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# Characteristics and spatial distribution of strong warming events in the central Arctic (2000–2019)

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**Abstract** Arctic amplification in the context of global warming has received considerable attention, and mechanisms such as ice–albedo feedback and extratropical cyclone activity have been proposed to explain such abnormal warming. Since 2000, several short-term episodes of significant temperature rise have been observed in the Arctic; however, long-duration warming events in the central Arctic are less common and lack comprehensive research. Previous studies identified that amplified Rossby waves could connect Arctic warming with extreme weather events in mid-latitude regions, and thus the recent increase in the frequency of mid-latitude extreme weather is also a subject of intensive research. With consideration of temperature anomalies, this study defined a continuous warming process as a warming event and selected strong warming events based on duration. Analysis of National Centers for Environmental Prediction Reanalysis-2 surface air temperature data found that nine strong warming events occurred during 2000–2019, which could be categorized into three types based on the area of warming. This study also investigated the relation between strong warming events and sea ice concentration reduction, sudden stratospheric warming, and extratropical cyclone activities. After full consideration and comparison, we believe that strong warming events in the central Arctic are induced primarily by continuous transport of warm air from mid-latitude ocean areas.

**Keywords Arctic amplification, warming event, mid-latitude, extreme weather, warm air**

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## 1 Introduction

Within the context of global climate change, significant warming events in the Arctic are becoming increasingly frequent. The global mean temperature has risen unequivocally (Cohen et al., 2014), and the warming in the Arctic region has been two to four times faster than the global average (Screen et al., 2012); a phenomenon commonly known as Arctic Amplification (AA) (Serreze and Francis, 2006; Graversen et al., 2008). Although AA is evident in all seasons, it is strongest in autumn and winter (Cohen et al., 2014). Therefore, this study focused on extreme Arctic warming events that occurred in winter.

Debate continues regarding the reasons for the observed AA and several causative mechanisms have been proposed, such as positive ice–albedo feedback (Holland and Bitz, 2003; Perovich et al, 2008; Bekryaev et al., 2010), considering that sea ice loss is the principal contributor to surface warming (Screen et al., 2012), cloud longwave radiative effects (Yamanouchi, 2019), and changes in the atmospheric content of water vapor. The underlying mechanisms of AA are considered most likely interconnected (Screen et al., 2012; Cohen et al., 2020). Therefore, comprehensive elucidation of the mechanism of AA is necessary, especially because results of various observations and model experiments have demonstrated links between Arctic warming and extreme weather events

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in mid-latitude regions (Holland and Bitz, 2003; Overland et al., 2016; Cohen et al., 2020). For example, mid-latitude extreme weather events could be associated with changes in the Arctic region via extratropical cyclone activity (Basu et al, 2019), atmospheric heat transport, and modern warm Atlantic water entering the Arctic Ocean (Spielhagen, 2011).

Within the context of long-term Arctic warming, several seasonally independent short-term high-temperature episodes have occurred in the region (Binder et al., 2017). Surface air temperature is closely associated with extreme warming events and many warming events with high surface air temperatures have been observed within the Arctic (Graham et al., 2017), including the extreme warming episodes that happened in 2016 (Binder et al., 2017; Kim et al., 2017; Yamanouchi, 2019) and in 2006 (Woods and Caballero, 2016). Previous studies have generally focused on only single warming events and no research has examined multiple warming events that have occurred in the 21st century. The findings of comprehensive research of an extreme wintertime Arctic warming event, which occurred in late December 2015 and early January 2016 (Boisvert et al., 2016; Cullather et al., 2016; Moore, 2016), suggested that increased downwelling longwave radiative flux might contribute to warm anomalies over the central Arctic region (Cullather et al., 2016). However, earlier studies neglected to seek and define other anomalous warming events in the Arctic region using a uniform and reliable standard (Graham et al., 2017). This has made it difficult to analyze the characteristics of multiple warming events, and to combine the findings of previous research into single warming events in the central Arctic, to reach conclusive agreement regarding recent Arctic warming. Analysis conducted in this study revealed that additional Arctic wintertime warming events have occurred in the 21st century. Therefore, considering the potential consequences of Arctic warming events (Martens et al., 2020), which include drastic impact on the global climate (Shepherd, 2016), it is essential to develop better understanding of the tendency and characteristics of Arctic warming events within the context of recent global warming. This study analyzed, compared, and classified a series of warming events that occurred in the central Arctic region during 2000–2019. The absolute surface temperature field of the Northern Hemisphere and within the Arctic Circle in winter was analyzed, and multiyear events with intensity defined by the accumulated anomaly temperature (AAT) were evaluated. Analysis of these major warming events in the central Arctic revealed their distribution characteristics and formation mechanisms. The occurrence of these strong warming events (SWEs) was then investigated with consideration of the findings of previous studies on the relevance of extratropical cyclone activity and sudden stratospheric warming (SSW).

# 2 Data and method

This study used National Centers for Environmental Prediction (NCEP)/Department of Energy (DOE) Atmospheric Model Intercomparison Project (AMIP-II) Reanalysis-2 data. The NCEP-DOE Reanalysis 2 is an improved version of the NCEP Reanalysis I model that fixed certain errors and incorporated updated parameterizations of physical processes. The dataset covers a wide range of meteorological data from January 1979 to August 2020. This study used 94 × 192 Gaussian gridded data (longitudinal resolution: 1.875°, latitudinal resolution: 1.8889°) of daily averaged 2-m surface temperature and NCEP AMIP-II multiyear monthly averaged 2-m surface temperature.

The research also used a climate data record of sea ice concentration obtained from passive microwave data provided by the National Snow and Ice Data Center. This record represents consistent daily and monthly time series of sea ice concentration in the polar regions from 9 July 1987 based on the most recent processing techniques. All data were presented on a 25 × 25 km grid and the temporal coverage extended from 2000 to 2019.

# 3 Classification and characteristics of SWEs in the central Arctic

In wintertime, anomalous warming events can occur in the Arctic, especially in the regions of the marginal seas. However, this study focused on anomalous warming events in the central Arctic, which occur less frequently.

Previous research has generally considered the central Arctic as an ambiguous concept without clear and uniform geographic division. Some studies considered the region north of 85°N as the central Arctic (e.g., Ulander and Carlstrom, 1993; Graham et al., 2017). However, the land–sea distribution in the eastern and western hemispheres is not symmetric about the North Pole; hence, instead of defining the central Arctic with a single latitudinal circle, it is reasonable to consider the distribution of the Arctic Ocean deep ocean basin. The scope of the central Arctic region considered in this research is shown in Figure 1. In the Atlantic sector (120°W–0°–120°E), the central Arctic is defined as the region north of 84°N; in the Pacific sector (120°E–120°W), the central Arctic is defined as the region north of 80°N (Zhao et al., 2018). The focus of this study was the warming events that occurred in the central Arctic region defined in Figure 1.

## 3.1 Definition and statistics of SWEs in the central Arctic

Even in the Arctic winter, a pattern of alternating cold and warm can occur; thus, abnormal warming is reasonably common. This study focused on SWEs with significant

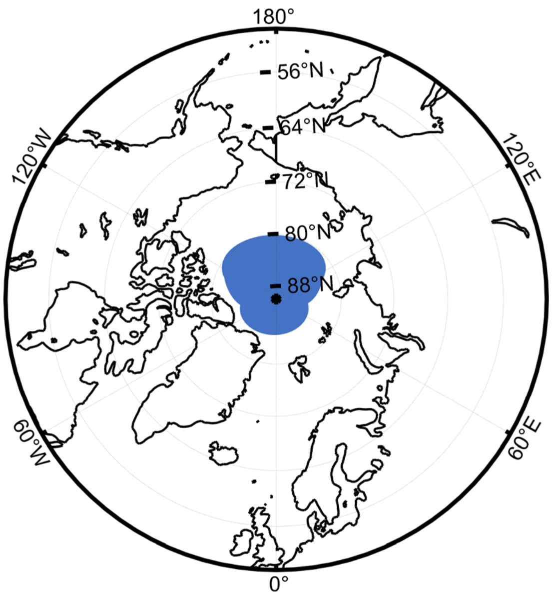


**Figure 1** Scope of the central Arctic considered in this study, defined as the blue area that is not symmetric about the North Pole.

temperature increase, long duration, and significant climatic impact. With consideration of the daily surface air temperature and taking the multiyear monthly average of each grid point as reference, a daily temperature anomaly ($\Delta T$) of ≥10°C was defined as a warming day. A period of more than 3 consecutive warming days was defined as a warming process. If a warming process that occurred in a certain range persisted for a period of time, it was called a warming event.

The numbers of winter warming processes in the central Arctic in all years included in the dataset (1980–2020) are illustrated in Figure 2. Overall, 450 wintertime warming processes occurred during 2000–2019. As the number of warming processes that occurred in 2008 represents a minimum, this year was considered a boundary. Before 2008, the number of warming processes was >25 only in the winters of 2000 and 2006. As shown in Figure 2a, the frequency of warming processes after 2008 increased considerably. The total number of warming processes was >35 in the winters of 2012, 2014, 2016, and 2018. The red dots in Figure 2a represent years in which the total number of days of the winter warming processes exceeded one standard deviation. Most of the years in which the total number of days of the warming processes exceeded one standard deviation occurred after 2008. Therefore, in recent years, the frequency of occurrence of warming events can be considered closely related to the warming trend of the Arctic (Figure 2b).

In many winters, warming days occurred only sporadically with short duration and limited climatic impact. Only a warming process that persists for a long period can produce abnormally high temperatures that can have significant impact on the Arctic climate. Hence, in this study, a warming process that occurred for more than 7 consecutive days was defined as an SWE. According to this definition, nine SWEs occurred during 2000–2019:

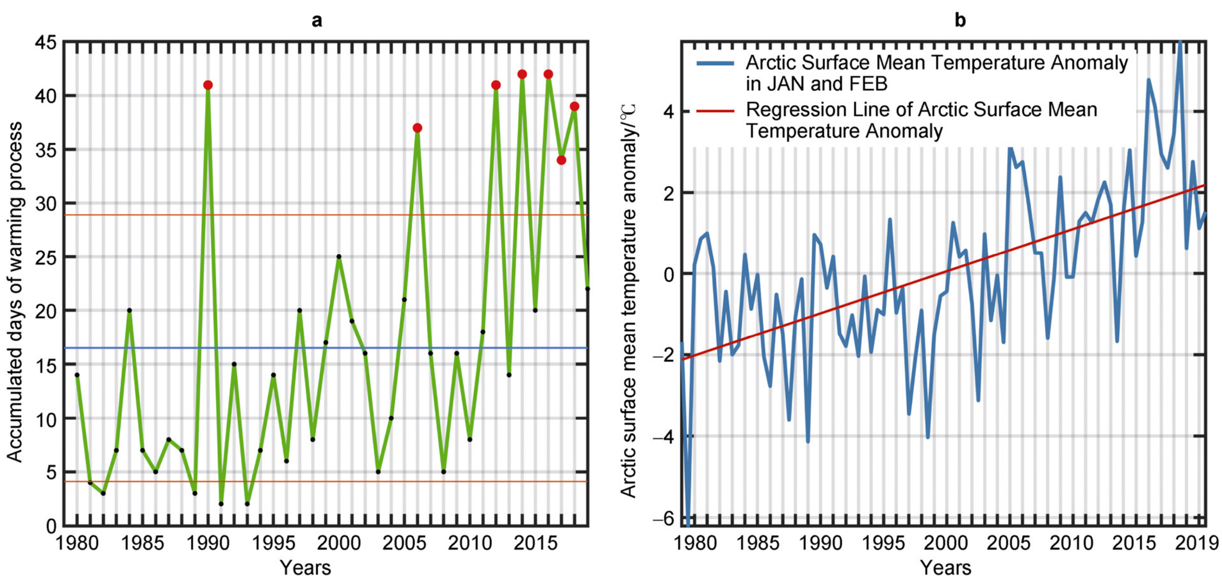


**Figure 2** **a**, Total number of warming processes in each winter (JFM) during 1980–2019. Green line and black dots represent the number of warming processes, straight blue line is the mean value, and orange lines represent the average ± one standard deviation. Red dots represent years in which the total number of warming process days exceeded the average number of days + one standard deviation, i.e., 1990, 2006, 2012, 2014, 2016, 2017, and 2018. **b**, Time series of Arctic surface mean temperature anomaly (blue line), and regression line of Arctic surface mean temperature anomaly (red line). For consistency, the monthly mean temperature anomaly in Jan and Feb inside the Arctic circle was used to represent the Arctic wintertime temperature. This figure shows the warming tendency of the entire Arctic.

2000.1, 2000.3, 2006.1, 2009.1, 2012.1, 2014.1–2014.2, 2016.2, 2018.1 and 2018.2 (where “year”, “month” is used to express the time of the warming event). Among them, the SWEs of 2006.1 and 2018.2 each persisted for more than 20 d in the corresponding months.

### 3.2 Three types of warming event

The longer an SWE persists, the greater the scope of its climatic impact. Hence, to determine the climatic impact of SWEs, the accumulated anomaly temperature (AAT) was adopted to represent the intensity of the warming events. During the period of occurrence of a warming event (i.e., from $d_1$ to $d_2$), the accumulated temperature $\theta$ of each grid point in the Arctic Circle can be defined as follows:

$$\theta = \int_{d_1}^{d_2} \Delta T dt \,, \qquad (1)$$

where $\Delta T$ is the daily temperature anomaly. The AAT distribution of each of the nine SWEs that occurred in the study period is shown in Figure 3. It is evident that warming events with longer duration produce higher AATs. Moreover, both the affected area and the scope of each warming event are different, and the main affected area of each SWE can be determined by the 70 d·℃ (=10 ℃ × 7 d) isoline (red line in Figure 3).

It can be seen from Figure 3 that the areas affected (area encircled by the 70 d·℃ contour line) by the warming events in 2000.1, 2009.1, 2006.1, and 2018.2 were similar. In each of these years, the affected area stretched to the eastern and northern seas of Greenland and covered the North Pole; however, their intensities (the highest values inside the affected area) differed markedly. The maximum AAT of the 2006.1 and 2018.2 events was significantly higher than that of the 2000.1 and 2009.1 events. The spatial distributions of the AAT of the 2000.3, 2012.1, 2016.1 (not shown in picture), 2016.2, and 2018.1 events were also similar; that is, the affected area was located around the Nansen Basin and reached the North Pole but

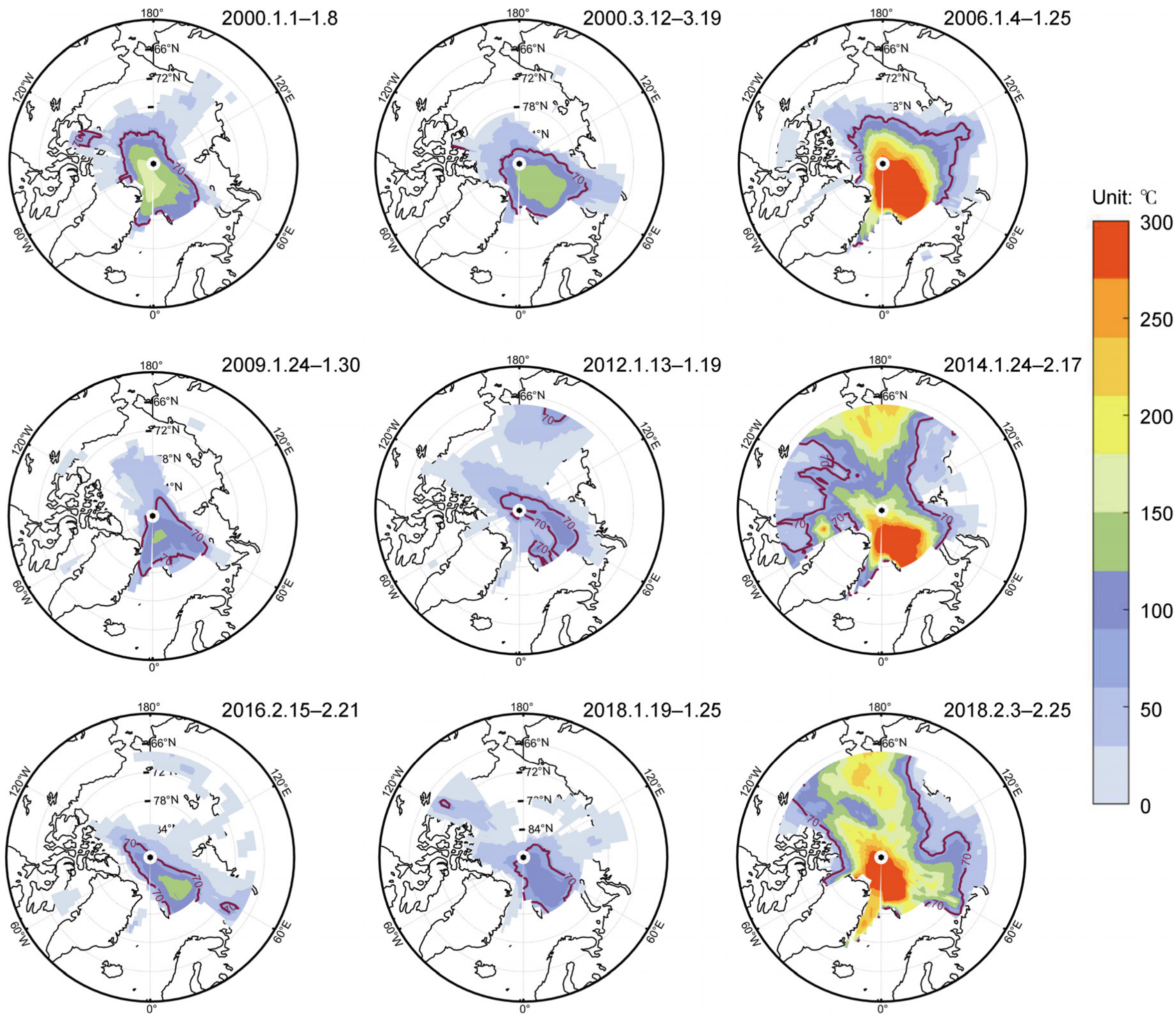


**Figure 3** Distribution of AAT within the Arctic Circle during the corresponding period of SWEs during 2000–2019. Dark red line is the 70 d·℃ isoline (contour of relatively high accumulated temperature in the entire region during the statistical period); the area enclosed by this line is the area affected by the warming event.

did not cover it. Additionally, the area affected by each of the warming events in 2014.1–2 and 2018.2 was comparable; it was only in these 2 years that the affected area stretched to the Pacific sector of the Arctic.

In the affected area (within the 70 d·℃ contour), the total accumulated temperature (Θ) of a warming event was considered as an intensity index of the event:

$$\Theta = \int_s \theta ds . \quad (2)$$

By calculating the total AAT in the affected area of a warming event, it was thus possible to represent the heating process and exhibit the induced impact of the warming event in the central Arctic. The total AAT of each SWE is shown in Figure 4. According to the heights (corresponding to the total AAT) of the columns in Figure 4, the 2018.2 SWE was strongest, followed by the 2006.1 SWE and the 2014.1–2 SWE. Although the intensity of the warming event in 2014.1–2 was strong, the scope of its influence (corresponding to the width of the column in the figure) was smaller than that of either of the events in 2006.1 and 2018.2. The intensity of the warming events in the other years was relatively low, and the average impact range of the events was similar.

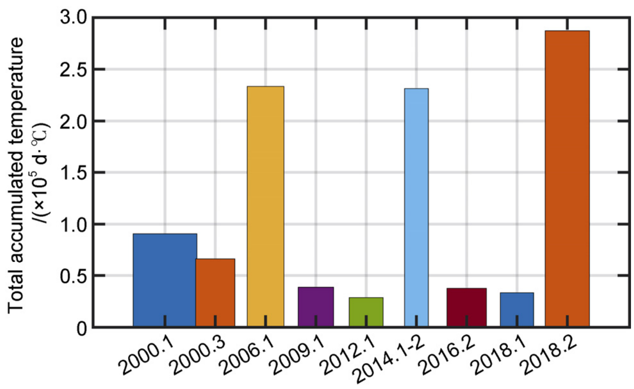


**Figure 4** Total AAT and mean affected area of each SWE. The $y$-axis refers to the value of the AAT during the occurrence of the SWE, which represents the intensity of the warming event; the column width represents the average affected area of the SWE, i.e., the range of the event. The colors have no special meaning and are used simply to distinguish the different warming events.

In this study, the warming events were defined relative to the multiyear average. Certain warming events that occurred with greater background warming did not require much additional energy, whereas other warming events that occurred within a colder background required a large amount of additional heat input. Hence, the temperature increase associated with each of the SWEs that occurred in the study period is shown in Figure 5. The blue bar indicates the lowest temperature that occurred before the warming event, which represents the background temperature; the orange bar indicates the first highest temperature of the warming event, which represents the warming impact. The distance between the end of the blue column and the end of the yellow column reflects the temperature increase of the warming event and the influence of that event in the central Arctic. The heights of the orange bars in Figure 5 indicate that the final temperature extremes of the different warming events were similar; however, owing to different background temperatures, the absolute temperature increase varied markedly. For example, the warming event of 2000.3 had the lowest background temperature (i.e., below −11°C), which meant that this event had the largest temperature increase (i.e., 28°C). Since then, there has not been another event with such a large temperature increase. The background temperature anomaly of the events 2009–2014 was above −5°C, and the absolute increases in temperature in these years were 15–20°C. In the 2018.2 event, despite the background temperature anomaly being positive, the temperature increase still reached 21°C.

### 3.2.1 Characteristics of the three types of SWE

On the basis of the above standards and Figure 3, the nine SWEs that occurred in the central Arctic during 2000–2019 can be categorized into three types.

**(1) Type A: warming inside the central Arctic**

In some years, warm air from the area of the North Atlantic Ocean directly enters and heats the central Arctic region, but has little impact on the Arctic marginal seas. Such warming events are classified as Type A (Figure 6); that is, a warming event inside the central Arctic region. Type A warming events reflect warming of the eastern and northern seas of Greenland and the seas around the North Pole. According to these characteristics, the 2000.1, 2006.1, 2009.1, and 2018.2 SWEs were classified as Type A events.

**(2) Type B: warming at the margins of the central Arctic**

Some SWEs occur at the margins of the central Arctic region and do not cover the sea area near the North Pole. Such warming events are classified as Type B; that is, warming at the margins of the central Arctic region. In Figure 3, the AAT distributions of the 2000.3, 2012.2 (not shown), 2014.1 (not shown separately), 2016.2, and 2018.1 SWEs are highly similar, and these events all belong to Type B. For example, the high value of AAT of the 2016.2 SWE was located at the margin of the central Arctic. When warm air moves northward along the eastern side of the Nordic Sea, a warm anomaly occurs in the eastern part of the Nansen Basin and the Arctic marginal seas, which contributes to the regionally high AAT. The warm anomaly then gradually expands into the central Arctic area, causing a warming event in the central Arctic. The area affected by Type B warming is shown as area B in Figure 6.

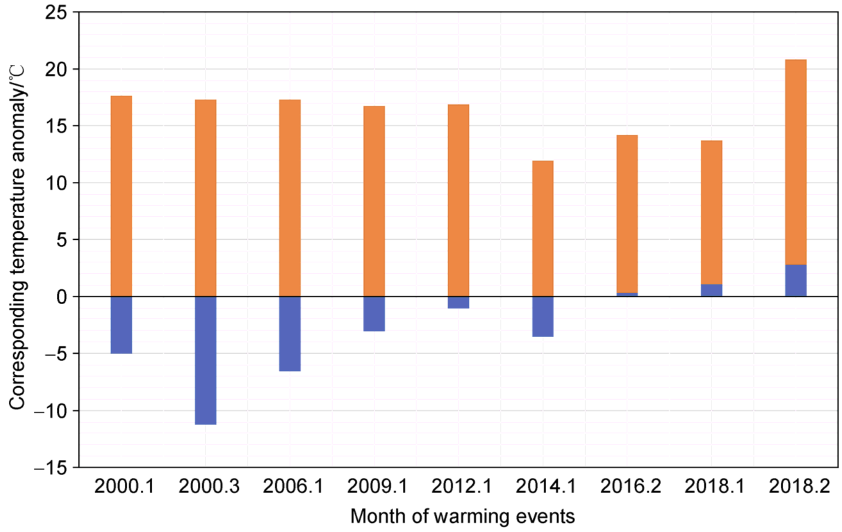


**Figure 5** Background temperature and temperature increase range of the nine warming events in the studied years. Blue bar represents the minimum temperature before the warming event; yellow bar represents the first extremely high temperature during the warming event.

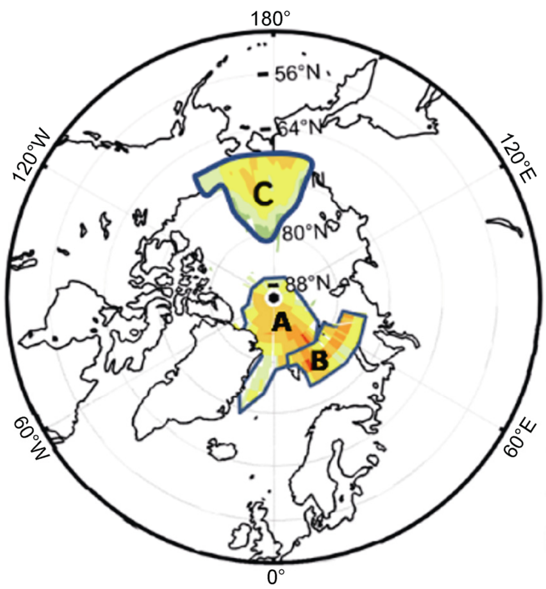


**Figure 6** Spatial characteristics of the three types of warming event in the central Arctic during the studied years. Area A is the area inside the central Arctic, and the corresponding warming is called Type A warming; Area B is the area at the margin of the Atlantic sector of the central Arctic, and the corresponding warming is called Type B warming; Area C is the area at the margin of the Pacific sector of the Arctic, and the corresponding warming is called Type C warming.

**(3) Type C: warming at the Pacific sector**

The Atlantic Ocean is the source of the warm air that induces Type A and Type B warming events; however, warm air derived from the Pacific Ocean can also sometimes induce warming events, which are classified as Type C warming events. In Figure 3, the 2012.1, 2014.1 (not shown separately), and 2018.2 SWEs all reflected warming in the Pacific sector. Among them, warm air from the Pacific in the 2018.2 SWE reached the interior of the central Arctic region and merged with a warm anomaly caused by warm air from the Atlantic during the same period, which is reflected by the extent of the area affected that covers almost the entire central Arctic.

### 3.2.2 SWEs at the margins of the central Arctic

The 2016.2 SWE is taken as an example to examine the process via which Type B warming gradually heats the central Arctic region. From December 2015 and 1 January 2016 to 10 February 2016, extensive abnormal warming occurred on the European side of Eurasia, indicating a continuous supply of warm air to this region. Surface air temperatures over the Barents–Kara seas increased and extremely high temperatures appeared (Figure 7), but this warming had not affected the central Arctic region at that time. On 15 February 2016, the warm anomaly over the Barents–Kara seas started to extend into the central Arctic region and this process continued until 22 February 2016. At the same time, warming also occurred over the North Canadian Arctic Islands and the North Pacific, although most of the warming area was outside the central Arctic. It is considered that the 2016.2 warming event was an extension of the high temperatures in the marginal seas in the 2016.1 event, and the result of the accumulation of warm air over the Barents–Kara seas, which ultimately caused the warming of the margins of the central Arctic. After 22 February 2016, the warm anomaly in the central Arctic gradually dissipated, whereas the warm anomaly over Eurasia persisted.

### 3.2.3 SWEs inside the central Arctic

The 2006 and 2018 SWEs are taken as examples to examine the process via which Type A warming heats the central Arctic. In 2006, the SWEs occurred in the central Arctic during 3–26 January.

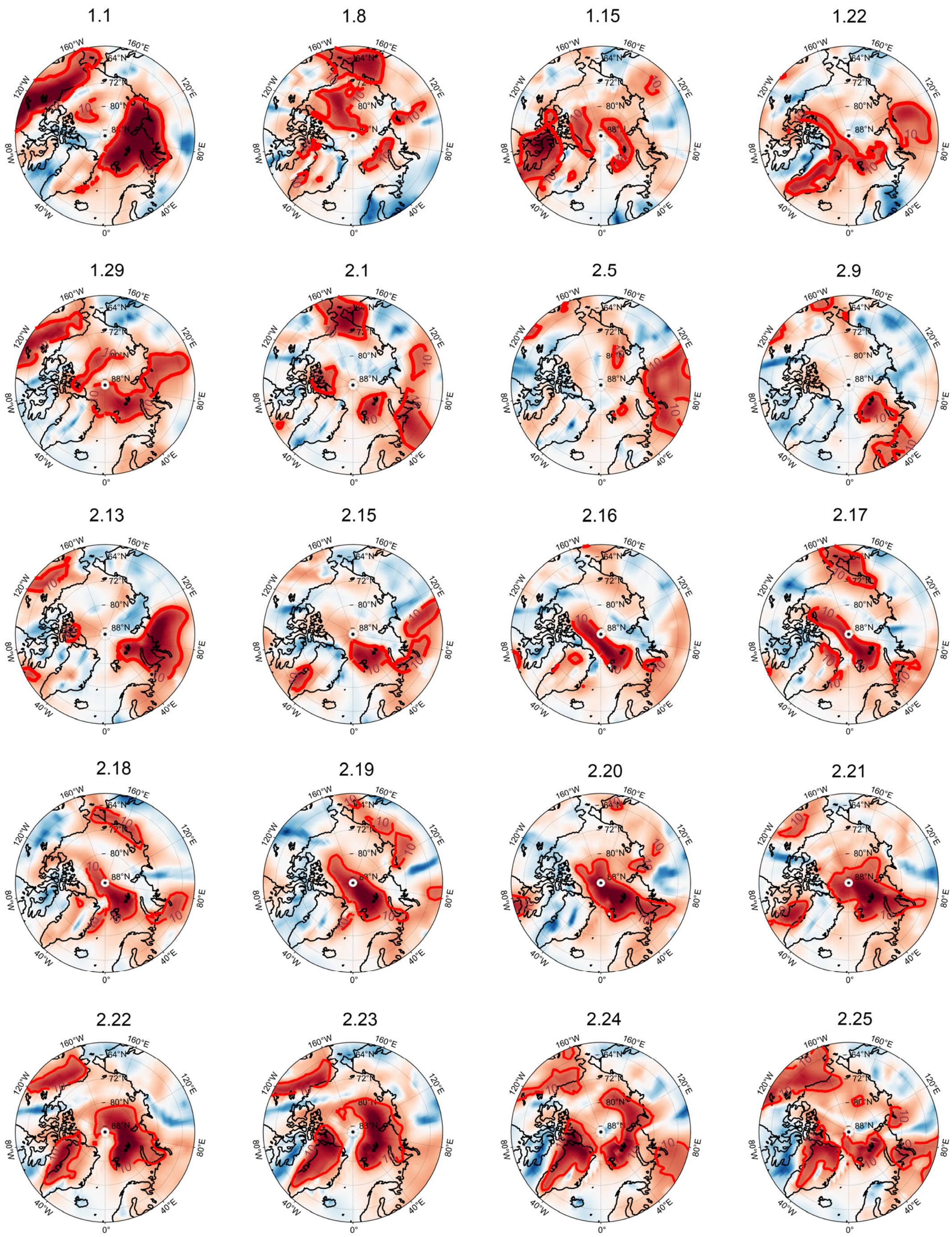


**Figure 7** Process of change of temperature anomaly in the Northern Hemisphere from January to February 2016, in which SWEs in the central Arctic occurred during 2.15–2.22 2016. Thick red line is the 10°C isoline.

The gradual warming process over the central Arctic in the 2006.1 SWE is illustrated in Figure 8. On 1 January, a negative temperature anomaly dominated the central Arctic and there was no signal of a warming event. From 3 January, a positive (warming) anomaly developed over the Greenland Sea along the eastern side of Greenland as a precursor of the SWE. On 4 January, this positive temperature anomaly moved further along the eastern side of Greenland to inside the central Arctic, and it dominated almost all of the Atlantic side of the Arctic Ocean on 5 January 2006. On 6 and 7 January, positive anomalies dominated the eastern side of Greenland, interior of the Nansen Basin, and center of the Arctic, exactly the area in which the high AAT of this month was distributed. The movement of the positive anomaly, shown in Figure 8, indicates that warm air gradually entered the Arctic along the eastern side of Greenland, causing regional warming. During 8–17 January, the warm anomaly was concentrated mainly near the Nansen Basin, the warm anomaly on the Greenland side gradually disappeared, and the European continent warmed.

The warm anomaly reappeared on the eastern side of Greenland on 18 January 2006. Subsequently, the warm anomaly reoccupied almost the entire central Arctic region until 26 January. After 26 January, negative anomalies gradually dominated the central Arctic. It can be seen from Figure 8 that the European continent was in a relatively warm state before 16 January. The European continent then gradually became colder from 17 January until 23 January, after which it gradually warmed again. The warm anomaly along the eastern side of Greenland and the negative anomaly over the European continent appeared almost simultaneously. In January 2006, warm anomalies occupied the central Arctic region for nearly 24 d. The consequence of such long-duration warming was the long-term, large-scale, high-intensity 2006.1 SWE in the central Arctic, which represents one of the strongest warming events in the central Arctic region.

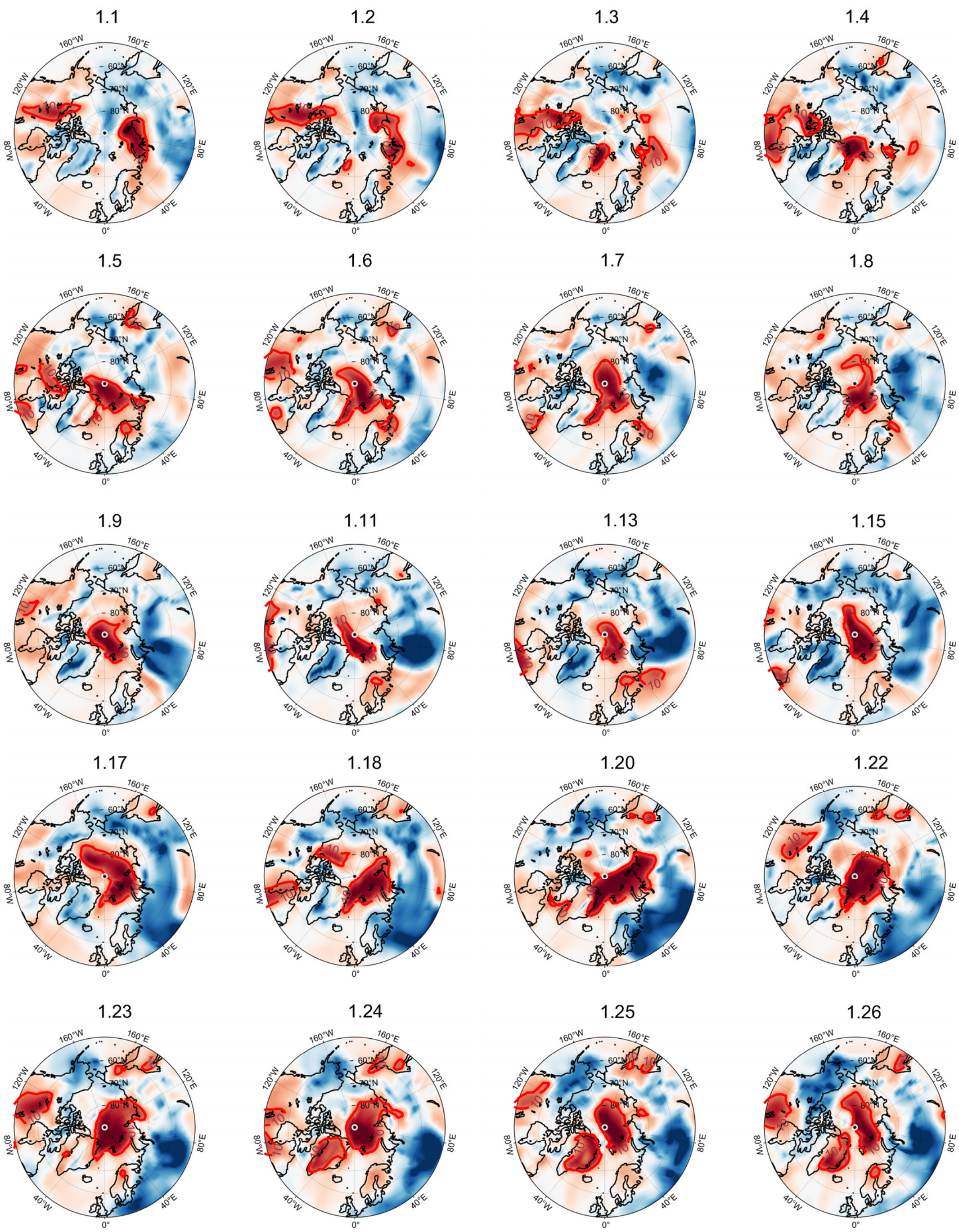


**Figure 8** Process of change of temperature anomaly in the Northern Hemisphere, in which the 2006.1 SWE occurred in the central Arctic during 3–23 January. Thick red line is the 10°C isoline.

The 2018.2 SWE started on 2 February 2018. The development process of this SWE was similar to that of the 2006.1 SWE. First, a positive anomaly occurred along the eastern side of Greenland on 2 February. Then, the warm anomaly began moving toward the Arctic interior, eventually covering almost all of the Atlantic sector of the central Arctic, including the Barents–Kara seas, by 5 February. At around the same time, starting on 7 February, the Pacific Ocean also experienced a warm anomaly that gradually approached the central Arctic. On 11 February, the Pacific warm anomaly overlapped the warm anomaly on the North Atlantic side in the central Arctic, which caused a robust large-scale change inside the central Arctic during this period. A wide range of warm anomalies formed in the area from the North Pacific–Bering Sea–Chukchi Sea to the central Arctic. On 18 February, as shown in Figure 9, the warm anomaly on the Atlantic side affected the area from the Greenland Sea along the eastern side of Greenland to

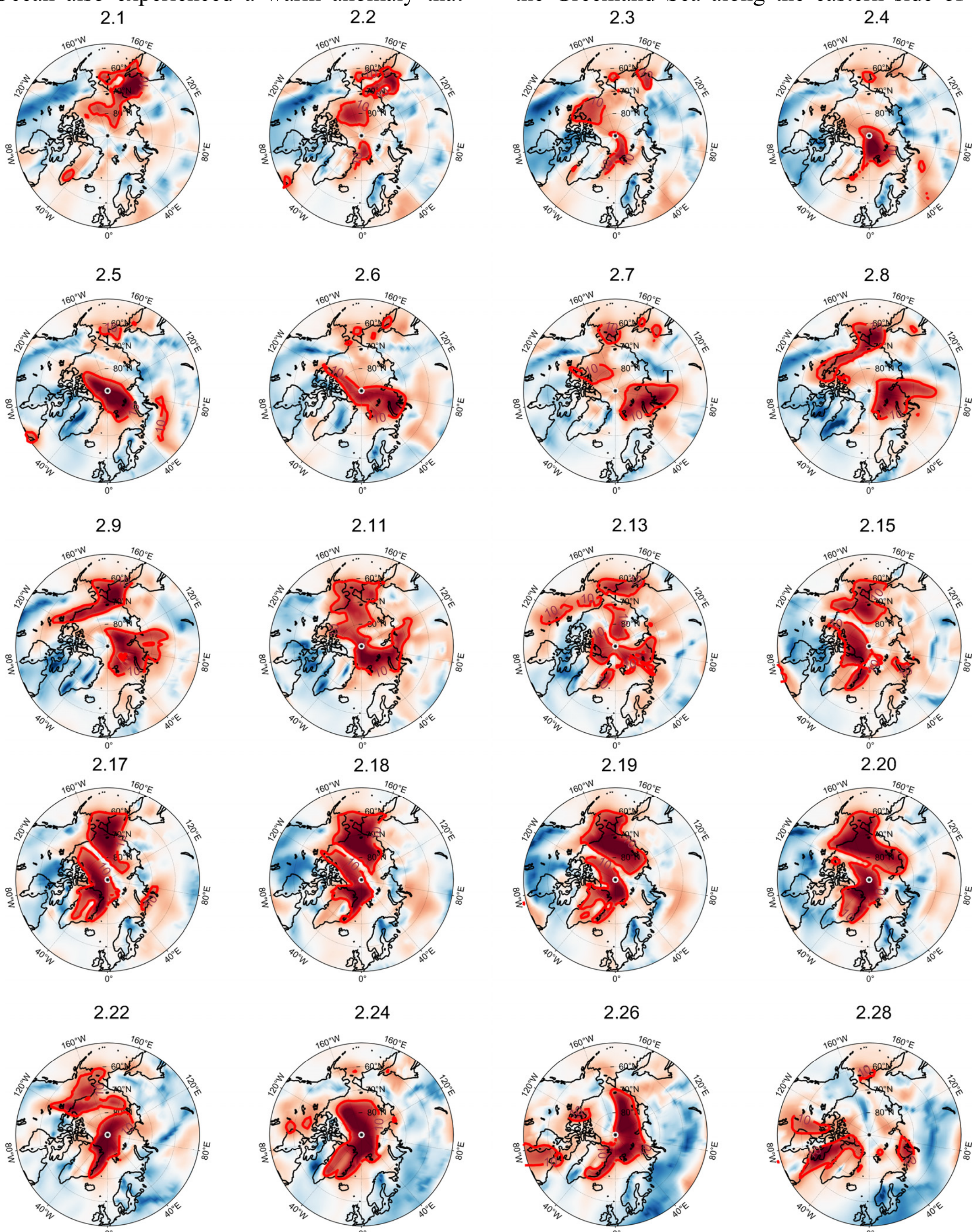


**Figure 9** Process of the 2018.2 SWE. The duration of the warming event extended from 3 February to 25 February. Thick red line is the 10°C isoline.

the central Arctic, and this connected with the warm anomalies on the Pacific side on 22 February 2018. Almost the entire central Arctic was then dominated by warm anomalies; in contrast, cold anomalies affected the European continent. This large-scale warming of the central Arctic region continued until 26 February, after which the warm anomaly in the central Arctic dissipated and the area became reoccupied by cold anomalies. From the perspective of hemispherical-scale change, the SWE in 2018 resulted from the combined effects of warm air from the North Atlantic directly entering the interior of the Arctic and the abnormal warming anomaly from the Pacific sector.

### 3.3 Intensity and spatial distribution characteristics of major warming events

On the basis of the above, the statistical results in terms of temporal change, spatial proportion, and formation mechanism of the wintertime (JFM) warming events that occurred in the central Arctic region during 2000–2019 are summarized in Figure 10. The percentage of grid points in the central Arctic region where warming events occurred over the years reflects the spatial extent of the effect of the SWEs in the central Arctic region. The percentage of grid points occupied by a warming process also represents the

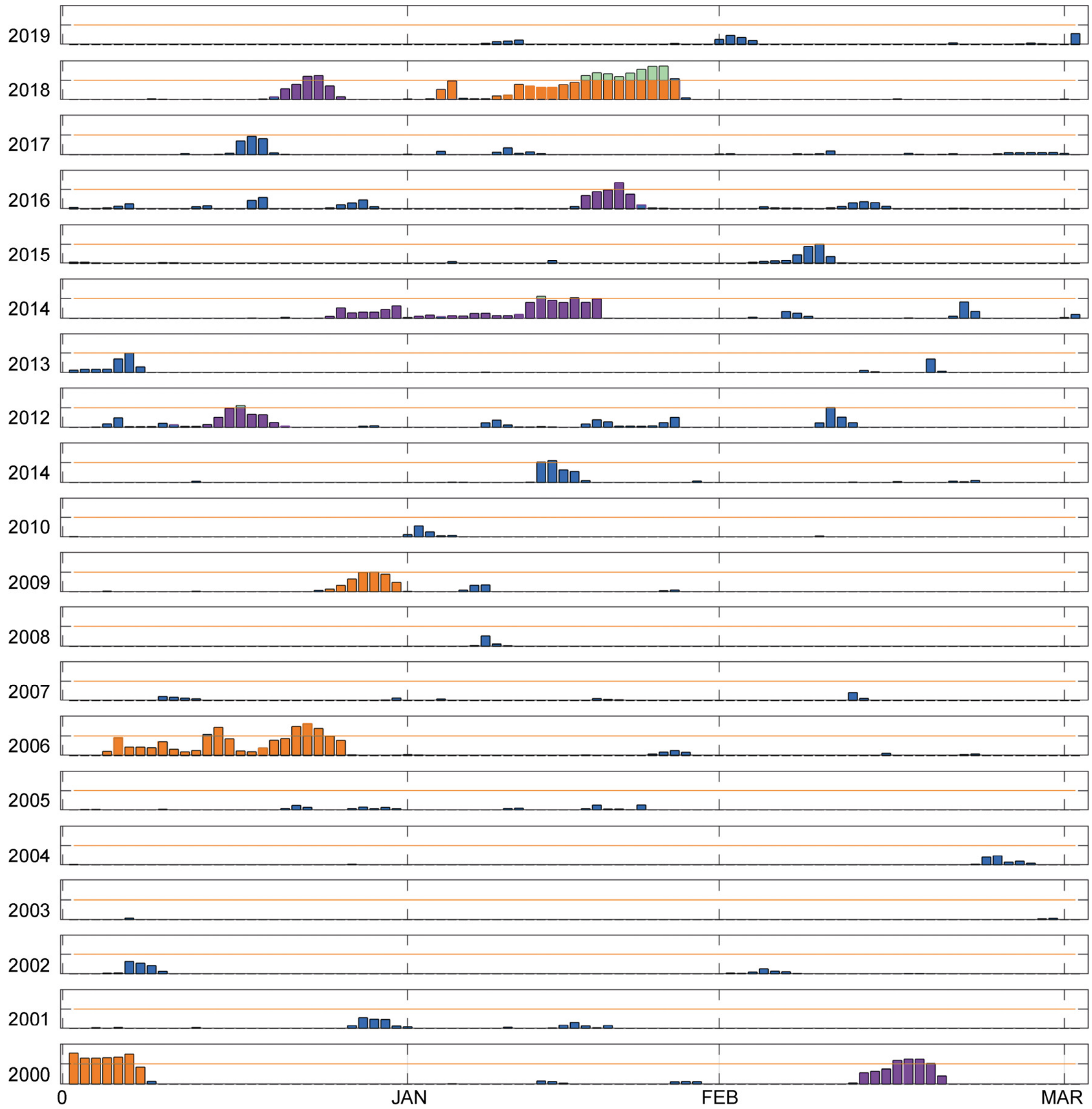


**Figure 10** Variation characteristics of winter (JFM) warming processes over time during 2000–2019 in the central Arctic. Column height represents the percentage of grid points occupied by warming events; the higher the column, the greater the percentage coverage. Orange line is the 50% proportion line. If the column is above the orange horizontal line, the proportion of grid points occupied by warm events exceeds 50%. Orange, purple, and green columns represent Type A, Type B, and Type C warming, respectively. Blue columns represent general sporadic warming events of insufficient duration (i.e., duration of warming process: <7 d) and for which the scope of influence is too small.

relative influence range of the warming process in the central Arctic. Therefore, the column height indicates the proportion of spatial grid points occupied by a warming process on a particular day; the higher the column, the larger the percentage and the broader the affected area. It is noteworthy that although the 2014 SWE persisted for a long time, the affected area in the central Arctic was relatively small. The continuous 2018.2 SWE not only persisted for a longer time but also affected a larger area. It can be seen that the percentage of spatial coverage was temporarily >50% during this event. The frequency of Arctic warming events has increased significantly since 2008 and there have been many occurrences of SWEs inside the central Arctic. In the 2000.1, 2006.1, 2009.1, and 2018.2 SWEs, the areas affected by the warming were inside the central Arctic, whereas in the 2000.3, 2012.1, 2014, 2016.1, and 2018.1 SWEs, the warming appeared at the margins of the central Arctic. Historically, the February 2018 warming event had the longest duration and affected the largest area. Generally, the warming events in the other years had a much smaller impact range and shorter duration, meaning that they had only limited impact on the central Arctic.

To understand the warming situation in the entire Arctic Circle over the studied years and the specific regional characteristics of Arctic warming, we also counted the daily anomalies of all grid points in the Arctic Circle in the 21st century that were >10℃ in January and February. The accumulated value is called the accumulated monthly anomaly temperature (AMAT) at that point. The difference between the AMAT and the warming event AAT is that the AMAT counts the temperature for an entire month, whereas the warming event AAT only counts the temperature during the warming event. Thus, the AMAT could reflect the general warming situation of the Arctic Circle in a month. By obtaining the AMAT for all grid points in the Arctic Circle, the highest AMAT in the Arctic Circle in January and February of each studied year was obtained, as shown in Table 1, which indicates the intensity of warming in the Arctic Circle in each month. As the highest AMAT increases, the warming in that month becomes stronger. Hence, according to the highest multiyear AMAT in the Arctic Circle in January and February, the standard deviation was determined as 379.55 d·℃. An AMAT value of >379.55 d·℃ in a certain month indicates that significant extremely high temperatures occurred in the Arctic Circle during that month.

It can be seen from Table 1 that significant extremely high winter temperatures occurred during the 2006.1, 2012.2, 2014.2, 2016.1, 2016.2, and 2018.2 SWEs. Consideration of Table 1 and Figure 10 reveals that extreme high temperatures do not necessarily occur in months with warming events in the central Arctic. For example, there were warming events in the central Arctic during January–February 2014, but extremely high temperatures actually occurred only in February of that year. Conversely, there were extremely high temperatures in January–February 2016, whereas warming events in the central Arctic occurred only in February of that year. Therefore, to investigate the relationship between the occurrence of extremely high temperatures and SWEs in the central Arctic, it is necessary to analyze and discuss specific warming processes in different years.

**Table 1** Highest AMAT in the Arctic Circle in January and February during 2000–2018 (d·℃). Values in bold and underlined are higher than the standard deviation of 379.55 d·℃

| Year | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 |
|---|---|---|---|---|---|---|---|---|---|
| JAN | 286.2 | 244.36 | 156.63 | 329.13 | 202.56 | 282.76 | **<u>497.66</u>** | 290.25 | 331.56 |
| FEB | 218.45 | 288.38 | 136.91 | 185.56 | 98.47 | 296.95 | 244.43 | 218.11 | 205.98 |

| 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 |
|---|---|---|---|---|---|---|---|---|---|
| 193.44 | 218.86 | 304.68 | 357.53 | 305.98 | 362.24 | 190.69 | **<u>434.52</u>** | 379.44 | 315.07 |
| 223.824 | 323.56 | 215.05 | **<u>436.06</u>** | 147.19 | **<u>461.25</u>** | 197.31 | **<u>422.10</u>** | 313.22 | **<u>411.75</u>** |

# 4 Discussion on SWEs

## 4.1 Explanation for the occurrence of the nine SWEs that occurred in the central Arctic

Type B warming, which refers to warming at the margins of the central Arctic, occurred during the 2012.2 (not shown), 2014.1–2, 2018.1, and 2016.1–2. Neither the monthly AAT distribution nor the warming event accumulated anomaly exhibited high values along eastern Greenland; instead, the high-value centers were all located at the edge of the Nansen Basin and close to the Barents–Kara seas in each of these periods. Among them, the marginal warming events in 2014.1–2, 2018.1, and 2016.2 eventually affected the central Arctic, leading to the occurrence of SWEs in the central Arctic. In 2016.1 and 2012.2, high temperatures were evident near Novaya Zemlya and the Laptev Sea, even though no warming events occurred in the central Arctic during these two periods. However, considering the extremely high temperatures that occurred in these months, they were classified as Type B warming events. Previous studies showed that an amplified Rossby wave could favor the transport of warm air from the low–middle latitudes of the North Atlantic into the Arctic, which could then affect the marginal seas of the Arctic, resulting in abnormal warming (Francis and Vavrus, 2012). Additionally, a previous study (Kim et al., 2017) highlighted that the Fram storm from late December 2015 to January 2016 induced the transport of a large amount of heat and moisture into the Arctic Circle from the low–middle latitudes of the Atlantic Ocean, which led to warming at the margins of the Arctic. The current study also demonstrated that all extreme high temperatures resulting from Type B warming are located at the margins of the central Arctic.

Type A warming appeared in 2000.1, 2009.1, and 2018.2, and the processes of these warming events were similar. However, although strong warming occurred in 2000.1 and 2009.1 in the central Arctic, there were no extremely high temperatures in the corresponding months. It can be seen from Figure 3 that although the AAT distribution in each of these two warming events was similar to that of 2018, the value was much smaller than in 2018. Additionally, the 2006.1 SWE was more akin to a superimposed state of Type A and Type B warming: The AAT during the period of the warming event showed warming along eastern Greenland and the central Arctic, whereas the area of high AAT was mainly in the Nansen Basin. The warming events in the central Arctic in 2006.1 and 2018.2 persisted for a long time, resulting in extremely high temperatures, and the intensity of the 2-month warming event was also extremely high (Figure 4).

Type C warming occurred in 2012.01, 2014.1–2, and 2018.2. Compared with the warming on the Atlantic side, the Type C warming events that occurred in 2012.1 and 2014.2 affected a limited area and were less intense, only reaching the edge of the Pacific sector of the central Arctic. Nevertheless, the Type C warming in 2018.2 reached deep into the central Arctic and was eventually able to connect with a warming anomaly on the Atlantic side. It is suggested that is one of the reasons for the extreme robustness of the 2018.2 SWE.

On the basis of analysis of the warming events in 2006 and 2018, the proposed heating process of Type A warming is as follows. First, a positive anomaly appears on the eastern side of Greenland, which then extends toward the central Arctic. Next, the central Arctic region gradually becomes dominated by positive anomalies until an SWE occurs within the central Arctic. It is worth noting that during a Type A warming event, the warm anomaly along the eastern side of Greenland and the negative anomaly over the European continent appear almost simultaneously.

On the basis of analysis of the SWEs in 2014 and 2016, the proposed warming process corresponding to Type B warming events is as follows. First, a persistent warm anomaly appears over the Arctic marginal seas (Barents–Kara seas). Over time, this warm anomaly gradually extends into the central Arctic. Eventually, a warming event occurs at the margins of the central Arctic. It was also found that Type B warming is usually accompanied by a warm anomaly over the European continent. Compared with Type A warming, the area affected by Type B warming is mainly located within a relatively marginal region of the central Arctic; hence, the intensity of Type B warming events is weaker than that of Type A warming events and the scope of Type B warming events is more limited. If warming events in the central Arctic are a consequence of the transport of warm air from lower latitudes into the Arctic region, then it can be considered that these two types of regional warming should result from different warm air pathways.

On the basis of comprehensive analysis of the highest AAT, total AAT, duration, and scope of the warming events, and with consideration of the SWE intensity (Figure 3) and average area affected by the warming process during the period of each warming event, the characteristics of extremely high temperatures and SWEs over the studied years are summarized in Table 2. Among them, the warming events of 2006.1 and 2018.2 not only produced higher maximum temperature values but also affected larger average areas.

**Table 2** Association between SWEs and extreme high temperatures

| Year | Occurrence of SWEs | Highest AAT SWEs/℃ | Total AAT of SWEs' scope/℃ | Warming area type | If there is an extremely high temperature in the corresponding month. If yes, the value/℃ |
|---|---|---|---|---|---|
| 2000 | 1.1–1.8 | 159.52 | 90606.72 | Area A | none |
| | 3.12–3.19 | 147.75 | 66365.72 | Area B | none |
| 2006 | 1.4–1.25 | 433.44 | 233423 | Area A+Area B | 497.66 |
| 2009 | 1.24–1.30 | 124.49 | 38593.08 | Area A | none |
| 2012 | 1.13–1.19 | 112.76 | 28825.44 | Area A+Area C | none |
| 2014 | 1.24–2.17 | 430.39 | 231318.4 | Area B+Area C | None in January<br>Feburary: 461.25 |
| 2016 | 2.15–2.21 | 95.43 | 37554.24 | Area B | 422.10 |
| 2018 | 1.19–1.25 | 112.68 | 33300.93 | Area B | none |
| | 2.3–2.25 | 376.16 | 287194.5 | Area A+Area C | 411.75 |

It can be determined from Figures 3 and 10 and Table 2 that the warming event in 2018 was strongest, followed by the warming events in 2006 and 2014. The 2006.1 and 2018.2 warming events each persisted for more than 20 d and had a large spatial proportion. The warming event in 2014, which began in January and persisted until February, was a little different from the 2006.1 and 2018.2 events. Even though the spatial percentage and the average impact range were small, the accumulated high temperature over a long period caused the high intensity of this event. It can be inferred from Table 2 that the Type A warming events in 2006.1 and 2018.2 contributed considerably to the extremely high temperatures of the current month (the highest value of the warming event AAT was close to the highest value of the AMAT of the current month). Owing to the SWE in the central Arctic of 2014 that spanned 2 months, the extreme heat that was eventually observed in February was probably the result of the joint effect of the warming events of the 2 months.

Extreme high temperatures were observed within the Arctic Circle in January and February 2016, but no warming event occurred in 2016.1 in the central Arctic, indicating that although strong warming did occur in the Arctic in 2016.1, this strong warming did not affect the central Arctic. Additionally, the highest value of the AAT of the warming event in 2016.2 was much lower than the highest value of the AAT of that month, which indicates that this warming event in the central Arctic was not that strong and did not contribute much to the extremely high temperatures of that month.

### 4.2 Relation with sea ice concentration variation

The variability of sea ice concentration in the central Arctic in the months of September and December since 2000 is illustrated in Figure 11, and the sea ice concentration shown is the average of the sea ice concentration in the central Arctic region defined in Figure 1. Before 2006, the sea ice concentration in September in the Arctic was >0.8. After 2007, the average sea ice concentration in September was mostly <0.8, and the lowest values (<0.7) occurred in 2012 and 2016. From 2000 to December 2019, the average sea ice concentration was at a high level; that is, mostly >0.97 and only as low as 0.96 and 0.90 in 2007 and 2016, respectively.

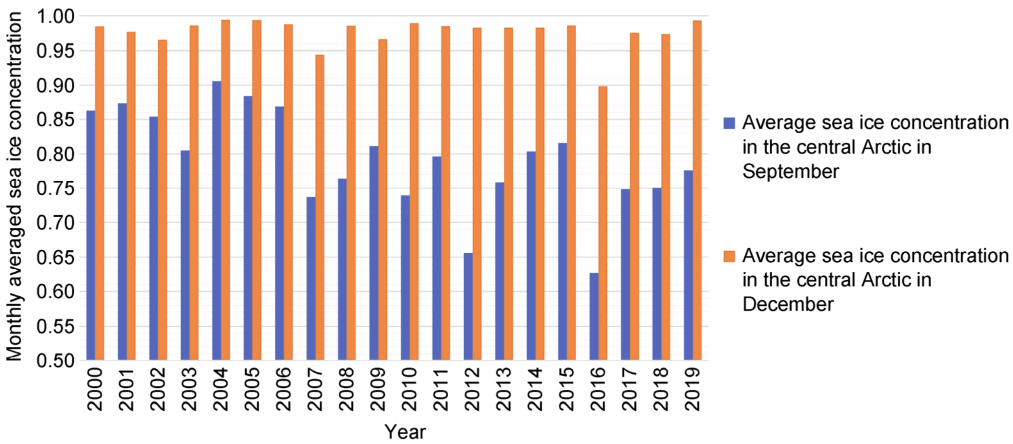


**Figure 11** Variability of sea ice concentration in the central Arctic during autumn (Sep) and winter (Dec) during 2000–2019.

The results show that a decrease in average sea ice concentration over the central Arctic in December is not a factor that induces winter warming. For example, the average sea ice concentration in the central Arctic was very low in 2007 and December 2016, but corresponding SWEs were not observed in 2008 and January 2017. Similarly, a low value of sea ice concentration in September cannot be considered a cause of wintertime SWEs. For example, the average sea ice concentration in the central Arctic in 2012 and September 2016 did not cause subsequent SWEs in 2013 and 2017. The above results indicate that the average sea ice concentration in the years in which SWEs occurred was not a low value, which indicates that the occurrence of SWEs in the Arctic is not dominated by oceanic heating.

The above implies that reduction of sea ice concentration in the central Arctic appears nonconducive to the occurrence of SWEs in the central Arctic. However, our analysis indicates that decrease in sea ice concentration in the central Arctic will increase the amount of oceanic heat that enters the atmosphere (Screen et al., 2014), increasing the occurrence of regional low pressure, which is conducive to warm air entering the marginal seas of the Arctic Ocean but detrimental to the movement of warm air directly into the central Arctic. Further research is needed on the mechanism of this connection.

### 4.3 Relation with sudden stratospheric warming

The phenomenon of SSW refers to reversal of the gradient (in the stratosphere at 10 hPa and below) between the temperature of the North Pole and the zonally averaged temperature of the 60°N latitudinal circle, while the corresponding geopotential height gradient is changed to a pattern of high in the north and low in the south. At high latitudes, the averaged westerly wind north of 60°N is also changed considerably and can even alternate into an easterly wind (Matsuno, 1971). In SSW in winter, the temperature of the stratosphere increases sharply in a short period, possibly by more than 40℃ (Li et al., 2012), and it is closely related to the heat exchange and solar activity of the thermosphere (Chandran et al., 2013). Disturbances generated from the underlying troposphere can propagate upward into the stratosphere (Matsuno, 1971), while anomalies in the stratosphere can also affect the troposphere (Baldwin and Dunkerton, 2001). In the Northern Hemisphere, the SSW that occurs almost annually (de Wit et al., 2014) can be divided into major warming and minor warming depending on its warming intensity. The findings of recent research on Arctic SSW during the studied years are listed in Table 3.

The findings of the current research indicate that the SSW did not closely relate with the occurrence of SWEs in the lower atmosphere. For example, major SSW occurred in 2006, 2007, 2008, 2009, and 2013, whereas surface SWEs occurred only in 2006 and 2009. Furthermore, in terms of temporal sequence, the surface warming events occurred in advance of the SSW. Additionally, it was found that SWEs occurred in the central Arctic region in 2014, 2016, and 2018, while only minor SSW occurred in the same years. It requires approximately 2–3 weeks for warming of the troposphere in response to downward propagation of heat in the polar stratosphere (Zhou et al., 2002). Therefore, based on comparison of the dates of occurrence of SSW (Table 3) and SWEs (Table 2), it is reasonable to claim that there is no inevitable connection between the two phenomena.

Physically, the lower atmosphere of the polar region is generally very stable in cold winter periods given that heat in the upper atmosphere will not sink into the lower atmosphere. Consequently, in such circumstances, the source of heat for lower atmospheric warming phenomena is the lower latitudes. However, an extreme surface warming event can destroy the static stability of the polar atmosphere, which might affect the structure of the upper atmosphere and promote conditions conducive to SSW events. One study has reported that SSW is generated by the propagation of tropospheric planetary waves into the stratosphere and their interaction with the mean currents (Matsuno, 1971). An abnormal increase in planetary waves is one of the characteristics of stratospheric warming. When the amplitude of planetary wave 1 reaches a maximum and the second amplitude reaches a minimum, explosive warming often occurs. An increase of planetary wave 1 is prerequisite for an outbreak of SSW (Labitzke, 1981).

**Table 3** Summary of characteristics of SSW during the studied years, derived from previous research (Manney et al., 2009; Martius et al., 2009; Harada et al., 2010; Gong 2018, 2019; Lü et al., 2020)

| Year | Staring date (MM-DD) | Intensity | Surface SWEs in this year |
|---|---|---|---|
| 2000 | 03-20 | - | 2000-01; 2000-03 |
| 2006 | 01-21 | Major warming | 2006-01 |
| 2009 | 01-23 | Major warming | 2009-01 |
| 2012 | 01-18 | Minor | 2012-01 |
| 2014 | 01-09 | Minor | 2014-01 |
| 2016 | 02-08 | Minor | 2016-02 |
| 2018 | 02-11 | Minor warming | 2018-01; 2018-02 |

### 4.4 Relation with extratropical cyclone activity

The Arctic warming phenomenon is associated with two processes: a strong continuous wind field and cyclonic activity. Generally, a northward airflow along a front can transport large amounts of heat into the Arctic region. However, the areas affected directly by fronts are mainly at the margins of the Arctic Ocean, and few fronts actually enter the central Arctic region. Cyclones can separate from their fronts and move northward into the Arctic Ocean (Basu et al., 2019). Although some Arctic cyclones are generated locally (Waseda et al., 2020), most originate in mid-latitude regions (Simmonds et al., 2008), and extratropical cyclones from mid-latitude ocean areas could contribute substantially to Arctic warming.

The extratropical cyclones that enter the Arctic Ocean region in winter are stronger than those in summer (Zhang et al., 2004). There are three pathways via which extratropical cyclones enter the Arctic region. In wintertime, areas east of the Barents and Kara seas between Norway and Svalbard generally have the highest density of cyclones, and thus cyclones mainly enter the Arctic region from the Norwegian and Barents seas (Serreze et al., 1993; Simmonds et al., 2008).

Cyclonic activity has significant impact on Arctic warming. For instance, studies found that during 28 December 2015 to 4 January 2016, an extremely strong Atlantic storm (called Storm Frank) entered the Arctic Circle and transported warm air from low-latitude areas into the Arctic Ocean region (Boisvert et al., 2016), which caused record-breaking warming in the Arctic in 2016.1 (Kim et al., 2017). In January and February 2016, the concentration of Arctic sea ice also decreased sharply (Kim et al., 2017) to a level recognized as the lowest sea ice concentration in the central Arctic (Wang and Zhao, 2020). Several studies (Boisvert et al., 2016; Moore, 2016) considered the extreme Arctic warming in 2015/2016 a consequence of extratropical cyclone activity. However, by calculating the monthly AAT, it is noteworthy that we found that the warming in January 2016 (not shown) was located over the marginal seas of the Arctic, that is, the Barents–Kara seas. There was no significant warming in the central Arctic in 2016.1, but rapid warming of the marginal sea areas was observed, and the SWE occurred in 2016.2. A previous study highlighted that the pervasive warming over the central Arctic Ocean that occurred in February 2016 was also associated with positive water vapor anomalies and enhanced downwelling longwave radiation (Cullather et al., 2016), which indicates that the SWE in the central Arctic should not simply be linked with extratropical cyclone activities.

Of the five strongest storms that occurred over the North Atlantic during 1979–2015, only two were associated with Arctic warming events, which both occurred after 2000: the storm on 24 December 2013 (called Storm Dirk) and the aforementioned Storm Frank (30 December 2015). This study found that the marginal seas of the Arctic experienced significant warming in both 2014.1 and 2016.1, but the SWEs in the central Arctic eventually occurred in 2014.2 and 2016.2. Figure 12 (taken from Kim et al., 2017) shows that Storm Frank caused an Arctic-wide temperature increase and that this warming continued to 15 February 2016, which provided a high background temperature for the 2016.2 SWE (as shown in Figure 5) that began on 15 February 2016. Therefore, it is plausible to speculate that extratropical cyclones can introduce large amounts of heat into the Arctic region that contribute substantially to Arctic marginal warming. When the marginal sea areas of the Arctic are heated by extratropical storms, such warming can cause subsequent warming events at the margins of the central Arctic.

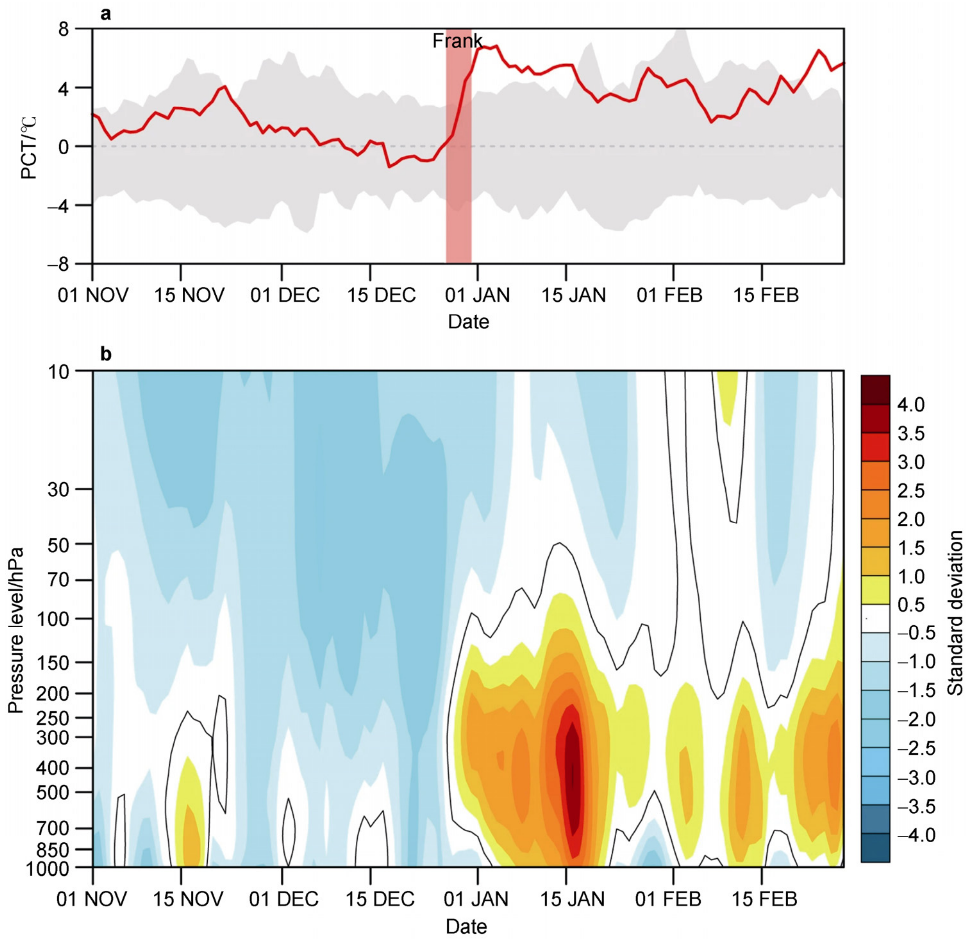


**Figure 12** **a**, Polar cap (north of 65°N) surface air temperature (SAT) anomaly (red line) and **b**, Normalized polar cap geopotential height anomaly (shading) at 32 pressure levels from 1 November 2015 to 28 February 2016. In (**a**), the range of the historical daily SAT anomaly (shading) is based on data from 1979–1980 to 2014–2015, and the translucent red bar indicates the lifetime of Storm Frank. The black solid lines in (**b**) show zero anomalies. The figure is taken from Kim et al. (2017) and exhibits the variation of SAT and geopotential height anomalies before, during, and after Storm Frank.

In some years without intense storms, SWEs still occurred in the central Arctic region. Therefore, although storms might have induced warming in the Arctic marginal sea areas in certain years, they were not the principal driving factor of the warming events in the central Arctic. This study found that of the nine SWEs that occurred during 2000–2019, most were unrelated to extratropical cyclone activities. Results showed that the heat and moisture transported by the extratropical cyclones in the study period did have robust impact on the Arctic climate; however, given that the cyclones could not supply energy continuously, their impact was temporary. Additionally, the average residence time of a storm within the polar region is 2.6 d (Sorteberg and Walsh, 2008), whereas the duration of all the SWEs considered in this research was >7 d. Cyclones can cause substantial warming in a short period, but they cannot account for long-duration SWEs in the central Arctic region. Apparently, SWEs that persist for more than 7 d require a continuous wind field to provide heat. Thus, SWEs that occur in the central Arctic are closely related to variabilities in the wind field.

## 5 Conclusions

On the basis of the number of occurrences, duration, scope, and intensity of Arctic warming events during 2000–2019, the impact of SWEs on Arctic warming was analyzed and the multiyear characteristics of SWEs and their pattern of spatial distribution in the central Arctic were obtained. Through investigation of specific warming events, the possible causes of multiple SWEs and their potential links with changes in sea ice concentration, SSW, and extratropical cyclone activities were explored.

The spatial distribution of abnormally high temperatures in the Arctic during the studied years was categorized into three types. Type A warming, which refers to large-scale warming inside the central Arctic, including warming at the Arctic center and along the north and eastern side of Greenland, occurred in 2000.1, 2009.1, 2018.2, and 2006.1. Type B warming, which refers to warming at the margins of the central Arctic, that is, mainly in the areas of the Nansen Basin and Barents–Kara seas, occurred in 2000.3, 2012.2, 2014.2, 2016.1, 2016.2, and 2018.1. Type C warming, which refers to warming of the edge of the Pacific sector of the Arctic, where high AATs occurred in the Bering Strait, Chukchi Sea Basin, and Mendeleev Ridge, occurred in 2012.1, 2014.1, and 2018.2.

It is noteworthy that the strongest warming event in the studied period was the 2018.2 SWE, followed by the 2006.1 SWE. Both events showed high total AAT values and affected large ranges. Additionally, these two SWEs were classified as Type A warming events, in which warming occurred within the central Arctic. The SWEs in 2006.1, 2014.1–2, and 2018.2 persisted for more than 20 d, whereas the duration of most other warming events was approximately 7 d. Although the SWEs did not necessarily correspond to extremely high temperatures in the same month, the long-term warming events in 2006.1, 2014.1–2, and 2018.2 did make substantial contributions to the extremely high temperatures of the corresponding months. In other warming events, most of the extreme high temperatures occurred not in the central Arctic but in the marginal sea areas.

Through investigation of multiple warming events and analysis of their mechanisms, we found that although warm moist air transported by extratropical cyclones could be the source of heat for warming over the marginal seas of the Arctic, it is not the main cause of all the observed warming events in the central Arctic. Additionally, the impact of SSW on surface warming events in the Arctic was studied; however, no direct temporal correspondence between the two processes was established. Moreover, according to the variability of average sea ice concentration in the central Arctic region in December of each of the studied years, we found that reduction of Arctic sea ice concentration in autumn and winter was not the main inducing factor of winter warming.

Our results showed that the number of warming events in the North Atlantic sector of the Arctic is significantly higher than that of the North Pacific sector; when the warming events occurred, the AAT in the North Atlantic sector was much higher than in other regions. In the 20-year study period, only 2018 experienced significant warming in the North Pacific sector. Many previous observational studies showed that the North Atlantic is the area in which winter warming events are observed most intensively, and it is also the area in which extremely high temperatures in the Arctic are observed most frequently (Graham et al., 2017).

In conclusion, this study found that the spatial characteristics of Arctic warming events can be divided into three categories: warming inside the central Arctic, at the margins of the central Arctic in the Atlantic sector, and at the margins of the central Arctic in the Pacific sector. Through analysis of specific warming event processes, we studied the process of movement of corresponding positive (warming) anomalies in these different warming events. After exploring the potential relationships between SWEs and the variability of sea ice concentration, SSW, and extratropical cyclone activities, we consider that the occurrence of warming events is strongly related to variability of the surface wind field because warm air generally enters the Arctic region in association with the surface wind. Warm anomalies in the Arctic region could reflect the pathway of warm air transport; however, the sources and factors that influence the pathways of warm air transport require deeper research. Hence, future research should analyze the specific causes and dynamic mechanisms of different types of warming event in the central Arctic, based on the characteristics and classification of warming events established in this research. Such an understanding will improve the simulation and prediction of the Arctic and mid-latitude climate by climate models, better illustrate the relationship between Arctic warming and extreme weather in mid-latitude regions, and provide improved support for decision-makers.

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