea ice loss contributes to phasic (or low-frequency) variations in winter atmosphere and makes the Arctic–Asia temperature association fluctuate over time. The weakening of the Arctic–Asia linkage post-2012/2013 was associated with amplified and expanded Arctic warming. The corresponding anomalies in sea level pressure resembled a positive-phase North Atlantic Oscillation during phase II. This study implies that the phasic warm Arctic—cold Eurasia and warm Arctic—warm Eurasia patterns would alternately happen in the context of Arctic sea ice loss, which increases the difficulty in correctly predicting Asian winter temperature.

1. Introduction
The Arctic has always been one of the key regions affecting weather events and climate variability in the Northern Hemisphere, especially during winter, when the strong cold air mass originating from the Arctic frequently outbreaks southward, leading to severe cold waves and gale weather processes in mid-latitudes and even affecting tropical regions (Chang and Lau 1980, Wu et al 2017). For example, during 20–25 January 2016, a strong cold wave process swept across East Asia and further influenced the tropic regions, leading to more than ten people dying in Thailand. In early January 2021, affected by the Arctic storm, Texas and other places in the United States experienced a rare low-temperature and heavy-snowfall process, which directly caused interruption of the power supply over a large area (Cohen et al 2021).

Over the Arctic, the location and strength of the polar vortex largely determine the path of cold air mass outbreaking southward and its intensity. The interactions between turbulent heat fluxes induced by Arctic sea ice/sea surface temperature (SST) anomalies and atmospheric circulation could give rise to a large-scale teleconnection pattern (Peng and Whitaker 1999, Peng et al 2003, Alexander et al 2004, Deser et al 2004, Li 2004, Wu et al 2013, Screen et al 2018, Luo et al 2019b), which is the atmospheric bridge to link the Arctic to mid-latitudes. Over the past two decades, accompanied by Arctic warming and Arctic sea ice loss, the association between the
Arctic and the mid-latitudes has been enhanced as a whole (Ding et al 2008, Honda et al 2009, Screen and Simmonds 2010, Francis and Vavrus 2012, Cohen et al 2014, Mori et al 2014, Jung et al 2015, Simmonds and Li 2021). As a result, the weakened Arctic polar vortex frequently releases cold air mass into the mid-latitudes and causes extreme cold and heavy snowfall (Jaiser et al 2013, Wu et al 2017, Cohen et al 2021). Since the 1950s southern China has suffered eight extreme low-temperature disasters, of which five occurred after the late 1990s (CMA 2011).

Two key regions are found in the Arctic to affect the mid-latitudes: one is the Barents–Kara Seas and the other is the Pacific sector of the Arctic Ocean (Kug et al 2015). Warm anomalies in the two regions could cause cold anomalies over Eurasia and North America, respectively. Generally, warm anomalies over the Barents–Kara Seas are dynamically linked with blocking height anomalies over and around the Ural Mountains, which strengthen the Siberian high and East Asian winter monsoon, creating the warm Arctic—cold Eurasia pattern (Overland et al 2011, Mori et al 2014, Feng and Wu 2015, Wu 2017, Yao et al 2017, Luo et al 2017a). On the other hand, a similar warm Arctic—cold Eurasia pattern can correspond to different atmospheric regimes (Wu 2017). Furthermore, the winter atmospheric circulation anomaly associated with Arctic warm anomalies shows a closer relationship with mid- and low latitudes relative to the high latitudes (Wu 2017). Consequently, the Arctic–mid-latitude linkage is complicated.

The impacts of Arctic warming and Arctic sea ice loss on the atmosphere in mid-latitudes are a controversial topic, and conclusions vary across different studies (Petoukhov and Semenov 2010, Ding et al 2014, Mori et al 2014, Barnes and Screen 2015, Jung et al 2015, Cohen 2016, McCusker et al 2016, Sun et al 2016, Vavrus 2018, Blackport et al 2019, Warner et al 2019, Cohen et al 2020, Liang et al 2020). Cohen (2016) suggests that Arctic sea ice loss is a dominant driver of the winter Eurasian cooling trend rather than tropical forcing, but other studies attribute the trend to internal variability and/or tropical forcing (McCusker et al 2016, Sun et al 2016, Warner et al 2019). Sun et al (2016) find that Arctic sea ice loss contributes to reduced daily temperature variability and fewer cold extremes at high latitudes.

The reasons for the lack of consensus among different studies could be simply attributed to differences in data sources, analysis techniques, models, simulation experiment design, and perspectives of researchers (Francis 2017, Cohen et al 2020, Luo et al 2017b). Additionally, atmospheric responses to sea ice variability are determined not only by direct effects but also by nonlinear processes (Petoukhov and Semenov 2010), background conditions (Semenov and Latif 2015, Luo et al 2019a), the background model state (Smith et al 2019), atmospheric initial conditions (Wu et al 2016, 2017), and other factors such as tropical forcing (Sato et al 2014, Screen and Francis 2016, Warner et al 2019, Rudeva and Simmonds 2021). Consequently, it is unlikely that winter atmospheric responses to sea ice loss exhibit a particular, consistent pattern over time and space.

Atmospheric circulation itself could not produce a quasi-decadal (or an interdecadal) fluctuation; as Kellogg (1975) indicated, an interdecadal variation contains effects of Arctic sea ice and oceanic currents. Maysak et al (1990) further investigated Arctic sea ice anomalies and their relation to an interdecadal Arctic climate cycle, and they believed that Arctic sea ice anomalies are indispensable for an interdecadal self-sustained climate cycle in the Arctic. Thus, phasic (or low-frequency) variations in both Asian winter temperatures and their associations with the Arctic require that external forcing plays an important role.

It is not clear how the temperature association between the Arctic and mid-latitudes has evolved over the past two decades and what role Arctic sea ice loss plays in it. The discussion of this issue will help us understand the instability of the relationship between the Arctic and mid-latitude regions, especially the uncertainty in the impact of Arctic sea ice loss on the winter atmosphere.

2. Data and methods

Datasets used in this study included the monthly mean sea level pressure (SLP), 1000 hPa air temperature, and 500 hPa geopotential height from January 1979 to December 2019, obtained from the NCEP/NCAR reanalysis I (http://iridl.ldeo.columbia.edu/SOURCES/NOAA/NCEP-NCAR/CDAS-1/MONTHLY/).

To isolate the influence of Arctic sea ice variability on atmospheric variables, simulation experiments were carried out using the Community Atmosphere Model Version 5.4 (CAM5.4) model, which is the atmospheric component of the Community Earth System Model (CESM1.2.2). Its horizontal resolution is 1.9° × 2.5°, with 30 levels in the vertical direction (Neale et al 2012), and this model was used to investigate the impact of Arctic sea ice loss on the stratospheric polar vortex (Kim et al 2014). A 39-year control run was performed with climatological SSTs and sea ice concentrations (SICs), both derived from monthly means averaged over the period from November 1981 to February 2006 (model-derived data). The control run started on 1 January. Simulation experiments were forced by climatological monthly mean SSTs (as in the control run) and observed monthly SICs (BADC, http://badc.nerc.ac.uk/data/hadisst/) for the period of January 1979 to December 2017, and simulation experiments were repeated 39 times with different model initial conditions that were derived from 1 January of each year of the 39-year control run. In
both the control run and simulation experiments forced by observed SICs, the greenhouse gas (GHG) emissions and aerosol forcing were fixed at the year 2000, according to the data of the model itself.

The signal-to-noise ratio (SNR) is defined as the variability induced by observed Arctic SICs divided by the model internal variability. For a given spatial location, \( A_F(M, N) \) represents a variable derived from the simulation experiments forced by observed SICs, \( M \) is the sampling number of simulated phasic variations, and \( N \) is the number of simulation experiments. \( A_C(K) \) is a variable derived from the control run; \( K \) is the length of the control run

\[
\overline{A_C} = \frac{\sum_{i=1}^{K} A_C(i)}{K} \tag{1}
\]

\[
A_F(M) = \sum_{j=1}^{N} A_F(M, j) / N \tag{2}
\]

The variability forced by observed SICs:

\[
\sqrt{\frac{\sum_{i=1}^{M} (A_F(l) - \overline{A_C})^2}{M}} \tag{3}
\]

The internal variability:

\[
\sqrt{\frac{\sum_{i=1}^{M} \sum_{j=1}^{N} (A_F(i, j) - \overline{A_F})^2}{M \times N}} \tag{4}
\]

Additionally, the wavelet power spectrum analysis was applied to the reanalysis and simulated winter temperatures. The results showed that both the reanalysis temperatures and the ensemble means of simulated winter regionally averaged temperatures consistently exhibit a dominant quasi-decadal fluctuation, and their interannual cycles are secondary. This study also used the wave activity flux (WAF) (Takaya and Nakamura 2001) to describe dynamical associations between the Arctic and Eurasia.

3. Results

3.1. Phasic features of winter atmospheric circulation anomalies over the last two decades

The Barents Sea is the northernmost open sea region in the world during the winter season owing to the inflow of warm water by the North Atlantic Drift and Norwegian currents, and is a key area affecting winter atmospheric variability and cold waves in East Asia. Accompanied by Arctic warming and the rapid melting of Arctic sea ice, a ‘warm Arctic—cold Eurasia’ pattern (Overland et al 2011, Mori et al 2014, Li et al 2021) has frequently occurred over the past two decades. The winter warm anomalies occur in the Arctic region centered on the Barents–Kara Seas, while opposite anomalies are seen in East Asia, northern Africa, and parts of Europe (figure 1(a)). Additionally, positive temperature anomalies cover nearly the whole of North America. Therefore, warm Arctic—cold Eurasia is, at least in the last 40 years of observations, one of the most important manifestations of the atmospheric circulation connection between the Arctic and Asia.

To quantitatively describe the winter temperature association between the Arctic and Asia, the regionally averaged 1000 hPa temperatures over the Barents–Kara Seas (30°E−90°E, 70°N–80°N) (figure 1(b)) and over the mid- and high latitudes of Asia (90°E−120°E, 35°N−55°N) (figure 1(c)) are calculated, respectively. The correlation coefficient between the two time series is −0.38 (−0.47 after detrended) for 40 winters. Consequently, their relationship is not as close as we thought; in other words, their association may fluctuate over time. The winter temperature in the Barents–Kara Seas shows apparent interannual variability superposed on a rising trend. A low-temperature phase was dominant until the winter of 2003/2004, when the temperature shifted to a high-temperature side afterward. This change is dynamically linked with the development of the blocking high anomaly over and near the Ural Mountains and strengthening of the northern Siberian high (Feng and Wu 2015, Wu 2017).

In the mid- and high latitudes of Asia, winter temperatures exhibit apparent low-frequency fluctuations (figure 1(c)). Wavelet power spectrum analysis shows a dominant fluctuation feature with periods of 6–8 years after 2008 (at the 95% confidence level) (supplemental figure 1 available online at stacks.iop.org/ERL/17/034030/mmmedia). It is seen that low temperatures frequently occurred in 2007/2008–2012/2013 (phase I), and then the temperatures after the winter of 2012/2013 (phase II) returned to their original level as in the late 1990s, though Arctic warm anomalies persisted. This implies that the winter association between the Arctic and Asia may weaken in phase II.

Temperature anomalies averaged over phase I showed a warm Arctic—cold Eurasia pattern, with the warmest center in the Barents–Kara Seas and the coldest center in the mid- and high latitudes of Asia (figure 2(a)). Negative anomalies occupied most of East Asia, indicating an enhanced East Asian winter monsoon. The anomalous temperature pattern in the Pacific sector displayed a negative phase of the Pacific decadal oscillation, which favors Arctic warm anomalies (Screen and Francis 2016). In phase II, accompanied by a further strengthening of Arctic warm anomalies, positive temperature anomalies were also observed in most of Eurasia and the mid- and low latitudes of North America (figure 2(b)). Differences in mean temperatures between phases II and I showed positive anomalies over most of Eurasia, with negative anomalies over the mid- and high latitudes of North America (not shown). Thus, the warm Arctic—cold
Environ. Res. Lett. 17 (2022) 034030 B Wu et al

Figure 1. (a) Winter 1000 hPa temperature anomalies, derived from a linear regression on the normalized time series of the winter regionally (30°E–90°E, 70°N–80°N) averaged 1000 hPa temperature. White and black contours denote temperature anomalies at 0.05 and 0.01 significance levels, respectively. (b) Winter Arctic regionally (30°E–90°E, 70°N–80°N, outlined in green in (a)) averaged 1000 hPa temperature; the purple, red, and blue dashed lines represent the means averaged over 1979/1980–2003/2004, 2004/2005–2018/2019, and 1979/1980–2018/2019, respectively. (c) Winter Asian regionally (90°E–120°E, 35°N–55°N, outlined in green in (a)) averaged 1000 hPa temperature; the purple, red, and blue dashed lines denote the means averaged over 2007/2008–2012/2013, 2013/2014–2018/2019, and 1979/1980–2018/2019, respectively. The correlation coefficient between two time series in (b) and (c) is −0.38 (−0.47 after detrending).

Eurasia pattern in phase I was replaced by a warm Arctic—warm Eurasia pattern in phase II, leading to a weakened East Asian winter monsoon.

In phase I, positive SLP anomalies emerged over the northern North Atlantic across Eurasia to the northern North Pacific, with negative anomalies over most of Europe and the mid- and low latitudes of Asia (figure 2(c)). This anomalous SLP pattern closely resembles the atmospheric circulation anomaly associated with Arctic warm anomalies (Wu
Figure 2. (a) Winter 1000 hPa temperature anomalies (°C) averaged over 2007/2008–2012/2013, relative to the mean over 1979/1980–2018/2019. White and black contours represent anomalies at 0.05 and 0.01 significance levels, respectively. (b) As in (a) but for 2013/2014–2018/2019. (c) and (d), as in (a) and (b), respectively, but for winter SLP anomalies (hPa). (e) As in (a) but for winter 500 hPa geopotential height anomalies (gpm) superposed on the corresponding WAF (m² s⁻²). (f) As in (e), but for 2013/2014–2018/2019.

2017), corresponding to a strengthened Siberian high and a weakened Aleutian low. Although Arctic warm anomalies were further enhanced in phase II, negative SLP anomalies occupied some regions of the Arctic and resembled a positive phase of the North Atlantic Oscillation (NAO) over the northern North Atlantic (figure 2(d)). Meanwhile, positive SLP anomalies also appeared over the mid- and high latitudes of Asia. Consequently, Arctic warm anomalies are not necessarily linked to a negative phase of the NAO.
Figure 3. (a) 11-year sliding correlation coefficient of winter regionally averaged 1000 hPa temperatures between the Arctic and Asia (outlined by green lines shown in figure 1(a)). '1990' refers to the correlation coefficient for the winters of 1985/1986–1995/1996. The blue and purple dashed lines denote the correlation coefficients at 0.10 and 0.05 significance levels, respectively. (b) Evolution of correlation coefficients of winter regionally averaged 1000 hPa temperatures with sampling numbers between the Arctic and Asia (outlined by green lines shown in figure 1(a)). '2005' refers to the correlation coefficient for the winters of 1979/1980–2005/2006, and the corresponding dashed line denotes the correlation coefficients at the 0.05 significance level.

The 500 hPa height anomalies showed a tripole structure over Eurasia in phase I, and the positive anomalous center was located over the area close to the Barents–Kara Seas with two negative anomalous centers over Europe and East Asia close to Lake Baikal (figure 2(e)). The corresponding WAF originating from the Arctic propagated into the mid-latitudes of Eurasia, indicating a strengthened dynamical linkage between the Arctic and Eurasia. In phase II, however, 500 hPa positive height anomalies occupied the whole of Eurasia, and no apparent WAF propagation was observed over Eurasia, indicating a very weak linkage between the Arctic and Eurasia (figure 2(f)). In contrast to Eurasia, the linkage between the Arctic and North America was stronger in phase II relative to phase I. This may imply that an enhanced Arctic–Eurasia linkage often corresponds to a weakened Arctic–North America linkage.

3.2. A recent weakening of the association between the Arctic and Asia
Arctic warming and Arctic sea ice loss favor weakening of the polar vortex and drive its center to shift southward, which would frequently release cold air mass into the mid-latitudes and enhance the linkage between the Arctic and the mid-latitudes. Recently, however, this situation is changing, though Arctic warming has persisted.

Figure 3(a) shows an 11-year sliding correlation of the regionally averaged 1000 hPa temperatures between the Arctic and Asia. It is shown that the relationship fluctuated over time. High correlations predominantly occurred in the winters of 1994/1995–2012/2013, while the correlations were gradually weakened during the winters of 2002/2003–2018/2019. This implies that when the data include the years after the winter of 2012/2013, the Arctic–Asia linkage becomes weak. The evolution of correlation coefficients with sampling numbers (figure 3(b)) also clearly indicates that significant correlations consistently appeared after the winter of 2002/2003, and gradually weakened since the winter of 2013/2014.

3.3. Arctic sea ice loss contributes to weakening of the Arctic–Asia linkage
In this section, we explore the possible impact of Arctic sea ice loss on winter temperature through simulation experiments forced by observed Arctic sea ice variability.

The time series of simulated winter regionally (60°E–120°E, 40°N–60°N) averaged 1000 hPa temperatures and their spreads are presented in figure 4(a), derived from ensemble means of all experiments forced by observed SICs. Although different simulation experiments display great spread, their ensemble means still display obvious phasic
Figure 4. (a) Ensemble means of simulated winter regionally (60°E–120°E, 40°N–60°N) averaged 1000 hPa temperatures (°C) for 39 experiments forced by observed monthly Arctic SICs from 1979 to 2017 (blue line). Purple and red lines denote the means averaged over 2004/2005–2010/2011 and 2011/2012–2016/2017, respectively. The shaded area represents the ranges of the ensemble means ± one standard deviation of simulated regionally averaged 1000 hPa temperature for 39 experiments (right coordinate). (b) Blue line as in (a), but for anomalies relative to the mean averaged over the winters of 1979/1980–2016/2017, with the red line representing its low-frequency component with period >4.5 years. The low-frequency component accounts for 56% of the variance. (c) Simulated winter 1000 hPa temperature anomalies (°C) (the means averaged over 2004/2005–2010/2011 minus the means averaged over 1979/1980–2016/2017). (d) As in (c), but for 2011/2012–2016/2017. (e) and (f) As in (c) and (d), respectively, but for winter SLP anomalies. White and black contours represent anomalies at 0.05 and 0.01 significance levels, respectively.
Figure 5. Wavelet power spectrum analysis of the ensemble means of simulated winter regionally (60°E–120°E, 40°N–60°N) averaged 1000 hPa temperatures (°C) for 39 experiments forced by observed monthly Arctic SICs from 1979 to 2017, as shown in figure 4(a). The black dots represent spectrum values at the 95% confidence level, and the red dashed line indicates the 95% confidence level for the global wavelet spectrum.

variations. It is shown that the low-frequency components (periods > 4.5 years) of the ensemble mean temperatures account for 56% of the variance (figure 4(b)). The wavelet power spectrum analysis for figure 4(a) shows two period ranges after winter 2006/2007 that respectively correspond to 7–9 year and 2–4 year periods (both are at the 95% confidence level), indicating that low-frequency variations are the dominant features in the responses of winter temperature to Arctic sea ice loss (figure 5). Consequently, the ensemble means effectively reduce the effects of both model internal variability and initial conditions on responses. This implies that the response of winter temperature to Arctic sea ice loss is dominant in phasic (or low-frequency) variations rather than interannual variability. It is shown that the ensemble means over the winters of 2004/2005–2010/2011 (simulation phase I) were in a low-temperature state, while the means over the winters of 2011/2012–2016/2017 (simulation phase II) recovered to their original level before 2004/2005.

In simulation phase I, strong warm anomalies appear over the Siberian marginal seas, northeastern Canada, and the Okhotsk Sea, with significant cold anomalies over the mid- and high latitudes of Eurasia (north of 40°N) (figure 4(c)). Thus, the simulation experiments well reproduce the warm Arctic—cold Eurasia pattern, consistent with figure 2(a). Compared to simulation phase I, Arctic warm anomalies are further enhanced and extend southward in simulation phase II; thus positive anomalies occupy most regions north of 40°N (figure 4(d)), creating a warm Arctic—warm Eurasia pattern. As a result, the time series of the regionally averaged 1000 hPa temperatures increase markedly during phase II (figure 4(a)). These results suggest that the widespread positive anomalies over mid- and high latitudes during phase II, induced by Arctic sea ice loss (supplemental figure 2), contribute to the weakened Arctic–Asia linkage in these years. An abrupt shift in temperature anomalies over Eurasia in different phases suggests a waxing and waning of the Arctic/mid-latitude linkage during the simulated period.

The mean SLP anomalies in the two phases (figures 4(e) and (f)) support this conclusion. Simulated SLP anomalies basically resemble those based on observations in figures 2(c) and (d). Positive SLP anomalies appear in the area from Greenland across the mid- and high latitudes of Eurasia into the northwestern Pacific, with an anomalous center located over the west of the Ural Mountains in simulation phase I (figure 4(e)). Thus, both the Siberian high and East Asian winter monsoon are strengthened accordingly, dynamically consistent with the spatial distribution of cold anomalies (figure 4(c)). In contrast to simulation phase I, negative SLP anomalies emerge in the mid- and high latitudes of Eurasia and the Siberian marginal seas, the northern North Atlantic, and northeastern Canada in simulation phase II (figure 4(f)), different from a negative phase of the NAO. Consequently, Arctic sea ice loss is not necessarily linked with a negative NAO.

Because winter atmospheric circulation variability induced by Arctic sea ice loss is generally weaker relative to atmospheric internal variability, it is necessary to estimate the contributions from Arctic sea ice loss to atmospheric variability in different simulation phases. In both simulation phases, a high SNR in winter temperature is seen over the Arctic, including the Siberian marginal seas, west of Greenland to northeastern Canada, and the Okhotsk Sea, reflecting...
the direct influence of Arctic sea ice loss (figures 6(a) and (b)). During simulation phase I, there is a large area over central Eurasia south to 60° N where the SNR is greater than 0.3, while the area with SNR ≥ 0.3 apparently retreats over Eurasia during simulation phase II, reflecting a weakened impact of Arctic sea ice loss. It is noteworthy that the contour with SNR = 0.3 extends southward to 60° N during simulation phase II, indicating a strengthened impact of Arctic sea ice loss. High SNR (≥0.3) in winter SLP appears over Eurasia, the northwestern North Pacific, the central North Pacific, and most of North America during simulation phase I (figure 6(c)); thus Arctic sea ice loss can influence the mid- and low latitudes in this phase. The impacts of Arctic sea ice loss become weaker over Eurasia during phase II relative to simulation phase I (figure 6(d)). In simulation phase II, the effect of sea ice loss on North America is greater than that on Eurasia.

Simulation experiments clearly indicate that the impact of Arctic sea ice loss on winter atmospheric variability changes with time and space, and this partly explains why the impact of Arctic sea ice displays great uncertainty. On the other hand, although winter atmospheric internal variability is predominant, Arctic sea ice loss can induce phasic (or low-frequency) variations through modifying atmospheric internal variability (figure 6). This implies that the impact of Arctic sea ice loss on the winter atmosphere is more important in the phasic (or
low-frequency) variation ranges relative to interannual variability.

4. Discussions

This study explores Asian winter temperature variability and its association with Arctic warming, and then further examines the possible role of Arctic sea ice loss in the resulting variations in Arctic–Asia linkage. In fact, these issues are more complicated than we expected, and Arctic sea ice loss is just one factor contributing to the variation in Arctic–Asia association. Firstly, the El Niño and South Oscillation have been dominant factors influencing Asian winter temperature variability, and La Niña (El Niño) events generally cause cold (warm) winters in Asia (Luo et al 2021). During phase I (II), two La Niña (El Niño) events occurred in 2007/2008 (2014/2015) and 2011/2012 (2015/2016), respectively (Ren et al 2018). Secondly, Arctic warming anomalies are also linked with the mid- and low latitudes, including tropical and mid-latitude SSTs (Sato et al 2014, Screen and Francis 2016, Wu 2017). Matsumura and Kosaka (2019) also suggested that the combination of tropical Pacific cooling and Arctic sea ice loss contributes to Eurasian cold winters, consistent with the results of Wu (2017). Consequently, the Arctic–Asia linkage contains influences from the mid- and low latitudes. It is necessary to explore the relative contributions from the tropical SSTs and Arctic sea ice loss to Arctic–Asia linkage in the future. Additionally, GHG emissions and aerosol forcing may have great impacts on the model’s climate background and further influence simulation results. Thus, it is necessary to explore the possible impacts of the observed GHG emissions and aerosol forcing on the results in the future.

This study divides these winters starting from 2007/2008 into two different phases. Alternatively, 2004/2005–2012/2013 and 2013/2014–2016/2017 can also be regarded as two different phases, and the corresponding phasic anomalies in the composite are similar to those shown in figures 2(a)–(d) (supplementary figure 3).

5. Conclusions

Winter low tropospheric temperatures in the mid- and high latitudes of Asia have experienced phasic variations over the last two decades. Mean cold anomalies predominantly occurred in the winters of 2007/2008–2012/2013 (phase I) and created a warm Arctic—cold Eurasia pattern, and then this pattern was replaced by a warm Arctic—warm Eurasia pattern in the winters of 2013/2014–2018/2019 (phase II). The association of interannual temperature variations between the Arctic and Asia apparently strengthened during phase I and then weakened during phase II, though winter Arctic warm anomalies have persisted since the winter of 2004/2005.

Low-frequency fluctuations in Asian winter temperatures objectively require that external forcing plays an important role. Simulation experiments forced by observed Arctic sea ice variability largely reproduce some major features in the observational analyses and verify that Arctic sea ice loss can give rise to phasic (or low-frequency) variations in the winter atmosphere and make the Arctic–Asia temperature association fluctuate over time. The weakening of the Arctic–Asia linkage post-2012/2013 was associated with amplified and expanded Arctic warming. The corresponding anomalies in SLP resembled a positive-phase NAO during phase II. This study implies that warm Arctic—cold Eurasia and warm Arctic—warm Eurasia patterns alternately happen in the context of Arctic sea ice loss, which increases the difficulty in correctly predicting Asian winter temperature.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: http://iridl.ldeo.columbia.edu/SOURCES/NOAA/NCEP-NCAR/CDAS-1/MONTHLY/.

Acknowledgments

The authors are grateful to NCEP–NCEP for providing atmospheric reanalysis data. BW was supported by the Major Program of the National Natural Science Foundation of China (41790472), the National Key Basic Research Project of China (2019YFA0607002), and the National Natural Science Foundation of China (41730959), and J F was supported by NASA Grant NNX14AH896 and funding from the Woodwell Climate Research Center.

ORCID iD

Bingyi Wu https://orcid.org/0000-0001-8434-0739

References

Alexander M A, Bhatt U S, Walsh J E, Timlin M S, Miller J S and Scott J D 2004 The atmospheric response to realistic Arctic sea ice anomalies in an AGCM during winter J. Clim. 17 890–905
Barnes E A and Screen J A 2015 The impact of Arctic warming on the midlatitude jet-stream: Can it? Has it? Will it? WIREs Clim. Change 6 277–86
Blackport R, Screen J, Wiel K and Bintanja R 2019 Minimal influence of reduced Arctic sea ice on coincident cold winters in mid-latitudes Nat. Clim. Change 9 697–704
Chang C and Lau K 1980 Northeasterly cold surges and near-equatorial disturbances over the winter MONEX area during December 1974 Mon. Weather Rev. 108 298–312
CMA 2011 Summary of Decision Makers of Assessment Report on South China Regional Climate Change (Beijing: China Meteorological Press) pp 1–16 in Chinese
Cohen J et al 2014 Recent Arctic amplification and extreme mid-latitude weather Nat. Geosci. 7 627–37
Cohen J 2016 An observational analysis: tropical relative to Arctic influence on midlatitude weather in the era of Arctic amplification Geophys. Res. Lett. 43 5287–94
Cohen J et al 2020 Divergent consensuses on Arctic amplification influence on midlatitude severe winter weather Nat. Clim. Change 10 20–9
Cohen J, Agel L, Barlow M, Garfinkel C I and White I 2021 Linking Arctic variability and change with extreme winter weather in the United States Science 373 1116–21
Deser C, Magnusdottir G, Saravanan R and Phillips A 2004 The effects of North Atlantic SST and sea ice anomalies on the winter circulation in CCM3. Part II: direct and indirect components of the response J. Clim. 17 877–89
Ding Q H, Wallace J, Battisti D S, Steig E J, Gallant A J E, Kim H-J and Geng I 2014 Tropical forcing of the recent rapid Arctic warming in northeastern Canada and Greenland Nature 509 209–12
Ding Y H, Wang Z Y, Song Y F and Zhang J 2008 Causes of the unprecedented freezing disaster in January 2008 and its possible association with the global warming Acta Meteorol. Sin. 66 809–25 in Chinese
Feng C and Wu B Y 2013 Enhancement of winter Arctic warming by the Siberian high over the past decade Atmos. Ocean. Sci. Lett. 8 57–63
Francis J A 2017 Why are Arctic linkages to extreme weather still up in the air? Bull. Am. Meteorol. Soc. 98 2551–7
Francis J A and Vavrus S J 2012 Evidence linking Arctic amplification to extreme weather in mid-latitudes Geophys. Res. Lett. 39 L06801
Honda M, Inoue J and Yamane S 2009 Influence of low Arctic sea-ice minima on anomalously cold Eurasian winters Geophys. Res. Lett. 36 L10807
Jaiser R, Dethloff K and Handorf D 2013 Stratospheric response to Arctic sea ice retreat and associated with planetary circulation changes Tellus A 65A 19375
Jung T et al 2015 Polar-lower latitude linkages and their role in weather and climate prediction Bull. Am. Meteorol. Soc. 96 ES197–200
Kellogg W W 1975 Climatic feedback mechanisms involving the polar regions Climate of the Arctic, Geophys. Inst., Univ. Of Alaska (Fairbanks, AL; Geophysical Institute, University of Alaska) ed G Weller and S A Bowling pp 111–6
Kim B, Son S, Min S, Jeong J, Kim S, Zhang X, Shim T and Yoon J 2014 Weakening of the stratospheric polar vortex by Arctic sea-ice loss Nat. Commun. 5 4646
Kug J, Jeong J, Jang Y, Kim B, Folland C, Min S and Son S 2015 Two distinct influences of Arctic warming on cold winters in the Northern Hemisphere J. Clim. 28 5799–5807
Li M, Luo D, Simmonds I, Dai A, Zhong I and Yao Y 2021 Anchoring of atmospheric teleconnection patterns by Arctic sea ice loss and its link to winter cold anomalies in East Asia Int. J. Climatol. 41 547–58
Li S 2004 Impact of northwest Atlantic SST anomalies on the circulation over the Ural Mountains during early winter J. Meteorol. Soc. Japan 82 971–88
Li Y-C et al 2020 Quantification of the Arctic sea ice-driven atmospheric circulation variability in coordinated large ensemble simulations Geophys. Res. Lett. 47 e2019GL085397
Luo D, Luo D, Dai A, Simmonds I and Wu L 2021 A connection of winter Eurasian cold anomaly to the modulation of Ural blocking by ENSO Geophys. Res. Lett. 48 e2021GL094304
Luo B, Wu L, Luo D, Dai A and Simmonds I 2019b The winter midlatitude–Arctic interaction: effects of North Atlantic SST and high latitude-blocking on Arctic sea ice and Eurasian cooling Clim. Dyn. 52 2981–3004
Luo D, Chen X, Overland J, Simmonds I, Wu Y and Zhang P 2019a Weakened potential vorticity barrier linked to recent winter Arctic sea ice loss and midlatitude cold extremes J. Clim. 32 4235–426
Luo D, Chen Y, Dai A, Mu M, Zhang R and Simmonds I 2017a Winter Eurasian cooling linked with the Atlantic multidecadal oscillation Environ. Res. Lett. 12 125002
Luo D, Yao Y, Dai A, Simmonds I and Zhong L 2017b Increased quasi stationarity and persistence of winter Ural blocking and Eurasian extreme cold events in response to Arctic warming. Part II: a theoretical explanation J. Clim. 30 3549–57
Matsumura S and Kosaka Y 2019 Arctic–Eurasian climate linkage induced by tropical ocean variability Nat. Commun. 10 3441
Mcusker K, Fyfe J and Sigmond M 2016 Twenty-five winters of unexpected Eurasian cooling unlikely due to Arctic sea-ice loss Nat. Geosci. 9 838–42
Mori M, Watanabe M, Shiogama H, Inoue J and Kimoto M 2014 Robust Arctic sea-ice influence on the frequent Eurasian cold winters in past decades Nat. Geosci. 7 869–73
Mysak L A, Manak D K and Marsden R F 1990 Sea-ice anomalies observed in the Greenland and Labrador Seas during 1901–1984 and their relation to an interdecadal Arctic climate cycle Clim. Dyn. 5 111–33
Neale R et al 2012 Description of the NCAR Community Atmosphere Model (CAM 5.0) NCAR Technical Note NCAR/TN-486 + STR p 274 (available at: www.cesm.ucar.edu/models/cesm1.0/cam/docs/description/cam5_desc.pdf) (Accessed 2020)
Overland J E, Wood K R and Wang M 2011 Warm Arctic–cold continents: climate impacts of the newly open Arctic Sea Polar Res. 30 15787
Peng S, Robinson W A and Li S 2003 Mechanisms for the NAO responses to the North Atlantic SST tripole J. Clim. 16 1987–2004
Peng S and Whitaker J S 1999 Mechanisms determining the atmospheric response to midlatitude SST anomalies J. Clim. 12 1393–408
Petoukhov V and Semenov V A 2015 Nonlinear winter atmospheric response to the North Atlantic SST tripole J. Clim. 28 167–86
Rudeva I and Simmonds I 2021 Midlatitude winter extreme temperature events and connections with anomalies in the Arctic and tropics J. Clim. 34 3733–49
Sato K, Inoue J and Watanabe M 2014 Influence of the Gulf Stream on the Barents sea ice retreat and Eurasian coldness during early winter Environ. Res. Lett. 9 084009
Screen J, Bracegirdle T and Simmonds I 2018 Polar climate change as manifest in atmospheric circulation Curr. Clim. Change Rep. 4 383–95
Screen J and Francis J 2016 Contribution of sea-ice loss to Arctic amplification is regulated by Pacific Ocean decadal variability Nat. Clim. Change 6 856–60
Screen J and Simmonds I 2010 The central role of diminishing sea ice in recent Arctic temperature amplification Nature 464 1534–38
Semenov V A and Latif M 2015 Nonlinear winter atmospheric circulation response to Arctic sea ice concentration anomalies for different periods during 1966–2012 Environ. Res. Lett. 10 054020
Simmonds I and Li M 2021 Trends and variability in polar sea ice, global atmospheric circulations, and baroclinicity Ann. New York Acad. Sci. 1504 167–86
Smith D M et al 2019 The Polar Amplification Model Intercomparison Project (PAMIP) contribution to CMIP6: investigating the causes and consequences of polar amplification Geosci. Model Dev. 12 1139–64
Sun L, Perlwitz J and Hoerling M 2016 What caused the recent ‘Warm Arctic, Cold Continents’ trend pattern in winter temperatures? Geophys. Res. Lett. 43 5345–52
Takaya K and Nakamura H 2001 A formulation of a phase-independent wave-activity flux for stationary and migratory quasigeostrophic eddies on a zonally varying basic flow J. Atmos. Sci. 58 608–27
Vavrus S J 2018 The influence of Arctic amplification on mid-latitude weather and climate Curr. Clim. Change Rep. 4 238–49
Warner J, Screen J and Scaife A 2019 Links between Barents–Kara sea ice and the extratropical atmospheric circulation explained by internal variability and tropical forcing Geophys. Res. Lett. 47 e2019GL083679
Wu B 2017 Winter atmospheric circulation anomaly associated with recent Arctic winter warm anomalies J. Clim. 30 8469–79
Wu B, Yang K and Francis J A 2016 Summer Arctic dipole wind pattern affects the winter Siberian High Int. J. Climatol. 36 4187–201
Wu B, Yang K and Francis J A 2017 A cold event in Asia during January–February 2012 and its possible association with Arctic sea-ice loss J. Clim. 30 7971–90
Wu B, Zhang R, d’Arrigo R and Su J 2013 On the relationship between winter sea ice and summer atmospheric circulation over Eurasia J. Clim. 26 5523–36
Yao Y, Luo D, Dai A and Simmonds I 2017 Increased quasi stationarity and persistence of winter Ural blocking and Eurasian extreme cold events in response to Arctic warming Part I: insights from observational analyses J. Clim. 30 3549–68