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Air temperature in Novaya Zemlya Archipelago and Vaygach Island from 1832 to 1920 in the light of early instrumental data

Rajmund Przybylak* and Przemysław Wyszyński
Department of Meteorology and Climatology, Nicolaus Copernicus University, Toruń, Poland

ABSTRACT: In this article, the results of an investigation into the air temperature conditions in Novaya Zemlya Archipelago and Vaygach Island (NZR) from 1832 to 1920, on the basis of all available early instrumental data gathered during exploratory and scientific expeditions, are presented. Traditional analysis based on mean monthly data was supplemented by an approach less popular in the scientific literature, i.e. the additional use of daily data. Moreover, the daily data used were not limited only to mean daily air temperature, but include also maximum daily temperature, minimum daily temperature and diurnal temperature range. Such rich sets of data allowed for more comprehensive and precise recognition of air temperature conditions in the NZR. Based on these kinds of daily data, it was also possible to calculate the number of so-called 'characteristic days' (i.e. the number of days with temperatures exceeding specified thresholds) and day-to-day temperature variability and, for the first time, to determine different characteristics of thermal seasons (duration, onset and end dates) according to Baranowski's (1968) proposition. The results were compared with contemporary temperature conditions (1981–2010) to estimate the range of their changes between historical and present times.

Analysis reveals that in 1832–1920, the NZR was markedly colder than today in all seasons. Coldest was autumn (on average by *ca* 5 °C), and least – summer (by 1.6 °C). Mean annual air temperature was colder than today by about 3 °C. The majority of mean monthly air temperatures in historical times lie within two standard deviations from the modern mean. This means that values of air temperature in historical times lie within the range of contemporary air temperature variability. Different air temperature characteristics calculated on the basis of daily data for the NZR for historical/contemporary periods also confirm the occurrence of climate warming between the studied periods.

KEY WORDS Arctic; air temperature; early instrumental data

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1. Introduction

The Arctic plays a key role in shaping the climate of the lower latitudes, and generally this has been known since the first International Polar Year (IPY) in 1882/1883 (Przybylak, 2002). From that important date until today, the Arctic has been – and still is – the region of the most intense interdisciplinary and international research (suffice to mention the organization of four IPYs, the most recent being 2007–2009). Rapid climate and environmental changes observed in the Arctic in recent decades, and in particular in the last 20 years (Przybylak, 2007, 2016), are influencing the climate of the rest of the globe ever more strongly. A longer perspective is needed in order to state reliably the range of natural variability of the Arctic climate and to estimate if recent changes are exceptional or not. Quite a large number of climate reconstructions for the Arctic have recently been published based on proxy data (for a review see Przybylak, 2016). The most detailed answers are given by ice-core analyses, but other proxy data (in particular laminated lacustrine and marine sediments) are becoming increasingly important. However, even the best climate reconstructions based on proxy data are not as precise as information obtained from early instrumental observations, even though they are not complete in terms of time coverage. Therefore, for time periods where such observations exist (mainly limited to the 19th century and the beginning of the 20th century) research should be intensified to find all possible sources of data. Arctic data rescue activity, recently with the strong support of both the ACRE (The Atmospheric Circulation Reconstructions over the Earth) initiative (Allan *et al.*, 2011) and the Atmosphere Working Group of the International Arctic Science Committee (IASC), have helped to obtain research projects within which an enormous number of sources of meteorological data have been gathered. As a result, quite a large number of papers have been published covering the entire Arctic, or large parts of it (e.g. Przybylak, 2000; Wood and Overland, 2003, 2006, 2010; Przybylak and Vízi, 2004, 2005a; Przybylak and Jankowska, 2009; Brohan *et al.*, 2010; Przybylak *et al.*, 2010, 2013; Wyszyński and Przybylak, 2014). For areas including large parts of the Arctic or the entire Arctic, it is usually not possible to conduct more detailed and comprehensive investigations, e.g. based on daily or sub-daily data, and to present results in journal publication. Therefore, for a few years, work on

* Correspondence to: R. Przybylak, Department of Meteorology and Climatology, Nicolaus Copernicus University, Lwowska 1, 87-100 Toruń, Poland. E-mail: rp11@umk.pl

climate reconstructions for smaller Arctic areas has been being initiated. We began work on such an analysis starting from the Svalbard area (Nordli *et al.*, 2014; Przybylak *et al.*, 2014a, 2016). In preparation is a paper describing the historical climate of Franz Josef Land.

In this article, the characteristics of historical air temperature in Novaya Zemlya Archipelago and Vaygach Island [hereinafter called Novaya Zemlya Region (NZR)] is presented. Our knowledge of recent climate changes in this area (over the last 60–65 years) is, relatively speaking, fairly well developed. However, regular instrumental observations, extending back to the end of the 19th century, have only been carried out at Malye Karmakuly since 1896.

The oldest series of meteorological data for the NZR come from the scientific overwintering expeditions of Pakstusov at Kamenka Bay in 1832/1833, Pakstusov and Tsivolka at Matochkin Shar in 1834/1835, Tsivolka and Moyseyev at Melkaya Bay 1838/1839 and Tobiesen in Sajazkie Insel in 1872/1873. In the 1870s, a series of measurements at Malye Karmakuly were commenced under the leaderships of Bjerkan (1876/1877), Tyagin (1878/1879), Andreyev (1882/1883) and Jona (1891/1892). High-quality observations were also conducted during the Sedov expedition in Foka Bay in 1912/1913. It is worth adding here that in Novaya Zemlya – for the first time in the Arctic – non-instrumental weather observations (wind direction and force, cloudiness and hydrometeors) were undertaken by Willem Barents and his crew during overwintering on the eastern coast of this archipelago (Ledyana Gavan, $\varphi = 76°10'$N, $\lambda = 68°20'$E) in the years 1596/1597 (Golitsyn, 1900; de Veer, 1958).

There is a limited number of works describing air temperature in the NZR in the 19th century and the beginning of the 20th century based on instrumental data. Surprisingly, more such work was published in the distant past (e.g. Baer, 1837, 1840; Zapiski Gidrograficheskago Departamenta Morskago Ministerstva, chast I, 1842; Zapiski Gidrograficheskago Departamenta Morskago Ministerstva, chast II, 1844; Svenske, 1866; Toeppen, 1878; Lenz, 1886; Golitsyn, 1900; Hann, 1911; Korostelev, 1912; Vize, 1931) than in recent decades (Zeeberg, 2001; Klimenko, 2010; Klimenko *et al.*, 2014). A list of all published works before 1910 dealing with the natural environment of Novaya Zemlya, including a register of all expeditions and their descriptions, is available in a publication edited by Sosnovskiy (1910). As this work is rather difficult to find outside Russia, and because it is very important for studies of climate and environment reconstruction before 1910, we decided to attach in the Appendix a copy of six pages from this publication presenting all works from the following fields: astronomy, meteorology, oceanography, hydrology and geomagnetism (Figure S1, Supporting information).

The main objective of this article is to roughly describe the air temperature conditions in the NZR from 1832 to 1920 on the basis of all available early instrumental data gathered during exploratory and scientific expeditions. A detailed description of four thermal parameters is presented, including mean daily air temperature (MDAT), maximum daily temperature (TMAX), minimum daily temperature (TMIN), diurnal temperature range (DTR) and the number of characteristic days (i.e. the number of days with temperatures exceeding specified thresholds), day-to-day temperature variability and thermal seasons according to Baranowski (1968). Having obtained this information, the results were compared with contemporary temperature conditions (1981–2010), to estimate the range of their changes between historical and present times.

2. Area, data and methods

NZR are parts of the Russian northern territory. Novaya Zemlya consists of two main islands (northern and southern) separated by a narrow strait (1.6–2.4 km), Matochkin Shar, and lying between the Barents and Kara seas. The latitudinal stretch of the archipelago is quite large, reaching about 1000 km, and stretching from latitude 70°30′ to 77°N, while its width is small, varying around 100 km (Figure 1). Novaya Zemlya is for the most part mountainous, though the southern portion of the southern island is merely hilly. About 25% of its area is covered by ice, which is very common in the northern island in particular. Vaygach Island is a small island (area about 3.4 km^2)

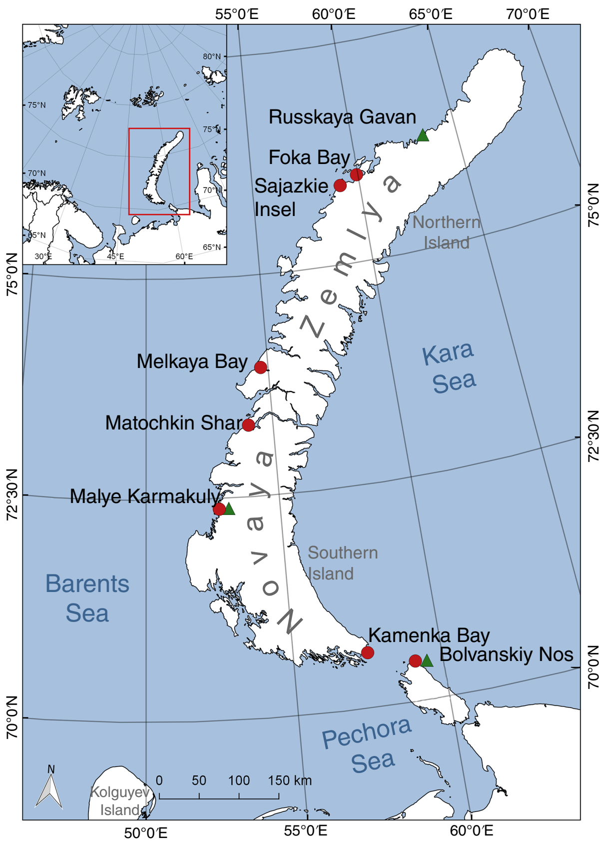

Figure 1. Location of historical (dots) and modern (triangles) land meteorological stations in NZR. [Colour figure can be viewed at wileyonlinelibrary.com].

Table 1. Sources of air temperature series for NZR in the early instrumental period used in this article.

No.	Region	Station	φ	λ	Leader	Period	Resolution of raw data	Source of raw data	Source of monthly data
1	Novaya Zemlya	Kamenka Bay (Felsenbai)	70°37′N	57°31′E	Pakstusov	1832.09–1833.07	d (TMIN, TMAX, DTR)	Golitsyn (1900)	Wild (1881)
2		Matochkin Shar	73°19′N	53°50′E	Pakstusov and Tsivolka	1834.09–1835.09	d (TMIN, TMAX, DTR)	Golitsyn (1900)	Wild (1881)
3		Melkaya Bay (Seichte Bay)	73°57′N	54°42′E	Tsivolka and Moysyeyev	1838.09–1839.08	m (diurnal courses every 1 h)	Baer (1840)	Wild (1881)
4		Sajazkie Insel (Hasen Insel)	75°55′N	59°00′E	Sievert Tobiesen	1872.10–1873.04	t (8, 14, 20)	Mohn (1874)	Mohn (1874)
5		Malye Karmakuly	72°22′N	52°42′E	Bjerkan	1876.10–1877.06	t (8, 12, 16, 20)	Steen (1878)	RIHMI-WDC, http://meteo.ru/
6		Malye Karmakuly	72°22′N	52°42′E	Tyagin	1878.09–1879.08	t (7, 13, 19)	Wild (1880)	RIHMI-WDC, http://meteo.ru/
7		Malye Karmakuly	72°22′N	52°42′E	Andreyev	1882.09–1883.09	h	Lenz (1886)	RIHMI-WDC, http://meteo.ru/
8		Malye Karmakuly	72°22′N	52°42′E	Pater Jona	1891.10–1892.07	t (7, 13, 21)	Golitsyn (1900)	RIHMI-WDC, http://meteo.ru/
9		Malye Karmakuly	72°22′N	52°42′E		1896.08–1920.12	m	RIHMI- WDC, http://meteo.ru/	RIHMI-WDC, http://meteo.ru/
10		Foka Bay	76°00′N	59°55′E	Sedov	1912.09–1913.09	h	Vize (1931)	Vize (1931)
11	Vaygach Island	Bolvanskiy Nos	70°27′N	59°04′E		1914.07–1920.12	m	RIHMI-WDC, http://meteo.ru/	RIHMI-WDC, http://meteo.ru/

m – monthly; d – daily; t – terminal; h –hourly; TMIN – minimum daily temperature; TMAX – maximum daily temperature; DTR – diurnal temperature range; RIHMI-WDC – All-Russia Research Institute of Hydrometeorological Information – World Data Centre.

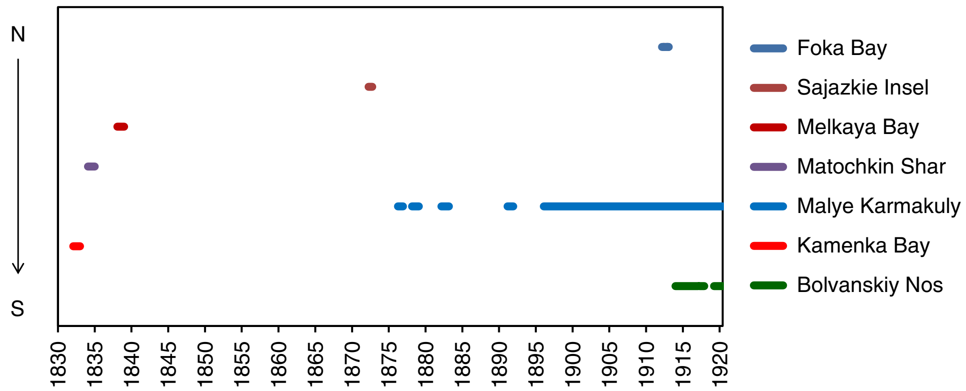

Figure 2. Temporal distribution of the air temperature observations from meteorological land stations used in the study of the NZR from 1832 to 1920. [Colour figure can be viewed at wileyonlinelibrary.com].

lying between the mainland (separated by the Yugorsky Strait) and the Novaya Zemlya Archipelago (separated by the Kara Strait). The island is surrounded from the west by the Pechora Sea and from the east by the Kara Sea (Figure 1).

All available air temperature data with sub-daily, daily or monthly resolutions extracted from sources listed in Table 1 were transcribed. Figure S2 presents one example of a source published by Mohn (1874), which was used in this article. In order to avoid errors, data were extracted manually into digital format. This kind of approach guarantees the lowest error rates when acquiring data from antique books and prints (Brönnimann *et al.*, 2006). All outliers were checked and suspect ones removed after inspection from the data set. However, it is worth noting that the oldest data from the Pakstusov, Tsivolka and Moysyeyev expeditions in particular were checked and corrected during transposition from Réaumur scale to Celsius scale (Wild, 1881) before publishing in the historical source. The rest were quality controlled by national (Russian or Norwegian) meteorological services before being published. In this way, a verified database of uniform structure was established and included into the existing Historical Arctic Database (HARD, http://www.hardv2.prac.umk.pl/) and the most valuable early instrumental data with daily resolution can be found in Appendix S1. The locations of sites for which air temperature data are available, and their time coverage, are shown in Figures 1 and 2. For the purposes of comparison with present temperatures, data from regular meteorological stations have been collected for the period 1981–2010, and also for the period 1961–1990. The following sources were used: the Environmental Working Group Arctic Meteorology and Climate Atlas (Fetterer and Radionov, 2000), All-Russia Research Institute of Hydrometeorological Information – World Data Centre (RIHMI-WDC, http://meteo.ru/) and Global Surface Summary of the Day (GSOD, https://gis.ncdc.noaa.gov/maps/ncei/cdo/daily).

Standard methods commonly used in climatology were utilized in the work. TMAX and TMIN were provided directly from historical sources for Kamenka Bay 1832–1833, Matochkin Shar 1834–1835 and Foka Bay 1912–1913. We were unable to acquire precise metadata about meteorological instruments used during the first Pakstusov overwintering 1832–1833, except information that a mercury thermometer was used. However, from the second Pakstusov expedition (1834–1835), there is more detailed information on this matter. We have found that alcohol thermometers protected against sunshine were installed on the pole *ca* 1.8 m above the ground and located at a distance of *ca* 4 m away from the winter hut (Baer, 1840). As Golitsyn (1900) provides only TMAX, TMIN and DTR as source data, it is reasonable to assume that they were taken from extreme thermometers' measurements. During the Sedov expedition of 1912–1913, extreme thermometers were used three times a day (7, 13, 21 LMT). In the case of Malye Karmakuly 1882/1882, TMAX and TMIN were chosen for each day on the basis of hourly data. DTR was calculated by subtracting TMIN from TMAX. MDAT has been calculated as follows:

- Kamenka Bay and Matochkin Shar: MDAT = (TMAX + TMIN)/2
- Malye Karmakuly and Foka Bay: MDAT = ($t1 + t2 + t3 + \ldots + t24$)/24

where $t1$, $t2$, $t3$, … $t24$ are values of air temperature measured at 01, 02, 03, … 24 LMT.

Contemporary MDATs were calculated for the NZR using data with synoptic resolution, i.e. every 3 h (only available in the RIHMI-WDC), while TMAX and TMIN were derived from extreme thermometers. Przybylak and Vízi (2005b) estimated that MDATs calculated based on data measured every 3 h and every hour are almost equal in all months (the differences oscillate from −0.04 to 0.05 °C). It was shown that differences between long-term means (1961–1990 and 1981–2010) of the MDAT calculated for two modern stations in the NZR (Malye Karmakuly and Bolvanskiy Nos) using eight measurements a day and separately based on TMAX and TMIN are small (from −0.25 to −0.11 °C) in the cold half-year (September–May). Thus, it can be assumed that they are not greater than the value of the observational accuracy. On the other hand, in summertime (June–August) the differences are greater and oscillate from 0.18 to 0.47 °C. This means that MDAT values for two historical stations (Kamenka Bay and Matochkin Shar) are slightly overestimated in summer. Biases connected with the used method of selection of TMAX and TMIN values from 24 measurements per day were estimated for the NZR based on data from the Sedov expedition to Foka Bay from 1912 to 1913. They are similar to those calculated for the Canadian Arctic by Przybylak and Vízi (2005b) and are equal to −0.5 °C (for TMAX) and 0.5 °C (for TMIN). It follows from the values of those biases that the error for DTR is equal to −1.0 °C.

Basic statistical characteristics [coefficient of correlation (r), standard deviation (σ), skewness (γ_1) and kurtosis (γ_2)] of analysed series of air temperature data were calculated according to formulas recommended by von Storch and Zwiers (1999).

Characteristic days were distinguished according to thresholds proposed by Przybylak and Vízi (2005a):

1 TMAX > 15 °C – exceptionally warm day
2 TMAX > 10 °C – very warm day
3 TMAX > 5 °C – warm day
4 TMAX > 0 °C and TMIN ≤ 0 °C – slight frost day
5 TMAX < 0 °C – frost day
6 TMAX < −10 °C – cold day
7 TMAX < −20 °C – very cold day
8 TMAX < −30 °C – day with severe frost.

Thermal seasons in the NZR were analysed according to the proposition given by Baranowski (1968). He distinguished four thermal seasons in Svalbard based on mean daily temperatures (winter, spring, summer and autumn). As threshold temperature values, he used −2.5 and 2.5 °C. The thermal seasons fulfil the following criteria:

1 winter: MDAT ≤ −2.5 °C
2 spring and autumn: −2.5 °C < MDAT < 2.5 °C
3 summer: MDAT ≥ 2.5 °C.

To determine these thresholds, the method proposed by Kosiba (1958) was applied. This method allows seasons to be distinguished in 1-year series of MDAT. As the first day of a given season, Kosiba (1958) proposed using the day from which onwards, more days fulfil the criteria of the new season than of the previous season.

Series of both monthly and daily air temperature data in the area of the NZR are strongly correlated [Pearson's coefficient of correlation (r) being always greater than 0.95 and 0.86 for monthly and daily values, respectively, Table S1] and therefore data from present working stations located near the historical sites can reliably be used for comparison purposes. In the case of series of mean monthly air temperatures, corrections due to different geographical locations have additionally been introduced. Unfortunately, we could not use ERA-Interim reanalysis in direct comparison with historical sites due to large bias in comparison with present point observation, e.g. for the Russkaya Gavan site, reanalysis underestimates the multiyear 1981–1990 temperature mean by up to 3 °C in the cold half-year. However, due to the strong correlation between the nearest grid point and present stations (Table S2), we used spatial distribution from reanalysis to introduce corrections.

Differences in air temperature (T_d) between historical and contemporary periods (1981–2010 and 1961–1990) were calculated using the following formula:

$$T_d = T_h - \left(T_m + c\right) \quad (1)$$

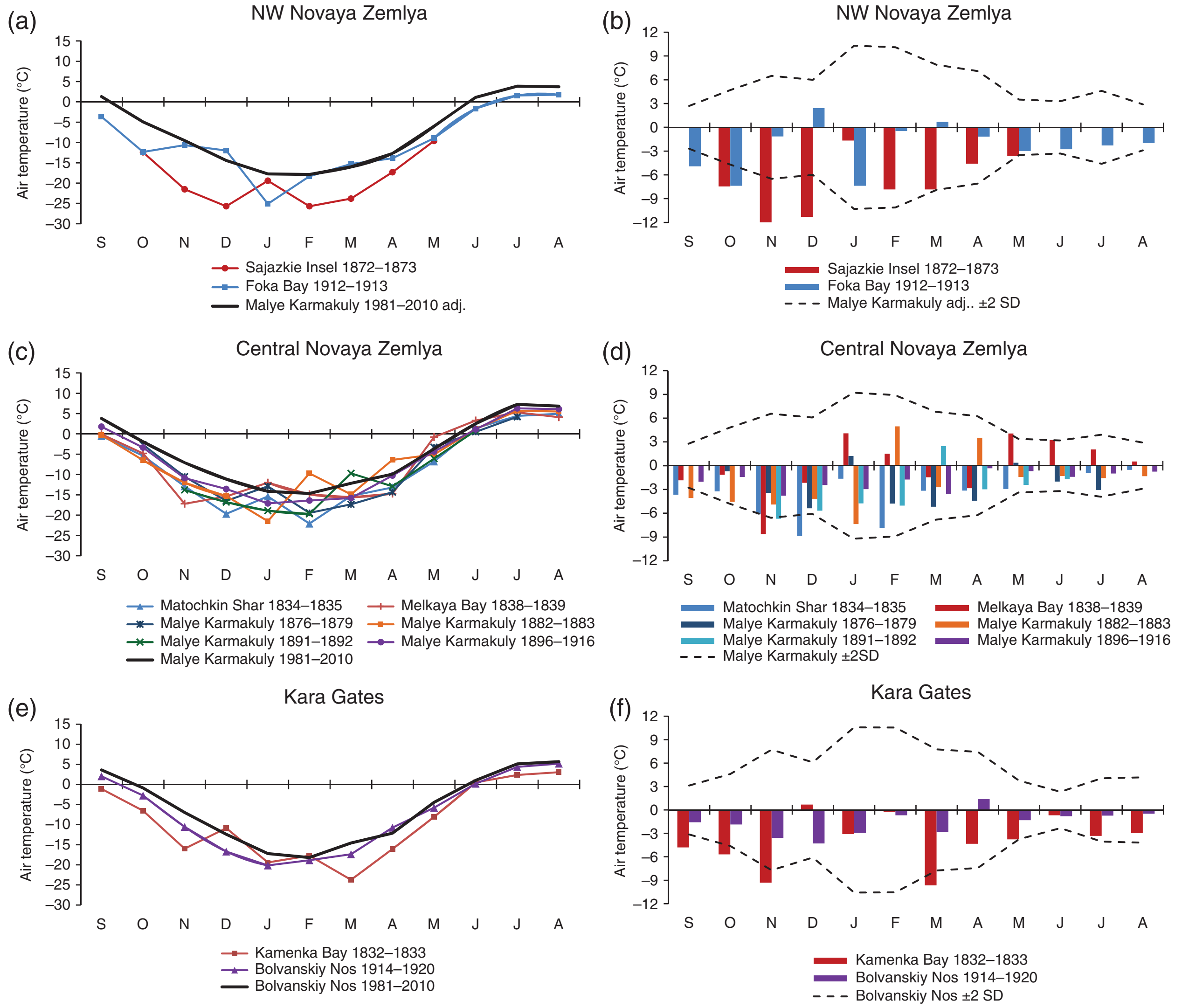

Figure 3. Annual courses of historical and modern air temperatures based on monthly means (left panels) and differences between them (right panels) in NZR. SD has been calculated on the basis of present data (1981–2010). Note: adj. – spatially adjusted to Foka Bay location.

where T_h is the monthly mean air temperature from a historical site, T_m is the long-term monthly mean air temperature from the nearest modern station and c is the spatial correction for different locations of historical and modern measurements sites calculated based on spatial diversity of air temperature of ERA-Interim reanalysis (Dee *et al.*, 2011) with its spatial resolution 0.125×0.125 or longitudinal temperature gradient between existing meteorological stations.

The spatial correction 'c' was calculated using the following formula:

$$c = T_{h1} - T_{m1} \tag{2}$$

where T_{h1} is the ERA-Interim monthly mean air temperature at the location of historical site in the period 1981–2010 and T_{m1} is the ERA-Interim monthly mean air temperature at the location of modern station site in the period 1981–2010. The modern values of air temperature obtained in this way for historical sites were compared with those from the period 1832–1920. For the northern historical station, the same procedure was applied, but spatial differences were calculated between the observational stations Russkaya Gavan and Malye Karmakuly for the period 1961–1990.

3. Results

3.1. Monthly resolution

For the study period, 37 years of mean monthly temperatures were gathered for the NZR. The majority of them (27 years) were available for the central part of the NZR, while for its southern (Kara Gates) and NW parts only 8 and 2 years, respectively. Based on these sets of data, yearly courses of air temperature have been drawn and shown on the background of 30-year means from the contemporary period 1981–2010 (Figure 3, left panels). Visual inspection of all curves presented in this figure allows it to be stated that air temperature in the historical period (1832–1920) was usually colder than today. This finding is better seen when air temperature anomalies, calculated in reference to the mentioned contemporary

Table 2. Seasonal means of air temperature in NZR in the period 1832–1920 and their differences between the historical and contemporary periods (1981–2010 and 1961–1990).

Region	SON	DJF	MAM	JJA	SEP–AUG
Air temperature means (°C)					
NW Novaya Zemlya (1872–1873, 1912–1913)	−10.7	−21.0	−14.8	0.6	−11.5
Central Novaya Zemlya (1834–1835, 1838–1839, 1876–1879, 1882–1883, 1891–1892, 1896–1916)	−5.7	−16.5	−10.4	3.9	−7.2
Kara Gates (1832–1833, 1914–1920)	−5.8	−17.3	−13.6	2.6	−8.5
NZR (1832–1920)	−7.4	−18.3	−12.9	2.4	−9.1
Differences of air temperature (°C) from the ref. mean 1981–2010					
NW Novaya Zemlya (1872–1873, 1912–1913)	−6.3	−4.4	−3.3	−2.3	−4.1
Central Novaya Zemlya (1834–1835, 1838–1839, 1876–1879, 1882–1883, 1891–1892, 1896–1916)	−4.0	−3.2	−1.7	−0.9	−2.5
Kara Gates (1832–1833, 1914–1920)	−4.5	−1.8	−3.4	−1.5	−2.8
NZR (1832–1920)	−4.9	−3.1	−2.8	−1.6	−3.1
Differences of air temperature (°C) from the ref. mean 1961–1990					
NW Novaya Zemlya (1872–1873, 1912–1913)	−5.2	−3.3	−1.9	−1.9	−3.1
Central Novaya Zemlya (1834–1835, 1838–1839, 1876–1879, 1882–1883, 1891–1892, 1896–1916)	−3.0	−2.1	−0.6	−0.5	−1.6
Kara Gates (1832–1833, 1914–1920)	−3.8	−0.8	−2.6	−1.0	−2.1
NZR (1832–1920)	−4.0	−2.1	−1.7	−1.2	−2.2

period, are analysed (Figure 3, right panels). The majority of monthly means of air temperature is lower than today, and such a situation is particularly well observed – with a frequency of 91.7% – in the Kara Gates region (Figure 3). This predominance of colder-than-today months is slightly smaller in two other regions and varies from 85.0 (in NW Novaya Zemlya) to 83.1% (in Central Novaya Zemlya). However, on average, the greatest rise of annual air temperature (by 4.1 °C between historical and present times was noted in the NW part of Novaya Zemlya, while the lowest was in its central part (by 2.5 °C), except for winter when the lowest rise occurred in the Kara Gates. The areally-averaged difference between mean annual air temperatures taken from historical and present times reaches −3.1 °C. In the study period, autumn was particularly cold (4.9 °C lower than today's norm) and winter (by 3.1 °C). On the other hand, summer experienced the smallest changes, with an air temperature of only 1.6 °C colder than today (Table 2). In the annual cycle, the greatest changes occurred in November, which was 6.1 °C colder in historical time than today's norm, while the smallest was in June (by only 1.4 °C). In Table 2, we also put temperature differences in relation to the period 1961–1990, because until recently this was the most popularly used normal period, utilized also by us for the Canadian Arctic Archipelago (CAA) (Przybylak and Vízi, 2005a). The new World Meteorological Organization (WMO) normal period (1981–2010) in the NZR was on average 0.9 °C warmer than the normal period 1961–1990. As a consequence, mean annual and all seasonal differences of air temperature calculated for the latter period are smaller than those calculated for the 1981–2010 period. The smallest changes occurred in summer (by 0.4 °C) and the greatest in spring (by 1.1 °C) (Table 2).

Analysis of Figure 3 (right panels) clearly shows that the majority of monthly means calculated for the historical time lie within a distance of ±2 SD (standard deviations) from the modern mean (1981–2010). This means that values of air temperature in this time lie within the range of contemporary temperature variability. Thus, based on the definition of climate change proposed by the WMO (Mitchell *et al.*, 1966), we must say that the magnitude of temperature changes in the NWR between historical and present times is still too small to fulfil the criteria of this definition.

3.2. Daily and sub-daily resolution

In our first work analysing daily temperature data for the Arctic for historical times (Przybylak and Vízi, 2005a) it was stated that: "In the process of averaging, important climatic information may very often be lost." For this reason, we decided in this article to again analyse the air temperature regime, this time in the NZR, in a more precise way, using different parameters of daily data (MDAT, TMAX, TMIN and DTR). For the temperature series listed in Table 1, such analysis was only possible for four series (Nos. 1, 2, 7 and 10) for which the mentioned types of data are available. This set of stations, however, represents very well the climate conditions in the NZR (Figure 1). For comparison purposes, a number of temperature characteristics (for a list of them see Section 1) analysed for the CAA (typical continental climate) by Przybylak and Vízi (2005a) have also been calculated for the NZR (oceanic type of climate).

Annual courses in the historical period, based on MDAT from stations located in the NZR, when superimposed on their present-day (1981–2010) mean annual courses derived from the nearby stations, show that in the study period there occurred spells both warmer and colder than today. Of course, the colder ones were markedly more common than the warmer, in particular in the warm half-year. On the other hand, warm spells were more frequent, and also of greater magnitude, in the cold half-year

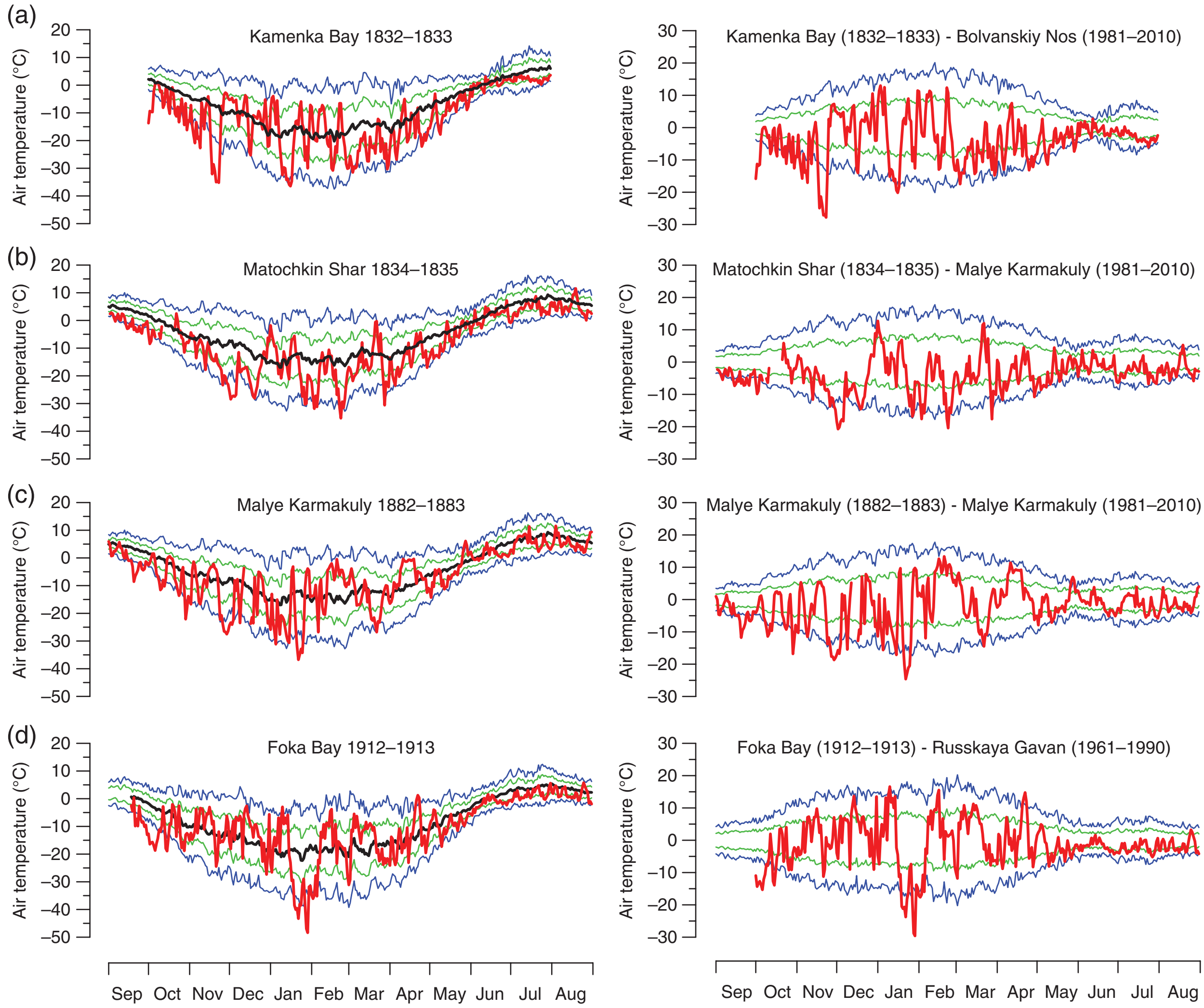

Figure 4. Annual courses of MDAT in historical (red) and modern (multiyear 1981–2010 daily mean, black) sites (left panels) and their differences (red, right panels). Green and blue lines indicate ±1 and ±2 SD, respectively. SDs have been calculated on the basis of present data (1981–2010) taken from nearby stations. Note that for Foka Bay, due to lack of present daily data, a different reference period (1961–1990) was used.

than in the warm half-year (Figure 4). The positive differences of the MDAT very seldom exceed 10 °C, while the negative ones do so quite often. In a few cases, the cold spells had a lower temperature of as much as 20 °C more than today. Almost all positive differences vary within the distance of two SDs from the present long-term mean. Negative differences cross this boundary markedly more often than positive ones, but their frequency in comparison to the rest was also small. The greatest differences occur in the cold half-year as a result of the greatest variability of MDAT during this period. Roughly speaking, the results presented here for the NZR are similar to those shown for the CAA (Przybylak and Vízi, 2005a). In line with expectations, negative temperature differences in the NZR (region of high cyclonic activity in the cold half-year) were markedly greater than in the CAA (domination of anticyclonic activity). The magnitude of warm spells is more or less the same in both regions, while they were noted more frequently in the CAA. The fact that different years were analysed for each of the two regions may be partly responsible for that.

More precise information about the character of air temperature changes between historical and present times is contained in Figure 5, where relative frequencies of occurrence of air temperature stratified into one-degree intervals are shown. As results from Figure 5, MDATs in the four analysed seasons in the NZR usually have multi-modal distributions both in historical and contemporary periods, except for summer, when the most normal distribution is noted, except for Kamenka Bay. In the period 1981–2010, quite a lot of new intervals appeared, sometimes even 6–10 °C warmer than the highest MDAT in the historical period (Figure 5). An exceptionally large number of them can be seen in autumn and summer, in particular in southern NZR (Kamenka Bay, Figure 5(a)). The smallest changes in MDAT distributions between historical and modern times occurred in winter. For example, in Foka Bay and Malye Karmakuly, the rise in air temperature from historical to present times was caused mainly by the greater frequency of occurrence of moderate MDAT intervals in the latter period than in the former (Figures 5(c) and (d)). The change of shape of MDATs distribution

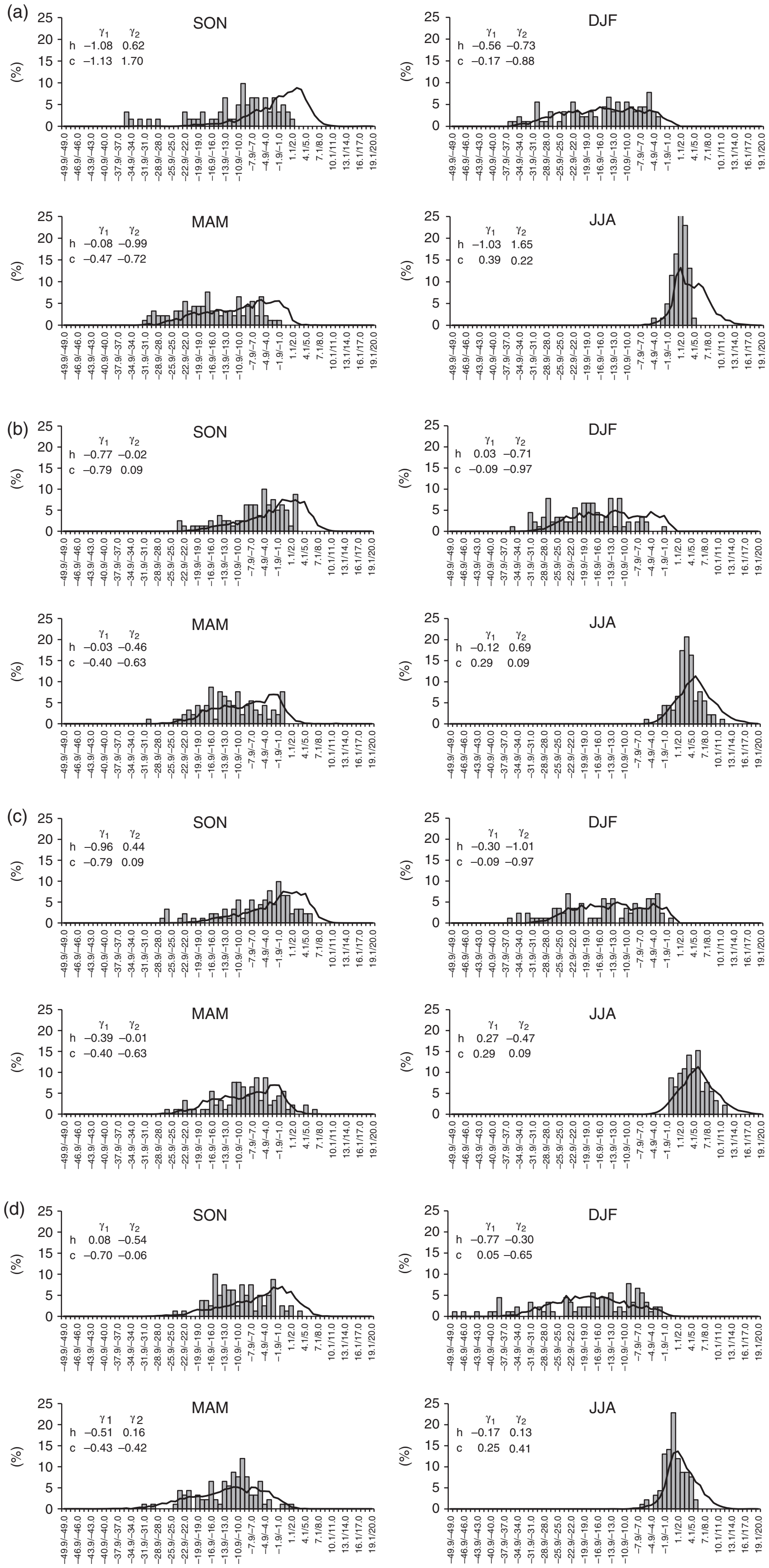

Figure 5. Seasonal (September–November, December–February, etc.) relative frequencies of occurrence (in %) of MDAT in historical (bars) and modern (lines) sites located near the (a) Kamenka Bay 1832–1833 and Bolvanskiy Nos 1981–2010, (b) Matochkin Shar 1834–1835 and Malye Karmakuly 1981–2010, (c) Malye Karmakuly 1882–1883 and Malye Karmakuly 1981–2010 and (d) Foka Bay 1912–1913 and Russkaya Gavan 1961–1990. Values of skewness (γ_1) and kurtosis (γ_2) for historical (*h*) and contemporary (*c*) times are also shown.

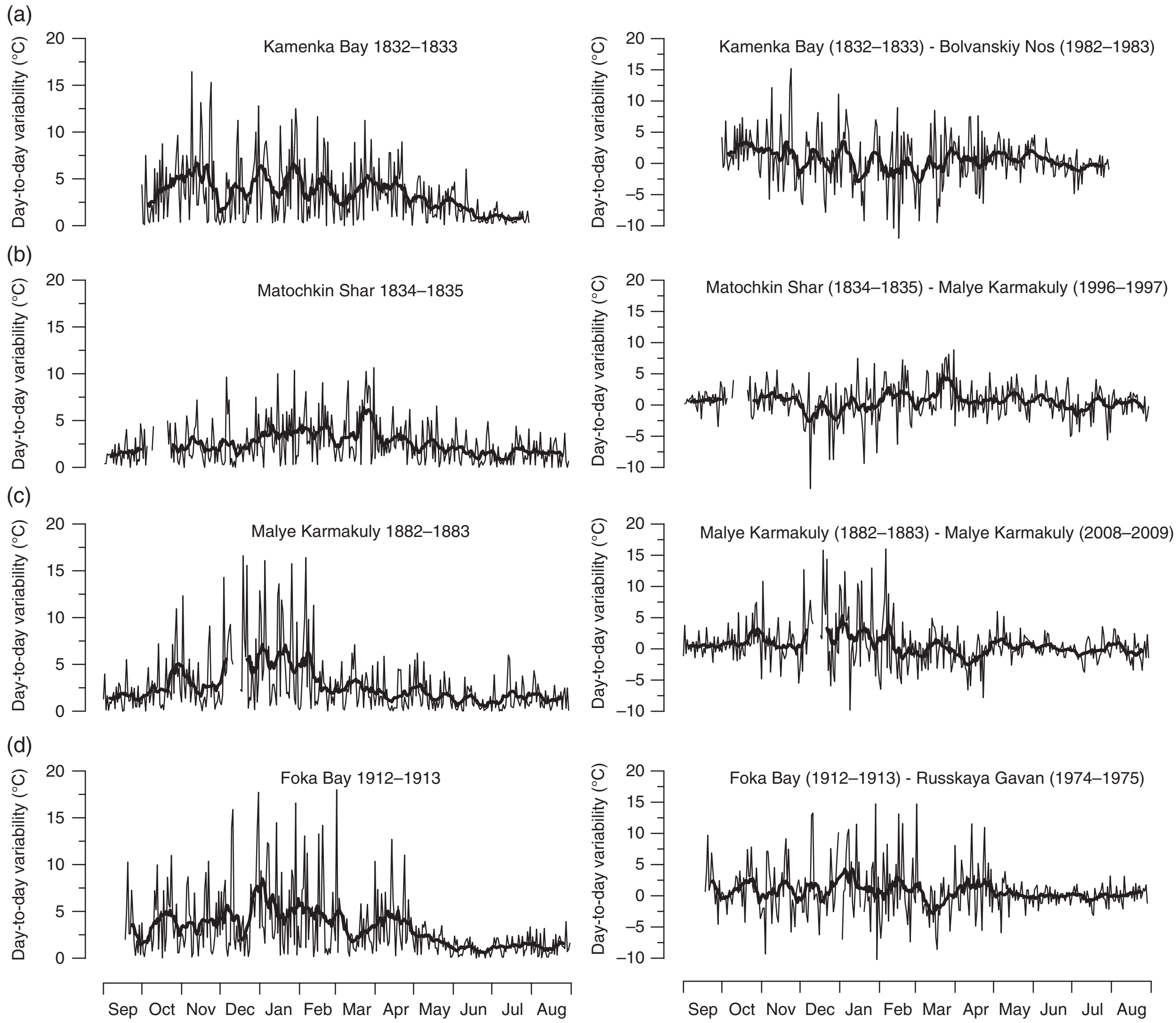

Figure 6. (Left panels) Annual courses of day-to-day variability of MDAT in historical sites and their differences from the present-day, randomly-selected, 1-year annual courses of day-to-day variability of MDAT from nearby stations. Thick line indicates 11-day moving average. The differences were obtained by subtracting the historical values from the modern ones.

in transitional seasons (spring and autumn) is very well seen from the study period to modern times (Figure 5, left panels). In recent times, a left-skewed distribution of MDATs in the mentioned seasons is very characteristic and is a new, recognized common feature of climate. In the CAA, the observed changes in MDAT distributions between the 19th century and contemporary period were markedly smaller than in the NZR and, in addition, small changes in the shape of MDAT distribution were noted (Figure 4 in Przybylak and Vízi, 2005a). Platykurtic distribution is characteristic for winter, but leptokurtic for summer. In transitional seasons, platykurtic distributions dominate, although they are less frequent and weaker than in winter (Figure 5).

Day-to-day variability of MDAT (meant as a magnitude of the change from one day to the next) in the NZR in historical times, similarly to the present climate (Przybylak, 2002), was greatest in winter (and in Kamenka Bay also in autumn), and lowest in summer (Figure 6). In summer, values of MDAT variability in all historical stations are more or less similar, usually not exceeding 2.0–2.5 °C and varying mainly between 0.5 and 1.5 °C. High winter day-to-day MDAT variability usually starts in December or January and ends in February (Malye Karmakuly and Foka Bay), March (Matochkin Shar) or April (Kamenka Bay). Out of all analysed historical sites, the greatest variability in this season was observed in Malye Karmakuly (greatest openness to the influence of incoming cyclones). On average, day-to-day variability of MDAT ranged here from 5.0 to 7.5 °C, in some periods even exceeding 15 °C (Figure 6). Clearly, the lowest variability, also reaching an untypical maximum in March, was noted in Matochkin Shar. From March/April, steady decreases in variabilities are noted until summer, when their values more or less stabilize. In spring, day-to-day variability of MDAT is greater than in autumn. As expected, day-to-day variability of MDAT in the NZR is higher than that observed in the CAA, in particular in the cold half-year (Figure 5

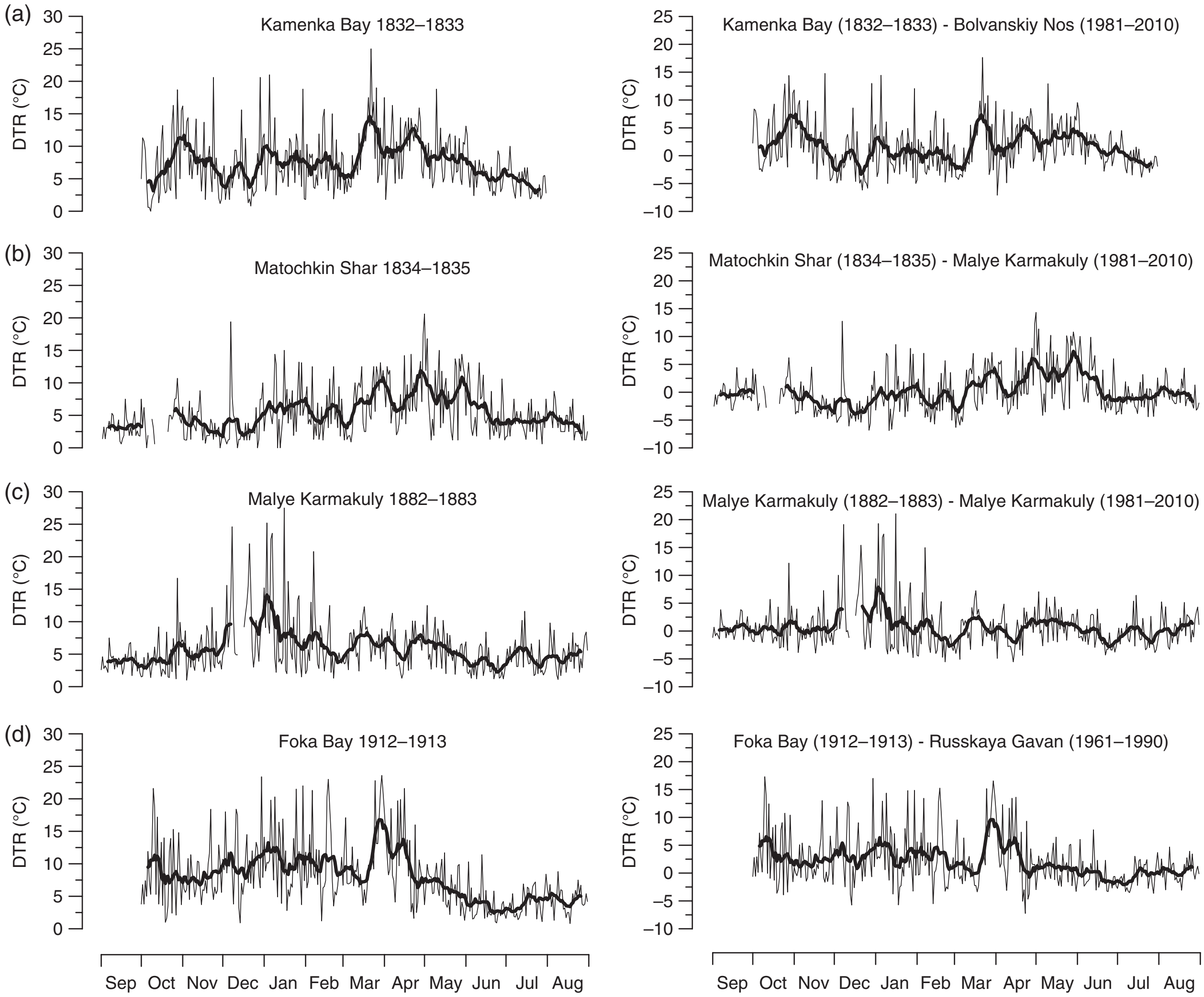

Figure 7. (Left panels) Annual courses of DTR in historical sites and (right panels) their differences from the present-day (1981–2010) annual courses of DTR from nearby stations. Note that for Foka Bay due to lack of present daily data, a different reference period (1961–1990) was used. Thick line indicates 11-day moving average. The differences were obtained by subtracting the historical values from the modern ones.

in Przybylak and Vízi, 2005a), when vigorous cyclonic activity is common in the NZR.

As can be seen from Figure 6, day-to-day variability of MDAT generally did not change markedly between historical and present times. In some stations and at certain times of year, differences are greater or lower than today's, but range more or less regularly around zero. Annual (i.e. precisely October–July) mean differences are slightly positive in the entire NZR, varying between 0.5 and 0.7 °C.

Annual courses of the DTR in the NZR (Figure 7) differ markedly from those observed in the CAA (Figure 6 in Przybylak and Vízi, 2005a). In the latter region, the highest values of the DTR occurred from April to June, while in the former it was from October to March. In two stations (Foka Bay and Malye Karmakulya) a clear maximum is seen in the winter months, while in one (Matochkin Shar) it is at the turn of March–April. On the other hand, multi-modal distribution with maxima exceeding 5 °C can be distinguished in Kamenka Bay. The greatest DTRs are observed in northern and southern parts of the NZR (on average 8.2 and 7.4 °C, respectively), while in the central part (Malye Karmakuly, Matochkin Shar) the smallest are observed (6.1 and 5.6 °C, respectively), which can be explained by the openness of this area to the inflow of maritime air masses.

A decrease in the DTR between historical and present-time values has been noted in the entire NZR. Such a tendency occurred both for mean DTR calculated for a 30-year period (1981–2010) (Figure 7) and for data taken from a randomly chosen year (Figure S3). Again, the greatest changes occurred in northern and southern parts of the NZR (on average 2.0 and 1.6 °C, respectively). In the central western part of the NZR, today's DTRs are on average smaller by 0.2 (Matochkin Shar) and 0.7 °C (Malye Karmakuly). However, taking the bias of calculation of the DTR in Malye Karmakuly into account (based here on hourly measurements, see Section 2), the decrease of the DTR in the modern period is about 1.7 °C. The opposite tendency was found for the continental climate, represented by the CAA (Przybylak and Vízi, 2005a, 2005b). However, this disagreement is partly caused by the fact that TMAX and TMIN have been chosen in the

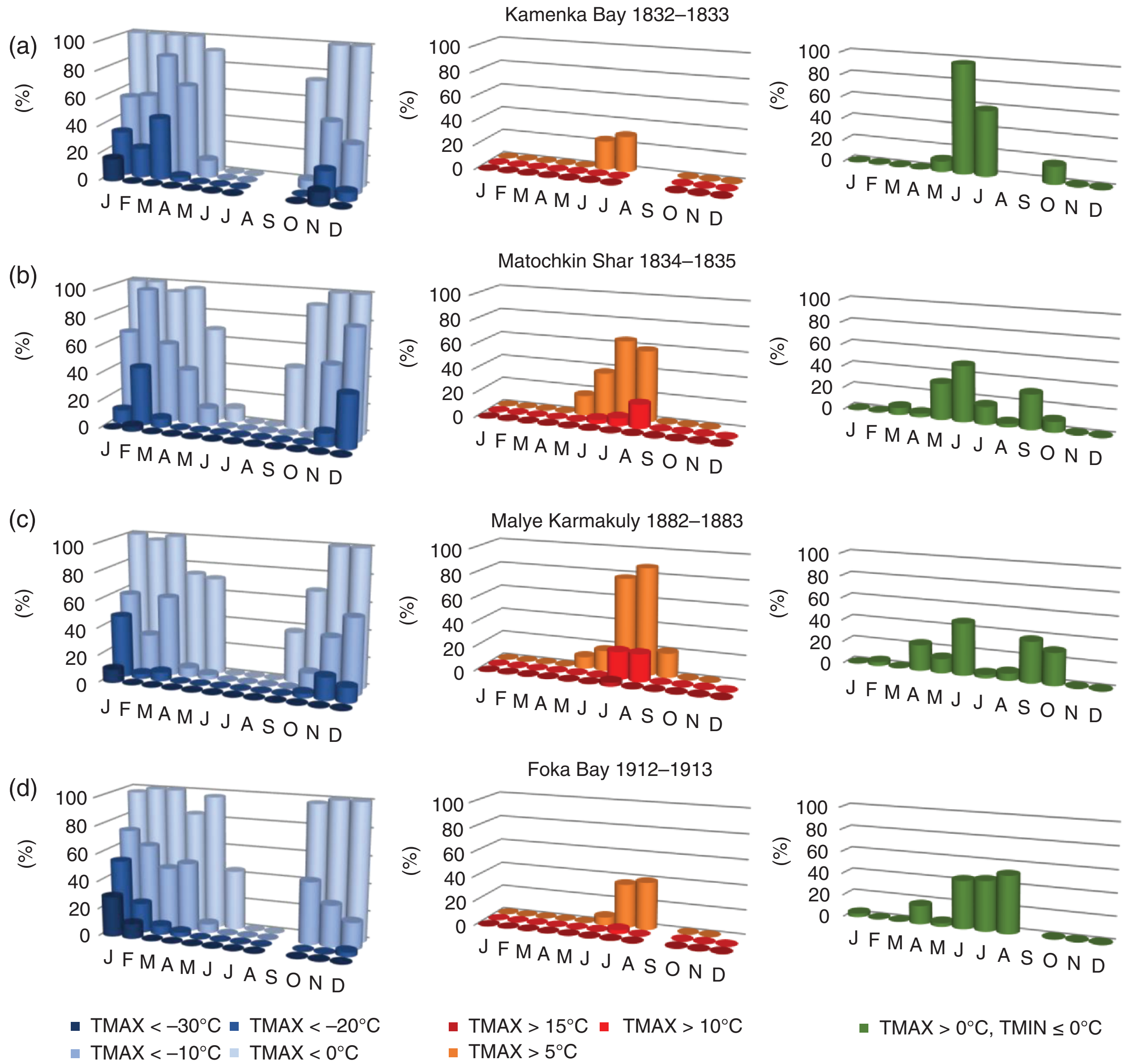

Figure 8. Annual courses of relative frequency of occurrence (in %) of characteristic days in NZR in historical times.

CAA from 2-h measurements, while in the NZR they are from hourly measurements or from extreme thermometers (see Section 2 for details). In the continental climate (with distinctly less cloudiness and greater solar radiation), DTR is underestimated on a much greater scale than in the case of the maritime climate, where advection of air masses is a main actor, generally throughout the entire year, but particularly in the cold half-year. Thus, data from the NZR provide more realistic results than CAA. The decrease of the DTR in the NZR in modern times is a response to the increase of climate oceanity in the Atlantic Arctic region (Gjelten *et al.*, 2016), which is caused by the inflow of warm Atlantic waters (Walczowski and Piechura, 2006) and sea-ice decline (Walsh *et al.*, 2016). Sea-ice loss has driven increased energy transfer from the ocean to the atmosphere, enhanced warming and moistening of the lower troposphere and increased low-level cloud cover (Screen *et al.*, 2013; Abe *et al.*, 2016), which has led to damping the DTR by increasing the TMIN in winter when sunshine length is short and the greenhouse warming effect of clouds exceeds their solar cooling effect (Dai *et al.*, 1999). However, variations in the DTR are much more sensitive to changes in feedbacks than in direct forcings (Stone and Weaver, 2003).

The relative frequencies of occurrence of different kinds of characteristic days in the study period are shown in Figure 8. Exceptionally warm days (TMAX > 15 °C) occurred only in Malye Karmakuly and only on 1 day in July (Table 3, Figure 8). Very warm days (TMAX > 10 °C) were also quite rare, but occurred in all places (except Kamenka Bay) and only in summer. Their frequencies were highest in the central part of the NZR where they varied from 9.8 in Matochkin Shar to 15.2% in Malye Karmakuly (Table 3). In the northern part of NZR (Foka Bay) only one such day was noted (Table 3, Figure 8). The spatial structure of the occurrence of warm (TMAX > 5 °C)

Table 3. Relative frequency of occurrence (in %) of characteristic days in the NZR in historical times.

Characteristic days	Kamenka Bay 1832–1833					Matochkin Shar 1834–1835					Malye Karmakuly 1882–1883					Foka Bay 1912–1913				
	DJF	MAM	JJA[a]	SON[b]	Year	DJF	MAM	JJA	SON	Year	DJF	MAM	JJA	SON	Year	DJF	MAM	JJA	SON[b]	Year
TMAX > 0 °C, TMIN ≤ 0 °C	0.0	3.3	77.0	8.2	18.1	0.0	14.1	22.8	13.8	12.7	1.2	12.0	18.5	22.0	13.6	1.1	6.5	46.7	0.0	14.9
TMAX < 0 °C	100.0	96.7	0.0	86.9	76.3	100.0	85.9	3.3	77.5	66.1	98.8	81.5	0.0	68.1	61.5	98.9	93.5	14.1	98.4	74.0
TMAX < −10 °C	48.9	55.4	0.0	27.9	36.8	80.0	37.0	0.0	20.0	34.5	47.7	22.8	0.0	17.6	21.6	50.0	33.7	0.0	37.7	29.6
TMAX < −20 °C	20.0	16.3	0.0	9.8	12.8	30.0	2.2	0.0	3.8	9.0	20.9	2.2	0.0	6.6	7.2	25.6	3.3	0.0	0.0	7.8
TMAX < −30 °C	5.6	0.0	0.0	4.9	2.6	1.1	0.0	0.0	0.0	0.3	3.5	0.0	0.0	0.0	0.8	13.3	0.0	0.0	0.0	3.6
TMAX > 5 °C	0.0	0.0	26.2	0.0	5.3	0.0	5.4	53.3	0.0	15.3	0.0	3.3	60.9	6.6	18.0	0.0	0.0	27.2	0.0	7.5
TMAX > 10 °C	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.8	0.0	2.5	0.0	0.0	15.2	0.0	3.9	0.0	0.0	1.1	0.0	0.3
TMAX > 15 °C	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.1	0.0	0.3	0.0	0.0	0.0	0.0	0.0

[a]Without August. [b]Without September.

days is generally similar to that presented for very warm days. Of all three mentioned categories of days (i.e. exceptionally warm, very warm and warm) only warm days occurred in Kamenka Bay and their number was lower than in other parts of the NZR – even its northern part (Foka Bay) (Table 3, Figure 8). In the central part, warm days in summer months were about two times more frequent (exceeding 60–80%) than in other parts of the NZR (<40%).

Days with severe frost (TMAX < −30 °C) were noted very rarely in the entire NZR, and mainly in January and February. A greater number of them occurred in southern and northern parts (5 and 9 days, respectively) than in the central part of the NZR (only 1–3 days) (Table 3, Figure 8). This can again be explained by the greatest openness of the central part of the NZR (in comparison to the other two parts) to warm and humid maritime air masses from the western sector (the Barents Sea). In comparison to CAA, the number of days with severe frost in the NZR was markedly lower (Przybylak and Vízi, 2005a, 2005b). Surprisingly, very cold (TMAX < −20 °C) and cold (TMAX < −10 °C) days were most frequent in Kamenka Bay (12.8 and 36.8%, respectively) and then in Matochkin Shar (9.0 and 34.5%, respectively). These days were observed least frequently in Malye Karmakuly (7.2 and 21.6%, respectively) (Table 3). Frost days (TMAX < 0 °C) in the NZR are very common from November to March when their frequencies ranged from 93 to 100%. These days were only not observed in July and August (Figure 8), which was not the case in the CAA (Figure 7 in Przybylak and Vízi, 2005a, 2005b).

Slight frost days (TMAX > 0 °C and TMIN ≤ 0 °C) occurred most often from May to September/October, with the maximum usually in June, when at least 40% of such days were observed (Figure 8). They were particularly common in the southern part of the NZR, where in this month the frequency reached 96.7%.

As expected, the number of characteristic days changed from historical to present times, in agreement with observed warming, i.e. the number of different categories of cold/warm days significantly decreased/increased (Figure 9). In some months, both categories of days saw decreases and increases exceeding even 40%, although the majority of differences did not exceed 20%. Slight frost days (TMAX > 0 °C and TMIN ≤ 0 °C) show individual patterns of change. Their number in spring, and particularly in summer, largely increase from historical to contemporary times, while in the cold half-year (October–March) the decrease reached its greatest values in autumn (October and November) (Figure 9).

The described changes in number of characteristic days in the NZR from historical to present-day times differ significantly from those presented for CAA by Przybylak and Vízi (2005a). The reason for this may lie in the different reference periods used for both areas (1961–1990 for CAA and 1981–2010 for the NZR) and in the different thermal character of individual analysed years from the historical period.

In the subject literature, it is possible to find different divisions of the year for seasons in the Arctic (Putnins *et al.*, 1959; Baranowski, 1968; Gavrilova and Sokolov, 1969; Przybylak, 1992). Traditional division into four seasons of equal duration (so-called 'meteorological seasons': December–February, March–May, etc.) is not appropriate if we want to describe real climate conditions, but of course is helpful and even necessary for comparisons with other areas. For this reason, Putnins *et al.* (1959) and also Gavrilova and Sokolov (1969) have proposed the following division into seasons: winter (November–March), spring (April–May), summer (June–August) and autumn (September–October). All these kinds of division of the year into seasons (including also here divisions into seasons based on astronomical features) are subjective ones and, more importantly, do not allow for precise description of real weather/climate conditions. Therefore, in some countries a division into so-called 'thermal seasons' was introduced, based on some threshold values of MDAT. In Poland such a division (threshold values of 0, 5 and 15 °C) was proposed more than a 100 years ago by Merecki (1914). For details, see Przybylak *et al.* (2014b). For the climate of the Arctic, these criteria are not appropriate and, therefore, Baranowski (1968) proposed using two threshold values (−2.5 and 2.5 °C) to delimit four thermal seasons (for more details see Section 2). One advantage of this division is the fact that it is possible to study (besides mean values of air temperature in the given season) changes in

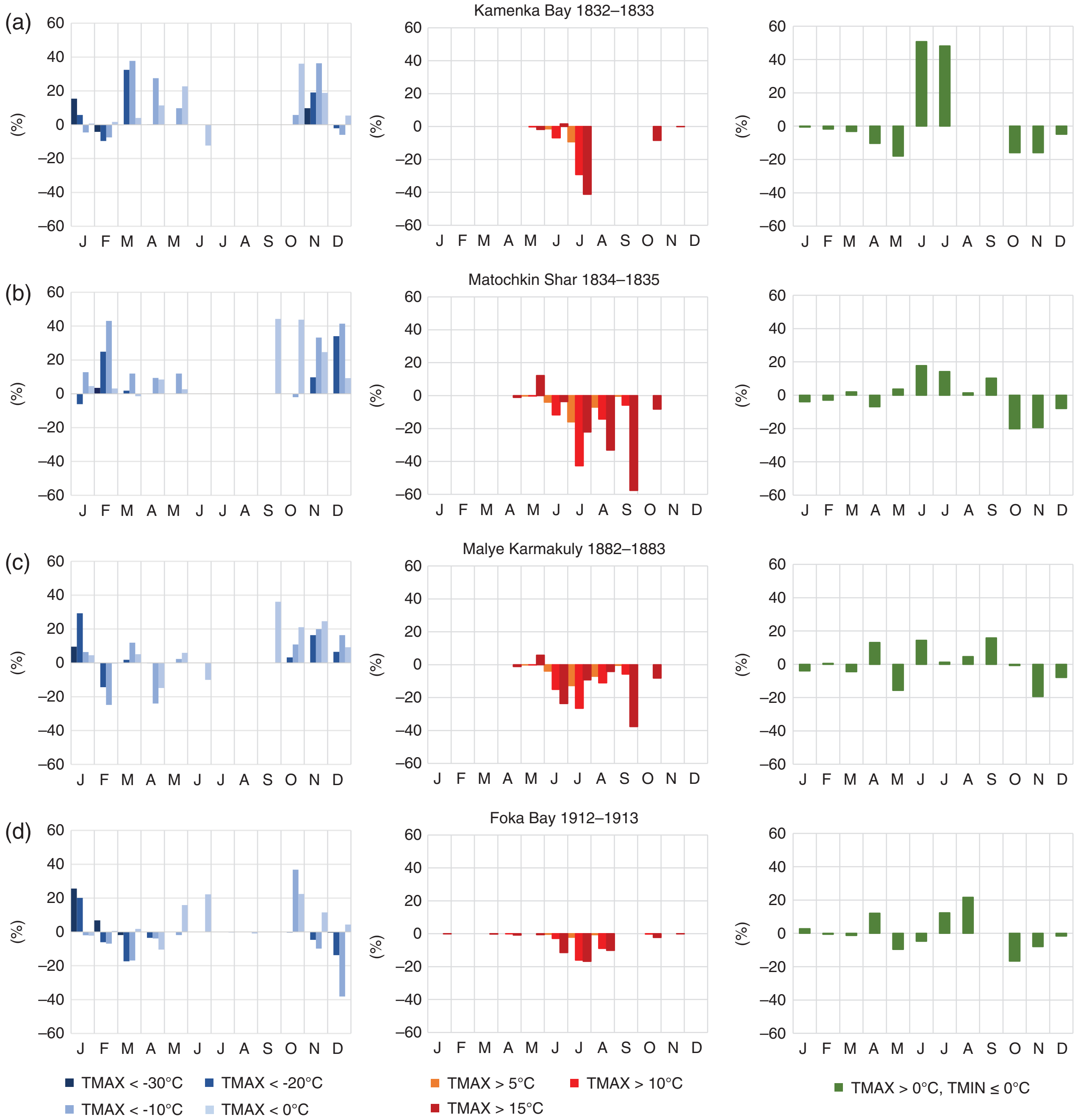

Figure 9. Annual courses of differences between the number of characteristic days (in %) in NZR in historical times and modern period (1981–2010). Note that for Foka Bay, due to lack of present daily data, a different reference period (1961–1990) was used. The differences were obtained by subtracting the historical values from the modern ones.

onset, end and duration of each thermal season. For these reasons, we have utilized the proposition of Baranowski's criteria for studies of changes in thermal season characteristics between historical and present-day times.

Table 4 presents dates of the onset and end of each thermal season in historical and modern sites (present station located near the historical one) in the NZR. Thermal seasons in both historical sites (Matochkin Shar and Malye Karmakuly) were compared with data from the contemporary station located in Malye Karmakuly. At present, autumn onsets and ends on average about half of month later than in the historical time, when the end of this season in 1882 is not taken into account (very short duration and early start of winter). Winter ($Ti \leq -2.5\,^{\circ}C$) began earlier in historical time (by about 20–30 days) but finished at practically the same time (24–25 May). As a result, winter is presently shorter by 18–30 days. From historical to present times, a large shortening of spring is observed from about 40 to 20 days (Table 4). Summer ($Ti \geq 2.5\,^{\circ}C$) in central NZR at present usually starts half a month earlier and also ends about half a month later; as a result, its duration is about a month longer than in historical times. In northern NZR, represented here by Foka Bay, a generally similar scheme of changes as that in central NZR is observed, i.e.

Table 4. Dates of the onset and end of each thermal season in historical and modern sites in NZR.

Thermal seasons	Autumn				Winter				Spring				Summer			
	Date		Duration		Date		Duration		Date		Duration		Date		Duration	
	Onset	End	Days	%	Onset	End	Days	%	Onset	End	Days	%	Onset	End	Days	%
Matochkin Shar 1834–1835	4.09	30.09	27	7.4	1.10	24.05	236	64.7	25.05	6.07	43	11.8	7.07	3.09	59	16.2
Malye Karmakuly 1882–1883	12.09	19.09	8	2.2	20.09	25.05	248	67.9	26.05	30.06	36	9.9	1.07	11.09	73	20.0
Foka Bay 1912–1913	12.08	17.09	37	10.1	18.09	8.06	264	72.3	9.06	29.07	51	14.0	30.07	11.08	13	3.6
Malye Karmakuly 1981–2010	23.09	18.10	27	7.4	19.10	24.05	218	59.7	25.05	14.06	21	5.8	15.06	22.09	99	27.1
Malye Karmakuly adj. 1981–2010	31.08	3.10	34	9.3	4.10	30.05	239	65.5	31.05	30.06	31	8.5	1.07	30.08	61	16.7

adj. – spatially adjusted to Foka Bay location.

shortening of winter (by 25 days) and spring (20 days) and lengthening of summer (by 48 days) (for details, Table 4). The short summer (only 13 days) of 1913 in Foka Bay might be historical evidence of the influence of the eruption of Katmai in 6 June 1912, which forced a decline in surface air temperature along the northern coast of Asia of about 0.5 °C in the summer (June, July and August) following its eruption (Oman *et al.*, 2005, Figure 7 in their work). In the case of autumn, no change in duration was noted; however, at present, autumn starts and ends later than in historical times. Analysis of these changes is fully in agreement with what we should expect due to the observed warming of the NZR between the analysed periods.

4. Discussion

Until recently, Novaya Zemlya was closed to scientific research for reasons both military (nuclear weapon testing range) and political. As a consequence, there are very few works trying to reconstruct its environment and climate changes in the last millennium. For details (including also a description of proxy data) see the recently published review paper of Miller *et al.* (2010) summarizing temperature and precipitation history in the Arctic in the past (including the last millennium), analysis of which markedly shows that Novaya Zemlya, as concerns the so-called ‘proxy data’, is a white spot on the Arctic map (see also Overpeck *et al.*, 1997 or Przybylak, 2016 for more details).

There is a really very limited number of works which have used proxy data from the NZR to reconstruct some features of environment, and based on this, also of main changes in climate (mainly air temperature) (e.g. Tarussov, 1992; Zeeberg *et al.*, 2003; Murdmaa *et al.*, 2004; Polyak *et al.*, 2004; Klimenko, 2010; Klimenko *et al.*, 2014). Generally, all these studies allow three main traditional climatic periods to be distinguished in the NZR in the last millennium, i.e. Medieval Warm Period (MWP), Little Ice Age (LIA) and Contemporary Warming Period (CWP). For example, Murdmaa *et al.* (2004) and Polyak *et al.* (2004) using high-resolution multiproxy sedimentary record ASV-987 from Russkaya Gavan’ fjord (north-western part of Novaya Zemlya) stated that MWP/LIA ended/onset here *ca* 1400 AD. They estimated also that late LIA began *ca* 1600 and ended either in 1800 or 1900 AD. Thus, the start of the CWP in northern Novaya Zemlya, according to these investigations, could not be precisely estimated. However, recent air temperature reconstructions made by Klimenko (2010) for the Barents and Kara seas basin (based on historical evidence) and Klimenko *et al.* (2014) for north-eastern Europe (including also historical sources from Novaya Zemlya) based on dendrochronological data, pollen data and historical data, as well as the results presented in this article, locate the end of the LIA rather more closely to 1900 AD. The same conclusion can be drawn from the recently presented reconstruction of air temperature for the entire Arctic by Kaufman *et al.* (2009). Klimenko (2010, his Figure 13.2) supplied a quantitative reconstruction of annual air temperature since 1435 for an area only slightly wider than the NZR analysed in this article. According to this reconstruction, the coldest conditions in the Barents and Kara seas basin occurred at the beginning and end of the 19th century, while the warmest period was observed from *ca* 1840 to 1870. The second mentioned cold period was also continued in the first two decades of the 20th century. This means that the years analysed here from expeditions are representative for the 2/3 years of the study period. We found that the rise of annual air temperature between historical and present time (1981–2010) reached *ca* 3 °C (Table 2). This difference for the entire period (1832–1920) is probably lower by about 0.5 °C, when data from period 1840–1870 are included for calculations (correction based on data presented in Figure 13.2 in Klimenko, 2010).

This rise in the Klimenko (2010) reconstruction based on historical evidence is smaller and is equal to about 1 °C. However, our finding is in excellent correspondence with the magnitude of air temperature change (3 °C) reconstructed for Yamal (Hantemirov and Shiyatov, 2002), Taymyr Peninsula (Naurzbaev *et al.*, 2002) and Svalbard (Przybylak *et al.*, 2016), and in good agreement with the temperature reconstruction for Salekhard region (2 °C) (Velichko *et al.*, 1997). A similar change as for Salekhard was also found for SW Greenland (Vinther *et al.*, 2006), Atlantic Arctic (Przybylak *et al.*, 2010) and the entire Arctic (Przybylak *et al.*, 2010) between the periods 1861–1920 and 1981–2010. According to Klimenko (2010), the warmest 50-year period in the Barents and Kara seas basin in the last 500 years occurred in the first half of the 20th century. On the other hand, Miller *et al.* (2010) found that the warmest 50-year interval in the reconstruction of air temperature for the entire Arctic occurred between 1950 and 2000 AD. The latter result was also found in temperature reconstructions from Yamal and Taymyr Peninsula.

Standard comparison of air temperature between historical and present-day times in the NZR and other Arctic regions, as results from the above discussion, is possible. On the other hand, such comparison for different thermal characteristics calculated based on daily air temperature data shown and analysed in this article cannot be compared with other neighbouring regions lying in the Atlantic Arctic or Russian Arctic, because such knowledge simply does not exist. This type of climate description for historical time, and comparison with modern conditions is only available for the CAA (Przybylak and Vízi, 2005a, 2005b). Therefore, because such knowledge exists for only one region, the authors decided – for greater clarity and readability of the article – to present comparisons of those characteristics between the NZR and CAA directly in Section 3.

5. Conclusions

The main results obtained from our investigations can be summarized as follows.

1 Meteorological data gathered for the area of NZR during the various scientific expeditions brought a significant contribution to the recognition of temperature changes in this area in the 19th century and beginning of 20th century.
2 Analysis reveals that in 1832–1920 the area of NZR was markedly colder than today (1981–2010) in all seasons. Coldest was autumn (on average by *ca* 5 °C) and least cold – summer (by 1.6 °C). Mean annual air temperature was colder than today by about 3 °C. Observed temperature changes between historical and present day in the NZR were similar to those identified for many neighbouring Arctic areas (e.g. Svalbard, Yamal) and more distant areas (SW Greenland, the Atlantic Arctic) or even the entire Arctic.
3 The majority of mean monthly air temperatures in historical times still lie within two SDs from the modern 1981–2010 mean. This means that values of air temperature in historical times lie within the range of contemporary temperature variability. Similar results were obtained for the Canadian Arctic (Wood and Overland, 2003; Przybylak and Vízi, 2005a, 2005b) and Svalbard (Przybylak *et al.*, 2016), as well as for the entire Arctic (Przybylak *et al.*, 2010).
4 Different air temperature characteristics calculated for the NZR for historical/contemporary periods based on daily and sub-daily data such as: MDAT, TMAX, TMIN and DTR, as well as the number of characteristic days, day-to-day variability and thermal seasons according to Baranowski (1968) also confirm the occurrence of climate warming between the studied periods. In addition, they allowed for a more precise description of different aspects of this warming.
5 MDATs in the four analysed seasons in the NZR usually have multi-modal distributions both in the historical and contemporary periods, except summer when the most normal distribution is noted, except for Kamenka Bay. In the period 1981–2010, quite a lot of new intervals appeared, sometimes even 6–10 °C warmer than the highest MDAT in the historical period. Exceptionally large numbers of them can be seen in autumn and summer, in particular in southern NZR (Kamenka Bay).
6 Day-to-day variability of MDAT generally did not change markedly between historical and present times. In some sites, and at certain times of year, differences are greater or lower than today's, but vary more or less regularly around zero. Annual (i.e. precisely October–July) mean differences are slightly positive in the entire NZR, varying between 0.5 and 0.7 °C.
7 A decrease of the DTR between historical and present-time values has been noted in the entire NZR. Such a tendency occurred both for mean DTR calculated for a 30-year period (1981–2010), as well as for data taken from a randomly chosen year.
8 As expected, the number of characteristic days changed from historical to present times, in agreement with observed warming, i.e. the numbers of instances of the different categories of cold/warm days significantly decreased/increased. In some months, in both categories of days, decreases and increases exceeded even 40%, although the majority of differences did not exceed 20%.
9 Changes in duration (also onset and end) of thermal seasons are in line with observed warming. The main features of observed changes are as follows: shortening of winter (by 20–30 days) and spring (20–30 days) and lengthening of summer (by 30–50 days). Small changes in duration were found for autumn, but quite large changes were found in the onset and end of this season. At present this season usually starts and ends 2–3 weeks later than in historical times.
10 Reconstructions of climate based on proxy data from the NZR and covering the last millennium (including late LIA) are very few, and general in character.

This article is the third one written by us which gives a deeper regional insight (Novaya Zemlya and Vaygach Island region) into climate changes in historical times in the Arctic (previous ones were Przybylak and Vízi, 2005a, 2005b; Przybylak *et al.*, 2016). The next article of this kind describing climate for the Zemlya Frantsa Josifa Archipelago is in preparation. Saving the old instrumental data and making them available to the scientific community is very helpful in supporting the correctness and reliability of our knowledge of the history of the Arctic climate in recent decades and centuries. As we also stated in a previous article (Przybylak *et al.*, 2016), better reanalysis products are urgently needed for the present time because, due to the scant network of meteorological stations, comparison of old data with new is difficult. Unfortunately, the current reanalyses which are available still give excessively large errors for the Arctic regions. Cullather *et al.* (2016) indicate that ‘there is a “representativeness” error associated with the point measurements, since the gridded analysis is intended to estimate the average state of a grid volume’. For example, for this reason there is a big challenge to use grid points lying near the locations of historical sites, when they are situated in a sea–land border with strongly differentiated relief and surface of land (e.g. glaciers).

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Supporting information

The following supporting information is available as part of the online article:

Table S1. Pearson’s coefficient of correlation (*r*) of monthly and daily air temperature values between main stations in Novaya Zemlya Region in the period 1961–1990. All correlation coefficients are statistically significant at the $p \leq 0.05$ level.

Table S2. Pearson’s coefficient of correlation (*r*) of monthly air temperature values between main stations in Novaya Zemlya Region and the nearest ERA-Interim grid points. All correlation coefficients are statistically significant at the $p \leq 0.05$ level.

Figure S1. List of published historical works dealing with the Novaya Zemlya natural environment, including register of all expeditions and their descriptions (Sosnovskiy, 1910).

Figure S2. Excerpt with meteorological observations collected during Tobiesen’s expedition to Malye Karmakuly, 1872–1873 (Mohn, 1874).

Figure S3. (Left panels) Annual courses of DTR in historical sites and (right panels) their differences from the present-day, randomly-selected, 1-year annual courses of DTR from nearby stations. Thick line indicates 11-day moving average. The differences were obtained by subtracting the historical values from the modern ones.

Appendix S1. Early instrumental air temperature dataset for Novaya Zemlya Region. Data with daily resolution.

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