Seasonal, interannual and long-term variability of precipitation and snow depth in the region of the Barents and Kara seas

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Observation data of temperature, precipitation and snow depth have been compiled and generalized climatologically for a network of 38 stations in and around the Barents and Kara seas, for the period 1951–1992. The monthly precipitation totals were corrected for measuring errors, and the correction method is described in detail. The corrected precipitation values show that the annual precipitation in the region ranges from more than 500 mm along the coast of the Kola Peninsula to less than 200 mm in parts of the north-eastern Kara Sea. The solid fraction of the annual precipitation ranges from 70 % in northern parts to 35 % in southern parts. For the period 1951–1992 the analysis indicates decreasing trends in annual values of temperature, precipitation and snow depths in the north-eastern parts of the region.

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Meteorological observations have been made at a network of stations in and around the Barents and Kara seas. In this paper, observations of temperature, precipitation and snow depth are compiled and analysed, mainly for the years spanning 1951 and 1992. This period was chosen because of the availability of precipitation observations from these years at all stations. This period also covers the main peculiarities of climatic changes in the Arctic over the years of most intense meteorological studies since the late 1930s: after the warming event in the Arctic in the 1930s, there was a temperature decrease up to the mid-1960s; from the second half of the 1960s and up to the present, the temperature increases.

Variation in the freshwater budget in this region is also important in the context of global climate change (Walsh et al. 1998) as it may be linked to the intermittency of North Atlantic deep water formation and the global thermohaline circulation, which is a major determinant of global climate. The Arctic freshwater budget is driven by river runoff, accumulation/ablation of glaciers and precipitation over the Arctic Ocean. Spatial and temporal characteristics of solid precipitation are important, because snow cover directly influences the formation and destruction of the ice cover in the Arctic seas. A significant volume of fresh water penetrates rapidly into the upper layers of the ocean during the melting of snow in spring. However, it is difficult to estimate what portion of the freshwater balance of the Arctic region comes from precipitation. This is connected with the fact that all existing methods of precipitation measurement give significant errors, especially during snowstorms. To obtain objective estimates both of the amount of precipitation over different periods of time and of its variability at different time scales (from intra-annual to multiyear), correction of the measurement results is necessary. The methodology applied in this study is described below, along with the results of analysis of variability parameters of the corrected monthly precipitation totals, snow cover thickness and temperature at the meteorological stations in the study area. The resulting data can be of use for estimates of the contribution of precipitation to the freshwater balance of the Barents and Kara seas in different seasons of the year and in general for the period 1951–1992.

Meteorological observations and climatic conditions in the region of the Barents and Kara seas

Systematic meteorological observations in the region of the Barents and Kara seas have been carried out since the end of 19th century. However, the main network of meteorological stations was established in the 1930s and 1940s. Meteorological observations at the stations were performed according to the manual for hydrometeorological stations and posts (Nastavlenie 1985). Meteorological observations were made around the clock. Observation hours were changed several times within the period of record. Observations were performed at 01:00, 07:00, 13:00 and 19:00 local solar time from 1936 to 1965, and at 00:00, 03:00, 06:00, 09:00, 12:00, 15:00, 18:00 and 21:00 Moscow local time from 1966 to 1991. (There have been major problems with meteorological observation in the Russian Arctic in the 1990s.) The parameters measured at the stations are described in the Appendix. A detailed description of the meteorological observations and their accuracy is presented in Fetterer & Radionov (2000). The original data from standard meteorological observations are now kept at the All-Russian Research Institute of Hydrometeorology, World Data Center (RIHMI), Obninsk, Russia, and are partly digitized. Average monthly values of meteorological parameters were calculated from individual observations, and from the mid-1960s on, they were published in Russian in regular issues of the *Monthly weather report* (MWR) prepared at RIHMI. We have used mean monthly values of precipitation, temperature and wind speed from the MWRs and from other publications (*Nauchno-prikladnoy spravochnik* 1988–1991; *Spravochnik* 1965–68; National Snow and Ice Data Center 2003) for our investigation.

The locations of the stations are shown in Fig. 1 and their names, coordinates and elevation are presented in Table 1. In the Barents Sea region the stations are mostly located on mainland coasts, while in the Kara Sea region some stations are located on islands.

The period 1951 to 1980 was selected as the basic one to calculate the average monthly stand-

Table 1. Meteorological stations in the region of the Barents and Kara seas.

No.	Station	Elevation (m a.s.l.)	Lat. N	Long. E
1	Barentsburg	70	78° 04'	14° 13'
2	Bjørnøya	16	74° 31'	19° 01'
3	Vayda-Guba	8	69° 56'	31° 59'
4	Murmansk	51	68° 58'	33° 03'
5	Tsyp-Navolok	24	69° 43'	33° 08'
6	Viktoria Island	8	80° 09'	36° 46'
7	Tersko-Orlovsky lighthouse	72	67° 12'	41° 20'
8	Kanin Nos Cape	48	68° 39'	43° 18'
9	Shoyna	16	67° 53'	44° 08'
10	Nagurskaya	15	80° 49'	47° 38'
11	Indiga	4	67° 42'	48° 46'
12	Kolguev Island	12	69° 30'	49° 05'
13	Bugrino	11	68° 47'	49° 21'
14	Malye Karmakuly	16	72° 23'	52° 44'
15	Narjan-Mar	7	67° 39'	53° 01'
16	Menshikova Cape	12	70° 43'	57° 36'
17	Rudolpha Island	52	80° 48'	57° 58'
18	Bolvanskiy Nos	13	70° 27'	59° 04'
19	Amderma	53	69° 46'	61° 41'
20	Russkaya Gavan	18	76° 11'	63° 34'
21	Harasavey Cape	10	71° 08'	66° 49'
22	Marresalya	24	69° 43'	66° 49'
23	Zhelaniya Cape	8	76° 57'	68° 34'
24	Im. M.V. Popova	4	73° 20'	70° 02'
25	Vilkitsky Island	3	73° 31'	75° 46'
26	Vize Island	10	79° 30'	76° 59'
27	Ushakova Island	47	80° 49'	79° 33'
28	Leskina Cape	10	72° 21'	79° 33'
29	Dikson Island	42	73° 30'	80° 14'
30	Uedineniya Island	22	77° 30'	82° 14'
31	Isvestuya Tsyk Island	11	75° 32'	83° 05'
32	Sterlegova Cape	10	75° 25'	88° 54'
33	Isachenko Island	10	77° 09'	89° 12'
34	Golomyanny Island	7	79° 33'	90° 37'
35	Pravdy Island	10	76° 16'	94° 17'
36	Russky Island	9	77° 10'	96° 26'
37	Krasnoflotskiye Island	8	78° 38'	98° 43'
38	Geiberga Island	6	77° 36'	101° 31'

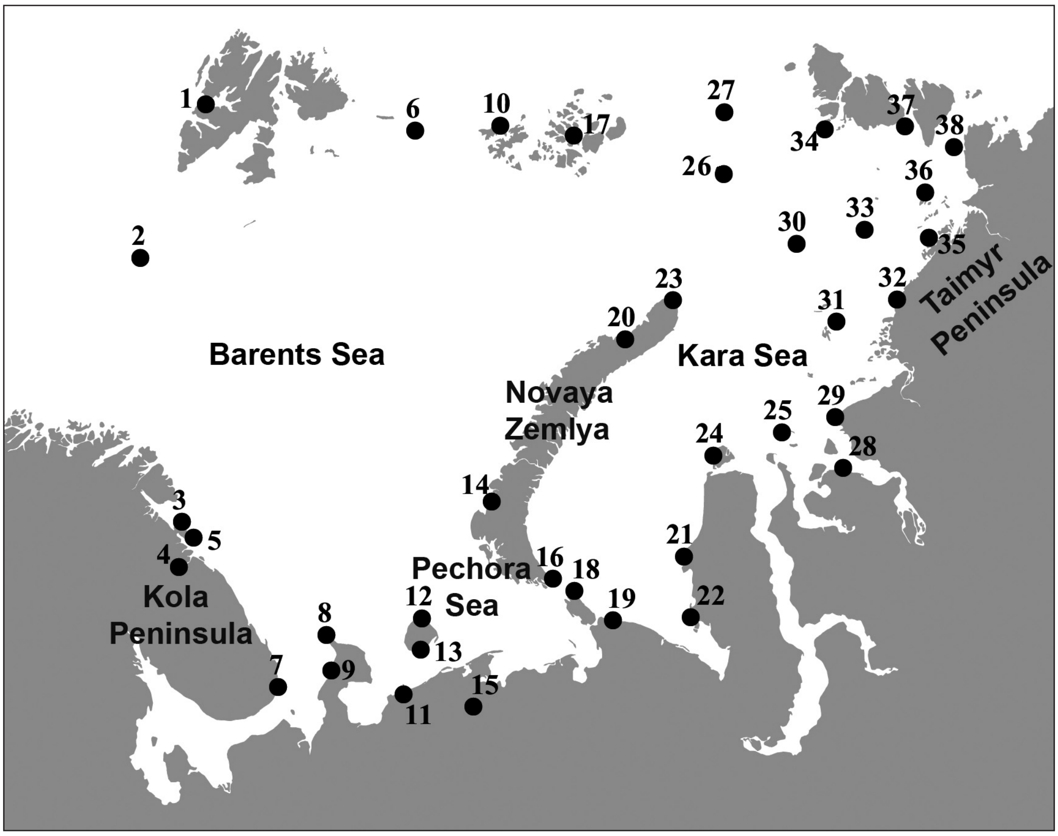

Fig. 1. Location of meteorological stations.

ards. It encompasses the post-1940s regional cold spell in the climate as well as the period with warming from the mid-1960s.

Climatic conditions in the region are characterized by the high latitude position and non-uniform incoming solar radiation within a year. The atmospheric circulation also exerts a significant influence on the climate. Atlantic air masses penetrate into this region with frequent and sometimes intense cyclones. Extensions of the Arctic and Siberian high pressure systems also reach the area.

The underlying surface plays an important role for the climate conditions in the region. The Barents Sea, in the western part of the region, is never completely covered with ice. The central and south-eastern Barents Sea contains first-year ice of local formation. Ice formed during the cold period of the year melts completely during the warm period. From July through October there is open water in the south-eastern Barents Sea. During the other eight months, ice covered by snow is observed. Multi-year ice transported by wind and currents from the Arctic Basin and the Kara Sea is observed in the extreme north and the north-eastern Barents Sea area. The Kara Sea, in the eastern part of the region, is ice-covered during most of the year. The compact ice cover slightly smoothes the climatic contrasts of some areas. Ice impedes heat exchange between ocean and atmosphere, but does not completely abolish it. That is why the climate over the Kara Sea in winter is warmer than that over the adjacent continental areas.

The climate of the region is rather severe: long winters, long duration of snow cover in the eastern area, short intermediate seasons (spring and autumn), short and cool summers, early frosts in autumn and late ones in spring, and in the eastern part of the region, some years have no days with a mean temperature $\geq 0°$. The climate becomes more severe, on the whole, from west to east.

Processing of observed precipitation values in the Arctic

Frequent precipitation and long duration of snow cover are characteristic features of the climate in the northern polar area. In spite of the frequent occurrence of precipitation in the Arctic, the total amount is much smaller than in temperate latitudes. In addition, the error in an individual precipitation measurement during winter snowstorms can comprise 200 % and more. Therefore, the analysis of the variability of monthly and annual precipitation totals requires an accurate correction of measurement errors.

The World Meteorological Organization (WMO) pays a great deal of attention to the problem of precipitation measurement correction. Since 1985, when the WMO initiated the Solid Precipitation Measurement Intercomparison Project (Goodison et al. 1998), investigators from several countries have made substantial contributions to resolving this problem (Yang et al. 1995; Førland et al. 1996; Golubev et al. 1999; Yang 1999; Førland & Hanssen-Bauer 2000; Yang & Ohata 2001; Bogdanova et al. 2002). A very good review of the methods for correction and intercomparison of precipitation measurements in the Arctic was made by Bogdanova et al. (2002).

Russian scientists began developing correction methods in the late 1960s. This work resulted in creation of specific methodologies and recommendations for correction of the precipitation observation series (Struser & Bryazgin 1971; *Rekomendatsii* 1980; *Metodicheskie ukazaniya* 1985). However, these and many other studies were published only in Russian and are practically unknown outside Russia. A methodology for correction of the monthly precipitation totals was developed by N. N. Bryazgin specifically for Arctic conditions. This methodology has been successfully used at the Arctic and Antarctic Research Institute for more than 20 years for the analysis of interannual and multiyear variability of precipitation and snow cover parameters in the Arctic region. Its main principles were presented at a workshop (Bryazgin 1996). Below, we present the methodology in detail, probably for the first time in English.

First of all, it was difficult to obtain homogeneous precipitation series because different equipment was used. A rain gauge with a Nipher shield was used to carry out the measurements in the region before 1954. The main error of this gauge is connected with solid precipitation blowing out of it. The precipitation gauge of Tretyakov (O-1) was used starting in 1952. The main error of the Tretyakov gauge is connected with wind effects around the gauge, and the influence of drifting/blowing snow. The change of instruments caused inhomogeneity within the data series, especially during the winter season. This effect is apparent from Table 2.

In 1950–54, comparisons of these two precipitation gauges were organized at the Arctic stations. It was concluded (Bryazgin 1976) that the systematic differences between precipitation monthly totals measured by Tretyakov gauge and rain gauge with Nipher shield:

(1) were always positive;
(2) depended on the type of precipitation (solid, mixed, liquid);
(3) depended on the amount of precipitation when the precipitation was solid;
(4) increased with increasing wind speed regardless of the type and amount of precipitation.

Based on these comparisons, Bryazgin (1976) elaborated a methodology for adjusting the monthly precipitation totals obtained using the rain gauge with Nipher shield to those obtained with the Tretyakov precipitation gauge. Later this methodology was formalized and published in Russian (*Rekomendatsii* 1980) and in English (Bryazgin 1996).

To adjust the monthly precipitation totals measured by rain gauge with Nipher shield to those measured with Tretyakov's precipitation gauge, we used the coefficients published by Bryazgin (1996). These are presented in Table 3.

Table 2. Monthly precipitation totals in January at Dikson Island measured by rain gauge (1945–1952) and Tretyakov precipitation gauge (1953–1960).

Year	Jan total (mm)	Year	Jan total (mm)
1945	4	1953	49
1946	4	1954	168
1947	3	1955	86
1948	3	1956	49
1949	4	1957	32
1950	3	1958	39
1951	8	1959	18
1952	5	1960	13

When the average monthly air temperature is higher than +2 °C the precipitation was considered to be liquid within the month. In the western Barents–Kara region this period usually lasts from July through September. The period with an average monthly air temperature from +2 °C to –2 °C was taken to have had mixed precipitation. Periods with an average monthly air temperature below –2 °C were assumed to have had solid precipitation.

For our calculations, the monthly totals of precipitation obtained before 1954 by rain gauge with a Nipher shield were corrected using data of average monthly values of wind speed, temperature and monthly totals of precipitation for each station.

The method used for measuring the amount of precipitation at the stations necessitates systematic corrections for loss due to wetting of the inside parts of the gauge (Nastavlenie 1985). This error is equal to 0.2 mm for liquid and mixed precipitation and 0.1 mm for solid precipitation for each measurement done with the Tretyakov gauge. From 1966 on, this correction was introduced directly by observers at the stations and is taken into account in calculation of monthly totals of precipitation.

The monthly precipitation totals before 1966 were corrected for wetting loss (ΔP_w) with the following formula (*Rekomendatsii* 1980; *Metodicheskie ukazaniya* 1985):

$$\Delta P_w = q \cdot n$$

where n is number of days with ≥ 0.1 mm precipitation in a month, q is wetting loss per case according to Table 4.

In principle, it is necessary to account for moisture loss because of evaporation from the precipitation gauge between observation periods. The correction for evaporation (ΔP_E) depends on wind speed and air humidity, and is estimated with the following formula:

$$\Delta P_E = b \cdot d \cdot 0.75 \cdot v \cdot n$$

where b is an empirical coefficient (Table 4), d is average monthly deficit of saturation (hPa), v is average monthly wind speed (m/s) at a height of 10 m, and n is the number of days with ≥ 0.1 mm of precipitation. The long-term average value of ΔP_E in the studied area is 1 - 2 mm/month. Evaporation is a small source of error compared to the other factors that may cause errors in precipitation measurements in the Arctic. Thus the monthly totals of precipitation are not corrected for evaporation loss in this study.

The largest errors of precipitation measurements in the Arctic are connected with the influence of wind, especially in winter.

On the basis of long-term field experiments at different Arctic stations in the 1950s, Bryazgin determined that the wind-induced error—and thus the correction factor—depended on wind speed, precipitation type (solid, mixed, liquid), solid precipitation intensity or measured amount of solid precipitation, and on whether there were snowstorms within the specified month. He proposed a method for correction of wind-induced error in monthly totals of precipitation (*Rekomendatsii* 1980; Bryazgin 1996).

Table 3. Correction factors for adjusting precipitation monthly totals measured by rain gauge to those measured by precipitation gauge for liquid (C_L), mixed (C_M) and solid (C_S) precipitation.

Mean monthly wind speed (m/s)	C_L	C_M	C_S, if amount of solid precipitation measured by rain gauge is in the range (mm) of:		
			0 - 10	11 - 20	> 21
1	1.02	1.15	1.4	1.3	1.2
2	1.03	1.26	1.9	1.7	1.3
3	1.05	1.37	2.5	2.0	1.4
4	1.07	1.48	3.2	2.3	1.5
5	1.09	1.55	3.9	2.5	1.6
6	1.12	1.66	4.2	2.7	1.8
7	1.15	1.71	4.4	2.9	1.9
8	1.17	1.85	4.6	3.1	2.1
9	1.20	1.93	4.8	3.3	2.2
10	1.24	2.00	5.0	3.5	2.3
11	1.27	2.10	5.2	3.6	2.4
12	1.30	2.20	5.4	3.8	2.6
13	–	–	5.6	4.0	2.7
14	–	–	5.8	4.1	2.9

Table 4. Correction factors for wetting loss (q) and evaporation loss (b).

Prevailing precipitation type	q	b
Liquid precipitation (mean monthly air temperature higher than +2 °C)	0.30	0.004
Mixed precipitation (mean monthly air temperature from +2 °C to –2 °C)	0.20	0.012
Solid precipitation (mean monthly air temperature below –2 °C)	0.15	0.020

The monthly totals of precipitation are corrected for wind influence with the following formula:

$$P_C = P \cdot C$$

where P is measured precipitation (in mm) and C is a correction factor (C_L for liquid precipitation, C_M for mixed, C_S for solid; see Table 5).

The correction factors C_L and C_M, as well as C_S in months without snowstorms, are larger than 1.0, and they increase with increasing wind speeds (Table 5). However, in months with snowstorms, the measured amount gives an overestimate of the true precipitation because of snow blowing from the surface and into the gauge. Usually the blowing snow effects begin at wind speeds of 6 to 7 m/s (the wind speed is measured at a height of 10 m). In these cases the correction factor $C \leq 1$ (see Table 5).

Table 5. Correction factors for the influence of wind on monthly total of precipitation measured by Tretyakov gauge (C_L, liquid; C_M, mixed; C_S, solid precipitation).

Mean monthly wind speed (m/s)	C_L	C_M	C_S							
			Amount of measured solid precipitation (mm)							
			During snowstorms				Without snowstorms			
			0-10	11-20	21-50	>50	0-10	11-20	21-50	>50
0.0	–	–	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
0.5	1.00	1.03	1.08	1.07	1.06	1.05	1.10	1.08	1.06	1.04
1.0	1.02	1.05	1.16	1.14	1.12	1.08	1.18	1.16	1.14	1.12
1.5	1.04	1.07	1.23	1.20	1.17	1.12	1.27	1.20	1.17	1.15
2.0	1.06	1.10	1.30	1.27	1.22	1.16	1.36	1.25	1.20	1.19
2.5	1.08	1.12	1.37	1.35	1.28	1.17	1.45	1.32	1.27	1.24
3.0	1.10	1.14	1.48	1.42	1.24	1.18	1.51	1.40	1.35	1.29
3.5	1.12	1.17	1.39	1.31	1.22	1.12	1.63	1.50	1.42	1.38
4.0	1.14	1.20	1.30	1.26	1.18	1.06	1.70	1.60	1.49	1.42
4.5	1.16	1.24	1.22	1.29	1.15	1.00	1.75	1.65	1.54	1.46
5.0	1.18	1.27	1.19	1.16	1.08	0.86	1.80	1.70	1.60	1.50
5.5	1.20	1.31	1.17	1.12	1.00	0.80	1.86	1.76	1.67	1.55
6.0	1.22	1.36	1.13	1.00	0.90	0.74	1.93	1.85	1.75	1.60
6.5	1.25	1.39	1.10	0.96	0.86	0.68	–	–	–	–
7.0	1.27	1.42	1.05	0.90	0.78	0.62	–	–	–	–
7.5	1.30	1.46	1.00	0.88	0.73	0.56	–	–	–	–
8.0	1.33	1.50	0.96	0.85	0.70	0.52	–	–	–	–
8.5	1.35	1.52	0.86	0.82	0.66	0.48	–	–	–	–
9.0	1.37	1.57	0.82	0.76	0.63	0.44	–	–	–	–
9.5	1.40	1.60	0.78	0.72	0.61	0.40	–	–	–	–
10.0	1.43	1.64	0.75	0.68	0.58	0.37	–	–	–	–
10.5	1.47	1.66	0.71	0.66	0.54	0.32	–	–	–	–
11.0	1.53	1.72	0.68	0.63	0.50	0.28	–	–	–	–
11.5	1.58	1.76	0.64	0.60	0.47	0.24	–	–	–	–
12.0	1.64	1.80	0.60	0.58	0.44	0.22	–	–	–	–
12.5	1.71	1.86	0.57	0.55	0.40	0.20	–	–	–	–
13.0	1.77	1.95	0.53	0.50	0.34	0.19	–	–	–	–
13.5	1.84	2.00	0.49	0.45	0.30	0.18	–	–	–	–
14.0	1.91	2.06	0.46	0.40	0.25	0.17	–	–	–	–
14.5	1.95	2.13	0.43	0.35	0,21	0.15	–	–	–	–
15.0	2.05	2.18	0.40	0.30	0.18	0.14	–	–	–	–
15.5	–	–	0.36	0.26	0.16	0.13	–	–	–	–
16.0	–	–	0.32	0.22	0.14	0.12	–	–	–	–
16.5	–	–	0.28	0.18	0.12	0.10	–	–	–	–
17.0	–	–	0.26	0.14	0.11	0.08	–	–	–	–

Correcting the monthly totals of solid precipitation (selecting the correction factor) thus necessitates knowing whether snowstorms were observed within the specified month or not. For our study, we took this information from the monthly weather reports provided by RIHMI.

Outcome of the correction procedures

On the average, the corrected values of monthly precipitation totals in the summer months are 10 - 15 % higher than the measured values. In winter, the corrected values of monthly precipitation totals are an average of 10 - 20 % lower than the measured ones, but in some years at the stations with frequent snowstorms (e.g. Dikson Island [29], Amderma [19], Malye Karmakuly [14]) the corrected monthly totals of solid precipitation were just half the measured ones.

The validity of the method for correction of monthly totals of precipitation was verified by comparison with snow water equivalent (SWE) data measured simultaneously at the North Pole (NP) drifting stations in the Arctic Basin (Colony et al. 1998). The multiyear mean corrected total of precipitation at the NP drifting stations, September through April, was 75.7 ± 9.5 mm, and the April SWE had a multiyear mean of 72.5 ± 10.5 mm.

According to Warren et al. (1999) the mean annual total of precipitation over the Arctic Basin was 164 mm. The independent method for bias correction of daily precipitation (Bogdanova et al. 2002) gives the value of 165 mm. As noted by Bogdanova et al. (2002, p. 709), "such consistency of the results obtained using the independent methods points to their robustness and reliability".

The total monthly precipitation data used for the analysis of precipitation conditions in the region of the Barents and Kara seas were corrected for all types of errors using the method outlined above. As illustration, Fig. 2 presents the results of application of Bryazgin's method for correction of monthly precipitation totals for some stations with long series representing different parts of the region. In this figure, the water equivalent values of the snow cover and the corresponding totals of snow precipitation are compared before and after the correction of measured values. At all Russian Arctic stations, similar to the four presented in Fig. 2, the corrected precipitation totals during the period with abundant snow cover turn out to be much closer to the corresponding SWE values than the initial ones. The greatest discrepancies are observed when the stable snow cover begins to form and when it begins to decay.

Based of the aforementioned facts it seems that this method can reliably be used in climatic (long-term) studies of precipitation parameters, snow accumulation and water balance components in the Arctic.

Climatology of precipitation (1951–1980)

The amount and the regional distribution of precipitation in the area under consideration is determined mostly by the atmospheric circulation and the topography. Table 6 presents the average number of days with precipitation at some stations. Several stations have precipitation as many as 200 days a year.

The high precipitation frequency in the Arctic is related to the high relative humidity: a small decrease in temperature can cause condensation and thus precipitation. However, although precipitation in some months is frequent at the coastal stations in the Barents and Kara seas, the total annual precipitation is low. Table 7 presents the average totals of monthly, seasonal and annual precipitation for the period 1951–1980, corrected for wind effects and wetting loss as described above.

The highest annual precipitation (about 500 mm) is found in the southern Barents Sea, along the coast of the Kola Peninsula. The relatively large amounts of precipitation in this region are related to high cyclonic activity. The amount of precipitation decreases to 380 mm in the south-eastern and 230 mm in the northern Barents Sea. In the Kara Sea, the amount of precipitation decreases from 370 mm in the south-west to 180 - 200 mm in the north-east. The low annual precipitation in the northern areas of the Barents and Kara seas is related to the low moisture level of the prevailing Arctic air; in the eastern Kara Sea, Asian and Arctic anticyclones have an additional effect. Figure 3 shows how total monthly precipitation varies throughout the year at different stations.

Table 8 presents the distribution of the monthly precipitation amounts by their type: solid (S), liquid (L) and mixed (M). Determining the amounts of solid, liquid and mixed precipitation is of greatest importance in the intermediate sea-

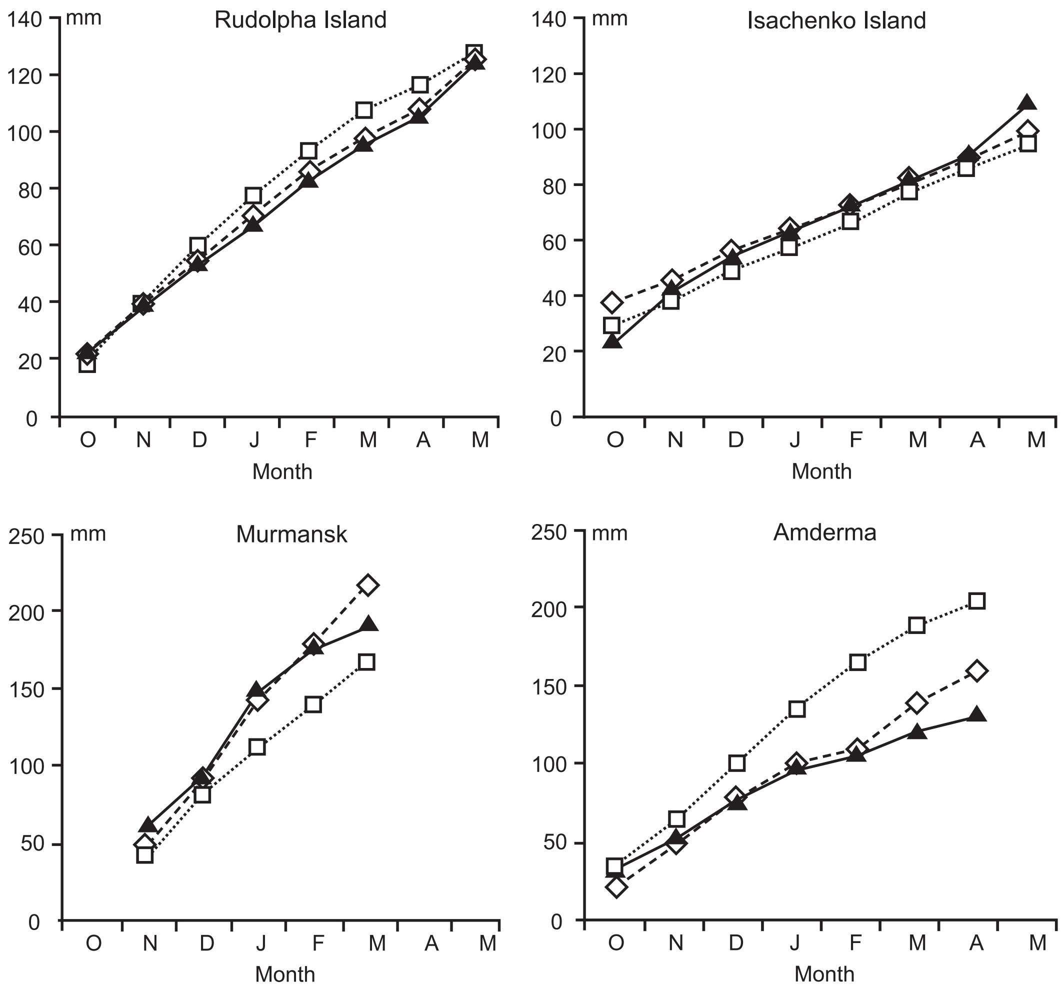

Fig. 2. Snow water equivalent (triangles), cumulative amount of precipitation after correction (diamonds), before correction (squares) at the stations Rudolpha Island (17), Isachenko Island (33), Murmansk (4) and Amderma (19). Data from 1951–1992.

Table 6. Number of days with daily total of precipitation ≥0.1 mm average for the period 1951–1980.

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Barentsburg (1)	17	16	17	15	14	12	13	15	16	17	18	17	187
Rudolpha Island (17)	13	12	14	13	17	16	18	19	19	19	14	16	190
Malye Karmakuly (14)	19	15	17	16	16	15	14	16	18	18	17	19	200
Murmansk (4)	17	14	16	14	14	15	14	16	17	18	17	18	190
Tersko-Orlovsky lighthouse (7)	16	14	14	13	14	14	13	16	18	19	17	17	184
Kanin Nos Cape (8)	20	17	18	15	15	13	11	16	20	23	22	20	209
Narjan-Mar (15)	19	17	17	15	16	14	12	16	19	21	21	20	207
Zhelaniya Cape (23)	16	13	15	15	17	14	14	17	19	20	16	17	193
Amderma (19)	20	17	17	16	16	15	12	17	21	23	22	21	217
Dikson Island (29)	20	16	17	16	18	18	15	18	22	22	19	20	221
Golomyanny Island (34)	12	12	13	10	14	13	14	16	17	17	14	15	167
Russky Island (36)	12	11	11	10	14	12	14	14	17	17	12	14	158

sons, when the formation and destruction of the snow cover occur. In the northern and north-eastern part of the region 50 - 70 % of the annual precipitation is solid, 12 - 20 % is liquid and 17 - 19 % is mixed. The solid precipitation fraction decreases to 35 - 43 % in the south of the region, while the fraction of liquid precipitation increases to 40 - 50 %. In total for the whole region, the maximum amount of liquid precipitation is observed in August. The maximum amount of solid precipitation in the north-east of the region falls in October, and in the south in December–January. The proportions of precipitation types in the region change from south-west to north-east. Mixed and liquid precipitation is observed in April in the southern area of the region. Mixed precipitation is observed in May in the north and north-east of the region, and in the east of the region in June. In the southern Barents Sea (Malye Karmakuly [14]) mixed precipitation is observed all year round. The rate of mixed precipitation in the annual total for the Barents–Kara region is 9 - 10 % higher than in the adjacent continental regions to the south. In the north and east of the region, liquid precipitation is observed only from June through September.

Coefficients of variation characterize the interannual variability of monthly and annual precipitation totals (Table 9). The interannual variability of the annual precipitation totals is small; the coefficient of variation ranges between 0.2 and 0.3. This indicates that annual precipitation totals in the region are stable. However, within a year the coefficients of variation significantly change. In winter the values are above 0.6 in almost the whole region. Maximum interannual precipita-

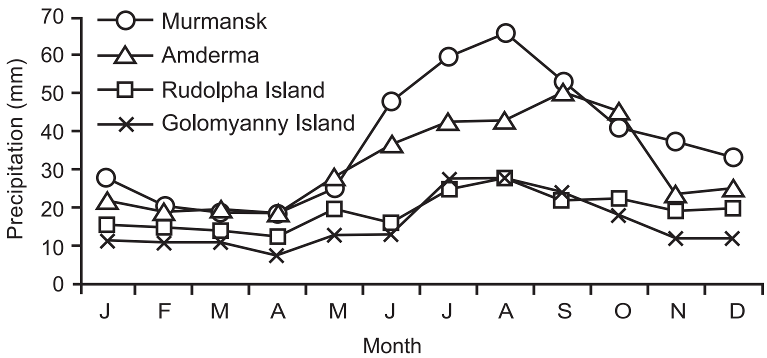

Fig. 3. Mean monthly totals of precipitation at the stations Murmansk (4), Rudolpha Island (17), Amderma (19) and Golomyanny Island (34). Data from 1951–1992.

Table 7. Corrected monthly, seasonal and annual precipitation amounts (mm) average for the period 1951–1980.

Station	J	F	M	A	M	J	J	A	S	O	N	D	Oct–May	Jun–Sep	Year
Barentsburg (1)	57	55	52	37	25	24	35	52	50	56	55	68	405	161	566
Rudolpha Island (17)	16	15	14	12	20	16	24	28	22	22	19	20	138	90	228
Malye Karmakuly (14)	30	22	24	23	28	29	44	46	43	42	30	24	223	162	385
Murmansk (4)	32	26	27	23	34	48	57	63	53	44	42	39	267	221	488
Tersko-Orlovsky lighthouse (7)	26	19	21	26	27	41	48	58	54	48	38	30	235	201	436
Kanin Nos Cape (8)	39	29	25	19	20	32	35	44	47	51	38	33	254	158	412
Narjan-Mar (15)	25	18	20	23	30	40	48	60	61	45	34	26	221	209	430
Zhelaniya Cape (23)	15	15	16	17	23	22	28	38	31	30	14	18	148	119	267
Amderma (19)	22	19	19	19	28	37	42	43	50	45	24	25	201	172	373
Dikson Island (29)	21	17	20	17	26	32	40	46	45	34	20	20	175	163	338
Golomyanny Island (34)	11	11	11	7	13	13	27	28	23	18	12	12	95	91	186
Russky Island (36)	14	15	14	14	15	16	34	33	24	19	15	14	120	107	227

tion variability is observed in the winter months in the north-eastern Barents Sea near the western coast of Novaya Zemlya (Malye Karmakuly [14]). Coefficients of variation decrease in the summer, although they are relatively high. On the average, the monthly coefficients of variation for the region are greater than 0.4. Minimum interannual precipitation variability is observed in September–October, when thermobaric fields of winter type are formed due to radiation and circulation factors.

Seasonal, interannual and long-term variability of the climate in the region of the Barents and Kara seas

The long-term variability of air temperature in January (the middle of the cold season) and July (the middle of the warm season), precipitation in the cold season (October–May) and snow depths measured along defined snow survey paths (Radionov et al. 1996) in the month with maximum snow accumulation (which is April in most cases) was

Table 8. Monthly and annual amount of liquid (L), solid (S) and mixed (M) precipitation (mm), average for 1951–1980.

Station		J	F	M	A	M	J	J	A	S	O	N	D	Year
Barentsburg (1)	L					2	12	23	25	12	2			76
	S	57	55	52	37	19	8	2	10	25	52	55	68	440
	M					4	4	10	17	13	2			50
Rudolpha Island (17)	L						2	8	11	3	2			26
	S	16	15	14	12	19	9	5	5	14	16	17	18	160
	M					1	5	11	12	5	4	2	2	42
Malye Karmakuly (14)	L				1	3	19	40	44	33	14	3		157
	S	28	21	23	18	19	2			2	12	18	21	164
	M	2	1	1	4	6	8	4	2	8	16	9	3	64
Murmansk (4)	L				3	15	41	57	63	47	16	3		245
	S	31	25	25	14	7	1			2	15	29	35	184
	M	1	1	2	6	12	6			4	13	10	4	59
Tersko-Orlovsky	L				3	10	33	47	58	48	18	2		179
lighthouse (7)	S	26	19	20	16	9	2			1	15	25	26	159
	M			1	7	8	6	1		5	15	11	4	58
Kanin Nos Cape (8)	L				2	8	25	35	44	36	15	3		168
	S	35	28	23	11	6	2			1	15	24	30	175
	M	4	1	2	6	6	5			10	21	11	3	69
Narjan-Mar (15)	L				2	10	32	48	59	51	12	1		241
	S	22	16	16	12	9	2			2	13	20	21	116
	M	3	2	4	9	11	6		1	8	20	13	5	73
Zhelaniya Cape (23)	L						6	19	26	10				61
	S	15	15	16	16	21	5	1	4	7	26	12	17	155
	M				1	2	11	8	8	14	4	2	1	51
Amderma (19)	L				1	4	26	37	41	37	7			153
	S	22	19	19	14	16	2			2	20	21	24	159
	M				4	8	9	5	2	11	18	3	1	61
Dikson Island (29)	L					1	14	38	43	23	2			121
	S	21	17	20	17	19	5			6	24	19	20	168
	M					6	13	2	3	16	8	1		49
Golomyanny Island (34)	L						4	18	19	7				48
	S	11	11	11	7	12	3	1	3	6	15	11	11	102
	M					1	6	8	6	10	3	1	1	36
Russky Island (36)	L						5	25	16	6				52
	S	14	15	14	14	15	5	2	2	10	17	15	14	137
	M						6	7	15	8	2			38

studied for the 38 stations (Table 1) for the period 1951–1992. Results from selected long-term series are presented in Figs. 4-6 and in Table 10.

Figure 4 indicates a tendency toward low January temperatures in the mid-1960s, and higher temperatures in the 1980s. At the stations in the northern part of the region (Rudolpha Island [17], Golomyanny Island [34]) the transition from low to higher temperatures is observed some years earlier than in the southern part of the region (Murmansk [4], Narjan-Mar [15]). At the northern and eastern stations, the temperature trend in January is positive during 1951–1992 (Table 10), while the trends are negative at the southern stations. In July the character of temperature change at the stations is more diffuse (Fig. 4), but at practically all stations there is a tendency toward decreasing temperatures (Table 10).

Table 10 and Fig. 5 indicate a decrease in the amount of winter precipitation (October–May) at the northern stations (Rudolpha Island [17], Golomyanny Island [34]) and the eastern stations (Dikson Island [29], Sterlegova Cape [32]) for the period 1951–1992. In the south-western (Murmansk [4]) and southern parts (Narjan-Mar [15], Amderma [19]), there is a tendency toward increasing winter precipitation. Most of the trends in summer precipitation (June–September) have the same signs as during winter.

Figure 6 shows the changes of snow depth at

Table 9. Coefficient of variation of monthly and annual amounts of precipitation for the period 1951–1980.

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Barentsburg (1)	0.65	0.79	0.71	0.56	0.45	0.57	0.44	0.40	0.35	0.44	0.55	0.61	0.25
Rudolpha Island (17)	0.68	0.84	0.64	0.52	0.39	0.52	0.48	0.43	0.34	0.46	0.56	0.54	0.24
Malye Karmakuly (14)	0.95	0.75	0.60	0.54	0.61	0.55	0.64	0.56	0.51	0.41	0.57	0.66	0.22
Murmansk (4)	0.63	0.70	0.85	0.64	0.63	0.62	0.51	0.54	0.43	0.44	0.55	0.62	0.26
Tersko-Orlovsky lighth. (7)	0.67	0.65	0.58	0.64	0.65	0.57	0.60	0.55	0.43	0.48	0.53	0.56	0.23
Kanin Nos Cape (8)	0.55	0.50	0.53	0.53	0.42	0.59	0.90	0.53	0.42	0.39	0.40	0.51	0.21
Narjan-Mar (15)	0.60	0.54	0.59	0.56	0.51	0.57	0.59	0.56	0.44	0.37	0.45	0.52	0.22
Zhelaniya Cape (23)	0.78	0.78	0.87	0.73	0.85	0.47	0.66	0.51	0.48	0.51	0.62	0.70	0.29
Amderma (19)	0.45	0.60	0.36	0.53	0.39	0.52	0.64	0.46	0.36	0.30	0.37	0.62	0.17
Dikson Island (29)	0.67	0.65	0.62	0.61	0.50	0.54	0.42	0.45	0.40	0.44	0.54	0.53	0.23
Golomyanny Island (34)	0.69	0.56	0.70	0.57	0.39	0.55	0.52	0.40	0.43	0.59	0.61	0.70	0.22
Russky Island (36)	0.61	0.63	0.64	0.87	0.52	0.71	0.52	0.54	0.42	0.40	0.76	0.74	0.28

Table 10. Linear trends (1951–1992) of air temperature (T), precipitation (P), and snow depth (H). Unlike Tables 6-9, Table 10 presents data for the Sterlegova Cape station (32) instead of the Tersko-Orlovsky lighthouse station (7). The trend values at Tersko-Orlovsky lighthouse station (7) are the same as at Kanin Nos Cape station (8). Values in boldface are significant at the 0.95 confidence level.

Station	T (°C/10 years)			P (mm/10 years)			H (cm/10 years)
	January	July	Annual	Oct–May	Jun–Sep	Annual	April
Barentsburg (1)	−0.03	0.02	−0.10	−7.3	−3.1	−10.3	**−8.0**
Rudolpha Island (17)	0.37	−0.00	−0.25	**−20.2**	−4.8	**−25.0**	−7.8
Malye Karmakuly (14)	**−0.91**	0.02	−0.04	4.8	−3.1	1.8	No data
Murmansk (4)	−0.48	−0.01	0.06	11.0	4.3	15.3	−0.3[a]
Sterlegova Cape (32)	0.24	−0.12	−0.16	**−6.5**	−4.2	−10.7	−8.9
Kanin Nos Cape (8)	−0.57	−0.35	0.03	−4.9	3.36	−1.6	**−5.7**
Narjan-Mar (15)	−1.08	−0.14	0.01	**11.9**	1.4	13.3	1.3*
Zhelaniya Cape (23)	−0.24	**−0.23**	−0.31	**−12.7**	1.2	−11.4	No data
Amderma (19)	**−0.94**	−0.34	−0.07	**10.6**	1.18	11.7	**5.0**
Dikson Island (29)	0.01	−0.28	−0.06	**−13.7**	−0.5	**−14.2**	−4.5
Golomyanny Island (34)	0.25	−0.00	−0.28	**−7.0**	−3.1	**−10.1**	−0.1
Russky Island (36)	0.32	−0.19	−0.24	−2.1	−6.9	−9.0	−2.2

[a] For the period 1961–1992 at Murmansk and 1966–1992 at Narjan-Mar stations.

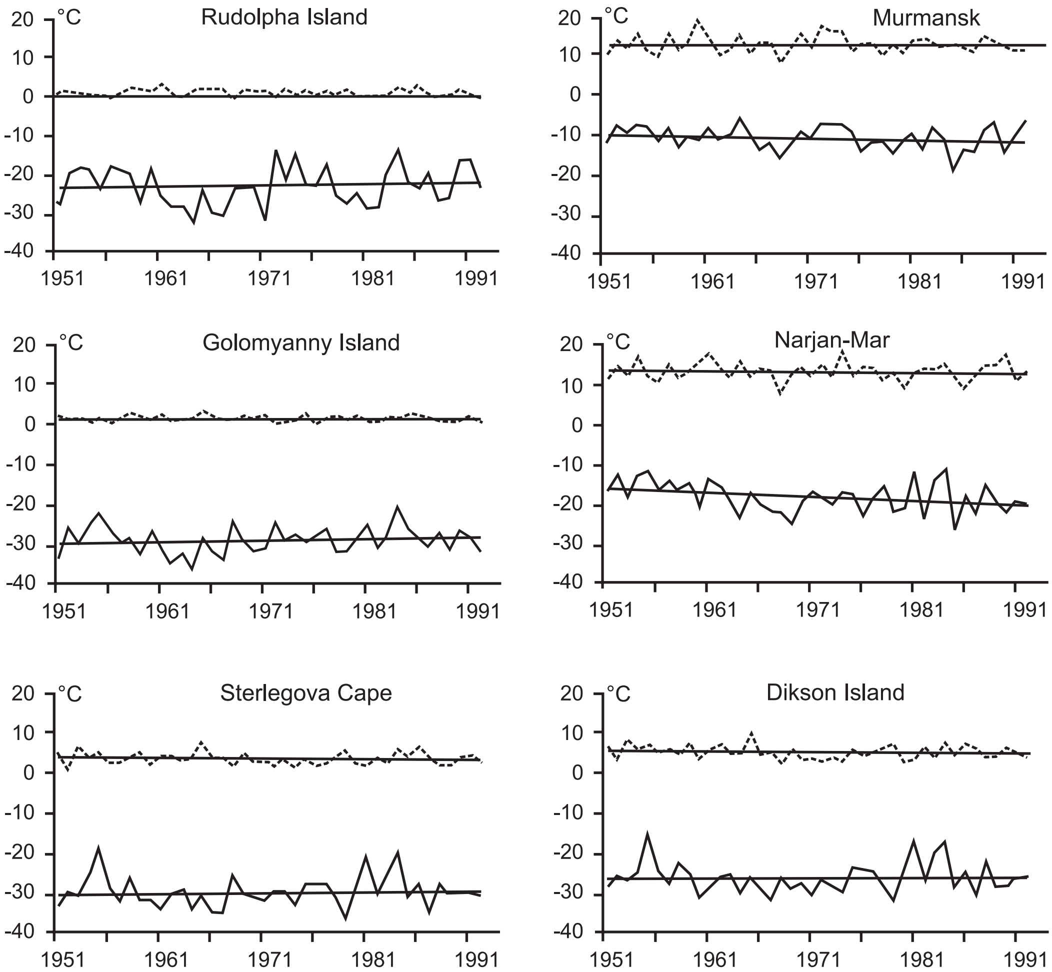

Fig. 4. Interannual variability and linear trends of air temperature in January (solid line) and July (dotted line) at Rudolpha Island (17), Murmansk (4), Golomyanny Island (34), Narjan-Mar (15), Sterlegova Cape (32) and Dikson Island (29).

some stations in the month with maximum snow accumulation (May in the northern and eastern areas, April in the south). Overall, snow depths are decreasing in the northern Barents Sea and the eastern Kara Sea and increasing on the southern coast of the Barents Sea (the Kola Peninsula and the Pechora Sea). Accumulated snow depth is poorly correlated with winter total precipitation at all stations. The coefficient of correlation ρ is 0.33 at Dikson Island (29), 0.23 at Rudolpha Island (17) and Sterlegova Cape (32), 0.27 at Golomyanny Island (34). In Murmansk (4) and Narjan-Mar (15) ρ is less than 0.13. For comparison, Aleksandrov et al. (1999) calculated the correlation between monthly snow depth change and monthly precipitation at the North Pole drifting stations for the period 1954–1991. The correlation was small there too ($\rho=0.25$). This is related to low total precipitation and frequent redistribution of fallen snow by wind. A significant correlation of 0.48 was obtained only when precipitation and snow accumulation were integrated over the entire winter period from September through April (Colony et al. 1998).

The largest uncertainties are observed at the stations in the areas with strong winds (wind speed ≥ 15 m/s). These areas include the zone from Novaya Zemlya to the open part of the Barents Sea, and the south-eastern coast of the Kara Sea.

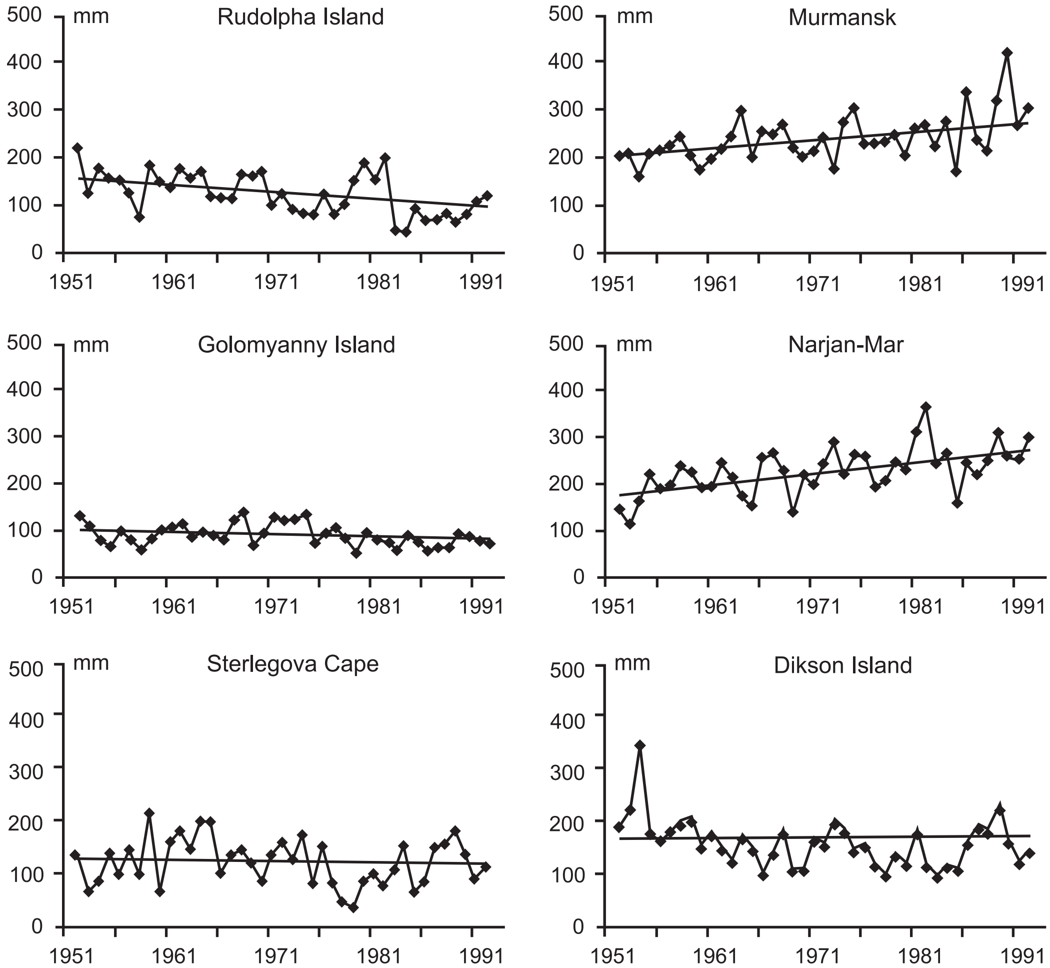

Fig. 5. Interannual variability and linear trends of winter (October–May) precipitation at Rudolpha Island (17), Murmansk (4), Golomyanny Island (34), Narjan-Mar (15), Sterlegova Cape (32) and Dikson Island (29).

Wind speeds of 15 m/s or more are observed more often in winter than in other seasons, and more often in coastal than in continental areas. On average 10 - 12 days per month with wind speeds ≥ 15 m/s are observed between November and March on the coast of the Kola Peninsula, in the vicinity of Amderma (19) and Dikson Island (29), on Franz Josef Land, and particularly on the coast of the Taimyr Peninsula. In the coastal zones of Novaya Zemlya, wind speeds ≥ 15 m/s are recorded on almost half of the days every winter month (Bryazgin & Dementyev 1996).

The biggest discrepancies between total precipitation (both before and after correction) and snow accumulation parameters (accumulated snow depth or snow water equivalent) are observed at Dikson Island (29) and Sterlegova Cape (32). This is related to local orographic effects and a very high frequency of snowstorms in winter. After a snowstorm one often observes an absence of snow cover at the measuring site but snow-filled precipitation gauges and snowdrifts covering the constructions around the meteorological site. A few peculiarities of snow accumulation at Dikson Island (29) are presented in Table 11. The table shows long-term (1952–1990) average values of monthly and seasonal precipitation totals (P) before and after correction, SWE values averaged for the period 1954–1990, and snow depth (H) measured at three fixed snow stakes at the meteorological site and averaged for 1954–1990. There is a big difference between the mean sea-

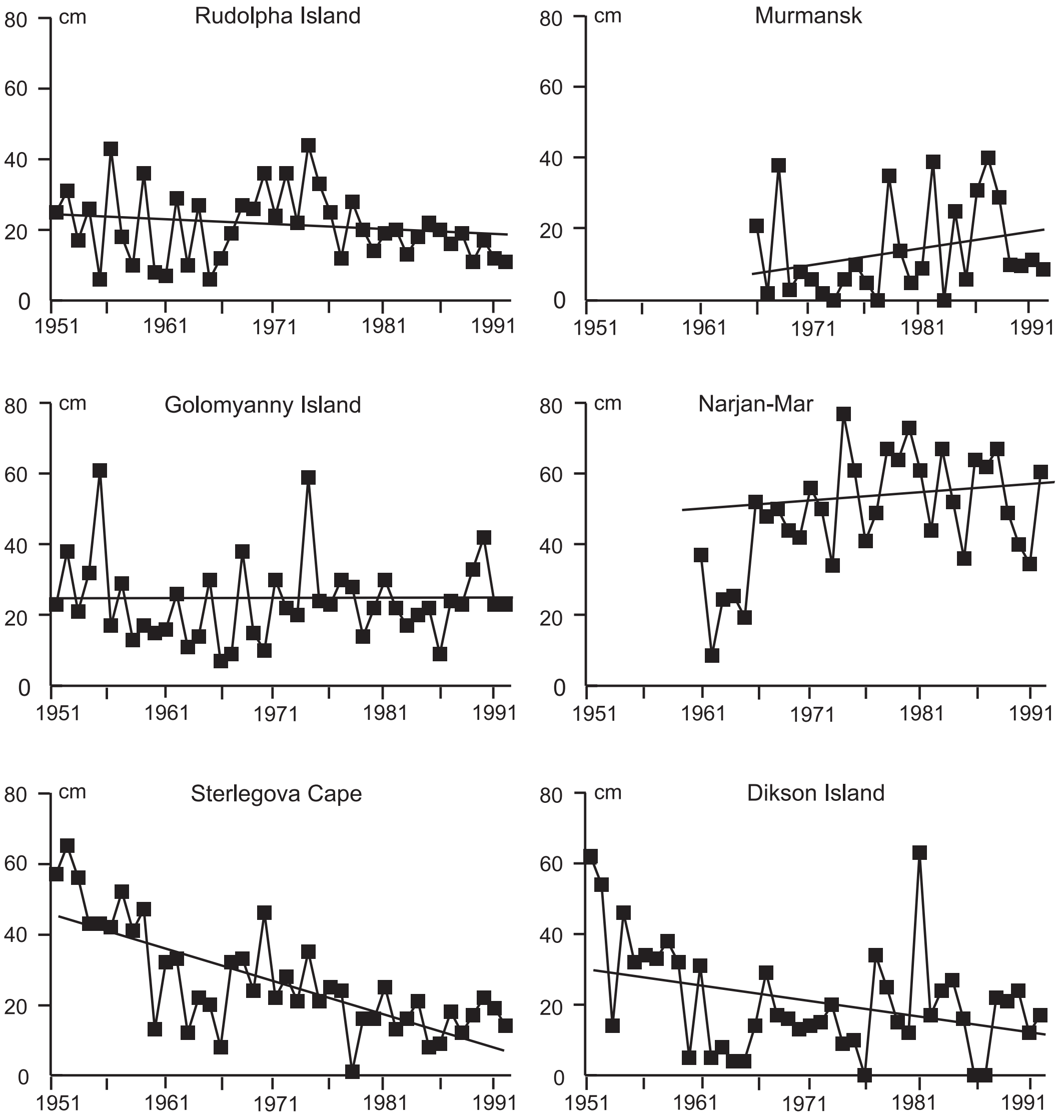

Fig. 6. Interannual variability and linear trends of snow depths at Rudolpha Island (17), Murmansk (4), Golomyanny Island (34), Narjan-Mar (15), Sterlegova Cape (32) and Dikson Island (29).

sonal (October–May) total of solid precipitation and accumulated SWE in May. The main reason is drifting snow. The snow transport effect is so strong at this station that it influences the annual variability of long-term mean monthly values of SWE and accumulated snow depth: e.g. the SWE value is lower in January than in December, and the SWE value is lower in April than in March, even though the snow depth is greater in April than in March (see Table 11).

On the whole, one could say that the Dikson Island station is not the best place to study snow cover parameters. On the other hand the data from Dikson Island constitute one of the longest meteorological observation series in the Arctic: air temperature, pressure, precipitation and total cloud cover have been measured since 1916, relative humidity since 1917, low clouds since 1936 and snow depth since 1937. We must use all available data for climatic studies, but take into account the quality and the limitations of the information.

Table 12 demonstrates long-term values of accumulated SWE at some stations in the south-west area of the Kara Sea. The weather conditions at all of these stations are controlled by the same atmospheric circulation processes as at Dikson Island (29); the monthly and seasonal precipitation totals on average are equal at the stations and very close to 160 - 180 mm during cold season. But the SWE of the snow that accumulates in October–May is 2.5 to 3 times lower at Sterlegova Cape (32) than at the other stations. As at Dikson Island (29), this is due to snow transport. Both stations are situated close to the coastline.

Discussion and conclusions

Measuring solid precipitation under the harsh climate conditions in the Arctic is extremely difficult, and is influenced by several error sources. The corrections by the Bryazgin method (see Tables 3-5) take into consideration precipitation type, wind speed and amount of solid precipitation. The correction method also compensates for the overestimation of solid precipitation in periods with blowing snow. The corrected values give an improved estimate of true precipitation, and are in better agreement with SWE measurements than uncorrected values (Fig. 2). However, it should be noted that the correction factors outlined in Table 5 are influenced by, for example, snow depth (distance from snow surface to the gauge orifice), structure of the snow surface on the ground, temporal variability in wind speed and structure of snow particles in the air. A few data series are now available that could be used to validate the Bryazgin method once more. One of them (Radionov et al. 2004) includes daily precipitation data from 20 of the 38 stations presented in Table 1. Meteorological observations made at North Pole drifting stations (National Snow and Ice Data Center 1996; Fetterer & Radionov 2000) may also be used. These datasets make it possible to evaluate whether correction of daily values would give improved estimates of total precipitation than the (corrected) monthly values

Table 11. Long-term mean (1952–1990) of monthly and seasonal amount of precipitation (P), in mm, as measured with precipitation gauge before and after correction; long-term mean (1954–1990) of accumulated snow water equivalent (SWE), in mm, measured along defined snow survey paths; long-term mean of accumulated snow depth at meteorological site (three stake measurements) (H) in cm, all at Dikson Island (29). Values are given ± root mean square deviation.

	Parameter	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Oct–May
Before correction	P (mm)	25.2±10.4	21.8±12.5	30.5±22.6	37.1±31.7	27.4±23.3	26.7±22.2	16.4±9.9	17.5±10.3	202.6
After correction	P (mm)	34.0±14.4	19.0±6.9	20.2±11.0	20.7±10.0	16.6±11.8	19.1±10.5	14.8±7.3	23.6±13.3	168.0
Mean for 1954–1990	SWE (mm)	19.5±12.4	27.2±6.8	33.6±11.4	32.6±9.1	36.3±10.9	39.9±15.3	39.2±10.4	45.7±14.7	45.7
Mean for 1954–1990	H (cm)	8.3±4.8	11.3±4.2	12.7±6.7	14.9±7.5	18.7±23.3	18.3±11.6	21.5±15.6	19.7±13.6	63.0*

* SWE (mm) based on snow depth at meteorological site in May, calculated according to the formula SWE = $10 \cdot H \cdot \rho$, where H is snow depth (cm); density $\rho = 0.32$ g/cm^{-3} (Warren et al. 1999).

Table 12. Long-term mean of accumulated snow water equivalent and its standard deviation (mm) at the stations in the south-west Kara Sea area.

Station	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
Im. M.V. Popova (24) 1954–1990	28.3±11.3	54.1±15.7	80.2±23.7	100.6±31.7	124.3±51.2	138.9±34.4	156.9±34.9	180.6±47.3
Vilkitsky Island (25) 1965–1990	32.3±12.3	60.8±19.3	80.6±25.6	101.5±24.6	117.4±25.4	130.3±28.1	149.8±34.2	163.5±37.1
Leskina Cape (28) 1954–1990	20.3±9.1	43.0±15.3	63.3±24.4	76.5±21.2	89.7±28.3	104.8±26.6	126.8±33.4	149.2±35.4
Sterlegova Cape (32) 1954–1990	24.0≥16.9	32.5±17.1	36.5±15.6	41.4±17.4	44.7±17.1	49.5±18.2	54.7±21.0	63.9±21.8

used here.

The present analysis demonstrates large spatial contrasts in climatology and trends in the region of the Barents and Kara seas for the period 1951–1992. Increasing temperatures from the cold years in the mid-1960s caused changes in precipitation regime and snow accumulation in the region. The warming over a major part of the region caused decreasing amounts of solid precipitation and accordingly decreasing snow depths. The main conclusions are:

- Annual precipitation, corrected for measuring errors, ranges from 180 mm in north-eastern Kara Sea areas to around 500 mm along the coast of the Kola Peninsula.
- In northern and north-eastern parts of the Barents and Kara sea region, 50 - 70 % of the annual precipitation is solid; in the southern parts the solid fraction is 35 - 43 %.
- The annual precipitation has decreased by 10 - 25 mm/decade during 1951–1992 at the north-eastern stations (Rudolpha Island [17], Golomyanny Island [34], Sterlegova Cape [32] and Dikson Island [29]). At the south-western stations Murmansk (4) and Narjan-Mar (15) there is a tendency to increasing annual precipitation.
- During 1951–1992 the average annual temperature appears to have decreased by 0.2 - 0.3 °C/decade at the north-eastern stations. However, because of large interannual variations, the trend is not statistically significant at the 95 % level.
- The snow depth in the month with maximum snow depth (April or May) has decreased at the north-eastern stations. The decrease is 8 - 9 cm/decade during 1951–1992.

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Appendix

The meteorological parameters recorded at the meteorological stations.

Meteorological parameter	Observation characteristic
Air temperature	Temperature, maximum, minimum (with thermograph)
Air pressure	Pressure, pressure tendency (with barograph)
Air humidity	Partial pressure of water vapour, relative humidity, moisture deficit (with self-recording hygrometer)
Precipitation	Measurement of amount, duration period (during a 24-hour period) and type of precipitation two or four times within 24 hours
Wind	Direction and wind speed (with anemorumbograph or recording anemometer)
Cloud	Amount of total and low cloud, its form and type (observation made visually)
Visibility	Horizontal meteorological visibility measured by devices or visually (using landmarks)
Atmospheric phenomena	Snowstorms, fogs, squalls, thundershowers, precipitation (noted by observer within a 24-hour period)
Sunlight	Duration period (by heliograph)
Sheet of glaze and rime accretion	Thickness and diameter of accretion
Temperature of soil or snow surface	Temperature and daily maximum and minimum
Snow cover	At meteorological site: snow depth, fractional area of snow cover (daily). On snow survey course 0.5 - 2 km: depth and density of snow (every 10 days and monthly)