Arctic temperature trends from the early nineteenth century to the present
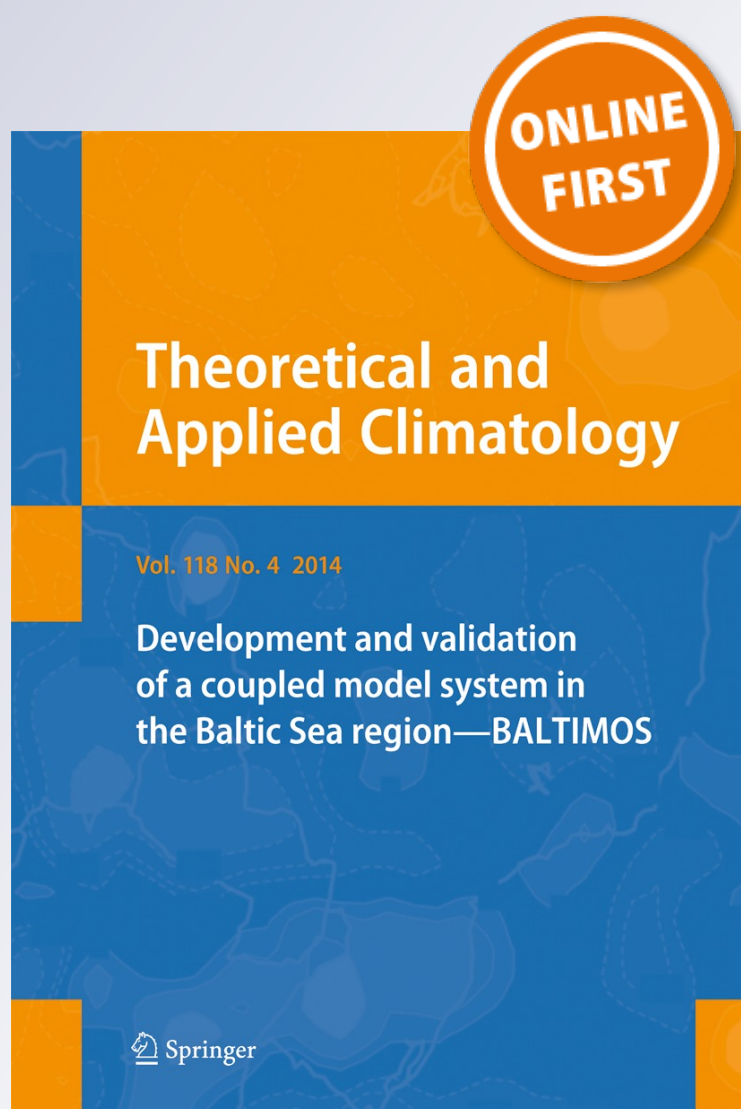
W. A. van Wijngaarden

ONLINE FIRST

Theoretical and Applied Climatology

Vol. 118 No. 4 2014

Development and validation of a coupled model system in the Baltic Sea region—BALTIMOS

Springer

Springer

Springer

ORIGINAL PAPER

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Abstract Temperatures were examined at 118 stations located in the Arctic and compared to observations at 50 European stations whose records averaged 200 years and in a few cases extend to the early 1700s. Nearly all stations exhibited warming trends. For each station, the temperature relative to the average value during 1961–1990 was found. The resulting temperature change averaged over the Arctic stations was plotted. For the period 1820–2014, trends were found for the January, July and annual temperatures of 1.0, 0.0 and 0.7 °C per century, respectively. Decadal variations are evident and much of the temperature increase occurred during the 1990s. Over the past century, Siberia, Alaska and Western Canada have experienced somewhat greater warming than Eastern Canada, Greenland and Northern Europe. The temperature change experienced by the Arctic stations during the last two centuries closely tracks that found for the European stations.

1 Introduction

Anthropogenically caused global climate change is now well recognized as detailed in the most recent report of the Intergovernmental Panel on Climate Change (IPPC 2013). The average global temperature has increased by about 1 °C over the past century (Mann 2014) although the rate of temperature increase has slowed over the past 15 years (Held 2013). It has been proposed that increased absorption of heat by the oceans as supported by some observations in the Pacific is responsible for the global warming hiatus (Watanabe et al. 2013; Balmaseda et al. 2013).

W. A. van Wijngaarden (✉)
Physics Department, York University, Petrie Bldg., 4700 Keele St., Toronto, ON M3J 1P3, Canada
e-mail: wlaser@yorku.ca

Some regions of the Earth such as the Arctic appear to be experiencing continued warming (Jeffries et al. 2013; Walsh et al. 2011). This has resulted in record low observations for the extent of the Arctic summer ice cap during the summer of 2013 and record melting of Greenland's ice sheet (NSIDC 2014). The Arctic is predicted to experience more dramatic warming as melting ice increases the concentration of water vapour which in turn acts as a greenhouse gas (Serreze and Barry 2011). Thawing permafrost may also release substantial amounts of methane (Hodgkins et al. 2014). A number of studies have found evidence of Arctic warming (Krupnik and Jolly 2002). Our group analysed surface temperatures observed at hundreds of stations in North America during 1948–2010 and found that stations in Alaska and the Canadian Arctic experienced larger warming trends in winter than in summer (Isaac and van Wijngaarden 2012). Similar results have also been found by other studies (Przybylak and Vizi 2005). Recently, we analysed data recorded during 1895–2014 at 27 stations in the Canadian Arctic (van Wijngaarden 2014). For each station, the difference between the temperatures relative to the average value found during 1961–1990 was found. The resulting temperature change averaged over the 27 stations was then plotted to give a time series covering the period 1895–2014. Trends were found for the January, July and annual temperatures of 3.1, 1.6 and 1.9 °C per century, respectively. The trend depends significantly on the time period considered due to decadal fluctuations. For the period 1915–1995, the annual temperature trend was only 0.4 °C per century.

This study examined average monthly temperatures observed at 118 stations located throughout the Arctic. A few of these stations had data extending more than 200 years. Trends were found for the January, July and annual temperatures. The temperature change relative to 1961–1990 was found at each station. This change in temperature averaged over all stations was examined for four different regions of the

Arctic: Northern Europe; Western and Central Siberia; Far Eastern Siberia, Alaska and Western Canada and Eastern Canada, Greenland and Iceland. Finally, the average temperature change was compared to that observed using 50 stations in Europe having observations for as long as 300 years.

2 Dataset description

The lists of Arctic and European stations considered in this study are given in Tables 1 and 2. The locations of the Arctic stations which are defined as having a latitude north of 60° N are shown in Fig. 1. This study included four stations lying just south of 60° N latitude that border Hudson Bay, Canada which is generally considered part of the Arctic. Five stations, Archangel'sk, Russia; Helsinki, Finland; Stykkisholmur, Iceland and Bergen and Trondheim, Norway, are on both lists. Data was downloaded from the digital archives available at either Environment Canada (Environment Canada 2014) or the Royal Dutch Archives (KNMI 2014). The latter has extensive datasets for stations located around the world. The average data period for the Arctic stations was 100 years, with recorded observations available for over 90 % of all months. The data periods were shorter for Canadian stations, a number of which only began operation after 1940. These were included as the Canadian Arctic archipelago together with Greenland, constitutes the most northerly located land mass. European stations were considered that had at least 150 years of observations. An average of over 200 years of data with observations listed for over 95 % of all months was available for each station. Annual temperatures were computed only for years in which no monthly data was missing. Over 200 years of annual temperatures could be determined for 20 European stations. Station measurements were sometimes missing during periods of great civil strife, notably the Second World War and the Russian Revolution. A significant number of stations closed during the 1990s as a result of the breakup of the Soviet Union and reduced government funding in Canada and the USA.

An obvious concern is the reliability of the temperature measurements. The most recent data has been subject to quality control as prescribed by the World Meteorological Organization (WMO 1976). Stations were inspected regularly to ensure compliance by national governmental bodies responsible for meteorological observations such as Environment Canada (van Wijngaarden 2004) and the US Weather Bureau (US Weather Bureau 2014).

A number of uncertainties affect temperature data in the 1700s. The measurements in the first decades of the 1700s used neither the Fahrenheit nor Celsius temperature scales and used thermometers based on the expansion of alcohol such as ethanol or even air rather than mercury (Geurts and van Engelen 1983). It has been suggested that a possible

disadvantage of an alcohol thermometer is that the liquid volume may decrease if impurities cause the alcohol to polymerize. This could cause a gradual lowering of the measured temperature over a period of years. Other subtle effects arising from the composition of the thermometer glass may have caused errors as large as 1 °C in temperature measurements observed in the mid 1800s at Hohenpeissenberg, Germany (Winkler 2009). These effects are difficult to accurately quantify as the original instruments no longer exist.

A number of studies have suggested temperature measurements prior to 1860 differ from proxy data (Frank et al. 2007; Böhm et al. 2010). Temperature measurements in Stockholm and Uppsala, Sweden indicate summers from the mid eighteenth century until around 1860 were on average warmer than those in 1961–1990 (Moberg et al. 2003). However, diaries recorded at eight farms located in southeastern Norway and two in western Sweden show no evidence of an earlier start to the spring planting season. Early thermometers were sometimes placed in front of a north-facing window of the observer's home and were therefore exposed to direct sunlight. The possibility that this effect introduced a warm bias in the summer temperature measurements was investigated by computing the mean temperature observed on clear, half-clear and cloudy days (Moberg et al. 2002; Bergström and Moberg 2002). The authors found no evidence of warmer summer temperatures for clear-sky days compared with cloudy days, "in fact rather the opposite", and concluded there was no significant problem with exposure of the thermometer to direct sunlight. A later study investigated thermometer exposure to indirect sunlight and concluded that summer temperatures observed before 1860 were positively biased by about 0.7–0.8 °C. This bias was eliminated with the introduction of wooden Stevenson screens that were introduced in the second half of the nineteenth century.

Inadequate shielding of the thermometer was also found to have introduced a warm bias in temperatures taken at 12 stations in Switzerland during 1864–2000. Correcting temperatures for this effect increased the annual temperature trend by 0.4 °C per century (Begert et al. 2005). A similar result was found in a study of 32 stations located in the Alps during 1760–2007 (Böhm et al. 2010). This study concluded that prior to 1870, inadequate sheltering also caused a cold bias in the estimate of winter temperature albeit smaller than the warm summer bias. This effect was studied by taking 8 years of data using screened and unscreened thermometers at Kremsmünster, Austria. The unsheltered thermometer overestimated the average summer temperature by 0.4 °C. This result agrees with a warm-season temperature bias of 0.5 °C obtained by comparing tree-ringed-based temperature reconstructions and instrumental measurements for the Northern hemisphere before 1900 and the European Alps before 1850 (Frank et al. 2007).

Table 1 Arctic stations examined in this study

Country	Station	Lat.	Long.	Data period	% Annual data	Trend (°C per century)		
						Jan.	July	Annual
Canada	Aklavik	68.22	−135.00	1927–2009	51[a]	2.1	0.4	1.6
	Alert	82.52	−62.28	1951–2006	98	0.3	0.7	0.9
	Baker Lake	64.30	−96.08	1946–2014	97	6.4	2.7	3.4
	Chesterfield	63.33	−90.72	1922–2007	77	2.2	2.9	1.5
	Churchill	53.97	−101.10	1929–2014	95	3.4	0.6	2.1
	Clyde	60.48	−68.52	1943–2014	84	−1.6	1.6	−0.4
	Coral Harbour	64.20	−83.37	1945–2014	84	4.2	3.9	2.3
	Eureka	79.98	−85.93	1947–2014	100	2.0	2.3	2.8
	Ft. Good Hope	66.25	−128.63	1910–2014	79	3.3	0.7	1.3
	Ft. Resolution	61.17	−113.67	1912–2010	61[a]	2.0	1.9	1.5
	Ft. Simpson	61.77	−121.23	1897–2014	79	4.3	1.5	2.6
	Ft. Smith	60.02	−111.97	1928–2014	91	5.9	1.7	3.6
	Hall Beach	68.78	−81.25	1957–2014	95	1.7	3.3	4.6
	Hay River	60.83	−115.78	1895–2014	88	4.9	1.1	2.4
	Inukjuak	58.47	−78.08	1922–2014	85	3.0	4.2	2.1
	Iqaluit	63.75	−68.55	1946–2014	100	2.8	1	0.5
	Kuujjuarapik	55.28	−77.77	1926–2014	83	2.9	2.8	2.5
	Kuujjuaq	58.10	−68.42	1947–2014	99	1.9	2.3	2.4
	Mayo	63.62	−135.87	1925–2014	97	3.6	2.1	2.6
	Mould Bay	76.23	−119.33	1948–2013	85	3.7	1.9	2.8
	Norman Wells	65.28	−126.80	1943–2014	100	4.5	2.1	2.8
	Pond Inlet	74.68	−77.98	1923–2014	41[a]	0.1	2.9	0.7
	Resolute	74.72	−94.98	1948–2014	100	3.0	1.7	3.5
	Sachs Harbour	72.00	−125.27	1956–2014	83	7.1	2.2	5.7
	Watson Lake	60.12	−128.82	1939–2014	91	4.4	0	0.9
	Whitehorse	60.72	−135.07	1941–2014	92	5.0	0.8	1.1
	Yellowknife	62.40	−114.43	1943–2014	96	5.8	3.2	3.3
Denmark	Thorshavn	62.02	−6.77	1867–2014	95	0.2	0.1	0.2
Finland	Helsinki	60.30	25.00	1829–2013	99	1.0	0.9	0.9
	Sodankyla	67.37	26.65	1908–2014	98	0.0	−0.4	0.5
Greenland	Angmagssalik	65.60	−37.63	1895–2013	95	0.2	−0.2	0.7
	Danmarkshavn	76.77	−18.67	1951–2014	97	3.7	1.7	2.2
	Egedesminde	68.70	−52.75	1949–2014	97	5.6	1.4	2.1
	Godthab	64.17	−51.75	1866–2014	88	2.6	0.1	0.6
	Ivigtut	61.20	−48.20	1875–1966	96	3.7	−0.2	1.8
Iceland	Akureyri	65.68	−18.08	1882–2014	99	1.6	0.4	1.1
	Grimsey	66.53	−18.02	1874–1998	78	0.7	−0.2	0.8
	Reykjavik	64.13	−21.90	1901–2014	98	0.9	0.3	0.2
	Stykkisholmur	65.08	−22.73	1846–2014	94	1.1	0.4	0.7
	Vestmannaeyja	63.40	−20.28	1884–2000	100	−0.1	−2.2	−1.0
Norway	Andenes	69.30	16.20	1868–1955	100	0.3	1.5	1.3
	Bergen	60.40	5.30	1816–2014	97	0.7	0.3	0.5
	Bodo	67.72	14.37	1868–2014	99	0.0	0.5	0.9
	Bronnoysund	65.60	12.30	1870–1955	99	−0.7	1.5	1.0
	Dombas	62.00	9.10	1864–1976	100	−0.6	0.3	0.9
	Fokstua	62.12	9.28	1923–2014	84	2.1	0.3	1.5
	Haugastol	60.30	7.50	1884–1976	98	−1.1	0.0	0.1

Table 1 (continued)

Country	Station	Lat.	Long.	Data period	% Annual data	Trend (°C per century)		
						Jan.	July	Annual
	Hellisoy	60.75	4.72	1867–1955	100	−0.5	0.9	0.8
	Jan Mayen	70.93	−8.67	1921–2014	91	−0.4	−0.2	0.1
	Karasjok	69.47	25.50	1876–2014	82	−0.6	0.7	0.8
	Roros	62.57	11.38	1871–1989	100	−1.1	0.5	0.8
	Tromso	69.50	19.00	1920–2014	97	0.0	−0.4	0.7
	Trondheim	63.40	10.50	1761–1981	100	0.7	−0.6	0.1
	Vardo	70.37	31.10	1829–2014	95	1.2	0.6	1.0
Russia	Anadyr	64.78	177.57	1898–2014	75	0.0	0.9	0.6
	Archangel'sk	64.50	40.73	1813–2014	99	0.6	0.4	0.6
	Berezovo	63.93	65.05	1881–2014	76	1.5	1.2	1.0
	Bor	61.60	90.02	1934–2014	97	−0.3	1.8	1.3
	Cerdyn'	60.40	56.52	1891–2014	84	1.6	1.3	1.4
	Cokurdah	70.62	147.88	1939–2014	81	2.4	2.7	2.7
	Dudinka	69.40	86.17	1906–2012	73	1.2	1.9	1.1
	Dzardzan	68.73	124.00	1936–2014	78	2.7	1.0	0.5
	Erbogacen	61.27	108.02	1937–2014	95	0.7	0.5	1.2
	GMO	77.72	104.30	1932–2014	88	−0.4	0.0	0.1
	Hanty-Mansijsk	61.02	69.03	1897–2014	80	0.9	1.0	1.1
	Hatanga	71.98	102.47	1929–2014	82	1.0	0.3	1.1
	Hoseda-Hard	67.08	59.38	1931–2002	83	−4.9	2.2	−1.4
	Jakutsk	62.02	129.72	1829–2014	83	2.9	0.1	1.3
	Kandalaksa	67.15	32.35	1912–2014	79	−1.7	0.1	0.2
	Kanin Nos	68.65	43.30	1915–2014	83	−0.1	2.2	0.6
	Kem'-port	64.98	34.80	1862–2006	81	−0.5	0.2	0.9
	Kojnas	64.75	47.65	1912–1989	73	−3.1	0.2	−1.0
	Korf	60.35	166.00	1929–2012	84	−4.7	1.5	0.2
	Malye Karmaku	72.37	52.70	1897–2014	64	1.2	1.1	0.9
	Markovo	64.68	170.42	1894–2014	75	3.0	0.6	1.5
	Murmansk	68.97	33.05	1918–2014	97	−0.9	0.0	0.2
	Mys Shmidta	68.90	−179.37	1932–2013	83	2.0	2.0	2.6
	Mys Uelen	66.17	−169.83	1922–2014	77	0.5	2.3	1.9
	Narjan Mar	67.63	53.03	1926–2014	90	−2.7	2.1	0.9
	Njaksimvol	62.43	60.87	1933–2014	81	0.1	2.9	1.3
	Olekminsk	60.40	120.42	1882–1990	81	2.6	−1.6	0.4
	Olenek	68.50	112.43	1935–2014	86	8.2	1.0	3.6
	Ojmjakon	63.25	143.15	1930–2014	88	4.5	1.4	2.2
	Onega	63.90	38.12	1887–2014	83	0.2	1.5	1.4
	Ostrov Dikson	73.50	80.40	1916–2014	92	−0.3	0.9	0.5
	Ostrov Kotel	76.00	137.87	1933–2014	71	2.3	1.1	0.2
	Ostrov Vrange	70.98	−178.48	1926–2014	76	3.0	1.4	1.5
	Reboly	63.83	30.82	1927–2004	87	−0.5	−0.1	−0.1
	Salehard	66.53	66.67	1882–2014	96	1.1	1.0	1.3
	Sejmchan	62.92	152.42	1933–2004	89	1.9	2.4	1.5
	Suntar	62.15	117.65	1933–2014	90	1.3	0.8	1.8
	Surgut	61.25	73.50	1884–1985	96	3.3	0.9	1.6
	Tarko Sale	64.92	77.82	1937–2014	91	−1.2	1.7	1.9
	Troicko-Pecer	62.70	56.20	1888–2014	79	0.9	1.0	1.2

Table 1 (continued)

Country	Station	Lat.	Long.	Data period	% Annual data	Trend (°C per century)		
						Jan.	July	Annual
	Tura	64.27	100.23	1928–2014	92	1.8	1.8	1.7
	Turuhansk	65.78	87.93	1881–2014	87	2.0	0.8	1.7
	Ust-Cilma	65.43	52.27	1889–2014	81	0.4	1.6	1.0
	Ust'-Maja	60.38	134.45	1893–2014	68	1.3	0.9	1.5
	Verkhoyansk	67.55	133.38	1885–2014	91	4.6	1.2	1.5
	Viliujsk	63.77	121.62	1898–2014	91	2.4	1.2	1.3
	Vytegra	61.02	36.45	1881–2014	79	0.9	0.0	0.7
	Zyrjanka	65.73	150.90	1935–2014	94	2.8	2.7	1.9
Sweden	Haparanda	65.83	24.15	1860–2009	100	0.6	0.8	1.3
UK	Lerwick	60.13	−1.18	1931–2014	99	0.7	0.0	0.1
USA (Alaska)	Anchorage	61.17	−150.02	1916–2014	97	4.7	1.5	2.1
	Bethel	60.78	−161.80	1923–2014	94	−0.1	1.1	1.0
	Cordova	60.50	−145.50	1909–2004	98	−1.0	0.1	−1.1
	Fairbanks	64.82	−147.87	1929–2014	99	2.9	2.8	2.1
	Kotzebue	66.87	−162.63	1929–2014	88	2.9	2.5	1.8
	Mantanuska	61.57	−149.27	1917–1990	89	1.9	0.2	0.4
	McKinley Park	63.72	−148.97	1923–1990	90	−0.8	−0.1	−2.1
	Nome	64.50	−165.43	1906–2014	97	1.7	1.5	1.0
	Point Barrow	71.30	−156.78	1901–2014	84	3.2	1.2	2.0
	Seward	60.12	−149.45	1908–2000	91	3.1	0.5	0.9
	Tanana	65.17	−152.10	1903–2000	93	2.5	1.7	1.1
	Talkeetna	62.30	−150.10	1918–2014	94	4.5	1.4	1.4
	Univ. Exp. Stn.	64.85	−147.87	1904–1990	93	5.0	1.3	1.3
	Valdez	61.13	−146.35	1909–2004	81	3.8	1.9	2.8

[a] These stations were included as they are located in the Canadian Arctic where only 12 of 27 stations recorded data before 1930. The amounts of July data present are considerably higher: Aklavik (67 %), Fort Resolution (87 %) and Pond Inlet (73 %)

Standardized thermometers and measurement procedures, including stipulating the times each day that measurements should be made to obtain average daily temperatures, were instituted by the British Royal Society in the 1700s (Geurts and van Engelen 1983). Typically, temperatures at European stations were measured three times a day: in the morning between 7:00 and 8:00, at noon between 12:00 and 2:00 and in the evening around 22:00. The average daily temperature was determined by modelling the temperature during daylight hours using a sinusoidal function while an exponential decaying function described night temperatures (Parton and Logan 1981). This model was tested by comparing the estimated hourly temperatures to the hourly temperature observed at De Bilt, Netherlands during 1971–1980. The difference between the average monthly temperatures calculated using the observed and estimated hourly temperatures was less than 0.1 °C.

Measurement procedures sometimes changed when one observer retired and data collection continued, possibly at a different location. These factors have been carefully considered and extensively documented for the longest time series for De Bilt, Netherlands (Geurts and van Engelen 1983). This time series was also checked by comparing it to temperatures for central England covering the time period 1659 to 1973 (Manley 1974). The uncertainty of the temperature data for the 1700s is believed to be ±1 °C (Braandsma 2014) while for the first half of the 1800s is about ±0.5 °C primarily due to inadequate thermometer shielding. The uncertainty of later data is estimated to be less than ±0.2 °C (Brohan et al. 2006).

Unfortunately, station histories describing site alterations and/or changes in instruments or measurement procedures are poorly documented. The data were therefore checked for inhomogeneities (van Wijngaarden and Vincent 2005; Vincent et al. 2007). This study examined data recorded at 180 stations. Data from 17 stations were rejected as they exhibited sudden discontinuities or had gaps in the data observations extending for over a decade.

Table 2 European stations having more than 150 years of data examined in this study

Country	Station	Lat.	Long.	Data period	% Annual data	Trend (°C per century)					
						Entire data period			1881–2014		
						Jan.	July	Annual	Jan.	July	Annual
Austria	Innsbruck	47.30	11.40	1777–2000	76	0.4	−0.3	−0.3	2.3	0.7	0.8
	Kremsmünster	48.05	14.13	1767–2014	88	1.4	−0.2	0.3	1.7	0.7	0.8
	Vienna	48.25	16.37	1775–2014	100	1.0	0.2	0.4	1.9	1.4	1.3
Belgium	Uccle	50.80	4.35	1833–2014	97	1.1	0.4	0.7	1.3	0.6	0.9
Croatia	Zagreb	45.82	15.98	1862–2014	98	1.8	0.3	0.9	2.3	0.7	1.2
Denmark	Copenhagen	55.68	12.55	1768–2014	100	1.3	0.3	0.7	1.6	1.0	1.4
Estonia	Tallinn	59.42	24.80	1806–2014	92	1.3	0.2	0.8	0.7	0.5	0.8
Finland	Helsinki	60.30	25.00	1829–2013	99	1.0	0.9	0.9	0.1	0.7	0.7
France	Marseilles	43.30	5.40	1838–2014	97	0.0	1.6	0.7	0.3	2.3	1.1
	Nantes	47.17	−1.60	1851–2014	99	0.9	0.4	0.8	1.5	1.0	1.1
	Paris	48.80	2.50	1757–2000	100	0.9	−0.4	0.0	1.7	0.8	1.0
Germany	Berlin Dahlem	52.47	13.30	1769–2014	98	1.2	−0.1	0.3	0.8	−0.2	0.2
	Berlin Tempel	52.47	13.40	1701–2014	89	0.8	0.5	0.4	1.0	0.9	0.8
	Frankfurt	50.10	8.70	1757–1961	80	0.8	0.2	0.1	1.7	1.0	1.2
	Hohenpeisse	47.80	11.02	1781–2014	100	0.4	0.3	0.3	1.5	1.0	1.1
	Munich	48.10	11.70	1781–1991	100	−0.1	−0.1	0.1	1.0	0.3	0.7
	Stuttgart	48.83	9.20	1792–2014	80	1.1	−0.5	−0.2	0.7	−0.2	−0.3
Greece	Athens	37.97	23.72	1858–2014	96	0.9	0.6	0.4	0.9	1.0	0.7
Hungary	Budapest	47.52	19.03	1780–2000	99	0.8	−0.4	0.1	1.8	0.1	1.0
	Debrecen	47.48	21.63	1853–2014	100	0.8	0.4	0.3	1.6	−0.4	0.5
Iceland	Stykkisholmur	65.08	−22.73	1846–2014	94	1.1	0.4	0.7	1.2	0.4	0.8
Ireland	Belfast	54.65	−6.22	1834–2014	89	0.1	0.2	0.2	0.1	0.7	0.5
	Dublin	53.43	−6.25	1831–2014	95	0.3	0.3	0.3	0.6	0.6	0.8
Italy	Milan	45.43	9.28	1763–1986	91	0.4	0.0	−0.1	0.2	−1.2	−0.7
	Rome	41.80	12.60	1811–1991	93	0.4	−0.1	0.1	1.7	−0.9	0.3
Latvia	Riga	56.97	24.05	1795–2000	87	0.9	−0.4	0.1	1.0	−0.4	0.6
Lithuania	Vilnius	54.63	25.10	1777–2014	97	0.9	−0.4	0.1	1.2	−0.6	0.3
Malta	Luqa	35.85	14.48	1853–2014	97	−0.3	0.6	0.1	0.3	1.0	0.5
Moldova	Kisinev	47.02	28.98	1825–2014	84	1.1	0.5	0.1	1.7	0.7	0.9
Netherlands	De Bilt	52.10	5.18	1706–2014	99	0.8	0.3	0.3	1.4	−0.1	0.5
Norway	Bergen	60.40	5.30	1816–2014	97	0.7	0.3	0.5	0.9	0.7	0.9
	Oslo	59.90	10.70	1816–1991	99	0.4	0.4	0.5	−1	−0.8	−0.3
	Trondheim	63.40	10.50	1761–1981	100	0.7	−0.6	0.1	−1.6	−0.6	−0.2
	Vardo	70.37	31.10	1829–2014	95	1.2	0.6	1.0	1.2	1.0	1.2
Poland	Warszawa Okec	52.17	20.97	1779–2014	92	1.4	0.1	0.6	0.9	0.0	0.5
	Warsaw II	51.10	16.88	1792–2014	99	1.4	0.4	0.6	0.7	0.0	0.3
Romania	Sibiu	45.80	24.15	1851–2014	97	1.0	0.3	0.5	1.3	−0.4	0.0
Russia	Archangel'sk	64.50	40.73	1814–2014	99	0.6	0.4	0.6	0.3	0.9	1.0
	St. Petersburg	59.97	30.30	1743–2014	95	1.7	0.3	0.9	1.7	1.3	1.6
Sweden	Stockholm	59.33	18.05	1756–1994	100	1.1	−0.1	0.5	0.1	0.7	0.9
Switzerland	Basel	47.60	7.60	1755–1980	97	1.0	0.2	0.4	1.9	0.6	1.1
	Geneva	46.25	6.13	1753–2014	99	1.0	0.2	0.3	1.7	0.6	0.8
	St. Bernard	45.70	6.90	1818–1985	99	0.6	1.0	0.5	0.6	1.8	1.2
	Zurich	47.38	8.57	1836–2014	92	1.4	−0.2	0.4	1.8	0.5	0.7
Ukraine	Kiev	50.40	30.57	1812–2014	93	1.3	0.7	1.0	2.2	1.2	1.6

Table 2 (continued)

Country	Station	Lat.	Long.	Data period	% Annual data	Trend (°C per century)					
						Entire data period			1881–2014		
						Jan.	July	Annual	Jan.	July	Annual
	Mikolaiv	47.03	31.95	1808–2014	82	1.4	−0.2	0.3	1.6	−0.2	0.4
	Odesa	46.43	30.77	1821–2014	87	1.8	−0.1	0.7	2.3	−0.2	0.8
UK	Edinburgh	55.90	−3.20	1764–1960	100	1.0	−0.2	0.3	−0.3	0.5	0.4
	Greenwich	51.50	0.00	1763–1969	98	1.3	0.3	0.5	1.4	1.1	1.3
	Oxford	51.70	−1.20	1828–1980	100	0.7	0.4	0.6	0.3	0.5	0.6

3 Data analysis and results

The January, July and annual temperature time series are shown in Fig. 2 for four stations Archangel'sk, Western Russia; Jakutsk, Siberia; Hay River, Canada and Stykkisholmur, Iceland. These stations have very different climates, yet all have experienced rising temperatures. January temperature trends are significantly greater than those for July

Fig. 1 Locations of arctic stations examined in this study

Fig. 2 Temperature time series for January (*blue*), July (*red*) and annual (*black*). For **a** Archangel'sk, the slopes of the trend lines are 0.6, 0.4 and 0.6 °C per century for the January, July and annual data, respectively. The corresponding January, July and annual trends in units of degree Celsius per century are 2.9, 0.1 and 1.3 at **b** Jakutsk; 4.9, 1.1 and 2.4 at **c** Hay River and 1.1, 0.4 and 0.7 at **d** Stykkisholmur. For 1881–2014, the January, July and annual trends in units of degree Celsius per century are 0.3, 0.9 and 1.0 at Archangel'sk; 5.1, 0.5 and 1.6 at Jakutsk and 1.2, 0.4 and 0.8 at Stykkisholmur

a) Archangel'sk, Russia
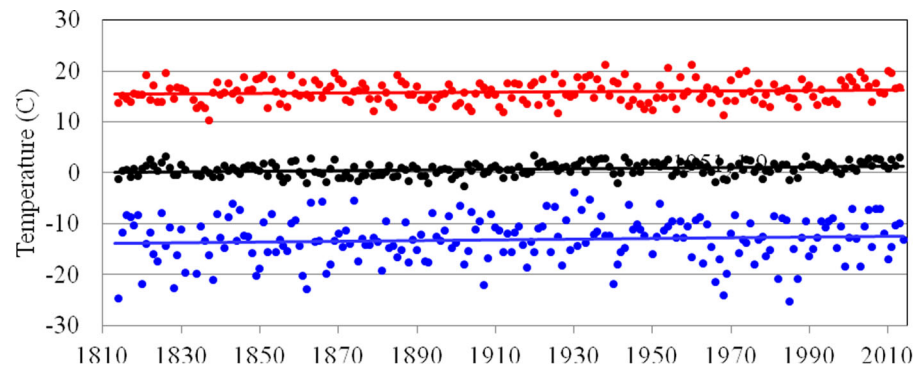
b) Jakutsk, Russia
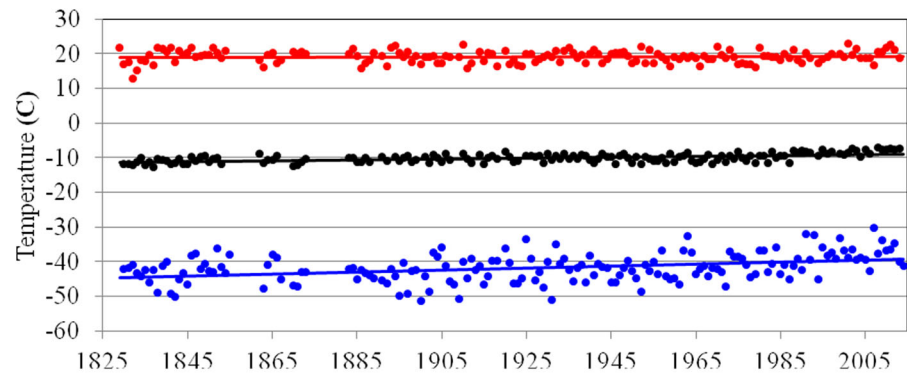
c) Hay River, Canada
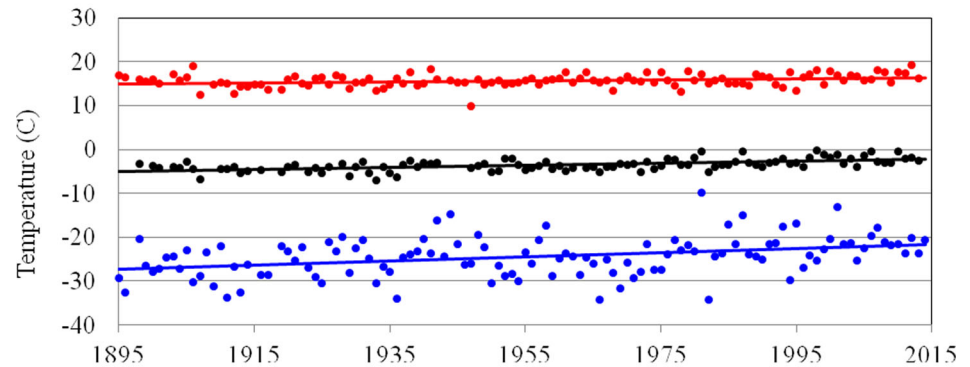
d) Stykkisholmur, Iceland
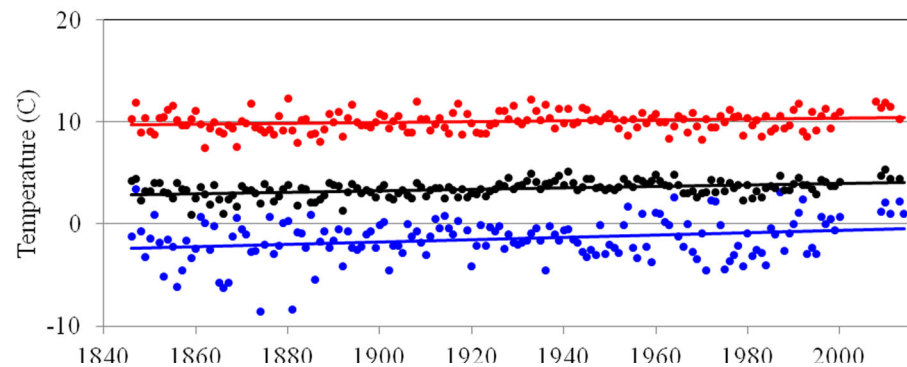
Fig. 3 Temperature change for **a** January, **b** July and **c** annual relative to the temperature during 1961 to 1990 for Arctic stations. The *red curve* is the moving 5-year average while the *blue curve* is the number of stations

a) January

b) July
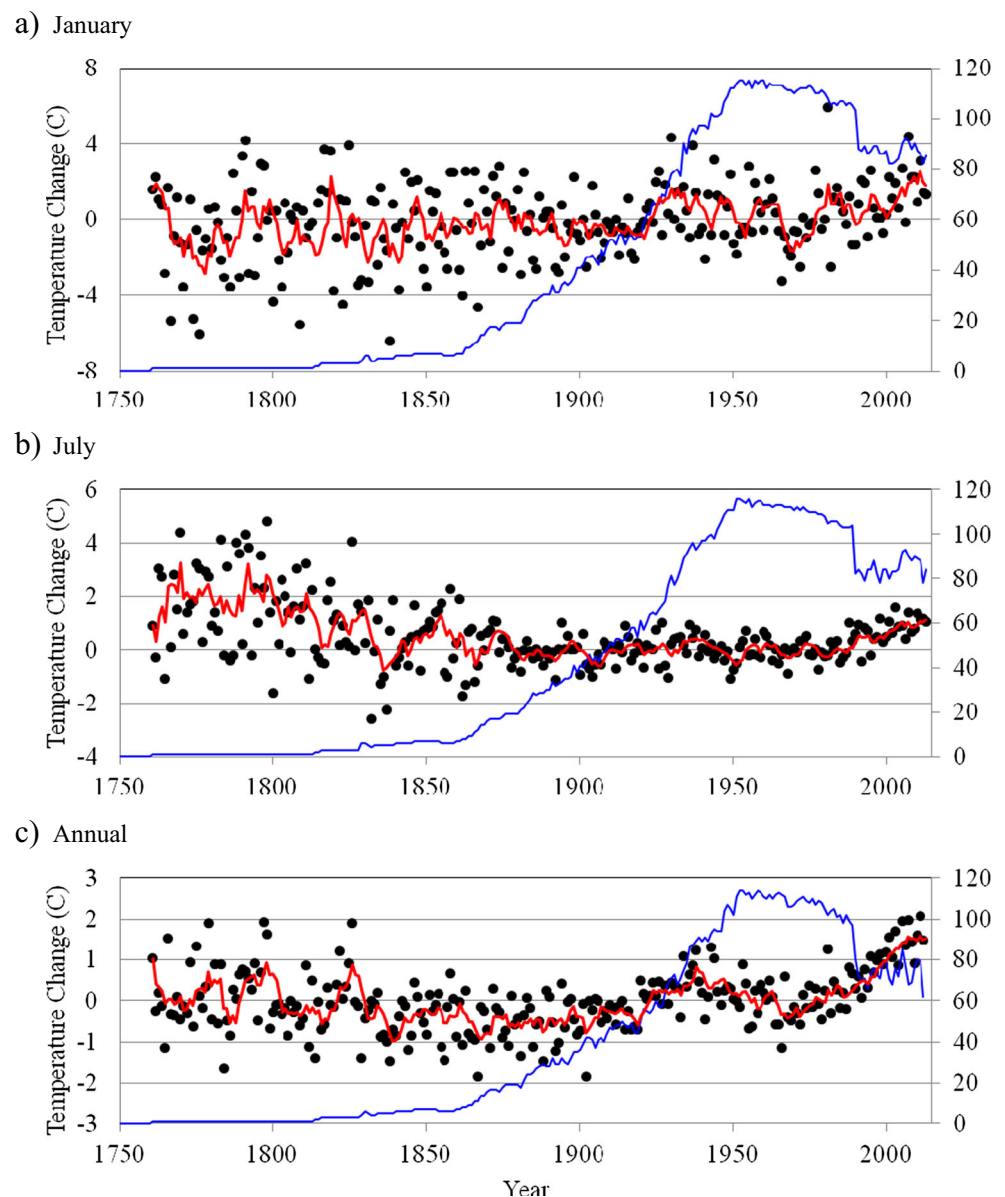
c) Annual

although the year to year scatter of January temperatures is much larger. Only seven of the 118 Arctic stations had negative annual temperature trends as shown in Table 1, and about two thirds of the stations had larger January than July temperature trends.

The temperature change at each station was found relative to that observed between 1961 and 1990. The temperature change averaged over all 118 stations is shown in Fig. 3. Prior to 1820, there is significant scatter in the data because data is available from very few stations. For the period 1820–2014, the trends for the January, July and annual temperatures are 1.0, 0.0 and 0.7 °C per century, respectively. A number of stations discontinued operation during the 1990s. If one only considers stations operating during the 1990s, the corresponding trends are 0.9, 0.2 and 0.7 °C per century. The trends are

strongly affected by the period considered due to decadal fluctuations such as the rise in temperatures evident during the 1990s. For the period 1820–1990, the trends are 0.7, −0.3 and 0.4 °C per century for the January, July and annual temperatures, respectively.

The trends were also examined for the four different longitudinal quadrants of the Arctic. Figure 4 shows the change in annual temperature for Northern Europe (−10 to 80° E); Western and Central Siberia (80 to 170° E); Far Eastern Siberia, Alaska and Western Canada (170 to 260° E) and Eastern Canada, Greenland and Iceland (260 to −10° E). The trends in units of degree Celsius per century for the period 1900–2014 are 1.0 (Northern Europe), 1.6 (Western and Central Siberia), 1.6 (Far Eastern Siberia, Alaska and Western Canada) and 1.0 (Eastern Canada,

Fig. 4 Annual temperature change for Arctic stations located in **a** Northern Europe (−10° to 80° E longitude), **b** Western and Central Siberia (80° to 170° E longitude), **c** Far Eastern Siberia, Alaska and Western Canada (170° to 260° E longitude) and **d** Eastern Canada, Greenland and Iceland (160° E to −10° E longitude) relative to the average temperature between 1961 and 1990. The *red curve* is the moving 5-year average while the *blue curve* shows the number of stations
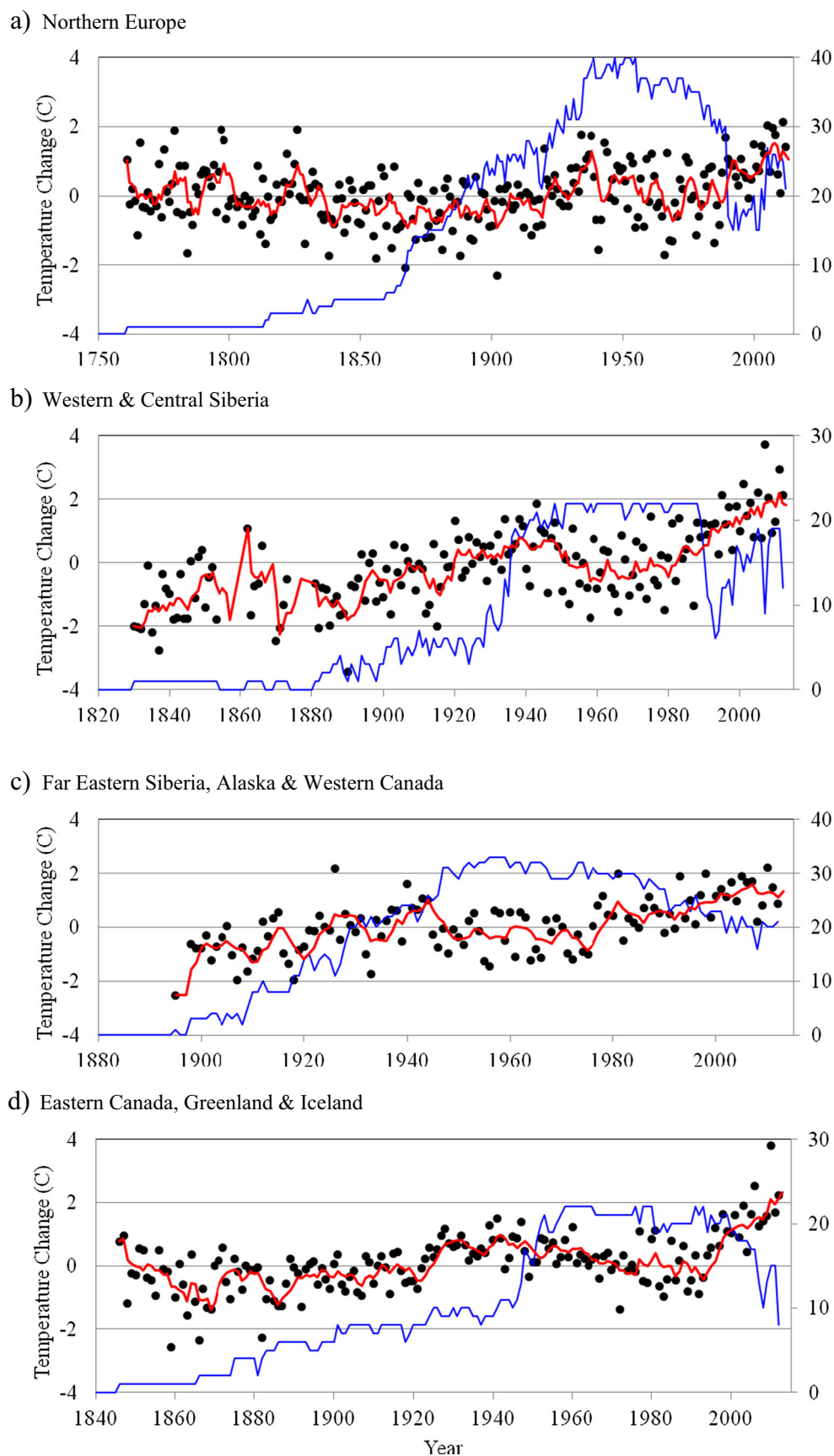

a) Northern Europe

b) Western & Central Siberia

c) Far Eastern Siberia, Alaska & Western Canada

d) Eastern Canada, Greenland & Iceland

Fig. 5 Temperature time series for January (*blue*), July (*red*) and annual (*black*). For **a** De Bilt, the slopes of the trend lines are 0.8, 0.3 and 0.3 °C per century for the January, July and annual data, respectively. The corresponding January, July and annual trends in units of degree Celsius per century at **b** Geneva are 1.0, 0.2 and 0.3 and **c** at St. Petersburg are 1.7, 0.3 and 0.9. For 1881–2014, the January, July and annual trends in units of degree Celsius per century are 1.4, −0.1 and 0.5 at De Bilt; 1.7, 0.6 and 1.1 at Geneva and 1.7, 1.3 and 1.6 at St. Petersburg

a) De Bilt, Netherlands

b) Geneva, Switzerland

c) St. Petersburg, Russia
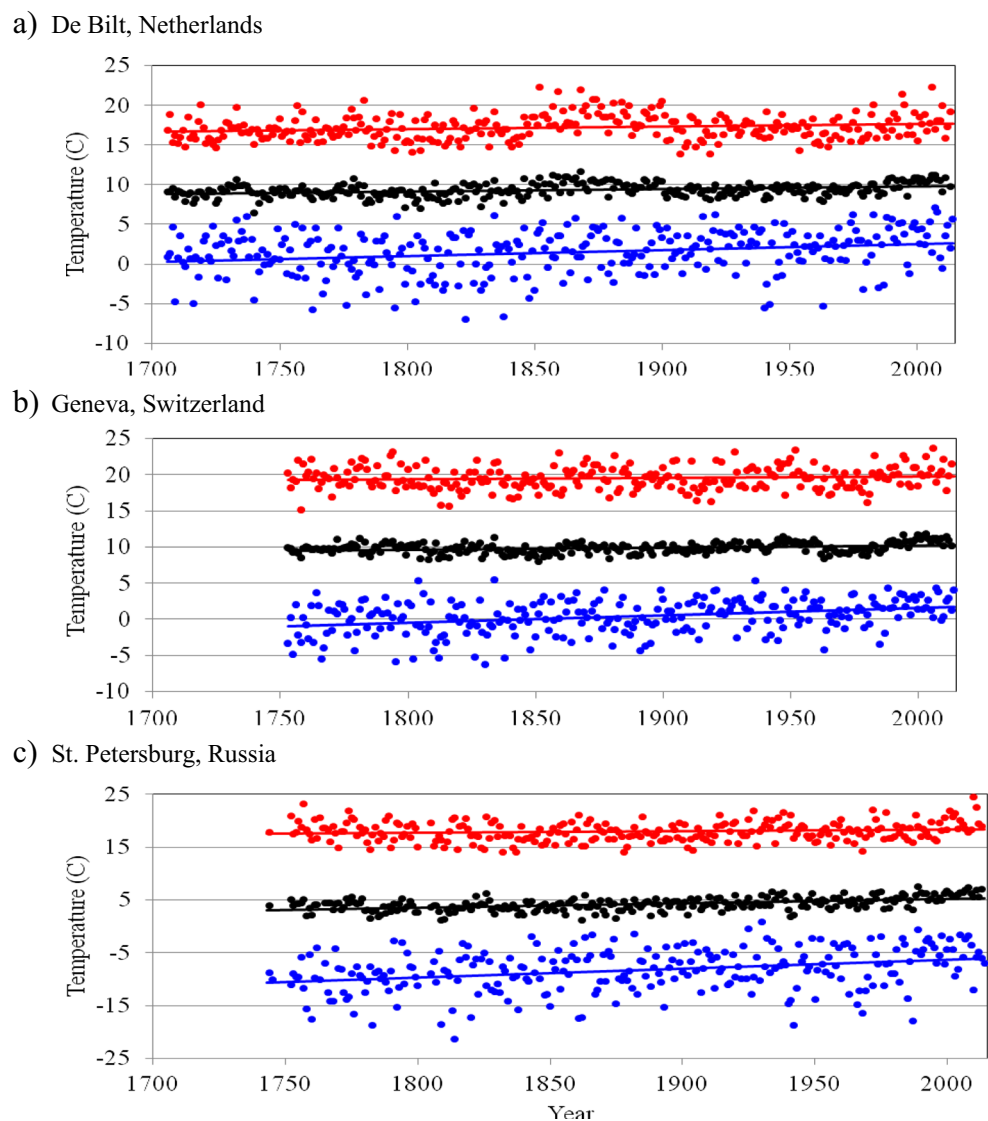
Greenland and Iceland). During the 1900s, all four regions experienced increasing temperatures until about 1940. Temperatures then decreased by about 1 °C over the next 50 years until rising in the 1990s.

Temperatures were also studied for 50 European stations that constitute the world's longest record of temperature observations. Figure 5 shows positive January, July and annual temperature trends at De Bilt, Netherlands; Geneva, Switzerland and St. Petersburg, Russia. Table 2 shows that over 85 % of all European stations had larger January than July temperature trends. Only three of the 50 stations exhibited a decreasing annual temperature trend. Most of the stations experienced increased warming trends for the period 1881–2014.

Figure 6 shows the change in temperature relative to that found for the period 1961–1990 averaged over 50 European stations. Data is available for a nontrivial number of stations beginning about 1750. For the period 1750–2014, trends of 1.0, 0.0 and 0.3 °C per century were found for the January, July and annual temperatures, respectively. For the period 1750–1990, the corresponding trend values are 0.8, −0.2 and 0.2 °C per century. It is interesting to compare the January, July and annual temperature trends for the preindustrial period 1750–1880: 0.8, −0.3 and −0.1 °C per century, to trends during 1881–2014: 1.3, 0.7 and 0.9 °C per century. For the period 1881–1990, the corresponding trend values are 0.4, 0.0 and 0.5 °C per century. The numerical values change by less than 0.05 °C per century if one restricts the dataset to only include the 20 stations having observations for more than 200 years.

A comparison of the change in annual temperature of the Arctic and European stations is shown in Fig. 7. The five European Arctic stations (Archangel'sk, Bergen, Helsinki, Stykkisholmur and Trondheim) were removed from the curve representing the European station temperature change. The two curves representing the 5-year moving average of the

Fig. 6 Temperature change for **a** January, **b** July and **c** annual relative to the temperature during 1961 to 1990 for stations in Europe having more than 150 years of observations. The *red curve* is the moving 5-year average while the *blue curve* shows the number of stations

a) January

b) July

c) Annual
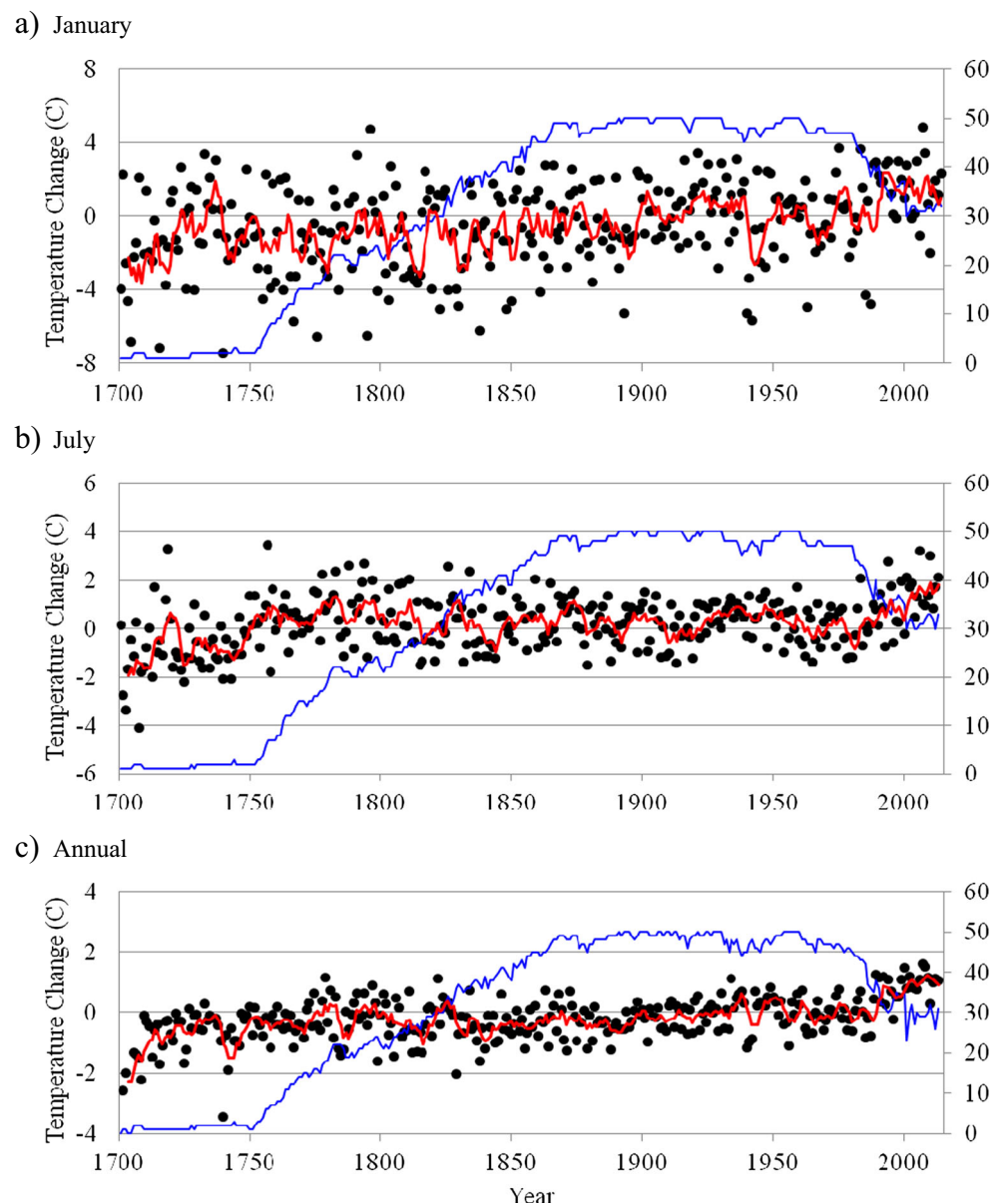
Arctic and European data very closely follow each other. The average temperature difference between the two curves is 0.0 °C. It is particularly striking that the decadal fluctuations evident in the two curves are closely synchronized.

Fig. 7 Comparison of annual temperature change relative to the temperature during 1961 to 1990 for European stations (*black dots*) and Arctic stations (*open black triangles*) as discussed in the text. The *red* (*blue*) curve is the moving 5-year average for the European (Arctic) data
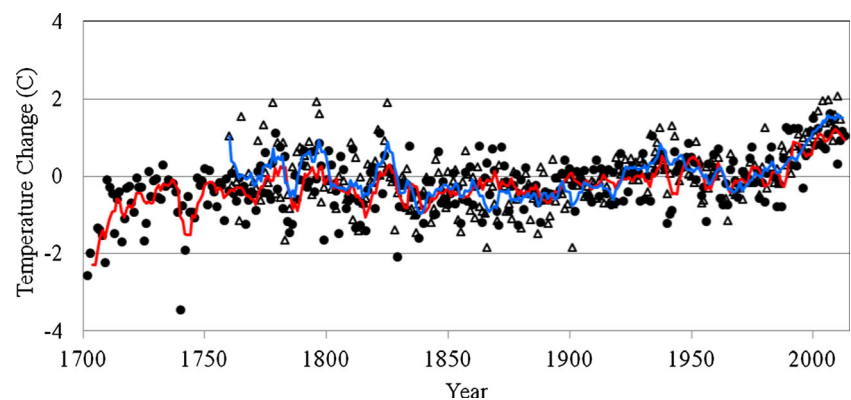
4 Conclusions

Arctic temperatures have increased during the period 1820–2014. The warming has been larger in January than in July. Siberia, Alaska and Western Canada appear to have warmed slightly more than Eastern Canada, Greenland, Iceland and Northern Europe. The warming has not occurred at a steady rate. Much of the warming trends found during 1820 to 2014 occurred in the late 1990s, and the data show temperatures levelled off after 2000. The July temperature trend is even slightly negative for the period 1820–1990. The time series exhibit multidecadal temperature fluctuations which have also been found by other temperature reconstructions. In the case of Stockholm and Central Europe, warming around 1730 was absent in climate model simulations (Zorita et al. 2009).

European stations have experienced an increasing annual temperature trend of 0.3 °C per century during the period 1750–2014. January temperatures have increased but not July temperatures. The lower July temperature trend may be partly due to inadequate solar radiation shielding and/or other limitations of early thermometers. Some studies have found that these effects can cause a bias as discussed in section 2. Unfortunately, few studies have attempted to check the calibration of these early instruments and precisely replicate measurement procedures used two centuries ago (Böhm et al. 2010). Additional examinations are desirable. The trends determined for 1750–1880 are somewhat smaller than those for 1881–2014. However, most of this increase occurred in the single decade of the 1990s. These trends are smaller than those found for the Arctic during 1820–2014 which is reasonable since anthropogenic emissions were relatively small in the late 1700s. These results are consistent with other studies of European temperatures (Brohan et al. 2006; Brázdil et al. 2010). It is not clear however if a temperature increase is solely due to the increase of atmospheric carbon dioxide (ESRL 2014). Other factors such as the variation of solar irradiance are important to consider (ACRIM 2012). Nearly all of the European stations unlike the Arctic stations are located in large metropolitan areas that have expanded substantially during the past 250 years as their populations have greatly grown. Studies have shown that this urban heat island effect (UHI) has increased temperature by as much as 1 °C although there is some evidence for London that it has levelled off since 1981 (Jones and Lister 2008). The UHI induced increase in minimum temperature also has been found to be twice that for the maximum temperature. This is consistent with the result of this study that temperatures have increased more in January than in July.

An interesting result of this work is that the change in Arctic temperatures closely tracks changes in European temperatures. The Arctic has warmed at the same rate as Europe over the past two centuries. Heretofore, it has been supposed that any global warming would be amplified in the Arctic.

This may still be true if urban heat island effects are responsible for part of the observed temperature increase at European stations. However, European and Arctic temperatures have remained closely synchronized for over 200 years during the rapid growth of urban centres. This shows the desirability of further research to improve the accuracy of global climate projections.

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