Past and future climate variations in the Norwegian Arctic: overview and novel analyses

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Sparse stations and serious measuring problems hamper analyses of climatic conditions in the Arctic. This paper presents a discussion of measuring problems in the Arctic and gives an overview of observed past and projected future climate variations in Svalbard and Jan Mayen. Novel analyses of temperature conditions during precipitation and trends in fractions of solid/liquid precipitation at the Arctic weather stations are also outlined. Analyses based on combined and homogenized series from the regular weather stations in the region indicate that the measured annual precipitation has increased by more than 2.5% per decade since the measurements started in the beginning of the 20th century. The annual temperature has increased in Svalbard and Jan Mayen during the latest decades, but the present level is still lower than in the 1930s. Downscaled scenarios for Svalbard Airport indicate a further increase in temperature and precipitation. Analyses based on observations of precipitation types at the regular weather stations demonstrate that the annual fraction of solid precipitation has decreased at all stations during the latest decades. The reduced fraction of solid precipitation implies that the undercatch of the precipitation gauges is reduced. Consequently, part of the observed increase in the annual precipitation is fictitious and is due to a larger part of the "true" precipitation being caught by the gauges. With continued warming in the region, this virtual increase will be measured in addition to an eventual real increase.

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A combination of instrumental records and reconstructions from proxy sources indicate that Arctic air temperatures in the 20th century were the highest in the past 400 years (Serreze et al. 2000). During the 20th century an increase in annual precipitation has been observed at higher northern latitudes (Hulme 1995; Dai et al. 1997). The Norwegian Arctic has experienced a substantial increase in precipitation during the 20th century, but although the temperature has increased during the latest decades there is no significant long-term trend in annual temperatures (Førland et al. 2002; Hanssen-Bauer 2002).

Global climate models project significant increase of temperature and precipitation in high northern latitudes as greenhouse gas concentrations increase (IPCC 2001). The warming in high northern latitudes may be amplified by feedbacks from changes in snow and sea ice extent and thawing of permafrost. The freshwater budget in the Arctic has become an increasingly important consideration 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 (Aagaard & Carmack 1989; Mysak et al. 1990). The Arctic freshwater budget is driven by

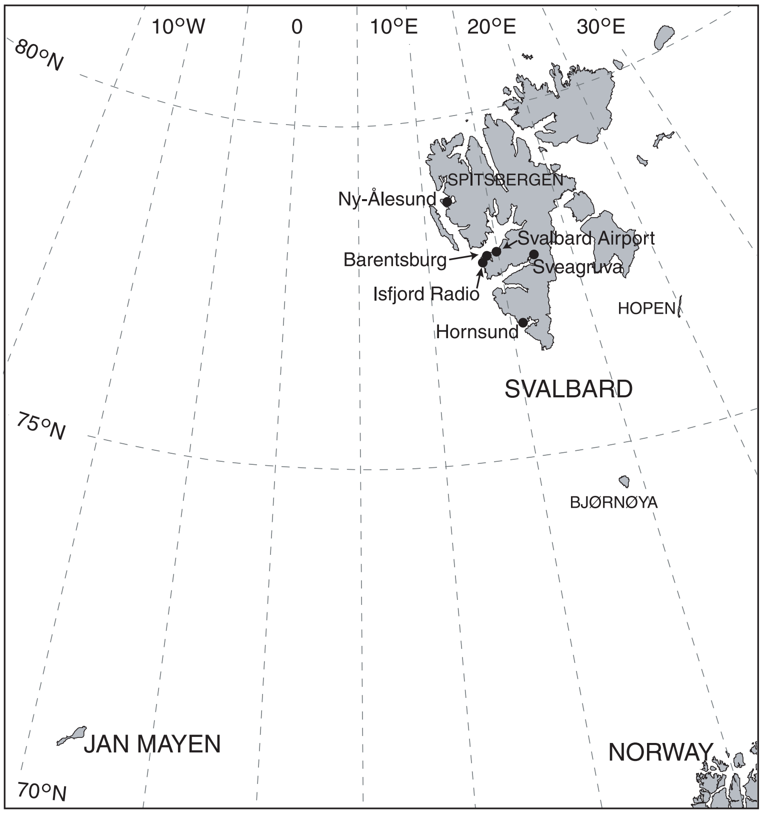


Fig.1. Location of current manual weather stations in the Norwegian Arctic. Bjørnøya: elevation 16 m a.s.l., start of measurements 1920. Hopen: 6 m a.s.l., 1944. Hornsund (Polish): 10 m a.s.l., 1978. Sveagruva 9 m a.s.l., 1978. Barentsburg (Russian): 70 m a.s.l., 1933. Svalbard Airport: 28 m a.s.l., 1975. Ny-Ålesund: 8 m a.s.l., 1974. Jan Mayen: 10 m a.s.l., 1921.

river runoff, accumulation/ablation of glaciers and precipitation over the Arctic Ocean. The observed and projected increases in temperature and precipitation in Svalbard and Jan Mayen (Fig. 1) thus have broad implications for Arctic and, perhaps, global climate and the monitoring of climatic trends in these regions is therefore also important in a global context.

Analyses of climatic trends in the Arctic are hampered by the sparse station network and serious measuring problems. The large year-to-year variations imply that the climate signals have to be strong to be statistically significant. Although the scenarios indicate substantial climate changes in the Arctic, it is not necessarily the case that the first significant "greenhouse signal" will be found in this region. Real climatic trends may be masked or amplified when analyses are based upon inhomogeneous series. Studies have revealed that inhomogeneities in Arctic climate series are often of the same magnitude as typical long-term trends (Hanssen-Bauer & Førland 1994; Nordli et al. 1996). For Arctic stations in Canada, Mekis & Hogg (1999) demonstrated that the precipitation trend was almost doubled after adjusting the series. Accordingly, it is of crucial importance to adjust series for inhomogeneities when they are used in studies of long-term climate variations.

The climate and long-term climatic variations at the Norwegian Arctic stations are described in a number of old and new publications, e.g. Birkeland (1930), Hesselberg & Johannessen (1958), Steffensen (1969, 1982), Hisdal (1976), Vinje (1982), Hanssen-Bauer et al. (1990), Førland et al. (1997a) and Winther et al. (2003). Serreze et al. (2000) review observational evidence of recent changes in the Arctic environment.

In this paper a discussion of measuring problems in the Arctic and an overview of past and future climate variations are given in the first sections. In the last sections novel analyses of temperature conditions during precipitation and trends in fractions of solid/liquid precipitation at the Arctic stations are outlined, and it is demonstrated that the observed trends in measured precipitation may deviate from the real precipitation trends.

Meteorological measuring problems in the Arctic

General measuring problems

The Arctic climate poses several serious challenges for the monitoring of the main weather elements. Icing and wet snow may cause malfunctioning of the various sensors at the weather stations. During the polar night, the combination of darkness and harsh weather occasionally complicates manual observations.

The combination of dry snow, high wind speed and open tundra increase dramatically the measuring errors for precipitation and snow depth at most stations in the Norwegian Arctic. Because of blowing snow, the snow layer on the ground is likely to show large local variations (Winther et al. 1998; Winther et al. 2003), and the regular snow depth measurements at weather stations are therefore seldom representative for the snow accumulation in the station area. Consequently, measurements of snow cover and snow depth have been given little priority at the Norwegian Arctic weather stations.

Errors in precipitation measurements

Several types of errors are connected to precipitation measurements (Goodison et al. 1998). For the Nordic countries, Førland et al. (1996) concluded that the real amount of precipitation ("true precipitation") might be expressed as:

$$P_C = k \cdot (P_m + \Delta P_W + \Delta P_E), \qquad (1)$$

where P_C is true precipitation, k is the correction factor due to aerodynamic effects, P_m is measured precipitation, ΔP_W is precipitation lost by wetting, and ΔP_E is precipitation lost by evaporation from the gauge. Other error types, such as splash in/out, instrumental errors, misreadings etc., are either corrected in routine quality controls or may be neglected under Nordic climate conditions. However, drifting or blowing snow occasionally cause substantial problems in the Arctic. "Precipitation" caused solely by blowing snow is excluded through the quality control at the Norwegian Meteorological Institute, but there is often a combination of precipitation and blowing snow. In such cases it is difficult to distinguish the proportions of real precipitation and blowing snow.

In the Arctic, typical values of the combined effect of wetting and evaporation loss ($\Delta P_W + \Delta P_E$) for the Norwegian gauge is 0.10 - 0.15 mm/case for solid, liquid and mixed precipitation (Førland & Hanssen-Bauer 2000). At most measuring sites, wind speed is the most important environmental factor contributing to the undercatch of the precipitation gauges. Based on results from the World Meteorological Organization Solid Precipitation Measurement Intercomparison (Goodison et al. 1998), Nordic precipitation gauge studies (Førland et al. 1996) and field measurements in Ny-Ålesund, Førland & Hanssen-Bauer (2000) deduced correction models for hourly and daily measurements in the Norwegian precipitation gauge under Arctic conditions. The correction factor for solid precipitation was found to increase with increasing wind speeds, and decrease with increasing temperature.

By considering typical values of wind speed, temperature and precipitation intensity, Førland & Hanssen-Bauer (2000) suggested the following rough correction factors for unsheltered stations on Spitsbergen: liquid precipitation $k_l = 1.15$, solid $k_s = 1.85$ and mixed $k_m = (0.5 * k_l + 0.5 * k_s) = 1.5$. It should be stressed that using these typical correction factors does not necessarily produce accurate estimates of true precipitation at particular individual stations. Further, the corrections do not reflect differences in wind exposure between different measuring sites.

Adjustment for inhomogeneities

Inhomogeneities in climatic series may be caused by relocation of sensors, changed environment (such as new buildings) and instrumental improvements. To acquire reliable long-term climate series in the Arctic is particularly complicated. Because of the harsh weather conditions, even small changes at measuring sites may cause substantial changes in measuring conditions for precipitation, for example. Identification of inhomogeneities in Arctic climate series is further hampered by the sparse station network. Homogeneity tests based upon comparison with neighbouring stations are difficult to perform for Bjørnøya (the southernmost island of Svalbard) and Jan Mayen, for example, as the nearest neighbouring stations are more than 300 km away. A detailed survey of the results of the homogeneity analyses for Norwegian Arctic series is given by Nordli et al. (1996).

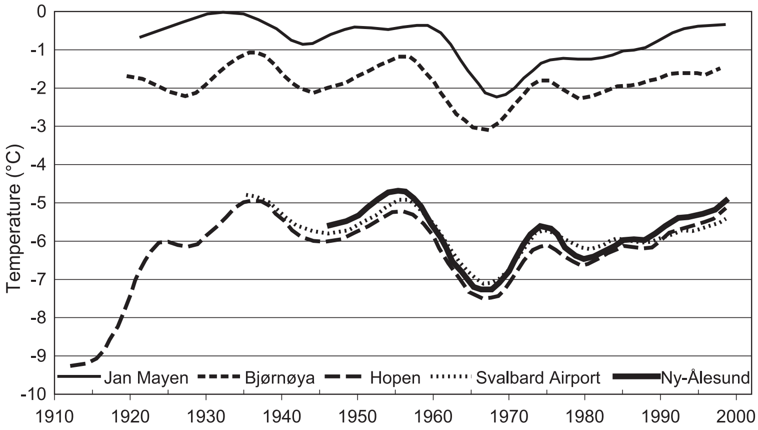


Fig. 2. Low-pass filtered series of annual temperature at Norwegian Arctic stations. The series are smoothed using Gaussian weighting coefficients and show variations on a decadal time scale. (The last three years of the curves are omitted as filtered series are unreliable at the ends.)

Temperature and precipitation variations in the 20th century

Climate series for the Norwegian Arctic

The available climate data from the Norwegian Arctic is rather limited. The present network of synoptical weather stations consists of five stations on Spitsbergen and three stations on other Arctic islands (Fig. 1). The oldest meteorological observations from the Norwegian Arctic were made during scientific expeditions to Svalbard and Jan Mayen. In 1911 a permanent weather station was established in Green Harbour, western Spitsbergen. Around 1920, weather stations were established at Bjørnøya and Jan Mayen.

Long-term climate series for Spitsbergen are established by joining series from different sites, and applying statistical methods (Nordli et al. 1996). For Svalbard Airport the combined series is mainly based upon observations from Green Harbour/Barentsburg and Longyearbyen/Svalbard Airport. The Ny-Ålesund series is based upon measurements from Isfjord Radio and Ny-Ålesund. The weather stations in Ny-Ålesund and Svalbard Airport were both moved to their present sites in 1975. The long-term temperature and precipitation series are adjusted before 1975 to be valid for the present sites.

Temperature

There are pronounced fluctuations in Arctic climate on daily, monthly and annual time scales. The lowest recorded temperature at the Norwegian Arctic stations is –46.3 °C, but even during midwinter, temperatures well above zero have been recorded at all stations (e.g. +12.3 °C at Jan Mayen on December 2001). During summer, maximum temperatures above 20 °C have occasionally been recorded at Bjørnøya and Svalbard Airport.

There are no significant trends in the annual temperature at Svalbard Airport, Bjørnøya and Jan Mayen from the start of the series to the present (Table 1). However, a closer examination of the series reveals three sub-periods with significant trends. From the start in the 1910s there is a positive trend up to the late 1930s, a temperature decrease from the 1930s to the 1960s, and from the 1960s to the present the temperature has increased significantly. Figure 2 shows that despite the warming in the recent decades, the warmest two decades on an annual basis are still

Table 1. Linear trends (°C per decade) in observed temperatures. Statistical significant trends (Mann-Kendall) are in boldface (5 % level) and underlined (1 % level).

Station	1912–2001	1910–1945	1946–1975	1976–2001
Bjørnøya	(–0.01)	(+0.08)	–0.29	+0.49
Hopen	(+0.05)	–	–0.53	**+0.84**
Sveagruva	–	–	–	**+1.84** [b]
Svalbard Airport [a]	+0.15	+1.20	–0.48	+0.78
Ny-Ålesund [a]	–	–	–0.40	+0.42
Jan Mayen	(–0.08)	(–0.20)	–0.71	+0.49
Northern Hemisphere (land)	+0.07 [c]	+0.14 [d]	–0.04	+0.31 [e]
Global (land)	+0.06 [c]	+0.11 [d]	–0.01	+0.22 [e]

[a] Combined series before 1975 [c] 1901–2000 [e] 1976–2000
[b] 1979–2001 [d] 1901–1945

the 1930s and the 1950s. An interesting feature is that the long-term series from the Norwegian Arctic stations show that on a decadal time scale, local temperature minima and maxima largely occur within the same decades for all seasons (Førland et al. 1997a).

Because of substantial seasonal differences in standard deviations, the variation in annual mean temperatures is generally more affected by the variation in winter temperature than by summer temperatures. Accordingly, both for the warming up to the 1930s and for the decrease in annual temperature from the 1930s to the 1960s, variations in winter temperatures were dominant. However, during the latest three decades, increased spring temperatures gave the largest single contribution to the increase in annual temperature.

The temperature level at the Norwegian Arctic stations is currently somewhat lower than in the 1930s. This is contrary to the rest of northern Europe and for the globe as a whole, where the present level is significantly higher than the 1930s level (Parker & Alexander 2002).

In Table 1 temperature trends are given for the sub-periods applied in the latest Intergovernmental Panel on Climate Change report (Folland & Karl 2001). During 1946–1975, all stations experienced a negative trend of –0.3 to –0.7 °C/decade. For recent decades (1976–2001), the trend is positive at all stations, with the strongest warming at Hopen, Sveagruva and Svalbard Airport. Despite the rather strong trends since 1976, the Svalbard Airport series is the only one with a statistically significant trend at the 1 % level.

Hanssen-Bauer & Førland (1998a) found that though the temperature increase in the Norwegian Arctic during the latest decades to a large degree may be explained by changes in atmospheric circulation, this is apparently not the case with respect to the early 20th century warming. A model based on regional atmospheric circulation indices was able to account for most of the trend from the 1960s to the present, but only about one-third of the observed temperature increase at Svalbard from 1912 to the 1930s and for the subsequent temperature decrease from the 1930s to the 1960s. Fu et al. (1999) suggest that ocean circulation and sea surface temperatures may be important for explaining the warming in the northern North Atlantic region before 1940; they conclude that this warming is not yet fully understood.

Precipitation

The severe measuring problems discussed above create serious uncertainties in Arctic precipitation values. Precipitation in the Arctic is low because air masses are usually stably stratified and contain only small amounts of water vapour. The normal (1961–1990) annual precipitation at Svalbard Airport (190 mm) is the lowest at any Norwegian station. There are large local gradients in precipitation between the Spitsbergen stations: although the distance is just 35 km, the annual precipitation at Barentsburg is almost three times as high as at Svalbard Airport. By measuring several transects, Sand et al. (2003) revealed both west–east and south–north gradients of snow accumulation on Spitsbergen. They found that the winter accumulation rates along the east coast were about 40 % higher than on the west coast, and that the southern part of the island receives about twice as much winter precipitation as the northern part. Large local precipitation gradients were also found for the Ny-Ålesund area (Førland et al. 1997b). The precipitation distribution was found to be strongly dependant on the large-scale wind direction. With winds from the south and south-west, the precipitation at a glacier (Brøggerbreen) a few kilometres south-west of Ny-Ålesund was about 60 % higher than in Ny-Ålesund, while with winds from the north-west Ny-Ålesund received more precipitation than the glacier.

Annual precipitation (Fig. 3) has increased substantially during the 20th century at most of the stations in the Norwegian Arctic. Both at Svalbard Airport and Bjørnøya the increase is larger than 2.5 % per decade (Table 2). At Jan Mayen most of the increase happened before 1960, while the increase at the other stations is more evenly distributed throughout the 20th century.

The course of the precipitation increase at Svalbard parallels the increase in coastal parts of northern Norway (Hanssen-Bauer & Førland 1998b), with a trend that seems to be fairly constant throughout the 20th century. However, the relative precipitation increase on Spitsbergen and Bjørnøya is considerably higher than the concurrent increases on the Norwegian mainland. It is also higher than the "average high latitude increase" estimated by Hulme (1995).

The observed long-term variations in precipitation on the west coast of Spitsbergen during the 20th century may be explained largely by varia-

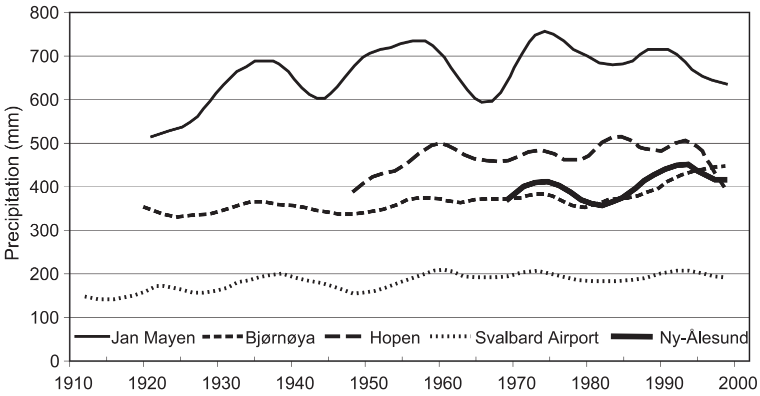


Fig. 3. Low-pass filtered series of measured annual precipitation at Norwegian Arctic stations. The series are smoothed using Gaussian weighting coefficients and show variations on a decadal time scale. (The last three years of the curves are omitted as filtered series are unreliable at the ends.)

tions in the average atmospheric circulation conditions (Hanssen-Bauer & Førland 1998a). Hanssen-Bauer (2002) concluded that about 70 % of the trend in annual precipitation at Svalbard Airport during the period 1912–1997 was accounted for by variations in atmospheric circulation.

Future climate development

Scenarios of temperature and precipitation for Svalbard for the next 50 years have been worked out by Hanssen-Bauer (2002) by empirical downscaling of an integration with the Max-Planck Institute's coupled atmosphere–ocean global climate model ECHAM4/OPYC3. The integration (GSDIO) has a physical parameterization which accounts for direct and indirect effects of sulphur aerosols in addition to greenhouse gases, including tropospheric ozone (Roeckner et al. 1999), and is based upon the emission scenario IS92a (Houghton et al. 1992).

The trend in the downscaled temperatures from the GSDIO integration for the period 1960–2000 is mainly in accordance with what has been observed during that period, while the projected annual warming rate up to 2050 is almost five times greater than that observed for the last 90 years (Table 3). A similar warming rate is projected in this area by dynamical downscaling based upon the same climate model (Bjørge et al. 2000). The projected warming is statistically significant at the 1 % level in all seasons.

Hanssen-Bauer & Førland (2001) concluded that less than 20 % of the warming projected by the GSDIO integration in Svalbard could be accounted for by changes in the atmospheric circulation. When compared to the warming during recent decades, this implies that a diminishing part of the projected warming will be attributed to changes in circulation. Some of the warming is probably directly connected to the greenhouse warming. However, the GSDIO integration shows extensive melting of sea ice east of Svalbard, and feedback effects from the melting probably contribute significantly to the strong warming in the area (Bjørge et al. 2000). Benestad et al. (2002) compared downscaled temperature scenarios for Svalbard based upon three different global climate models. They concluded that differences between the models concerning sea ice conditions lead to highly variable local temperature projections in Svalbard. The realism of future temperature scenarios is therefore critically dependent on

Table 2. Linear trends (% per decade) in observed and projected annual and seasonal precipitation. Statistical significant trends (Mann-Kendall) are in boldface (5 % level) and underlined (1 % level). The magnitude of the trend is relative to the (observed) 1961–1990 normal.

Station	Period	Annual	Winter	Spring	Summer	Autumn
Bjørnøya	1920–2001	+2.8	+3.9	+4.8	+1.3	+2.1
Jan Mayen	1921–2001	**+1.7**	+2.5	+4.6	+1.9	–0.6
Svalbard Airport (observed)	1912–2001	+2.7	–0.2	+2.2	+4.9	+3.7
Svalbard Airport (projected)	1961–2050	**+1.4**	+1.7	+4.6	-0.9	+0.6

the reliability of the projected changes in the sea ice concentrations in the region.

The downscaled precipitation scenario (Hanssen-Bauer 2002) also indicates that annual precipitation will increase significantly up to 2050, mainly because of a highly significant projected increase in spring precipitation (Table 2, bottom row). Dynamical downscaling (Bjørge et al. 2000) projects an even higher precipitation increase (ca. 2 % per decade) at the west coast of Spitsbergen.

Analyses of the Svalbard Airport series indicate that precipitation variation to a larger degree than temperature variation may be explained by changes in the atmospheric circulation. This is at least partly due to the local topography, which shelters against precipitation from some sectors while it orographically enhances the precipitation from other sectors. This is also valid for the climate scenario, but the influence of atmospheric circulation on the long-term trend in the scenario is considerably smaller than it has been during the 20th century. A major part of the projected precipitation trend is accounted for by the temperature increase, which is used in the empirical downscaling models as a proxy for increased air humidity. As different climate models seem to show a closer agreement concerning the temperature signal than concerning changes in atmospheric circulation (Räisänen 2001), this part of the trend is probably also more credible than the part caused by variations in the atmospheric circulation.

Precipitation characteristics

Frequencies of different precipitation types

The frequency of precipitation events is substantially higher at the island stations Bjørnøya and Jan Mayen than at the Spitsbergen stations Svalbard Airport and Ny-Ålesund (Table 4). Based on four observations per day (00, 06, 12 and 18 UTC), the average number of events at Jan Mayen implies that there is precipitation about 31 % of the time. The value for Svalbard Airport is 20 %.

Snow is the most frequent precipitation type. At Svalbard Airport, for example, around 75 % of precipitation events are reported as snow. At all stations, 15 - 20 % of precipitation events are reported as rain and about 5 % as sleet. Drizzle constitutes 20 % of precipitation events at Jan Mayen but just 4 % at Svalbard Airport.

Air temperature during precipitation

At Svalbard Airport, 35 % of snow events are reported at air temperatures below –10 °C; at Jan Mayen the value is 13 % (Fig. 4a). At all stations less than 10 % of snow events are observed at temperatures above 0 °C. At Svalbard Airport, 30 % of the cases with sleet are reported for temperatures $\geq +2$°C; at Bjørnøya just 5 % (Fig. 4b). For rain (Fig. 4c), around 25 % of the events at Svalbard Airport are reported at temperatures lower than 3 °C; at Bjørnøya the percentage is above 50 %. The geographical differences in temperature distribution are smaller for drizzle (Fig. 4d) than for rain. At Svalbard Airport and Ny-Ålesund, ca. 30 % of drizzle events are reported at temperatures below +3 °C; at Jan Mayen and Bjørnøya around 40 %.

Wildlife, particularly the reindeer on Spitsbergen, are vulnerable to events with snow crust or icy conditions. Extensive starving and death

Table 3. Linear trends (°C per decade) in observed and projected annual and seasonal temperature at Svalbard Airport. Statistical significant trends (Mann-Kendall) are underlined (1 % level). (From Hanssen-Bauer 2002.)

	Annual	Winter	Spring	Summer	Autumn
Observed (1912–2000)	+0.14	+0.04	<u>+0.37</u>	+0.04	+0.11
Projected (1961–2050)	<u>+0.61</u>	<u>+0.99</u>	<u>+0.52</u>	<u>+0.29</u>	<u>+0.62</u>

Table 4. Frequencies of various precipitation types. The frequencies are given as percentage of the total number of cases based on 4 observations per day (at 00, 06, 12 and 18 UTC). However, at Ny-Ålesund there are no observations at 00 UTC and the number of cases is adjusted to 4 per day.

	Bjørnøya	Svalbard Airport	Ny-Ålesund	Jan Mayen
No. of cases per year	365.2	289.0	295.6	455.9
Drizzle (%)	16.5	3.9	8.6	20.1
Rain (%)	19.9	16.5	17.0	19.5
Sleet (%)	5.5	4.0	5.8	5.2
Snow (%)	55.3	73.6	65.2	51.8
Freezing rain/ drizzle (%)	0.4	0.3	0.2	1.0
Hail, snow crystals (%)	2.4	1.8	3.2	2.4

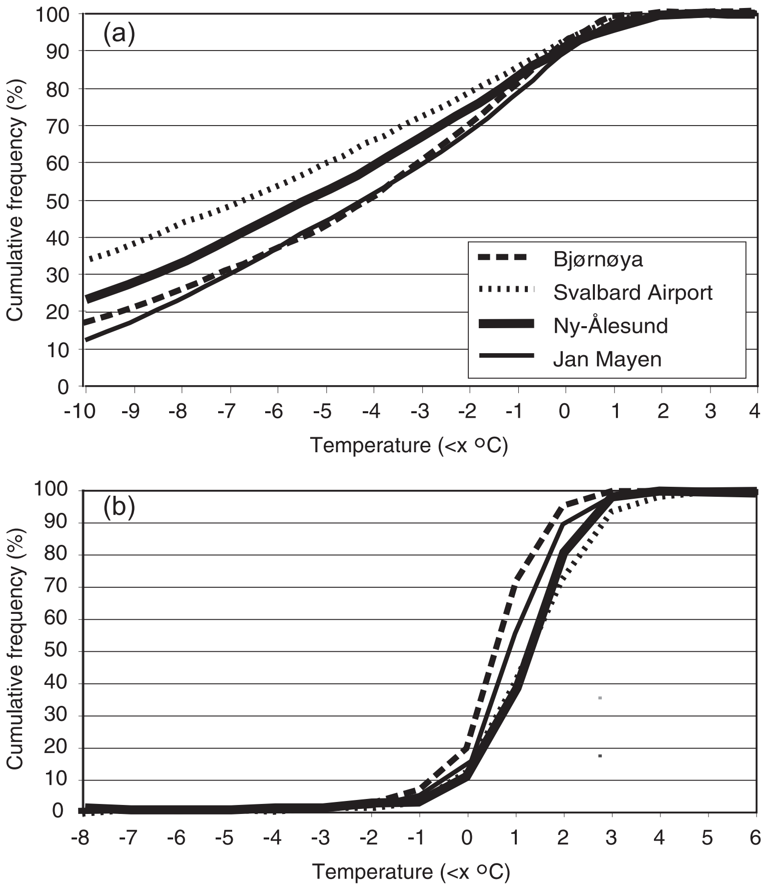


Fig. 4. Cumulative distribution of air temperature during precipitation as (a) snow, (b) sleet, (c, opposite page) rain and (d, opposite page) drizzle.

of reindeer was reported after severe crust and ground ice formation in November and December 1993. Table 5 shows that episodes with rain or drizzle falling at temperatures below 0 °C are rather infrequent at Spitsbergen; it occurs on average just once a year in Longyearbyen, Svalbard Airport and Ny-Ålesund. At Jan Mayen it is more frequent, with nearly 10 cases per year.

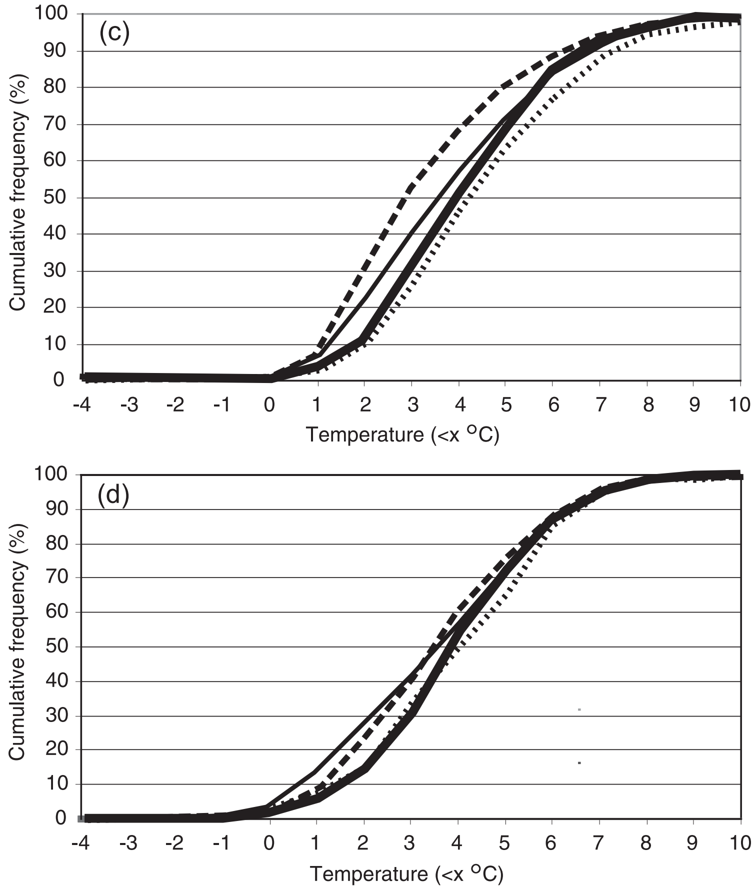
Table 5. Threshold temperature for equal probability of solid and liquid precipitation, and number of events (4 observations/day) per year with liquid precipitation observed for $T < 0$ °C.

Station name	Period	Threshold temp. (°C)	Events/yr
Bjørnøya	1956–1999	0.84	3.0
Svalbard Airport	1975–1999	1.70	1.1
Longyearbyen	1957–1977	1.96	1.0
Ny-Ålesund	1975–1999	1.62	1.0
Jan Mayen	1956–1999	1.03	8.5

The low frequencies of freezing rain/drizzle at Spitsbergen taken into consideration, it seems that it is rather seldom that events with comprehensive snow crust or ice formation are caused by liquid precipitation at temperatures below zero. Other causes include melting and refreezing at the snow surface, or rain absorbed and subsequently frozen in the surface snow layer.

Fractions of snow and rain as a function of air temperature

Figure 5 demonstrates that there are distinct geographical differences in fractions of liquid/solid precipitation as a function of air temperature. For near zero temperatures on Bjørnøya and Jan Mayen, the fraction of liquid precipitation is generally higher than at the Spitsbergen stations. On Bjørnøya, the precipitation is liquid in 90 % of precipitation events when the temperature is above 1.5 °C, while in Longyearbyen, Svalbard



Airport and Ny-Ålesund this threshold is reached at around 3 °C.

The "threshold" temperature—where the probability for liquid and solid precipitation is equal— differs at the individual Arctic stations (Table 5). At the stations on Bjørnøya and Jan Mayen, this threshold temperature is below or close to 1.0 °C, while at the Spitsbergen sites it is higher than 1.5 °C. The same pattern is also found for sleet (Fig. 4b), where the median temperature is lower on Bjørnøya and Jan Mayen than at the Spitsbergen stations. This indicates that, at the same 2 m air temperature, the air mass aloft during precipitation is colder over Spitsbergen than over Bjørnøya and Jan Mayen. Bearing in mind that rain or snow in this region may occur throughout the year, two possible reasons for this apparently more stably stratified air over the island stations during precipitation might be: (1) the contribution from convective precipitation over Spitsbergen caused by solar heating of the ground during summer; (2) during most of the year, Bjørnøya and Jan Mayen are farther from the sea ice border than the Spitsbergen stations, and cold air masses from sea ice covered areas are better mixed because of the longer travel distance over open sea.

Trends in annual amounts of solid and liquid precipitation

At Hopen and Svea, ca. 60 % of the annual precipitation amount during the period 1975–2001 was reported as snow, and only about 20 % as rain. At Svalbard Airport and Ny-Ålesund, the figures were ca. 45 and 25 %, while ca. 25 % fell as sleet or a mixture of rain and snow. On Bjørnøya and Jan Mayen, the amounts of snow, rain and mixed precipitation were nearly equal. These fractions are based on semi-daily measurements of precipitation amounts and the precipitation types report-

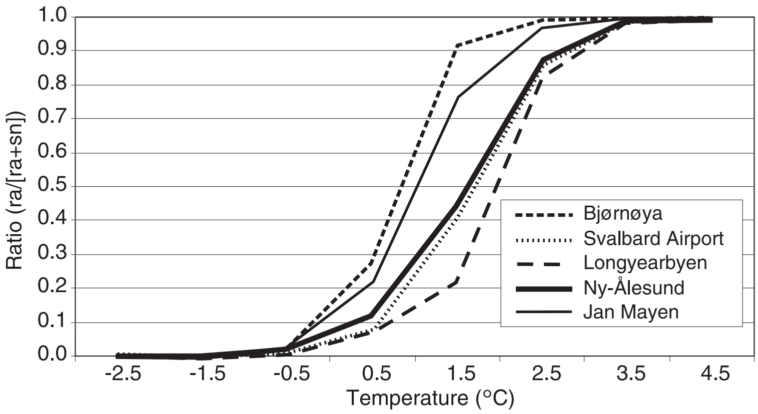


Fig. 5. Fractions of observations classified as liquid precipitation at different temperatures (ra and sn are amounts of precipitation as rain and snow, respectively).

ed by the observers. No correction for gauge undercatch has been performed and, accordingly, the fraction of solid precipitation is underestimated.

The fractions of solid precipitation have diminished at all stations during the latest decades, particularly at Svalbard Airport and Jan Mayen. Based on linear regression, the fraction of solid precipitation on Jan Mayen is reduced from 39 % in 1975 to 20 % in 2001. The fraction of annual precipitation reported as mixed precipitation (i.e. sleet, or a combination of rain and snow during the 12h sampling interval) has increased at all stations.

Fictitious trends in precipitation amounts

Precipitation records from the Arctic are influenced by substantial measuring errors, e.g. caused by undercatch of conventional precipitation gauges. As the gauge undercatch is different for snow and rain, and further depends on wind and temperature, changes in climate will result in changes in the undercatch of the gauges. Reduced fractions of annual precipitation falling as snow lead to a reduced annual gauge undercatch, and thus a fictitious positive trend for precipitation even if the true precipitation does not change at all (Førland & Hanssen-Bauer 2000). The potential for such artificial trends is maximum in areas with strong winds and where a large percentage of the annual precipitation is solid, for example, in the Norwegian Arctic.

By applying the rough correction factors presented earlier on the annual amounts of solid, liquid and mixed precipitation it is possible to give crude estimates of "true" precipitation (P_c). In Table 6, the same correction factors for solid, liquid and mixed precipitation have been applied to all the Arctic stations, with no consideration taken to differences in wind and temperature conditions at the stations. The measured values

Table 6. Changes in precipitation, 1975–2001. P_m is mean measured annual precipitation. Mean correction factor is the ratio between corrected (P_c) and measured (P_m) precipitation. Change is the difference between levels in 1975 and 2001, based on linear regression. Change for measured and corrected precipitation is given both in millimetres and as a percentage per decade of the 1975 level.

	P_m (mm)	Mean correction factor	P_c (mm)	Precipitation change: Measured		Corrected	
				Change (mm)	Change (%)	Change (mm)	Change (%)
Bjørnøya	396	1.52	602	129	15.0	198	15.2
Hopen	469	1.64	767	–65	–5.0	–119	–5.6
Sveagruva	271	1.66	451	–40	–5.2	–100	–7.6
Svalbard Airport	192	1.56	299	10	2.1	5	0.7
Ny-Ålesund	403	1.56	631	88	9.4	142	9.8
Jan Mayen	680	1.48	1007	–97	–5.2	–203	–7.2

are not corrected for evaporation and wetting effects. The rough estimates of P_c presented in Table 6 indicate that the true precipitation at all stations in the Svalbard region is more than 50% higher than the measured values.

The estimates in Table 6 are based on a short time period and rather crude approximations, but nonetheless illustrate the importance of correcting Arctic precipitation series for undercatch. For most stations there are substantial differences between trends based on measured and corrected values, both in material amounts and also for relative changes. For instance, the increase in measured annual precipitation at Svalbard Airport during the period 1975–2001 is 2.1% per decade. However, by correcting for gauge undercatch, the increase in the resulting estimates for "true" precipitation is 0.7% per decade. The scenarios currently available (Table 3) indicate a 3 °C increase in annual temperature from the present to 2050 in Svalbard. For an increase in annual temperature of 4 °C, Førland & Hanssen-Bauer (2000) estimated a fictitious precipitation increase of 2% per decade. This virtual increase, which is caused solely by reduced measuring errors, is thus of the same magnitude as the projected precipitation increase of 1.4% per decade (Table 2) under global warming. This virtual increase will be measured in addition to an eventual real increase.

Conclusions

Annual temperatures in the Longyearbyen/Svalbard Airport area have increased by more than 1 °C since 1910, but because of large interannual and decadal variations this trend is not statistically significant. Although the temperature has increased significantly since the cold 1960s, the present temperature level is still lower than in the 1930s at all stations in the Norwegian Arctic.

Measured annual precipitation in the Svalbard region and at Jan Mayen has increased substantially (15 - 25%) during the last 80 to 90 years. At Bjørnøya, Svalbard Airport and Jan Mayen, the positive precipitation trend during the 20th century is statistically significant.

The fraction of annual precipitation falling as snow has decreased at all stations in the Norwegian Arctic during recent decades. This leads to a reduced annual undercatch in the precipitation gauges, and consequently a fictitious positive trend in measured precipitation.

There are substantial differences between measured and "true" precipitation in the Arctic, both with respect to material amounts as well as trends. Accordingly, corrected precipitation values should be used in studies of historical trends as well as for monitoring future trends. Estimates of "true" precipitation are also important for water balance assessments in the Arctic.

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