

RESEARCH/REVIEW ARTICLE

Variability of humidity conditions in the Arctic during the first International Polar Year, 1882–83

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Keywords

Humidity conditions; Arctic; early instrumental period; historical climatology.

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Abstract

Of all the early instrumental data for the Arctic, the meteorological data gathered during the first International Polar Year, in 1882–83 (IPY-1), are the best in terms of coverage, quality and resolution. Research carried out during IPY-1 scientific expeditions brought a significant contribution to the development of hygrometry in polar regions at the end of the 19th century. The present paper gives a detailed analysis of a unique series of humidity measurements that were carried out during IPY-1 at hourly resolutions at nine meteorological stations, relatively evenly distributed in the High Arctic. It gives an overall view of the humidity conditions prevalent in the Arctic at that time. The results show that the spatial distribution of atmospheric water vapour pressure (e) and relative humidity (RH) in the Arctic during IPY-1 was similar to the present. In the annual course the highest values of e were noted in July and August, while the lowest occurred in the cold half of the year. In comparison to present-day conditions (1961–1990), the mean values of RH in the IPY-1 period (September 1882 to July 1883) were higher by 2.4–5.6%. Most of the changes observed between historical and modern RH values are not significant. The majority of historical daily RH values lie between a distance of less than two standard deviations from current long-term monthly means.

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Water vapour is a driving force in a number of atmospheric processes. Being the main greenhouse gas, it has a significant influence on the global climate and its changes. Understanding the variability of water vapour concentration and its causes is extremely important in order to comprehend the way in which the Earth's climate system works. According to the Clausius–Clapeyron equation, increasing the temperature of air leads to an exponential growth of the water-holding capacity of the atmosphere. Correspondingly, a 1°C increase in air temperature will raise the saturated vapour pressure by 7% (Willett et al. 2008).

In the Earth's climate system, polar areas are considered to be particularly important regions which are first to respond to global climate changes and where the responses are the strongest. The recently observed considerable warming of the Arctic (Symon et al. 2005; Przybylak 2007) is causing the melting of sea ice and an increase in water

vapour in the atmosphere (Serreze et al. 2012), which may trigger positive feedback, as a result of which the air temperature will continue to rise (Serreze & Barry 2011).

To predict the extent of climate changes in the future, we need to reconstruct their historical course in as detailed a manner as possible. In recent years, one of the branches of climatology, historical climatology, has seen dynamic growth in a lot of countries. In order to enhance research work in this area, in a number of cases international cooperation has been established, good examples of which are the Atmospheric Circulation Reconstructions over the Earth programme (Allan et al. 2011) and the Old Weather project (<http://www.oldweather.org/>), both intended to discover, collect and digitize historical weather data for the whole world.

In the Arctic, regular instrumental observations started relatively late—mainly after 1920—compared with other

areas of the globe (for more details see Przybylak et al. 2010; Przybylak et al. 2013). This makes all available data from before 1920 significant and indispensable to evaluate the climate fluctuations and changes in the Arctic, encouraging researchers to make an effort and retrieve the data concerning the early instrumental period for the Arctic and the Subarctic region (Kay 1995; Przybylak 2000; Klingbjør & Moberg 2003; Polyakov et al. 2003; Wood & Overland 2003, 2006; Lüdecke 2004, 2005; Przybylak 2004; Przybylak & Dzierżawski 2004; Przybylak & Vizi 2004, 2005; Klimenko & Astrina 2006; Vinther et al. 2006; Klimenko 2008, 2010; Vizi 2008; Brohan et al. 2010; Przybylak et al. 2010; Wood et al. 2010; Wilkinson et al. 2011; Wyszyński 2012; Przybylak et al. 2013). The majority of this work has been aimed at reconstruction of the air temperature and atmospheric pressure.

Measurements made as part of expeditions mounted during the first International Polar Year 1882–83 (IPY-1) provide a vital contribution to the discovery of knowledge about the Arctic climate of the 19th century. Moreover, of all the early instrumental data available for the area, they are definitely the best in terms of coverage, quality, resolution and other aspects.

So far, the literature does not offer any detailed studies of the humidity of air in the Arctic during the early instrumental times, due to the fact that it was extremely difficult to take reliable measurements of atmospheric humidity in the polar regions with negative air temperatures prevailing most of the year. The problem is addressed in the works of Koch & Wegener (1930), Loewe (1935), Sverdrup (1935) and Golcman (1939, 1949). In this paper, a detailed analysis is provided of a unique series of air humidity measurements taken during IPY-1, which improves our knowledge of humidity conditions in the Arctic at that time.

Area, data and methods

During IPY-1 in 1882–83, 12 main and a large number of auxiliary research stations were operating in the Northern Hemisphere (mainly on the Labrador Peninsula); for more details see Barr (2008) and Barr & Lüdecke (2010). This study makes use of data from nine stations representing the so-called High Arctic (Fig. 1), whose boundaries and division into climatic regions were assigned in accordance with the *Atlas of the Arctic* (Trešnikov 1985). The evenly distributed stations (Table 1, Fig. 1) of Godthåb, Jan Mayen, Kapp Thordsen, Malye Karmakuly, Sagastyr, Point Barrow, Lady Franklin Bay, Kingua Fjord and Kara Sea are representative of nearly all climatic regions of the Arctic.

The Kara Sea data series includes meteorological observations made during the drift of the Dutch vessel the SS *Varna*, which moved from Vaygach Island in the east–north-east direction, along the Yamal Current. Between 15 January and 31 July 1883, measurements were taken in the vicinity of a building erected on pack ice in case the ship was destroyed by ice, which actually happened on 21 January that year. Most of the observations and meteorological measurements were made in the area situated between 70°00'N and 71°45'N, and 62°29'E and 65°25'E (Table 2). The Dutch steam ship eventually sank in the icy waters of the Kara Sea on 24 July 1883 (for more details see Snellen & Ekama 1910; Barr 2008).

According to the recommendations of the International Polar Commission (St. Petersburg 1882), meteorological measurements were to be performed at 1-h intervals (Table 1). However, in the harsh polar conditions not all of the expeditions managed to comply with this recommendation. At most of the analysed stations, the measurements were recorded according to mean local time (Table 3), the only exception here being two American stations (Lady Franklin Bay and Point Barrow), where the records refer to Washington local time. This is why the references

Table 1 Geographical coordinates of the meteorological International Polar Year 1882–83 (IPY-1) stations, resolution of the data, height of instruments and list of source materials.

IPY-1 stations	Location		Data resolution ^a	Height of psychrometer above ground level (m)	Source
	φ	λ			
Godthåb	64°11'N	51°44'W	24 times per day	1.95	Paulsen 1886
Jan Mayen	71°00'N	8°28'W		3.05	von Wohlgemuth 1886
Kapp Thordsen	78°28'N	15°43'E		2.00	Ekholm 1890
Malye Karmakuly	73°22'N	52°36'E		2.80	Lenz 1886b
Kara Sea	Drift of <i>Varna</i> ^b			3.00	Snellen & Ekama 1910
Sagastyr	73°22'N	124°05'E		2.40	Lenz 1886a
Point Barrow	71°14'N	156°40'W		1.23	Ray 1885
Lady Franklin Bay	81°44'N	64°45'W		1.52	Greely 1886
Kingua Fjord	66°36'N	67°19'W		2.00	Neumayer & Børgen 1886

^aDetailed information concerning the gaps and changed measurement intervals at individual stations are provided in the explanatory notes to Tables 4 and 6.

^bSteamship. See Table 2.

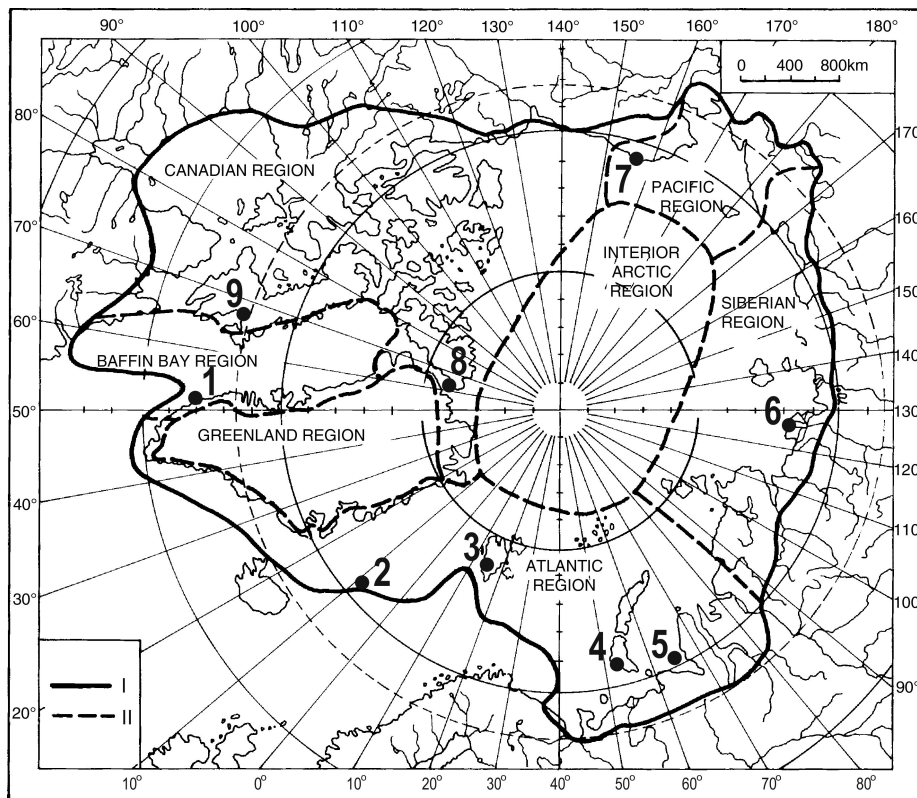


Fig. 1 Location of meteorological stations operating in the Arctic in the period of the first International Polar Year, in 1882–83. The Arctic and its climatic regions are defined according to Trešnikov (1985). The southern Arctic boundary has been delimited based on analysis using long-term mean values of all meteorological variables, their seasonal cycles and variability characteristics. The boundary of the Arctic is shown as the thick solid line (I); boundaries between climatic regions are indicated with thick dashed lines (II); the Arctic Circle is indicated with a thin dashed line. The stations comprised the following: Godthåb (1), Jan Mayen (2), Kapp Thordsen (3), Malye Karmakuly (4), Kara Sea (5), Sagastyr (6), Point Barrow (7), Lady Franklin Bay (8) and Kingua Fjord (9).

from Lady Franklin Bay and Point Barrow were corrected by +1 h and –5 h, respectively, to reduce them to the common mean local time. About 20-min deviations from

Table 2 Geographical coordinates of the drift of the steamer *Varna*; highest (φ_1, λ_1) and lowest (φ_2, λ_2) latitude and longitude of the *Varna* in each month.

Year	Month	φ_1 N	φ_2 N	λ_1 E	λ_2 E
1882	Aug	73°25'	69°21'	59°53'	50°32'
	Sep	70°15'	69°55'	64°21'	60°25'
	Oct	70°24'	70°00'	64°35'	63°49'
	Nov	70°27'	70°11'	64°07'	64°06'
	Dec	70°54'	70°21'	65°09'	64°29'
1883	Jan	71°03'	70°53'	65°20'	64°04'
	Feb	71°20'	71°01'	64°53'	63°57'
	Mar	71°39'	71°20'	65°11'	64°34'
	Apr	71°45'	71°29'	65°25'	64°37'
	May	71°35'	71°19'	64°19'	63°52'
	Jun	71°20'	71°11'	64°10'	63°30'
	Jul	71°11'	71°03'	63°16'	62°36'
	Aug	71°10'	70°04'	62°29'	58°30'

Source: Snellen & Ekama (1910).

the local time at Kapp Thordsen and on the Kara Sea were considered hardly significant, and remained unadjusted.

The quality and correctness of the data gathered during the IPY-1 expeditions were already being verified during the expeditions themselves. Furthermore, corrections were made to the measurements to accommodate the methodology accepted at the third meeting of the International Polar Commission in St. Petersburg, held from 1 to 8 August 1881 (Wild 1882). It should be noted that properly trained members of the individual expeditions took the measurements themselves. The instruments had been carefully calibrated at national meteorological centres, such as the Kew Observatory near London and the Central Physical Observatory of St. Petersburg in Russia. After the expeditions, the instruments were verified at the same facilities.

Atmospheric humidity can be measured in several ways. During IPY-1, air humidity was determined using both the psychrometric (measuring e : pressure of the current water vapour content of the air) and hygrometric methods (measuring RH : relative humidity, or the ratio of

Table 3 Time of execution of meteorological observations at nine polar stations during the first International Polar Year, 1882–83.

Station	Time of observation
Godthåb	Local mean time
Jan Mayen	
Kapp Thorsden	According to Göttingen time, correction to local mean time +26 min
Malye Karmakuly	Local mean time
Kara Sea	1882 J Local mean time
	A
	S Correction to local mean time –23 min
	N
	D Correction to local mean time –21 min
	1883 J
	F Correction to local mean time –22 min
	M
	A
	M
	J Correction to local mean time –26 min
	J
	A Local mean time
Sagastyr	Local mean time
Point Barrow	Washington mean time, correction to local mean time –5 h 17 min
Lady Franklin Bay	Washington mean time, correction to local mean time +49 min
Kingua Fjord	local mean time

the actual pressure of the water vapour [e] in the air to the pressure of the saturated water vapour [E] at the specific temperature). The August psychrometer comprised standard mercury thermometers (dry-bulb and wet-bulb types). All the thermometers were precisely calibrated at relevant national meteorological centres and, for example, the indication error of the thermometers used at the Siberian station of Sagastyr did not exceed 0.25°C at temperatures above -20°C (Wood & Overland 2006). At most of the stations, the thermometers were placed in instrument shelters designed by Wild at a height of 1.5–3 m above ground level (Table 1). In the hygrometric method, for example, a Saussure-type hair hygrometer was used (Fig. 2).

According to the Programme for the International Polar Expeditions and recommendations of H. Wild (for more details see Supplementary File 1), when the air temperature exceeded 0.5°C on a wet-bulb thermometer, both a hair hygrometer and a psychrometer were used; at lower temperatures, the relative humidity (RH) was determined using a hair hygrometer only, and the corresponding value of e was calculated with the help of psychrometric charts in relation to the temperature of air read on a dry-bulb thermometer. According to Wild's experience, hair hygrometers could entirely replace the psychrometer at 0°C , as well as at low temperatures if they were properly



Fig. 2 Saussure-type hair hygrometer, manufactured by Hottinger & Cie, Zürich, ca. 1900. Image published with kind permission of the Technik Museum, Switzerland.

managed and occasionally verified by comparison with a psychrometer above 0°C . He had, moreover, often found that the two instruments remained in perfect accordance between -5°C and -15°C at the Russian stations (*Proceedings of the Meteorological Conference at Leipzig 1873*).

At the end of the 19th century, the psychrometric charts of Wild–Jelinek (1876) were in use. The values of the saturation pressure of water vapour were given here with respect to supercooled water (E_{water}). The table of saturation pressure with respect to ice (E_{ice}) was added in the next edition, in 1911 (Anonymous 1912). Adjustments to the calculations of e and RH for negative temperatures of the air, made by Ekholm (1890) during his experiments

carried out at the Kapp Thordsen station during IPY-1, were not applied to psychrometric charts of the Norwegian Meteorological Institute until 1895 (Birkeland 1944). The methodology, and its inherent difficulty providing reliable measurements of atmospheric humidity at times of negative air temperature, is best reflected in the reports of the members of the Swedish expedition at Kapp Thordsen (Ekholm 1890; see Supplementary File 1), and of the Dutch expedition covering the Kara Sea (Snellen & Ekama 1910; see Supplementary File 1).

Condensation hygrometers, such as Alluard or Regnault (measuring the temperature at the dew point [T_d], that is, the temperature at which the water vapour contained in the air becomes saturated), were used together with a chemical approach as control measures for the psychrometric and hygrometric methods. It is interesting to note that the benefits of the measurement of a dew point as an efficient method of determination of atmospheric humidity in the Arctic were emphasized as early as at the end of the 19th century: “Yet I believe that, my experiments have demonstrated that Regnault’s instrument may be utilised even in the polar lands, and that it is a device which failed to win due appreciation when considering correlations between the indications of a hair hygrometer and those of a thermometer, whilst it may be well applied to correct the indications of the hygrometer regarding changes in the values of temperature” (Ekama quoted in Snellen & Ekama 1910: 75). The method has been widely used in meteorological stations in the Canadian Arctic since 1950 (van Wijngaarden & Vincent 2005; Vincent et al. 2007).

The meteorological data used in this paper were sourced from the reports of the polar expeditions organized during IPY-1, published in various years between 1886 and 1910 (Table 1). A majority of these reports are available as part of the internet resources of the Central Library of the US National Oceanic and Atmospheric Administration (NOAA; Fiolek 2007). Photocopies of reports kept at the library of the Scott Polar Research Institute in Cambridge were also used, and—in the case of a Russian expedition to Novaya Zemlya (Malye Karmakuly)—a photocopy of the report kept at the library of the Russian Geographical Society of St. Petersburg.

The data were digitized manually, because this kind of approach guarantees the lowest error rates when acquiring data from antique books and prints (Brönnimann et al. 2006). Optical character recognition software could not be used because it did not recognize the 19th-century typefaces. Manual digitization enabled preliminary verification of incorrect values. Moreover, the editors of all the reports which would provide data for this study carried out a quality control to reject any unreliable data.

Comparing original diurnal means given in the reports with means calculated from the digitized values also eliminated obvious digitization errors. Prior to any calculations, the collected data were also subject to a final substantive check using standard methods applied in climatological studies.

At Point Barrow, water vapour pressure was not measured. Therefore, this element was calculated on the basis of the air temperature and relative humidity data available in the report, according to the following formula:

$$e = RH * E_{water}/100,$$

where E_{water} was taken from psychrometric charts (Rózdzyński 1995) for the appropriate measured air temperature.

Mean diurnal values of individual parameters of air humidity were calculated as an actual arithmetic mean, whereas maximum and minimum diurnal values were selected from 24 measurements. As a result of difficulties with the acquisition of measurements in winter, there is a lack of data for some IPY-1 stations. Therefore, in the common reference period of IPY-1, and for all stations, this weather element was described only for the 3 months of May, June and July 1883 (Tables 4, 6).

See Supplementary File 2 and 3 for corrected measured water vapour pressure (e) and relative humidity (RH) data, with hourly resolutions.

It is important to point out here that although the first digitized meteorological data from IPY-1 were made available on NOAA’s website (<http://www.arctic.noaa.gov/aro/ipy-1>) by Wood & Overland (2006), it comprised only daily and monthly resolutions (air temperature, atmospheric pressure, direction and wind velocity). Krause et al. (2010) have recently developed a complete database for IPY-1, which has been added to the resources of the World Data Center for Marine Environmental Sciences (<http://127.0.0.1:8800/PangaVista>). The database was compared with the aforementioned NOAA and Nicolaus Copernicus University databases and no significant differences were found.

Comparison of the historical humidity conditions with current ones has been made using the RH parameter. Five of the nine IPY-1 stations for which year-round RH measurements are available were chosen. The second data set includes contemporary RH data (1961–1990) obtained from the historical sites. In four cases (Godthåb, Jan Mayen, Malye Karmakuly and Point Barrow) the locations of the observations in the two periods were identical. For the Siberian station (Sagastyr), the data from the nearest modern station (Sagylah Ary, situated approximately 80 km from the historical site) have been used. Data for modern stations were taken from the

Table 4 Basic characteristics of water vapour pressure (e , hPa) at nine stations operating in the Arctic during the first International Polar Year, 1882–83.

Station	Parameter	A	S	O	N	D	J	F	M	A	M	J	J	A	MJJ
Godthåb	$e_{max\ abs}$	10.9	10.3	6.7	6.3	6.5	5.7	6.4	7.3	6.7	7.7	9.9	12.7	10.4	12.7
	e	7.6	6.5	3.9	3.1	2.7	2.4	1.9	3.9	3.5	5.4	6.5	8.4	7.3	6.8
	$e_{min\ abs}^a$	4.8	2.9	1.9	1.1	0.9	0.8	0.7	0.9	1.3	3.5	4.4	5.3	4.1	3.5
Jan Mayen	$e_{max\ abs}$	10.7	10.1	9.3	8.4	6.8	6.9	6.9	6.3	6.9	7.3	9.5	10.5		10.5
	e	7.2	6.4	6.7	4.8	3.2	3.9	4.3	2.6	4.5	4.1	6.5	7.3		6.0
	$e_{min\ abs}$	4.1	3.6	3.7	1.3	0.4	0.5	1.1	0.8	1.7	1.7	4.3	5.1		1.7
Kapp Thordsen ^b	$e_{max\ abs}$	8.7	7.9	8.0						6.4	7.6	8.2	9.0	9.7	9.0
	e	5.7	4.7	4.2						3.0	3.1	6.0	7.0	7.2	5.4
	$e_{min\ abs}$	3.3	1.9	0.9						0.5	1.1	3.6	4.9	5.0	1.1
Malye Karmakuly ^c	$e_{max\ abs}$		10.0	8.8	5.7	5.3	5.5	6.1	4.9	6.3	10.1	7.6	10.4	10.5	10.4
	e		5.9	3.7	2.5	2.0	1.4	3.0	1.7	3.3	3.6	5.8	7.7	7.0	5.7
	$e_{min\ abs}$		2.5	0.4	0.4	0.4	0.1	0.5	0.4	0.8	1.2	3.7	5.3	4.3	1.2
Kara Sea ^d	$e_{max\ abs}$			6.5	5.7	5.2		5.7	4.4	6.3	6.4	6.8	8.3		8.3
	e			2.6	2.2	1.8		2.0	1.9	2.8	2.9	5.3	6.5		4.9
	$e_{min\ abs}$			0.5	0.5	0.5		0.5	0.5	0.5	0.5	3.6	4.9		0.5
Sagastyr	$e_{max\ abs}$		10.0	4.4	1.3	1.2	0.7	0.5	1.3	2.7	7.2	10.0	13.9	12.5	13.9
	e		5.7	2.0	0.6	0.4	0.2	0.2	0.4	1.1	3.1	6.1	8.0	7.1	5.7
	$e_{min\ abs}$		2.1	0.4	0.2	0.0	0.0	0.0	0.1	0.3	0.8	2.1	6.0	5.2	0.8
Point Barrow ^e	$e_{max\ abs}$	13.7	10.3	7.3	4.8	1.4	2.4	4.1	4.2	2.4	6.0	10.7	12.3	12.9	12.3
	e	6.9	5.3	2.1	0.9	0.5	0.5	0.9	0.8	1.0	3.8	5.4	6.4	6.9	5.2
	$e_{min\ abs}$	3.8	2.8	0.4	0.1	0.1	0.1	0.2	0.1	0.2	0.6	3.2	4.8	3.7	4.8
Lady Franklin ^f Bay	$e_{max\ abs}$	7.5	4.3	2.0						2.4	5.2	9.8	7.6	7.1	9.8
	e	5.1	2.3	0.9						1.0	2.7	5.1	5.9	5.6	4.6
	$e_{min\ abs}$	2.8	1.0	0.1						0.1	0.5	2.3	4.5	3.8	0.5
Kingua Fjord ^g	$e_{max\ abs}$			5.9							7.3	8.0	10.1	12.8	10.1
	e			2.4							4.5	5.7	7.6	8.3	5.9
	$e_{min\ abs}$			0.8							2.1	2.9	6.0	6.0	2.1
Arctic	$e_{max\ abs}$			9.3							10.1	10.7	13.9		13.9
	e			3.2							3.7	5.8	7.2		5.6
	$e_{min\ abs}$			0.1							0.5	2.1	4.5		0.5

^a $e_{max\ abs}$ and $e_{min\ abs}$ are the highest and the lowest observed water vapour pressure, respectively; e is mean monthly water vapour pressure.
^bAugust 1882 days 1–14 without data, August 1883 days 24–31 without data.
^cDecember 1882 days 13–16 without data.
^dOctober 1882 days 1–9 without data, November 1882 days 4–7, 13–14, 28–30 without data, December 1882 days 3–4, 18, 21, 24–31 without data; February 1883 days 6, 10–11 without data, March 1883 days 17–22 without data.
^eAugust 1883 days 28–31 without data.
^fObservations every 4 h, August 1882 days 1–4 without data, April 1883 days 1–5 without data.
^gOctober 1882 days 1–26.

following sources: the Danish Meteorological Institute (Cappelen 2012, for Godthåb), the Norwegian Meteorological Institute (<http://www.eklima.met.no>, for Jan Mayen), the *Environmental Working Group Arctic meteorology and climate atlas* (Fetterer & Radionov 2000; for Malye Karmakuly and Saggyllah Ary), and the National Climatic Data Center (<http://www.ncdc.noaa.gov>, for Point Barrow).

For purposes of comparison with modern RH data, historical RH_{water} data from low temperatures used in this paper have not been recalculated to RH_{ice} . According to the World Meteorological Organization, modern measurements of RH at temperatures less than 0°C are evaluated with respect to water, because: (1) most hygrometers indicate relative humidity with respect to water at all temperatures, and (2) the majority of existing records of RH at temperatures below 0°C are expressed on

a basis of saturation with respect to water (WMO 2008). However, the reader must be aware that some sources of errors and biases still remain. For example, as a result of the use of different types of instruments and psychrometric charts to determine the RH calculations.

Results and discussion

Water vapour pressure (e)

Generally speaking, the water vapour content of the air in the whole Arctic is low because of low temperatures of the air (T). This is a result of both reduced evaporation and a limited water-holding capacity of cold air (Przybylak 2003). Therefore, the annual course of e in the Arctic is very similar to the annual course of T .

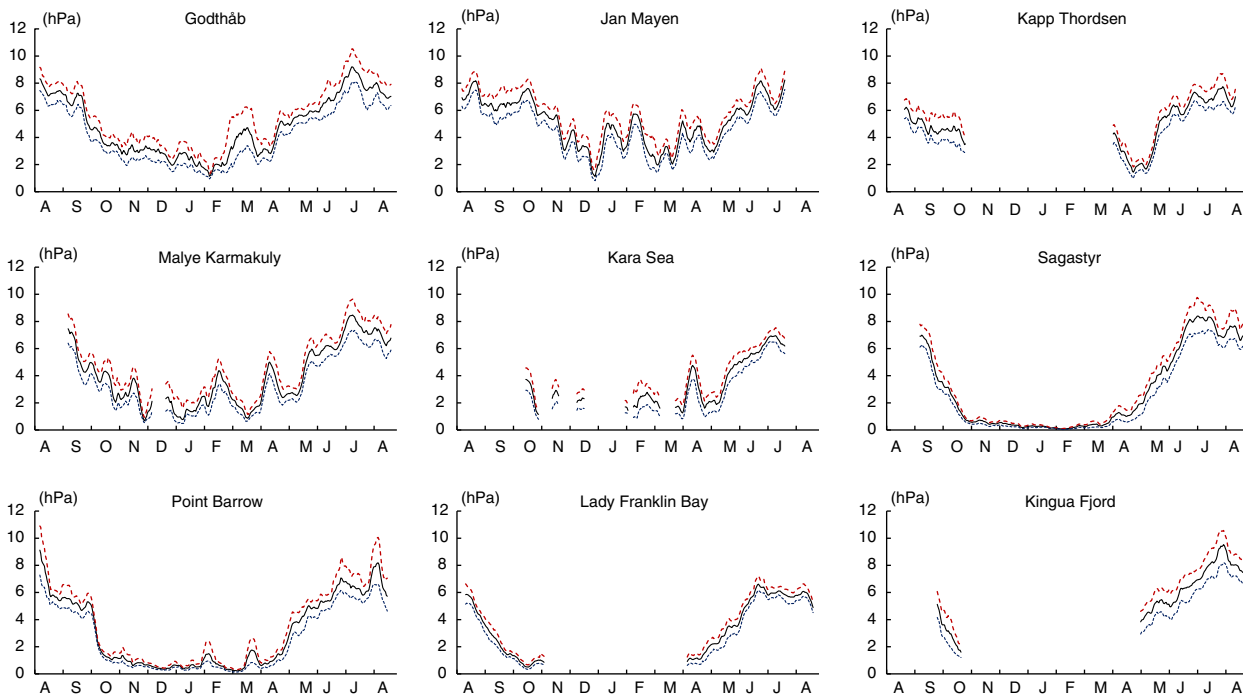


Fig. 3 Annual courses of water vapour pressure parameters (hPa) in the Arctic in the period of the first International Polar Year, in 1882–83, according to 11-day running averages. Mean daily (black solid line), daily maximum (red dashed line) and minimum (blue dotted line) water vapour pressure are presented.

The highest monthly mean values of e (Table 4) during IPY-1 were observed in the areas of the Arctic with the most oceanic type of climate, that is, at Godthåb (6.8 hPa) and Jan Mayen (6.0 hPa). In the north of the Canadian Arctic, where the climate is more continental, much lower values of e prevailed, as compared with the areas affected by the oceanic climate, for example, 4.6 hPa at Lady Franklin Bay. This kind of spatial distribution of e in the Arctic at the time of IPY-1 might have been caused by a meridional inflow of humidity towards the North Pole in the Atlantic Region, connected with North-Atlantic cyclonic activity and northerly air currents over the Canadian Arctic, leading to a reduction of humidity in the area. Correlations like this are currently observed (Serreze, Barry, Rehder et al. 1995; Serreze, Barry & Walsh 1995; Serreze, Rehder, Barry et al. 1995; Sorteberg & Walsh 2008), however it must be noted that the highest water vapour pressure ($e_{max\ abs}$) was not observed in the Atlantic Region (Godthåb 12.7 hPa), but in Siberia (Sagastyr 13.9 hPa).

In the annual course of e (Table 4, Fig. 3), at all the IPY-1 stations the highest content of water vapour in the atmosphere was recorded in July or August. In the Atlantic Arctic, the area of the Baffin Bay and in Alaska, monthly mean values of e in the summer season reached 7–8 hPa. On the other hand, in the north part of the

Canadian Arctic and on the Kara Sea, these did not exceed 5 or 6 hPa. In the cold season, that is, from November until March, the lowest amount of water vapour was observed. In that period, the mean value of e in the Atlantic Arctic ranged from 1.4 to 4.8 hPa, whereas in Siberia and Alaska only 0.2–0.9 hPa. The annual course of absolute values ($e_{max\ abs}$ and $e_{min\ abs}$) was similar to the one for the mean values (e). At most of the stations, $e_{max\ abs}$ were observed in August or July and the highest of those exceeded 13 hPa. Only at one station, Lady Franklin Bay, was the absolute maximum value recorded in June. The lowest values of $e_{min\ abs}$ were frequent during the winter months.

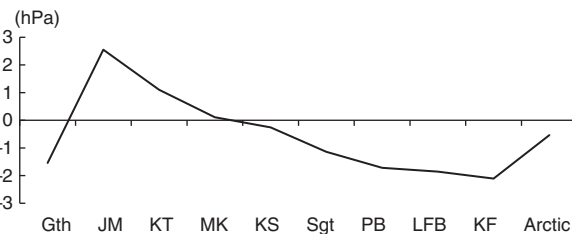


Fig. 4 Differences in water vapour pressure (hPa) between October and May in the Arctic during the first International Polar Year, in 1882–83. Station names are abbreviated as follows: Godthåb (Gth), Jan Mayen (JM), Kapp Thordsen (KT), Malye Karmakuly (MK), Kara Sea (KS), Sagastyr (Sgt), Point Barrow (PB), Lady Franklin Bay (LFB) and Kingua Fjord (KF).

Table 5 Seasonal standard deviations of e (hPa) and RH (%) at nine stations operating in the Arctic during the first International Polar Year, 1882–83. Station names are abbreviated as follows: Godthåb (Gth), Jan Mayen (JM), Kapp Thordsen (KT), Malye Karmakuly (MK), Kara Sea (KS), Sagastyr (Sgt), Point Barrow (PB), Lady Franklin Bay (LFB) and Kingua Fjord (KF).

Station	SON		DJF		MAM		JJA	
	e	RH	e	RH	e	RH	e	RH
Gth	1.8	11.7	1.0	12.8	1.3	9.0	1.0	8.4
JM	1.6	8.9	1.9	5.5	1.5	6.8	1.2	4.6
KT	1.5	9.7			1.6	9.8	1.0	8.4
MK	2.2	10.2	1.5	8.8	1.6	9.9	1.1	10.7
KS	1.4	0.7	1.0	0.5	1.4	7.1	0.8	3.5
Sgt	2.5	4.2	0.2	2.8	1.4	4.6	1.4	4.9
PB	2.1	5.5	0.5	5.8	1.7	5.8	1.5	3.6
LFB	0.9	10.6			1.1	14.9	0.9	5.8
KF							1.4	8.5

The most developed annual courses of e occurred in those regions of the Arctic where the climate was the most affected by continentality, that is, in Siberia and the Canadian Arctic, as well as in Alaska (Fig. 3). At all the analysed stations, the greatest variations in e took place between April and June (positive) and between September and November (negative). In the summer and winter months, the course of e was stable.

The annual course of e revealed an evident asymmetry (Fig. 4). In the Atlantic Arctic a higher mean value of water vapour pressure (ca. 1.3 hPa) was recorded in the autumn than in spring, while the opposite pattern occurred in the Siberian, Canadian, Pacific and Baffin Bay regions (a difference of ca. 1–2 hPa).

The greatest day-to-day changes in e in the Atlantic Arctic occurred in the autumn and winter seasons (Table 5, Fig. 3). These must have been caused by atmospheric circulation, due to the open Atlantic waters that lack an ice-pack in the seasons mentioned above (ACSYS 2003), which brought in air masses of different temperature and humidity. This is the interpretation assumed by Przybylak (1992) for the area of the south Spitsbergen in modern times, confirmed for the IPY-1 period by the values of standard deviation of e which amounted to 1.8 and 2.2 hPa at Godthåb and Malye Karmakuly, respectively, in the autumn, and 1.9 hPa at Jan Mayen in the winter. In the summer, the variations in water vapour pressure were smaller at the Atlantic Region stations and the standard deviation fell within the range of 0.8–1.2 hPa.

In Siberia and Alaska, the greatest day-to-day variability occurred in the autumn as well. In that season, the standard deviations at Sagastyr and Point Barrow were 2.5 and 2.1 hPa, respectively (Table 5). However, the smallest variability at the two stations was not observed in the summer, but in the winter (SD = 0.2 and 0.5 hPa). Such stable values of e (Fig. 3) resulted from an increased atmospheric pressure which was prevalent in the area at the time (Wood & Overland 2006; Wyszynski 2012;

Przybylak et al. 2013). This also contributed to a higher frequency of bright days (Wyszynski 2012). According to Przybylak (1992), this type of weather occurs on Spitsbergen during the inflow of intensely chilled air masses with very low water vapour content. The lack of cloud cover also favours reduction of air temperature through the greater loss of heat from surface to space through infrared radiation. Therefore, the fluctuations of e were considerably smaller. In the summer seasons, these were comparable to the variations observed in the spring.

Relative humidity (RH)

Relative humidity, being the measure of saturation of atmospheric air with water vapour, is the most frequently used parameter to describe the humidity of air in the Arctic. In the winter, RH should be calculated with reference to the maximum pressure of water vapour over ice (E_{ice}), which is lower than over water (E_{water}). Therefore, the air is oversaturated with water vapour when RH is determined over ice. The state of oversaturation of air with water vapour within the atmospheric boundary layers in the Arctic, where there is no condensation, occurs most frequently in the winter at very low temperatures (Przybylak 2003).

The correlation above was observed and described by Malmgren (1926), a scientific assistant to H.U. Sverdrup, as he was analysing observation data collected during a Norwegian polar expedition in the Arctic, on board the *Maud* in 1922–25. As Fig. 5 clearly shows, the differences between relative humidity calculated for ice (RH_{ice}) and for water (RH_{water}) are big, exceeding 30%. Oversaturation of the air with water vapour in the areas of the Arctic where a continental type of climate prevails usually holds on from November until March, so this must be taken into consideration when analysing data for the cold season of the year.

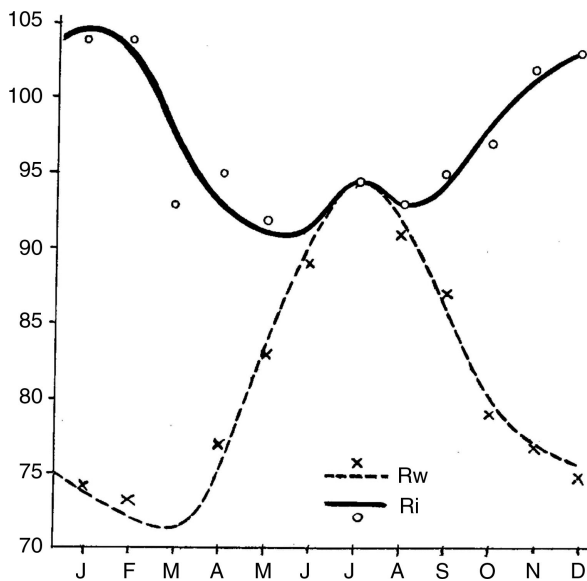


Fig. 5 Mean annual course of relative humidity (RH , %), in the Arctic Ocean. Source: Malmgren (1926). R_w denotes RH with respect to the water; R_i denotes RH with respect to the ice.

During IPY-1 the mean monthly values of RH in the Arctic (calculated for measurements taken over water) for the common reference period of May–July 1883 were high and exceeded 80% (Table 6). The highest mean RH of all the stations considered during IPY-1 was recorded in Siberia (Sagastyr 91.8%), whereas the lowest mean was obtained on Spitsbergen (Kapp Thordsen 79.8%). A high RH (90%) was also observed in the area of the Norwegian Sea (Jan Mayen), characterized by the greatest influence of climate oceanicity.

The annual courses of RH (Table 6, Fig. 6) in the areas of the Arctic which were affected by frequent cyclonic activity, that is, in the Norwegian Arctic (Jan Mayen, Kapp Thordsen), on the Barents and Kara seas (Mal'ye Karmakuly, Kara Sea) and on the coast of Baffin Bay (Godthåb, Kingua Fjord), were rather balanced, with individual values falling within the range of 75–90%. Such annual courses of RH are observed in the Norwegian Arctic today, as well (Araźny 2003). Moreover, monthly mean diurnal amplitudes of RH (i.e., the differences between RH_{max} and RH_{min} ; see Fig. 6) were relatively steady and amounted to 15–25% in specific months. More distinct changes in the annual courses of RH were observed in Siberia (Sagastyr) and Alaska (Point Barrow), where the annual course of RH resembled the annual course of the air temperature (see Przybylak et al. 2010). The highest monthly mean of RH at those stations was observed in July or August (> 90%), whereas the lowest values were recorded in February, March or April. Monthly mean amplitudes of the diurnal values of RH in

Siberia and Alaska (Fig. 6) reached ca. 15% in the late spring, summer and early autumn when the effects of solar radiation were the greatest, but only 5–6% in the winter.

In the north part of the Canadian Arctic (Lady Franklin Bay), the highest mean monthly diurnal amplitudes of RH (Fig. 6) were observed in October (24%), April (50%) and May (24%). In the summer months, on the other hand, the variability of RH did not exceed 12–16%. In the autumn and spring seasons, at the Lady Franklin Bay the highest day-to-day variability in RH was noted ($SD = 10.6\%$ and 14.9%). Such high mean monthly diurnal amplitudes (particularly in April) and day-to-day changes in RH at the station seem hard to explain. These should instead be associated with difficulties faced during hygrometric measurements in the cold seasons of the year. Naturally, the observations continued from November until March, yet the researchers refrained from publishing the results in reports due to their uncertainty as to the reliability of the data; the report of the American expedition (Greely 1886), for example, contains only fragmentary measurements of RH for the cold season months.

During IPY-1 there were situations in the Arctic where the relative humidity was found to decrease substantially (Fig. 7). On 11 January 1883, RH at Godthåb remained at a level of 90–100% during the first half of the overcast day (10, stratus) with air masses flowing from the south-west sector. In the evening though, the air started to come from the east, which resulted in a decrease in the air temperature of 2–3°C and a decrease in the amount of cloud cover to 0–2 (mainly cirrostratus). A katabatic flow of dry air (e values were 1.0–1.5 hPa) and cold Greenland air brought in a drop in relative humidity to ca. 45% within only a few hours. Such dramatic decreases of RH resulting from the effects of katabatic flows are also observable today (Renfrew & Anderson 2002). The situation continued until the afternoon of 13 January 1883, only disrupted by an inflow of warmer and more humid air from the south-west which lasted for a few hours on 12 January. Eventually, on 14 January the direction of the wind changed back to southerly, bringing warm and humid air ($RH > 80\%$) from over the Atlantic Ocean, which made the sky overcast.

The data gathered by the Dutch expedition on the Kara Sea provided the basis for the conclusion that the air there was permanently saturated with water vapour ($RH_{ice} > 100\%$) in the period from November 1882 until March 1883 (see Fig. 5). This assumption was supported by the values of $RH_{min\ abs}$, which did not fall below 96% in the period concerned, and the mean values of RH , which were 100% (Table 6, Fig. 6). The observers considered the saturation point to be when the hair of the hygrometer

Table 6 Basic characteristics of relative humidity (*RH*, %) at nine stations operating in the Arctic during the first International Polar Year, 1882–83.

Station	Parameter	A	S	O	N	D	J	F	M	A	M	J	J	A	MJJ
Godthåb	<i>RH_{max abs}</i>	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	<i>RH</i>	89.8	85.9	78.5	74.5	75.7	80.8	92.8	85.0	84.1	88.0	87.5	88.8	84.5	88.1
	<i>RH_{min abs}</i>	42.0	32.0	43.0	38.0	33.0	12.0	54.0	26.0	40.0	51.0	52.0	33.0	30.0	33.0
Jan Mayen	<i>RH_{max abs}</i>	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0		100.0
	<i>RH</i>	93.0	89.7	92.5	85.2	91.2	91.8	88.8	82.7	86.0	86.8	92.5	91.4		90.2
	<i>RH_{min abs}</i>	57.0	60.0	49.0	46.0	64.0	71.0	29.0	56.0	58.0	53.0	59.0	69.0		53.0
Kapp Thordsen ^b	<i>RH_{max abs}</i>	96.0	100.0	100.0						97.0	97.0	100.0	100.0	100.0	100.0
	<i>RH</i>	77.3	82.2	83.6						72.9	70.3	85.5	83.6	78.6	79.8
	<i>RH_{min abs}</i>	57.0	56.0	50.0						49.0	38.0	51.0	51.0	41.0	38.0
Malye Karmakuly ^c	<i>RH_{max abs}</i>		100.0	100.0	100.0	100.0	100.0	100.0	100.0	99.0	99.0	99.0	99.0	100.0	99.0
	<i>RH</i>		95.2	86.8	82.1	85.9	81.7	90.1	79.2	80.4	80.1	87.3	84.6	78.3	84.0
	<i>RH_{min abs}</i>		71.0	50.0	31.0	56.0	46.0	62.0	48.0	36.0	48.0	49.0	49.0	31.0	48.0
Kara Sea ^d	<i>RH_{max abs}</i>			100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0		100.0
	<i>RH</i>			99.5	99.9	99.8	99.6	100.0	98.7	96.6	85.5	92.0	96.6		91.4
	<i>RH_{min abs}</i>			88.0	98.0	96.0	97.0	100.0	88.0	81.0	58.0	77.0	85.0		58.0
Sagastyr	<i>RH_{max abs}</i>		100.0	100.0	98.0	90.0	89.0	89.0	92.0	100.0	100.0	100.0	100.0	100.0	100.0
	<i>RH</i>		89.0	89.6	87.3	81.9	83.2	80.7	83.6	86.8	91.4	91.9	92.2	90.6	91.8
	<i>RH_{min abs}</i>		56.0	78.0	79.0	71.0	79.0	76.0	80.0	59.0	64.0	63.0	63.0	58.0	59.0
Point Barrow ^e	<i>RH_{max abs}</i>	97.0	97.0	95.0	94.0	97.0	98.0	97.0	93.0	86.0	98.0	97.0	98.0	97.0	98.0
	<i>RH</i>	86.5	87.9	85.2	84.1	87.1	85.1	80.1	76.5	77.0	85.3	87.6	87.8	90.3	86.9
	<i>RH_{min abs}</i>	57.0	60.0	75.0	62.0	80.0	67.0	68.0	67.0	66.0	73.0	74.0	70.0	67.0	70.0
Lady Franklin Bay ^f	<i>RH_{max abs}</i>	97.0	100.0	100.0						100.0	100.0	99.0	95.0		100.0
	<i>RH</i>	80.0	93.7	83.0						67.4	87.9	80.1	78.4		82.1
	<i>RH_{min abs}</i>	54.0	25.0	19.0						9.0	32.0	58.0	56.0		32.0
Kingua Fjord ^g	<i>RH_{max abs}</i>			100.0						98.0	100.0	100.0	100.0	100.0	100.0
	<i>RH</i>			76.6						78.4	78.8	82.5	81.6		79.9
	<i>RH_{min abs}</i>			50.0						44.0	32.0	54.0	46.0		32.0
	<i>RH_{max abs}</i>			100.0						100.0	100.0	100.0			100.0
Arctic	<i>RH</i>			86.2						83.7	87.0	87.3			86.0
	<i>RH_{min abs}</i>			19.0						32.0	32.0	33.0			32.0

^a*RH_{max abs}*, *RH_{min abs}* are the highest and the lowest observed relative humidity, *RH* is mean monthly relative humidity.

^bAugust 1882 days 1–14 without data, August 1883 days 24–31 without data.

^cDecember 1882 days 13–16 without data.

^dOctober 1882 days 1–9 without data, November 1882 days 4–8, 12–14 without data, December 1882 days 21, 24–31 without data, January 1883 days 16–31, March 1883 days 17–22 without data.

^eAugust 1883 days 28–31 without data.

^fObservations every 4 h, August 1882 days 1–4 without data, November 1882 days 1–2, 8–9, 13, 15, 18–21, 24–27, 29–30 without data, October 1882 days 5, 19 without data, April 1883 days 1–3, 17, 24, 27–28 without data, May 1883 days 9, 23–24 without data.

^gOctober 1882 days 1–26.

was covered by hoar frost (for more details see Supplementary file 1). According to Malmgren (1926), hoar frost is generally formed when *RH_{ice}* is greater than 100% but never when *RH_{ice}* is below 100%. Moreover, the probability of hoar frost building increases when the wind velocity is low (up to 2 ms⁻¹). Such winds often occurred on the ice-pack of the Kara Sea during the IPY-1 period. Their frequency from November 1882 to March 1883 was 30–50% (Wyszynski 2012).

Throughout the year, days with the maximum saturation of air with water vapour occurred at nearly all the IPY-1 stations (with the exception of Sagastyr and Point Barrow) (Table 6). On the other hand, at the Sagastyr station in Siberia the air never reached the level of

complete saturation from November until March (the values of *RH_{max abs}* were lower than 100%). At Point Barrow, the saturation deficit persisted year-round.

Day-to-day variability of *RH* in the areas of the Atlantic Arctic and Alaska influenced by intense cyclonic activity was the greatest in the cold time of the year, and the lowest in the summer. In the area of the Kara Sea, the waters of which were frozen over in the early spring (Hovgaard 1884), resulting in a unification of the geographical environment, the smallest day-to-day variability in *RH* was observed in the autumn and winter seasons (SD = 0.5–0.7%). When the sea ice was melting in the spring, on the other hand, the day-to-day changes were considerably greater (SD = 9.9%). In the area where the

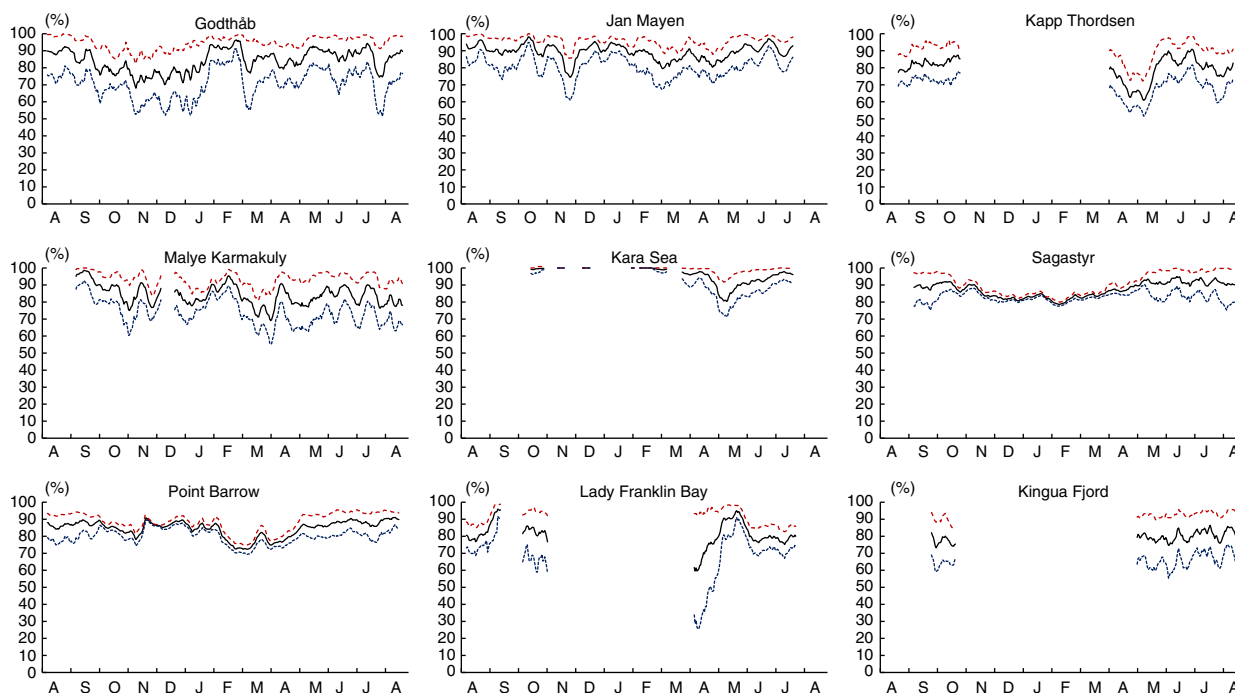


Fig. 6 Annual courses of relative humidity parameters (%) in the Arctic in the period of the first International Polar Year, in 1882–83, according to 11-day running averages. Mean daily (black solid line), daily maximum (red dashed line) and minimum (blue dotted line) relative humidity are presented.

continentality affected the climate the most (Sagastyr), the variability in *RH* followed a different day-to-day pattern than in the areas characterized by the maritime climate.

Comparison with present-day conditions

The mean values of *RH* in the IPY-1 period (September 1882 to July 1883) for five of the nine stations analysed were higher than today's values, by 2.4–5.6%, because the air temperature was colder at that time than today, by 1.0–1.5°C on average (for more details see Przybylak et al. 2010). Values higher than those currently prevailing were noted mainly in the Norwegian Sea and Barents Sea regions (5.6 and 5.0%, respectively), whereas in the continental part of the Arctic (the Siberian region represented by Sagastyr station), the positive differences were smaller and their variability around the modern long-term (1961–1990) monthly means were the most stable (Table 7).

Because the content of the water vapour pressure in the Arctic is generally small, so the changes in *RH* are mainly the function, as mentioned above, of air temperature changes. The highest positive anomalies of *RH*, exceeding +2 SDs in some months (Fig. 8) were noted in the Atlantic Arctic. These noticeable differences were the result of atmospheric circulations carrying, in the vicinity

of the analysed stations, air masses characterized by different thermal and humidity conditions. For example, in February of 1883 in Godthåb, the greatest noted positive anomaly of *RH* occurred while the station was under the influence of cold air masses (Table VIII in Przybylak et al. 2010). On the other hand, in February of 1883 in Malye Karmakuly, the large positive *RH* anomaly (13.4%) there was connected with the inflow of warmer but very wet air masses (Fig. 3) from the south–SSW direction (Wyszynski 2012). Large positive anomalies (by 10–13%) were also noted at Point Barrow in winter, which was characterized by strong negative thermal anomalies in comparison with present-day conditions. Such variation in *RH* is also observable today, indicated by the high range of ± 2 SDs in the cold half of the year (Fig. 8).

Despite the exemplary cases described above, most of the observed changes between historical and modern *RH* values are not significant. The majority of historical daily *RH* values lie between a distance of +2 SDs from the present long-term (1961–1990) monthly means (Fig. 8).

Conclusions

Meteorological data gathered for the Arctic during IPY-1 are the best in terms of coverage, quality, resolution and other characteristics out of all the early instrumental data

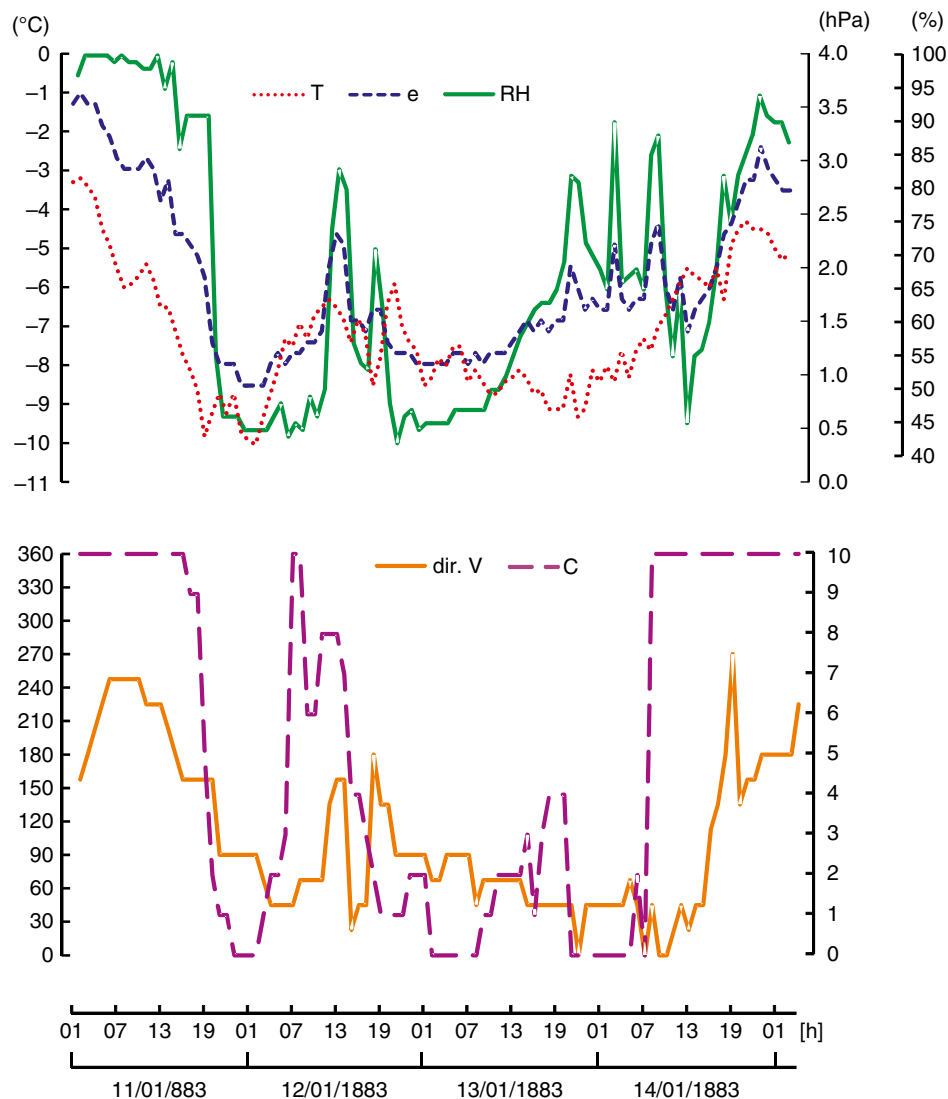


Fig. 7 Courses of relative humidity (*RH*, %), water vapour pressure (*e*, hPa), air temperature (*T*, °C), wind directions (*dir. V*, 0–360°) and cloud cover (*C*, 0–10) in Godthåb on 11–14 January 1883.

Table 7 Relative humidity differences (%) between mean monthly values from the first International Polar Year, 1882–83, and the modern period (1961–1990). Positive values are shown in boldface.

Station ^a	A	S	O	N	D	J	F	M	A	M	J	J	A	SEP-JUL
Godthåb ^b	3.0	3.5	0.9	–1.8	–1.0	3.5	14.0	4.2	3.2	3.7	3.1	2.3	–2.3	3.2
Jan Mayen ^c	6.9	6.9	10.4	5.4	9.5	8.6	6.3	–0.4	3.7	2.2	5.9	3.3		5.6
Malye Karmakuly ^d		10.8	5.1	2.5	6.6	3.8	13.4	1.1	4.2	0.5	4.0	2.8	–5.1	5.0
Sagastyr ^e		1.0	2.5	4.3	–0.3	2.5	–0.2	2.0	3.3	4.8	1.8	4.2	1.8	2.4
Point Barrow ^f	–4.1	–2.3	0.2	5.3	13.5	12.8	10.5	6.1	1.1	–1.0	–0.6	0.2	–0.3	4.1

^aFor purposes of comparison, data from the following modern stations located at the same sites, or nearest to the historical stations, have been used.

^bNuuk.

^cJan Mayen.

^dMalye Karmakuly.

^eSagyllah Ary.

^fPoint Barrow.

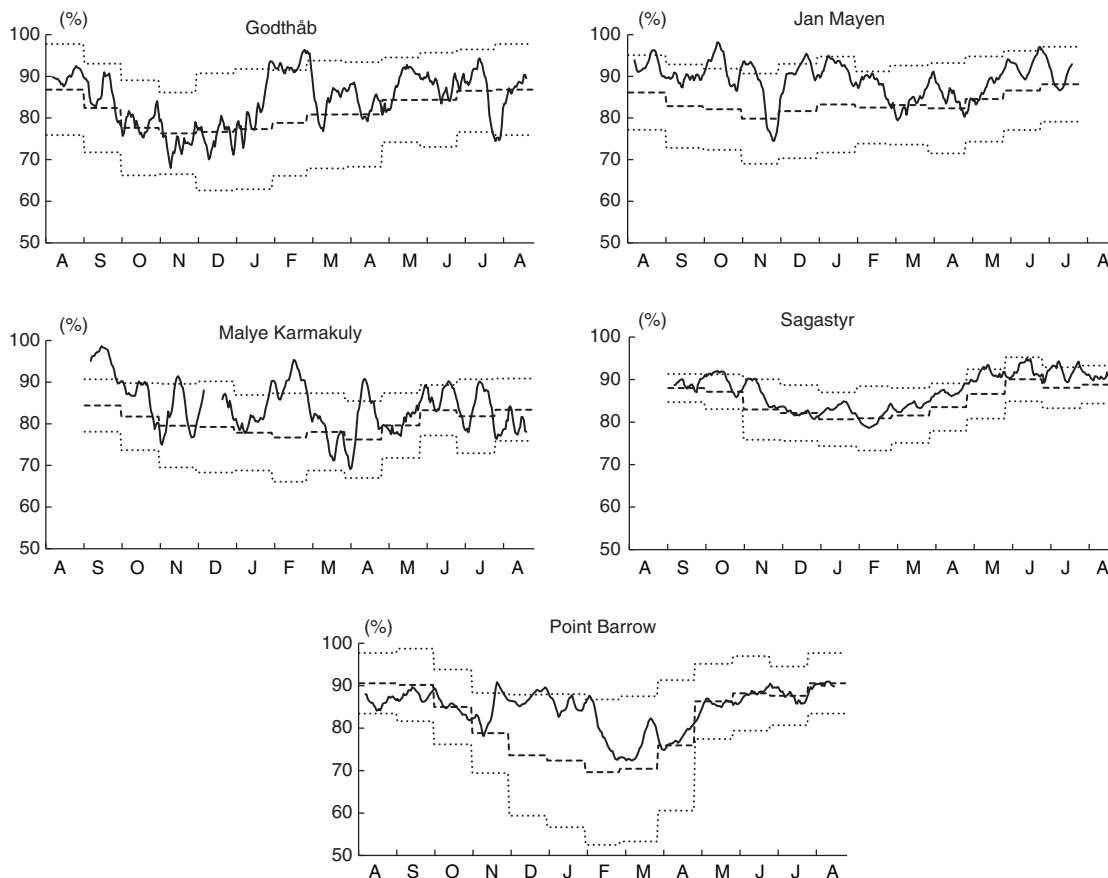


Fig. 8 Annual courses of historical International Polar Year 1882–83 (solid line) and modern (1961–1990, dashed line) relative humidity (*RH*, %). Standard deviations (± 2 SD, dotted lines) have been calculated on the basis of the present data. International Polar Year courses are based on daily means, modern and SDs based on monthly means. Data from the modern stations located nearest the historical stations have been used (see Table 7).

for the area. Research carried out during the IPY-1 scientific expeditions brought a significant contribution to the development of hygrometry in polar regions at the end of the 19th century.

The spatial distribution of atmospheric water vapour in the Arctic during IPY-1, in the common observational period (May–July 1883), was similar to the present distribution. The highest monthly means of e for the common reference period of May–July 1883 were determined for the area of Baffin Bay (6.8 hPa) and the Atlantic Ocean (6.0 hPa), where the oceanic influences were the greatest. In the north part of the Canadian Arctic, where the continental type of climate prevails, lower values of water vapour pressure predominated (4.6 hPa) in comparison with the areas subject to the oceanic climate.

In the annual course, the highest values of e during IPY-1 were noted in July and August, while the lowest were in the cold half of the year. The annual course of e is evidently asymmetrical. In the Norwegian Arctic, more water vapour (by about 1.3 hPa) was in the air in autumn

than in spring, while the opposite relation occurred in Siberia and the American Arctic.

Monthly means of *RH* were high, and most often exceeded 80%. The highest mean of *RH* of all the IPY-1 stations was observed in Siberia (91.8%), and the lowest on Spitsbergen (79.8%). A high *RH* was found in the area of the Norwegian Sea (90%), with the most oceanic climate. Over the year, the course of relative humidity in the areas of the Arctic that are subject to cyclonic activity remained fairly constant, that is, in the Norwegian Arctic, the basin of the Barents and Kara seas, as well as in Baffin Bay, with values within the range of 75–90%. This kind of annual course of *RH* in the Norwegian Arctic is also observed at present (Araźny 2003).

In comparison to present-day conditions, mean *RH* values in the IPY-1 period (September 1882 to July 1883) were higher by 2.4–5.6%. The greatest differences mainly occurred in the Atlantic Arctic, whereas in the continental part of the Arctic the positive differences were smaller and more stable (Table 7). Most of the observed changes

between historical and modern *RH* values are not significant. The majority of historical daily *RH* values lie between a distance of +2 SDs from the present long-term (1961–1990) monthly means.

Acknowledgements

The research in this article was supported by the Variability of the Russian Arctic and Subarctic Climate in the Last Three Hundred Years grant, funded by the National Science Centre (Decision No. DEC-2012/07/B/ST10/04002) and by the Polish–Norwegian Fund as part of the Arctic Climate System Study of Ocean, Sea Ice and Glaciers Interactions in the Svalbard Area project (AWAKE-2). We would also like to thank Dr Zsuzsanna Vízi for assistance in calculating the water vapour pressure for Point Barrow in the FORTRAN programming language.

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