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Air temperature changes in Svalbard and the surrounding seas from 1865 to 1920

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ABSTRACT: In this article, air temperature variability in the Svalbard region (74–82°N, 6–30°E) from 1865 to 1920 is presented based on a large amount of early instrumental land and marine data. Measurements were taken during many exploratory and scientific expeditions to the study area. In addition, changes of air temperature from historical times to the present day (1981–2010) were investigated. Present-day air temperatures for land were taken from regular meteorological stations and from campaign measurements, while for marine environment data were taken from three reanalysis products: 20CR, ERA-20C and ERA-Interim.

Analysis reveals that Svalbard (land data) in the period 1865–1920 was markedly colder than today (1981–2010, by about 3 °C) in all seasons except summer, when air temperature was similar in both periods. However, the majority of mean monthly air temperatures in historical times still lie within two standard deviations (SDs) from the modern mean. Marine data show good correspondence with land data. The May–September average air temperature for the period 1871–1910 was slightly lower in the seas surrounding Svalbard (by 0.4 °C) than today. About 90% of these mean air temperatures lie within the range of ±3SDs from the ERA-Interim present-day mean.

Seasonal patterns of air temperature changes in the Svalbard archipelago between historical and standard normal (1961–1990) periods show generally very good correspondence to similar changes, not only for the Atlantic region, but also for some other Arctic regions (e.g. SE Greenland, Canadian Arctic, Barents and Kara seas), as well as for the entire Arctic. All available reconstructions of annual air temperature using isolated series of early instrumental observations reveal that in historical times, air temperatures were colder than the standard normal (1961–1990) by about 0.5–1.0 °C. Compared with the new normal period (1981–2010), those differences rise to about 1.5–2.5 °C.

KEY WORDS Svalbard; Arctic; air temperature; historical climatology; climate change

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1. Introduction

Svalbard is an archipelago located in a part of the Arctic that is the most sensitive and vulnerable to climate change. The opening of this region to the Atlantic Ocean facilitates strong and very frequent advection of warm and humid air masses within cyclone systems, originating mostly in the area of Iceland. In addition, oceanic currents (mainly Norwegian and West Spitsbergen Currents) transport large amounts of heat to the area, particularly to its western part (Walczowski and Piechura, 2007). As a result, the entire Svalbard archipelago is one of the warmest part of the Arctic. The thermal privilege of this region is in particular very well seen in winter, when the main factors controlling air temperature in the Arctic (especially the Norwegian part) are atmospheric and oceanic circulation (Przybylak, 2002). As a result, the Svalbard Archipelago is about 20 °C warmer than the north-eastern part of the Canadian Arctic lying at the same latitude (Przybylak, 2003). For centuries now, access to Svalbard has been relatively easy due to a mild climate and a lack of sea ice around the western part of the archipelago. As a result, this area has often been chosen as a destination for many expeditions, both exploratory and scientific (see, e.g. Nathorst, 1909; Dybwad, 1913; Brown, 1920; Hoel, 1929; Szupryczyński, 2007 and references herein). The above-mentioned conditions favouring navigation must have been one of the main reasons for the establishment of one of the first meteorological stations in the Arctic located outside Greenland on the western coast of Spitsbergen (in Green Harbour) in 1911. Thanks to that, the climate history for Svalbard for almost the entire 20th century is quite well known (for details, see, e.g. Steffensen, 1969; Steffensen, 1982; Hanssen-Bauer *et al.*, 1990; Førland *et al.*, 1997; Przybylak, 2002; Przybylak, 2003, 2007; Nordli, 2010). Recently, the Svalbard series has been extended to 1898 with the inclusion of observations made by hunting and scientific expeditions (Nordli *et al.*, 2014). However, markedly less is known about climate changes prior to this time. For the Holocene (including the last millennium), some information is available based on different proxy data (e.g. ice-cores, laminated

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lake sediments). For a short synthesis of this knowledge, see, e.g. Przybylak (2003, 2016).

Early instrumental meteorological observations available for this region were used in works describing climate changes in the whole Arctic (Luedecke, 2004; Przybylak, 2004; Wood and Overland, 2006; Przybylak *et al.*, 2010, 2013; Wyszyński and Przybylak, 2014), as well as certain parts of it (Przybylak and Dzierżawski, 2004; Przybylak and Panfil, 2005; Nordli *et al.*, 2014). Climate reconstructions based on different proxy data are also available (for a review see, e.g. Overpeck *et al.*, 1997; Kaufman *et al.*, 2009; Miller *et al.*, 2010 or Przybylak, 2016).

The main aim of the present paper is to extend the known history of instrumental-based air temperature (now mainly covering the most recent 100 years) in Svalbard and its surrounding seas even further back. Any earlier climatic data – in particular for the 19th century – are very important to the evaluation of a natural range of climatic variation and change in this part of the Arctic. Such information, for the period when human impact on the Arctic climate (including Svalbard) was negligible, is needed to more precisely estimate the contemporary man's influence on climate change in this area. Extensive searches conducted in libraries and archives around Europe have allowed us to collect quite a large quantity of new early meteorological data, measured during both exploratory and scientific expeditions. The thus-constructed air temperature data bank covers the period from 1865 to 1920. A large quantity of new and more detailed air temperature data were used to estimate the magnitude and importance of air temperature change between historical and present-day times (1981–2010).

2. Area, data and methods

2.1. Area

Svalbard is an archipelago lying in the Norwegian Arctic midway between mainland Norway and the North Pole, from 74° to 81°N latitude, and from 10° to 35°E longitude. Spitsbergen is the largest island of this archipelago, followed by Nordaustlandet and Edgeøya (Figure 1). Despite its high-latitude location, Svalbard's climate is mild, and as mentioned in the Introduction, this results from the positive influence of circulation, both atmospheric and oceanic, carrying warmth from moderate latitudes to the area. The western part of Svalbard has a milder climate than the eastern part, due to (1) easier access of warm air masses usually coming from the southern and south-western sectors and (2) the occurrence of the warm West Spitsbergen Current and the cold East Spitsbergen Current near the coasts of the western and eastern parts of the archipelago, respectively. Their influence on sea-ice production has opposite effects: the first one significantly reduces the area covered by sea-ice due to the transport of large amounts of warm Atlantic waters to the Arctic, whereas the second one creates good conditions (cold waters) for its existence. As a result, the entire western coast of Svalbard is free of sea-ice, even in winter, while its eastern coast features sea-ice far to the south (see Figure S1, Supporting Information). It is worth noting here that in recent years (since 2004), the West Spitsbergen Current saw substantial increases in temperature, salinity and heat transport to the Arctic (Walczowski and Piechura, 2007). For more details about the mechanisms driving Svalbard's climate, see Steffensen (1982), Hisdal (1985) or Hanssen-Bauer *et al.* (1990).

2.2. Land data and methods of their analysis

The locations of all historical sites for which air temperature data from the land were gathered are shown in Figure 1. As can be seen from Table S1 and Figure 1, land data were found for 13 sites; the majority of them were located in the southern part of Svalbard, particularly in the central part of Spitsbergen and on Edgeøya island. For some sites, more than one series was gathered in the period from 1865 to 1920. As a result, the number of series is greater than the number of sites and is equal to 26 (for more details see Table S1). Four sub-regions were distinguished in the area of Svalbard (N – Northern, C – Central, E – Eastern and S – Southern) (Figure 1). Table S1 also contains information about geographical location of sites, time period and resolution of observations as well as about sources of data.

The oldest series of meteorological observations found until now for the Svalbard area comes from Bjørnøya island. Observations began here on 6 August 1865 and ended on 19 June 1866 (Nordenskiöld, 1870). Air temperature measurements and observations of atmospheric phenomena were taken thrice a day at 0800, 1400 and 2000 local time (0700, 1300 and 1900 UTC). The next two oldest series come from Mossel Bay and Kapp Thordsen, and partly cover the years 1872–1873. Until 1890, only four series are available, while for the period 1891–1920 as many as 22 series have been collected (see Table S1 and Figure 2(a)). A significant increase in the number of meteorological observations in the Svalbard area (similar to that observed for the whole Arctic, see Przybylak *et al.*, 2010) is seen in a period after the end of the First International Polar Year 1882/1883. As mentioned earlier, the majority of the series for the Svalbard region were gathered during exploratory and scientific expeditions and therefore carry durations varying from less than 1, and up to 10 years, with series shorter than 1 year markedly dominant (76.9%), while only one series (Green Harbour) reaches 10 years (Figure 2(a)).

The series of historical mean monthly air temperature data from land were taken directly from the various publications mentioned, or were calculated by the authors using available data of a higher resolution (e.g. daily or sub-daily). It is interesting to note that in the early instrumental period, many meteorological measurements were made in the eastern and northern parts of the Svalbard archipelago. Generally, until the AWAKE project (2010), when automatic weather stations were installed there (for details, see Przybylak *et al.*, 2014), only old historical measurements were available for the area. This means

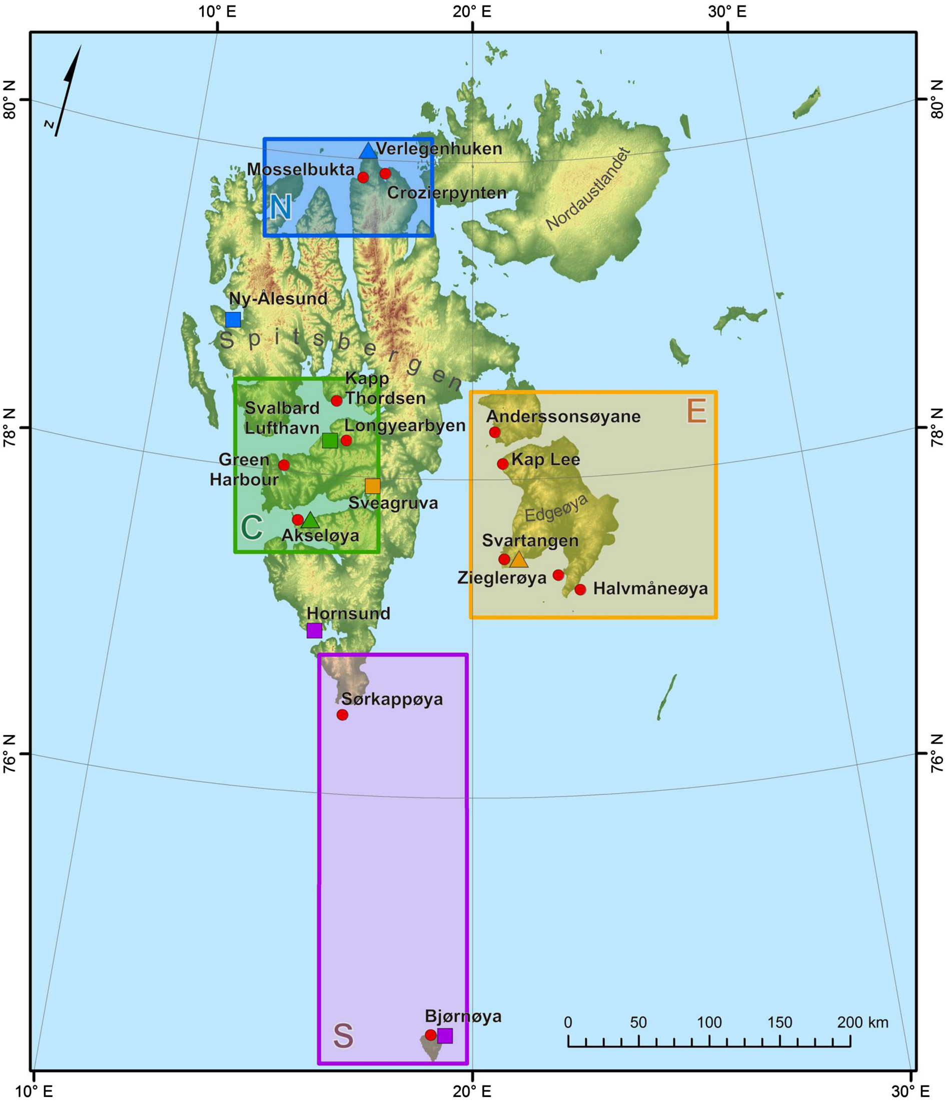

Figure 1. Location of historical (dots) and modern (squares) land meteorological stations and campaign measurement sites in 2010–2011 (Przybylak *et al.*, 2014, triangles) on Svalbard. Shaded areas indicate split sub-regions; N, Northern; C, Central; E, Eastern; S, Southern.

that we still do not have climatological series for eastern and northern parts of the Svalbard archipelago. Therefore, for comparison purposes with the present climate (1981–2010), we had to use air temperature data from Svalbard stations located solely on the western coast of Spitsbergen (Ny-Ålesund, Svalbard Lufthavn, Sveagruva, Hornsund and Bjørnøya) (Figure 1). Mean daily values of air temperature, used for calculation of monthly statistics, were downloaded from the Norwegian Meteorological Institute (http://eklima.met.no), besides data from Hornsund which were provided by the Institute of Geophysics of the Polish Academy of Sciences. The latter data were recently quality controlled as part of a Polish-Norwegian partnership under the AWAKE-2 project (*Arctic climate system study of ocean, sea ice and glaciers' interactions in Svalbard area*).

To reduce the differences resulting from different geographical locations of historical and modern observation sites, the corrections were made based on the analysis of the spatial distribution of air temperature between the historical site and the nearby modern station. For this purpose, the results of campaign air temperature measurements in Svalbard in 2010–2011 from the AWAKE project were used (for details, see Przybylak *et al.*, 2014). Differences in air temperature (T_d) between historical and contemporary (1981–2010) periods were calculated using the following formula:

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

where T_h is the monthly mean air temperature from a historical site, T_m is the long-term monthly mean air temperature from the nearest modern station and c is the spatial correction for different locations of historical and modern measurements sites calculated based on spatial diversity of air temperature on Svalbard presented by Przybylak *et al.* (2014).

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

$$c = T_{h1} - T_{m1}$$

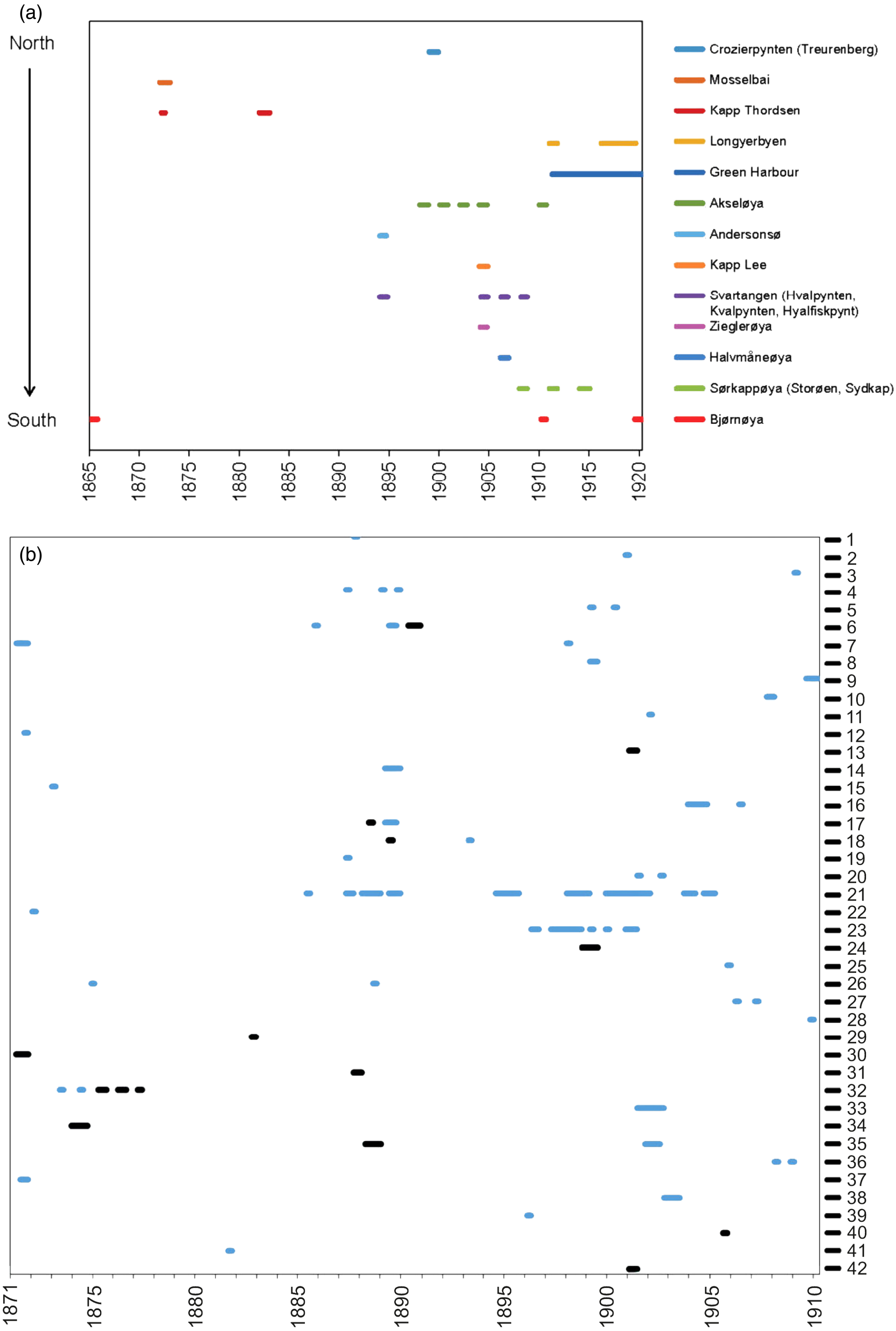

Figure 2. Temporal distribution of the air temperature observations from meteorological land stations (a), and ships (b), used in the study of the Svalbard archipelago and its surrounding seas from 1865 to 1920. Key to the lower panel: The black lines indicate data taken from the Arctic Norwegian Logbook Data: 1867–1912 at CISL RDA (http://rda.ucar.edu/, dataset 539.1), and the blue lines indicate data from the Nicolaus Copernicus University database. Numbers describe names of ships: 1 – Amanda, 2 – Anna, 3 – Bela, 4 – Calibri, 5 – Capella, 6 – Diana, 7 – Elida, 8 – Elina, 9 – Farm, 10 – Foenix, 11 – Fora den Blinde, 12 – Freja, 13 – Gjøa, 14 – Gottfried, 15 – Greenland, 16 – Gurim, 17 – Harald Haarfagre, 18 – Hekla, 19 – Hoidfisken, 20 – Hvalfiskpynt, 21 – Hvidfisken, 22 – Isbjørnen, 23 – Jasai, 24 – Johan Hagerup, 25 – Laura, 26 – Magdalena, 27 – Maria, 28 – Minerva, 29 – No name 1, 30 – No name 2, 31 – No name 8, 32 – Nordland, 33 – Ost Spitsbergen, 34 – Polarstjernen, 35 – Rivalen, 36 – Roald, 37 – Samson, 38 – Tromsø, 39 – Vega, 40 – Victoria, 41 – Viking, 42 – Yjra. Note that for Fig. 2B. data only for May–September in the period 1871–1910 are shown.

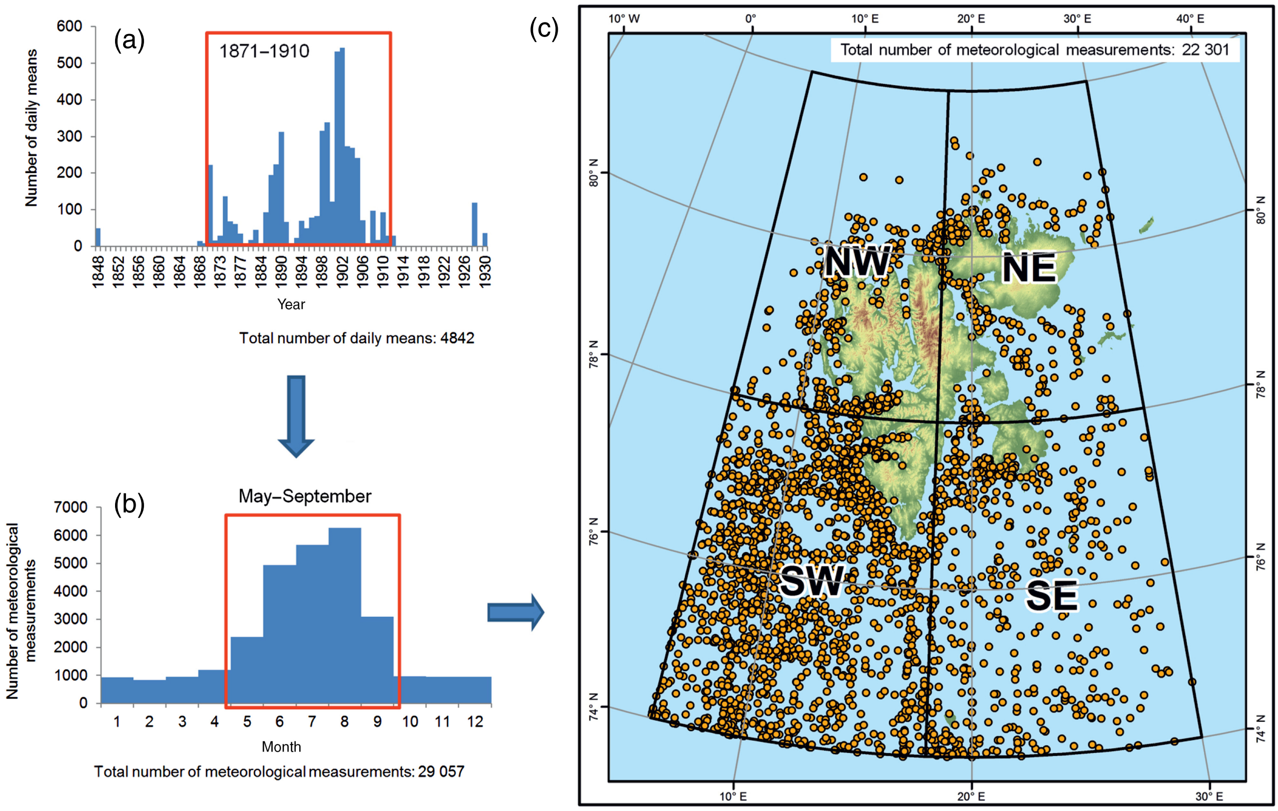

Figure 3. (a) Statistics of the collected data for all logbooks in the analysed area; the square marks the selected time frame. (b) Statistics of the collected data for the years 1871–1910 in the analysed area (monthly resolution); the square marks the selected time frame. (c) Mean daily positions (dots) of Norwegian ships in the waters surrounding Svalbard in the analysed period (1871–1910, May–September). The research area lies between 74–82°N and 6–30°E and was divided into grid boxes (black lines) with a resolution of 4° latitude and 12° longitude (SW, SE, NE and NW).

where T_{h1} is the monthly mean air temperature in the location of historical site in the period of 2010–2011 and T_{m1} is the monthly mean air temperature in modern station in the period of 2010–2011. The modern values of air temperature obtained in this way for historical sites were compared with those from the period 1865–1920.

2.3. Marine data and methods of their analysis

Maritime air temperature data for the seas surrounding Svalbard (74–82°N, 6–30°E) come from observations made on ships, and are taken from their logbooks. Their location is shown in Figure 3. Analysis was conducted of four grid boxes (regions), named North-Western (NW), North-Eastern (NE), South-Western (SW) and South-Eastern (SE) (see Figure 3). The majority of the data were taken from a Norwegian collection entitled *Arctic Norwegian Logbook Data: 1867–1912* available at the Computational Information Systems Laboratory Research Data Archive (CISL RDA, http://rda.ucar.edu/, dataset 539.1). Up until now, this collection of data had not been blended into the release 2.5 of the International Comprehensive Ocean–Atmosphere Data Set (ICOADS, R 2.5), because translation into the International Marine Meteorological Archive (IMMA) format and quality control procedure had still not been done (Wilkinson *et al.*, 2011; Woodruff *et al.*, 2014). Air temperature data from logbooks were originally digitized in Russia (St. Petersburg) by Ecoshelf (2003). We subsequently found that about 40% of the data had been wrongly keyed. The logbooks' authors used abbreviations which were not always correctly read by the Ecoshelf team. For example, simplified notations for positive or negative values of air temperatures were common in logbooks. When all air temperatures on a page were below zero, the minus sign was placed only at the top of the table. Another method used by the logbooks' authors to inform readers that air

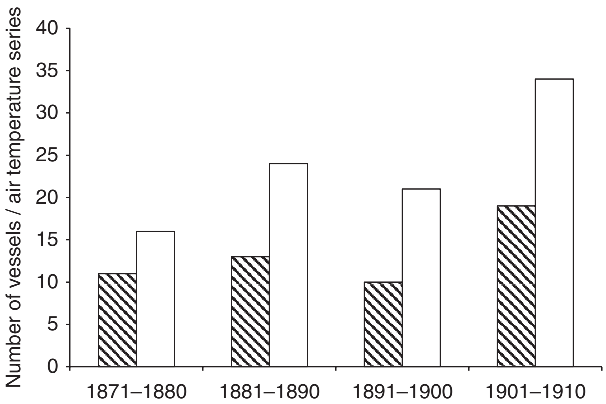

Figure 4. Number of vessels (dashed bars) and marine air temperature series (white bars) in 10-year periods in the Svalbard area from 1871 to 1910.

Table 1. Adjustment factor, a_r (°C day^{-1}), for each Svalbard sub-region given for months from May to September.

Month	SW	SE	NW	NE
May	0.088	0.120	0.138	0.248
June	0.095	0.092	0.091	0.119
July	0.058	0.056	0.040	0.023
August	−0.052	−0.035	−0.056	−0.040
September	−0.110	−0.096	−0.132	−0.116

temperatures are positive or negative was the addition of a plus or minus symbol only when the air temperature crossed 0 °C. When these signs were un-noted in the process of digitization, the wrong values were applied. Another source of errors discovered by us was an incorrectly recognized air temperature scale. This happened because in some of the logbooks, there was no information given about the thermometers used. Less significant errors were the incorrect reading of the name of the ship, and typos in geographical positions. The data were corrected by us and made available in the Supporting Information (SOM, see Appendices S1 and S2).

Besides data downloaded from the CISL RDA, we also used air temperature data digitized from logbooks not available from this source, gathered in recent years by the first author within the two projects Arctic Climate Early Instrumental Period (ACEIP) and Arctic Climate and Environment of the Nordic Seas and the Svalbard–Greenland Area (AWAKE) (for details, see Table S2 and Figure 2(b)).

Marine air temperature data are limited mainly to the warm half-year (Table S2 and Figure 3) with the maximum density seen in the summer months (5000–6000 observations). Many (2000–3000) are also available for May and September. Data exist outside this period for all months, but their frequency is very low and not enough for scientific elaboration. Therefore, in this study reconstruction of air temperature is shown and analysed only for the period May–September. Time coverage for which relatively enough marine data exists to reliably reconstruct air temperature (compared to land data), is shortened to 1871–1910 due to the almost total lack of data for periods before 1871 and after 1910 (see Table S2 and Figure 3). The greatest density of gathered data exists for the last decade (34 series), and the lowest for the first decade (16 series) of the study period (Figure 4). See Table S2 for more details about sources and resolution of marine air temperature data (including names of vessels, names of Captains, period, etc.).

Preparation of monthly air temperature statistics based on measurements taken from moving objects, i.e. ships, was more complicated than those made for land data. Based on collected sub-daily measurements (hourly, 2-hourly, etc.), daily means were calculated and attributed to locations lying in the middle of the route taken by the vessels on the day. For the study period 1871–1910, we did not gather enough daily data for the particular months and grid boxes in order to be able to reliably calculate mean monthly air temperature. Having a limited number of daily means for each month, the following procedure was utilized to calculate (reconstruct) monthly statistics. In the first step, correction for the yearly cycle was introduced. In May and June, air temperatures generally increase in the Arctic. Therefore, those observed in the first part of the months tend to be biased too low, while those occurring at the end of the months tend to be biased too high compared to the monthly means. In July and August, the monthly trends in air temperature are low, but in September the air temperatures tend to decrease from the first to the last day in the month. Air temperatures for all months have therefore been adjusted. The trend of daily mean air temperatures within each month was calculated using mean data from 1981 to 2010, taken from the ERA-Interim reanalysis dataset, which is the latest global atmospheric product produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) (for details, see Dee *et al.*, 2011). These reanalysis data were chosen because long-term (1981–2010) monthly air temperatures calculated for the analysed months were closer to observations than analogical statistics (see Figure S2) derived for the other two reanalyses, ERA-20C by ECMWF and the 20th Century Reanalysis (20CR; Compo *et al.*, 2011). To properly characterize air temperature in the four distinguished regions surrounding the Svalbard archipelago (SW, SE, NW and NE), data from the ERA-Interim reanalysis were taken for the grids, from more or less their centres: 76°N × 12°E, 76°N × 24°E, 79°N × 10°E and 79°N × 24°E, respectively. Every daily mean air temperature (T) available for a given month was adjusted to the time of the middle of that month (T_{adj}) according to the formula:

$$T_{adj} = T + a_r \left(D_m - D\right)$$

where T_{adj} is the adjusted air temperature for the D day, T is the mean air temperature of the particular day of the month, a_r is the trend of daily mean air temperature, D is the date of mean daily air temperature available in the particular month and D_m is the mid date in the month being 16 for May, July and August (which have 31 days) and 15.5 for June and September (which have 30 days).

The trend of mean daily air temperatures within each month (a_r) calculated according to the above formula varied in the analysed months and grid boxes from −0.132 to 0.248 °C day^{-1} (Table 1). As a result, the maximum introduced adjustment was equal to ±2.1 and ±1.9 °C for the first and last day in a month (for May and September, respectively), but only ±0.9 and ±0.8 °C for July and August, respectively.

At the next step, all values of T_{adj} available for a given month and given grid box were used to calculate mean monthly air temperature. Figure S3 shows the numbers reconstructed in this way for mean monthly air temperatures for the seas surrounding Svalbard for the entire 1871–1910 period and for two 20-year sub-periods. For purposes of comparison with the marine historical data (including change of climate until the present-day), data taken from the following reanalyses were used: 20CR, ERA-20C and ERA-Interim.

Table 2. Monthly and seasonal means of air temperature in Svalbard in the period 1865–1920 and their differences between the historical and contemporary period (1981–2010).

Region	S	O	N	D	J	F	M	A	M	J	J	A	SON	DJF	MAM	JJA	SEP–AUG
Air temperature means (°C)																	
Northern 1872–1900	−0.5	−11.6	−11.1	−13.2	−9.2	−22.7	−22.3	−17.4	−9.0	0.0	2.9	2.5	−7.7	−15.0	−16.2	1.8	−9.3
Central 1872–1920	0.1	−6.0	−11.4	−15.0	−15.4	−19.5	−17.4	−13.6	−4.8	2.3	5.5	4.2	−5.8	−16.6	−12.0	4.0	−7.6
Eastern 1894–1909	−1.7	−8.9	−13.2	−20.5	−18.6	−21.0	−18.3	−12.0	−4.9	1.3	3.0	0.8	−7.9	−20.1	−11.7	1.7	−9.5
Southern 1865–1920	0.6	−2.1	−7.3	−8.4	−11.4	−13.7	−10.7	−9.2	−2.1	1.9	4.8	2.8	−2.9	−11.2	−7.3	3.1	−4.6
Svalbard 1865–1920	−0.4	−7.2	−10.7	−14.3	−13.7	−19.2	−17.2	−13.1	−5.2	1.4	4.0	2.6	−6.1	−15.7	−11.8	2.6	−7.7
Differences of air temperature (°C)																	
Northern 1872–1900	0.5	−5.9	−1.3	1.6	6.1	−7.4	−6.0	−4.5	−3.9	0.6	0.0	−0.3	−2.3	0.1	−4.8	0.1	−1.7
Central 1872–1920	−0.1	−1.1	−4.2	−4.3	−2.9	−6.8	−4.6	−4.0	−1.5	0.7	0.9	0.1	−1.8	−4.7	−3.4	0.6	−2.3
Eastern 1894–1909	−3.0	−6.0	−5.7	−8.4	−4.3	−6.0	−5.9	−0.5	−0.7	1.2	−0.6	−2.4	−4.9	−6.2	−2.3	−0.6	−3.5
Southern 1865–1920	−1.6	−1.6	−4.0	−1.8	−3.5	−4.4	−3.8	−3.8	−0.9	0.3	1.1	−1.7	−2.4	−3.2	−2.8	−0.1	−2.1
Svalbard 1865–1920	−1.1	−3.7	−3.8	−3.2	−1.2	−6.1	−5.1	−3.2	−1.7	0.7	0.3	−1.1	−2.9	−3.5	−3.3	0.0	−2.4

Calculations are based on land stations. **Italics indicate negative values. Stations from the Northern, Central, Eastern and Southern regions were compared with the following modern stations: Ny-Ålesund, Svalbard Lufthavn, Sveagruva and Hornsund or Bjørnøya, respectively (see Figure 1).

In both described air temperature datasets, some sources of errors and biases probably still exist. For example, such errors and biases may result from the use of different types of instruments and recording procedures (which determined the methods for calculating daily means and monthly means), and differences in thermometers' exposure. The problem is that it is impossible to estimate some of these errors because of a lack of information. Przybylak and Vízi (2004) estimated, however, that biases connected with different methods of calculating monthly means in historical and present times are small and generally do not exceed 0.2 °C.

3. Results and discussion

3.1. Land data

Monthly, seasonal and yearly characteristics of air temperature over the Svalbard archipelago in 1865–1920 and its change from then until the present-day climate of 1981–2010 are presented in Table 2 and Figures 5 and 6. Annual cycles of air temperature based on one or several years of observations conducted during expeditions to Svalbard, distributed into the four distinguished regions, are shown in Figure 5. For comparison purposes, present-day annual cycles are also drawn, based either on data taken from regular stations or measurement sites working within the AWAKE project (see Przybylak *et al.*, 2014), both of which were located near historical sites. In all regions in the study period, areally averaged air temperature was coldest in February and warmest in July (Table 2). The most severe winters occurred in the Eastern region and the most mild in the Southern region. Relatively warm winters in the Northern region were connected with very warm air temperatures in January in both available years, i.e. 1872/1873 and 1899/1900. In the rest of the seasons, Northern and Eastern regions were coldest, while the Southern region was the warmest (except summer), and this is in line with the present-day distribution of air temperature in Svalbard (see Przybylak *et al.*, 2014). From Table 2, as well as from investigations conducted by Przybylak (1997) and Przybylak *et al.* (2014), it is evident that air temperature in the Central region is a good representation of average thermal conditions for the entire Svalbard, for all seasons (except summer) and for the year. The air temperature variability of the monthly means is, as today, markedly greater in winter than in summer (Figure 5). Usually, this is explained by significantly greater synoptic activity and by larger thermal contrast between the Equator and the Pole in winter than in summer (for more details, see Przybylak, 2002 or Serreze and Barry, 2014).

Changes of air temperature from historical times to present-day conditions are investigated using data from individual sites (Figures 5 and 6) and areally averaged data for four regions (Table 2, lower part). In Figure 5, historical air temperature is compared with short-term series of contemporary observations (2010–2011 or/and 2001–2010), while in Table 2 and Figure 6 the long-term reference period (1981–2010) was used for this purpose. Analysis of this documentation evidently reveals that Svalbard from 1865–1920 was markedly colder than it is today (by about 3 °C) in all seasons, except summer when the air temperature was similar in both periods (Table 2). Mean annual

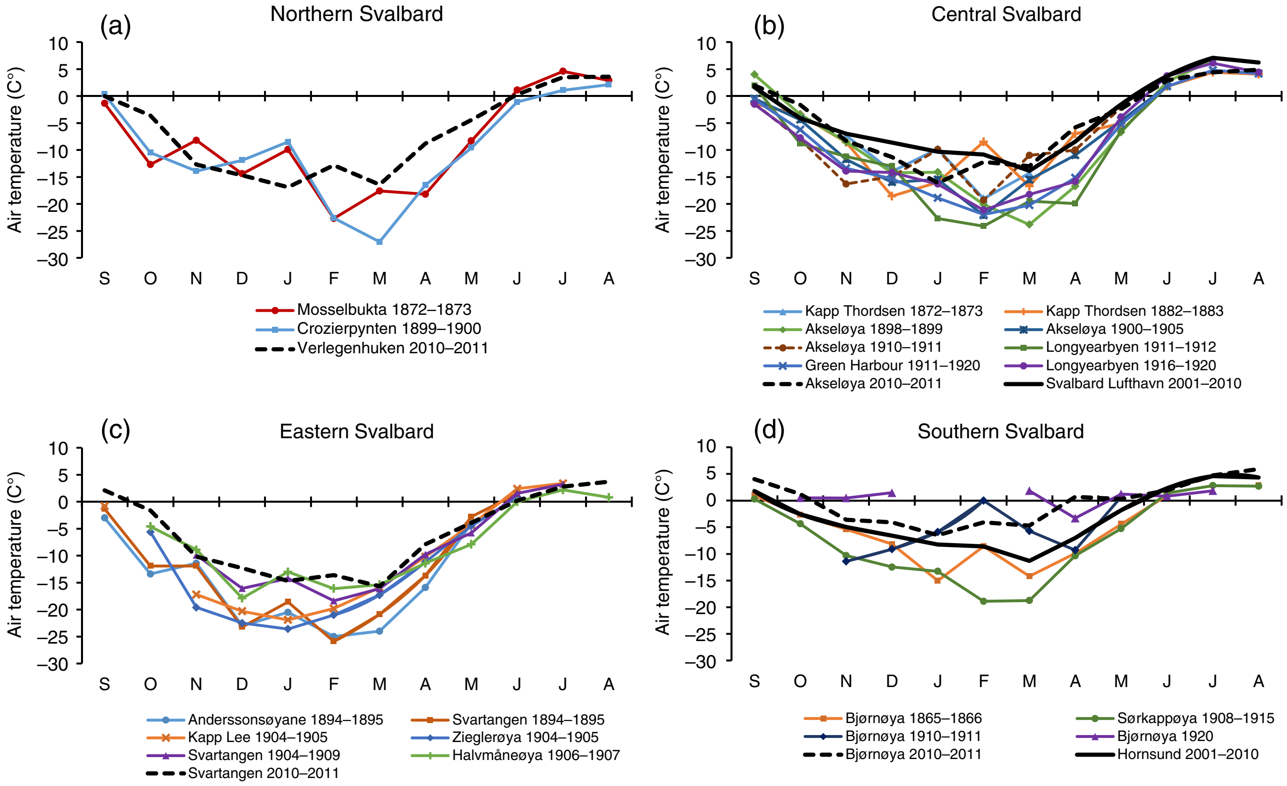

Figure 5. Annual courses of air temperature (°C): in historical times 1865–1920 (thin solid lines); average 10-year means 2001–2010 (thick solid line), and 1-year 2010–2011 mean (dashed line) in sub-regions of Svalbard. Note that for the historical stations Akseløya 1900–1905, Svartangen 1904–1909 and Sørkappøya 1908–1915, the annual courses were averaged based on a few 1-year long overwinterings; for more details, see Figure 3(a) or Table S1.

air temperature was 2.4 °C lower than today. Out of all regions, the greatest changes were noted in the Eastern region (annual values lower in historical times by 3.5 °C and in winter even by as much as 6.2 °C). Also, only in this region was summer colder (by 0.6 °C) than today. This regional differentiation of air temperature changes can probably be explained by the greatest historical-to-present decrease of sea ice area in the eastern marine part of the Svalbard archipelago [for details, see Figure S1, where the historical and mean-present (1981–2010) extent of sea ice are shown], compared to the in western marine part of the archipelago. The role of atmospheric circulation in this process was negligible, as atmospheric pressure changes from the 19th century to the present times, both in Svalbard and probably also in most parts of the Arctic and sub-Arctic, were insignificant (see Bärring *et al.*, 1999; Hanna *et al.*, 2004; Slonosky and Graham, 2005; Przybylak *et al.*, 2013). Other analysed regions showed that the study period was about 2 °C colder than present-day air temperatures. Only in the Northern region did mean winter air temperature not change from historical to present times (Table 2, and Figures 5 and 6), which is a result of the very limited amount of data – only two years – which in addition were characterized by very warm Januaries (anomalies above mean air temperature from 1981–2010 exceed more than 7 °C/5 °C in 1900 and 1873, respectively). In conclusion, it can be said that the majority of mean monthly air temperatures in historical times lie within two standard deviations (SDs) from the modern mean (1981–2010) (see Figure 6).

For comparison purposes in the present paper, we used a new normal period (1981–2010), in which air temperature in the entire Arctic was significantly higher than in the standard normal period (1961–1990). In central Svalbard, air temperature increased by 2.4 (in winter), 2.1 (in spring), 0.7 (in summer), 1.1 (in autumn) and 1.6 °C (on average in the year) from the standard normal period to the 1981–2010 normal period, as we also call the present-day climate. Air temperature changes for this part of Svalbard were calculated by the authors of this paper based on the homogenised Svalbard Lufthavn series presented in Table 6 in the study by Nordli *et al.* (2014). In order to ease comparison of results presented in this paper with those from literature for other Arctic regions (where air temperature anomalies were calculated in reference to means for the period 1961–1990), anomalies in the Central region (Table 2) were adjusted so as to be valid for the reference period 1961–1990. The following anomalies were obtained between 1865–1920 and 1961–1990: −0.7 °C for autumn, −2.3 °C for winter, −1.3 °C for spring, −0.1 °C for summer and −0.7 °C for the entire year.

Seasonal patterns of air temperature changes in the Svalbard archipelago between the historical and standard normal (1961–1990) periods show good agreements with similar changes calculated for the Atlantic region, as well as for the entire Arctic (see Table 3 and Figure 6

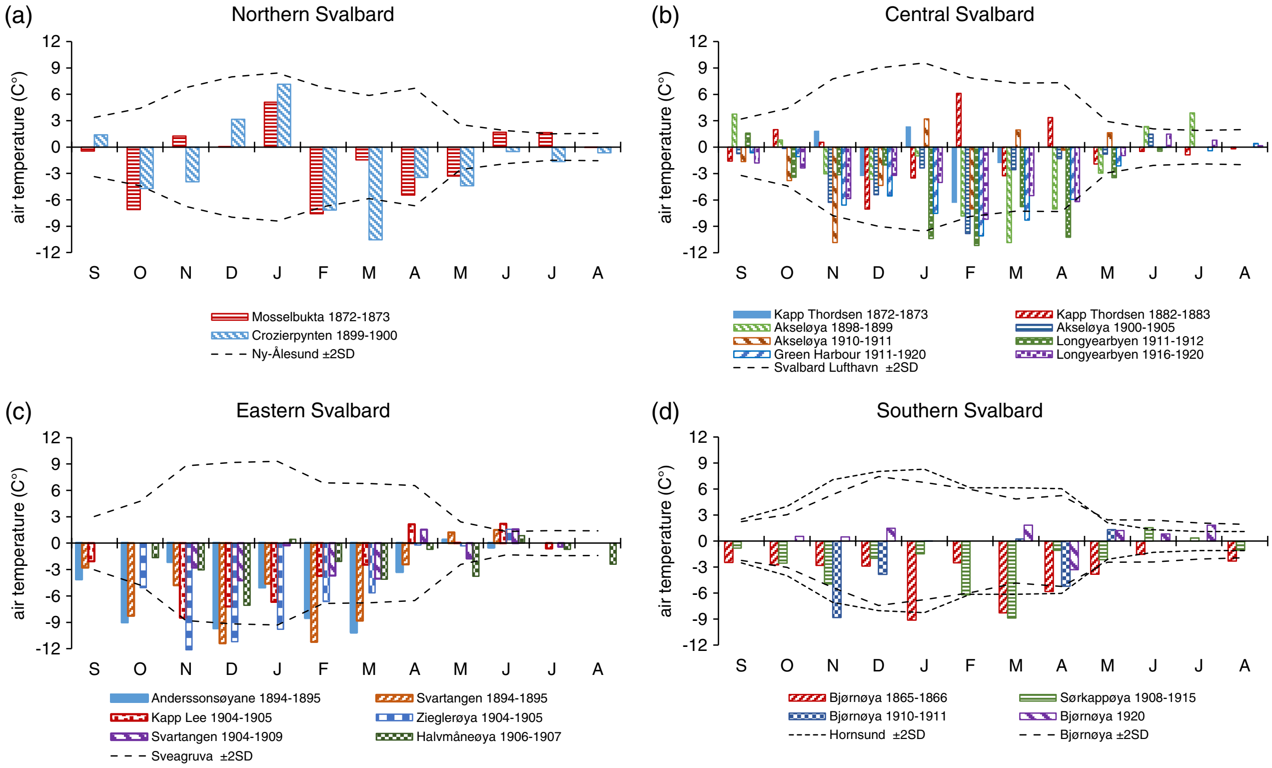

Figure 6. Air temperature differences (°C) between monthly values from the historical and present (1981–2010) periods for selected sub-regions in Svalbard. Standard deviations (±2 SD, shaded lines) have been calculated on the basis of the present period. Bars with anomalies for particular stations are placed chronologically in each month. Note that for the historical stations Akseløya 1900–1905, Svartangen 1904–1909 and Sørkappøya 1908–1915, monthly differences were averaged based on a few 1-year long overwintering expeditions; for more details, see Figure 3(a) or Table S1.

in the study by Przybylak *et al.*, 2010), although the anomalies in spring (−0.6 and −0.2 °C, respectively) were less than for autumn (−1.3 and −0.7 °C), and in particular for winter (−1.9 and −1.7 °C). Almost the same changes between historical and 1961–1990 air temperature occurred in summer. Central Svalbard and the entire Atlantic region were colder in the study period than in the standard normal period by only 0.1 °C, and in the entire Arctic by 0.3 °C. Colder winters and small change in the summers between 19th century and 1961–1990 were also found for south-western Greenland (Vinther *et al.*, 2006) and the Canadian Arctic (Przybylak and Vízi, 2005) (see also Table 3). For example, anomalies for the period 1861–1920 (reference period 1961–1990) calculated by the authors of this study using decadal merged Greenland air temperature taken from Table 8 published by Vinther *et al.* (2006), were equal to −2.2 and −0.1 °C, respectively. Thus, these anomalies are almost identical to those calculated for the Central region in Svalbard. Additionally, in autumn exactly the same anomaly was calculated for both regions (−0.7 °C). Only in spring was less cooling in historical times observed in SW Greenland than in central Svalbard (anomalies −0.5 and −1.3 °C, respectively). When we look to the west to the Canadian Arctic, discrepancies between spring air temperatures in comparison with Svalbard's are still greater than between Svalbard and Greenland. In the Canadian Arctic, spring was very warm (anomaly 2.3 °C, Table 3) in historical times (in particular in April when

Table 3. Air temperature differences in various regions of the Arctic between the historical and standard normal period (1961–1990).

Region	SON	DJF	MAM	JJA	Annual
Central Svalbard 1865–1920 (this study)	*−0.7*	*−2.3*	*−1.3*	*−0.1*	*−0.7*
SW Greenland 1861–1920 (Vinther *et al.*, 2006)	*−0.7*	*−2.2*	*−0.5*	*−0.1*	*−1.0*
Resolute region 1848–1859 (Przybylak and Vízi, 2005)	*−0.1*	*−2.7*	2.3	0.7	0.1
Atlantic Arctic 1861–1920 (Przybylak *et al.*, 2010)	*−1.3*	*−1.9*	*−0.6*	*−0.1*	*−0.7*
Whole Arctic 1861–1920 (Przybylak *et al.*, 2010)	*−0.7*	*−1.7*	*−0.2*	*−0.3*	*−0.7*

Italics indicate negative values.

positive anomalies relative to the 1961–1990 mean reach almost 4 °C – see Table 2 or Figure 2(c) in the study by Przybylak and Vízi, 2005), while in the Central region of Svalbard this anomaly was negative (−1.3 °C). This discrepancy might, however, partly be a result of the different periods used for comparison purposes (1848–1859 for the Canadian Arctic and 1865–1920 for Svalbard). However, autumn was slightly colder in the Canadian Arctic than today (anomaly −0.1 °C), i.e. to a lesser degree than was observed in Svalbard, SE Greenland and in the entire Arctic (−0.7 °C), and in particular in the Atlantic region (−1.3 °C).

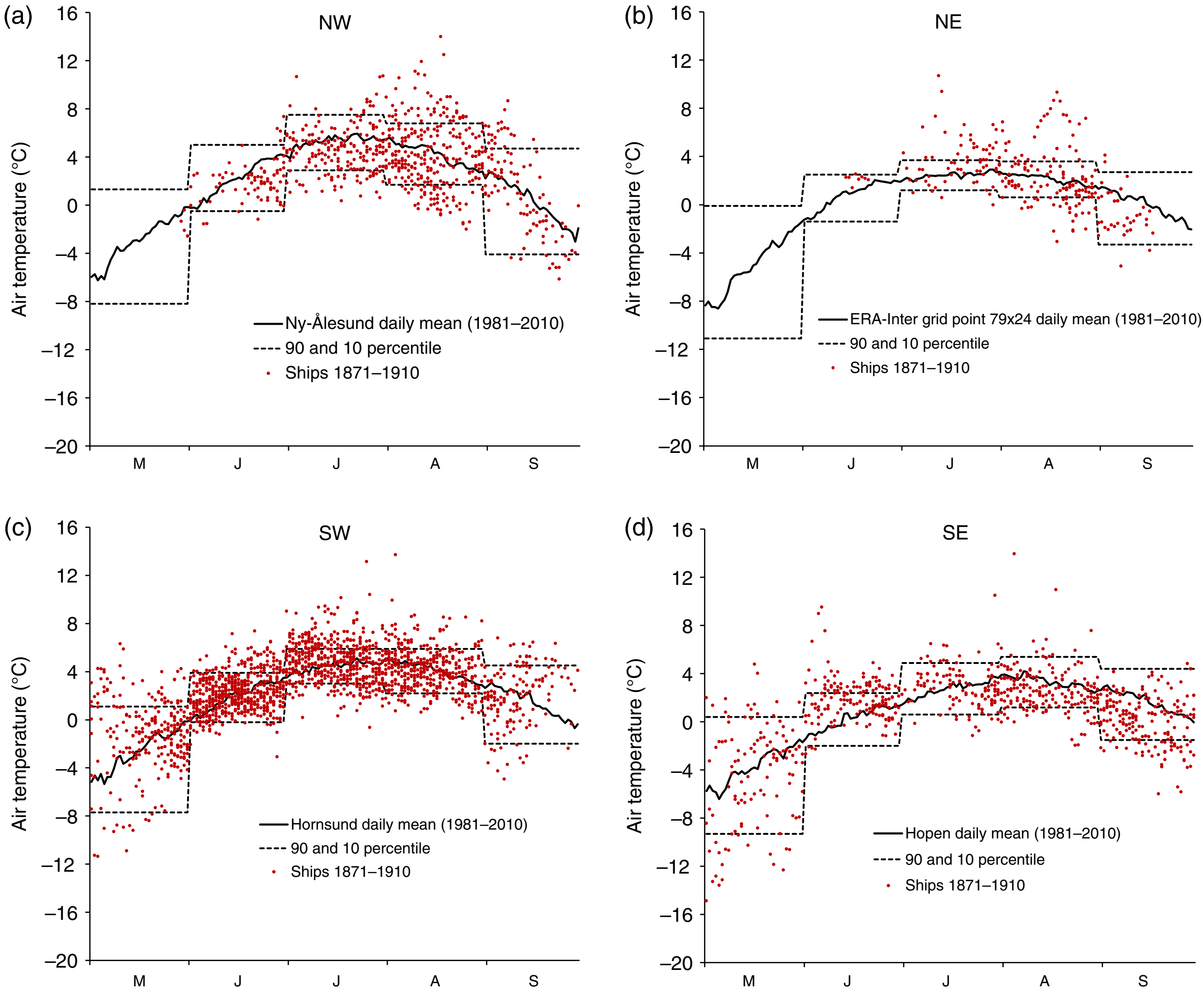

Figure 7. Courses of air temperature (°C) based on daily means from ships (dots) in the historical period (1871–1910) and daily means (1981–2010) for land stations (solid lines) for the sub-regions at Svalbard during each month from May to September. Thresholds of 90 and 10 percentiles (dotted lines) were calculated on the basis of daily means from the present period. Note that for the NE region, the 79°N and 24°E grid point of the ERA-Interim reanalysis dataset was used, due to the lack of a meteorological station in this area.

There also exist other references to reported air temperature changes in the 19th century, mainly for the southern marine parts of the Arctic and sub-Arctic (e.g. Brohan *et al.*, 2010; Klimenko, 2010; Wood *et al.*, 2010). All these sources concluded that air temperature in historical times was generally colder than today (1961–1990). For example, annual air temperature in the Atlantic–Arctic boundary was lower in the 19th century than today by about 0.5–1.0 °C (see Figure 1 in the study by Wood *et al.*, 2010). Slightly greater changes oscillated between 0.7 and 1.0 °C were calculated (1) by Przybylak *et al.* (2010) for the entire Arctic (0.7 °C) and the Atlantic region (1.0 °C), (2) by Vinther *et al.* (2006) for SW Greenland (1.0 °C) and (3) by the authors of this study for the Central region of Svalbard (0.7 °C). Reconstruction of annual air temperature presented for the Barents and the Kara seas' basins reveal large variability in the 19th century of almost 1.5 °C (Klimenko, 2010). According to this source, air temperature in this period was lower than today (reference period 1951–1980) almost all the time (except about 1850–1870), but by no more than 0.5 °C.

In addition, long-term air temperature reconstructions for the Arctic, constructed based on high-resolution proxy climate records (mostly tree-rings, ice-core and lake sediments), have recently been published (e.g. Overpeck *et al.*, 1997; Guilizzoni *et al.*, 2006; Kaufman *et al.*, 2009). Comparison with early instrumental data is, however, limited only to the summer season, or at best to the warm half-year. This is due to the fact that climatic proxy data are sensitive only to the air temperature of this part of the year. Between the 19th century and the present (1961–1990), reconstruction of mean summer Arctic air temperatures made by Kaufman *et al.* (2009) shows a rise equal to about 0.5 °C (see their Figure 3).

What are the factors that caused such a change in the Svalbard archipelago from the 19th century to the present time? It is commonly accepted that the Arctic climate (including Svalbard) until about mid-1970s was mainly

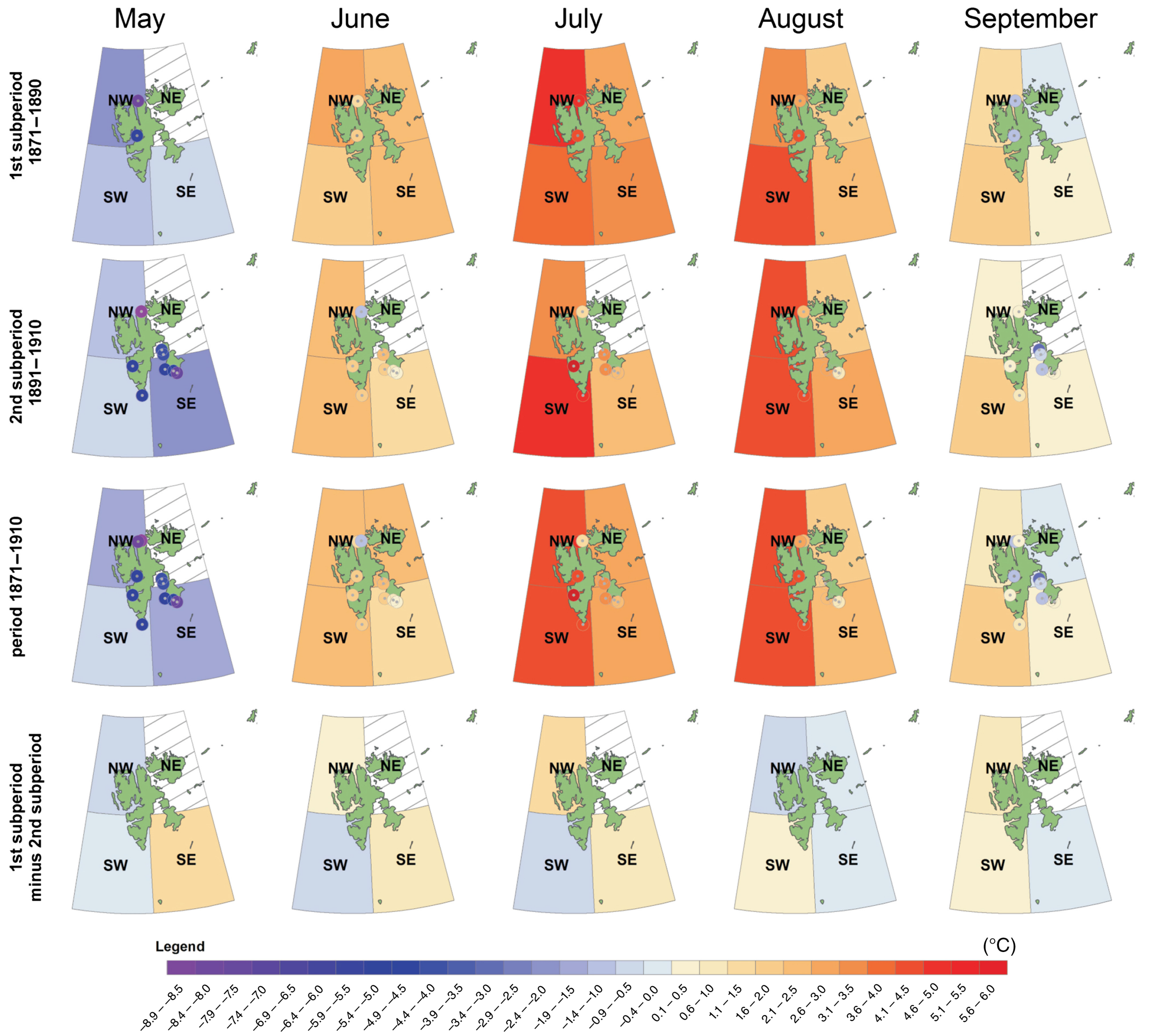

Figure 8. Mean monthly air temperature (°C) based on land stations (dots) and marine expeditions (grid boxes) in Svalbard and its surrounding seas, from May to September in the entire analysed period of 1871–1910, and its sub-periods 1871–1890 and 1891–1910, as well as the differences between them. White patterned grid boxes indicate areas with a lack of data.

driven by natural factors, such as solar irradiance, volcanic activity and the internal variability of the Arctic Climate System (Overpeck *et al.*, 1997; Moritz *et al.*, 2002; Polyakov *et al.*, 2003; Bengtsson *et al.*, 2004; Johannessen *et al.*, 2004; Overland and Wang, 2005; Turner *et al.*, 2006; Przybylak, 2007). Since about 1975 (the contemporary warming phase), the majority of scientists have assumed that anthropogenic factors (greenhouse effect and sulphate aerosols) were the main drivers of climate change. Przybylak (2007) has given a comprehensive review of existing views on the mechanisms of climate change in the Arctic in recent decades, and therefore there is no need to repeat them here. Nevertheless, in Svalbard's case, it appears that both atmospheric and oceanic circulation, as well as sea-ice changes around the archipelago, whether naturally or anthropogenically driven, were the main direct causes of observed warming in the area from the 19th century to the present.

From the short review presented above, it can be concluded that changes in land air temperature in the Svalbard archipelago between historical (1865–1920) and present-day (1961–1990) periods shows very good correspondence with results of similar reconstructions presented earlier for other Arctic regions, as well as the entire Arctic. Every new reconstruction of a regional character, similar to that presented here, which shows reliable results supports, corrects and improves the reliability of our knowledge of the history of Arctic climate in recent decades and centuries.

3.2. Marine data

A total of 4842 values of daily mean air temperatures were grouped into four regions (grid boxes, 4°latitude × 12°longitude) NW, NE, SW and SE, and plotted together with daily means (1981–2010) taken from land stations lying in a given region (Figure 7),

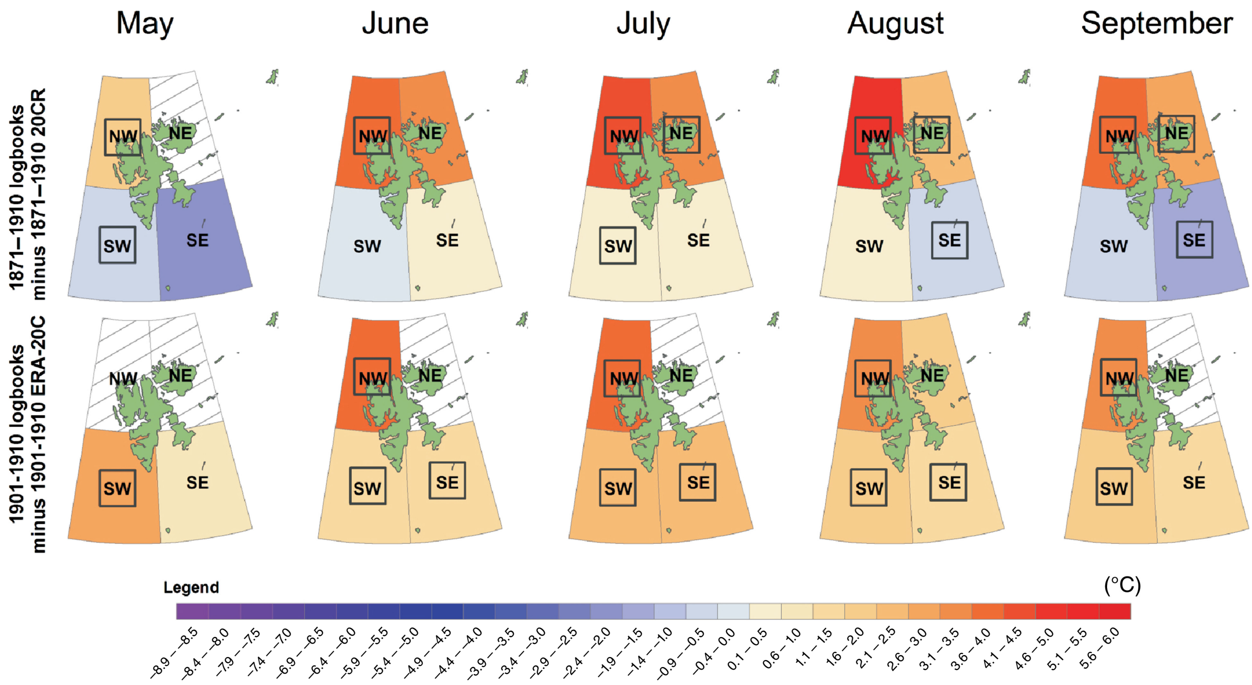

Figure 9. Mean monthly differences of air temperature (°C) between measurements taken from logbooks and the 20CR reanalysis (upper panel, for 1871–1910) and the ERA-20C reanalysis (lower panel, for 1901–1910) in the seas surrounding Svalbard. White patterned grid boxes indicate areas with a lack of data. Statistically significant differences at the $p \leq 0.05$ level are shown by a grid label with squares.

except for the NW region where the ERA-Interim dataset was used due to a lack of land stations. From Figure 7, it can be clearly seen that the distribution of historical daily means around the contemporary (1981–2010) run of daily means is roughly symmetrical, which could suggest the existence of comparable air temperatures in both periods. Quite a large number of daily means are available for southern regions, while significantly less exist for northern regions, in particular for May and June. This, of course is connected with the presence of sea ice in these months (see Figure S1). Not many data lie significantly outside the lines that represent the 90 and 10 percentile thresholds that were calculated based on daily data for each month from 1981 to 2010. All outliers were checked and suspect ones removed from the dataset.

Mean monthly air temperatures averaged for all grid boxes for the entire historical period and its two sub-periods (1871–1890 and 1891–1910) are presented in Figure 8. For comparison, data from land stations are also shown. Of all the analysed months (May–September), May was the coldest and July the warmest. The spatial distribution of air temperature is generally according to expectations, i.e. the highest/lowest air temperatures occur in the southern/northern and western/eastern grid boxes. This pattern is particularly clear in May and September, while in summer the change of air temperature with latitude is lesser in western regions. This feature is well-known in Svalbard and was recently also confirm by detailed studies investigating the spatial diversity of air temperature in this region (Przybylak *et al.*, 2014). The continentality of the climate is characterised by cold winters and warm summers and plays a more important role than the change of latitude. As a result, in summer the inner part of Spitsbergen is warmer than its northern and southern parts (see Figure 3 in Przybylak *et al.*, 2014). Mean monthly air temperatures throughout 1871–1910 were usually slightly colder over land than over sea (Figure 8). Quite often, the same air temperature also occurred, while there was no one situation when land air temperature was higher than that over sea. New reanalysis products cover completely (20CR) or partly (ERA-20C) our reconstruction records, and therefore we compared the results of these datasets. Mean monthly air temperature differences between our reconstruction of Svalbard air temperatures and air temperatures taken from both reanalyses are shown in Figure 9. Reanalyses are usually too cold in comparison with observations, except certain southern grid boxes in the case of 20CR. In particular, large differences (2–5 °C) have been found in northern regions. The majority of differences are statistically significant.

To study changes of air temperature over the seas surrounding Svalbard from historical times to the present day, three reanalysis products were used (ERA-Interim, ERA-20C and 20CR) for contemporary data. All data available from reanalyses for grids located in each of our regions were averaged for all months for 1981–2010. More or less similar results of historical to present-day air temperature differences were obtained for ERA-Interim and 20CR (Figure 10). Southern regions in all months reveal colder conditions in 1871–1910 than today (up to about −4 °C in the SE, in particular in May and September). However, northern regions (NE and in particular NW) were warmer than present-day conditions (reaching

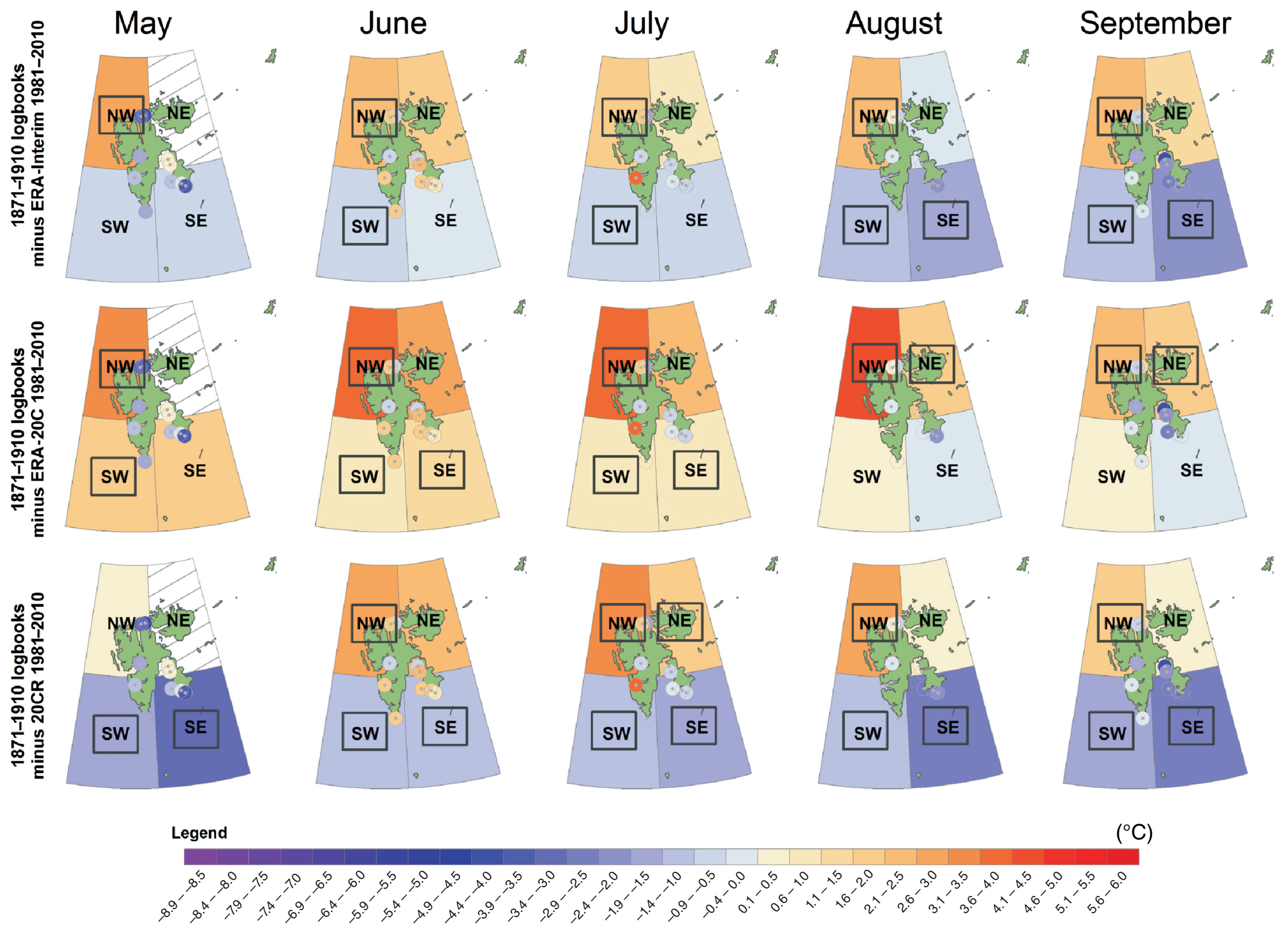

Figure 10. Mean monthly differences of air temperature (°C) between historical (1871–1910) and contemporary (1981–2010) times. Dots indicate differences between historical land sites and present land stations. Grid boxes indicate differences between historical logbooks and present reanalysis: ERA-Interim (upper panel), ERA-20C (middle panel) and 20CR (lower panel). White patterned grid boxes indicate areas with a lack of data. Statistically significant differences at the $p \leq 0.05$ level are shown by a grid label with squares.

a maximum of 3–4 °C in the NW region in some months), except for the NE region in August for the ERA-Interim. Evidently greater positive differences were observed between historical observations and contemporary data from ERA-20C for northern regions. In contrast to the two previous reanalysis products, differences calculated using ERA-20C for southern regions show mainly small positive values (up to 2 °C), except in the SE region in August and September when they were slightly negative. In our opinion, the most reliable estimation of air temperature changes between the historical and present-day periods is available for contemporary data taken from 20CR, and particularly from ERA-Interim. The latter reanalysis product is suggested as being most accurate in simulating Arctic air temperatures (Lindsay *et al.*, 2014; Serreze and Barry, 2014). Nevertheless, suspected results appear to be achievable for northern regions (too warm in historical times). This is probably connected with the fact that northern latitudes could be reached by ships only in very warm summers, when the extent of the sea ice was significantly reduced (changes of sea ice extent in the region are shown in Figure S1). Thus, it appears reasonable to compare air temperature for this area from historical times with data taken instead from the set of warmest months in 1981–2010, than from all years. Such calculations, based on data averaged from the five warmest months, are presented in Figure S4. It appears to us that now the results are more reliable for the northern grid boxes, the differences are still mainly positive, but their magnitudes are significantly smaller. In the case of the contemporary data taken from ERA-Interim and 20CR, they do not even exceed 2 °C. The more common occurrence of lower air temperature in historical times than today, particularly clearly seen in September, was also observed. Figure 10 also shows historical to present-day differences between air temperatures measured on land (dots). These are mainly slightly negative and therefore show a better correspondence with the marine data presented for the southern regions. A worse, but still not bad correspondence, also exist for the northern grid boxes, although it is significantly closer when differences for marine data are calculated using contemporary data taken from sets of the five warmest months (compare Figure 10 and Figure S4).

Marine air temperature reconstruction for the entire Svalbard area for 1871–1910 is presented in Figure 11, and is also compared to other available air temperature series for the historical period (Figure 11(a)). It is worth noting here that 20CR is generated by assimilating only surface pressures and using monthly SST and sea ice distributions as boundary conditions. In turn, ERA-20C assimilates observations of surface pressure and surface marine winds only. Thus, in both these products air temperature has been modelled. However, HadCRUT4 is a combined land–air temperature data set (CRUTEM4, Jones *et al.*, 2012), and sea-surface temperature dataset (HadSST3, Kennedy *et al.*, 2011a, 2011b). The latter dataset allows for reliable calculation of near-surface air temperatures, whereas the CRUTEM4 dataset does not contain land data for the Svalbard Archipelago for the period 1871–1910. In addition, SSTs available in the HadSST3 dataset are very sparse for this period, because they are taken from the ICOADS R2.5 dataset. In turn, the ICOADS R2.5 dataset contains SSTs limited only to the southern grids of our area, and as a result on average only 6–20 monthly means for the period May–September 1871–1910 were available for analysis. In the light of these weaknesses in the aforementioned global datasets, the new air temperature data presented here from marine vessels' observations significantly improve the existing knowledge, both for the study area (in particular for its northern part) and the period.

Areally averaged air temperatures oscillate here from about 0 °C in 1875, 1876 and 1903, to slightly more than 4 °C in 1891 and 1895. The year-to-year variability of air temperature from our reconstruction is comparable to that seen for the Svalbard area (extracted from the HadCRUT4 dataset, Morice *et al.*, 2012), SW Greenland, Archangelsk and Vardø, and is significantly greater than seen in the data taken from the 20CR and ERA-20C reanalyses for the Svalbard area, as well as in the Arctic air temperature series (with recent updates) constructed by Polyakov *et al.* (2003). Air temperature calculated for the study area using reanalysis products, as well as obtained by averaging grid data from the HadCRUT4 dataset, is evidently about 2–3 °C too cold. Our reconstruction shows good correspondence in many sub-periods with the air temperature presented for SW Greenland (see e.g. beginning of series or 1889–1891). In turn, in the last 15 years (1895–1910) of reconstruction, a better correspondence is seen with air temperature runs in Archangelsk and Vardø. For example, the occurrence of warm periods in 1894–1898 is very clearly seen, and also in the grid data from the HadCRUT4 dataset, but not in SW Greenland (see Figure 11(a)). As Morice *et al.* (2012) conclude, '… independent studies of near-surface temperatures should be maintained', further adding '… recommend that, in addition to the use of HadCRUT4, data set users consider testing the robustness of their results by comparison to other available data sets'.

The mean air temperature in May–September in the Svalbard area was most often lower than present-day air temperatures, usually less than 1 °C (Figure 11(b)). There are also many years with higher air temperatures than today, but with values usually not exceeding 1 °C. Average air temperature for the entire period (1871–1890) was slightly colder in Svalbard (by 0.4 °C) than today. Majority (about 90%) of mean May–September air temperatures lies within range of ±3SD from its contemporary long-term mean air temperature (Figure 11(b)).

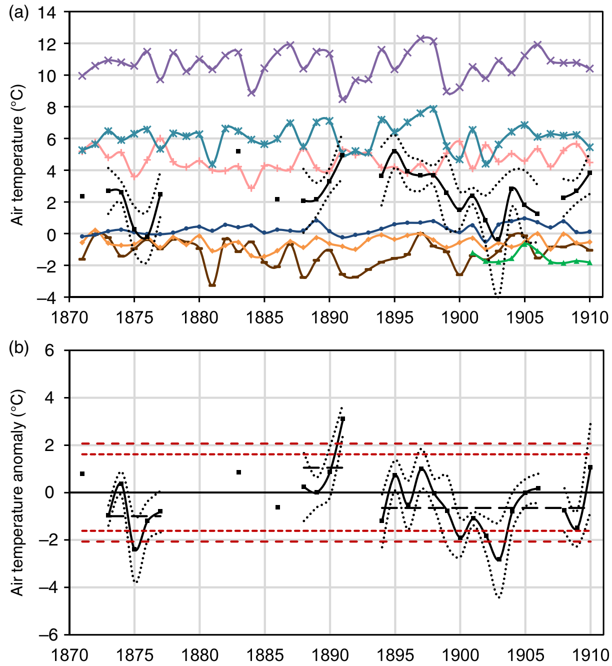

Figure 11. Air temperature variability in the Svalbard area (74–82°N and 6–30°E) in the period May–September 1871–1910, with comparison to other datasets (a) and present climatology 1981–2010 (b). Panel (A): reconstruction based on areally averaged data used in this study (black with squares) with a 95% confidence interval (dotted); Archangelsk (crosses); Vardø (stars); SW Greenland (Vinther *et al.*, 2006, pluses); 20CR (Compo *et al.*, 2011, circles); Arctic 57–84°N (Polyakov *et al.*, 2003, **updated, rhombuses); HadCRUT4 (Morice *et al.*, 2012, dashes); and ERA-20C (triangles). Panel (B): air temperature anomalies based on data used in this study (black with squares) with a 95% confidence interval (black dotted) with respect to the reference period 1981–2010 based on ERA-Interim reanalysis; short-term means of the anomalies (horizontal black long-dashed); ±3SDs of the mean ERA-Interim 1981–2010 (Dee *et al.*, 2011, horizontal short-dashed); 3SDs of the mean observational 1981–2010 as an average of Ny-Ålesund, Svalbard Lufthavn, Hornsund, Bjørnøya and Hopen (horizontal medium-dashed). Note that data were not available for all regions in all years (NW, NE, SW and SE), therefore mean daily anomalies for the entire area were calculated in the following way: the daily mean for each location in the given region was subtracted from the mean air temperature for 1981–2010 taken from ERA-Interim for the same region. In the next step, all obtained daily anomalies were averaged for the entire area and for each year separately.

Air temperature trends by region and month in 1871–1910 are presented in Table 4. Statistically significant positive trends were noted in the SE region, but only in September (0.28 °C/10 years), while in the NW region they were observed in June (0.55 °C/10 years), July (0,4 °C/10 years) and September (0.55 °C/10 years). However, a statistically significant negative trend occurred only in the SW region, in August (−0.24 °C/10 years).

Taken together, all of the information presented in Tables S1 and S2 and in Figures 2–4 makes it clear that information about air temperature conditions in the Svalbard region for different periods and seasons of the year is variable and limited. Therefore, the averaged results that are presented for the study area should be treated as the best

Table 4. Air temperature trends (°C/10 years) in the Svalbard archipelago in 1871–1910 on the basis of daily data from logbooks.

Month	SW	SE	NW	NE
May	−0.31	–	−0.37	–
June	0.08	0.02	**0.55**	–
July	0.18	−0.34	**0.41**	–
August	**−0.24**	0.00	−0.04	0.22
September	0.02	**0.28**	**0.55**	−0.33

Values in bold indicates significance on the $p \leq 0.05$ level. SW, SE, NW and NE regions divided according to 18°E meridian and 78°N parallel (see Figure 2).

approximation of the real climate that currently exists. We are still looking for new data series in the hope that, if they exist, they will allow us to improve our knowledge in the future. Thus, any assistance that readers of the current paper may offer in providing such series would be welcomed.

4. Conclusions and final remarks

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

1 Land data:

(a) Both annual cycles and spatial distribution of air temperature in the Svalbard region in the historical time were roughly similar to those of the present, described recently by Przybylak *et al.* (2014). It was also found that air temperature in the Central region represents average thermal conditions for the entire Svalbard archipelago for all seasons (except summer) and for the year quite well.

(b) The inter-annual air temperature variability of the monthly means is, as today, markedly greater in winter than in summer.

(c) Analysis reveals that in 1865–1920, Svalbard was markedly colder than today (by about 3 °C) in all seasons, except summer when the air temperature was similar in both periods. However, the majority of mean monthly air temperatures in historical times still lie within two SDs from the modern, 1981–2010 mean. This means that values of air temperature in historical times lie within range of contemporary air temperature variability.

(d) Seasonal patterns of air temperature changes in the Svalbard archipelago between the historical and standard normal (1961–1990) periods show a generally good correspondence with analogical changes calculated not only for the Atlantic region but also for some other Arctic regions (e.g. SE Greenland, Canadian Arctic, the Barents and Kara seas), as well as also for the entire Arctic. All these sources concluded that annual air temperature in historical times was generally colder than the standard normal period (1961–1990) by about 0.5–1.0 °C. When we took as the reference period the new normal period (1981–2010), the difference increases to about 1.5–2.5 °C.

2 Marine data:

(a) As with the land data, the spatial distribution of air temperature over the seas surrounding the Svalbard archipelago is similar to the present day, i.e. the highest/lowest air temperatures occur in the southern/northern and western/eastern grid boxes. This pattern is particularly clear in May and September, while in summer the change of air temperature with latitude is small in the western regions.

(b) Reanalyses are usually too cold in comparison with observations, except some southern grid boxes in the case of 20CR. In particular, large differences (2–5 °C) have been found in northern regions.

(c) More or less similar results of historical minus present-day air temperature differences were obtained for ERA-Interim and 20CR. Southern regions in all months reveal colder conditions in 1871–1910 than today (up to about −4 °C in the SE region, particularly in May and September). However, the northern regions (NE and in particular NW) were warmer than present-day conditions (reaching a maximum of 3–4 °C in the NW region in some months), except for the NE region in August for ERA-Interim.

(d) Historical minus present-day differences between air temperatures measured on land show good correspondence with marine data, in particular in southern regions.

(e) Our reconstruction shows good correspondence in many sub-periods with air temperatures presented for SW Greenland (see, e.g. the beginning of the series or 1889–1891). But in the latest 15-year period (1895–1910), the reconstruction corresponds better with air temperature from Archangelsk, Vardø and with gridded data from HadCRUT4 than with air temperature from SW Greenland.

(f) May–September average air temperature for the entire period 1871–1910 was slightly colder in Svalbard (by 0.4 °C) than today. The majority (about 90%) of these mean air temperatures lie within range of ±3SD from its contemporary long-term mean air temperature.

Our data rescue activity for recent decades was concentrated on a search for early meteorological data on the Arctic in many libraries and archives in Europe and North America, and therefore it is with high probability that we can guarantee that all available main datasets from land for Svalbard were used in the present analysis. In the case of marine data, we were able to collect many series of data from Norwegian logbooks, but not all. In particular, there are difficulties gaining access to Russian logbooks.

The new reconstruction presented in this paper can be thought of as having a regional character, and is the first of a series of such reconstructions which we are planning. Deeper regional insight into climate changes in historical times in the Arctic (using a greater amount of data than large-scale reconstructions are able to use) is very helpful in supporting the correctness and reliability of our knowledge of the history of the Arctic climate in recent decades and centuries. For a comparison of air temperature reconstructions based on marine data with present-day conditions, better reanalysis products are needed, because the current ones still show worse climate simulations for the Arctic than for the lower latitudes.

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Supporting Information

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

Figure S1. Mean ice extent (lines) and positions of ships (dots) in the Svalbard area during May to September 1871–1910. To make the picture clearer, the ice edge extent in the particular months was shown only for the years for which the meteorological measurements were collected in this study. The same colour indicates ice edge and vessel positions for a given year. Source: Arctic Climate System Study (ACSYS), 2003.

Figure S2. Mean monthly air temperature (°C) based on land stations (dots) and reanalyses (grid boxes): ERA-Interim (upper panel), ERA-20C (middle panel) and 20CR (lower panel) in Svalbard and its surrounding seas, during May to September 1981–2010.

Figure S3. Number of reconstructed monthly means of air temperature (°C) in each grid box in the seas surrounding Svalbard in 1871–1910 and its sub-periods 1871–1890 and 1891–1910.

Figure S4. Mean monthly differences of air temperature (°C) between historical (1871–1910) and contemporary five warmest months, selected from 1981–2010. Grid boxes indicate differences between historical logbooks and the present reanalysis: ERA-Interim (upper panel), ERA-20C (middle panel) and 20CR (lower panel). White patterned grid boxes indicate areas with a lack of data.

Table S1. Sources of air temperature series (land component) for Svalbard in the early instrumental period used in the present paper. m, monthly; t, terminal; h, hourly.

Table S2. Sources of air temperature series (marine component) for Svalbard in the early instrumental period used in the present paper. CISL RDA, Computational Information Systems Laboratory Research Data Archive; DMC NCU, Department of Meteorology and Climatology, Nicolaus Copernicus University; no name, no record of the marine vessel’s name; C, Celsius; R, Réaumur; F, Fahrenheit. Our complete marine database is shown, with data series used in the present paper shaded in grey.

Appendix S1. Marine early instrumental dataset for Svalbard (MEIDS). Air temperature and sea-surface temperature with sub-daily resolution.

Appendix S2. Marine early instrumental dataset for Svalbard (MEIDS). Air temperature with daily resolution.

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