Comparison of Early-Twentieth-Century Arctic Warming and Contemporary Arctic Warming in the Light of Daily and Subdaily Data

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ABSTRACT: A review of many studies published since the late 1920s reveals that the main driving mechanisms responsible for the early-twentieth-century Arctic warming (ETCAW) are not fully recognized. The main obstacle seems to be our limited knowledge about the climate of this period and some forcings. A deeper knowledge based on greater spatial and temporal resolution data is needed. The article provides new (or improved) knowledge about surface air temperature (SAT) conditions (including their extreme states) in the Arctic during the ETCAW. Daily and subdaily data have been used (mean daily air temperature, maximum and minimum daily temperature, and diurnal temperature range). These were taken from 10 individual years (selected from the period 1934–50) for six meteorological stations representing parts of five Arctic climatic regions. Standard SAT characteristics were analyzed (monthly, seasonal, and yearly means), as were rarely investigated aspects of SAT characteristics (e.g., number of characteristic days, day-to-day temperature variability, and the onset, end, and duration of thermal seasons). The results were compared with analogical calculations done for data taken from the contemporary Arctic warming (CAW) period (2007–16). The Arctic experienced warming between the ETCAW and the CAW. The magnitude of warming was greatest in the Pacific (2.7°C) and Canadian Arctic (1.9°C) regions. A shortening of winter and lengthening of summer were noted. Furthermore, the climate was also a little more continental (except the Russian Arctic) and less stable (greater day-to-day variability and diurnal temperature range) during the ETCAW than during the CAW.

SIGNIFICANCE STATEMENT: It is well established that human activity (particularly increased greenhouse gas emissions) is the primary driving mechanism of the recent dramatic warming in the Arctic. However, the causes of a similar warming here in the first half of the twentieth century remain uncertain. The limited knowledge about the climate of that period—which mainly results from the low resolution of data—is a significant obstacle to a definitive determination of the forcing mechanisms. Therefore, the main aim of our paper is to improve our understanding of specific aspects of weather and climate (including extremes) using long-term series of daily and subdaily data that have rarely been applied for this purpose. This new, more comprehensive knowledge about the historical Arctic climate should allow the scientific community (particularly climate modelers) to better validate both climate models and reanalysis products and, consequently, to more precisely identify the causes of the early-twentieth-century Arctic warming.

KEYWORDS: Atmosphere; Arctic; Airflow; Extreme events; Climate change; Climatology; Surface temperature; Temperature; Climate records; In situ atmospheric observations; Surface observations; Statistics; Time series; Reanalysis data; Annual variations; Climate variability; Diurnal effects

1. Introduction

The 1930s, which were part of the early-twentieth-century Arctic warming (ETCAW, usually defined in the literature as the period 1921–50; see, e.g., Yamanouchi 2011), were the warmest decade in the twentieth century in the Arctic (Przybylak 2007). On the other hand, 10-yr running means of surface air temperature (SAT) calculated for the period since the mid-1990s, when the contemporary Arctic warming (CAW) began, exceeded the values observed in the 1930s (see Przybylak 2007, 2016; Przybylak and Wyszyński 2020). The ETCAW was a prevalent subject of study and analysis among scientists of the time. Wood and Overland (2010) reported that in the first half of the twentieth century, over 1000 articles were published. The literature of this period is reviewed in, for example, Jensen (1939), Ahlmann (1948), Veryard (1963), Wállen (1984), Ellsaesser et al. (1986), Przybylak (1996, 2000a, 2002a, 2003, 2016), Wood and Overland (2010),

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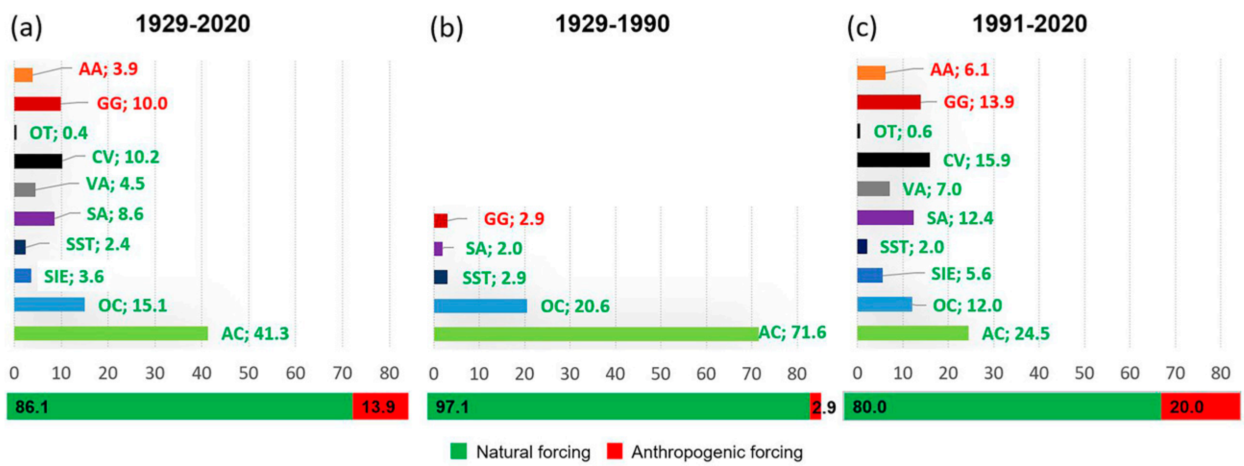

FIG. 1. Development of views on the reasons for occurrence of ETCAW in papers published in (a) 1929–2020, (b) 1929–90, and (c) 1991–2020. Key: Numbers denote percentage of publications in which a given view was presented. Natural forcings: AC, atmospheric circulation; OC, oceanic circulation; SIE, sea ice extent; SST, sea surface temperature; SA, solar irradiation or solar activity; VA, volcanic activity; CV, internal climate variability; OT, other. Anthropogenic forcings: GG, greenhouse gases; AA, atmospheric aerosols.

Brönnimann (2015), and Przybylak et al. (2021). Since the 1980s there has been increased interest in the ETCAW period, and particularly in the reasons for the warming (e.g., Grant et al. 2009; Wood and Overland 2010; Yamanouchi 2011; Hegerl et al. 2018; Svendsen et al. 2018; Xiao et al. 2020, and for more details see Table S1 and supplement 1 in the online supplemental material).

Table S1 shows that there is no general agreement on the causes of the ETCAW, despite nearly a century of effort (see also Bokuchava and Semenov 2021). This is particularly true when articles published in the last 30 years are analyzed (Fig. 1). Conversely, the main driving mechanisms had previously generally been agreed upon among scientists. They believed that the ETCAW was an effect of natural forcing—mainly of changes in atmospheric circulation (71.6%) and, to a lesser degree, oceanic circulation (20.6%). Only Callendar (1938) connected this warming to increased CO_2 concentrations (Table S1, Fig. 1). One possible reason for the lack of consensus over the driving mechanisms still ascribed as having caused the ETCAW is that we have limited knowledge about (i) the weather and climate (including extremes) in this period, (ii) other components of the Arctic climate system (e.g., sea ice, glaciers, SST, aerosols, vegetation cover), and (iii) some forcings (in particular, solar and volcanic) (see, e.g., Bengtsson et al. 2004; Wood and Overland 2010; Suo et al. 2013; Klaus et al. 2018; Przybylak et al. 2021).

Most up-to-date published studies also try to (or their results allow readers to) compare the scale of warming during the ETCAW against the CAW in the Arctic using annual mean values and, more rarely, monthly or seasonal ones (see, e.g., Hanssen-Bauer and Forland 1998; Jones et al. 1999; Delworth and Knutson 2000; Jones and Moberg 2003; Polyakov et al. 2003; Kuzmina et al. 2008; Box et al. 2009; Wood and Overland 2010; Wood et al. 2010; Yamanouchi 2011; Fyfe et al. 2013; Johannessen et al. 2016; Łupikasza and Niedźwiedź 2019; Brennan et al. 2020; Nordli et al. 2020). Meanwhile, Wood and Overland (2010), Yamanouchi (2011), and recently also Wegmann et al. (2017) suggest that a reliable explanation of the ETCAW requires data with greater resolution. To date, however, we have few studies that use measurement data with greater resolution (daily or subdaily) for climate comparison between the studied periods. The direct reason is the limited availability of such data because the instrumental records of Arctic temperature are brief, incomplete, and geographically sparse (Przybylak 2000a). Indeed, only six records extend back to the second half of the nineteenth century (Upernavik: date of start 1874; Jakobshavn: 1874; Godthåb: 1876; Ivigtut: 1880; Malye Karmakuly: 1882, and Angmagssalik: 1895). In the twentieth century, the first station was established in Spitsbergen in 1911 (Green Harbour). In the 1920s, seven stations came into operation, mainly in the Atlantic region of the Arctic. Following the Second Polar Year (1932/33), most Russian stations were established, while most Canadian stations were founded after World War II. As a result, the existing papers using daily and subdaily data analyze temperature in the ETCAW for only a small area, or even a single site, of the Arctic, and for a short time (usually one year) (see, e.g., Klaus et al. 2018; Przybylak et al. 2018; Araźny et al. 2019; Schweiger et al. 2019; Nordli et al. 2020). For the first time, the present paper uses these kinds of data for sites representing a significantly greater area of the Arctic and a more extended period of observations.

The methods used are similar to those that we used earlier for analyses conducted for historical periods before the onset of the ETCAW (Przybylak and Vízi 2005; Przybylak and Wyszyński 2017) and for the ETCAW period itself (Przybylak et al. 2018). Such an approach provides a longer perspective of weather and climate changes in the Arctic. The World Climate Research Program recently recommended an increased effort to extend the historical observational records and analysis to improve, among others, event attribution capabilities

Table 1. Location of Arctic meteorological stations whose daily data series are used in the present article, and their sources.

No.	Station	φ	λ	Altitude (m MSL)	Data used: ETCAW	Data used: CAW	Variable	Data sources
1	Barentsburg	78°04′N	14°15′E	73	1934–40, 1948–50	2007–16	MDAT, TMAX, TMIN	All-Russia Research Institute of Hydrometeorological Information–World Data Centre (RIHMI-WDC), http://meteo.ru/
2	Kanin Nos	68°39′N	43°18′E	48	1934–40, 1948–50			
3	Tiksi	71°35′N	128°55′E	6	1936–40, 1946–50			
4	Ostrov Vrangel	70°59′N	181°31′E	18	1936–40, 1946–50			
5	Coppermine	67°50′N	115°07′W	9	1934–40, 1946, 1947, 1950			The Government of Canada (Environment and Climate Change Canada), https://climate.weather.gc.ca/
6	Ilulissat	69°08′N	51°02′W	39	1939–46, 1948, 1950		TMAX, TMIN	Danish Meteorological Institute (DMI), Cappelen 2020, https://www.dmi.dk/publikationer/

(see National Academies of Sciences Engineering and Medicine 2016). Weather and climate information (including the probability, magnitude, and circumstances of events) is also urgently needed for the so-called counterfactual world (in which human influence on climate is absent). In the Arctic, anthropogenic influences are minimal before the mid-twentieth century, which covers the entire ETCAW.

The main objective of this article is to provide new (or improved) knowledge about rarely studied aspects of SAT conditions (including extremes) in the Arctic during the ETCAW. High-resolution data (daily and subdaily) for selected meteorological stations in five climatic Arctic regions (Treshnikov 1985) have been used. The improved and widened knowledge should be helpful for further investigations, including (i) for the development and validation of climatic models [Latonin et al. (2021) showed that even the multimodel ensemble means in the new generation of high-resolution CMIP6 models do not correctly reproduce the ETCAW (expressed in terms of winter and annual means)] and (ii) for better understanding of the causes and mechanisms of that warming.

This article is structured as follows. Section 2 describes the area, as well as the data and methods used. Section 3 presents the results of the climate comparison between the two analyzed periods (ETCAW and CAW). Section 4 discusses the obtained results, while section 5 presents the most important conclusions and final remarks.

2. Area, data, and methods

The present analysis uses daily and subdaily SAT from six meteorological stations [Barentsburg, Kanin Nos, Tiksi, Ostrov Vrangel, Coppermine, and Ilulissat (Jacobshavn)] located in the five climatic regions (Atlantic, Siberian, Pacific, Canadian, and Baffin Bay) that Treshnikov (1985) distinguished for the Arctic. The analysis characterizes the climate during the ETCAW and its changes in comparison to the CAW periods (Table 1, Fig. 2). The data come directly from the national institutes responsible for meteorological measurements in the Arctic (see Table 1) and therefore are most reliable. The southern boundary of the Arctic and its climatic regions were delimited by the authors of the *Atlas Arktiki* based on (i) analysis of the distribution of mean long-term seasonal and annual fields of all meteorological variables (in case of SAT and sea level pressure, data were taken from period 1881–1965), which covers the study period analyzed in the paper, and (ii) the character of variability of these variables and factors controlling the climate of the Arctic [for more details, see Treshnikov (1985)]. This means that the weather and climate conditions within the distinguished climatic regions must be similar. Przybylak (1997) found that the radius of the extent of statistically significant correlation coefficients of mean seasonal SAT changes at some Arctic stations [Svalbard Lufthavn (Norwegian Arctic), Ostrov Kotelny (Russian Arctic), and Resolute Airport (Canadian Arctic)] in period 1951–90 was equal to 2000–2500 km in winter and 1500–2000 km in summer. Similar results were also obtained by, among others, Eserkepova et al. (1982), Smirnova and Subbotin (1983), and Subbotin (1983). Spatial correlation maps of mean monthly and annual SATs between most of the analyzed stations and the rest of the Arctic (area > 50°N) were drawn using data from 20CRv3 for the periods 1931–50 and 1991–2010. In Figs. S1a and S1b (see supplement 2 in the online supplemental material) we present some of them for January, July, and the full year. The results confirm the significant correlation of SAT in the Arctic during the two periods up to an average radius of about 1000–1400 km around the selected stations in winter and 700–1000 km in summer (except for Barentsburg in the period 1991–2010, where the radius was about 450 km). For the annual means, these ranges

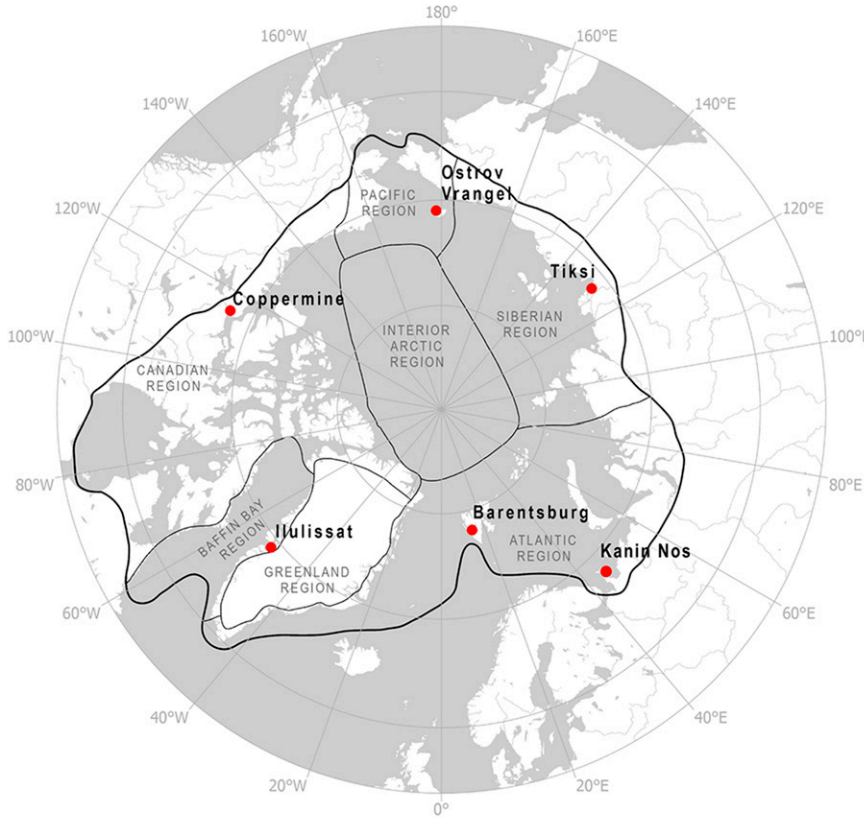

FIG. 2. Location of selected meteorological stations operating in the Arctic during the ETCAW and CAW study periods for which good-quality daily and subdaily air temperature data are available. The Arctic and its climatic regions are defined according to Treshnikov (1985). The southern Arctic boundary is delimited based on analysis using long-term averages of all meteorological variables, their seasonal cycles, and variability characteristics. The thick line is the boundary of the Arctic; thin lines are boundaries between climatic regions.

oscillated between 800 and 1400 km (period 1931–50) and 1400–2100 km (1991–2010). Rigor et al. (2000) also found a significant correlation between 12-hourly SAT observations from land stations and over ice (data from buoys, the International Arctic Buoy Program/POLES) from 1979 to 1998 at ranges of up to 1000 km in winter when most of the bias occurs, and 400–450 km in summer. Donat et al. (2013) estimated the same statistics also (which they called "decorrelation length scales") for the entire globe, but for an extreme temperature index (maximum monthly value of daily maximum temperature) for January, July, and the year. Their results revealed that the correlation of this temperature index is greatest in the polar regions, particularly in the Arctic. The decorrelation length scale values in the Arctic reached about 1100 km for January and 700–800 km for July and the year. The well-documented significant spatial correlation of SAT in the Arctic allows it to be concluded that the different SAT characteristics analyzed for the six stations selected in the paper are representative for large parts of the regions where they lie [i.e., on average within a radius of at least 400–500 km in summer and 1000 km in winter; we also obtained such results for data taken from the ERA5 (Hersbach et al. 2020) reanalysis for period 1991–2010; not shown].

The source data were mean daily air temperature (MDAT) and maximum and minimum daily temperature (TMAX and TMIN, respectively) for all stations except Ilulissat, for which only TMAX and TMIN were available. MDAT was calculated using the following simple formula for this station: MDAT = (TMAX + TMIN)/2. Only the Ilulissat and Kanin Nos stations cover the entire ETCAW, but there are many gaps in the analyzed series, particularly for the 1920s (both stations) and 1930s (only Ilulissat). Other stations were established at the end of the 1920s (Coppermine and Ostrov Vrangel) or shortly after the Second International Polar Year 1932/33 (Barentsburg and Tiksi). For greater comparability of SAT data between the mentioned stations, data were extracted from 1934 to 1950. This period represents the second part of the ETCAW, which is its warmest and climatically most stable subperiod. However, there are also some crucial gaps in the data during World War II, which are particularly large for Barentsburg station (August 1941–November 1947). Because of these gaps, there was no period of at least 10 years for which a continuous sequence existed for all stations. We were able to find only data from 10 individual years. Unfortunately, the gaps also made it impossible to find data for a single set of years common to all stations (see Table 1). These differences in groups of utilized years may have introduced some biases.

The almost complete data series for 1934–50 for Kanin Nos station at the edge of the European Arctic was used to estimate the scale of possible biases. Using these data, we estimated that biases in mean annual and seasonal SAT values at all stations (except Ilulissat) do not exceed ±0.1° and ±0.4°C, respectively. On the other hand, the set of years used for Ilulissat data should introduce a cold bias of about 0.5°C in annual values, on the condition that year-to-year SAT changes in both regions (the European Arctic and the western coast of Greenland) were similar. Such an assumption for these two regions is probably wrong (differences in the influence of the NAO; see Przybylak 2000a). Therefore, we also calculated the differences in mean seasonal and annual SAT between the period 1941–45 and other years from the ETCAW period that were available for Ilulissat station. For both periods, the mean yearly SATs at Ilulissat were the same. Small differences (up to ±0.2°C) were recorded in spring, summer, and fall; winter was 0.4°C colder during World War II. We also checked the influence of these different sets of years on diurnal temperature range (DTR) values in Kanin Nos and Ilulissat. The biases were significantly smaller than those for mean values and did not exceed ±0.2°C for seasonal and annual means. Negligible biases were also found for continentality and oceanicity indices (about 1.5%–2.0% and 0.1, respectively).

The most significant yearly number of gaps in daily data during the ETCAW was recorded at Ilulissat but did not exceed 20 days. Gaps of longer than 10 days occurred only in two years: 1940 and 1948. In the entire 10-yr set of daily data at that station, gaps constitute only about 2%. The only other very small gaps (0.1%–0.2%) were found for Barentsburg and Coppermine, while the data from the other stations are complete. We estimate thus that the influence of those gaps on the presented results is negligible. In accordance with expectation data availability is better for the CAW than for the ETCAW. For the CAW, a continuous 10-yr series of data was used for comparison purposes. Because there is a large gap in the years 2005 and 2006 for Ilulissat station, we took the first available period for analysis (i.e., 2007–16). Detailed dates of gaps in the four thermal parameters are shown in Table S2 (supplement 1).

The following statistics have been calculated using the abovementioned thermal parameters:

1) Monthly, seasonal, and annual means.
2) Annual temperature range (ATR), by subtracting the coldest month's mean temperature from the warmest month's mean temperature.
3) Continentality/oceanicity of climate, using indices proposed by Ewert (1972) and Marsz (1995). The continentality index (K) proposed by Ewert was calculated according to the formula: $K = [\mathrm{ATR} - (3.81\sin\varphi + 0.1)/(38.39\sin\varphi + 7.47)] \times 100\%$, while the oceanicity index of climate (Oc) was calculated according to the formula $\mathrm{Oc} = (0.732\varphi + 1.767)/\mathrm{ATR}$. In both formulas, ATR is the annual temperature range, and φ geographical latitude. Based on the distribution of values of Oc around the world, Marsz (1995) distinguished the following types of climate: ultracontinental (Oc < 1), continental (Oc 1.00–1.99), suboceanic (Oc 2.00–2.99), oceanic (Oc 3.00–3.99), and ultraoceanic (Oc > 3.99). For more details, see Przybylak et al. (2014).
4) Day-to-day MDAT variability (DDTV); two methods were used to describe this characteristic: 1) modulus of MDAT change from one day to the next, and 2) standard deviation (SD) calculated for series of MDAT data taken from each month and season (MAM, JJA, etc.). To investigate the reasons for the highest observed change in DDTV during the ETCAW, we utilized the Twentieth Century Reanalysis version 3 (20CRv3; Slivinski et al. 2019) as synoptic background.
5) Number of days with DTR of ≥5°C, ≥10°C, and ≥15°C; DTR was calculated by subtracting TMIN from TMAX.
6) Number of so-called characteristic days, distinguished according to criteria proposed originally by Przybylak and Vízi (2005) and slightly modified for the present paper:

   TMAX > 15°C = exceptionally warm day
   TMAX > 10°C = very warm day
   TMAX > 5°C = warm day
   TMIN > 0°C = no-frost day
   TMAX > 0°C and TMIN ≤ 0°C = slight frost day
   TMAX < 0°C = frost day
   TMAX < −10°C = cold day
   TMAX < −20°C = very cold day
   TMAX < −30°C = exceptionally cold day

7) Thermal seasons (winter, spring, summer, and fall), using the following criteria proposed by Baranowski (1968):

   winter: MDAT ≤ −2.5°C
   spring and fall: −2.5°C < MDAT < 2.5°C
   summer: MDAT ≥ 2.5°C

The threshold values were distinguished based on analysis of the yearly cycle of MDATs in Hornsund (1957–60) and their monthly distributions stratified into 2°C intervals.

The onset and end of a particular thermal season were calculated using the following formulas constructed by Gumiński (1948):

$$x = \frac{t_p - t_1}{t_2 - t_1} 30, \qquad (1)$$

$$x = \frac{t_1 - t_p}{t_1 - t_2} 30, \qquad (2)$$

where

(1) is the formula used for rising air temperature in the annual cycle,
(2) is the formula used for falling air temperature in the annual cycle,

t_1 = mean air temperature in the month preceding occurrence of threshold temperature,
t_2 = mean air temperature in the month following the occurrence of threshold temperature,
t_p = value of threshold air temperature, and
x = number of days between the day of threshold air temperature and the 15th day of the preceding month.

Method assumptions:

- Monthly mean air temperature falls on the 15th day of the month
- Every month has 30 days
- Air temperature changes steadily (rise, fall) from month to month

The number of days (x) calculated from both formulas is added to the 15th day of the preceding month. If the value is greater than 15, the real number of days in this month (28, 30, or 31) is used in the process of adding. In this way, the sought date is obtained: it will be the date of the end of a given season or the date of the onset of the next season, depending on which seasonal threshold the air temperature is being counted for.

3. Results

a. Monthly resolution

Looking at spatially averaged SAT changes in the Arctic (65°–90°N) in 1900–2014, it is apparent that the two study periods (1934–50 and 2007–16) represent the warmest phases of the ETCAW and CAW, respectively [see Fig. 1 in Bekryaev et al. (2010) or Fig. 1 in Johannessen et al. (2016)]. This means that the period of greatest warming rate (in historical time or in the present) can be more correctly estimated.

Annual cycles of mean monthly SATs in the analyzed Arctic stations during the ETCAW and CAW periods are presented, alongside their differences, in Table S3 (supplement 1) and Fig. 3. Almost all monthly and seasonal means were greater in the CAW than in the ETCAW, except at the Ilulissat station (Table 2, Fig. 3). The evidently most significant SAT increases between the ETCAW and the CAW occurred in the Pacific region (2.7°C on average) and the Canadian region (1.9°C) (Table 2). Warming in these regions was recorded mainly in the cold half-year, at more than 3° and 2°C, respectively. By contrast, the smallest warming was recorded in the Baffin Bay region (on average only 0.2°C) and occurred only in winter (being of 1.2°C) and summer (0.5°C) (Table 2).

A significant feature of climate classification procedures is a description of the degree of climate continentality/oceanicity. To roughly estimate climate continentality/oceanicity, the ATR is usually used. Still, for scientific purposes, climate continentality/oceanicity needs to be evaluated precisely by calculating indices (see section 2 for more details) that eliminate the influence of latitude on the ATR value.

The highest continentalities and lowest oceanicities of climate in both study periods occurred in the Siberian region (Tiksi) and the Canadian region (Coppermine), at about 80%–85% and 1.3–1.4, respectively. By contrast, the smallest continentality and greatest oceanicity of climate were recorded in the Atlantic region; at Barentsburg, calculated indices are about 30% and 3.2–3.6, respectively (Table 3). The climate continentality index in the Arctic was usually 1%–4% greater during the ETCAW than during the CAW, except in the Russian Arctic.

b. Daily and subdaily resolution

It is well known that in the process of averaging "raw" meteorological data for increasingly longer periods, important climatic information (including climate change detection) may very often be lost (Robinson et al. 1995). Therefore, as in our previous papers analyzing temperature changes in the Arctic from historical periods to the present (Przybylak and Vízi 2005; Przybylak and Wyszyński 2017; Przybylak et al. 2018), we decided to analyze more precisely the SAT regime for the Arctic using different parameters of daily data [TMEAN (mean monthly air temperatures), TMAX, TMIN, and DTR].

1) Annual cycles

A comparison of 10-yr mean annual cycles of MDAT in both analyzed periods and their differences is shown in Fig. 4. On average, most days in the ETCAW were colder than in the CAW, except at Ilulissat station, where a more or less equal number of positive and negative daily differences is recorded. It is very apparent that areas of greatest climate continentality (the Siberian and Canadian regions) have a less stable range of differences than the places with the smallest continentality (the Atlantic and Pacific regions). There is a clear domination of negative differences in these latter areas, with only minor exceptions (Figs. 4b,d,h). On the other hand, in areas with large climate continentality, many positive differences are recorded, particularly in February and March (see Figs. 4f,j).

2) Day-to-day MDAT variability

Several papers based on climate model simulations argue that high-frequency temperature variability should decrease in a warmer climate (e.g., Houghton et al. 1990, 1992, 1996; Karl et al. 1995, and references cited therein; Mearns et al. 1995; Zwiers and Kharin 1998; Moberg et al. 2000; Screen 2014). In the present paper, intraseasonal variability of MDAT is analyzed using DDTV and SD. Earlier in the article, we proved that the ETCAW was colder than the CAW, and therefore greater MDAT variability is expected in the ETCAW than in the CAW. Analysis of Table 4 and Fig. 5 generally confirms the existence of such a tendency, except in the Baffin Bay region.

In both study periods, DDTV and SD are greatest in winter and smallest in summer (Table 4, Figs. 5a,c). Such a pattern is typical for the Arctic (e.g., Przybylak 2002b; Schweiger et al. 2019). Differences in MDAT variability between the ETCAW and CAW periods, both positive and negative, are greatest from October to April and smallest in July and August (see Fig. 5b,d). It is worth noting that the decrease in MDAT

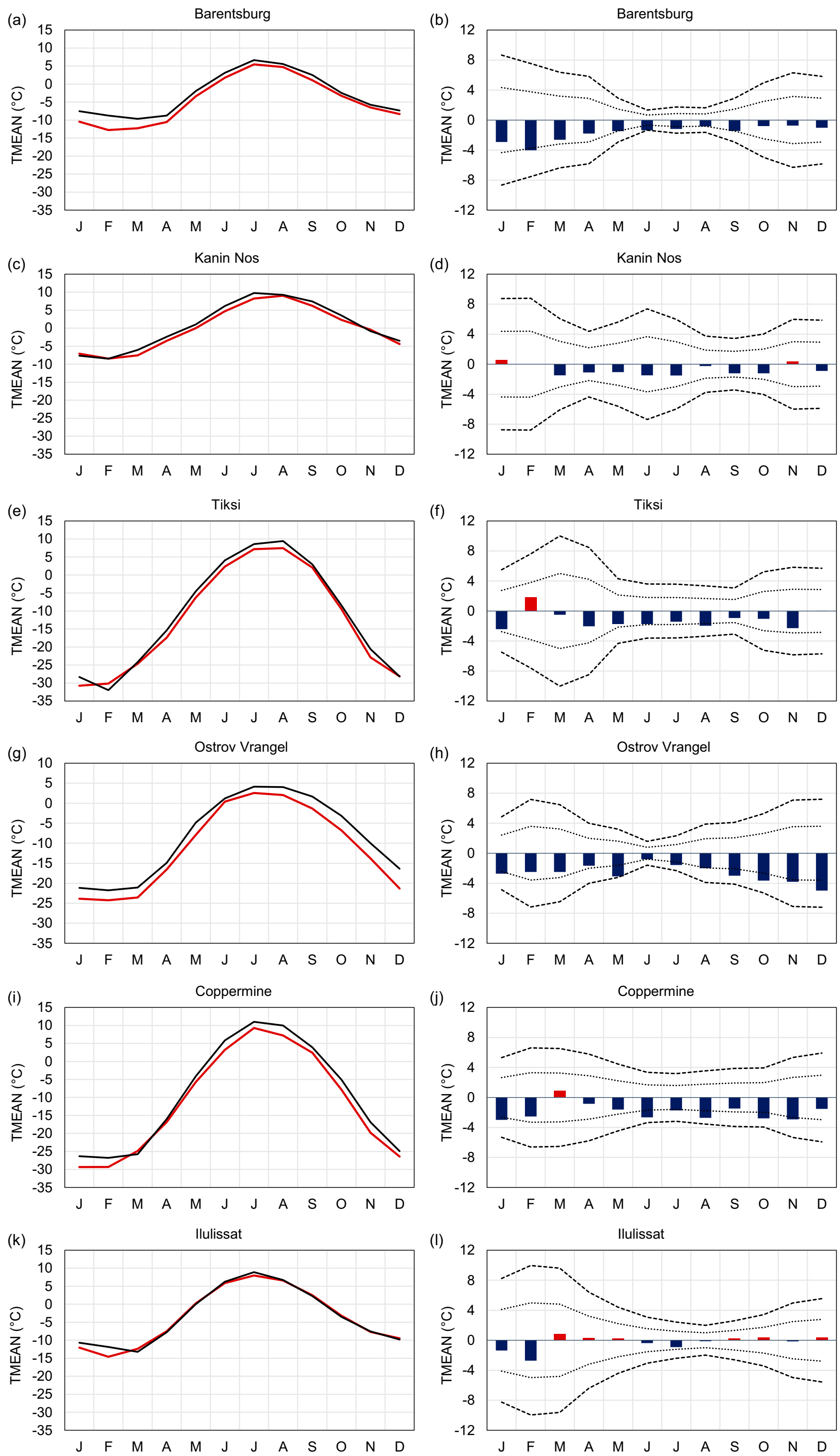

FIG. 3. (a),(c),(e),(g),(i),(k) Annual cycles of 10-yr mean monthly air temperatures (TMEAN) in the analyzed Arctic stations during ETCAW (solid red line) and CAW (solid black line) periods and (b),(d),(f),(h),(j),(l) their differences (bars) between ETCAW and CAW periods. Data from CAW were subtracted from ETCAW. Variability of mean monthly air temperature shown using SD calculated from a 30-yr period (1990–2019), with distances of ±1 and ±2 SD from mean presented as dotted and dashed lines, respectively.

TABLE 2. 10-yr seasonal and annual (YEAR) means of air temperature (°C) in analyzed Arctic stations in ETCAW and CAW periods, and differences (ETCAW − CAW).

Station	Period	DJF	MAM	JJA	SON	YEAR
Barentsburg	ETCAW	−10.5	−8.7	4.0	−2.9	−4.5
	CAW	−7.9	−6.8	5.1	−1.9	−2.9
	ETCAW − CAW	−2.6	−1.9	−1.1	−1.0	−1.6
Kanin Nos	ETCAW	−6.6	−3.7	7.3	2.7	−0.1
	CAW	−6.5	−2.5	8.4	3.4	0.7
	ETCAW − CAW	−0.1	−1.2	−1.1	−0.7	−0.8
Tiksi	ETCAW	−29.7	−16.1	5.7	−10.1	−12.5
	CAW	−29.5	−14.7	7.4	−8.7	−11.4
	ETCAW − CAW	−0.2	−1.4	−1.7	−1.4	−1.1
Ostrov Vrangel	ETCAW	−23.2	−16.0	1.7	−7.3	−11.2
	CAW	−19.8	−13.6	3.1	−3.8	−8.5
	ETCAW − CAW	−3.4	−2.4	−1.4	−3.5	−2.7
Coppermine	ETCAW	−28.3	−15.8	6.6	−8.4	−11.5
	CAW	−26.0	−15.3	8.9	−6.0	−9.6
	ETCAW − CAW	−2.3	−0.5	−2.3	−2.4	−1.9
Ilulissat	ETCAW	−12.0	−6.5	6.8	−2.8	−3.6
	CAW	−10.8	−7.0	7.3	−2.9	−3.4
	ETCAW − CAW	−1.2	0.5	−0.5	0.1	−0.2

variability in a warmer climate is markedly registered. Its rate usually increases in areas with smaller (greater) climate continentality (oceanicity). Therefore, the most significant changes between ETCAW and CAW periods were observed in stations lying on islands (Barentsburg and Ostrov Vrangel) in the Atlantic and Pacific regions.

The annual cycles of extreme DDTV (Fig. S2, supplement 2) show similar features, as do the mean values of DDTV (Fig. 5). In both analyzed periods, markedly greater extremes of DDTV were recorded in the cold half-year than in the warm half-year. The contrast between them is particularly huge in the areas with a degree of climate continentality (Barentsburg and Ostrov Vrangel) (see Fig. S2). An unclear pattern of changes in extreme DDTV (both rises and drops) between the ETCAW and CAW is generally recorded (see red and blue values in Fig. S2).

In the cold half-year (November to April), extreme DDTV (both drops and rises) usually exceeds 10°C, and very often also 15°C. The highest observed jump in DDTV (of 25.8°C) occurred at Barentsburg from 14 to 15 March 1948 (Table S4, supplement 1). Araźny (2008) also documented similar large jumps in DDTV in the Norwegian Arctic in contemporary times; for example, at Svalbard Airport (approximately 35 km northeast of Barentsburg), MDAT increased from −28.2°C on 3 March 1976 to −0.9°C the next day. Przybylak (1992) found that the greatest DDTV changes in the Arctic are associated with nonperiodic changes in air temperature caused by changes in atmospheric circulation.

In the analyzed case study of extreme DDTV (14–15 March 1948), within 24 h atmospheric pressure fell by about 30 hPa, wind speed increased from 1 to 10 m s^{-1}, and wind direction changed from north to southeast at the grid point near Barentsburg (see Fig. 6). The synoptic situation that mainly explains the described dramatic, highly atypical weather changes in Svalbard is shown as an animation in online supplement 3. A deep cyclone with pressure oscillating around 970 hPa in the center of the Greenland Sea pushed a high pressure system situated over Svalbard eastward, causing the fast advection of very warm (5°–10°C) air masses from the south to reach Svalbard. Therefore, it can be stated that 20CRv3 correctly reproduced this extreme weather pattern, similarly as was earlier documented for other extreme weather cases from lower latitudes (see Fig. 16 in Slivinski et al. 2019, and Fig. 3 in Slivinski et al. 2021).

3) Diurnal temperature range

Diurnal temperature range is a very useful and valuable weather characteristic. For the Arctic its high values in the warm half-year, and particularly in the summer months, are a proxy for more or less stable, sunny weather with calm or weak wind resulting from the occurrence of a high pressure system (anticyclone). Only in this period does a statistically significant negative correlation exist between cloudiness and DTR, although not in all Arctic regions (Przybylak 1997). On the other hand, a slight positive correlation prevailed in winter that was not statistically significant, except for one station located in the Baffin Bay region. This means that, in this season, other factors controlled the magnitude of the DTR. Baranowski (1968), Przybylak (1992), Araźny (2008, 2019), and Araźny et al. (2018) used temperature data from Svalbard to show that the DTR in winter, early spring, and late fall (when the solar radiation is low or not present) was shaped mainly by nonperiodic day-to-day changes in air temperature. Conversely, the latter changes were controlled largely by the advection of warm and humid air masses associated with synoptic-scale cyclones and anticyclones.

The highest values of the DTR in the Arctic during the ETCAW were observed in March and April (except at stations in the Atlantic region), while the lowest occurred almost exclusively in September (Fig. 7). Continental parts of the Arctic

TABLE 3. 10-yr averages of annual air temperature range (ATR), thermal climate continentality index (K) according to Ewert's (1972) formula, and thermal oceanicity index (Oc) according to Marsz's (1995) formula during ETCAW and CAW periods, and differences (ETCAW − CAW).

	ETCAW			CAW			ETCAW − CAW		
Station	ATR (°C)	K (%)	Oc	ATR (°C)	K (%)	Oc	ATR (°C)	K (%)	Oc
Barentsburg	18.2	32.4	3.2	16.3	28.2	3.6	1.9	4.2	−0.4
Kanin Nos	17.5	32.5	3.0	18.2	34.1	2.9	−0.7	−1.6	0.1
Tiksi	38.2	79.0	1.4	41.4	86.3	1.3	−3.2	−7.3	0.1
Ostrov Vrangel	26.8	53.3	2.0	25.9	51.2	2.1	0.9	2.1	−0.1
Coppermine	38.6	81.7	1.3	37.8	79.8	1.4	0.8	1.9	−0.1
Ilulissat	22.6	44.1	2.3	22.1	43.1	2.4	0.5	1.0	−0.1

have the highest mean annual DTR values (Tiksi and Coppermine: about 7°–8°C), while the most oceanic had the lowest (Barentsburg and Kanin Nos: 4°–5°C) (Table 5). In the mentioned continental parts of the Arctic, mean seasonal values were highest in both analyzed periods in spring (8.5°–9.0°C) and lowest in fall (6.1°–6.6°C). In turn, in the Atlantic region, DTR is highest in winter and lowest in summer (Barentsburg) or shows two maxima, one in summer and one in winter (Kanin Nos) (Table 5).

A comparison of mean monthly, seasonal, and annual values of DTR between the ETCAW and CAW is shown in Table 5 and Fig. 7. Their analysis reveals that, during the ETCAW, the DTR was usually greater than in recent times, excluding in the most continental parts of the Arctic where, in annual terms, there was no change (Tiksi) or DTR was lower (Coppermine) (Table 5). Such a pattern was also usually observed in all seasons, except summer, when rises in DTRs dominated between the ETCAW and CAW periods (except for the Atlantic region) (Table 5, Fig. 7).

The occurrence of large and extremely large DTR values reaching at least 5°, 10°, or 15°C during the ETCAW period reveal a clear annual cycle similar to that shown for mean values (cf. Figs. 7 and 8). The probability of occurrence of such defined DTRs, particularly those reaching at least 10°C, is definitely greater during the cold half-year (October–April) than the warm half-year. This pattern is evident in stations representing the most oceanic climate, where in summer extremely large DTRs (at least ≥10°C) were observed either not at all (Barentsburg) or very rarely (Kanin Nos, Ilulissat, and Ostrov Vrangel; <10%) (see Table S5, supplement 1).

Both large (≥5°C) and extremely large (≥10°C and ≥15°C) DTRs in areas of oceanic climate mainly showed the greatest average frequency of occurrence in the ETCAW period rather than in present times in all seasons except summer (see Table S5 and Fig. 8). At Ilulissat, large DTRs occurred during the ETCAW period far less frequently than at present (on average 11.2% less), while extremely large DTRs showed opposite relations, except in summer (see Table S5 and Fig. 8). For stations representing continental climate (Tiksi and Coppermine), the picture is more complicated, particularly for extremely large DTRs. Generally, changes are smaller and more stable here than in the oceanic stations; their monthly values usually do not exceed 10% (Fig. 8).

4) CHARACTERISTIC DAYS

To estimate in more depth the thermal conditions during the ETCAW, the frequencies of occurrence of days that exceed defined thresholds have been calculated (for details, see section 2) and presented in Table S6 (supplement 1), Fig. S4 (supplement 2), and Fig. 9.

Exceptionally cold days (TMAX < −30°C) were not present or were recorded very rarely during the ETCAW period at stations representing oceanic climate (Barentsburg, Kanin Nos, Ostrov Vrangel, and Ilulissat), whereas in the continental parts of the Arctic (Tiksi and Coppermine) they occurred from November to March with a maximum frequency of about 20%–35% in January and February (Fig. S3, supplement 2). Very cold days (TMAX < −20°C) were significantly more common in the latter group of stations (50%–80%), while in the former they were not frequent (less than 10%), except at Ostrov Vrangel (40%–50%) (Table S6, Fig. S3). Such a frequency pattern of highest/lowest values in continental/oceanic parts of the Arctic is also seen for cold days (TMAX < −10°C). On the other hand, frost days were not registered only in July and August (except at Ostrov Vrangel), whereas in the cold half-year (November–April) they were the norm.

Slight frost days (TMAX > 0°C and TMIN ≤ 0°C) and no-frost days (TMIN > 0°C) were recorded in almost all months in stations lying in oceanic parts of the Arctic (except Ostrov Vrangel) (Fig. S3). At the rest of the stations, these days were not usually present from November to March.

TMAX above 5°C was recorded mostly from April/May (except Ilulissat, where they occurred in all months) until October. Their greatest frequency at all stations was recorded in July and August (80%–100%), except at Ostrov Vrangel (40%–50%). Temperatures above 10°C were not very frequent at Svalbard and Ostrov Vrangel (usually much below 10% of days in a month). At the other stations, they occurred with a frequency oscillating between 40% and 70% in July and August (Fig. S3). During the ETCAW exceptionally warm days (TMAX >15°C) were recorded only at stations representing a continental climate and at Ilulissat from May to September, with a maximum usually in July (Fig. S3).

Table S6 and Fig. 9 summarize the results of changes that occurred in the described frequency of characteristic days between the ETCAW and CAW periods. At present, we usually have fewer days of all categories of cold days and more

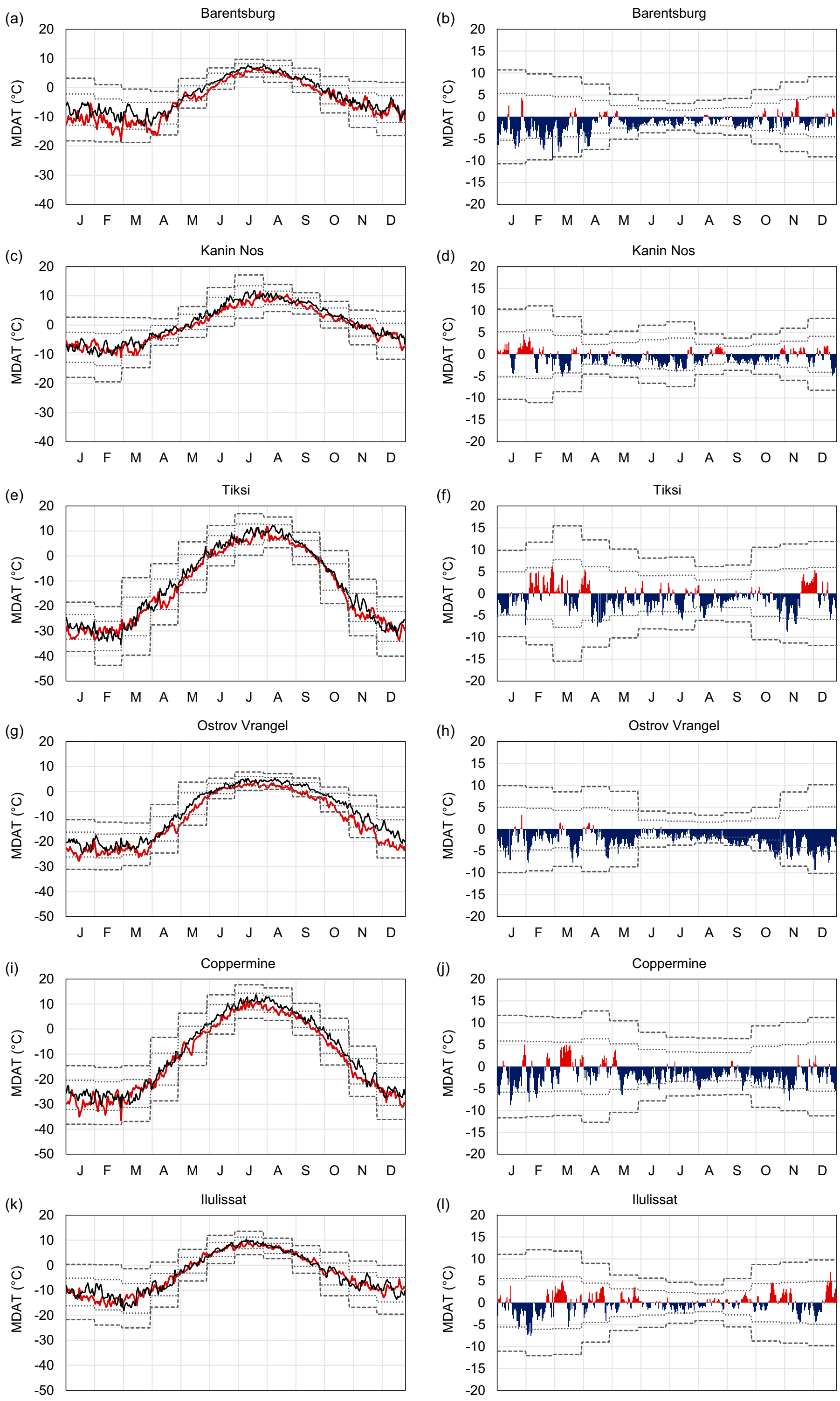

FIG. 4. (a),(c),(e),(g),(i),(k) 10-yr mean annual cycles of MDAT in ETCAW (solid red line) and CAW (solid black line) periods, and their (b),(d),(f),(h),(j),(l) mean daily differences (bars) between ETCAW and CAW periods. Data from CAW were subtracted from ETCAW. Dotted and dashed lines indicate ±1 SD and ±2 SD, respectively. SDs are calculated on basis of data for 2007–16.

TABLE 4. Mean seasonal and annual values of DDTV and SD in analyzed Arctic stations in the ETCAW and CAW periods.

Station	Period	DJF	MAM	JJA	SON	Year
DDTV (°C)						
Barentsburg	ETCAW	3.4	2.3	1.1	2.0	2.2
	CAW	2.6	1.9	0.9	1.9	1.8
Kanin Nos	ETCAW	2.2	1.6	1.6	1.3	1.7
	CAW	2.2	1.5	1.6	1.2	1.6
Tiksi	ETCAW	3.4	3.4	2.3	2.5	2.9
	CAW	3.3	3.1	2.4	2.4	2.8
Ostrov Vrangel	ETCAW	3.1	2.4	1.3	2.0	2.2
	CAW	2.8	2.0	1.3	1.5	1.9
Coppermine	ETCAW	3.4	3.0	2.3	2.4	2.8
	CAW	3.6	2.8	2.1	2.4	2.7
Ilulissat	ETCAW	2.6	2.2	1.5	1.8	2.0
	CAW	2.9	2.3	1.6	2.1	2.2
SD (°C)						
Barentsburg	ETCAW	5.6	4.8	1.8	3.5	3.9
	CAW	4.9	3.6	1.7	3.1	3.3
Kanin Nos	ETCAW	4.2	3.0	3.0	2.3	3.1
	CAW	3.9	2.7	2.8	2.2	2.9
Tiksi	ETCAW	5.5	6.1	3.7	4.9	5.0
	CAW	5.6	6.3	3.8	4.7	5.1
Ostrov Vrangel	ETCAW	4.8	4.7	1.8	3.9	3.8
	CAW	4.9	4.5	1.8	2.9	3.5
Coppermine	ETCAW	5.5	5.8	3.3	4.5	4.8
	CAW	5.7	5.7	3.5	4.3	4.8
Ilulissat	ETCAW	5.2	4.5	2.4	3.5	3.9
	CAW	5.5	4.5	2.4	3.9	4.1

warm days than in the ETCAW, except at Ilulissat, where no significant changes occurred (Table S6, Fig. 9). The direction of changes (decrease/increase) in the number of slight frost days depends on the month, but this category of days was generally more common during the ETCAW than today.

5) THERMAL SEASONS

Baranowski (1968) proposed to use two thresholds of MDAT values for Arctic climate conditions (−2.5° and 2.5°C) to delimit four seasons (for more details, see section 2). His proposition was used in our previous papers studying historical climate in Novaya Zemlya (Przybylak and Wyszyński 2017) and Svalbard (Przybylak et al. 2018). Such an approach allows us to study other valuable aspects of thermal seasons (besides their mean values) such as onset, end, and duration. These additional aspects of thermal seasons are also crucial, as are their mean values, and therefore more research is needed.

Winter is the longest season, exceeding 200 days everywhere except at Kanin Nos (Table 6). However, from the ETCAW to the CAW, the winter became shorter by 2%–8% (8–28 days), except at Ilulissat, where it is presently two days longer (Fig. 10). Summer in all analyzed stations is usually the second-longest season. The summer duration between ETCAW and CAW lengthened by between 12 days (Tiksi) and 63 days (Ostrov Vrangel), except at Ilulissat station, where at present it is two days shorter (Table 6). Changes in duration were smallest for the transitional seasons, except at Ostrov Vrangel in fall (Table 6, Fig. 10). In conclusion, one must say that the ETCAW was characterized by longer winters, springs, and falls, and shorter summers (Fig. 10). The greatest changes in almost all areas were recorded in summer. In contrast, in terms of mean values the most significant changes occurred in winter at most stations. The direction of these changes agrees well with the changes expected due to the increasing warming of the Arctic, which has been particularly great in the twenty-first century.

4. Discussion

The current warming of the Arctic, which is progressing at a rate comparable to that recorded in the first half of the twentieth century, has undoubtedly inspired many researchers to analyze in detail the climatic conditions (especially SAT) of this second period. They have been interested not only in studying the magnitude of the warming but also its causes. The literature review presented in the introduction shows that although many publications have appeared, many of the thermal characteristics analyzed in this paper (other than the standard monthly, seasonal, or annual averages) have been little studied for the Arctic.

This paper analyzes several important thermal characteristics based on daily and subdaily data (including extremes). All climate models simulating future climate indicate that extremes will play a more significant role than they do now. They are expected to increase in both frequency and magnitude. The models reveal that, in the future, average values of

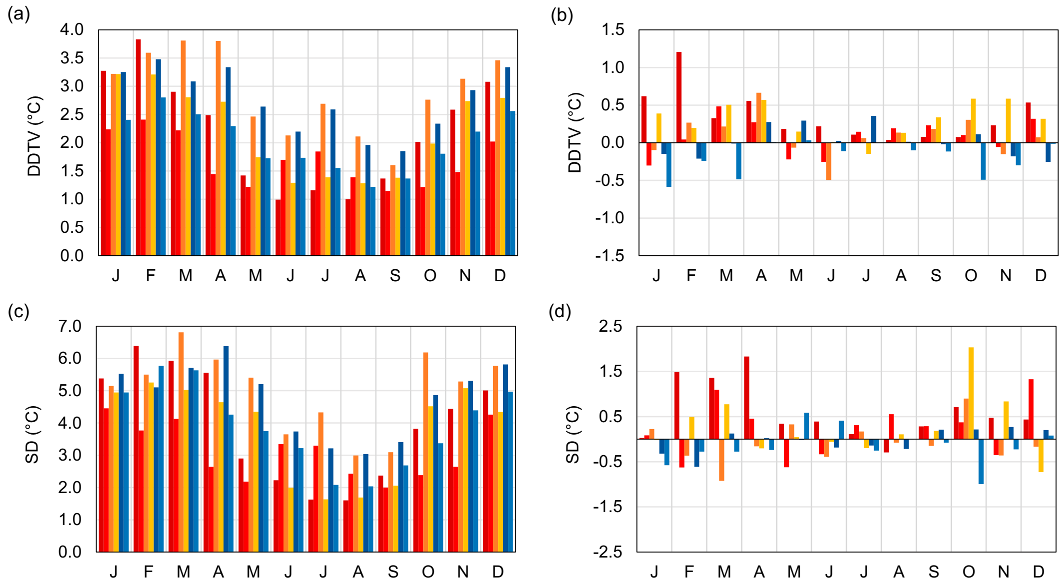

FIG. 5. (a) Average 10-yr monthly means of DDTV in the Arctic stations during the ETCAW period, and (b) their differences in relation to the CAW period. Bars from left to right denote Barentsburg (dark red), Kanin Nos (light red), Tiksi (orange), Ostrov Vrangel (yellow), Coppermine (dark blue), and Ilulissat light blue), (c),(d) As in (a) and (b), but for SD.

extreme temperature will increase by double the warming in mean temperature. Hegerl et al. (2004) and Portmann et al. (2009) found that changes between means and extremes, minimum and maximum, and upper and lower tail can be significantly different in rate, and even opposite. Zhang et al. (2011) also underline that information about the far tails of the SAT distribution is more relevant to society and the environment than information about temperatures characterizing more frequently occurring aspects of the distribution. For these reasons, the climate models need to simulate both the mean states of the future atmosphere and its extreme conditions (Sillmann et al. 2013). However, the models should first be validated using both present and historical climate data. For validation, however, good-quality data are needed. Such data are particularly crucial for the Arctic, where, even today, the network of stations is very scarce (see section 2).

Latonin et al. (2021) showed that even the multimodel ensemble means in the new generation of high-resolution CMIP6 models do not correctly reproduce the ETCAW (expressed in terms of winter and annual means). The HIRHAM5 regional climate model, too, was not able correctly to reconstruct the annual cycle of daily temperature (overwintering 1930–31) in Franz Joseph Land, particularly in the cold half of the year (Klaus et al. 2018). We can thus expect that temperature extremes for the ETCAW period will also not be captured well, and those discrepancies in observations will be greater than those for mean values. Such a conclusion is strongly supported by results obtained by Sillmann et al. (2013). They showed a large discrepancy between globally averaged extreme temperature indices (hottest and coldest day of a year) selected from four reanalyses (ERA-40, ERA-Interim, NCEP–NCAR, and NCEP–DOE) for the period 1948–2010. Substantial differences between the models (CMIP3 and CMIP5) and the mentioned reanalyses are also evident in their study. The models and reanalyses also disagree with HadEX2 (gridded dataset of indices, updated version; Donat et al. 2013) for the abovementioned temperature extreme indices and the DTR. This discrepancy is particularly evident in Alaska and Greenland (two Arctic regions they analyzed). Sillmann et al. (2013) also suggest that HadEX2 values may be biased by poor observational network coverage in these regions. This weakness of the network is confirmed by the results of climate extremes (data taken from five regional and global reanalyses from the period 2000–16) across the North American Arctic presented recently by Avila-Diaz et al. (2021). Relative to observations, the reanalyses reveal the weakest performance over far northern basins (e.g., the Arctic Ocean and Hudson Bay basins), where observation networks are less dense. However, whatever the shortcomings of the present network, it is nevertheless significantly denser now than it was during the ETCAW.

Investigations conducted by, among others, Brönnimann et al. (2018, 2019) and Slivinski et al. (2019, 2021) have documented the importance of historical data for improving the quality of reanalyses and simulating past climates using climate models, and for identifying factors controlling climate changes. Therefore, there is an urgent need to study climate change in the Arctic in a longer perspective—as Avila-Diaz et al. (2021) described it: “not just in an average sense, but in extreme events that have significant impacts on people and places” (p. 2385). The climate analysis presented in the paper using the many different temperature characteristics (including extremes) for the Arctic for the ETCAW is unique in terms of the characteristics’ comprehensiveness and the

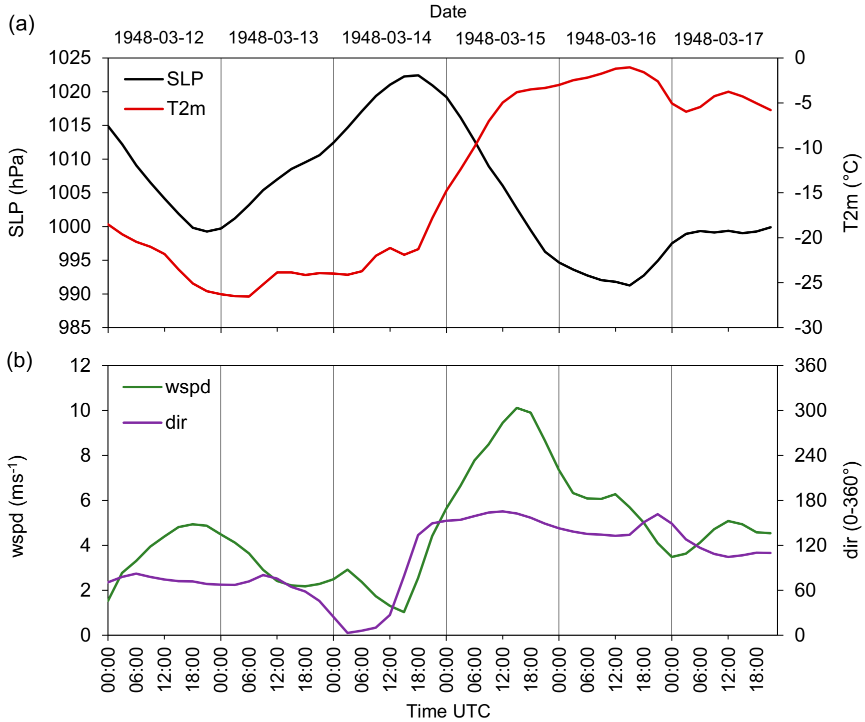

FIG. 6. Courses of (a) sea level pressure (SLP; hPa) and air temperature at 2 m AGL (T2m; °C) and (b) wind speed at 10 m AGL (wspd; m s^{-1}) and wind direction (dir; 0°–360°) in the nearest 20CRv3 (Slivinski et al. 2019) grid point (78.00°N, 14.00°E) to Barentsburg (78.07°N, 14.25°E) from 12 Mar 1948 to 17 Mar 1948.

number of daily and subdaily data used from meteorological stations. Based on the review of recently published results done by Przybylak and Wyszyński (2020) and the present analysis, we can conclude that good-quality data series from stations should still be used to analyze long-term SAT trends and other temperature characteristics (including extremes) in the Arctic.

As was mentioned in the introduction, there exist very few studies that analyze the climate of the ETCAW using daily and subdaily data. As a result, the comparison of the results presented here and in other studies is limited. Similar to other authors (e.g., Johannessen et al. 2016), we confirmed that the rate and magnitude of warming are greater in the present than in the historical period. From the ETCAW to the CAW, the scale of warming in the Arctic was not spatially homogeneous. The greatest warming occurred in the Pacific and Canadian Arctic regions, as Przybylak (2007) noted. During the ETCAW, the warming was greatest in the Atlantic region (Przybylak 2000a, 2002a). This ETCAW–CAW change in the spatial pattern of warming is connected with the decrease in sea ice extent being greatest in the Pacific sector of the Arctic (Shalina et al. 2020). The smallest changes between the ETCAW and the CAW occurred in the western coast of Greenland, which is in line with results presented for

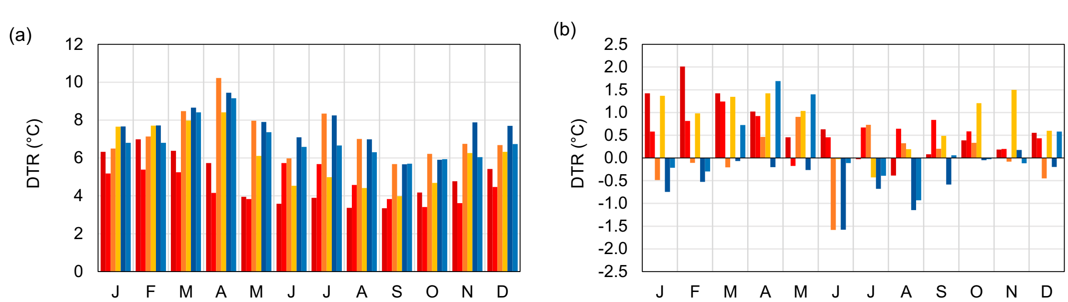

FIG. 7. (a) Average 10-yr monthly means of diurnal temperature range (DTR) in the Arctic stations during the ETCAW period, and (b) their differences in relation to the CAW period. Bars from left to right denote Barentsburg (dark red), Kanin Nos (light red), Tiksi (orange), Ostrov Vrangel (yellow), Coppermine (dark blue), and Ilulissat (light blue).

TABLE 5. 10-yr seasonal and annual means of DTR (°C) in analyzed Arctic stations in the ETCAW and CAW periods, and differences (ETCAW − CAW). Key: highest (lowest) seasonal means are shown in bold (italic).

Station	Period	DJF	MAM	JJA	SON	Year
Barentsburg	ETCAW	**6.2**	5.4	*3.6*	4.1	4.8
	CAW	**4.9**	4.4	*3.5*	3.9	4.2
	ETCAW − CAW	1.3	1.0	0.1	0.2	0.6
Kanin Nos	ETCAW	5.0	4.4	**5.3**	*3.6*	4.6
	CAW	4.4	3.7	**4.7**	*3.1*	4.0
	ETCAW − CAW	0.6	0.7	0.6	0.5	0.6
Tiksi	ETCAW	6.8	**8.9**	7.1	*6.2*	7.2
	CAW	7.1	**8.5**	7.3	*6.1*	7.2
	ETCAW − CAW	−0.3	0.4	−0.2	0.1	0.0
Ostrov Vrangel	ETCAW	7.2	**7.5**	*4.6*	5.0	6.1
	CAW	**6.2**	**6.2**	4.7	*3.9*	5.3
	ETCAW − CAW	1.0	1.3	−0.1	1.1	0.8
Coppermine	ETCAW	7.7	**8.7**	7.4	*6.5*	7.6
	CAW	8.2	**8.8**	8.6	*6.6*	8.1
	ETCAW − CAW	−0.5	−0.1	−1.2	−0.1	−0.5
Ilulissat	ETCAW	6.8	**8.3**	6.5	*5.9*	6.9
	CAW	6.8	**7.0**	**7.0**	*5.9*	6.7
	ETCAW − CAW	0.0	1.3	−0.5	0.0	0.2

Greenland as a whole by Box et al. (2009). They also stated that the rate of warming in 1919–32 and 1994–2007, directly preceding the warmest parts of the ETCAW and the CAW analyzed in the present paper, was 0.6°C greater in the earlier period than in the later one.

Climate continentality is one of the most important indicators of climate change. Hirschi et al. (2007) found that the most significant changes (decreases) in continentality due to current global warming (1948–2005) occurred in the polar regions, particularly in the Arctic. Furthermore, Stonevicius et al. (2018), analyzing climate continentality (Conrad's continentality index) in the Northern Hemisphere above 30°N in 1950–2015, confirm this finding. Our results using another precise metric of climate continentality (the Ewert index) confirm this tendency for most of the analyzed Arctic regions. Such changes in the Arctic are in line with tendencies observed in recent decades and centuries in many parts of the world and for the world as a whole (Sadowski 1991; Braganza et al. 2003; Przybylak et al. 2005; Hirschi et al. 2007; Wypych 2010; Stonevicius et al. 2018), while opposite changes recorded in the Russian Arctic (rise in continentality from the ETCAW to the CAW) are atypical. Some local influences and/or circulation changes probably increased the ATR in the CAW relative to the ETCAW. It seems likely that the decline in sea ice extent observed in the Arctic in recent decades led to the decrease in climate continentality. At present, air masses developing over open seas in the Arctic are more frequent than in more cold periods. Thus, the degree of continentality can indirectly tell us about sea ice conditions. It is widely known that sea ice is a significant forcing. Knowledge about its occurrence during the ETCAW is incomplete and not very reliable [for more details, see, e.g., the recently published book *Sea Ice in the Arctic* (Johannessen et al. 2020)].

Another important temperature characteristic analyzed in the paper is intraseasonal DDTV. This aspect of the climate of the Arctic has not previously been investigated for the ETCAW. We found that most Arctic areas (except the Baffin Bay region) show a decrease in DDTV between the ETCAW and the CAW. The most pronounced reductions occurred in the Atlantic and Pacific regions, where the greatest increases in oceanicity of climate were also recorded. Trends in DDTV in 1951–90 were positive in the Norwegian Arctic and eastern Greenland and negative in the Canadian and Russian Arctic, but everywhere were not statistically significant (Przybylak 2002b). Moberg et al. (2000) identified decreasing trends in winter, spring and fall DDTV for northern Europe in a series of 275 years. Screen (2014) also confirmed that intraseasonal DDTV in the cold season significantly decreased over the mid- to high-latitude Northern Hemisphere in 1979–2013. He explained this by arguing that cold days, being the result of advection of winds from the north, warmed more than warm days (advection from the south), and therefore Arctic amplification reduced subseasonal temperature variance. Furthermore, Collow et al. (2019) found significant decreases in cold-season (November–April) intraseasonal temperature anomaly variability for two areas centered over northern Eurasia and northern North America from 1981–90 to 2005–14. They generally confirm Screen's (2014) conception. Collow et al. (2019) also conclude that the weakened latitudinal temperature gradient results from decreased sea ice in the Arctic.

Out of all temperature extremes analyzed in the present paper, DTR shows the poorest performance over the Arctic in the reanalyses, including the newest ones used by Avila-Diaz et al. (2021), even for recent data (2000–16). The reanalyses usually tend to underestimate the value of DTR. Good knowledge about DTR changes in stations near the coast is crucial because they are sensitive to changes in their surroundings (e.g., sea ice changes). As a result, they can potentially serve as a proxy to reconstruct sea ice presence/absence. Isaksen et al. (2016) found a close relationship between the

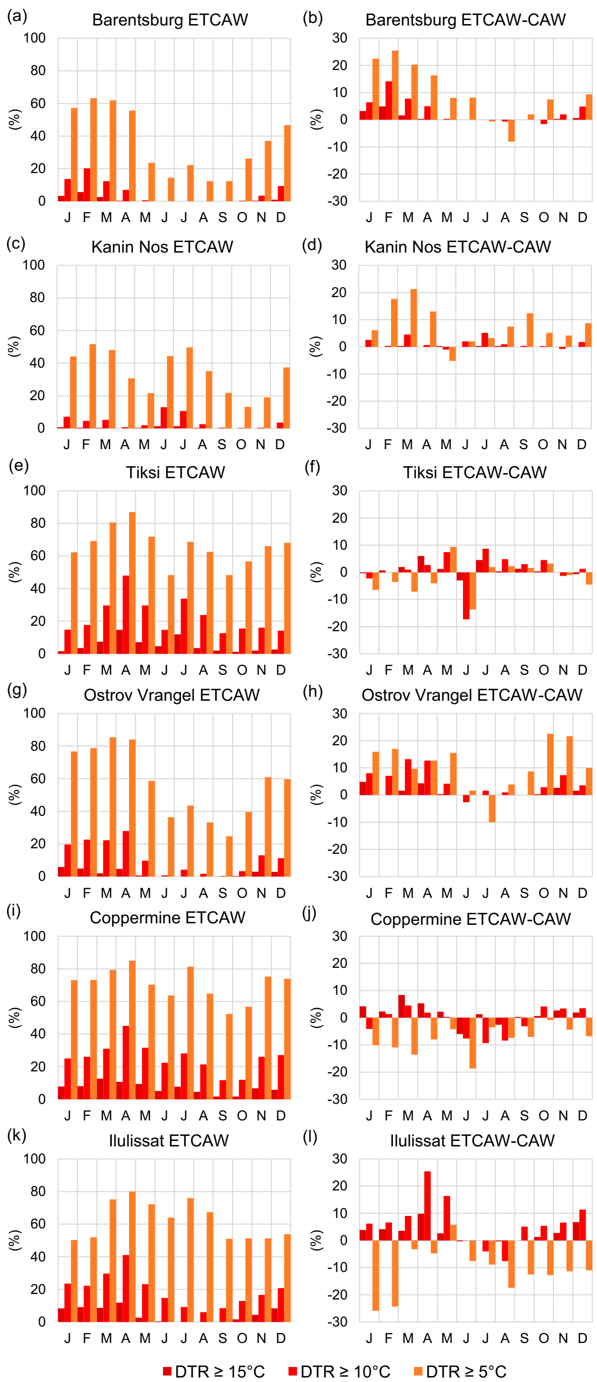

FIG. 8. (a),(c),(e),(g),(i),(k) Annual cycles of relative frequency of occurrence (in %) of characteristic days with DTR of ≥15°C, ≥10°C, and ≥5°C) in the analyzed Arctic stations during the ETCAW period, and (b),(d),(f),(h),(j),(l) their differences. Data from CAW period were subtracted from ETCAW period.

land-based SAT at Spitsbergen and local and regional sea ice concentration, particularly during the occurrence of anticyclonic circulation. It seems likely that a highly significant relationship also exists between sea ice and DTR.

DTR data for the ETCAW period (the expedition year 1944/45) in the Arctic are available only for Haudegen station in the north of Nordastlandet Island (Przybylak et al. 2018). An apparent decrease in DTR is recorded between ETCAW and the present time (2011–16 and 2014–17, data from Verlegenhuken and Rijpfjorden stations, respectively). Greater DTR in the ETCAW in comparison to today's values was also found by us for Barentsburg (the closest station to Haudegen) based on 10-yr periods of observations. Sea ice reductions (more open water) observed recently in the vicinity of the Svalbard archipelago probably led to the decrease in DTR directly or through atmospheric circulation (more vigorous and more frequent advection of warm and humid air from southern latitudes). Based on Chernokulsky and Esau's (2019) studies, the role of cloudiness in this DTR reduction should be excluded. Observed changes in cloudiness (no change in total cloudiness, but increase in convective and decrease in stratiform clouds) in the western part of the Eurasian Arctic should instead enlarge the DTR. Most continental parts of the Arctic show no change (Tiksi) or even an increase (Coppermine) in DTR between the ETCAW and the CAW. Such behavior agrees with the positive DTR trends observed in some parts of the Canadian Arctic in the periods 1951–90 and 1961–90 (particularly in summer) (see Przybylak 2000b). In the Siberian region, the decrease in DTR in winter and summer is correlated with rising cloudiness over 1936–2012. At the same time, an increase in DTR in spring and autumn is probably related to the rising frequency of convective and falling frequency of stratiform clouds, as Chenokulsky and Esau (2019) document. The spatial pattern of the DTR values in the Arctic during the ETCAW was also similar to the DTR patterns presented by Przybylak (2000b) for 1951–90, based on data from 39 stations.

In this paper, we analyze significantly more temperature extreme indices than are proposed by the Expert Team on Climate Change Detection and Indices (Donat et al. 2013). Some are similar, like DTR and selected characteristic days (e.g., frost days). Only one paper analyzing the occurrence of characteristic days is available for the Arctic for the ETCAW (Przybylak et al. 2018). Data come from the Haudegen station (northern part of Nordaustlandet Island, Svalbard) from the 1944/45 expedition year. Analysis reveals no apparent changes in the occurrence of characteristic days between this year and the present period (the increase in cold days was balanced out by the increase in warm days). We obtained more reliable results for Barentsburg based on 10 years of observations during the ETCAW. The frequencies of all cold (warm) days categories were greater (smaller) during the ETCAW than now. However, Donat et al. (2013) found that the hottest days (defined as a monthly maximum value of daily Tmax) in the 1930s had similarly high values as today. The trend of this index in the Arctic in 1951–2010 was negative, excluding the Canadian Arctic. On the other hand, the coldest nights (monthly minimum value of daily TMIN) revealed significant warming in the entire globe, including the Arctic (Donat et al. 2013).

In climatological studies, the year is usually divided into four seasons (DJF, MAM, etc.). Such a division has a physical

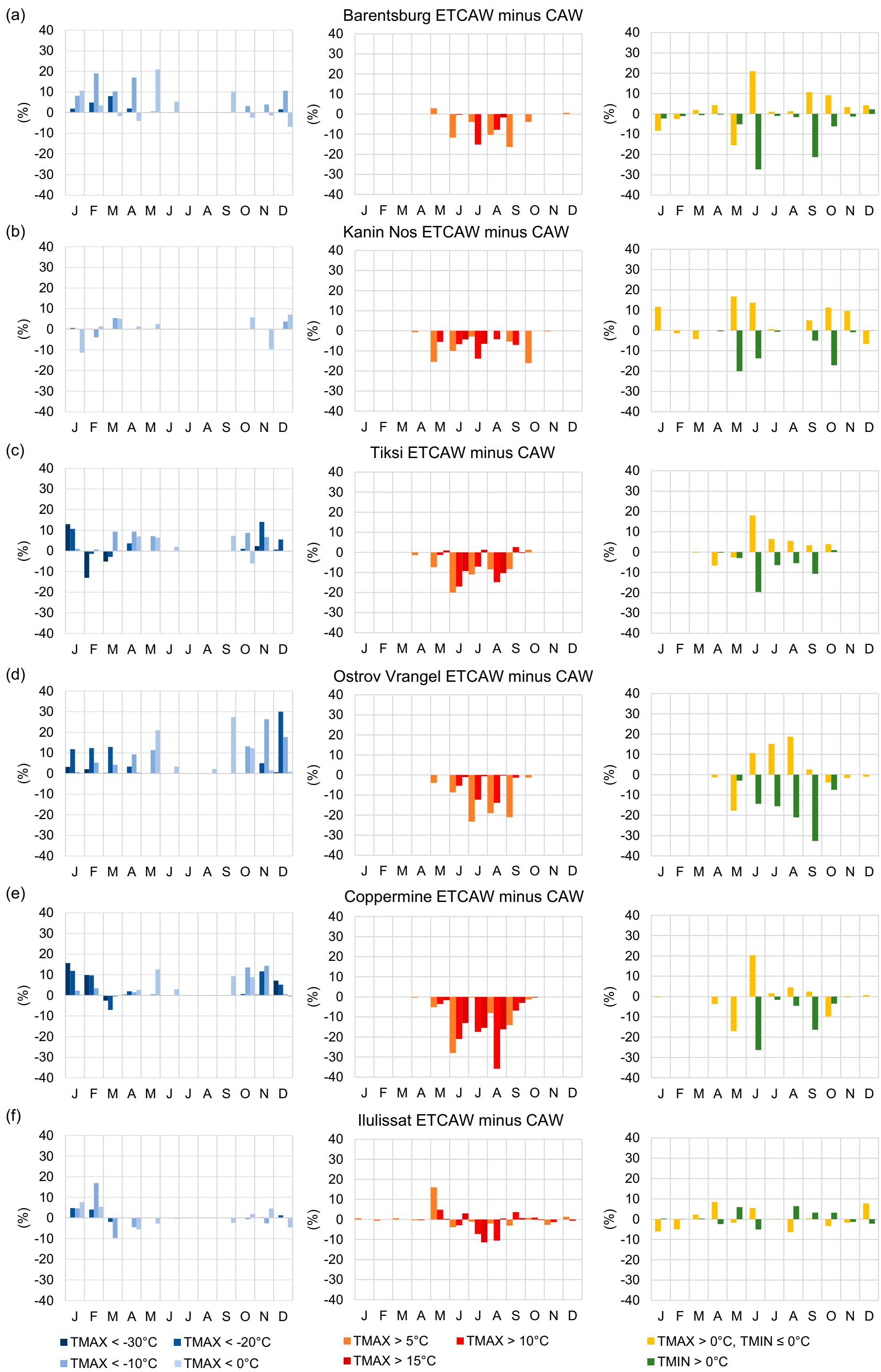

FIG. 9. Annual courses of differences between number of characteristic days (in %) in the analyzed Arctic stations. Data from CAW period were subtracted from ETCAW data. Order of characteristic days from coldest to warmest is shown from left to right.

TABLE 6. Dates of onset, end, and duration of each thermal season in analyzed Arctic stations during ETCAW and CAW periods.

		Winter				Spring				Summer				Fall			
		Date		Duration		Date		Duration		Date		Duration		Date		Duration	
Station	Period	Onset	End	Days	Percent (%)	Onset	End	Days	Percent (%)	Onset	End	Days	Percent (%)	Onset	End	Days	Percent (%)
Barentsburg	ETCAW	11 Oct	19 May	221	60.5	20 May	20 Jun	32	8.8	21 Jun	2 Sep	74	20.3	3 Sep	10 Oct	38	10.4
	CAW	16 Oct	12 May	209	57.3	13 May	9 Jun	28	7.7	10 Jun	14 Sep	97	26.6	15 Sep	15 Oct	31	8.5
Kanin Nos	ETCAW	3 Dec	23 Apr	142	38.9	24 Apr	30 May	37	10.1	31 May	14 Oct	137	37.5	15 Oct	2 Dec	49	13.4
	CAW	5 Dec	12 Apr	129	35.3	13 Apr	22 May	40	11.0	23 May	22 Oct	153	41.9	23 Oct	4 Dec	43	11.8
Tiksi	ETCAW	28 Sep	27 May	242	66.1	28 May	15 Jun	20	5.5	16 Jun	12 Sep	89	24.3	13 Sep	27 Sep	15	4.1
	CAW	30 Sep	21 May	234	64.1	22 May	7 Jun	17	4.7	8 Jun	16 Sep	101	27.7	17 Sep	29 Sep	13	3.6
Ostrov Vrangel	ETCAW	22 Sep	3 Jun	255	69.9	4 Jun	13 Jul	40	11.0	14 Jul	19 Jul	6	1.6	20 Jul	21 Sep	64	17.5
	CAW	12 Oct	26 May	227	62.2	27 May	27 Jun	32	8.8	28 Jun	4 Sep	69	18.9	5 Sep	11 Oct	37	10.1
Coppermine	ETCAW	30 Sep	25 May	238	65.2	26 May	11 Jun	17	4.7	12 Jun	14 Sep	95	26.0	15 Sep	29 Sep	15	4.1
	CAW	8 Oct	19 May	224	61.4	20 May	3 Jun	15	4.1	4 Jun	20 Sep	109	29.9	21 Sep	7 Oct	17	4.7
Ilulissat	ETCAW	12 Oct	3 May	204	55.9	4 May	26 May	23	6.3	27 May	14 Sep	111	30.4	15 Sep	11 Oct	27	7.4
	CAW	11 Oct	4 May	206	56.4	5 May	26 May	22	6.0	27 May	12 Sep	109	29.9	13 Sep	10 Oct	28	7.7

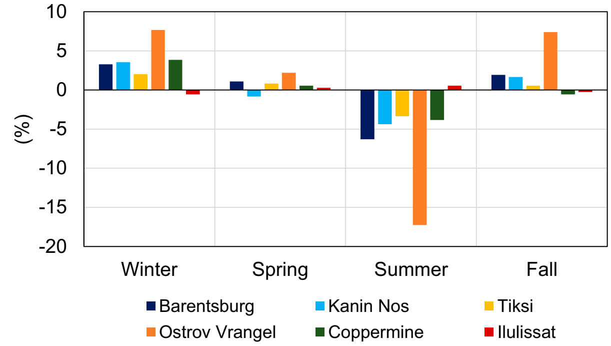

FIG. 10. Changes in duration of thermal seasons between ETCAW and CAW periods (ETCAW − CAW) expressed in percentage of their duration in an entire year.

meaning for moderate latitudes (it more or less correctly resembles the annual temperature cycle), but not for the Arctic, where the winter is much longer than the other seasons. Moreover, such an arbitrary division of the year omits such useful information as the season's onset, end, and duration (Baranowski 1968). Such knowledge is essential for, among other things, vegetation, economic activity, and the lives of indigenous people. That is why we utilized the criteria proposed by Baranowski (1968) to delimit four standard seasons. Our findings (i.e., a shortening of winter and lengthening of summer) between the ETCAW and the CAW agree well with similar analyses available for Novaya Zemlya (Przybylak and Wyszyński 2017) and northern Svalbard (Przybylak et al. 2018). However, a rather unexpected result, given that the warming is greater in winter than in summer (Bintanja and van der Linden 2013; Przybylak and Wyszyński 2020), is that the changes in the duration of seasons between ETCAW and CAW were more significant in summer than in winter.

This decade will see us pass 100 years since the beginning of continuous research by thousands of scientists trying to solve some major challenges associated with the ETCAW. One such challenge is to unambiguously establish a reliable explanation for the main mechanisms driving this great warming. In Table S1 and Fig. 1 we show how frequently opinions have different and conflicted among scientists throughout the 90-yr history of research, but particularly in articles published in the last 30 years. By contrast, before this time, the main driving mechanisms were generally agreed upon among scientists. Most of them (97.1%) presented the opinion that the ETCAW was an effect of natural forcings—mainly changes in atmospheric circulation (71.6%) and to a lesser degree in oceanic circulation (20.6%). Only Callendar (1938) connected this warming to an increase in CO_2 concentrations (2.9%). This cause is now more commonly proposed (13.9%), but still the ascribing of the early twentieth-century warming to natural forcings predominates (80%). In recent papers, however, scientists have proposed a greater set of forcings. Besides atmospheric (24.5%) and oceanic (12.0%) forcings, there are also usually mentions of internal variability (15.9%), solar radiation or solar activity (12.4%), and volcanic activity (7.0%) (Fig. 1). It seems that this evolution of views between those presented in papers published in 1929–90 and those from 1991 to 2020 is due to the improvement in knowledge of the ETCAW with regard to (i) the Arctic climate system (including the development of new global databases, in particular different types of reanalyses and gridded products), and (ii) forcings (in particular solar and volcanic). In recent decades, the dynamic development of global and regional climate models has also played an important role in this process. These are the most efficient tools commonly now in use for detection and attribution analyses. However, improvements in all the mentioned categories of our knowledge are still necessary.

5. Conclusions and final remarks

The analysis of new aspects of Arctic climate during the ETCAW done based on daily and subdaily data gives new or improved knowledge about the character of climate in that period. From the literature review, we know that the scale of the ETCAW was comparable to the scale of the CAW until the beginning of the twenty-first century. The results we present here also show that, in the last 10–15 years, the warming has become greater than during the ETCAW, particularly in the Pacific and Canadian regions (Table 2).

Our investigations also support the conclusion that, in most study areas, the climate was a little more continental (Table 3) and less stable during the ETCAW than at present (Tables 4 and 5, Figs. 5 and 7). It is essential to underline that the greatest decreases in climate continentality between the ETCAW and the CAW in the Arctic occurred in areas with the smallest degree of climate continentality (Atlantic and Pacific regions), but also where the greatest decreases in sea ice extent have recently occurred. The greater amount of open seawater now than in the ETCAW period is also responsible for the more stable character of weather and climate recently observed in the Arctic, as we documented using the DDTV and DTR indices. Again, changes were the most remarkable in those parts of the Arctic most sensitive to sea ice changes (i.e., the Atlantic and Pacific regions). Our results showed that the reactions to global warming differ between continental and oceanic parts of the Arctic and are sometimes even opposite to expectations. Examples include (i) the increase in climate continentality in the Siberian region and (ii) changes in weather variability between the ETCAW and the CAW being smaller in the Canadian Arctic region than elsewhere, or even absent. In conclusion, we must underline that any Arctic-wide averaging of results for these aspects of climate must be treated with caution; at best, this should be done separately for continental and oceanic parts of the Arctic.

Another important finding is the lengthening of summer from the ETCAW to the CAW being greater than the shortening of winter, mainly in the Pacific and Atlantic regions (Table 6, Fig. 10). This seasonal pattern contrasts with the intensity of warming being greater in winter than in summer in oceanic parts of the Arctic between the two periods and the opposite relation in continental parts (see Table 2).

As with other studies of historical periods in the Arctic, this study has certain limitations due to the scarcity of data. First, it is limited by the discontinuity of the data series, such that no continuous, 10-yr period of the ETCAW is represented by full data for any set of stations. Moreover, no set of 10 non-continuous years for the ETCAW could be found for which there was data for all stations. In light of the impossibility of generating historical datasets that simply do not exist and the pressing need to perform the best analysis that the actual data permit, the selected stations are represented by 10 non-continuous years that do not entirely coincide, but that were selected to maximize overlap. Other measures taken to reduce the negative impact of this problem were also detailed in the study. A second limitation is that the scarcity of data restricts the capacity for any set of stations to be fully representative of their sector. Thus an assessment was made of the geographical range for which each selected station can be deemed to be representative, which varies by season.

Almost 100 papers were reviewed to document the evolution of views about the reasons for the ETCAW (Fig. 1). The markedly dominant opinions/findings (for details see Table S1) presented since 1929 (the first paper) have been that the ETCAW was caused by natural forcings (97.1% and 80.0% in articles published in 1929–90 and 1991–2020, respectively), particularly by atmospheric circulation (71.3% and 24.5%, respectively). It is also clear that there has recently been significantly greater diversity of opinions—probably due to, for example, better knowledge about climate and forcings, newly available datasets, and the use of statistical and modeling tools. As a result, no explanation of the main driving mechanisms responsible for the ETCAW is yet definitive. A workshop devoted to this issue could be one of the best solutions.

We hope that the expanded and improved knowledge about climate during the ETCAW presented in the paper will be useful in research on, for example, 1) state and changes observed in other components of the Arctic climate system from ETCAW to present times, and 2) causes of the early-twentieth-century warming using both statistical and modeling tools. However, there is still an urgent need for more investigations similar to that presented in this paper [i.e., based on data of finer-than-monthly resolution (daily and subdaily)]. To date, however, as our review shows, only a very limited number of such studies are available for the ETCAW period. Data-rescue activity aiming to collect, copy, and digitize "old" data from the entire world (including the Arctic) should be intensified [for details, see Brönnimann et al. (2019)]. Such activity is necessary to study the historical climate and environmental changes in every area of the world. We need more data available in libraries, archives, and private collections that have not yet seen the light of day. More efforts and more scientists are therefore urgently needed to obtain these data for analysis.

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Author contributions. Study design by RP. Data collection and selection by PW and RP. Literature review by RP. Statistical analysis and visualization by PW and AA. Interpretation of results by RP, PW, and AA. Preparation of manuscript by RP with contributions from all co-authors.

Data availability statement. Datasets for this research were derived from the following public domain resources: 1) All-Russia Research Institute of Hydrometeorological Information–World Data Centre (RIHMI-WDC), http://meteo.ru/; 2) The Government of Canada (Environment and Climate Change Canada), https://climate.weather.gc.ca/; 3) Danish Meteorological Institute (DMI), https://www.dmi.dk/publikationer/ [as cited in Cappelen (2020)].

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