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RESEARCH/REVIEW ARTICLE

Long-term temperature trends and variability on Spitsbergen: the extended Svalbard Airport temperature series, 1898–2012

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Abstract

One of the few long instrumental records available for the Arctic is the Svalbard Airport composite series that hitherto began in 1911, with observations made on Spitsbergen, the largest island in the Svalbard Archipelago. This record has now been extended to 1898 with the inclusion of observations made by hunting and scientific expeditions. Temperature has been observed almost continuously in Svalbard since 1898, although at different sites. It has therefore been possible to create one composite series for Svalbard Airport covering the period 1898–2012, and this valuable new record is presented here. The series reveals large temperature variability on Spitsbergen, with the early 20th century warming as one striking feature: an abrupt change from the cold 1910s to the local maxima of the 1930s and 1950s. With the inclusion of the new data it is possible to show that the 1910s were colder than the years at the start of the series. From the 1960s, temperatures have increased, so the present temperature level is significantly higher than at any earlier period in the instrumental history. For the entire period, and for all seasons, there are positive, statistically significant trends. Regarding the annual mean, the total trend is 2.6°C/century, whereas the largest trend is in spring, at 3.9°C/century. In Europe, it is the Svalbard Archipelago that has experienced the greatest temperature increase during the latest three decades. The composite series may be downloaded from the home page of the Norwegian Meteorological Institute and should be used with reference to the present article.

To access the supplementary material for this article, please see Supplementary files under Article Tools online.

Surface air temperature in the Atlantic boundary region to the Arctic reflects a low-frequency climate variation during the 20th century. This pattern is defined by two distinct periods of warming. The first one has come to be known as the Early 20th Century Warming (E20thCW), starting around 1920 and persisting until around the middle of the century. It has been proposed that the warming is linked to patterns connected to the meridional overturning circulation (e.g., Bjerknes 1964; Wigley & Raper 1987; Schlesinger & Ramankutty 1994; Polyakov et al. 2009; Wigley & Santer 2012). The second warming period began around 1980 (Przybylak 2007; Wood et al. 2010; Hanna et al. 2012) and is on-going. The E20thCW was mostly predominant in the Atlantic region (Overland et al. 2004); however, the second warming phase persists over the whole Arctic, and is thought to be caused by

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anthropogenic warming in combination with other driving factors, such as the inflow of warm Atlantic Water and circulation changes (Overland & Serreze 2012). This resulted in, among other things, a record minimum of summer Arctic sea-ice extent in September 2012.

To help explain these intrinsic low-frequency variations there is a need for long-term instrumental climatic series. Unfortunately these are scarce in Arctic regions. The Svalbard Airport composite temperature series (Fig. 1; Nordli 2010), which began in September 1911, is one of only a few long-term (ca. 100-year) instrumental temperature series from the High Arctic. As such, it is an extremely important record, not least because the extensive on-going interdisciplinary research activity on Svalbard often requires information on long-term temperature variability and trends.

It may be noted that earlier efforts to homogenize the temperature observations at Isfjorden (Nordli et al. 1996; Nordli & Kohler 2004; Nordli 2010) have resulted in slightly different results. The main reason for this has been an on-going digitalization of Svalbard data that has made it possible to use more daily data in the more recent reconstructions. In a new effort presented here, more daily data have been added in the form of data from the main Russian settlement Barentsburg (Fig. 1) that have now become available.

Although not continuous, extensive measurements exist for Svalbard during the period 1898–1911. Some of these observations were made by scientific expeditions, but most were made by Norwegian hunting expeditions. Some cabins, remain showing exactly where the hunters stayed during the winter. In order to incorporate these valuable observations in a new series, extensive work was undertaken during the summer of 2010. In the context of the Arctic Climate and Environment of the Nordic Seas and the Svalbard–Greenland Area (AWAKE) project, new automatic weather stations were erected near these cabins with the specific aim of calculating transfer functions between the old sites and the present Svalbard Airport station (see Fig. 2).

The new, longer, composite series from Svalbard Airport is presented here. The series is used to examine the E20thCW, and in particular, how it is related to the period before 1911, where data have now been added. In addition to this, the whole period from 1898 is considered, allowing for the analyses of long-term temperature trends and variability and testing for regime shifts. In addition, uncertainties related to the extension of the Svalbard Airport temperature series are presented and discussed. Finally, the trends inferred from the composite Svalbard Airport series are compared to other Arctic temperature series.

Methods, metadata and data

Methods

The Svalbard Airport composite series is based on direct observations from Svalbard Airport from 1975 to the present, which we will call the principal series. Before 1975, it is a composite series consisting of many local series. The composite is established in two steps: (1) quality checking and homogenizing the local series; and (2) adjusting the local series to ensure their comparability with the principal series (the Svalbard Airport site). The Standard Normal Homogeneity Test (SNHT) introduced by Alexandersson (1986) checked the local series. This is a relative homogeneity test that requires reference stations for comparison. However, the number of reference stations is sparse in Svalbard, so taking metadata into account is even more important than when working with denser networks. During some periods the neighbouring stations are so remote that the analysis of the metadata is the only real homogeneity test. Inhomogeneities in a data series might be due to radiation screen changes, changed observational procedures, site relocations and so on. After finishing the first step, a network was available in which the series were considered to be homogeneous. In the second step, the local series were adjusted to be directly comparable with the principal series by regression analysis. The daily mean temperature of the principal series, T_s, can be written:

$$T_S = \alpha_1 T_A + C_1 + e_A, \quad (1)$$

where T_A is the daily mean temperature of a local series that partly overlaps the principal series, α_1 and C_1 are constants calculated by the least square method and e_A represents noise (residuals). The predicted daily mean temperature of the principle series, $\hat{T}_s$, is given by Eqn. 2:

$$\hat{T}_s = \alpha_1 T_A + C_1 \quad (2)$$

Similarly, for another local series B partly overlapping series A:

$$T_A = \alpha_2 T_B + C_2 + e_B, \quad (3)$$

where T_B is the daily mean temperature of series B, α_2 and C_2 are constants and e_B represents noise (residuals). If series B does not overlap with the principal series, series B may still be used for the prediction of the principal series' temperature. Combining Eqns. 1 and 3 gives us:

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Fig. 1 Map of the northern part of Svalbard showing the sites for historical and present meteorological stations referred to in the article.

$$\begin{aligned} T_S &= \alpha_1(\alpha_2 T_B + C_2 + e_B) + C_1 + e_A \\ &= \alpha_1\alpha_2 T_B + \alpha_1 C_2 + \alpha_1 e_B + e_A + C_1, \end{aligned} \tag{4}$$

where $\alpha_1 e_B + e_A$ represents the noise.

The Svalbard Airport composite series consists of monthly mean temperatures, from 1975 onwards based on direct observations, and, before that year, on regression-based predictions. These were calculated by taking the arithmetic means of the predicted daily values within each month. If the local series A overlaps with the principal series the monthly means adopted in the composite series, $\hat{T}_{sm}$, are given by Eqn. 5, and for a local series that does not overlap by Eqn. 6:

$$\hat{T}_{Sm} = \alpha_1 T_{Am} + C_1, \tag{5}$$

$$\hat{T}_{Sm} = \alpha_1\alpha_2 T_{Bm} + \alpha_1 C_2 + C_1, \tag{6}$$

where T_{Am}, T_{Bm} are the monthly means for the local series A and the local series B, respectively.

For the whole sample, the mean values of ε_A and ε_B are zero per definition, but for a sub-sample, such as one particular month, this is not the case. If the daily mean values are not auto-correlated, the uncertainty will be reduced by a division of 5.5 (approximately the square root of the number of days in a month). Although the

Fig. 2 (a) The erection of the modern station on Akseløya in Bellsund (photo courtesy of Norwegian Polar Institute). (b) The modern station of Crozierpynten (Treurenberg; photo courtesy of Norwegian Polar Institute). (c) A remainder of the old observation screen at Crozierpynten, including one of its original single louvered sides (photo by Ragnar Brækkan).

composite series consist of monthly means, annual and seasonal means are also necessary for climate research. In the absence of autocorrelation, the uncertainty, s_e, for the temperature in a season is:

$$s_e = \frac{1}{m}\sqrt{\sum_{i=1}^{m} s_{ei}^2}, \tag{7}$$

where s_{ei} is the standard deviation for month i and m is the number of months in each season (m is usually 3) or in the whole year ($m = 12$).

Testing for trends in the data sets was performed with the non-parametric Mann-Kendall (M-K) test, which may be used without knowing the distribution of the time series as it is a rank test. Its test statistic, t, is defined by the equation

$$t = \sum_{i=1}^{n} n_i, \tag{8}$$

where n is the number of elements and n_i is the number of smaller elements preceding element x_i ($i = 1,2, \ldots n$; Sneyers 1990). Providing that $n > 10$, the test statistic is very nearly normally distributed under the hypothesis of randomness (the null hypothesis). Moreover, its expectation, E(t), and variance, var t, are given by the equations

$$E(t) = \frac{n(n-1)}{4} \tag{9}$$

$$\text{var}\ t = \frac{n(n-1)(2n+5)}{72} \tag{10}$$

The standard distribution, u(t), of the test statistic is then

$$u(t) = \frac{t - E(t)}{\sqrt{\text{var}\ t}} \tag{11}$$

A percent table of the normal distribution function can be used to decide whether the null hypothesis should be rejected or not. In order to study variations on selected time scales, the time series were smoothed by a Gaussian filter:

$$G_j = \frac{\sum_{i=1}^{n} w_{ij} \cdot x_i}{\sum_{i=1}^{n} w_{ij}}, \tag{12}$$

where

$$w_{ij} = \exp \frac{-(i-j)^2}{2s^2},$$

G_j is the value of the smoothed series in year j, x_i is the data point in year i, w_j is the weight in year j, n is the number of years in the series and s is the standard deviation in the Gaussian distribution. The degree of smoothing is established by the value of the standard deviation in the distribution; for example, a standard deviation of three years corresponds to an approximately 10-year rectangular low-pass filter.

Climate data series may also contain regime shifts (step changes) or a blending of steps and trends (Corti et al. 1999). However, interpretations of data in terms of steps and trends depend to an extent on what results are expected, and the scientific background of any particular researcher (BACC Author Team 2008: 14). For the detection of regime shifts, we used a sequential data processing technique introduced by Rodionov (2004). The testing procedure works as follows: for each new observation a test is performed to determine the validity of the null hypothesis, H0 (the existence of a regime shift). There are three possible outcomes of the test: accept H0, reject H0, or keep on testing. Before testing it is necessary to set a cut-off length, which roughly determines the minimum length of what is accepted as a regime. Student's test was used to decide whether two subsequent regimes were significantly different.

Table 1 Principle series and local series included in the composite Svalbard Airport series.

National station no.	Name	H. a.s.l. (m)	Whole period of observations	Inclusion in the composite series
99732	Halvmåneøya	10	1906.09.15–1907.08.31	1906.10.01–1906.10.20
				1907.08.01–1907.08.31
99733	Zieglerøya	7	1904.10.01–1905.06.30	Not included
99936	Kapp Lee	5	1904.09.01–1905.07.31	Not included
99737	Svarttangen	10	1904.11.10–1909.07.19	1905.07.01–1905.07.31
		10	(there are many gaps)	1906.10.21–1907.07.31
		20	2010.08.23–2011.02.28	
		20	2011.07.08–2012.06.16	
99752	Sørkappøya	10	1908.09.01–1915.09.25	1908.09.01–1909.06.30
			(there are many gaps)	1911.08.01–1911.08.31
99765	Akseløya	9	1898.01–1911.05.31	1898.09.01–1899.07.31
		5	(there are many gaps)	1900.09.01–1901.06.31
		3		1902.09.01–1903.06.31
		3		1904.09.01–1905.06.31
		5		1910.09.01–1911.05.31
		6	2010.08.23–present	
99860	Longyearbyen		1911.09–1977.07	1911.09.01–1912.06.30
		50	(there are many gaps)	1916.11.01–1919.09.30
		50		1919.11.01–1920.05.31
		50		1921.09.01–1923.08.31
		53		1930.09.01–1934.08.31
		40		1935.01.01–1935.09.30
				1936.11.01–1939.06.30
				1941.12.01–1942.06.30
				1945.09.01–1946.08.31
		37		1957.01.01–1975.07.31
99821	Green Harbour	4	1911.12–1930.08	1912.07.01–1916.10.31
				1919.10.01–1919.10.31
				1920.06.01–1921.08.31
				1923.09.01–1930.08.31
99820	Barentsburg	70	1933.02–present	1934.09.01–1934.12.31
				1935.10.01–1936.10.31
				1939.07.01–1941.08.31
				1947.12.01–1956.12.31
99790	Isfjord Radio	7	1934.09–1976.07	1946.09.01–1947.11.30
99840 (principle series)	Svalbard Airport	28	1975.08–present	1975.08.01–present
99928	Crozierpynten	22	1899.08.01–1900.08.15	1899.08.01–1900.07.31
		22	2010.07.11–2012.07.07	
	Janssonhaugen	270	2000.05–present	Not included
	Interpolations			1900.08.01–1900.08.31
				1901.07.01–1902.08.31
				1903.07.01–1904.08.31
				1905.08.01–1906.09.31
				1907.09.01–1908.08.31
				1909.07.01–1910.08.31
				1911.06.01–1911.08.31
				1941.09.01–1941.11.30
				1942.07.01–1945.08.31

Data and metadata

The many local series that have contributed to the composite Svalbard Airport series are listed in Table 1, with their national station number and names, and their locations are shown in Fig. 1. They are described briefly below.

Svalbard Airport. As the name suggests, the station is situated at Svalbard Airport (*Svalbard lufthavn* in Norwegian station lists), which is located near the outer part of Adventfjorden, a branch of Isfjorden (Fig. 1). Measurements began in August 1975 using an MI-33 screen, which is the standard Norwegian screen for harsh weather conditions (Nordli et al. 1997). The station is still in use (see Table 1). The temperature measurements have been undertaken in the same screen from the start of the measurements to 5 October 2010, when the screen was changed to pattern MI-74 and relocated to a site further away from the runway of the airport (see Supplementary file). This was done in order to prevent thermal influences on the measurements associated with the area cleared for airport purposes. The sparse grass growing near the previous site of measurements was replaced by sand and, in late July or early August 2010, covered with asphalt.

Longyearbyen. The series consists of three main series, one conducted by the northernmost coal-mining company, the Store Norske Spitsbergen Kulkompani, and two others by the Norwegian Meteorological Institute. There are also three shorter series. The sites of the main series as well as the shorter series are all located near each other, at approximately the same height above the valley floor (Nordli et al. 1996). A brief outline follows, first for the three main series, thereafter for the three shorter series. (i) The Store Norske Spitsbergen Kulkompani series extends from November 1916 to August 1923, during which time meteorological observations were carried out three times a day at Longyearbyen by this mining company. The daily observations were digitized, quality controlled and made ready for use in 2004. These observations had previously only been available in digital form as monthly-mean values. Only minor differences were discovered between the new monthly values based on digitized observations, and the old manually calculated monthly values. For annual means no difference was larger than 0.1°C. (ii) The Norwegian Meteorological Institute's series comprises measurements taken at Longyearbyen during two periods, the first one from September 1930 to June 1939 (period I), and the second from January 1957 to July 1977 (period II). During both periods, observations were carried out according to the specifications of the institute. The screen used in period II—and probably also in period I—was of the pattern MI-33. (iii) Meteorological observations were made by the German–Austrian scientific expedition at their base station in Longyearbyen (also known as Advent Bay) from September 1911 to June 1912 (Rempp & Wagner 1921). The thermometer screen was described as being situated on a flat plain, 33 m a.s.l. in the valley side near the mouth of the Longyear valley, a tributary valley to Adventdalen. This is very near the altitude (37 m a.s.l.) of the last meteorological station maintained in Longyearbyen by the Norwegian Meteorological Institute (period II). Because there are no other flat areas in the valley side at that elevation near the bay, the two sites of measurements must have been situated close to each other, not more than 100 m apart. (iv) German military forces undertook observations in Longyearbyen from December 1941 to June 1942. The location was presumably near the period II site. (v) Post-war observations were made from September 1946 to December 1947. They are reported to have been undertaken at a distance of 250 m north–north-west of the period II site. However, consulting a modern map suggests that the direction was more likely to have been north–north-east.

Green Harbour. Observations at Green Harbour (during the period December 1911–August 1930) were carried out according to the standards of Norwegian stations, that is, at the observation times of 07.00, 13.00 and 19.00 Coordinated Universal Time (UTC) until 1 July 1920, thereafter at 07.00, 13.00 and 18.00 UTC, with daily minimum temperatures taken at 08.00, but no maximum temperature recorded. The data quality of the series is variable, but tends to improve towards the end of the series. Temperatures were occasionally recorded as integer values. However, as long as the nearest whole degree was read correctly, this does not affect the monthly-mean temperature significantly. Further information regarding the quality of the series may be found in Nordli & Kohler (2004).

In some months, significantly different mean temperatures are found compared to the previous values published by the Norwegian Meteorological Institute (for details, see Nordli & Kohler 2004). One reason for this is that different instruments were used for the observation of minimum temperature: readings from a thermometer alternated with readings from a thermograph. Another possible reason is that the diurnal temperature range in Svalbard was not well understood when the observations started in 1911, that is, the weighting factors to be used for calculating mean temperatures from observations irregularly distributed over the course of the day were not well known (Nordli & Tveito 2008).

Barentsburg. Barentsburg is a Russian meteorological station located only 2.5 km to the north of Green Harbour (Fig. 1). Measurements there began in 1933 when the station was moved to Barentsburg from Grumantbyen (the first Russian station in Svalbard was located there at the end of 1931). In July 1941, observations were interrupted by the Second World War. They were resumed in 1947 (Ivanov & Svjaščennikov 2012).

The meteorological station from 1933 to May 1978 was located in the north-eastern part of the village, approximately 500 m from the shoreline and at an altitude of 70 m a.s.l. The nearest buildings (including an old consulate building 6 m in height) are located at distances of 100 m from the measuring site (Ivanov & Svjaščennikov 2012).

As a result of the start of the construction of a five-floor building in 1974, which was located 40 m to the south of the station, and plans for a new consulate building, in 1978 the station was moved to the location of the aerological station (22 m a.s.l.). Because of the lack of facilities for installation, not all of the instruments were moved. The meteorological observations began on 1 June 1978 in a new location and were continued until the end of January 1984. During this period, air temperature and humidity could have been influenced by a stream of warm water from the dining room or agriculture building (distance of about 10 m). However, the greatest bias could probably be connected with a wrong orientation of the meteorological screen—east–west instead of north–south—which resulted from the topographical limitation (location of the meteorological garden on a narrow terrace on the slope of the mountain). Starting on 1 February 1984 meteorological observations in Barentsburg were moved to a new place, located at almost the same altitude (74 m a.s.l) as in the first period of observations, and have been continued here to the present (Ivanov & Svjaščennikov 2012). Daily data from the station for the period 1940–2010 have been downloaded from the internet site http://www.meteo.ru/climate/. For the period January to November 1947 only monthly data are available on the web page. As these seem unreliable they are not used in the present article. However, monthly means from the 1930s are used (Table 1). They have been in the possession of the Norwegian Meteorological Institute for a considerable time, and have been tested and found reliable.

Isfjord Radio. The station was established on 1 September 1934 and situated on Kapp Linné at the mouth of Isfjorden (Fig. 1). It was destroyed by actions of war in September 1941 but re-established at the same place in July 1946. From 30 June 1976 onwards, the station was no longer used for climatological purposes. The radiation screen was altered between the patterns of 1930 and 1933. It started with MI-30, was changed to MI-33 in 1939, reverted to MI-30 in 1946 and changed again to MI-33 on 20 August 1951. It has remained unchanged since then.

Observations predating December 1911. Before the first permanent weather station was established in Svalbard, observations were carried out by groups of hunters and scientists. The first hunting expedition equipped with standard instruments from the Norwegian Meteorological Institute overwintered during 1898/99. This marks the time at which it is possible to begin the composite Svalbard Airport series. So-called extraordinary automatic weather stations were set in operation from the summer of 2010 to the summer of 2012 in the context of the AWAKE project at four historical sites: Akseløya (Bellsund); Crozierpynten (Sorgfjorden); Svarttangen (Edgeøya); and Sørkappøya (Cape of Spitsbergen). Thus, parallel measurements with the main station of Svalbard Airport were established during these two years. Using these measurements, transfer functions were developed between the historical sites and the Svalbard Airport station so that the historical series could be adjusted accordingly. Some of the metadata of the series are listed briefly below. The official place names are used; however, older names are given in parentheses to ensure that historical data may easily be connected to the correct site.

The island of Akseløya (also Axeløen) forms a barrier between Bellsund and Van Mijenfjorden. Cabins were built there early on and it remains a popular location for hunters. It was here that the first hunting expedition equipped with standard meteorological instruments overwintered. The data from the island adopted in the composite series comprises information from five winters, four from hunting expeditions and one from a scientific expedition. The leader of the scientific expedition was Niels Russeltvedt (1875–1946), who wrote a vivid description of the weather during the winter. He also described the instruments and their sites in some detail. A sea captain, Johan Hagerup (1846–1924) also joined Russeltvedt's expedition. Hagerup was the leader of the hunting expeditions during three other winters. However, the protocol for the last winter, 1910/11, is not signed so the leader is unknown. The altitude of the instruments differs from the first winter to the following winters. It is likely that the first cabin was on the higher part of the island, but probably less than 20 m a.s.l., whereas the later site was near the strait between Akseløya and a small neighbouring island (Mariaholmen) to the south. In this place, a cabin made of stone was built in 1910, which was certainly in use for the last winter. The present automatic weather station (Fig. 2) was established in August 2010 at 6 m a.s.l. and about 150 m north-west from the cabin.

The station at Svarttangen (also known as Hvalpynten, Kvalpynten) is on Edgeøya, the third largest island in the archipelago. This region has been much frequented by hunters of polar bears, which follow the ice drift around Spitsbergen. The meteorological observations from this station, which cover three winters (Table 1), were carried out by Hjalmar M. Jensen, an expedition leader from Tromsø. Data from two of the winters are used in the composite Svalbard series. An old wooden cabin is still present at the site and it is believed that this is where the hunting station was situated. On 23 August 2010 an automatic weather station was erected near this cottage, but on 28 February 2011 it was destroyed by a polar bear. It was re-erected on 8 July 2011 but finally closed on 17 June 2012.

Halvmåneøya (also Halvmåneøen) is a small island just south of Edgeøya (Fig. 1) where historical observations took place one winter (Table 1). According to the observation protocol they were carried out in a cage, which at that time was the standard thermometer shelter. The observations overlap those at Svarttangen except for 51 days. In the composite series, Svarttangen had higher priority than Halvmåneøya but due to the missing overlapping period the 51 days from Halvmåneøya had to be included (Table 1). The transfer functions from Svarttangen were chosen as no modern station was located at Halvmåneøya. Other historical stations in this region are Kapp Lee, farther to the north on Edgeøya, and Zieglerøya, near Halvmåneøya. However, observations from these two islands overlap with those at Svarttangen and are therefore not used in the composite series.

The island of Sørkappøya (also known as Storøen or Sydkap) is south of the Cape of Spitsbergen. There is some doubt about the exact site of the station, but it is certain that the station was on the island. Observations were undertaken for three winters but only the first winter, 1908/09, is used in the composite series as the two last winters overlap with the Green Harbour observations.

A station at Crozierpynten (also known as Treurenberg) was established during the winter of 1899/1900 by a Swedish–Russian scientific expedition that overwintered at Sorgfjorden (Fig. 2), on northern Spitsbergen, with the aim of measuring an arc of the Earth's meridian. The expedition established two meteorological stations, and the main station, called Treurenberg, was located 22 m a.s.l. (Przybylak & Dzierzawski 2004). The exact site of the old main station is easy to detect as its foundations and some remnants of the radiation screen may still be seen. An automatic weather station was established in July 2010 on the same spot and closed in July 2012. This station only has temperature observations without satellite transmission, so the data had to be manually collected.

Surface temperature at grid point 78°N, 16°E. Surface monthly-mean temperatures from grid point 78°N, 16°E of the Twentieth Century Reanalysis Project (Compo et al. 2011) were downloaded for the period 1898–2008. The data were used for interpolation purposes when no data from Svalbard were available.

Homogenization, adjustments and error estimation

Defining the Svalbard Airport series (1975–present) as the principal series for the homogenized, composite long-term series means that new data can be included in the composite series without any adjustments, whereas all other local series included have to be adjusted. The principal series is considered to be of exceptional importance as it has been chosen by the Norwegian Meteorological Institute as the only Reference Climate Series (RCS) on Spitsbergen.

Homogeneity of the Svalbard Airport series 1975–2012

After having started measurements at a new site farther from the airport runway from 5 October 2010 onwards, parallel measurements were performed in the period 27 October 2010–8 November 2011 (Supplementary file; for calibration of the sensors see the same file). The monthly means of the temperature differences between the new and old site all fall in the interval -0.09 to $+0.06$°C. It is therefore concluded that the Svalbard Airport temperature series is homogeneous through the relocation and screen type shift of 5 October 2010. Further to this, the Svalbard Airport series was tested for homogeneity in the period July 1978–December 2010 by use of the SNHT method relative to the stations: 99754 Hornsund; 99842 Barentsburg; and 99910 Ny-Ålesund. The test result indicated an inhomogeneity of the Svalbard series in the test period, although without an indication of the distinct year of the shift. For the annual data, the most likely year of the shift was 2004. Compared with the reference group, the temperature at Svalbard Airport was warmer than the reference group after the shift. Metadata were examined for a possible confirmation of the shift, but with a negative result. The same screen has been used in the whole test period, and the sensors inside the screen have been tested once a year without any detected malfunction. A possible explanation of the detected inhomogeneity might be an inadequate reference group, which reflects more maritime conditions than at the airport.

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In Adventdalen (only 23 km from Svalbard Airport), a permafrost station was established at Janssonhaugen (270 m a.s.l.) in May 1998 (Sollid et al. 2000; Isaksen et al. 2001, 2007). From May 2000, air temperature is available from a weather station (run by the University Centre in Svalbard) that was established 15 m north of the permafrost station. The weather station does not have complete data coverage as it lacks data for the periods June 2005–October 2006 and June 2010–April 2011. However, these are interpolated using another station in Adventdalen. The series was used as reference for the Svalbard Airport series in a SNHT test. No significant inhomogeneity was detected. On the basis of these tests, the Svalbard Airport series from 1975 to the present is considered to be homogeneous.

The adjustment of the Longyearbyen series

The nearest local series to Svalbard Airport was situated at the main settlement, Longyearbyen, at a distance of only 15 km. For the construction of the composite series, the Longyearbyen series has a key role as it overlaps both with the old local series, and with the principal series. It was tested for inhomogeneity by SNHT (Nordli et al. 1996) but no shift in the series was detected. Due to poor correlation and long distances to the neighbouring series, the SNHT test is not considered to be a strong test in this case. However, metadata studies show that the measurements have always been located approximately at the same height above the valley floor (Steffensen et al. 1996) which, in itself, is an indication of a homogeneous series.

In order to adjust the Longyearbyen series, linear regression analysis was performed with the Longyearbyen temperature as predictor, and the Svalbard Airport temperature as predictant, using the daily mean temperature during an interval of parallel measurements (November 1975 to July 1977). Analysis was performed separately for each month. The predicted Svalbard Airport temperature was given by Eqn. 2. The regression accounted for as much as 99% of the variance in large parts of winter and autumn, and in no month was it less than 90% (Table 2). Visualization of the regression is shown for March and September in Fig. 3a. For most of the year, the Longyearbyen series is warmer than Svalbard Airport so negative adjustments are needed (Fig. 4). This reflects the location of the station on a small plateau over the valley floor, which reduces the effects of inversions on the local climate in contrast to the location of the Svalbard Airport station.

The standard error of the estimates (RMSE) of the daily means is obtained directly by the regression. However, the composite series of monthly means has less uncertainty. If randomness is assumed, the uncertainty in the monthly values may be calculated from the uncertainty of the daily values by dividing by the square root of the number of days in the months. This gives an RMSE of only 0.2°C in winter and 0.1°C in summer, which is very satisfactory. These estimates might be realistic for the last period of the series, 1957–1977, in which the station was located at the same spot. However, for earlier periods, the sites differed and there might be some inhomogeneities in the series. Station history data suggest that any such inhomogeneities must be minor.

The adjustment of the Barentsburg series

The homogeneity of the Barentsburg series was tested by SNHT for the period 1978–2010 with use of the reference stations Hornsund, Svalbard Airport, and Ny-Ålesund. For this period, the Barentsburg station was found to be homogeneous. The first part of the series has earlier been tested for inhomogeneities (Nordli et al. 1996). Their conclusion was that this part of the series was also homogeneous. For inclusion in the composite series Longyearbyen is the first choice, although Barentsburg is a good alternative for some periods where Longyearbyen lacks data. These are mainly during 1947–1956, but also for some years in the 1930s (Table 1).

The overlap with the principal series during the period 1975–2010 amounted to about 1000 days in each month. The good data coverage reduced the uncertainties in the predictions. The relative variance accounted for by the regression is largest during the period from September to May, when it was no less than 93% in any month, whereas in July it was 84% (Table 2). For May and September, scatter plots are shown as well as the regression lines from Eqn. 2 (Fig. 3a). The negative adjustment during winter, and positive during the summer, for the Barentsburg series might reflect a more maritime climate compared to the Svalbard Airport site (Fig. 4). For the Barentsburg series, the assessment of uncertainty in the monthly means is straightforward as it overlaps for about 35 years with the principal series. By performing an extra regression using monthly means (instead of daily means) RMSE is calculated directly by the regression (Table 3). It amounts to 0.7°C during late winter, whereas in summer and autumn it is only about 0.4°C.

The adjustment of the Green Harbour series

For long periods, the Green Harbour series was the only series at Svalbard so that relative homogeneity tests such as SNHT cannot be used. There seem to be relatively

Table 2 Regressions on daily values: α and C are coefficients in Eqns. 2 and 3, SSR/SST is the regression sum of squares divided by the total sum of squares in % (accounted for by the regression), RMSE (°C) is the root mean square of the residuals.

Coefficient	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Svalbard Airport—Longyearbyen (1975–77)												
α	1.018	1.038	1.036	1.023	1.049	0.976	1.022	0.929	0.970	0.968	0.971	1.023
C	−0.52	−0.68	−0.88	−1.13	−1.10	−0.87	−1.01	−0.26	−0.57	−0.21	−0.36	−0.04
SSR/SST (%)	99	99	99	98	98	96	90	92	97	99	99	98
RMSE	0.7	0.9	1.1	0.8	0.6	0.6	0.7	0.5	0.4	0.5	0.6	1.2
Svalbard Airport—Barentsburg (1975–2010)												
α	1.087	1.089	1.068	1.059	1.048	1.018	0.988	1.031	1.083	1.100	1.096	1.082
C	0.10	0.22	0.15	0.15	0.47	0.53	0.49	0.16	−0.06	0.11	0.21	0.04
SSR/SST (%)	94	94	93	94	95	90	84	87	93	94	95	95
RMSE	2.1	2.1	2.2	1.6	0.9	0.8	0.9	0.8	0.9	1.2	1.5	1.7
Longyearbyen—Green Harbour (1911–1930)												
α	0.917	0.881	0.822	0.902	0.996	1.002	1.002	1.002	1.051	0.927	0.945	0.829
C	−0.48	−1.04	−1.75	−0.45	0.18	0.79	0.79	0.79	0.03	−0.60	−0.08	−1.21
SSR/SST (%)	96	90	92	92	94	78	78	78	89	84	92	91
RMSE	2.4	2.9	2.6	2.2	1.2	1.6	1.3	1.1	1.1	1.8	2.1	2.7
Longyearbyen—Isfjord radio (1957–1977)												
α	1.173	1.182	1.159	1.143	1.119	1.206	0.982	1.118	1.174	1.224	1.205	1.184
C	−0.53	−0.55	−0.25	−0.00	0.62	0.96	1.80	0.55	−0.10	−0.57	−0.49	−0.47
SSR/SST (%)	96	93	94	94	94	66	76	83	90	95	96	95
RMSE	1.7	2.1	2.0	1.6	1.0	1.0	1.0	1.1	1.0	1.3	1.4	1.7
Svalbard Airport—Akseløya (2010–12)												
α	0.909	0.960	0.921	1.063	1.093	0.979	0.979	0.979	1.244	1.176	1.171	0.999
C	−0.91	−1.06	−1.19	−0.125	0.61	1.63	1.63	1.63	−0.59	−1.18	−1.22	−0.81
SSR/SST (%)	96	93	96	93	89	69	69	69	93	93	97	92
RMSE	1.7	2.0	1.4	1.2	0.9	1.1[a]	1.1[a]	1.1[a]	0.7	1.1	1.1	1.6
Svalbard Airport—Crozierpynten (2010–12)												
α	0.835	0.915	0.863	0.766	0.621	0.447	0.447	0.447	0.707	0.995	0.881	0.753
C	−0.64	−0.56	0.45	−0.44	0.10	4.06	4.06	4.06	2.32	0.67	0.10	−0.41
SSR/SST (%)	87	66	89	73	60	36	36	36	60	77	78	85
RMSE	3.0	4.2	2.3	2.4	1.7	1.7[a]	1.7[a]	1.7[a]	1.4	2.1	2.7	2.2
Svalbard Airport—Svarttangen (2010–12)												
α	0.987	0.905	1.031	0.948	1.006	0.771	0.771	0.771	1.161	1.207	0.966	0.877
C	−0.59	−1.08	−0.15	−0.46	0.37	3.20	3.20	3.20	−0.33	−0.89	−1.22	−1.06
SSR/SST (%)	92	87	89	93	66	33	33	33	75	91	91	90
RMSE	2.4	2.6	1.6	1.1	1.5	1.8[a]	1.8[a]	1.8[a]	1.1	1.3	1.8	1.8

Table 2 *Continued*

Coefficient	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Svalbard Airport—Sørkappøya (2010–12)												
α	1.011	0.877	1.222	0.998	1.119	0.580	0.580	0.580	1.694	1.261	1.195	0.977
C	−1.34	−3.01	−1.04	−0.95	0.69	4.33	4.33	4.33	−1.45	−1.99	−2.57	−1.51
SSR/SST (%)	93	80	93	81	70	20	20	20	88	82	88	86
RMSE	2.3	3.3	2.0	2.0	1.5	1.8[a]	1.8[a]	1.8[a]	1.0	1.4	2.0	2.1
[b]Svalbard Airport—Grid point 78°N, 16°E												
α	2.327	2.666	2.212	2.334	1.492	0.751	0.679	0.630	1.047	1.388	1.986	2.272
C	−1.00	−0.18	−3.72	−2.25	−2.03	1.39	3.41	3.08	−0.09	−1.55	−0.72	−0.18
SSR/SST (%)	70	60	56	55	44	34	40	41	73	82	76	73

[a]JJA are joined before regression analysis took place.
[b]Mean monthly temperature.

good metadata from the station that indicate homogeneous conditions throughout the period of observation (Steffensen et al. 1996). The Green Harbour series is therefore considered to be homogeneous. The Green Harbour series does not overlap with the principal series, but it does overlap with the Longyearbyen series. The monthly means of the Green Harbour series could be adjusted by Eqn. 6 but not by Eqn. 5. This adds uncertainties in the prediction that might be assessed by use of the Barentsburg series.

As the Barentsburg series (local series B) also overlaps with the Longyearbyen series (local series A), predicted values of the principal series might also be inferred by Eqn. 6. The values obtained by Eqn. 5 could therefore be compared with those from Eqn. 6. It appeared that the use of Eqn. 6 increased the uncertainties by only 0.1°C or less, so the extra regression from the Longyearbyen series to the Svalbard Airport series had very little impact on the uncertainties of the monthly means. The uncertainty was assessed using monthly-mean values in a regression between Green Harbour and Longyearbyen, adding an extra uncertainty of 0.1°C (Table 3). It transpired that the uncertainty was larger for the periods predicted by Green Harbour than those for Barentsburg.

The adjustment of the Isfjord Radio series

During the period September 1946–November 1947, none of the adjusted series mentioned so far have data coverage. The only exception is the Isfjord Radio series, which is not an ideal series to be used as it is much influenced by open water off the coast of Spitsbergen. The series overlaps with the principal series by only one year, so the Longyearbyen temperature series was used for the prediction. Due to the maritime influence on the station, large negative adjustments had to be used in winter (about −3°C; Fig. 4), whereas positive adjustments were needed during summer. The uncertainties were assessed using the same procedure as for the Green Harbour series (Tables 3, 4).

The adjustment of the early Svalbard series 1898–1911

As new stations were established on the old sites Akseløya, Crozierpynten, Svarttangen and Sørkappøya, their data series overlap with the principal series during the period 2010–12. Equation 5 was therefore used for the adjustment of the series. For daily values it turned out that the prediction for most of the year accounted for roughly 90% of the variance (highest for Akseløya and lowest for Crozierpynten; see Table 2). For summer,

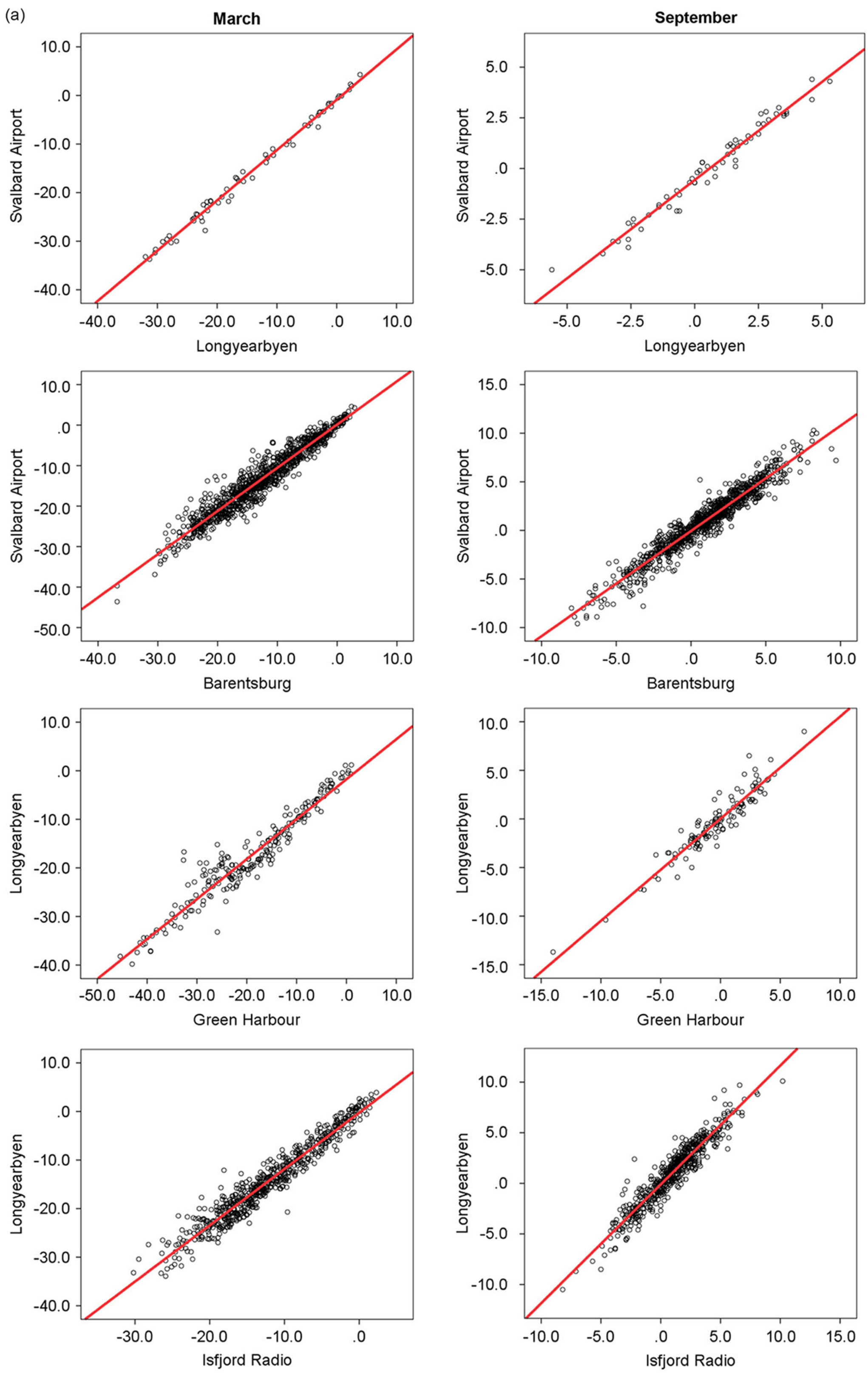

Fig. 3 (Continued).

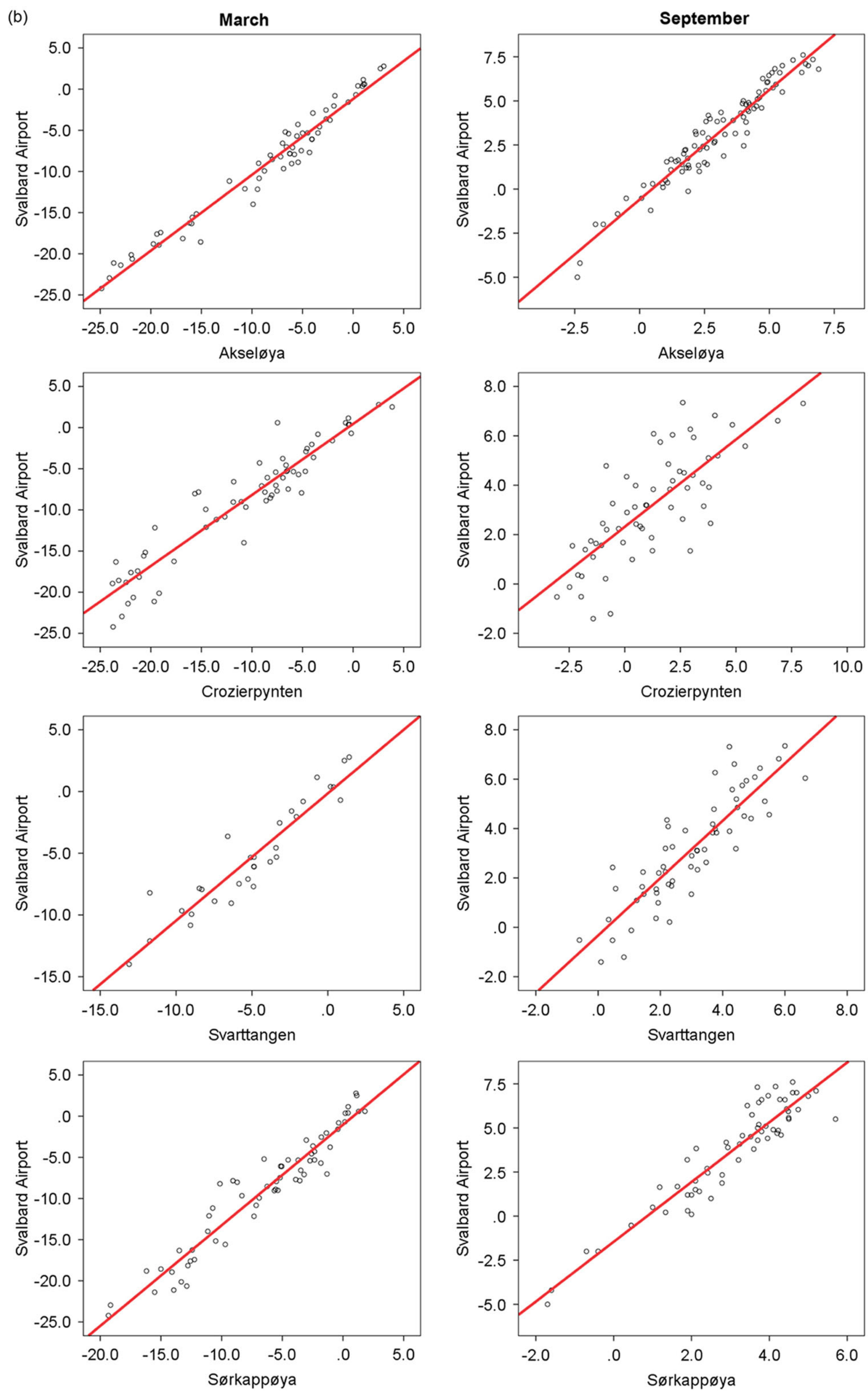

Fig. 3 (a) Scatter diagrams showing daily mean temperature (°C rings) for Spitsbergen series and linear regression lines, March (left column) and September (right column). (b) Scatter diagrams showing daily mean temperature (°C rings) for automatic weather stations in Svalbard placed at historic station sites, and linear regression lines with the Svalbard Airport series, March (left column) and September (right column).

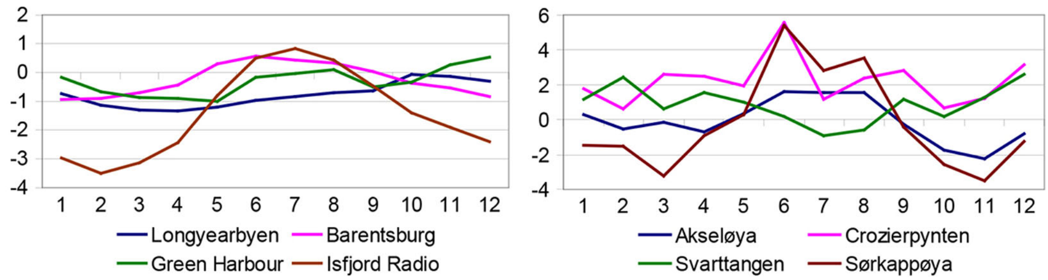

Fig. 4 Mean adjustments (°C, vertical axis) resolved for months (horizontal axes) of the local series so as to fit in the composite Svalbard Airport series in the reference period 1981–2010.

however, the prediction was very poor. The sample size was increased from 60 to 180 daily means by joining data from the three months of June, July and August. Nevertheless the predictions turned out to be of little use except for Akseløya. Scatter plots with regression lines for March and September are shown in Fig. 3b.

The old stations lie outside the Isfjorden area with quite long distances to the Svalbard Airport site: Akseløya is 70 km, Svarttangen 150 km, Crozierpynten 180 km and Sørkappøya 200 km. It can be argued that one day is too small a time window for the travelling weather systems, so over such distances they might be out of phase. A system might be at Sørkappøya one day, and at Svalbard Airport the next day. By increasing the time window to pentads, the same weather system could more easily be caught in the same pentad. Regression analyses were performed with pentads but hardly any improvement was seen (as the sample size was small deleted residuals were compared). The only exception might be Crozierpynten for summer where the variance accounted for amounted to 50% with pentads versus 36% with daily means.

During winter, autumn, and spring, the RMSE of the predicted daily means was about 1.5°C for Akseløya, 2.5°C for Crozierpynten, 2.0°C for Svarttangen and 2.0°C for Sørkappøya (Table 2). The adjustments differ between the series and months (Fig. 4). As long as the fjords are covered with ice, there are only small adjustments needed for the Akseløya series. Akseløya is cooled by the fjord during summer, whereas in autumn it is warmed by the open water in the fjord. It is also seen that the northernmost station Crozierpynten is colder than Svalbard Airport during the whole year. For Sørkappøya, the adjustments reflect its maritime influence with negative adjustments during the cold period of the year, and positive during summer. For Svarttangen (Fig. 4) the sign of the adjustments are opposite to those at Sørkappøya, that is, it is positive during the cold part of the year and negative during summer.

Interpolations

During the Second World War, and also during five winters in the period 1898–1911, no observations were made in Svalbard, so the only possibility for filling data gaps is by interpolation. Monthly-mean temperatures for the grid point 78°N, 16°E (Compo et al. 2011) were used for this. Regression lines for each month were established, with the composite series as predictand, and the grid point as predictor. Data before 1912 stem from series outside the Isfjorden area so they might be less accurate than the rest of the series. They were therefore omitted in the regression, which used the data for the period 1912–2008, which is complete except for the Second World War gap.

The variability of the monthly mean of the grid point was much lower than for the station data, in particular during winter, leading to a regression coefficient during winter larger than 2 (Table 2). In the season September through February, 60–82% of the variance was accounted for by the regression depending on the month, whereas in the season March through August only 34–56% was accounted for. During winter the RMSE in the monthly means was nearly 3°C, much higher than the

Table 3 Uncertainty (root mean square error in °C) of predictions in monthly mean temperatures for the composite Svalbard Airport series derived from different local series.

Local series	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Barentsburg	0.6	0.7	0.7	0.6	0.4	0.4	0.3	0.4	0.4	0.4	0.5	0.5
Green Harbour	0.9	0.9	0.9	0.9	0.5	0.5	0.5	0.5	0.5	0.5	0.9	0.9
Isfjord Radio	0.9	0.9	0.8	0.6	0.4	0.5	0.5	0.5	0.4	0.8	0.9	0.9
Interpolations	3.0	2.8	2.9	2.5	1.5	0.9	0.8	0.7	0.8	1.1	2.0	2.4

uncertainty in the station-based values in the Svalbard Airport composite series.

Uncertainty in seasonal and monthly values

Based on the assumption that the RMSE for monthly-mean temperatures are really white noise, the RMSE of the seasonal and annual means may be calculated by Eqn. 7. These are given in Table 4 for the series where regression analyses on monthly means are performed. Comparison with Table 3 shows how much uncertainties are reduced. The RMSE for the seasonal means is not higher than 0.5°C for winter and spring and 0.3°C for summer.

Results

Having calculated the regression equations necessary for adjusting the local series, the Svalbard Airport series is readily available as predictions in the period September 1898–July 1975, and as observations in the period August 1975–December 2012. However, due to large uncertainties of the predictions for the summer months based on series outside Isfjorden the composite series for summer starts in 1912.

Looking first at the individual means shown in Fig. 5 (annual or seasonal), the lowest temperatures are usually found in the early part of the series, except for autumn, in which there is a cluster of cold years in the late 1960s. The autumn of 1910 was also exceptionally cold (based on observations from Akseløya). The highest temperatures, however, are usually found in the most recent years, for example three very warm years occurred consecutively in the period 2005–07. Among these, 2006 stands out as being particularly warm, in fact the warmest year in the whole composite series. This year also includes the highest mean spring temperature. Warm years are also found in the 1930s, although these are less warm than the modern extremes. In 2012, the winter was particularly mild, even milder than the previous extreme value from 2006. The summer of 1922 is an example of a high temperature relatively early in the series. However, all extremes, annual as well as seasonal, are found in the 21st century except for autumn where the extreme occurred in 2000.

Table 4 Uncertainty (root mean square error in °C) of predictions in seasonal and annual mean temperatures for the composite Svalbard Airport series derived from different local series.

Series	Winter	Spring	Summer	Autumn	Annual
Barentsburg	0.4	0.3	0.2	0.3	0.2
Green Harbour	0.5	0.5	0.3	0.4	0.2
Isfjord Radio	0.5	0.4	0.3	0.4	0.2
Interpolations	1.6	1.4	0.5	0.8	0.6

Temporal variations were inferred by a low-pass Gaussian filter with a standard deviation of three years in its distribution, which corresponds to approximately 10 years of rectangular smoothing (Fig. 5). It is readily seen that the 1930s and the 1950s were particularly warm annually, as well as seasonally. Another striking feature is the warming of the Svalbard climate in the latest decades. The filtered curves show that recent temperatures are the highest seen since the start of the series in 1898, and since 1980 it has increased by about 4°C. At present (2012), the Spitsbergen climate is in a warm phase, which is seen in all seasons. The most pronounced cold phase is seen in the 1910s, which are colder than any other decade in the whole series, and in all seasons. Another cold phase culminated in the 1960s, which also showed a local minimum in all seasons.

Testing for regime shifts completes the picture of the long-term variations given by the Gaussian filtered values. With regard to mean annual temperature, for the period 1899–2012, the climate of Spitsbergen went through six different regimes (see Fig. 6a). The first one, ending in 1911, was relatively mild. This was followed by a very cold one during 1912–19. Then an abrupt change occurred with the E20thCW, and a long-lasting warm regime prevailed during 1920–1961, followed by a cold one during 1962–1971. The next regime, covering the period 1972–1998, was slightly warmer, whereas the last one covering 1999–2012 was very warm.

During the winter season, long-term variations of Arctic climate are very pronounced, so testing for winter regime shifts is of particular interest. However, the winter regimes very much resemble those for annual values (Fig. 6b). The cold 1960s, defined as a separate regime as regards the annual values, do not stand out as a separate regime with regard to the winter season. Thus, for the winter, the mild regime of the 1930s to the 1950s was, in effect, transformed in 1961 to one cold regime lasting for 44 years. This came to an end in 2004 with the three very mild winters of 2005–07, and the present warm phase of the Spitsbergen winter temperature was introduced. Temperature on Spitsbergen is currently in a warm phase for all seasons (not shown), but the onset differs slightly with each season. For the autumn season it began in 1996, for summer in 2001, for spring in 2004, and finally with the winter season in 2005, as noted above.

The composite Svalbard Airport temperature series shows positive trends at all seasons, and for testing the significance of the trends the non-parametric Mann-Kendall rank test with 0.01 and 0.05 significance levels was used. In order to infer the robustness of the

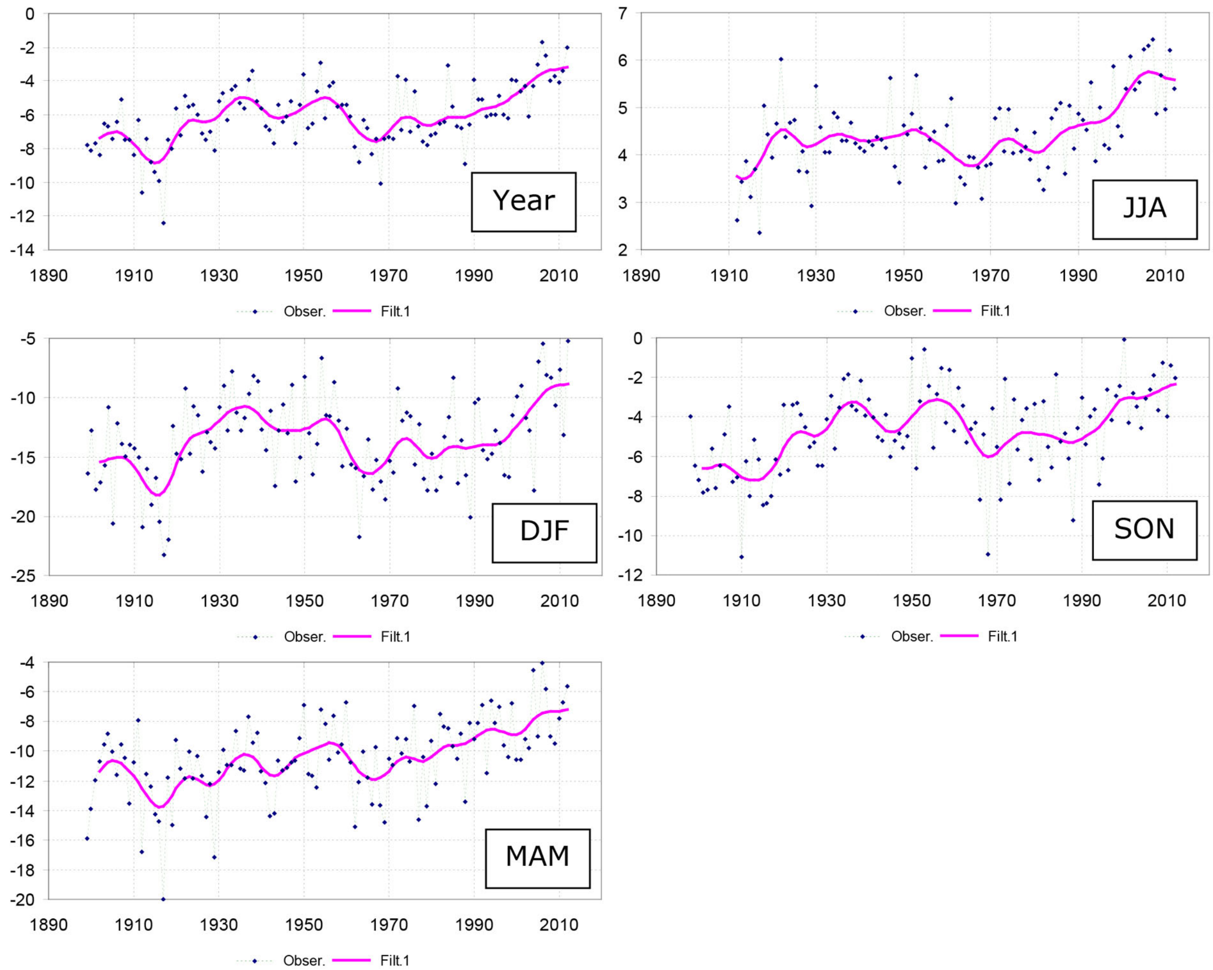

Fig. 5 Temperature (°C, vertical axis) for the composite Svalbard Airport series during the period September 1898–December 2012 for annual means (Year), winter (DJF), spring (MAM), summer (JJA) and autumn (SON). Individual years (dots) are filtered by a Gaussian low-pass filter (curve) with standard deviation of three years in its distribution, corresponding to a rectangular filter of about 10 years. (The ends of the curves are not significant as for the last year [2012] 38% of the weights will lie on unknown future observations; for the sixth last year [2006] it is only 5%.).

significance regarding the starting year repeated tests were performed. One by one, years were added to the data set, going backwards in time, and for each year added the test was repeated on the interval from the "new" starting year to the end of the series. In this way consecutive values of the test statistic with different starting years were developed (Fig. 7). Temperature has significantly increased since 1898/99 (1912 for summer) in all seasons. For spring and summer, the trends are significant even for periods beginning in the warm epoch of the 1930s, so their significance is robust and is not affected by earlier warm or cold phases at the start of the series. For winter and autumn, however, trends beginning in the 1930s fail to achieve statistical significance. However, continuing testing after adding data to the data set further back in time than the E20thCW the significance of the trend for autumn soon recovers, whereas the trend for winter recovers close to the start of the data set. For the 1% level the trends for winter remain insignificant.

The composite Svalbard Airport series was also tested for trends by linear regression analysis on annual values as well as on seasonal values. See Table 5, where the result is calculated using the full length of the data sets. The trend for annual means is 2.6°C per 100 years. The largest trends are detected in spring, 3.9°C, compared to 1.0°C in summer. The trend in winter (2.9°C) is much steeper than in summer, but the variability is also much larger. The signal-to-noise ratio (trend divided by standard deviation) is lowest in winter, which explains its low significance compared to summer (Table 5). Generally this illustrates the difficulties of climate-change detection in the Arctic where large natural variability hampers the detection of significant changes (Wigley & Jones 1981). Comparison between the local stations used in the

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composite series also show spatial differences (Table 6). It is colder in the north of Spitsbergen, spring occurs later in the south-east, there are milder winters in the maritime parts and the warmest summers are in the western inland part with fewer days of snow cover.

Many weather services currently use the "normal" period 1981–2010 for their comparison of mean meteorological values. For Svalbard Airport and Barentsburg, these normals are readily calculated by simply taking the arithmetic means for the period (Table 6). For the local stations at Svarttangen, Sørkappøya, Akseløya, Longyearbyen, Isfjord Radio and Crozierpynten, the normals are given by Eqn. 13 and for Green Harbour by Eqn. 14.

$$T_{NormA} = \frac{T_{NormS} - C_1}{\alpha_1}, \quad (13)$$

$$T_{NormB} = \frac{T_{NormS} - \alpha_1 C_2 - C_1}{\alpha_1 \alpha_2}, \quad (14)$$

where T_{NormA}, T_{NormB}, T_{NormS} are the normals for series A, series B and Svalbard Airport, respectively; compare Eqns. 13 and 14 with Eqns. 5 and 6.

Historically, standard "normal" periods have been widely used in climatology, that is, 30-year periods starting in 1901. For the Svalbard composite series, the first one (1901–1930) was the coldest, the next one was exceptionally warm (1931–1960), whereas the last one (1961–1990) again was cold (Table 6). The Norwegian Meteorological Institute is about to change from the normal period 1961–1990 to the normal period 1981–2010. This period is warmer than any of the earlier normal periods.

Discussion

Uncertainties

A key point for discussion is the uncertainties regarding variations in monthly, seasonal and annual mean temperatures, and the homogeneity of the local series. Inhomogeneous series may lead to biased composite series. In this regard, the Barentsburg series provided crucial information for the current reconstruction as it overlaps for some 40 years with the principal series. It became clear that the uncertainties in the monthly means during autumn and winter were slightly larger than 0.5°C, whereas during summer they were slightly lower than 0.5°C (Tables 3, 4). For the other old series, the addition of further information is not straightforward due to a lack of overlap with the principal series, so Eqn. 6 had to be used (see methods section). The question that needs to be addressed is therefore how much additional uncertainty was added by using Eqn. 6 instead of Eqn. 5. The Barentsburg series provided an excellent possibility to test this as it was possible to use both Eqns. 5 and 6. Comparison of the results showed that Eqn. 6 added very little additional uncertainty to the prediction, about 0.1°C.

Green Harbour is situated only 2.5 km from Barentsburg, and Longyearbyen only 15 km from Svalbard Airport, so it was expected that the regression between Green Harbour and Longyearbyen should lead to approximately the same uncertainty as that between Barentsburg and Svalbard Airport. It appeared, however, that the uncertainties in predicted monthly means by Green Harbour were somewhat larger than those from Barentsburg. This might be due to different time windows for the two stations as Green Harbour was closed before Barentsburg started. When Green Harbour station was active, that is, before 1930, Longyearbyen station was run by a private mining company, which might have carried out less accurate measurements than those done by the Norwegian Meteorological Institute when it took over in the 1930s.

There seem to be no changes in the Longyearbyen series during the period 1957–1977, that is, the most recent part of the Longyearbyen series, but it is likely that the Longyearbyen series is not strictly homogeneous for the whole period (although only slightly different sites and almost the same altitudes should imply that there would only be minor inhomogeneities. For annual values the RMSE is only 0.2°C for the stations in the composite series (Table 4), which is almost as good as the measuring accuracy of old thermometers. Therefore, while there are no RMSE errors that may hamper trend studies, there may be inhomogeneities. This is a problem in Arctic regions where there are very few or no reference stations. In order to redress this difficulty it is necessary to use metadata as much as is possible and feasible.

It is somewhat paradoxical that for the purpose of the current reconstruction the summer seasonal mean temperature predictions for the period 1899–1911 have been discarded, but the same values have been included in the predictions for annual means. The reason for not including them in the composite summer series relates to the fact that the regression sum of squares was almost as large as the total sum of squares so that predictions by regression analysis were considered to be of little use (see Table 2: Crozierpynten, Sørkappøya and Svarttangen). It is fortunate that the RMSEs (Table 2) for the summer months are smaller than for winter. In the case of Crozierpynten, Sørkappøya and Svarttangen, it was roughly one half of that in winter. Therefore, the main

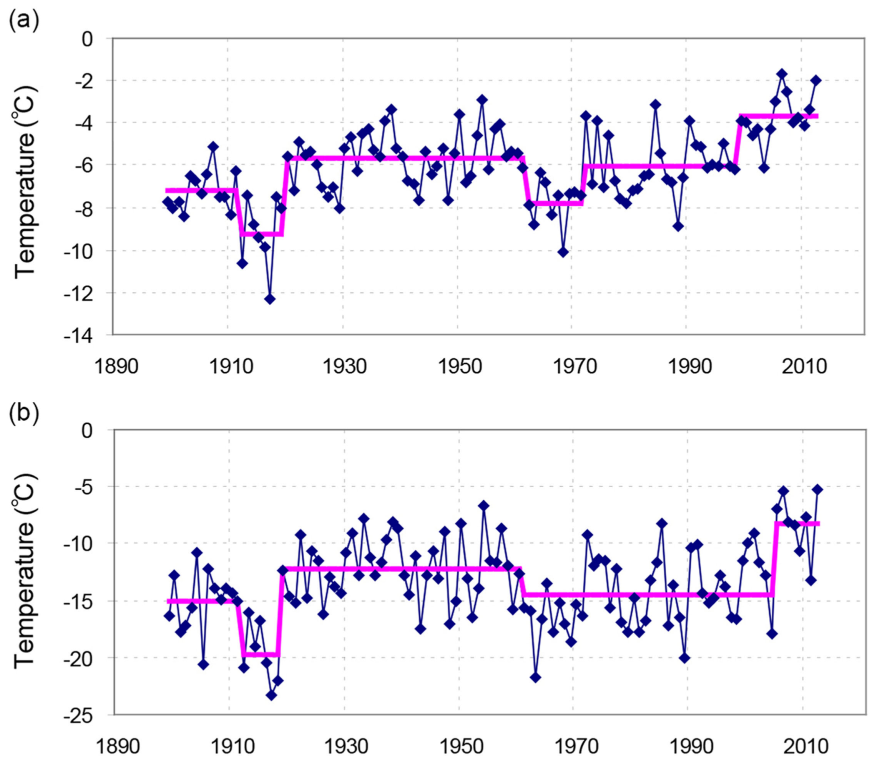

Fig. 6 Regime shifts of the composite Svalbard Airport series detected by the Rodionov test for (a) annual means and (b) winter means in the period 1899–2012 with significance level $p = 0.05$ determined by Student's test. (Cut-off length was 10.)

source of uncertainty in the annual means does not stem from the summer means despite the low variance accounted for by the summer regression.

In the later years of the period of observations, the Gaussian filtered curves show higher values than otherwise (also if the insignificant parts are omitted). This was also confirmed by the test for regime shifts as a regime warmer than all others in the period occurred at the latter end of the curves. However, it is important to note that there are settings in Rodionov's test programme that have to be chosen. For the level of significance $p = 0.05$ was chosen, whereas Rodionov's default value is $p = 0.1$. By changing the settings, information will be acquired regarding how robust the results are, so testing with $p = 0.1$ was also performed. The result was close to the same: the only change was that the cold 1960s for winter was now defined as one regime separated from the 1972–2004 period. Even with $p = 0.01$, a very strong constraint

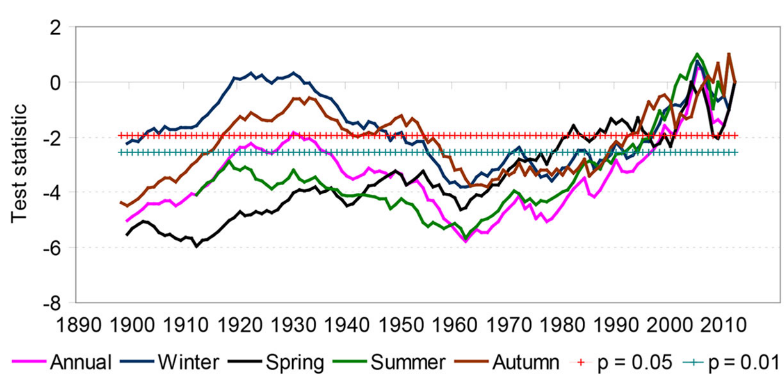

Fig. 7 Significance of trends in the Svalbard Airport composite series. The Mann-Kendall test statistics is shown for annual and seasonal means by using the test "backwards" in time by starting with the last year and adding one by one year and performing repeated tests until the start year has been added. Two significance levels are also shown: 0.05 and 0.01.

Table 5 Linear trends and signal to noise ratio (trend divided by standard deviation) in the Svalbard Airport homogenized series based on the period September 1898–December 2012 (for summer 1912–2012).

	Annual	Winter	Spring	Summer	Autumn
Trend (°C) per 100 yr	2.6	2.9	3.9	1.0	2.4
Signal to noise ratio	1.4	0.8	1.5	1.2	1.1

for regime shifts, the results were nearly the same so it is concluded that the results presented in Fig. 6 are robust. Another important setting is the cut-off length, which was set to 10 years. This means, a priori, that a regime of shorter duration than 10 years would not be accepted for the purpose of this reconstruction. However, in the testing procedure the onset of a regime is adjusted so that slightly shorter regimes than the cut-off length might be possible. Here, the cold period in the 1910s was accepted as a distinct regime although its length in the annual and winter series turned out to be only eight and seven years, respectively.

Wood et al. (2010) reconstructed air temperature back to 1802 for the northern Atlantic area (60°–90°N, 60°W–45°E) using the CRUTEM3v data set and four long-term series as predictors (from south-west Greenland, Iceland, Archangelsk in Russia and Tornedalen in Sweden) with a calibration period of 1950–1979. Comparing their results with ours (our Fig. 5; their figure 1) roughly the same pattern is seen in both figures; however, the trend seems to be somewhat smaller in their reconstruction than at Svalbard Airport. This is to be expected as their area extends as far south as 60°N, where less warming has occurred.

Sea ice has a large impact on air temperature, particularly during winter (Benestad et al. 2002; Screen et al. 2012; Semenov & Latif 2012). Open water is a heat source for the air. If the shores are ice-free or have little ice near one of the stations, and at another station the shores are ice-covered, then the differences between the temperatures at these two stations will be different from a situation where the shores at both stations are ice-free or ice-covered. Ideally, different ice classes would have been taken into account, but this has not been possible due to the lack of knowledge regarding local ice conditions in former times. Fortunately, it seems that the ice cover at Grønfjorden and the rest of Isfjorden do not develop very differently so that, in most cases, both fjords are either open or covered (Nilsen et al. 2008) with a possibility of slightly more open water in Grønfjorden as it lies near to the Atlantic Water off west Spitsbergen. As daily values were used in the regression equations it may be assumed that the lowest temperatures in winter and spring primarily represent ice-covered sea, whereas the highest temperatures mostly represent open sea.

With regard to the new automatic weather stations erected in the locations of the old expeditions, knowledge of sea ice is crucial; however, data are only available for two winters. It is fortunate therefore that these two winters were very different with regard to sea-ice conditions as the first one had a long period with sea ice, whereas in the second one sea ice was almost absent (see Supplementary file). It is also to be expected that the regression lines give a realistic adjustment for both ice-free and ice-covered conditions during the period 1898–1911.

Reanalysis data for the gridpoint (78°.0°N, 16°.0°E) lying in Reindalen, 30 km to the south of Svalbard Airport, has, on average, a bias that is much too warm, in particular during winter, where the difference is about 8°C in the months January through March. For the summer months, the gridpoint is about 2°C too cold in July and August. The gridded temperature is probably influenced by the open water off west Spitsbergen as it behaves more like an oceanic station than Svalbard Airport. As expected, the uncertainty of the interpolations are much larger than for the predictions based on local observations, up to 3°C for winter months, and about 1°C for summer (Table 3). For the assessment of the uncertainty of seasonal and annual means Eqn. 7 may be used. For the annual means, the uncertainty was estimated to be 0.6°C. Interpolations were used for the gaps during the Second World War, and for five years in the period 1898–1911. For most of the regressions, the data coverage is sparse, but not for all of them. It seems that the linear assumption is valid. The method of linear regression was therefore kept as a standard method for the entire reconstruction (see Fig. 3). It was not considered necessary to group the observations as is suggested, for example, by Della-Marta & Wanner (2006) in order to account for non-linearity.

The observations by hunting expeditions have been used very little in climatological analyses of the Svalbard climate until now. Clearly, this is due to the non-continuous character of the observations. After one season in a certain area the hunters tended to move to a new location as the wildlife became decimated. It might also be assumed that as soon as the first permanent observation station was established on Spitsbergen, meteorological interest concentrated on this. An exception is an article by Birkeland (1920), which uses the Green Harbour series as well as the shorter series. He admitted that the data were sparse: "the most one can say is that, in general, the temperature seems to decrease from south to north and from west to east" (Birkeland 1920: 288; our translation).

Table 6 Normals for the stations 99737 Svarttangen, 99790 Isfjord Radio, 99820 Barentsburg, 99821 Green Harbour, 99840 Svalbard Airport, 99860 Longyearbyen, 99928 Crozierpynten (the station identifiers are those used in the database of Met. Inst).

Station no.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Yr.
Normals 1981–2010													
99737	−12.5	−13.7	−12.6	−10.2	−3.2	−0.5	4.2	2.9	1.2	−3.3	−7.3	−11.7	−5.6
99790	−10.6	−10.9	−11.2	−8.8	−3.1	1.6	4.7	4.3	1.0	−3.6	−6.4	−9.2	−4.3
99820	−12.0	−12.7	−12.4	−9.7	−3.3	2.2	6.0	5.1	1.0	−4.7	−7.7	−10.5	−4.9
99821	−13.2	−13.8	−13.3	−9.6	−2.0	2.8	6.8	4.5	1.5	−4.3	−8.0	−12.4	−5.1
99840	−12.9	−13.5	−13.2	−10.1	−2.9	2.8	6.4	5.4	1.1	−4.9	−8.2	−11.3	−5.1
99860	−12.2	−12.3	−11.9	−8.8	−1.7	3.8	7.3	6.1	1.7	−4.9	−8.1	−11.0	−4.3
99928	−14.7	−14.1	−15.8	−12.6	−4.8	−2.7	5.2	3.0	−1.7	−5.6	−9.5	−14.5	−7.3
Standard normal 1901–1930													
99840	−15.2	−17.7	−17.5	−13.4	−5.4	2.2	5.3	4.7	−0.3	−6.4	−11.9	−12.8	−7.4
Standard normal 1931–1960													
99840	−12.4	−13.7	−15.0	−11.7	−4.0	2.3	5.9	4.9	0.7	−4.3	−7.6	−9.8	−5.4
Standard normal 1961–1990													
99840	−15.3	−16.3	−15.7	−12.3	−4.3	2.0	5.8	4.7	0.3	−5.4	−10.3	−13.3	−6.7

The new observations reveal a complicated picture. Of particular interest are the high winter temperatures at the mouth of Isfjorden, lower temperatures in the far north, and late temperature increase in the spring in the south-east (see Fig. 4). Generally, observations have been lacking on the eastern coast of Spitsbergen and on the eastern islands, but in the last two years this has been overcome. More comprehensive and detailed studies of east-west variations of the Svalbard climate are now available (Przybylak et al. in press) based on data from the new stations.

Long-term temperature trends and variability in the Arctic compared to Svalbard Airport

It is of great interest to see how trends inferred from the composite Svalbard Airport series differ from other Arctic temperature series. Przybylak (2007) analysed seasonal and annual trends from the warm epoch in the mid-1930s to 2005 for many long-term Arctic series, resulting in very little detection of significant ($p < 5\%$) positive trends. In the Norwegian Arctic the only significant trend detected was for mean spring temperatures at Bjørnøya. Seven years have now passed since that paper was written, so the two series at Bjørnøya and Jan Mayen were revisited and the recent period 2006–2012 was also added to the series. A consistent picture of the Norwegian Arctic then appeared with more significant trends detected than in the earlier paper (Przybylak 2007). However, the trends for winter and autumn still remain insignificant when the starting year is in the warm period of the 1930s.

When the data are compared with Arctic areas lying outside the Norwegian Arctic, it may be seen that, in the period 1936–2005, the trend at Svalbard Airport was larger than in Greenland and the western Euro-Asiatic part of the Arctic, but lower than in the rest of the Arctic (see Przybylak 2007; his table 2). In winter, Svalbard Airport exhibited one of the largest negative trends in the Arctic, whereas in spring and summer it showed one of the largest positive trends. In the shorter period, 1951–2005, trends of average annual temperature in Spitsbergen were slightly higher than in the rest of the Atlantic Arctic and western part of the Russian Arctic. The southern part of Greenland and the Baffin Bay region revealed significantly less warming and even cooling in some areas, while the Pacific side of the Arctic experienced markedly greater warming (Przybylak 2007; his figure 6). Temperature trends in winter and summer showed the same spatial patterns to those described for the annual values.

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Hanna et al. (2012) present an updated analysis of monthly-mean temperature from Greenland coastal weather stations and from a long-running site on the Greenland Ice Sheet. They demonstrate very strong recent warming along the west coast of Greenland, especially during winter (locally $>10°C$ since 1991), and rather weaker warming on the east Greenland coast, which is influenced by different oceanographic/sea-ice and meteorological synoptic conditions to the rest of Greenland. The greatest temperature changes in all seasons are seen on Greenland's west coast and on the ice sheet. Recent climate analyses were undertaken at the reindeer herding areas in northern Eurasia from northern Norway/Finland to the Bering Strait (Vikhamar-Schuler et al. 2010). The material was sparse as several stations were discarded from the long-term trend analysis, 1901–2008, due to many gaps in the series. The trends for annual means in this large area are all positive, but smaller than for Svalbard Airport, and only one was significant (Yakutsk).

The temperature increase on Svalbard Airport during the last 30–40 years shows the greatest increase among all areas in Europe, so the question can be posed: what is the reason for this? As demonstrated in this article, the temperature of Svalbard exhibits pronounced large-scale variations, which have been extensively discussed in the literature. Several causal factors have been suggested, in particular variations in sea-surface temperatures over periods longer than decades (Benestad et al. 2002; Polyakov et al. 2003; Johannessen et al. 2004). Debate also continues on the relative roles of local factors, such as sea-ice reduction, versus remote factors driving or amplifying Arctic warming (see, e.g., Screen et al. 2012). However, these authors conclude that local sea-ice concentration and sea-surface temperature changes explain a large portion of the observed warming. Direct radiative forcing due to changes in greenhouse gasses and total solar irradiance has mainly contributed to Arctic tropospheric warming in summer.

It has also been suggested that there has been a persistent change in early summer Arctic wind patterns during the last six years, 2007–2012, relative to previous decades (Overland & Serreze 2012). This pattern, which has previously been recognized as the Arctic Dipole, is characterized by relatively low sea-level pressure over the Siberian Arctic with high pressure over the Beaufort Sea, extending across northern North America and over Greenland. Coupled impacts of the new persistent pattern are increased sea-ice loss in summer, long-lived positive temperature anomalies and ice-sheet loss in west Greenland, and a possible increase in Arctic–Subarctic weather linkages through higher-amplitude upper-level flow (Overland & Serreze 2012). Thus, circulation changes may also have enhanced Arctic sea-ice melting in addition to warming due to increased greenhouse-gas concentrations.

Conclusions

The new composite temperature series from Svalbard for the period 1898–2012 was developed by nesting and adjusting local series. This proved to be a more accurate method than using a global, gridded network for extending the Svalbard series back to 1898. Adjustments of the local series turned out to be of crucial importance. Without the adjustments the composite series would have been strongly inhomogeneous. This is the first attempt to include the period September 1898 through August 1911 in the Svalbard composite series. With this inclusion it is still correct that the coldest decade in the series is the 1910s. The start of the series is cold, but not colder than the 1960s and 1980s. This has changed our understanding of the E20thCW for Svalbard. The temperature increase from the early starting year of 1899 is less compared to the former one of 1912.

As evidenced in the new series, variability is largest during winter, and less during summer. The series covers three standard, "normal" periods, with the 1931–60 period being warmer than 1961–90, and the 1901–30 period being the coldest one. The most recent normal period (1981–2010) is warmer than any of the three standard normal periods. In spite of the large variability significant positive trends over the whole period were detected for annual as well as seasonal means. For annual means the linear trend was 2.6°C per 100 years. The series reveals long-term variability with a minimum in the 1910s, a maximum in the 1930s, followed by another minimum in the 1960s. The 1950s were also mild, and during the last 40–50 years temperature has increased rapidly. The present regime of Spitsbergen temperatures, which covers the years 2005–2012, is the warmest one ever recorded.

The huge on-going research activity on Svalbard often requires information on long-term temperature variability and trends; for example, in the fields of palaeoclimatology, oceanography, glaciology and biology. It is expected that this new Svalbard Airport composite series for 1898 to present may fill the need for data in many research fields. The series is included in the online database of the Norwegian Meteorological Institute (http://eklima.met.no/), where data may be downloaded free of charge.

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