Acta Oceanol. Sin., 2017, Vol. 36, No. 11, P. 51–60
DOI: 10.1007/s13131-017-1137-5
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Investigation of Arctic air temperature extremes at north of 60°N in winter

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Received 11 May 2017; accepted 3 July 2017

Abstract

Air temperature is a key index reflecting climate change. Air temperature extremes are very important because they strongly influence the natural environment and societal activities. The Arctic air temperature extremes north of 60°N are investigated in the winter. Daily data from 238 stations at north of 60°N from the global summary of the day for the period 1979–2015 are used to study the trends of cold days, cold nights, warm days and warm nights during the wintertime. The results show a decreasing trend of cold days and nights (rate of –0.2 to –0.3 d/a) and an increasing trend of warm days and nights (rate of +0.2 to +0.3 d/a) in the Arctic. The mean temperature increases, which contributes to the increasing (decreasing) occurrence of warm (cold) days and nights. On the other hand, the variance at most stations decreased, leading to a reduced number of cold events. A positive AO (Arctic Oscillation) index leads to an increased (decreased) number of warm (cold) days and nights over northern Europe and western Russia and an increased (decreased) number of cold (warm) days and nights over the Bering Strait and Greenland. The lower extent of Arctic autumn sea ice leads to a decreased number of cold days and nights. The occurrences of abrupt changes are detected using the Mann-Kendall method for cold nights occurring in Canada in 1998 and for warm nights occurring in northwestern Eurasia in 1988. This abrupt change mainly resulted from the mean warming induced by south winds and an increased North Atlantic sea surface temperature.

Key words: extreme temperature events, trend analysis, abrupt change analysis, composite analysis

Citation: Sui Cuijuan, Zhang Zhanhai, Yu Lejiang, Li Yi, Song Mirong. 2017. Investigation of Arctic air temperature extremes at north of 60°N in winter. Acta Oceanologica Sinica, 36(11): 51–60, doi: 10.1007/s13131-017-1137-5

1 Introduction

The climate change tends to be stronger in the Arctic than globally or for any other specific region due to multiple positive feedbacks (Serreze and Barry, 2011; Stroeve et al., 2012) —a phenomenon known as the Arctic amplification. An annual mean near-surface air temperature change in the Arctic is as much as twice the global average value and is more than 1.5°C higher than the average value during 1971–2000 (Overland et al., 2013). Despite this mean temperature increase, an apparently large number of cold extremes have occurred at the Northern Hemisphere mid-latitudes over the past decade. Studies have shown that the Arctic amplification associated with diminishing sea ice and snow cover is altering the polar jet stream and increasing temperature variability (e.g., Francis et al., 2009; Francis and Vavrus, 2012, 2015; Tang et al., 2013). Overland et al. (2011) proposed a "warm Arctic, cold continents" mechanism caused by the Arctic amplification and the coupled changes in the sea ice and snow cover.

It is obvious that the natural environment, society, economy and human health are more vulnerable to extreme climate events than to the mean climate (Easterling et al., 2000). Extreme weather and climate events have severe consequences for the natural environment, society, economies, and human health (e.g., Yu et al., 2016). In particular, extreme temperatures affect society and ecosystems more than other types of extreme events. A shift in a mean temperature can lead to a broadening of the distribution of certain types of temperature extremes (Kodra and Ganguly, 2014; Screen, 2014). Because of this, several studies have analyzed the extreme temperature events at the mid-latitudes (Robeson, 2004; Vincent et al., 2005; Huang and Qian, 2008; Brown et al., 2010; Wang et al., 2012; Long et al., 2012; Cohen, 2014; Yang et al, 2016). Alongside this work, knowledge of the Arctic extremes themselves and their developments is also of highly relevant to society, however, our understanding of the regional trends of the Arctic weather and climate extremes remains poor owing to the lack of data in this region. In fact, the Arctic temperature extreme events are also of high societal relevance and can strongly influence an ecological environment and produce great challenges for

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Foundation item: The Chinese Polar Environment Comprehensive Investigation and Evaluation Program under contract No. CHINARE2016-04-04; the Public Science and Technology Research Funds Project of Ocean under contract No.201505013; the National Natural Science Foundation of China under contract No. 41576029.

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infrastructure (Rennert et al., 2009; Yu et al., 2017). Hence, it is necessary to investigate the changes and variability of the Arctic extreme temperature events.

Matthes et al. (2015) revealed that the temporal evolutions and variabilities of warm and cold spells in the winter and summer from 1979 to 2013 showed distinct interannual and decadal variabilities, and air temperature trended vary enormously with geographic location. However, Matthes et al. (2015) did not present a reason for this trend, and they used two indices (cold spells, warm spells). Extending the data of Matthes et al. (2015) to 19 February 2016 and defining four extreme temperature indices (cold days, cold nights, warm days and warm nights), we focus on the trends of, and potential reasons behind, the extreme temperatures in the Arctic winter. Section 2 describes the data and methods used in our study, including how we defined the extreme events. The results of the trend analysis and the possible reasons for the trends are presented in Section 3. A discussion and summary conclude the paper in Section 4.

2 Data and methods

Various approaches have been used to describe the extreme temperature events, including the total number of frost days, the intraannual extreme temperature ranges; the length of the growing season, the heat-wave duration index (Frich et al., 2002); the warmest day, the coldest day, and the number of warm days, cold days, cold nights and warm nights (Vincent et al., 2005). In the present study, the daily maximum and minimum temperature data north of 60°N were derived from the “Global summary of the day” (GSOD) data set, processed and distributed by the National Climate Data Center (www.ncdc.noaa.gov/oa/mpp/freedata.html). The wintertime (December, January and February) data from the 238 stations during the period 1979–2015 were then used to calculate a variety of temperature indices. We chose only stations with less than 40% of their data missing during every winter to calculate the extreme temperature events. Large-scale atmospheric circulation patterns during 1979–2015 were identified using the global monthly ERA-interim reanalysis data set produced by the European Centre for Medium-range Weather Forecasts (Dee et al., 2011; http://www.ecmwf.int/en/research/climate-reanalysis/era-interim), which has a horizontal resolution of 0.75° × 0.75°. The ocean data set over the same period was derived from AVHRR (advanced very high resolution radiometer) data, which have a horizontal resolution of 0.25° × 0.25°. The monthly AO index and the Arctic sea ice extent are available from the websites at http://www.cpc.ncep.noaa.gov/products/precip/ CWlink/daily_ao_index/ao.shtml and ftp://sidads.colorado.edu/ DATASETS/NOAA/ G02135/.

Four temperature indices are selected, and their descriptions are given in Table 1. All the wintertime daily maximum temperature data for the entire study period of 1979–2015 are used to derive a distribution of the daily maximum temperatures. The 90th (95th) percentile of the distribution is used as a threshold for warm days. In other words, a daily maximum temperature in the winter is considered as belonging to a warm day when it exceeds the specified threshold. In addition, the 10th (5th) percentile of the distribution is used as a threshold for extreme cold events. A day is considered a cold day when the daily maximum temperature in winter is less than the specified threshold. A similar process is applied to the daily minimum temperatures to obtain the wintertime warm nights and cold nights.

Table 1. Definitions of the temperature indices used in this study

Variable	Indicator name	Definition	Unit
T_{max}	warm days	No. of days with the daily maximum temperature being greater than 90th (95th) percentile	day
	cold days	No. of days with the daily maximum temperature being less than 10th (5th) percentile	day
T_{min}	warm nights	No. of days with the daily minimum temperature being greater than 90th (95th) percentile	day
	cold nights	No. of days with the daily minimum temperature being less than 10th (5th) percentile	day

Note: T_{max} and T_{min} are the daily maximum and minimum temperatures, respectively.

Trend analyses were conducted to identify the inter-annual variability of the wintertime extreme temperature events. The Mann-Kendall trend test (Mann, 1945; Kendall, 1955) is one of the widely used nonparametric tests that detect significant trends in time series. If the two lines (UF and UB statistics) intersected and an intersection point occurs between the critical lines (when significance is 0.05, the critical line is between –1.96 and 1.96), then the point of intersection corresponding to time is the mutations. In this paper, we use the Mann-Kendall test analysis to determine the abrupt changes in cold days, cold nights, warm days and warm nights. In addition, a composite analysis was used to explore the possible reasons behind the extreme temperature events. The statistical significance of the trends was tested at the 95% confidence level using Student’s *t*-test.

3 Results

3.1 *Trends in the extreme temperature indices in the Arctic*

Figure 1 shows that the number of cold days and nights decreased significantly in multiple regions, including Norway, Sweden, Greenland, northeastern Canada and northeastern Russia, where the trends ranged from –0.2 to –0.3 d/a. However, it is worth noting that there was an increase in cold events at three stations in northwestern Russia and one station in Victoria in Canada; the trends at these stations were between 0.2 and 0.3 d/a. The trends in the warm days and the warm nights significantly increased in Norway, Finland and northwestern Russia, as well as small parts of Canada, with a range from 0.2 to 0.3 d/a. However, the number of stations with the significant trends of the warm events was smaller than that of the old events. In summary, the results show a rising trend of the warm days and nights and a declining trend of the cold days and nights in the Arctic.

We also studied the trends of cold and warm events using the 5th and 95th percentile thresholds (Fig. 2). In contrast to the results shown in Fig. 1, the number of significant stations for trends of cold days and nights decreased, especially in northern Europe. Compared with the results using the 10th and 90th percentiles, both the number of stations with significant changes and the magnitude of the trends of the warm events decreased. An increase in the warm events was only found over the Arctic Ocean

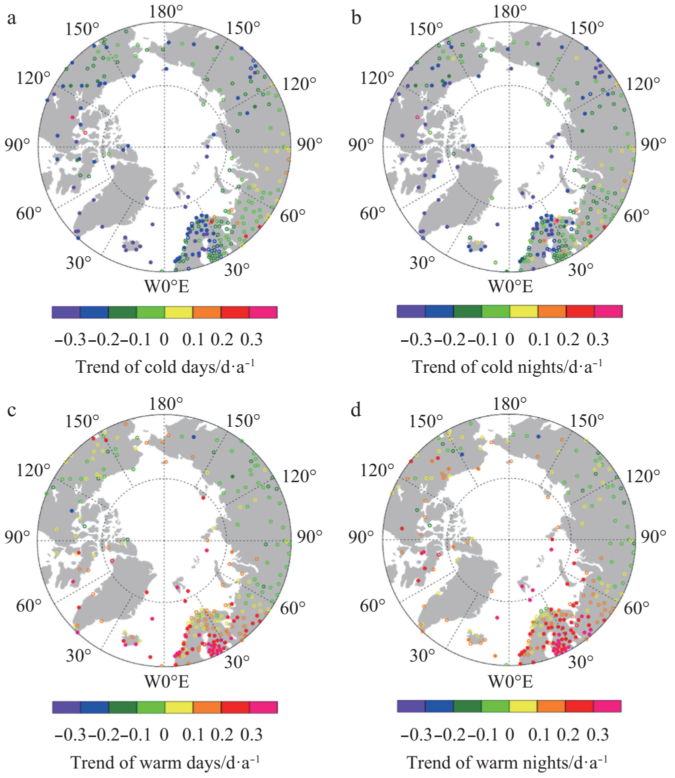

Fig. 1. Trends of wintertime extreme events during the period of 1979–2015 in the Arctic. a. Cold days, b. cold nights, c. warm days, and d. warm nights. The stations with statistically significant results at the 95% confidence level are shown as solid circles. The 10th and 90th percentiles are used in the definitions of extreme events.

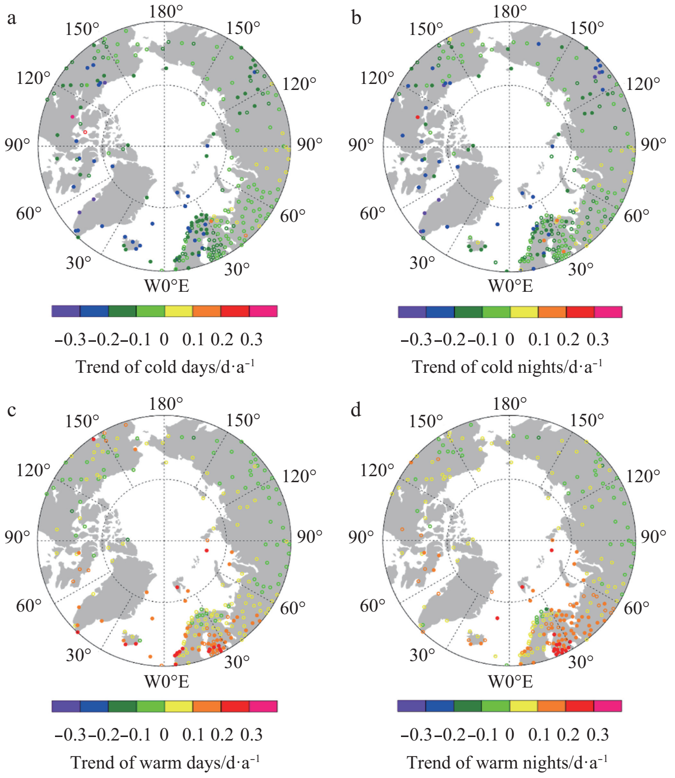

Fig. 2. Trends of wintertime extreme events during the period of 1979–2015 in the Arctic. a. Cold days, b. cold nights, c. warm days, and d. warm nights. The stations with statistically significant results at the 95% confidence level are shown as solid circles. The 5th and 95th percentiles are used in the definition of the extreme events.

and northern Europe, with a magnitude of 0.2 d/a. Although the values were different, the spatial patterns of the trends of the extreme temperature events measured using the different thresholds were similar, so only the results derived from the 10th/90th percentile thresholds were analyzed.

Kodra and Ganguly (2014) noted that the shift in the mean value, increased variability, and changed symmetry for a certain distribution can influence the tail of the distribution. They suggested that the “shifted mean” is an increase in the entire probability distribution of temperatures, leading to an increase in the distribution of the extreme warm events. In addition, “increased variability” is a symmetric widening of the variability of temperature, leading to the intensifications of the extreme cold and warm events in both tails. In this study, the mean and variance of the maximum and minimum temperatures were examined, and the relative contributions to the trend in the temperature extremes were analyzed. Figure 3 reveals a significant increasing trend in the mean wintertime maximum and minimum temperatures in northern Europe, Greenland, and some islands in the northern Atlantic Ocean, which would have favored an increasing (decreasing) occurrence of warm (cold) days and nights in these regions. The data for most of the stations indicate a decreasing trend in the variances of the wintertime maximum and minimum temperatures, consistent with the conclusions of Screen (2014), leading to a reduction in cold events.

In addition, to investigate the impact of the AO index and the extent of the Arctic sea ice on the Arctic extreme temperature events north of 60°N in the winter, correlation analyses were performed. Figure 4 shows the correlation coefficient between the wintertime AO index with cold days (a), cold nights (b), warm days (c), and warm nights (d) and displays only the stations that pass the 95% significance level threshold. For cold days and nights, significantly negative correlations occur over northern Europe and western Russia, and significantly positive correlations occur over the Bering Strait and Greenland. For warm days and nights, northern Europe and Russia show significant positive correlations, and eastern Canada and Greenland show significant negative correlations. Over northern Europe and the western Russia, a positive AO index leads to an increased (decreased) number of extreme warm (cold) temperature events, while the opposite occurs over the Bering Strait and Greenland. Yu et al. (2017) noted that the anomalous wintertime temperature ex-

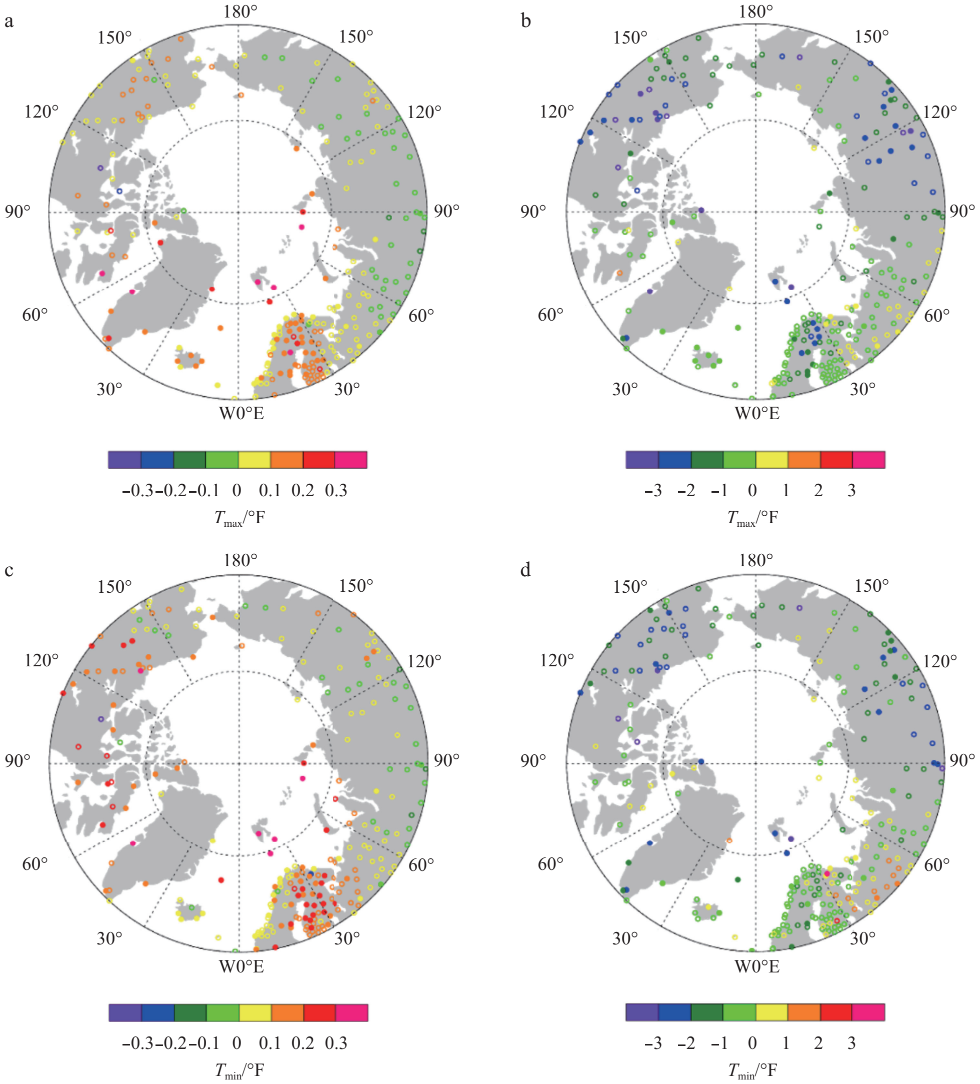

Fig. 3. Trends of wintertime means and variances of maximum (a and b) and minimum temperature (c and d) during the period of 1979–2015 in the Arctic. The stations with statistically significant results at the 95% confidence level are shown as solid circles.

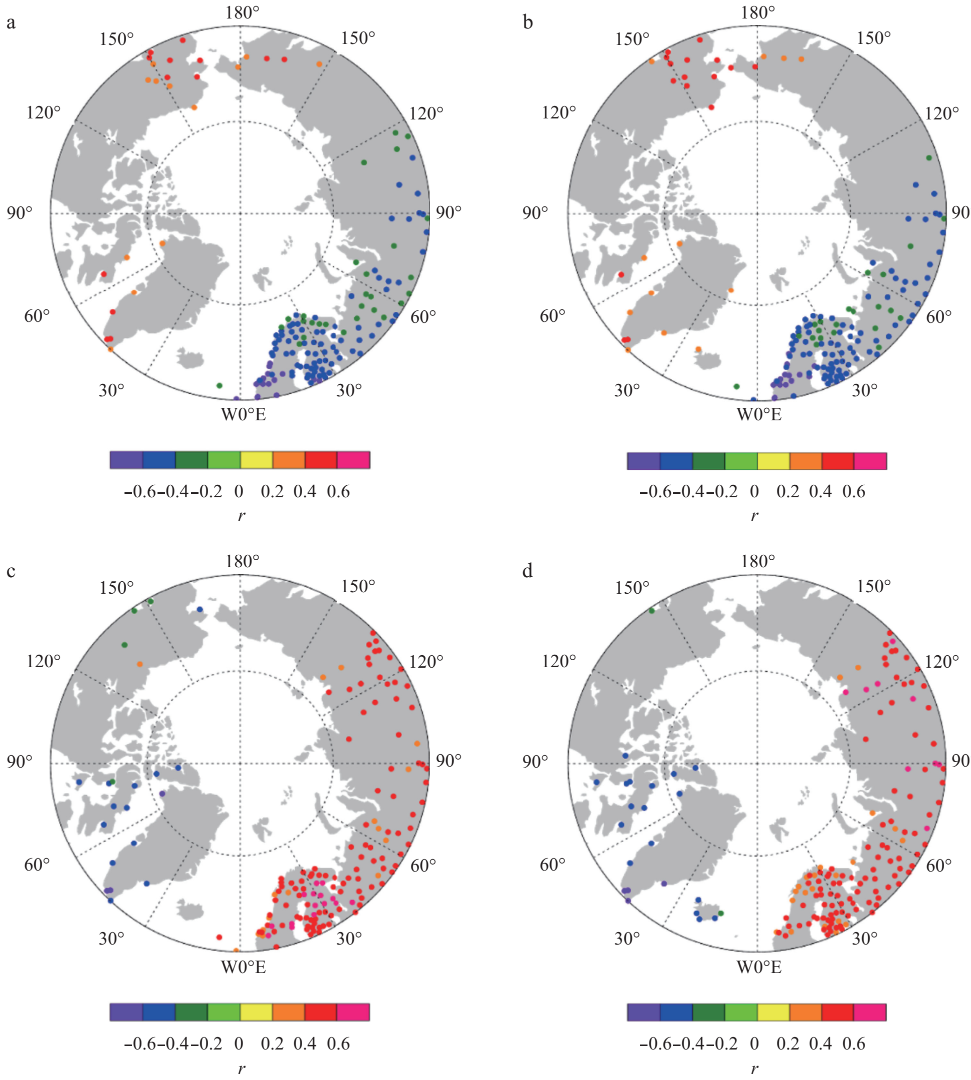

Fig. 4. The correlation coefficients (*r*) between the wintertime AO index and cold days (a), cold nights (b), warm days(c), and warm nights (d).

treme events are attributed to the anomalous wintertime mean temperatures related to the wintertime AO index.

Figure 5 shows the correlation coefficients between the Arctic autumn sea ice extent and the extreme events, displaying only the stations passing the 95% significance level threshold. For cold days and nights, significantly positive correlations occur at north of 60°N, except for one station in northwestern Russia (Fig. 5a), one station in Victoria in Canada and one station in Iceland (Fig. 5b). For warm days and nights, significant negative correlations occur at most stations over the Arctic. Northwestern Russia and Victoria in Canada show significant positive correlations, which is in accordance with the results of Overland et al. (2011). They proposed a "warm Arctic, cold continents" mechanism caused by Arctic amplification and the coupled changes in sea ice and snow cover.

3.2 *Trends in extreme temperature indices in different regions*

Following the methods of Matthes et al. (2015), the domain-averaged climate extremes in four geographic regions (Fig. 6) were calculated. The four regions are as follows: (1) northwestern Eurasia (including northern Europe, northern Russia west of the Ural Mountains, and the islands between 10° W and 60°E); (2) northeastern Eurasia (including northern Asia, east of the Ural Mountains between 60°E and 165°W); (3) Alaska (between 165°W and 140°W); and (4) Canada (including continental Canada and the islands between 140°W and 90°W).

The time series of cold days and cold nights in each region are basically identical, as are the time series of the warm days and warm nights (Fig. 7). For cold days and nights, the four domains show consistent decreasing trends, with the largest negative trend in Canada, followed by that in northwestern Eurasia (Table 2). The significant decreasing trends of cold days and nights in Canada correspond to the abrupt reductions of their time series in 1998 (Fig. 8a). Before 1998, the mean numbers of cold days and nights were 10.31 and 11.05, respectively, whereas after 1998, these values decreased to 6.13 and 5.36, respectively. Unlike for cold days and nights, the trends of warm days and nights were not consistent with the significant positive trend of northwestern Eurasia (Table 2). The increasing trends also correspond to the abrupt changes in their time series, with the abrupt points occurring in 1988 (Fig. 8b). Before 1988, the mean numbers of warm days and nights were 4.51 and 4.70, respectively, whereas after

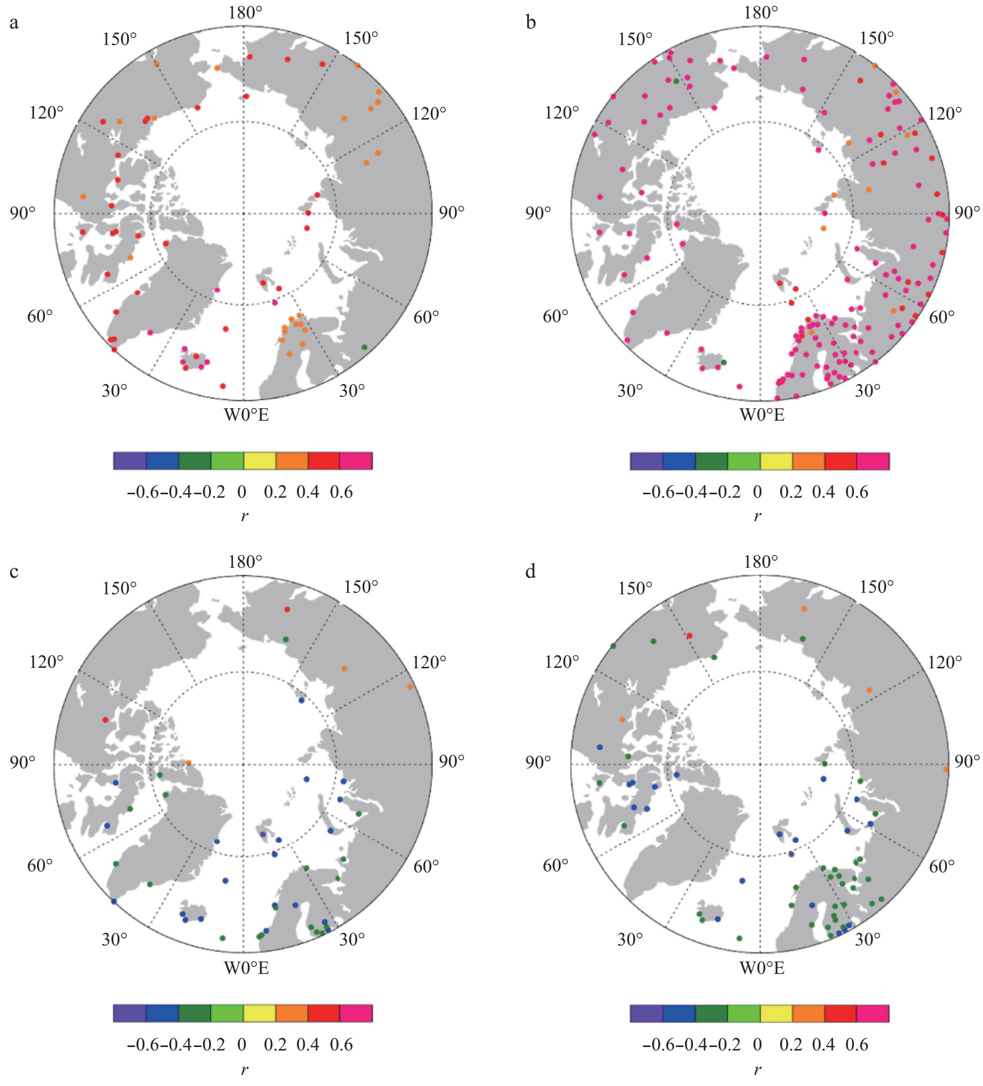

Fig. 5. The correlation coefficient (r) between the Arctic sea ice extent and cold days (a), cold nights (b), warm days(c), and warm nights (d).

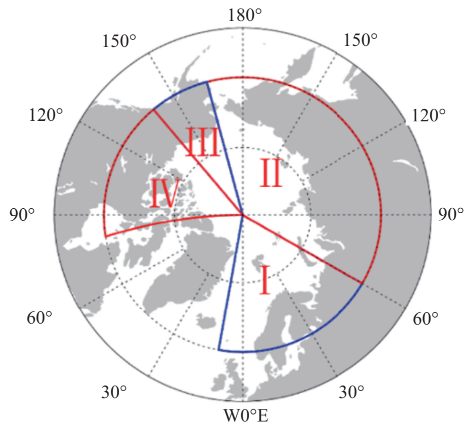

Fig. 6. Schematic view of the different regions investigated in this study: northwestern Eurasia (I), northeastern Eurasia (II), Alaska (III) and Canada (IV).

1988, the values increased to 10.02 and 9.96, respectively.

Because the abrupt changes occurred in cold nights in Canada and warm nights in northwestern Eurasia, we calculated the mean (Fig. 9a) and variance (Fig. 9b) of the minimum temperature differences before and after the abrupt transition point in these two domains. The results show that most of the variance do not pass the significance test, whereas the mean is found to have increased significantly. This would have been conducive to an enhancement of extreme warm events and a weakening of extreme cold events, bringing about an abrupt change.

We composited the atmospheric and oceanic circulation fields before and after the abrupt point of change in an attempt to explain the mean shifts in these two domains. The direction of the wind anomaly at 10 m was northeasterly before the abrupt point of change in northwestern Eurasia (Fig. 10a) and was caused by anticyclonic anomalies over Greenland and cyclonic anomalies over northwestern Eurasia (Fig. 10e). In contrast, the anomaly was southerly after the abrupt point of change (Fig. 10b), which was caused by the opposite pattern of the anomalous circulations at the 500 hPa height (Fig. 10f). Figures 10c and d show that respectively, in Canada, the cyclonic and anticyclonic anomalies in the Arctic led to a northwesterly flow before the abrupt point of change and a southeasterly flow after. The prevailing

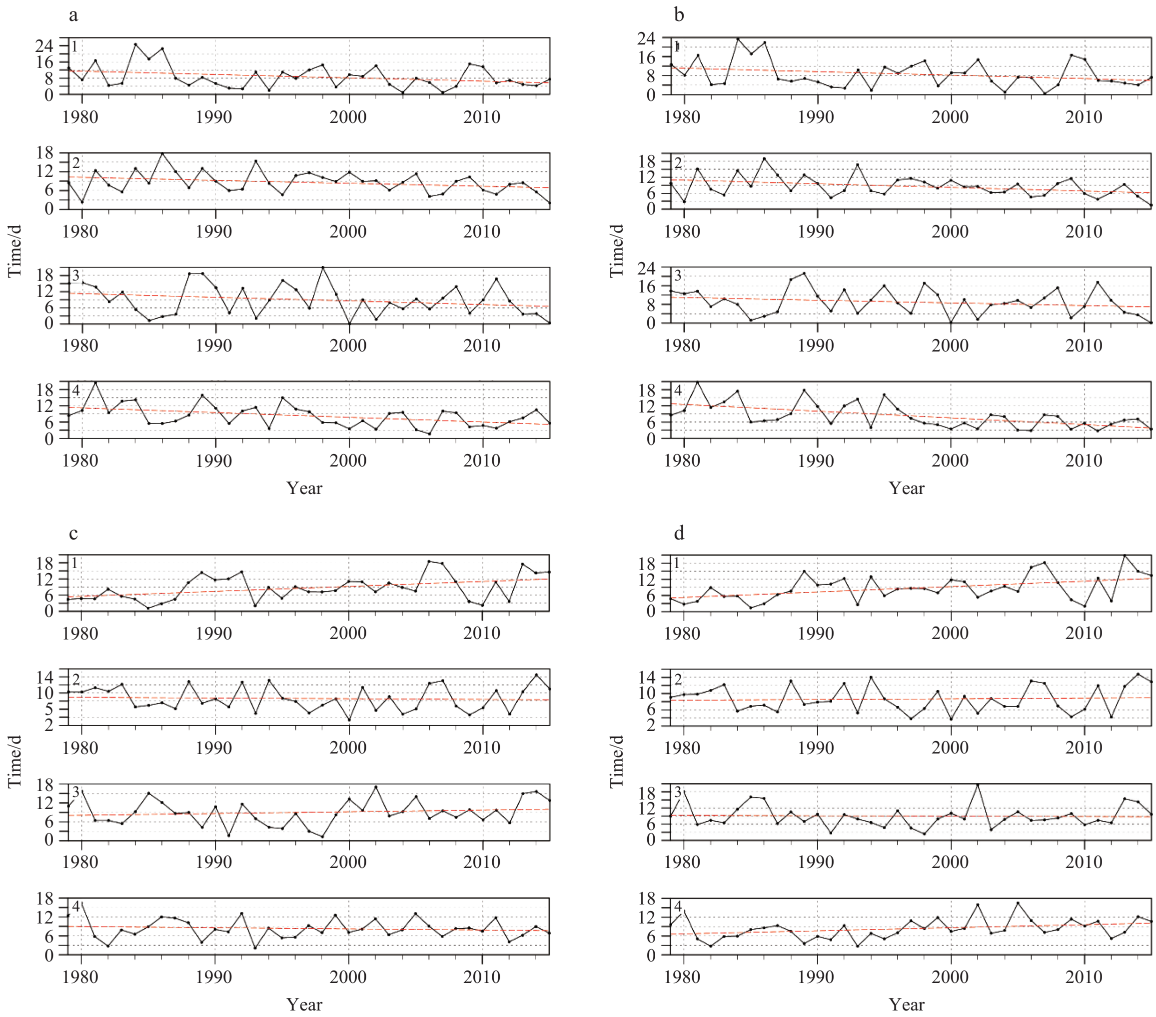

Fig. 7. Time series of cold days (a), cold nights (b), warm days (c), and warm nights (d) (black lines) and their trends (red lines). The numeral represents the region (I–IV) (see Fig. 4).

Table 2. Trends in extreme events (d/a) in different regions

Indicator	Northwest Eurasia	Northeast Eurasia	Alaska	Canada
cold days	–0.16	–0.09	–0.13	–0.18 1)
cold nights	–0.15	–0.14	–0.11	–0.25 1)
warm days	0.18 1)	–0.02	0.06	–0.04
warm nights	0.20 1)	0.02	–0.01	0.10

Note: 1) A statistical significance above the 95% confidence level.

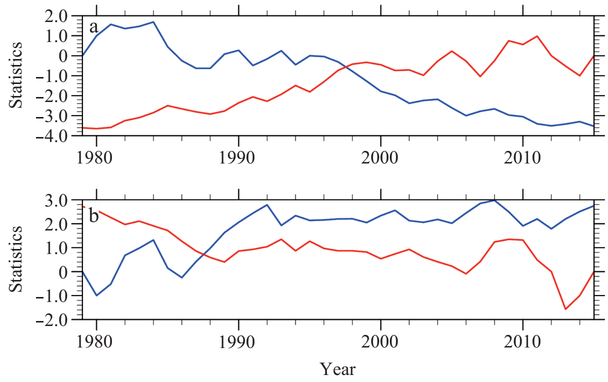

Fig. 8. Abrupt change in cold nights in Canada (a) and warm nights in northwestern Eurasia (b). The red line is the UB statistics and the blue line is UF statistics.

southerly winds brought warm and wet air in winter, which was conducive to increasing the number of warm nights in northwestern Eurasia and decreasing the number of cold nights in Canada.

Using the same method, we also composited the sea surface temperature (SST) anomaly. As shown in Fig. 11, the SST was rising in the Barents Sea and the Kara Sea in the North Atlantic Ocean (Fig. 11b), which would have increased the mean temperature and, subsequently, the number of warm nights in northwestern Eurasia. Similarly, the warming trend in Baffin Bay in the North Atlantic Ocean (Fig. 11d) would have decreased the number of cold nights in Canada.

4 Conclusions

With global warming and the rapid melting of the Arctic sea ice, the Arctic amplification phenomenon and its influence on

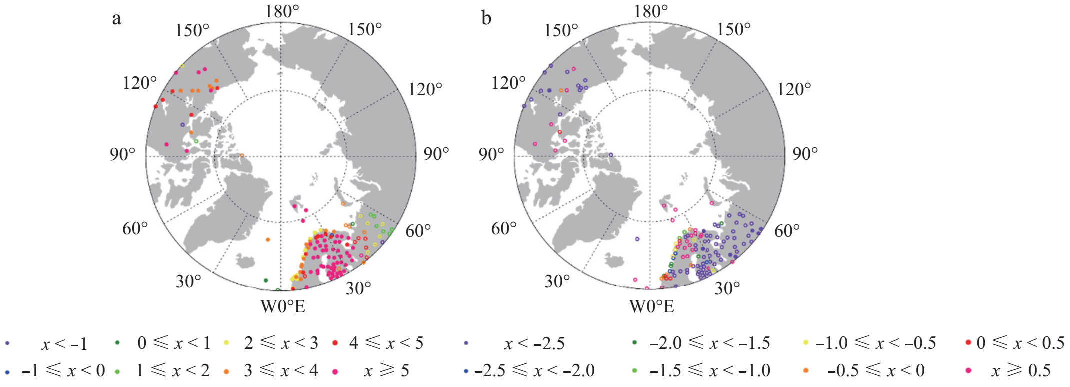

Fig. 9. The mean (a) and variance (b) of the minimum temperature difference (x, °F) before and after the abrupt point of change in northwestern Eurasia and Canada. The stations with statistical significances above the 95% confidence level are shown as the solid circles.

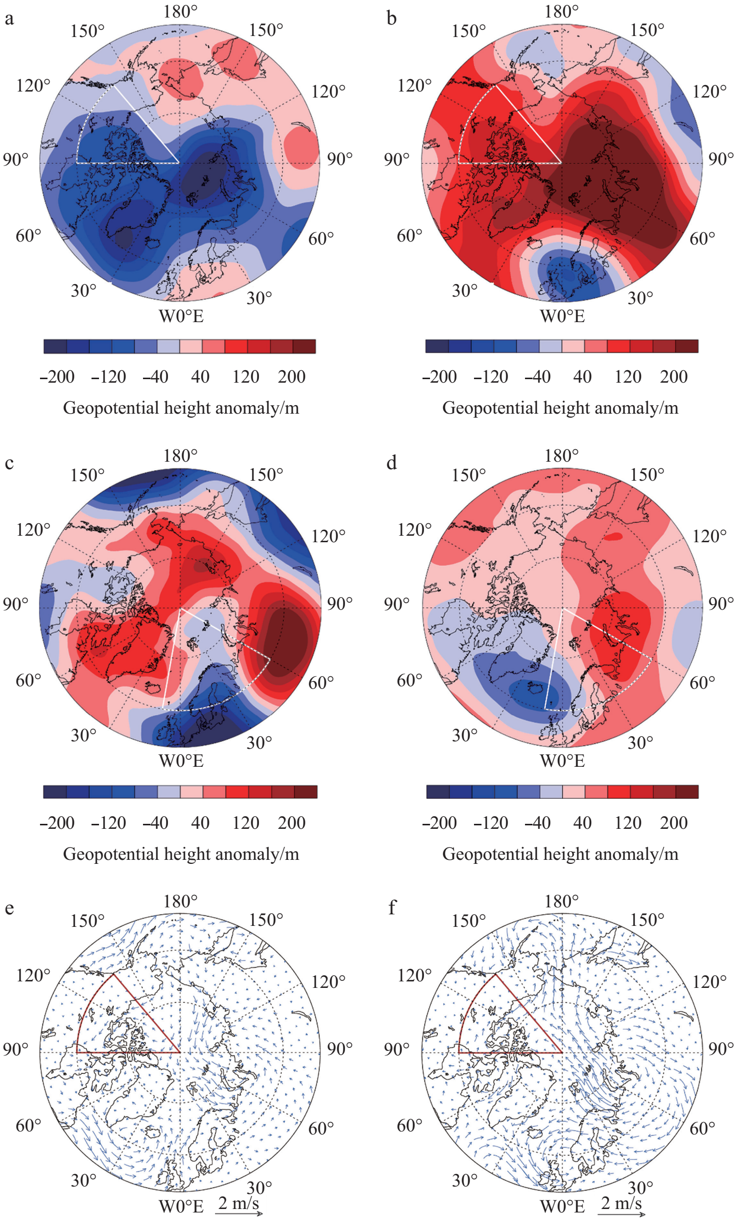

Fig. 10.

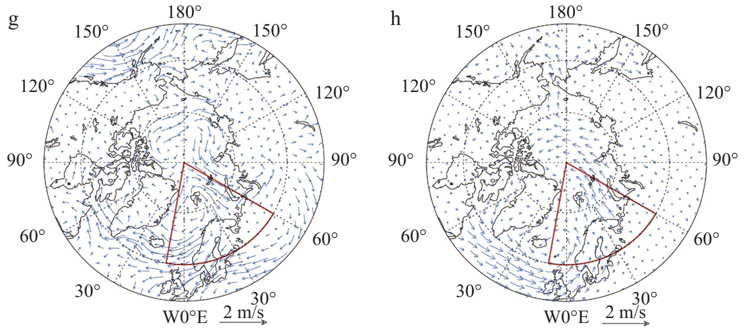

Fig. 10. Composite of 500 hPa geopotential height anomaly in 1979–1998 (a), 1998–2015 (b), 1979–1988 (c) and 1988–2015 (d) and 10 m wind anomalies in 1979–1998 (e), 1998–2015 (f), 1979–1988 (g), and 1988–2015 (h).

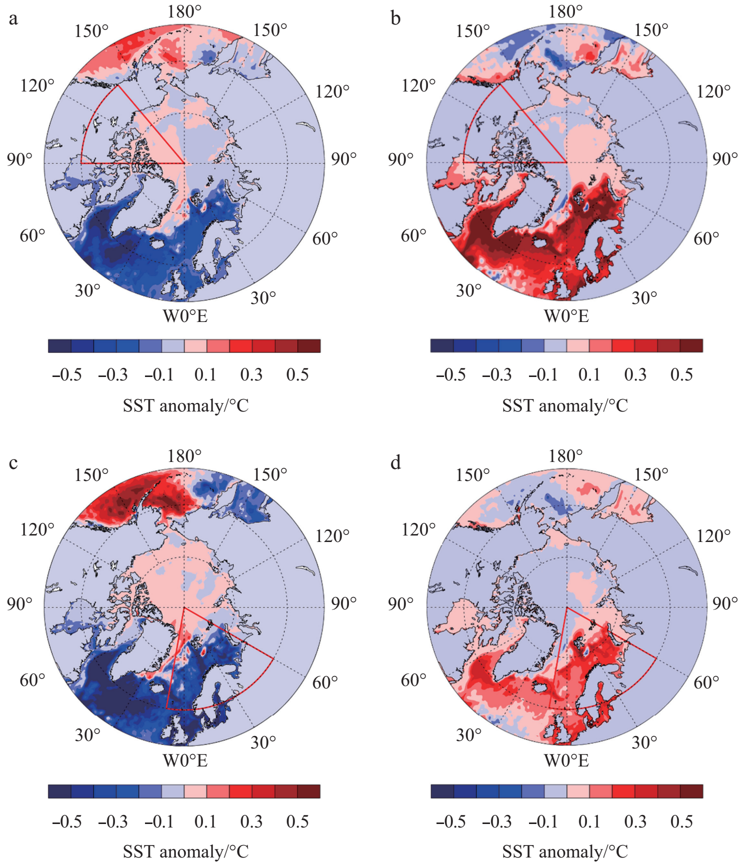

Fig. 11. Composite of SST anomalies in 1979–1998 (a), 1998–2015 (b), 1979–1988 (c), and 1988–2015 (d).

mid-latitude cold events have been gradually revealed. In this study, we defined four temperature indices using the daily maximum and minimum temperatures north of 60°N, as derived from the GSOD. The trends of the numbers of cold days, cold nights, warm days and warm nights of the winters of 1979–2015 were studied. The results can be summarized as follows.

(1) There were decreasing trends in the number of wintertime cold days and cold nights (between –0.2 and –0.3 d/a) and increasing trends in the number of warm days and nights (between 0.2 and 0.3 d/a) in the Arctic. Cold events also occurred at three stations in northwestern Russia and one station in Victoria in Canada, supporting the observed occurrences of mid-latitude extreme cold winter events in recent years.

(2) The contributions of the means and variances of the maximum and minimum temperatures to the trends show that a significantly increasing trend in the mean favors an increasing (decreasing) occurrence of warm (cold) days and nights. Moreover, most of the stations show a decreasing trend in their variances, leading to a reduced number of cold events. In addition, the effects of the wintertime AO index on the extreme temperatures of the Eastern and Western Hemispheres are hemispherically inverse. A positive AO index leads to an increased (decreased) number of warm (cold) days and nights over northern Europe and western Russia, and an increased (decreased) number of cold (warm) days and nights over the Bering Strait and Greenland. The reduced Arctic autumn sea ice extent leads to a decreased number of cold days and nights.

(3) Abrupt changes were found for the cold nights in Canada

and the warm nights in northwestern Eurasia, and the transition points were 1998 and 1988, respectively. The changes were mainly contributed to shifts in the mean temperatures. The results of the composite analyses suggest that southerly winds and rising SSTs in the North Atlantic Ocean increase the number of the warm nights in northwestern Eurasia and decrease the number of the cold nights in Canada.

Previous studies have mainly focused on extreme wintertime events at the mid-latitudes rather than in the Arctic because of the sparse availability of data in the Arctic Region. However, the Arctic plays an important role in the development of cold events at the mid-latitudes simply because it is the source of the cold. In this study, only extreme temperature events in the Arctic were studied. More variables, including extreme precipitation and wind, will be studied in the future work and can be used as predictors for the extreme events at the mid-latitudes. In addition, we will continue to study the mechanisms of the effects of the AO index and the sea ice extent on the extreme temperature events using models.

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