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AIR TEMPERATURE CHANGES IN THE CANADIAN ARCTIC FROM THE EARLY INSTRUMENTAL PERIOD TO MODERN TIMES

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ABSTRACT

This article presents a detailed account of air temperature (using four thermal parameters: mean daily air temperature (MDAT), maximum daily temperature (TMAX), minimum daily temperature (TMIN), and diurnal temperature range (DTR)) in the Canadian Arctic from 1819 to 1859. As source data, the authors have used hourly, two-hourly, four-hourly, or six-hourly temperature measurements carried out during exploratory (land or marine) expeditions sent mainly by the Royal Navy to find the Northwest Passage and later also during a lost expedition under the command of Sir John Franklin. Standard climate analyses (using monthly means) and more detailed and precise analyses based on daily data showing a wide spectrum of temperature regimes were conducted. The latter analysis examined the frequency of occurrence of MDAT in particular intervals, day-to-day variability of MDAT, annual courses of MDAT and DTR, and the frequency of occurrence of different kinds of characteristic days (e.g. very warm, warm, severe cold, very cold). All studied aspects of historical temperature changes in the Canadian Arctic from 1819 to 1859 were compared with present-day (1961–1990) values.

All the results obtained suggest that in the nineteenth century a moderate cooling occurred in the Canadian Arctic. The average annual temperature during the study period was only about 0.3 °C lower in comparison with the present-day value. The most typical features in the annual courses of air temperature in the study period were very cold winter months (December to February, 1.0–2.5 °C below today's norm) and warm springs (March to May, 0.2–2.6 °C above today's norm). The majority of mean monthly and daily temperatures lie within one SD from the modern mean. Copyright © 2005 Royal Meteorological Society.

KEY WORDS: Canadian Arctic; air temperature changes; early instrumental period

1. INTRODUCTION

The key role of the Arctic in shaping the climate of the northern hemisphere and the rest of the world is now very well recognised. However, the instrumental record of the Arctic climate is brief and geographically sparse, and is limited mainly to the twentieth century. Prior to this, regular instrumental observations were carried out only in the coastal parts of Greenland. For the Canadian Arctic, the available meteorological series of data are particularly short and most cover only the period after World War II (for details see Przybylak, 2002, 2003; Bobylev *et al.*, 2003). Therefore, any earlier climatic data – in particular for the nineteenth century – are very important for an evaluation of climatic variation and change in this part of the Arctic.

Awareness of this fact has prompted us to undertake a search for meteorological data for the early instrumental period. Investigations have shown that there are quite a number of valuable series ranging from between one and three years in length, which were gathered during different (land and marine) exploratory expeditions (for other details and locations of wintering of vessels see Table I and Figure 1). Most of those expeditions were sent to the Canadian Arctic by the Royal Navy to locate and transit the Northwest Passage.

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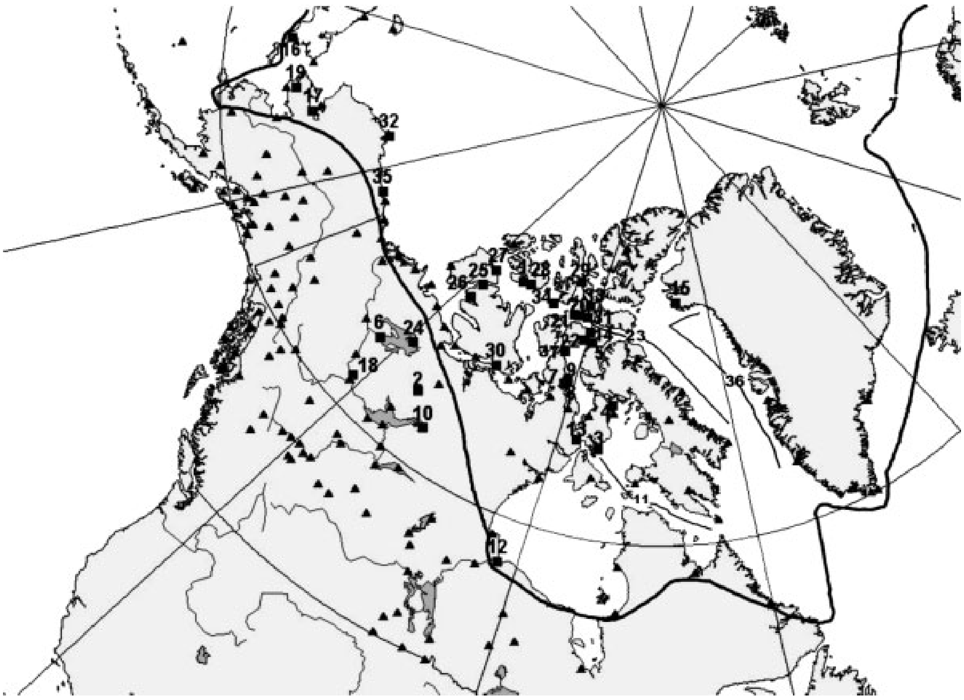

Figure 1. Location of historical sites of meteorological measurements (squares) used in the present paper and of the modern stations (triangles) utilised to construct the spatial distribution of mean (1961–1990) monthly, seasonal and annual temperatures

As can easily be seen from Table I, the majority of the expeditions were sent after 1845 in order to search for the lost expedition under the command of Sir John Franklin. Useful meteorological observations may be noted from the period when vessels, due to severe winter conditions, were frozen up. Usually, wintering lasts from September to July and the meteorological measurements, according to the high standards of the Royal Navy, were mostly carried out hourly, two-hourly, four-hourly, or six-hourly each day.

Up to now these sources of data have rarely been used to characterise the climate of the Canadian Arctic Archipelago (Kay, 1995; Przybylak, 2000a; Wood and Overland, 2003; Przybylak and Vizi, 2004). Significantly more research exists for the continental Canadian Arctic (Catchpole and Ball, 1981; Wilson 1982, 1983a,b, 1985, 1988, 1992; Ball, 1983, 1992; Catchpole and Faurer, 1983, 1985; Hopper, 1985; Catchpole and Hanuta, 1989) on the basis of data gathered mainly in posts kept by the Hudson Buy Company. Both these kinds of early instrumental data, although containing some biases and errors, are definitely better sources of information about climate in the Canadian Arctic than the best existing records of proxy data.

In the present paper, detailed characteristics of different thermal parameters for the Canadian Arctic are presented for the historical period (1819–1859), including mean daily air temperature (MDAT), maximum daily temperature (TMAX), minimum daily temperature (TMIN), diurnal temperature range (DTR), the number of characteristic days (i.e. the number of days with temperatures exceeding specified thresholds), and day-to-day temperature variability. Comparisons with modern data (1961–1990) have also been made.

2. AREA, DATA AND METHODS

The southern border of the Canadian Arctic (Figure 1) is determined after *Atlas Arktiki* (1985). The authors of this Atlas used climatic criteria to delimit this boundary (for more details see Przybylak, 2003). In Table I and Figure 1 we show all the expeditions that carried out meteorological observations in the North American

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Table I. A list of expeditions to the North American Arctic and Subarctic, and Tchukotka Peninsula from 1819 to 1859 that carried out meteorological observations (after Przybylak and Vizi, 2004, modified)

NOSF[a]	Location	φ	λ	Ships/station	Captain/ observer	Years	Number of months
1	Winter Harbour, Melville Island	74° 47′N	110° 48′W	H.M.S. 'Hecla'	Sir W.E. Parry	1819–1820	12
1	Winter Harbour, Melville Island	74° 47′N	110° 48′W	H.M.S. 'Griper'	Sir W.E. Parry	1819–1820	12
2	Fort Enterprise	64° 28′N	113° 06′W	Station	J. Franklin	1820–1821	9
3	Winter Island	66° 11′N	83° 10′W	H.M. Ships 'Hecla' and 'Fury'	Sir W.E. Parry	1821–1822	12
4	Igloolik	69° 21′N	81° 53′W	H.M. Ships 'Hecla' and 'Fury'	Sir W.E. Parry	1822–1823	12
5	Port Bowen	73° 13′N	88° 55′W	H.M. Ships 'Hecla' and 'Fury'	Sir W.E. Parry	1824–1825	12
6	Fort Franklin	65° 12′N	123° 13′W	Station	J. Franklin	1825–1826	11
6	Fort Franklin	65° 12′N	123° 13′W	Station	J. Franklin	1826–1827	7
7	Felix Harbour, Gulf of Boothia	69° 59′N	92° 06′W	'Victory'	Sir J. Ross	1829–1830	12
8	Victoria Harbour, Gulf of Boothia	70° 08′N	91° 35′W	'Victory'	Sir J. Ross	1830–1831	12
9	Mundy Harbour, Gulf of Boothia	70° 18′N	91° 40′W	'Victory'	Sir J. Ross	1831–1832	7
10	Fort Reliance	62° 43′N	109° 10′W	Station	G. Back	1833–1835	19
11	Hudson Strait	drift		H.M.S. 'Terror'	G. Back	1836–1837	12
12	York Factory	57° 00′N	92° 26′W	Station	J. Rae	1845–1846	6
13	Fort Hope, Repulse Bay	66° 32′N	86° 56′W	Station	J. Rae	1846–1847	11
14	Port Leopold	73° 50′N	90° 12′W	H.M.S. 'Investigator'	Sir J.C. Ross	1848–1849	12
15	Wolstenholm Sound	76° 34′N	68° 45′W	H.M.S. 'North Star'	J. Saunders	1848–1849	12
16	Port Providence	64° 26′N	173° 00′W	H.M.S. 'Plover'	T.E.L. Moore	1848–1849	9
17	Chamiso Island	66° 13′N	161° 46′W	H.M.S. 'Plover'	T.E.L. Moore	1849–1850	12
18	Fort Simpson	62° 07′N	121° 33′W	Station	J.W.S. Pullen	1849–1851	17
19	Port Clarence	65° 05′N	165° 30′W	H.M.S. 'Plover'	T.E.L. Moore	1850–1852	22
20	Assistance Bay	74° 40′N	94° 16′W	'Sophia'	W. Penny	1850–1851	12
20	Assistance Bay	74° 40′N	94° 16′W	'Lady Franklin'	A. Stewart	1850–1851	4

(*continued overleaf*)

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Table I. (*Continued*)

NOSF[a]	Location	φ	λ	Ships/station	Captain/ observer	Years	Number of months
21	Griffith Island	74° 34′N	95° 20′W	H.M.S. 'Resolute'	Sir H.T. Austin	1850–1851	12
22	Batty Bay	73° 12′N	91° 10′W	'Prince Albert'	W. Kennedy	1850–1851	8
23	Wellington Chanel to Baffin Bay	drift		'Advance'	E. De Haven	1850–1851	9
24	Fort Confidence	66° 40′N	119° 00′W	Station	J. Rae	1850–1851	9
25	Princess Royal Islands	72° 47′N	117° 35′W	H.M.S. 'Investigator'	Sir R.J. McClure	1850–1851	12
26	Walker Bay	71° 35′N	117° 39′W	H.M.S. 'Enterprise'	Sir R. Collinson	1851–1852	12
27	Mercy Bay	74° 06′N	117° 55′W	H.M.S. 'Investigator'	Sir R.J. McClure	1851–1853	20
28	Dealy Island	74° 56′N	108° 49′W	H.M.S. 'Resolute'	H. Kellett	1852–1853	12
28	Dealy Island	74° 56′N	108° 49′W	H.M.S. 'Intrepid'	H. Kellett	1852–1853	10
29	Northumberland Sound	76° 52′N	97° 00′W	H.M.S. 'Assistance'	Sir E. Belcher	1852–1853	12
29	Northumberland Sound	76° 52′N	97° 00′W	H.M.S. 'Pioneer'	Sir E. Belcher	1852–1853	12[b]
30	Cambridge Bay	69° 03′N	105° 12′W	H.M.S. 'Enterprise'	Sir R. Collinson	1852–1853	12
31	Beechey Island	74° 43′N	91° 54′W	H.M.S. 'North Star'	J.W.S. Pullen	1852–1854	13
32	Point Barrow	71° 21′N	156° 17′W	H.M.S. 'Plover'	R. Maguire	1852–1854	22
19	Port Clarence	65° 05′N	165° 30′W	H.M.S. 'Rattlesnake'	H. Trollope	1853–1854	11
33	Wellington Channel	75° 31′N	92° 10′W	H.M.S. 'Assistance'	Sir E. Belcher	1853–1854	12
33	Wellington Channel	75° 31′N	92° 10′W	H.M.S. 'Pioneer'	Sir E. Belcher	1853–1854	12[b]
34	Melville Sound	74° 42′N	101° 22′W	H.M.S. 'Resolute'	H. Kellett	1853–1854	8
34	Melville Sound	74° 42′N	101° 22′W	H.M.S. 'Intrepid'	H. Kellett	1853–1854	8
35	Camden Bay	70° 08′N	145° 29′W	H.M.S. 'Enterprise'	Sir R. Collinson	1853–1854	11
13	Fort Hope, Repulse Bay	66° 32′N	86° 56′W	Station	J. Rae	1853–1854	11
36	Baffin Bay	drift		'Fox'	F.L. McClintock	1857–1858	13
37	Port Kennedy	72° 01′N	94° 14′W	'Fox'	F.L. McClintock	1858–1859	12

[a] Number of site on Figure 1.
[b] Only wind and weather notations.

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Arctic and Subarctic, and in the Chukotka Peninsula. For the present analysis, we selected expeditions that wintered in the Canadian Arctic. The temperature data gathered for them cover almost the entire defined study area (Figure 1). The majority of them, however, are located in the area between 70–80 °N and 90–120 °W.

For the analysis, two sets of monthly and daily temperature data (mean, maximum and minimum) have been used: historical and modern. As mentioned earlier, the first dataset was gathered during the wintering of vessels, which were sent to the Canadian Arctic by the Royal Navy (1819–1859) in order to find the Northwest Passage and a lost expedition under the command of Sir John Franklin. Monthly data were taken from the publication entitled *Contributions to our Knowledge of the Meteorology of the Arctic Regions,* Parts I (1879), II (1880), III (1882), IV (1885) and V (1888). On the other hand, daily data were taken from original ships' log books (mainly from the parts entitled *Meteorological Registers*), the majority of which are available in different archives located in the United Kingdom (the Scott Polar Research Institute in Cambridge, the Meteorological Office in Exeter, and the Royal Geographical Society, Royal Society and Public Record Office in London). The second dataset includes contemporary data (1961–1990) obtained for all historical sites (monthly data) and for stations located near the historical sites (daily data). Data were taken from the web sites of Environment Canada and the National Climate Data Center (with monthly data derived from the *Historical Adjusted Climate Database for Canada*, version December 2002 (Vincent and Gullett, 1999, updated) and *Global Historical Climate Network, v2*).

For the fixed hour data (hourly, two-hourly, four-hourly or six-hourly) gathered for historical sites, which were used to calculate daily means, we introduced all corrections resulting from instrumental errors of the thermometers used, as suggested by Strachan (in *Contributions to our Knowledge*...). Evidently wrong values and small gaps in the hourly data for a given day were corrected and filled in (respectively) using average daily courses calculated from the neighbouring days.

TMAX and TMIN were chosen for each day on the basis of two-hourly data. DTR was calculated by subtracting TMIN from TMAX.

Different approaches have been adopted in the comparison of historical and modern temperature data depending on their resolution (monthly or daily). For the latter, daily data from the present stations located nearest to the historical observation points have been used. On the other hand, for the former, the procedure was as follows:

(1) Working from all available mean monthly long-term (1961–1990) data, maps presenting the spatial distribution of air temperature for each month were drawn using mathematical interpolation (kriging) (a reduction of temperature to sea level (0.6°C/100 m) was made),
(2) The modern long-term (1961–1990) mean monthly temperature values for the historical sites were derived,
(3) The modern values obtained in this way for historical sites were compared with those from the nineteenth century.

In this way, the differences resulting from different geographical locations of historical and modern observational points were removed.

However, the reader must be aware of the fact that some sources of errors and biases still remained. For example, such errors and biases may result from the use of different types of instruments and recording schedules (which determined the methods of calculating daily means and monthly means), and differences in thermometers' exposures. The problem is that it is impossible to estimate some of these errors because of the lack of any information. Przybylak and Vizi (2004) estimated that biases connected with different methods of calculating monthly means in historical and present times are small and generally do not exceed 0.2 °C (for more details about sources of data and their quality, also see that work).

3. RESULTS

3.1. Monthly data

Analysis of the data presented in Table II reveals that the annual mean air temperature in the Canadian Arctic in the period from 1819 to 1859 was colder than today (1961–1990) by 0.3 °C. The first part of

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the study period (1819–1832) was warmer than the 1850s by about 0.2°C, although most of the months were colder (March–August and November). This finding is in agreement with ice-core data results (see e.g. Koerner and Fisher, 1981; Alt *et al.*, 1992; Bradley and Jones, 1993; Przybylak, 2003).

The most typical features in the annual courses of air temperature in the study period were very cold winter months (December to February, 1.0–2.5 °C below today's norm) and warm springs (March to May, 0.2–2.6 °C above today's norm). On average, the Canadian Arctic was also colder than today by 1.5–2.2 °C in high summer (July and August) and in autumn (excluding November). Such a pattern in the annual courses

Table II. Air temperature differences (°C) between mean monthly and annual values from historical and modern (1961–1990) periods for the Canadian Arctic and Subarctic

Location	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Year
Melville Island, 1819–1820		−0.3	−3.8	−2.5	0.1	−0.5	−1.7	4.1	1.5	2.4	2.0	4.0	−1.8	0.2
Fort Enterprise, 1820–1821		−5.1	−1.8	−1.8	−10.2	1.7	3.0	−2.4	−4.9	−1.5				
Winter Island, 1821–1822	−3.9	−0.9	−2.8	4.3	0.2	−0.4	−2.2	2.1	2.8	2.5	−0.8	−5.9		0.3
Igloolik, 1822–1823	−3.9	−3.5	−0.4	−7.5	−5.8	4.5	3.1	0.8	1.5	5.2	−0.6	−1.8		0.0
Port Bowen, 1824–1825		−0.3	1.6	2.9	0.8	−1.3	0.3	−2.5	1.5	2.2	1.9	−2.1	−1.4	0.3
Fort Franklin, 1825–1827		−1.4	−1.4	0.7	0.8	−2.9	−1.3	−1.3	−3.6	−2.7	−4.2	−4.9	−3.1	−2.0
Felix Harbour, 1829–1830		0.3	−1.1	2.2	−1.0	2.7	0.8	2.2	4.8	0.7	2.0	−0.5	−0.4	1.2
Victoria Harbour, 1830–1831		−1.0	0.3	−0.5	1.3	3.5	−0.7	−5.1	1.8	1.2	−1.0	−4.2	−2.6	−0.5
Mundy Harbour, 1831–1832		−3.0	−0.7	5.0	−1.4	1.4	−2.1	−4.0	7.8	−6.1				
Fort Reliance, 1833–1835				3.6	−4.0	−3.8	−2.7	−3.3	−5.0	−0.8				
York Factory, 1845–1846				0.0	−1.6	8.0	−4.3	4.2	−3.1					
Repulse Bay, 1846–1847		−2.1	−1.9	2.5	−1.4	−0.8	−1.4	−4.2	−1.3	0.3	−2.6	−4.1		
Port Leopold, 1848–1849		−0.8	2.8	−0.2	−6.8	−3.2	−2.0	2.3	2.3	2.6	0.0	−2.9	−2.3	−0.7
Fort Simpson, 1849–1850			−2.7	2.3	−6.4	−7.7	2.9	−3.3	−0.7	1.4	1.6			
Assistance Bay, 1850–1851		−1.4	−1.9	2.7	−0.6	−1.7	−1.5	1.2	3.8	−0.2	2.3	−1.6	−0.5	0.1
Griffith Island, 1850–1851		−4.5	−3.1	2.5	−1.4	−2.7	−2.6	−0.7	1.8	−1.8	1.0	−2.4	−0.7	−1.2
Batty Bay, 1850–1851		−1.1	0.3	2.0	2.4	3.9	5.3	5.8	9.2					
Fort Confidence, 1850–1851			−3.7	5.2	−4.6	−7.3	−9.7	−2.3	1.0	−1.0				
Princess Royal Islands, 1850–1851		−1.4	−5.1	−0.4	−3.0	−4.9	−7.1	−4.2	1.1	2.5	1.0	−2.5	−0.3	−1.8
Walker Bay, 1851–1852		0.3	0.6	0.8	−0.7	1.9	3.6	−1.7	8.2	−0.2	−1.5	−0.9	−1.5	1.0
Mercy Bay, 1851–1853	−1.8	−2.4	−3.8	−1.8	−1.6	−5.6	−2.8	−2.0	3.4	−0.5	−1.1	−2.3		−1.6
Dealy Island, 1852–1853				2.4	−2.0	−5.2	−1.2	3.0	3.9	1.7	1.0	−2.4		
Northumberland Sound, 1852–1853		−1.2	−0.7	6.8	−3.6	−5.6	1.5	5.8	2.2	1.7	−0.4	−1.9	−1.5	0.4
Cambridge Bay, 1852–1853		−6.2	−4.2	1.3	−5.4	−4.9	−0.9	3.2	2.1	0.9	−1.6	−3.7	−2.3	−1.5
Wellington Channel, 1853–1854		−3.4	−1.9	2.8	4.0	4.6	3.0	3.0	7.6	−0.3	−1.2	−1.2	−0.2	1.5
Melville Sound, 1853–1854		−3.0	1.1	−3.9	−4.9	−4.0	−5.3	−2.3	4.1					
Repulse Bay, 1853–1854		−4.6	−3.2	−8.8	−5.6	−2.6	−6.6	0.2	2.4	3.1	1.1	−2.6		
Beechey Island, 1852–1854		−2.1	0.5	1.2	−2.1	−4.4	0.9	3.3	6.1	2.8	1.4	−0.9	−1.6	0.4
Port Kennedy, 1858–1859		−0.7	−0.8	−0.4	−7.0	−3.4	−4.4	3.6	3.4	1.0	1.6	−2.1	−0.4	−0.7
Mean, 1819–1832[a]		−1.7	−1.1	0.3	−1.7	1.0	−0.1	−0.7	1.5	0.4	−0.1	−2.2	−2.4	−0.1
Mean, 1850–1859[a]		−2.5	−2.2	0.6	−2.5	−2.7	−1.5	1.1	3.8	0.8	0.2	−2.0	−1.1	−0.3
Difference 1819–1832–1850–1859		0.8	1.1	−0.3	0.8	3.7	1.4	−1.8	−2.3	−0.4	−0.3	−0.2	−1.3	0.2
Mean, 1819–1859[a]		−2.1	−1.5	0.5	−2.3	−1.1	−1.0	0.2	2.6	0.7	0.0	−2.2	−1.7	−0.3
Arctic (60–90°N) 1851–1860[b]	−0.5	−0.2	−1.1	−0.8	−1.3	−1.3	−1.9	−0.9	−0.6	−0.4	−0.3	−0.1	−0.5	−0.8

[a] Mean values calculated from stations that have complete data at least for the period Sep–May.
[b] After Jones *et al.* (1999).

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of air temperature is seen in the majority of the analysed historical sites and years of observations (Table II and Figure 2).

For the 1850s, it is possible to compare our data with data for the whole Arctic (60–90°N) compiled by Jones *et al*. (1999). We should remember here, however, that for this decade there were no permanent meteorological stations working in the real Arctic (e.g. as defined after *Atlas Arktiki*, 1985). Thus, in reality, the dataset mentioned describes mainly temperature in the 60–70°N latitude band and therefore should rather be termed *Subarctic*. The signs of the anomalies of the annual values for both regions are the same but for the 'Subarctic' their values are almost three times greater than for the Canadian Arctic (Table II). On the other hand, some monthly anomalies differ significantly. However, most of them have the same signs (with the particular exception of spring months).

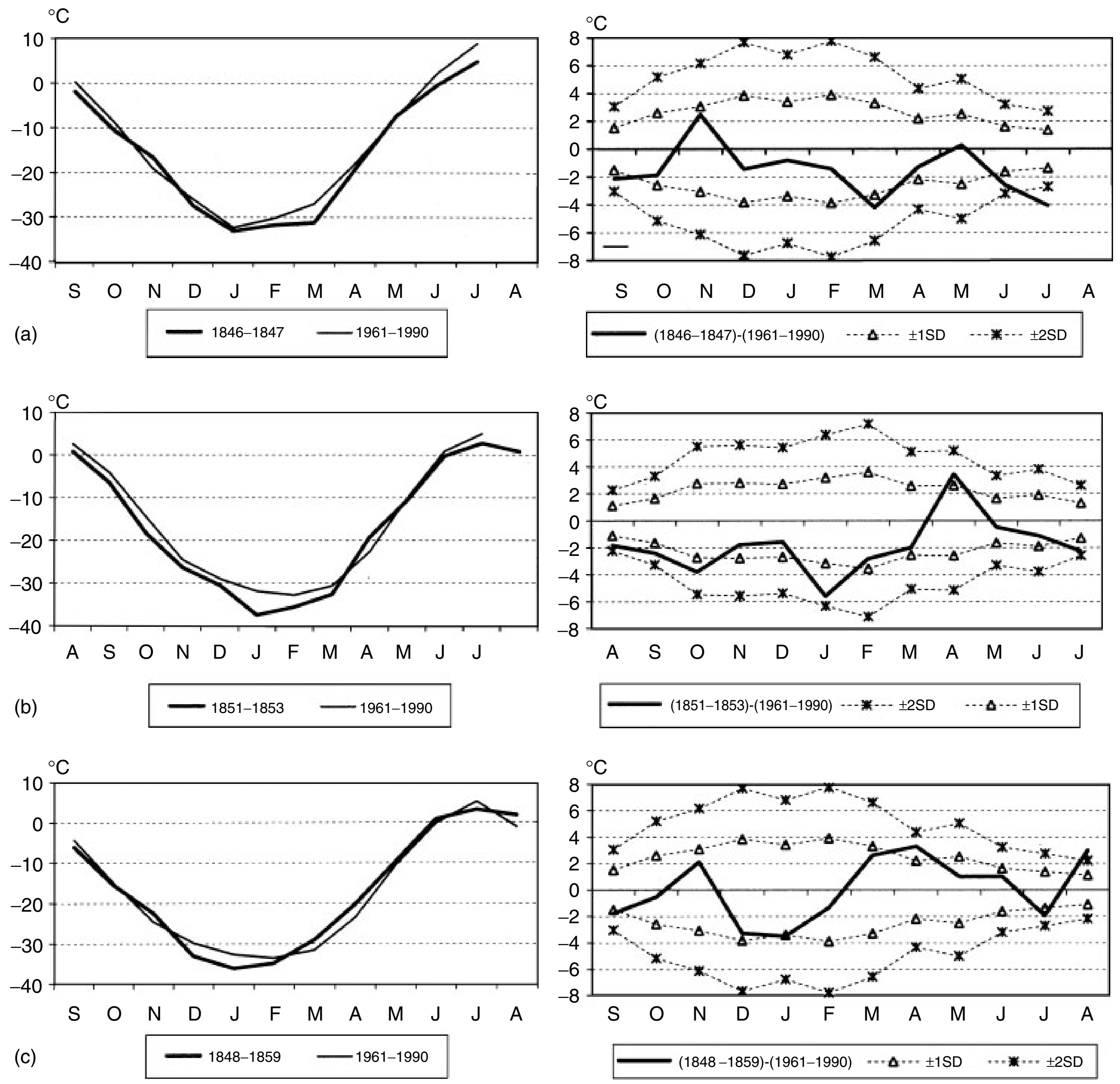

Figure 2. Annual courses of historical and modern air temperatures based on monthly means (left panels) and differences between them (right panels) in (a) Repulse Bay (b) Mercy Bay and (c) Resolute region. SD has been calculated on the basis of present data (1961–1990)

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The results showed that air temperatures in the Canadian Arctic from 1819 to 1859 were not as exceptionally cold as has been suggested by some analyses of proxy data (Koerner, 1977; Overpeck *et al.*, 1997). This conclusion is confirmed by the fact that the majority of the mean monthly air temperatures lie within one standard deviation (SD) from the modern mean (Figure 2), and only in a few cases do they exceed the level of two SDs.

3.2. Daily data

In the process of averaging, important climatic information may very often be lost. For this reason, we decided to additionally present the temperature regime in the Canadian Arctic in a more precise way, using different parameters of daily data. Temperature characteristics are shown here only for some selected expeditions. Two of them, which wintered in Melville Island (1819–1820) (No.1 in Figure 1) and in Winter Island (1821–1822) (No. 3 in Figure 1), were chosen to characterise temperature at the beginning of the nineteenth century. Both these historical sites were situated near the present locations of the Resolute (northern part of the Canadian Arctic) and Coral Harbour (southern part) meteorological stations, respectively. In addition, we also show averaged results from six historical sites (1848–1859) (Nos 13, 19, 20, 27, 29, and 38 in Figure 1) located no more than 150 km from the present locations of the Resolute meteorological stations (hereafter referred to as *Resolute region*).

Annual courses, based on MDAT in Melville Island, Winter Island and Resolute region, when superimposed on their present-day (1961–1990) mean annual courses derived from the nearby stations, show that in the nineteenth century there occurred spells which were both warmer and colder than today. Of course, the former were more common at the turn of the 1810s and 1820s, while the latter predominated from 1848 to 1859, especially during winters (Figure 3a–c). Warm spells were more frequent than today in late autumn (except for Melville Island) and in spring. The differences of the MDAT (both positive and negative) generally do not exceed 15^{o}C, and they oscillated mostly within the distance of one SD from the present long-term mean. The greatest differences occur in the cold half-year as a result of the greatest variability of MDAT during this period.

In summer, the differences are smaller and more stable. Cold summers occurring in the study period should have limited the melting both of the sea and land ice. But probably the greatest effect of weather was on land ice rather than on sea ice. Such a conclusion can be drawn by looking at paleoclimatic reconstructions based on ice core records (e.g. Koerner, 1977; Koerner and Fisher, 1990) that show exceptionally cold conditions at this time, while, on the other hand, analyses of summer sea-ice extent and thickness in the Canadian Arctic in the nineteenth century reveal the similarity to the present ice climatology (see Wood and Overland, 2003).

The normal distribution of the MDAT is seen only in winter and summer (Figure 4a–c). In transitional seasons, the ranges of MDAT are significantly greater and show multi-modal distributions. In winter, increases both in mean and variance are noted from historical to modern times, and this may be clearly seen for data from 1848 to 1859 in particular. Summers in the Resolute region were colder and the MDATs were more stable than at present, although in both periods there prevailed MDAT oscillating between 0 and 4^{o}C, with maximum frequencies in the 1.1–2.0 °C interval. The summer in Winter Island was especially cold and the variance was smaller (Figure 4b) than in the modern period. The maximum occurrences of MDAT in the historical and modern periods were noted here for the intervals 2.1–3.0 and 5.1–6.0 °C, respectively. In Melville Island, in comparison to present conditions, there were fewer cold temperatures, and the normal distribution was disturbed by the great occurrence frequency of warm temperatures, especially in the 6.1–7.0 °C interval (about 12%). As a result, bi-modal distribution is evident.

At present, in spring more cold and fewer warm MDATs occur than in the nineteenth century. In autumn, generally both fewer warm and fewer cold events occurred in the study period (with the exception of Melville Island) than today. In both transitional seasons, in any time and in any location, the frequency of occurrence of the MDAT in particular intervals does not exceed 10%.

Day-to-day variability of MDAT, similar to the present climate (see Przybylak, 2002), was greatest in winter, and lowest in summer (Figure 5a–c). From October to March, non-averaged day-to-day variability of MDAT (Figure 5a and b) oscillated mostly between 2 and 5 °C, rarely exceeding 5 °C, and 10 °C (6 cases) in

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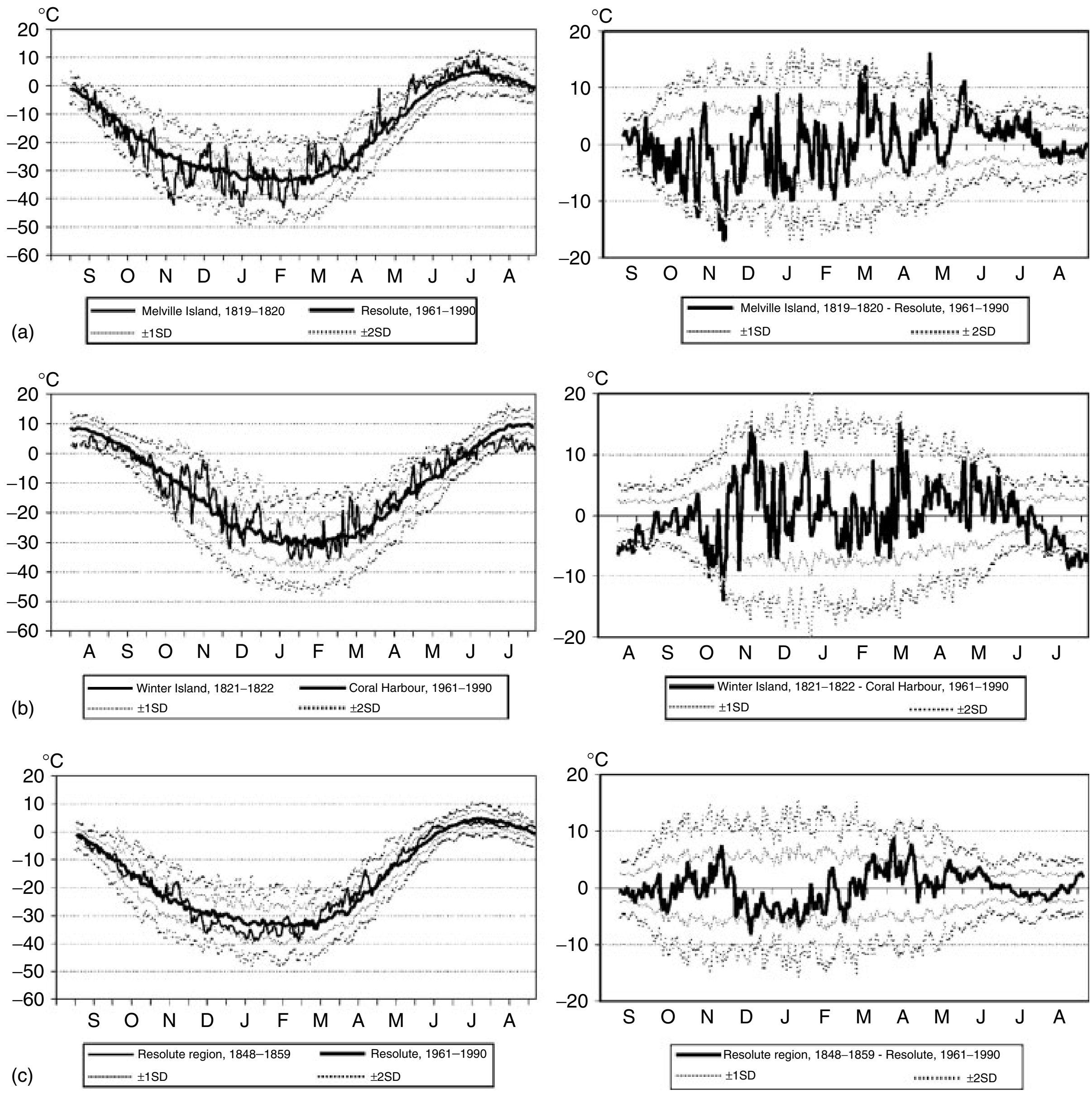

Figure 3. Annual courses of MDAT in historical and modern sites (left panels) and their differences (right panels). SD has been calculated on the basis of present data (1961–1990) taken from nearby stations

particular. Such abrupt mid-winter warming (or cooling) is also noted in the present climate in the Arctic (see e.g. Przybylak, 2002). In Winter Island (Figure 5b) and Resolute region (Figure 5c) two maximums of day-to-day variability of MDAT are clearly seen, one just before (November) and one just after (March/April) the standard winter (December/January/February). From March/April, steady decreases in variabilities are noted. In summer, the non-averaged day-to-day variabilities of MDAT (Figure 5a and b) do not exceed 2–3 °C.

In the nineteenth century, the day-to-day variability of MDAT was greater in the southern part of the Canadian Arctic than in the northern part, a trend that may also be noted in the present climate. The greatest changes in the day-to-day variability of MDAT from historical to present times occur in winter and (especially) in summer. In both seasons, increases in variances were noted (not shown). This means that at present the occurrence

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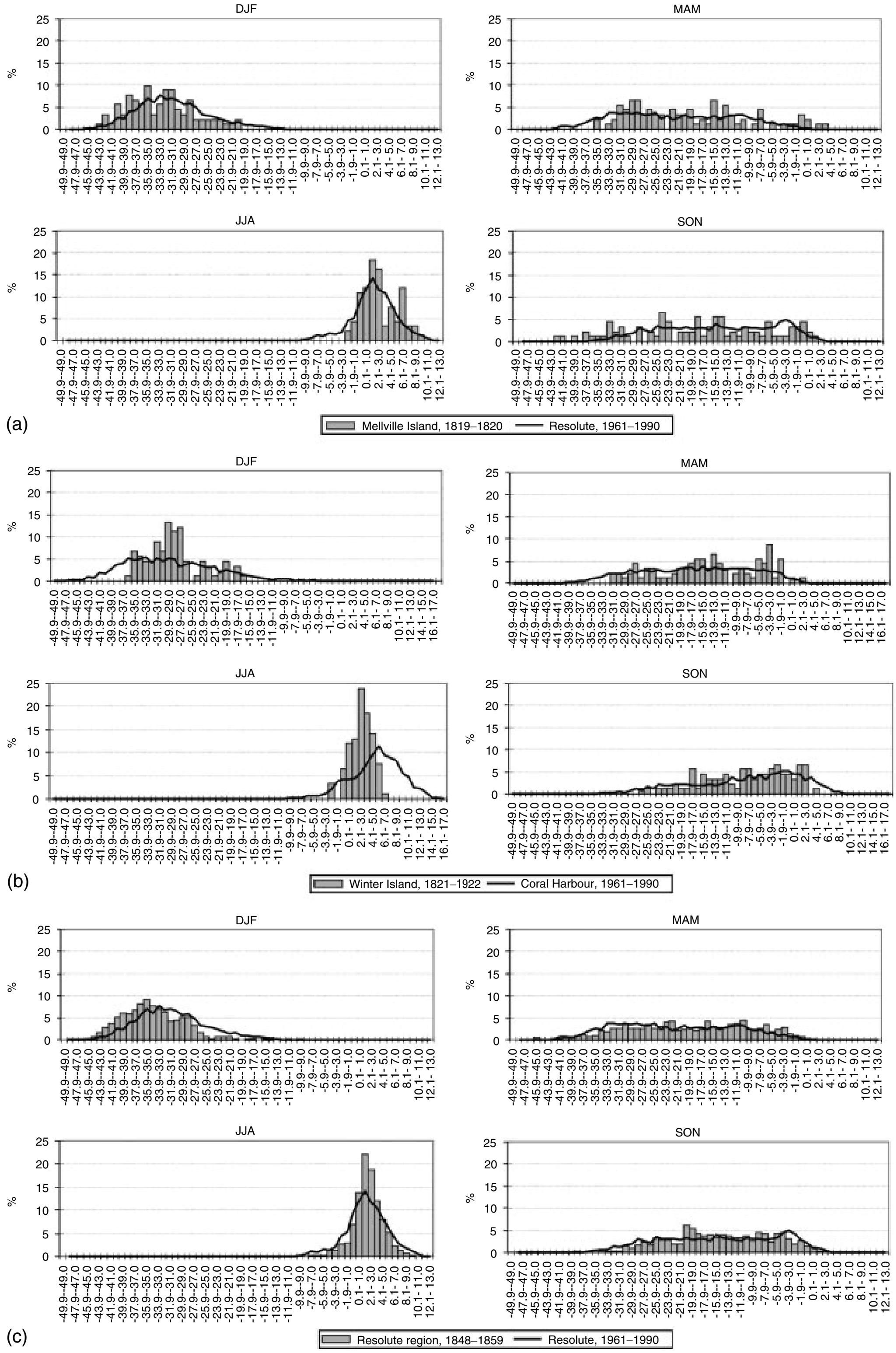

Figure 4. Seasonal (December/January/February, March/April/May, etc.) relative frequencies of occurrence (in %) of MDAT in historical and modern sites located nearest them

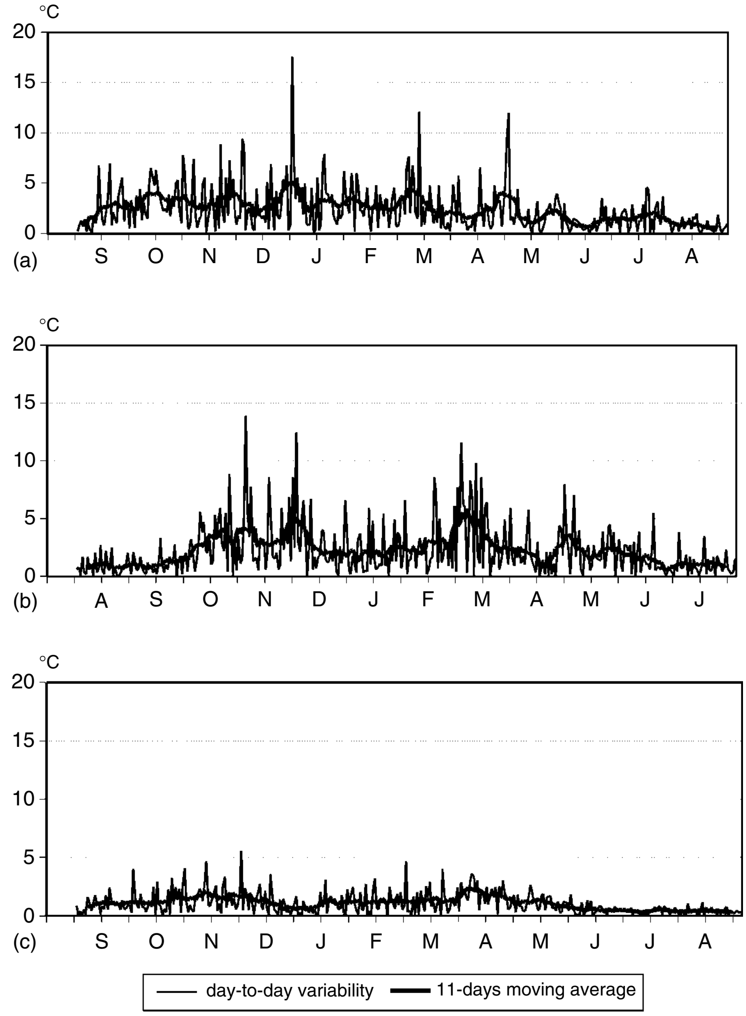

Figure 5. Annual courses of day-to-day variability of MDAT (in °C) in (a) Melville Island (1819–1820), (b) Winter Island (1821–1822) and (c) Resolute region (1848–1859)

of large day-to-day variability of MDAT (exceeding 5 °C in winter and 3 °C in summer) is more frequent, while small variability (0–1 °C) is less frequent. In transitional seasons, changes in variabilities were small, except for autumn in Melville Island, where a decrease in variance from historical to present times occurred (not shown).

In all the regions and historical periods analysed in the present paper, the DTRs were the greatest in spring, oscillating between 7 and 10 °C (Figure 6a–c, left panels). Throughout the rest of the year, the DTRs were lower and oscillated between 4 and 6 °C, except for August in the Resolute region, and September in all localities, where DTRs were mostly lower than 4 °C (Figure 6c, left panel). Przybylak and Vizi (2004) also found a similar distribution of the DTR in a year in the Canadian Arctic during the First International Polar Year 1882/1883. In comparison with the present DTR (see Przybylak, 2000b), the greatest changes in the shape of the annual courses occurred in the northern part of the Canadian Arctic, where winter DTRs (instead of spring) are the highest.

In the nineteenth century, in all months (except for June and some months in spring) the DTRs were significantly lower than at present (by up to 5 °C in Winter Island and 3 °C in other regions). In the Resolute region (1849–1858), the differences were the greatest (up to 3 – 4 °C) from November to February (Figure 6c, right panel). It should be remembered here that TMAX and TMIN for the nineteenth century were not derived from

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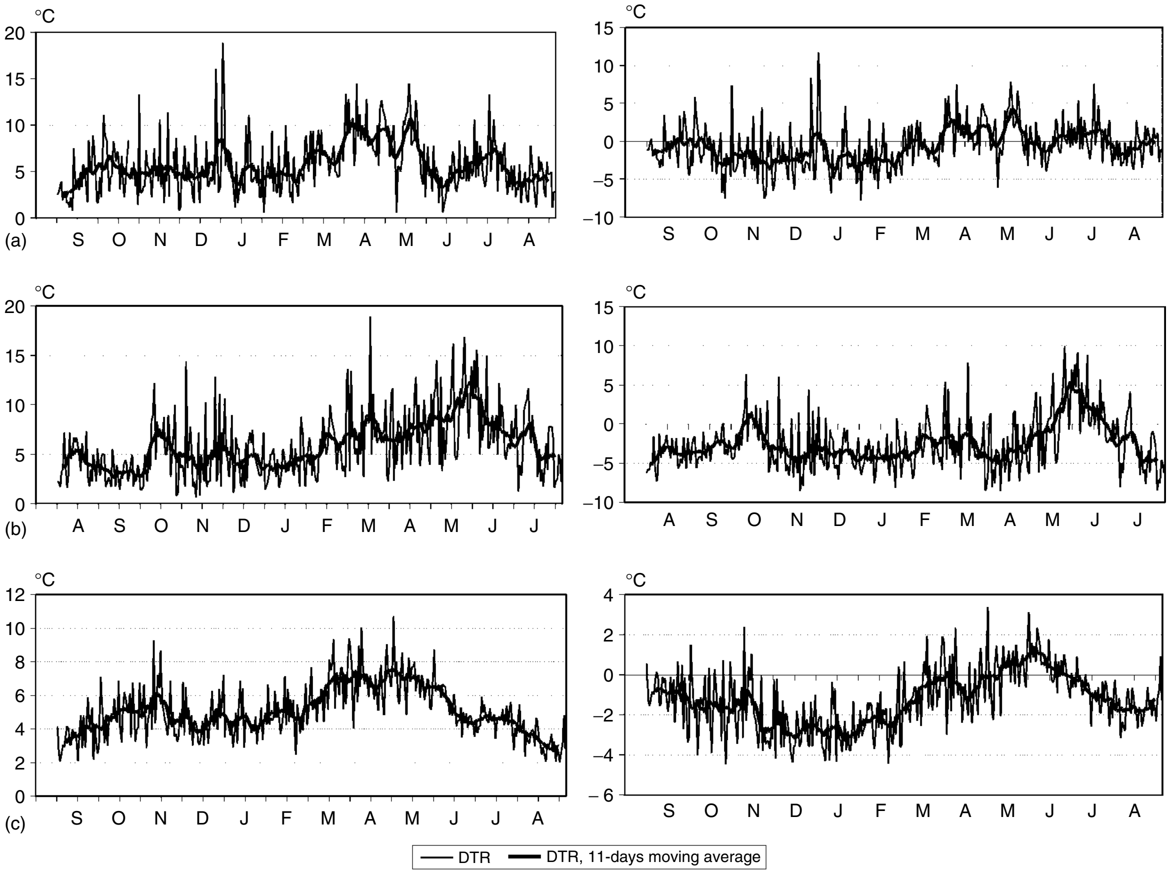

Figure 6. (Left panels) annual courses of DTR in (a) Melville Island (1819–1820), (b) Winter Island (1821–1822), (c) Resolute region (1848–1859), and (right panels) their differences from the present-day annual courses of DTR in: (a) Resolute (1961–1990), (b) Coral Harbour (1961–1990) and (c) Resolute (1961–1990), respectively

the maximum and minimum thermometers (as is the standard at present), but from two-hourly observations. Thus, the negative/positive DTR differences between historical and modern times shown in Figure 6 (right panels) are, in reality, a little smaller/greater, respectively.

The relative frequencies of occurrence of different kinds of characteristic days in the nineteenth century are shown in Figure 7a–c. Exceptionally warm days ($T\max > 15\,^{\circ}$C) occurred only in Melville Island in July 1820 (0.6% of all days in summer). Very warm days ($T\max > 10\,^{\circ}$C) were also quite rare, but occurred in all places and only in summer. Their frequency oscillated from 1.6% in the Resolute region to 7.8% in Melville Island (Table III).

Days with severe frost ($T\max < -30\,^{\circ}$C) were noted in the Resolute region and Melville Island from October to April (Figure 7a and c) with annual frequencies of 19.8 and 13.6%, respectively, while in the southern part of the Canadian Arctic (Winter Island) they were noted from October to February (Figure 7b) with a significantly lower frequency (5.5%). In line with expectations, their frequency is greatest in winter (Table III), exceeding more than 50% of days in the northern part of the Canadian Arctic. In particular winter months, the occurrence frequency of days like these can even reach almost 80% (Figure 7a and c). On the other hand, in Winter Island the days with severe frost did not exceed 30% (Figure 7b). The differences in frequencies of the occurrence of very cold ($T\max < -20^{o}$C) and cold ($T\max < -10\,^{\circ}$C) days between the analysed time periods and regions are significantly lower than in the case of severe frost days.

Days with slight frost ($T\max > 0\,^{\circ}$C and $T\min \leq 0\,^{\circ}$C) occurred most often from May to September. In the northern part of the study area, they were most common in June and August, while in its southern part they

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Table III. Relative frequency of occurrence (in %) of characteristic days in the Canadian Arctic in the nineteenth century

Characteristic days	Melville Island (1819–1820)					Winter Island (1821–1822)					Resolute region (1848–1859)				
	DJF	MAM	JJA	SON	Year	DJF	MAM	JJA	SON	Year	DJF	MAM	JJA	SON	Year
Tmax >0 °C, Tmin <= 0 °C	0.0	7.6	41.6	26.1	22.4	0.0	12.0	52.2	11.0	18.9	0.0	4.7	45.3	2.7	13.3
Tmax <0 °C	100.0	89.1	3.2	68.9	57.0	100.0	82.6	0.0	74.7	64.1	100.0	94.1	5.0	96.0	73.5
Tmax < −10 °C	100.0	69.6	0.0	46.2	46.1	100.0	52.2	0.0	26.4	44.4	99.7	65.8	0.2	59.1	56.0
Tmax < −20 °C	91.2	38.0	0.0	23.5	32.0	83.3	20.7	0.0	5.5	27.1	97.0	37.0	0.0	18.1	37.8
Tmax < −30 °C	51.6	3.3	0.0	10.1	13.6	22.2	0.0	0.0	0.0	5.5	67.9	10.4	0.0	1.4	19.8
Tmax >5 °C	0.0	2.2	31.8	1.7	11.6	0.0	4.3	54.3	1.1	15.1	0.0	0.9	34.9	0.0	9.0
Tmax >10 °C	0.0	0.0	7.8	0.0	2.6	0.0	0.0	4.3	0.0	1.1	0.0	0.0	1.6	0.0	0.4
Tmax >15 °C	0.0	0.0	0.6	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

occurred most frequently in July and August (Figure 7). In Melville Island, the large frequency (26.1%) of those days in autumn (three times greater than in spring) was noted. In the other two sites, the frequency of days with slight frost in spring and autumn was similar, but slightly greater during the first season. In winter, these kinds of days were not registered.

Very warm (Tmax >10 °C) and warm (Tmax >5 °C) days were more frequent in the northern part of the Canadian Arctic in both analysed historical periods than they are at present (Figure 8a and c). On the other hand, in the southern Canadian Arctic their number was significantly lower (Figure 8b). Very cold (Tmax < −20 °C) and severe cold (Tmax < −30 °C) days in the Resolute region were more frequent than at present (up to 10%) in December and January, while in other months they were less frequent (by up to about 30% in spring). In Melville Island, these days (except for October, February, and especially November) were less frequent (Figure 8a). In Winter Island, frequencies of occurrence of severe cold days in historical and present times were similar, while very cold days were, in most months, more frequent in the first period. In the nineteenth century, days with slight frost were generally more frequent than in the present period (except mainly for September and October in Winter Island, and July in Melville Island).

4. CONCLUSIONS AND FINAL REMARKS

(1) Both kinds of data (monthly and daily) clearly show that the Canadian Arctic in the nineteenth century (1819–1859) was colder than today, but the average annual temperature during this period was only about 0.7 °C lower in comparison with the present-day (1961–1990) value. It was also shown that in the period from 1819 to 1832, the annual temperatures were warmer than in the 1850s by about 0.3 °C. In the annual course, the greatest differences between the mentioned time periods occurred in winter and spring. During the first period, significantly warmer winter and colder springs were noted. Throughout the whole study period, the majority of mean monthly and daily temperatures lie within one SD from the modern mean.

(2) The most typical features in the annual courses of air temperature in the study period were very cold winter months (December to February, 1.5–2.5 °C below today's norm) and warm springs and early summers (April to June, 0.3–2.7 °C above today's norm).

(3) The normal distribution of the MDAT is seen only in winter and summer, while in transitional seasons, multi-modal distributions occurred. In winter, increases both in mean and variance are noted from

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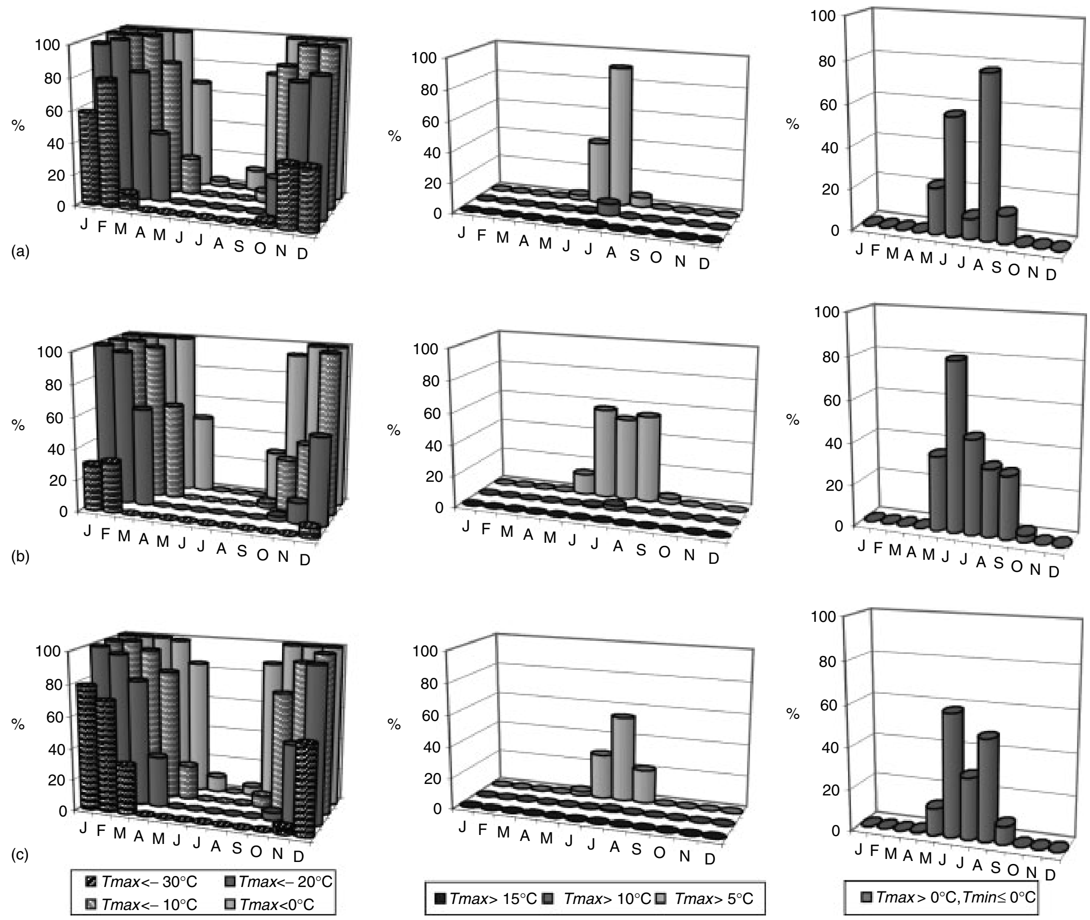

Figure 7. Annual courses of relative frequency of occurrence (in %) of characteristic days in (a) Melville Island (1819–1820), (b)Winter Island (1819–1820) and (c) Resolute region (1848–1859)

historical to modern times, while in summer only an increase in variance may be clearly seen. At present, there are more cold and less warm MDATs occurring in spring than in the nineteenth century. In autumn, generally both less warm and less cold events occurred in the study period than today (with the exception of Melville Island).

(4) The greatest increases in the day-to-day variability of MDAT from historical to present times occur in winter and (more particularly) in summer. In transitional seasons, changes in variabilities were small.
(5) In comparison with present-day DTR, the greatest changes in the shape of the annual courses occurred in the northern part of the Canadian Arctic. In the nineteenth century, the DTRs were the greatest in spring, while at present they are greatest in winter. In the whole Canadian Arctic, the DTRs in the nineteenth century were significantly lower in all months than they are today by up to 3–5 °C (except for June and some months in spring).
(6) Analysis of the frequency of occurrence of different kinds of characteristic days fully confirms the above conclusions that the MDATs in the nineteenth century were not as exceptionally cold as has been suggested by some analyses of proxy data (Koerner, 1977; Overpeck *et al*., 1997).
(7) The moderate cooling that occurred in the nineteenth century in the Canadian Arctic was also confirmed recently by the analysis of the behaviour of other indicators of climate change (summer sea-ice extent, annual sea-ice thickness and the onset of melt and freeze estimated from MDAT data), all of which showed changes not greater than the present range of variability (see Wood and Overland, 2003).

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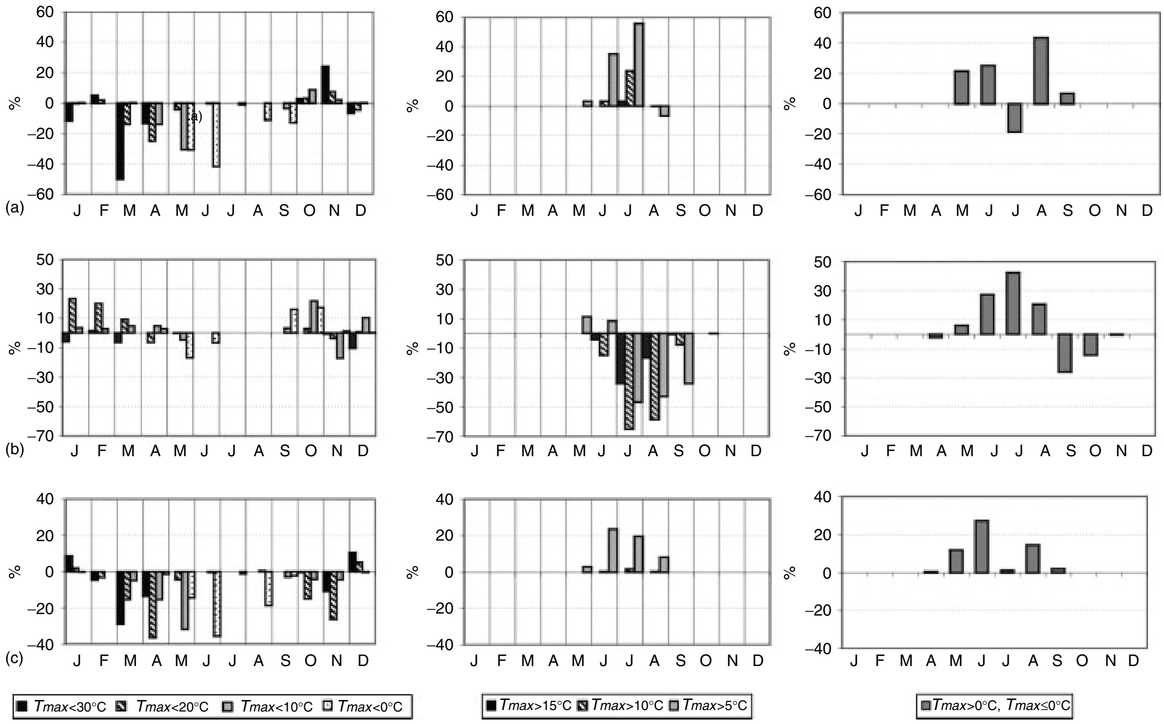

Figure 8. Annual courses of differences between the number of characteristic days (in %) occurring in (a) Melville Island (1819–1820) and Resolute (1961–1990), (b) Winter Island (1821–1822) and Coral Harbour (1961–1990) and (c) Resolute region (1848–1859) and Resolute (1961–1990)

Results of investigations presented here and elsewhere (Przybylak and Vizi, 2004) show that meteorological data gathered for the Canadian Arctic during different exploratory (land and marine) expeditions operating in the nineteenth century are reliable sources of climatic information and therefore should be used for climate change studies. Here we present the results for the most important climate variable, i.e. air temperature. The other variables (air pressure, wind direction, and speed) measured during the expeditions listed in Table I are currently being prepared and the results will be published later.

To eliminate some errors and biases still present in the data and connected, e.g. with the type of instruments used, their exposition and localization (on board a vessel, on sea ice or on land), we suggest organizing an expedition to try to repeat the meteorological measurements, in at least one place in the Canadian Arctic (at best, near the present location of the Resolute Meteorological Station where most expeditions wintered), in the same way as they were done during the historical expeditions (i.e. using old instruments (thermometers in particular), vessels of similar size, and heating only by fires etc.). Measurements should be done not only on board the vessel, but also on the sea ice and on land in order to compare the results. Of course, meteorological measurements should also be conducted in all locations simultaneously according to the present standards and using contemporary instruments (including automatic weather stations).

We hope that this idea will find some supporters (especially in Canada and the United States) who will be able to realise it during, e.g., the coming Fourth International Polar Year (1 March 2007–1 March 2009).

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