

SHORT COMMUNICATION

Towards normal Siberian winter temperatures?

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Abstract

Siberia is a region where despite global warming a winter cooling trend has been observed over last decades. This cooling trend and its potential linkage to Arctic sea ice loss are controversially discussed. However, recent winters have not been taken into account so far. Here, we analyse ERA-Interim reanalysis data until 2017 and ERA20C reanalysis to investigate the robustness of the winter surface air temperature trends to updated and extended time periods. Our results show that winter temperatures in Siberia were above normal after 2013 leading to strongly reduced cooling trends since 1980. The trend before 2014 was dominated by four cold winters between 2010 and 2013. These cold winters were mainly caused by strong negative phases of the North Atlantic Oscillation (NAO), except for the winter 2011/2012, where the NAO was positive and a strongly negative phase of the Pacific Decadal Oscillation (PDO) in combination with low sea ice in the Barents Sea caused the cold winter. Both NAO and PDO shift from more negative to positive phases in 2014 and contribute to a return to warmer Siberian temperatures. Furthermore, the NAO shows no trend between 1980 and 2017 indicating that the suggested linkage between Arctic sea ice loss and a negative trend in this mode is not robust. However, continuously low Arctic sea ice in recent years and a slightly negative trend in the PDO since 1980 contribute to the remaining observed cold trends over parts of Eurasia between 1980 and 2017.

KEYWORDS

Arctic sea ice reduction, climate variability, North Atlantic Oscillation, Pacific Decadal Oscillation, Siberian cooling, winter temperature trends

1 | INTRODUCTION

Observations in the Arctic indicate a rapid change of climate in the last decades. The annual mean Arctic 2-m air temperature (T2m) increased by more than 2°C since 1850. Together with the warming, sea ice cover and volume have strongly decreased in the last decades (Comiso *et al.*, 2008; Devasthale *et al.*, 2013). The year 2016 showed record low ice extents in the Arctic during 7 months, and most of the year the ice extent was more than two standard deviations

below the average for 1981–2010. Also, snow cover on the sub-Arctic continents is subject to extreme changes (Brown and Robinson, 2011) and might affect local and large-scale atmospheric conditions (Cohen and Entekhabi, 1999; Gong *et al.*, 2002; Orsolini and Kvamstø, 2009; Cohen *et al.*, 2012).

Temperature over Siberia is highly variable at different timescales. Tree-ring-based reconstructions of central Asian temperature (D'Arrigo *et al.*, 2001) showed strong variations at decadal to centennial timescales. The strongest

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positive trends over 20, 50 and 100 years all fall into the 20th century. The Siberian High is the most important atmospheric centre of action in Eurasia during the winter months. Gong and Ho (2002) showed a pronounced weakening of the Siberian High during 1980–2000. This went along with a strong warming over middle- to high-latitude Asia. Gong and Ho (2002) identified the Arctic Oscillation (AO) as most important driver for Eurasian climate. In contrast to the large Eurasian warming trends in the 20th century and the recent Arctic warming, a cooling trend in winter surface air temperature has been reported over Eurasia, in particular since around 2000. This observed cooling trend has been linked to the reduction of sea ice (a review is given by Vihma, 2014) and a shift in the sea level pressure (SLP) pattern along the Eurasian Arctic coast (Wu, 2017; Wu *et al.*, 2017). Recent studies linked the negative ice trend also to a more frequent occurrence of extreme cold weather situations, particularly in Eurasia (Mori *et al.*, 2014; Gao *et al.*, 2015; Semenov and Latif, 2015), but also in North America (Francis and Vavrus, 2012; Liu *et al.*, 2012).

Although controversial, most of these studies indicated that reduced sea ice in late summer or autumn is causing a negative phase of the North Atlantic Oscillation (NAO) in the following winter and consequently colder winters over Siberia. Sea ice changes in the Barents Sea–Kara Sea area have been identified as particularly important for the impact on lower latitudes (Inoue *et al.*, 2012; García-Serrano *et al.*, 2015; King *et al.*, 2016; Koenigk *et al.*, 2016; Yang *et al.*, 2016). The winter sea ice changes themselves may also result in regional circulation response associated with Siberian cooling. The importance of the Barents–Kara Sea ice was for the first time shown by Petoukhov and Semenov (2010).

However, the observed time series of sea ice are still short and it remains uncertain if the observed linkages between sea ice and atmospheric circulation are really robust or if they might be due to natural variations (Barnes, 2013; Screen *et al.*, 2014; McCusker *et al.*, 2016; Koenigk and Brodeau, 2017; Ogawa *et al.*, 2018).

It was also suggested that the cooling over the northern continents is linked to changes in the Atlantic (Peings and Magnusdottir, 2014). Since the observational time series are still short, the observed trends could change strongly if the length of the time series changes by a few years. Here, we will extend the time series until winter 2017 and investigate the effect on Siberian winter temperature trends.

2 | DATA AND METHOD

We analyse ERA-Interim data from 1980 to 2017 (Dee *et al.*, 2011) and ERA20C reanalysis data (Poli *et al.*, 2016) from 1900 to 2010. The focus of this study is on the winter

season. As winter, we define the average over December, January and February (DJF). All trends that are discussed are based on a linear regression technique. In order to evaluate the reliability of the reanalysis data, we also used observational station data (downloaded from <http://aisori.meteo.ru/ClimateE>). To compare the temperature in the Siberian/central Eurasian box (see Figure 1) between the reanalysis data and the station data, we averaged over all stations within the box. We noticed that the temporal coverage of the weather stations within our region of interest is composed by nine stations from 1900 to 1930, increasing in the decade of 1930s until reaching 22 weather stations in 1940. The period with biggest number of stations with temperature records is 1960–2016 with around 30 weather stations.

We defined the NAO index as the leading principal component of the winter mean SLP over the region between 20°–80°N and 90°W–40°E (Hurrell, 1995).

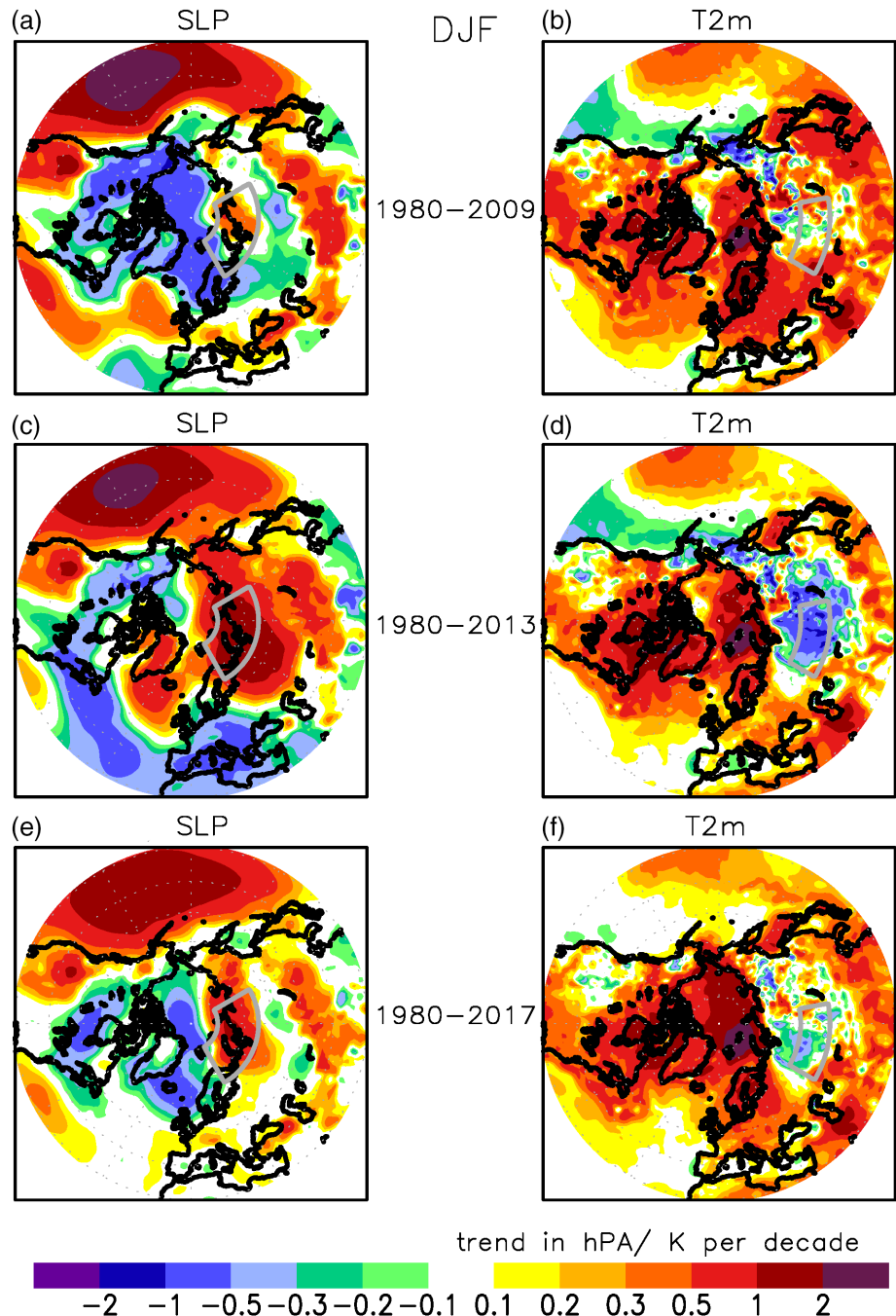
The Pacific Decadal Oscillation (PDO) index is defined as the leading principal component of North Pacific monthly sea surface temperature variability north of 20°N. For the calculation of the empirical orthogonal function, the global mean sea surface temperature (SST) climatology was first removed for each month (Mantua *et al.*, 1997).

We deliberately do not show areas with or without significant trends in Figure 1 since the time series are short and variability is large, which makes very strong trends necessary to get statistically significant values. As comparison the standard deviation of winter T2m and SLP is shown in Figure S1, Supporting Information). The main aim here is to investigate the impact of a few additional winters, and show how much inter-annual to decadal variations can affect the winter temperature trends.

3 | RESULTS

In an older study (Koenigk *et al.*, 2016), we showed trends of temperature, SLP and sea ice and their correlations between 1980 and 2013. In this study, we extended the time series by 4 years until 2017. Figure 1 shows how extension (1980–2017) and shortening (1980–2009) of the time series by 4 years affect the winter trends of T2m and SLP. The 1980–2009 SLP trend is dominated by a strong positive trend over the North Pacific and decreasing SLP over most parts of the Arctic. The only exception is the North Siberian coastal region, where slightly positive trends occur. Further to the south over subtropics to mid-latitudes of the North Atlantic, the Mediterranean region and southern central Asia, SLP trends are positive. T2m shows strong warming in most mid- and high-latitude areas but a cooling over north-eastern Siberia. The central Eurasian region that often is pointed out as the region with the largest cooling (Cohen *et al.*, 2012; Semenov, 2016) shows rather weak trends.

FIGURE 1 Winter SLP (hPa/10 years) and T2m (K/10 years) trends in ERA-Interim data between 1980–2009, 1980–2013 and 1980–2017. The boxes show the Eurasian Arctic region and Siberian/central Eurasian region that are used in Figures 2 and 4



This changes if we continue the time series until 2013 (Figure 1, middle). Now, the T2m over central Eurasia shows a pronounced negative trend. However, as shown in Ogawa *et al.* (2018), this trend is not significant at the 95% significance level. Also, the strong positive trends over most of Europe weaken. This is caused by a strongly increased positive SLP trend over northern Siberia and a trend towards negative values of the NAO index, which leads to advection of cold air masses to central Eurasia and to parts of Europe.

If we continue our time series another 4 years until 2017 (Figure 1, bottom), we find again pronounced differences in the trends. The SLP trends over the North Atlantic–Europe

region change completely again. The negative NAO-like pattern over the North Atlantic disappears, and no negative SLP trends occur over southern Europe anymore. We still see strongly positive trends over the North Pacific and over the Siberian Arctic coast but both trends are reduced compared to the 1980–2013 period. In general, we see a partly return to the trends from 1980 to 2009. This is also true for the temperature trends: the cooling over central Eurasia is reduced and the trends over Europe are enhanced again when adding the last four winters to the trend analysis. Three out of four winters in the period 2010–2013 were dominated by a strong negative NAO with related anomalously cold

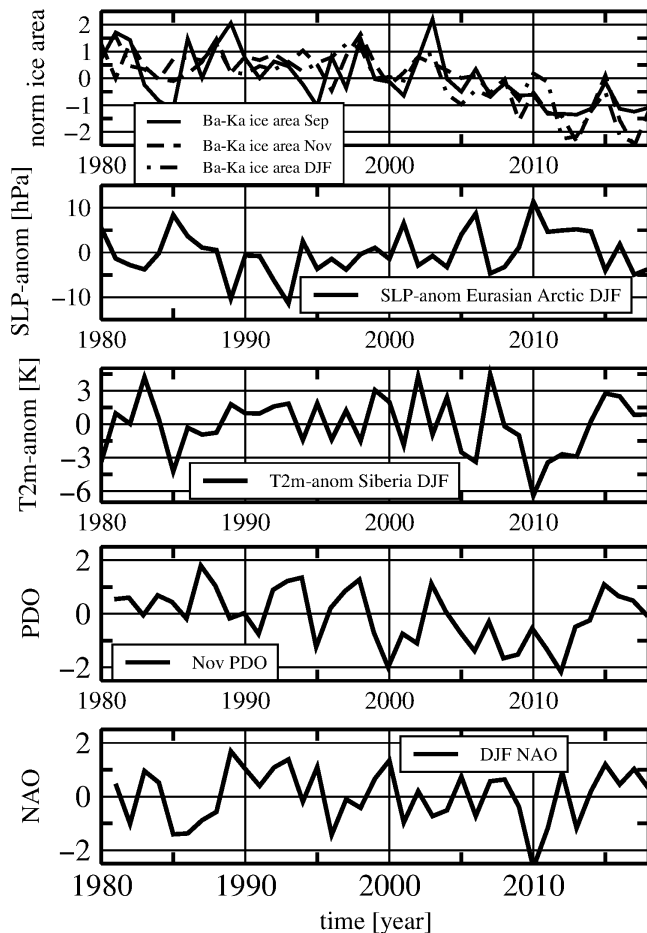


FIGURE 2 First row: Normalized November, September and winter (DJF) sea ice area anomalies in the Barents and Kara Seas, averaged over 70° – 82° N, 15° – 100° E. Second row: Winter (DJF) SLP anomalies, averaged over a box along the Eurasian Arctic coast (see Figure 1; 65° – 80° N, 30° – 120° E). Third row: Winter (DJF) T2m anomalies, averaged over a box in central Eurasia (see Figure 1; 50° – 60° N, 60° – 100° E). Fourth row: Normalized November PDO index. Fifth row: Normalized winter (DJF) NAO index

winter T2m over almost entire Eurasia. In the winter 2011/2012, an unusual SLP pattern with negative SLP anomalies over the Nordic Seas (and positive NAO index) but strong positive SLP anomalies over western Siberia occurred. The period 2014–2017 was dominated by a positive NAO with warm winters in most of Eurasia (S2). Only, a small region along the Siberian Arctic coast does not show negative SLP anomalies. As we will discuss further down, this might be an effect of the reduced sea ice in the Barents Sea–Kara Sea area. Interestingly, the comparison of the anomalies in 2010–2013 and 2014–2017 shows that both the Arctic and central Eurasia were much colder in 2010–2013 than in 2014–2017. Thus, it might be misleading to call the observed trend pattern a “warm Arctic–cold Siberia” pattern (Overland *et al.*, 2011; Inoue *et al.*, 2012). At least compared to the trend 1980–2017, both Siberia and the Arctic

were colder in the cold Eurasian winter years 2010–2013 than in the warm winter years 2014–2017.

Many studies linked the cooling trend over Asia to the Arctic sea ice reduction and particularly the ice reduction in the Barents–Kara Sea area (Vihma, 2014). Figure 2 shows the autumn and winter sea ice extent in the Barents–Kara Seas region, the winter SLP in a northern Eurasian coastal area with large positive SLP trends between 1980 and 2013 (averaged over 65° – 80° N, 30° – 120° E, see box in Figure 1), the winter T2m in a central Eurasian area with strong negative winter trends between 1980–2013 (averaged over 50° – 60° N, 60° – 100° E, see box in Figure 1) and PDO and NAO indices. The sea ice area is strongly reduced since the end of the 1990s. However, SLP over the northern Eurasian coastal region shows only a large increase between 2010 and 2013. This leads to the strong cooling over central Eurasia in these winters, and these four cold winters in a row explain most of the negative T2m trend over Asia until 2013. After 2014, both SLP and T2m return to normal values or show even negative SLP and positive T2m anomalies, respectively. This return to normal values despite continuously low autumn and winter Arctic and Barents–Kara Seas ice extents seems to indicate that sea ice does not provide the main feedback on the circulation, which leads to the central Eurasian cooling.

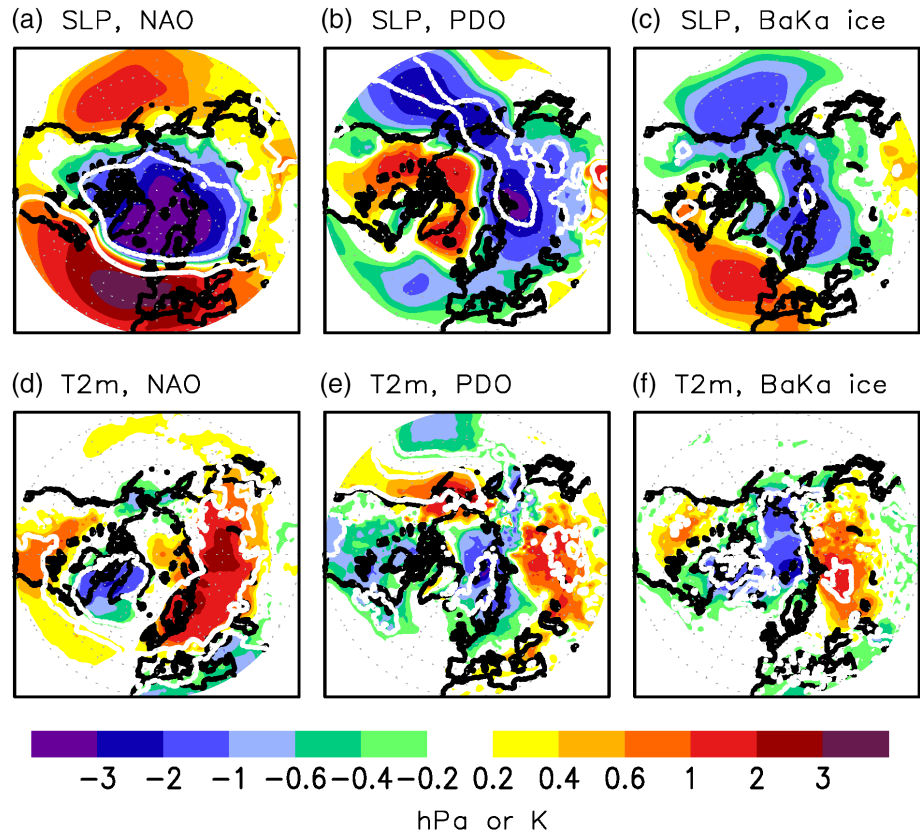
Previous studies indicated that the NAO (Hurrell, 1995; Osborne, 2006), the PDO (Kim *et al.*, 2018) and Barents–Kara Seas ice area (Inoue *et al.*, 2012; García-Serrano *et al.*, 2015; Koenigk *et al.*, 2016) all could affect winter Siberian SLP and T2m.

This is supported by the regression analysis in Figure 3. The NAO seems to be most important for SLP and T2m variations over Eurasia and the correlations between NAO and coastal northern Eurasian SLP (correlation coefficient $r = -.69$) and central Asian T2m ($r = .71$) are much higher than for PDO and Arctic sea ice. Figures 1–2 and S2 show that winters after 2013 were mainly dominated by positive NAO patterns, while the NAO was negative (except for 2012) in the years before 2014. This shift in the NAO explains a large part of the return to warmer winters over Eurasia.

However, since the NAO does not show any trend over the 1980–2017 period, the NAO cannot explain the remaining trends in coastal northern Eurasian SLP and central Eurasian T2m. However, when discussing the NAO link to sea ice and high-latitude climate, it is important to understand that this link is non-stationary and may change from strong positive correlations to even negative ones with temperature both in observations and climate models (Semenov, 2008; Smedsrud *et al.*, 2013; Koenigk and Brodeau, 2017).

As the NAO, the PDO regime shifted 2013–2014 from a cold PDO regime towards a warm PDO regime, in coincidence with the changes in central Eurasian T2m. As the

FIGURE 3 Regression between winter SLP and normalized indices of (a) winter NAO, (b) November PDO, (c) November ice are in Barents and Kara Seas in ERA-Interim data for 1980–2017. (d–f) The same as (a–c) but for T2m. White lines indicate the 95% significance level



regression pattern in Figure 3 reveals, a PDO change is connected to decreased SLP over coastal Eurasia and increased T2m in central Eurasia. A return of the PDO towards more neutral or positive states is connected to a reduction of the positive SLP anomaly at the Siberian coast and thus to a reduction of cold air advection to Siberian and consequently warmer temperatures over central Eurasia. Thus, it is likely that also the shift in the PDO contributed to a return to warmer Siberian winters. This finding is in line with results by, for example, Tokinaga *et al.* (2017), who showed that both Atlantic and Pacific variations played a governing role in the early 20th century Arctic warming, which was linked to reduced SLP at the Siberian Arctic coast and wide spread warming over Siberia.

Despite the shift to positive PDO regimes, the PDO trend since 1980 remains slightly negative (although not significant) and contributes to a negative T2m trend over central Eurasia. The PDO regression patterns on SLP and T2m (Figure 3b,e) agree relatively well with the observed trend patterns of winter SLP and T2m (Figure 1e,f). To further verify a potential impact of the PDO on the Eurasian temperature trend, we focus on winters, which are characterized by a combination of near neutral NAO values (between -0.3 and 0.3 in the normalized NAO time series) and positive and negative phases of the PDO, respectively, in the ERA20C time series from 1900 to 2010. Although largest responses in winter SLP and T2m are somewhat moved towards the west compared to the

trend and regression patterns (Figures 1 and 3), there is clear relation between PDO and Eurasian winter temperature in the ERA20C time period 1900–2010 (Figure S3). A recent model study from Kosaka and Xie (2013) found that equatorial Pacific SST is very important for the observed warming trend in northern parts of Eurasia but has limited impact on the observed winter cooling in central Eurasia.

The sea ice in the Barents–Kara Seas shows a smaller and less significant impact on coastal Eurasian SLP and central Eurasian T2m (Figure 3c,f) but has a very strong negative trend, thus supporting negative trends in the central Eurasian T2m and positive SLP over coastal Eurasia as well. Thus, sea ice trends in the Barents–Kara Seas might be a contributing factor to the remaining cold trend over parts of Eurasia as well. As also Figure S3 indicates, the November sea ice in the Barents–Kara Seas is significantly correlated with the November PDO ($r = .43$ for 1980–2017 in ERA-Interim).

In the following, we investigate if the occurrence of the four cold Eurasian winters is unusual in a longer time perspective. Figure 4 shows the T2m in the central Eurasian box in the ERA20C-reanalysis data and in station data. T2m shows a weak negative trend until around year 1970, superimposed by strong inter-annual and decadal variations. This negative trend is slightly stronger in January and February than in December. After 1970, T2m is strongly increased until year 2000, and thereafter decreased again until year 2013 before values returned to year 2000 level in

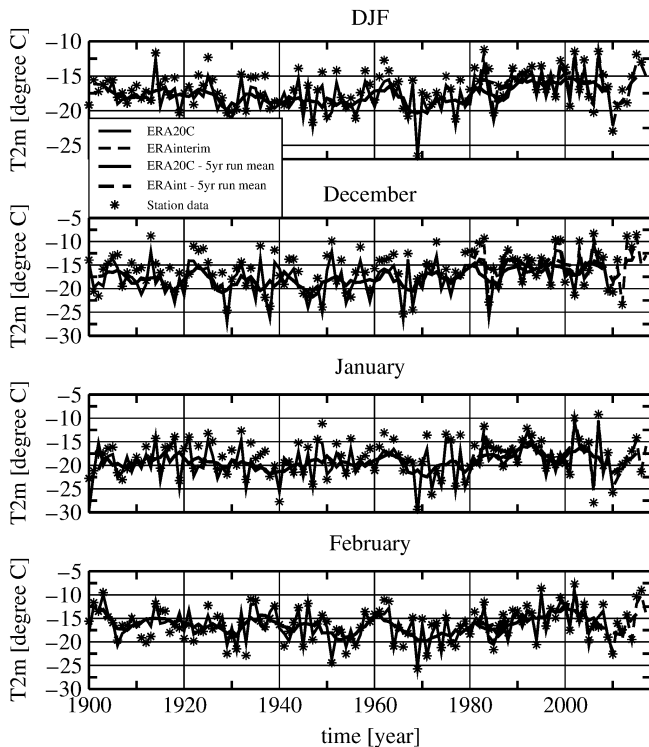


FIGURE 4 T2m, averaged over the central Eurasian box (see Figure 1; 50°–60°N, 60°–100°E) in ERA20C, ERA-Interim and in observations from station data (<http://aisori.meteo.ru/ClimateE>)

recent years. The winter 2010 is one of the coldest winters since year 1900 and the coldest in the ERA-Interim period 1980–2017, while the winters 2011–2013 are not sticking out as especially cold. If we look at single winter months, we see that February 2010 was likely the third-coldest February since 1900. Also Januaries 2006 and 2010, February 2010 and December 2012 were very cold months but not record-cold. The winter 2009/2010 is particularly cold since both January and February were very cold. Most other cold winters are dominated by one single very cold month and 2 months that are normal or slightly below normal. In this context, winter 1968/1969 sticks out with record-cold January and February and also a cold December. Similar to the cold winters, the warm recent winters were dominated by one very warm month: December 2015 and 2013 were the warmest and third warmest Decembers since 1900 and February 2016 was very warm as well. The results from the ERA20C data show a good agreement to the observations from the stations. Even before 1980, the agreement is large and the coldest and warmest winters are well reproduced. ERA20C data seem to be somewhat colder in the first decades than station data in December and the year-to-year variability is somewhat underestimated.

Also, the 5-year running mean winter T2m around 2010 is not unusual cold in a longer time context. However, it is the only period with four cold winters in a row, and the

period shows the largest drop of temperature compared to the 30-year average background temperature.

The winters after year 2000 show rather large inter-annual variations. This might be in line with findings by Francis and Vavrus (2012) that the amplitudes of Rossby waves are getting larger and waves are propagating slower leading to longer and more extreme temperature periods. However, time periods are short and single winter months showed also high inter-annual variations between the end of the 1960s and 1970s.

4 | CONCLUSIONS

We showed evidence that the strong negative winter temperature trends over central Eurasia between 1980 and 2013 were mainly due to four cold winters between 2010 and 2013. Particularly, the winter 2010 belonged to the coldest winters since 1900 and the occurrence of four cold winters in a row is unusual in the historical context. After 2013, central Eurasian temperature returned to normal or even above normal temperatures in winter, and the negative trend over the whole period from 1980 to 2017 is small, although still negative. This indicates that a large part of the observed trend since 1980 is due to natural variability, which is in line with recent results from a multi-model study by Ogawa *et al.* (2018) and results from long coupled climate simulations with the EC-Earth model (Koenigk and Brodeau, 2017). Both studies found large variability in the trends at 30-year timescales between different model simulations but no general cooling trend over central Eurasia.

In contrast to the Siberian winter temperature, the Arctic sea ice did not return to normal values after 2013 but continued to stay low. This indicates that the feedback of autumn Arctic sea ice on the circulation and Asian temperature is probably weaker than anticipated by previous studies. However, as shown by a number of studies (Petoukhov and Semenov, 2010; Semenov and Latif, 2015; Yang and Christensen, 2012), links between sea ice and circulation are non-stationary and the circulation response to sea ice forcing is nonlinear. We further showed that the NAO does not show any negative trend if we take the entire period 1980–2017 into account. Also, this finding is in agreement with the multi-model ensemble simulations by Ogawa *et al.* (2018) and indicates that the linkage of the NAO to the Arctic sea ice is likely weak. The return of the NAO from a mainly negative phase to its positive phase is the main reason for the return of Siberian temperature to normal values. It explains as well the increasing warming trends over large parts of Eurasia since 2013. In addition, the PDO switched rapidly from year 2013 to 2014 from its cold phase to the warm phase. This contributed to a warming over the central Eurasian region.

However, despite a reduction of the positive winter SLP trend over northern Eurasian coastal areas in recent years, the

positive SLP trend is still relatively large in this region. Since the NAO does not show any trend over 1980–2017, the NAO cannot be the driver for this positive SLP trend and the related remaining small negative T2m trend in central Eurasia. Although the negative sea ice trend does not significantly affect the NAO, it might affect SLP trends in this Siberian coastal region as a regression analysis between the sea ice and SLP revealed. Furthermore, the slightly negative trend of the PDO over the entire period 1980–2017 contributes to positive SLP trends over coastal Siberia. The high SLP here explains the remaining small negative winter T2m trend over central Eurasia despite increased greenhouse gas warming.

A combination of negative NAO, cold PDO regime and low sea ice in the Barents–Kara Sea region explain the wide spread winter cooling signal over Eurasia until 2013, and the return to both positive NAO and warm PDO regimes the switch back to more normal temperatures over central Eurasia.

In recent years, both winter months with very cold temperatures and with record warm temperatures occurred in central Eurasia. This might be in line with findings of Francis and Vavrus (2012) suggesting a wavier and slower propagation of Rossby waves. However, time series are still too short to conclude that winter-to-winter variations or the occurrence of extreme temperature periods over central Eurasia are increasing.

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