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Climate variations and implications for precipitation types in the Norwegian Arctic

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SUMMARY:

The first part of the paper gives a review of recent and projected climatic variations in the Norwegian Arctic. The annual temperature has increased in the Svalbard region and at Jan Mayen during the latest decades, but the present level is still lower than in the 1930s. Measured annual precipitation has increased by more than 2.5% per decade during the 20th century. Variations in atmospheric circulation may account for a major part of the long-term precipitation variations and recent warming, but not for the temperature variations up to the 1960s. Empirical downscaled scenarios for Svalbard Airport indicate a further increase in temperature and precipitation. The projected warming rate up to 2050 is almost five times greater than that observed for the last 90 years, while the rate of the precipitation increase is just half the one observed during 1912-2001.

In the second part novel analyses of precipitation types in Norwegian Arctic are presented. Almost 75% of the precipitation events at Svalbard Airport are reported as snow, and during 1975-2001 ca. 45% of the precipitation amounts in Ny-Ålesund and Svalbard Airport was falling as solid precipitation, and just 25% as liquid precipitation. 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 a part of the observed increase in the annual precipitation is fictitious, and is due to a larger part of the "true" precipitation caught by the gauges.

KEYWORDS:
Arctic, Precipitation, Temperature, Precipitation types

SIGNATURES:

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1. Introduction

Combination of instrumental records and reconstructions from proxy sources imply that Arctic air temperatures in the 20th century were the highest in the past 400 years (Serreze, 2000). During the 20th century an increase in annual precipitation has been observed at higher northern latitudes (Hulme, 1995, Dai et al., 1997). In the Norwegian Arctic substantial variations of temperature and precipitation have occurred during the 20th century (Førland et al., 2002, Hanssen-Bauer, 2002).

Global climate models project significant increases of temperature and precipitation in high northern latitudes as the greenhouse gas concentrations increase (IPCC, 2001). The warming in high northern latitudes may be amplified due to feedbacks from the 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 that is a major determinant of global climate (Aagaard & Carmack, 1989, Mysak *et al*., 1990). The Arctic freshwater budget is driven primarily by precipitation (Walsh *et al.,* 1998). The observed and projected increase in temperature and precipitation in the Norwegian Arctic thus has broad implications for Arctic and perhaps global climate, and the monitoring of climatic trends in this region is therefore important also 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 signals have to be strong to be statistically significant. Although the scenarios indicate substantial climate changes in the Arctic, it is thus not evident 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. Earlier studies have revealed that inhomogeneities in Arctic climate series often are of the same magnitude as typical long-term trends (Hanssen-Bauer & Førland (1994), Nordli et al. (1996)). Accordingly it is of crucial importance to adjust series for inhomogeneities before 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) and Førland et al. (1997b). A review paper concerning observational evidence of recent changes in the Arctic environment is given by Serreze et al. (2000).

In this paper the measuring problems in Arctic climate series are discussed in section 2, a review of past and future climate variations is given in section 3 and 4. In section 5 and 6 new analyses of temperature conditions during precipitation and trends in fractions of solid/liquid precipitation at the Arctic stations are outlined. In section 7 it is shown that the observed positive trends of measured precipitation are exaggerating the real precipitation trends.

2. Measuring problems in the Arctic

2.1 General measuring problems

The Arctic climate impedes several serious challenges for the monitoring of the main weather elements. Icing and wet snow may cause malfunctioning of the sensors for e.g. temperature, humidity, precipitation, wind speed and wind direction at manual as well as automatic weather stations. During the polar night, the combination of darkness and harsh weather occasionally complicates the 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), and the regular snow depth measurements at the weather stations therefore seldom are representative of 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.

2.2 Errors in precipitation measurements

The most difficult weather element to monitor in the Arctic is precipitation. 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:

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

where P_C is true precipitation, k is the correction factor due to aerodynamic effects, P_m measured precipitation, ΔP_W precipitation lost by wetting, and ΔP_E precipitation lost by evaporation from the gauge. Other error types like splash in/out, instrumental errors, misreading, etc., are either corrected in routine quality controls, or generally giving insignificant contributions in the Nordic climate. However, at the Norwegian Arctic stations, drifting or blowing snow occasionally cause substantial problems. «Precipitation» caused solely by blowing snow is excluded through the quality control at the Norwegian Meteorological Institute, but often there is a combination of precipitation and blowing snow. In such cases it is difficult to distinguish the proportions of real precipitation and blowing snow, though recently a method is proposed by Bogdanova et al. (2002).

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 both solid, liquid and mixed precipitation (Førland and Hanssen-Bauer, 2000). At most measuring sites, wind speed is the most important environmental factor contributing to the undercatch of the precipitation gauges. The undercatch is caused by wind acceleration over the gauge. Hydrometeors that during calm would have reached the catchment area of the gauge are thus deflected outside the orifice of the gauge. Based on results from the WMO Solid Precipitation Measurement Intercomparison (Goodison et. al., 1998), Nordic precipitation gauge studies (Førland et al., 1996) and field measurements in Ny-Ålesund, Førland and 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 for increasing wind speeds, and decrease with increasing temperature.

By considering typical values of wind speed, temperature and precipitation intensity, Førland and Hanssen-Bauer (2000) suggested the following rough correction factors for unsheltered stations at Spitsbergen: Liquid precipitation k_l=1.15, solid k_s=1.85 and mixed k_m=($0.5*k_l + 0.5*k_s$) = 1.50. These values are almost identical to the Nordic correction factors recommended for «extremely unsheltered locations at the coast or in the mountains» (Førland *et al.*, 1996). It should however be stressed that use of these typical correction factors is not reproducing appropriate estimates of true precipitation on an event-by-event basis, nor reflecting differences in wind exposure between different measuring sites.

2.3 Adjustment for inhomogeneities

Inhomogeneities in climatic series may be caused by relocation of sensors, changed environment (buildings etc.) 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 the measuring sites may cause substantial changes in measuring conditions for e.g. precipitation. Identification of inhomogeneities in Arctic series is further hampered by the sparse station network; e.g. for Bjørnøya and Jan Mayen the nearest neighbouring station is more than 300 km apart. For identification and adjustment of inhomogeities in the Norwegian Arctic temperature and precipitation series, the Standard Normal Homogeneity Test (Alexandersson, 1986, Hanssen-Bauer & Førland, 1994) is applied. A detailed survey of the results of the homogeneity analyses for Norwegian Arctic series is given by Nordli et al. (1996).

3. Temperature and precipitation variations in the 20th century

3.1 Climate series for the Norwegian Arctic

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

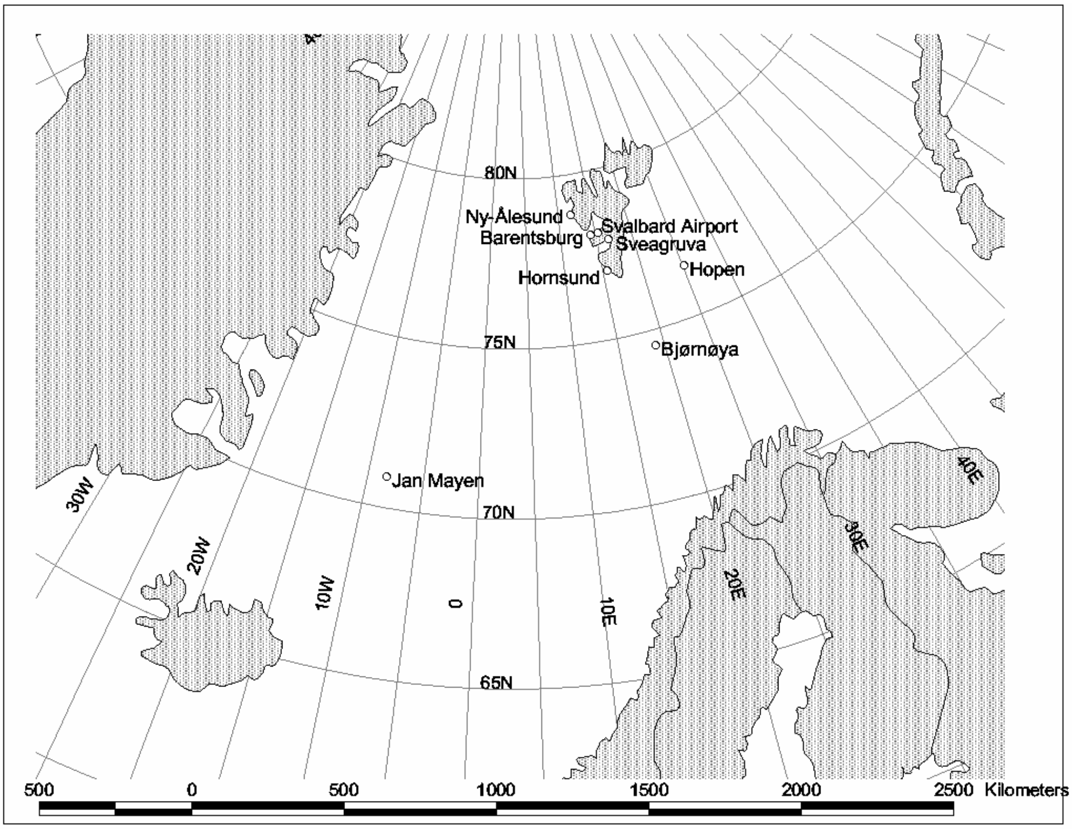

Figure 1. Location of currrent manual weather stations in the Norwegian Arctic (Bjørnøya [Elevation: 16 m a.s.l., Start: 1920]), Hopen [6, 1944], Hornsund (Polish) [10,1978], Sveagruva [9, 1978]), Barentsburg (Russian)[x,1933], Svalbard Airport [28, 1975], Ny-Ålesund [8, 1974], Jan Mayen [10, 1921]).

3.2 Temperature

There are pronounced fluctuations in Arctic climate, on daily, monthly and annual timescales. The lowest recorded temperature at the Norwegian Arctic stations is –46.3 °C (Svalbard Airport, 04.03.1986). But even during midwinter, temperatures well above zero have been recorded at all stations (e.g. +12.3 °C at Jan Mayen, 14.12.2001). During summer, maximum temperatures above 20°C have occasionally been recorded at Bjørnøya and Svalbard Airport.

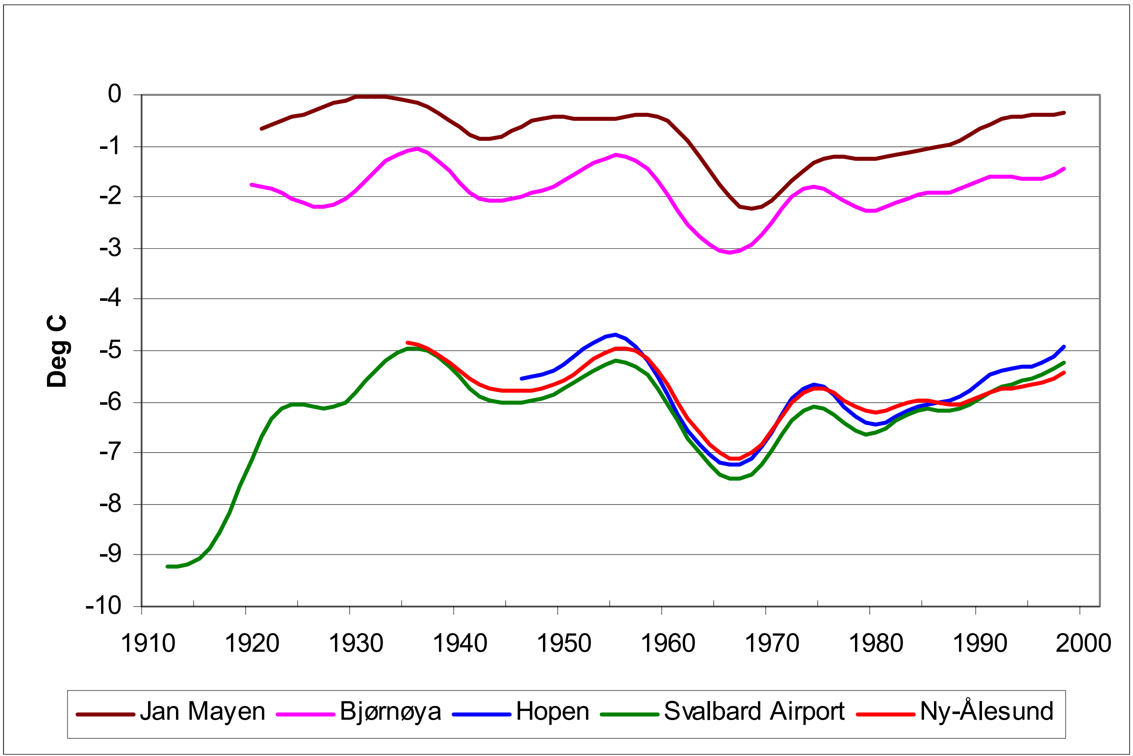

Figure 2. Low-pass filtered series of annual temperature at Norwegian Arctic stations. The series are smoothed by using Gaussian weighting coefficients, and show variations on a decadal time scale. (The series are based on data incl. 2001).

There are no significant trends in the annual temperature at Svalbard Airport, Bjørnøya and Jan Mayen from the start of the series to 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 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 the 1930s and the 1950s. Variation in winter temperatures gave the largest single contribution to the warming up to the 1930s, and also to the temperature decrease from the 1930s to the 1960s. Increased spring temperature gave the largest single contribution to the warming over the latest 3 decades.

The long-term series from the Norwegian Arctic stations show that on decadal time scale, local temperature minima and maxima largely occur within the same decades for all seasons (Førland et al., 1997b). Because of substantial differences in standard deviations, the variation in annual mean temperatures is more affected by the variation in winter temperature than by summer temperatures.

Table 1. Linear trends (°C per decade) in observed temperatures. Statistical significant trends (Mann-Kendall) are marked by * (5%-level) and ** (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*
Svea Gruver	-	-	-	+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 b). 1979-2001 c). 1901-2000 d). 1901-1945 e).1976-2000

The temperature level at the Norwegian Arctic stations is presently 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 level from the 1930s (Parker and Horton, 1999).

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

The temperature increase in the Norwegian Arctic during the latest decades may to a large degree be explained by changes in atmospheric circulation (Hanssen-Bauer and Førland, 1998a). However, variations in circulation account for only 1/3 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, and they conclude that this warming is not yet fully understood.

3.3 Precipitation

The severe measuring problems (section 2) endorse serious uncertainties to the precipitation values from the Arctic. Precipitation is low in the Arctic because air masses usually are stably stratified and contain only small amounts of water vapour. The normal (1961-1990) annual precipitation at Svalbard Airport (190 mm) is thus 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. Large local precipitation gradients were also found for the Ny-Ålesund area (Førland et al., 1997a). The precipitation distribution was found to be strongly dependant on the large-scale wind direction. For winds from south and southwest the precipitation at a glacier (Brøggerbreen) a few kilometres southwest of Ny-Ålesund was about 60% higher than in Ny-Ålesund, while for winds from northwest Ny-Ålesund got more precipitation than the glacier.

Annual precipitation (Figure 3) has increased substantially during the 20th century at most of the stations in the Norwegian Arctic. At Svalbard Airport the increase during 1912-2001 is ca. 2.7% per decade (Table 2). For Bjørnøya the annual precipitation increase (1920-2001) is 2.8% per decade, and for Jan Mayen (1921-2001) 1.7% per decade. 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.

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

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 course of the precipitation increase at Svalbard follows 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 at Spitsbergen and Bjørnøya is considerably higher than the similar increases on the Norwegian mainland, and also higher than the “average high latitude increase” estimated by Hulme (1995).

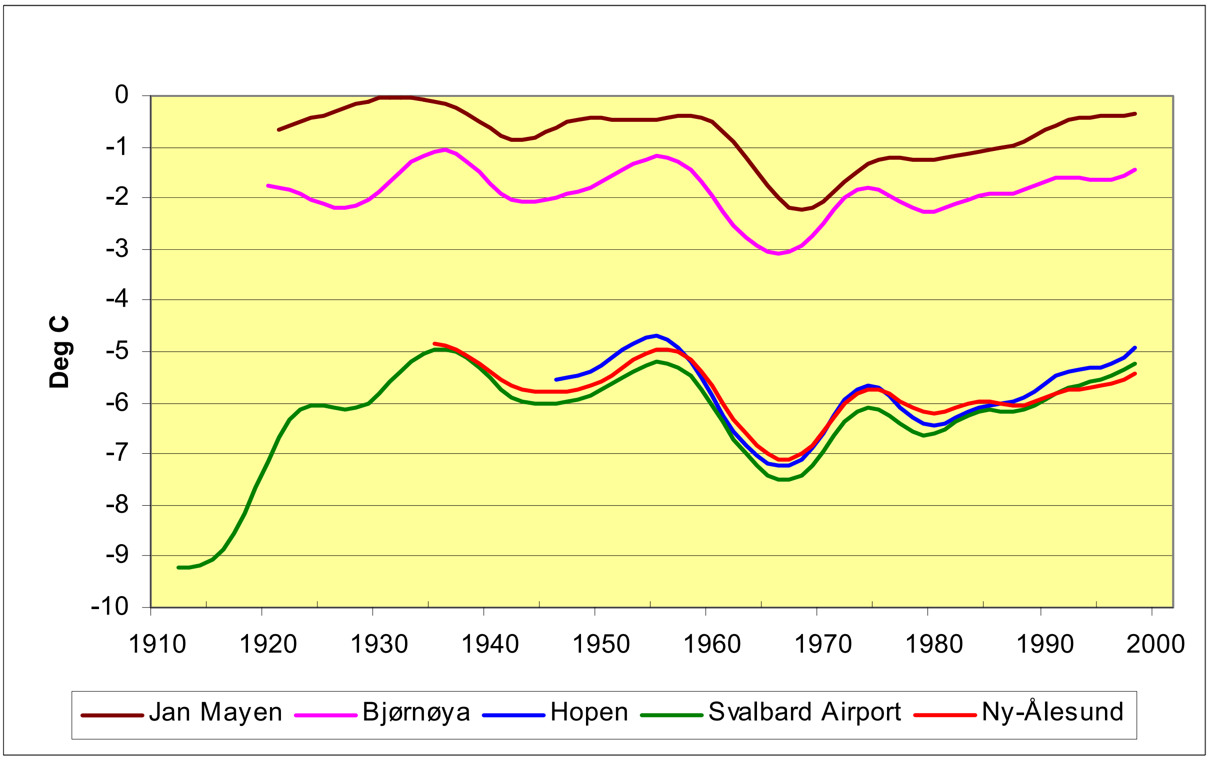

Figure 3. Low-pass filtered series of measured annual precipitation at Norwegian Arctic stations. The series are smoothed by using Gaussian weighting coefficients, and show variations on a decadal time scale. (The series are based on data incl. 2001).

The observed long-term variations in precipitation on the west coast of Svalbard during the 20th century may to a large degree be explained by variations in the average atmospheric circulation conditions (Hanssen-Bauer and 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.

4. Future climate development

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

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 (Haugen et al., 2002). The projected warming is statistically significant at the 1% level in all seasons.

*Table 3. Linear trends (°C per decade) in observed and projected annual and seasonal temperature at Svalbard Airport. Statistical significant trends (Mann-Kendall) are marked by * (10%-level) and ** (1%-level). (From Hanssen-Bauer, 2002)*

	Annual	Winter	Spring	Summer	Autumn
Observed, 1912-2000	+0.14	+0.04	+0.37**	+0.04	+0.11
Projected, 1961-2050	+0.61**	+0.99**	+0.52**	+0.29**	+0.62**

Hanssen-Bauer and Førland (2001) concluded that less than 20% of the warming projected by the GSDIO integration in the Svalbard area is caused by changes in the atmospheric circulation. When compared to the warming during the latest 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 (Haugen et al., 2002), and feedback effects from the melting probably contribute significantly to the strong warming in the area. The realism of the present temperature scenario is critically dependent on the credibility of the GSDIO integration's projected changes in the sea-ice concentrations in the Svalbard region.

The downscaled precipitation scenario (Hanssen-Bauer, 2002) indicates that also 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 (Haugen et al., 2002) project an even higher precipitation increase (~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 topography in the area, which shelters against precipitation from some sectors, while it orographically enhance 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, 2000), this part of the trend in probably also more credible than the part caused by variations in the atmospheric circulation.

5. Air temperature during precipitation

5.1 Frequencies of precipitation types for different temperature intervals.

Table 4 illustrates the large geographical differences in precipitation frequencies for drizzle, rain, snow and mixed precipitation, and the large span of observed temperatures during the various precipitation types. The figures are based on simultaneous observations of precipitation type and air temperature at 00, 06, 12 and 18 UTC. At Ny-Ålesund there is no observation at 00UTC. To make the values easier comparable, the Ny-Ålesund frequencies are multiplied by 4/3.

The largest frequencies of precipitation events (Table 4, rightmost columns) are found at Jan Mayen (456 observations per year), the lowest at Svalbard Airport and Ny-Ålesund (around 290 per year). This implies that at Jan Mayen there is precipitation in about 31% of the time, and Svalbard Airport in 20%. Snow is the most frequent precipitation type; e.g. at Svalbard Airport around 75% of the precipitation events are reported as snow. For Jan Mayen there are more than 90 observations per year with drizzle, at Svalbard Airport just around 10. For most of the drizzle events, the temperature is in the interval 1-8°C. At Jan Mayen and Bjørnøya the largest frequencies of mixed precipitation are found in the temperature interval 0-1°C, while Svalbard Airport and Ny-Ålesund have a maximum in the interval 1-2°C. At Ny-Ålesund, and particularly at Svalbard Airport a substantial part of the solid precipitation events are reported at temperatures below –10°C.

Table 4. Frequencies of various precipitation types for different temperature intervals.

Table 4. Frequencies of various precipitation types for different temperature intervals.

The bottom row show number of cases for each temperature interval, and the two rightmost columns show number of cases (also as percentage) for each precipitation type.

99710 Bjørnøya

Temperature (degC)	<-10	-10- -9.1	-9- -8.1	-8- -7.1	-7- -6.1	-6- -5.1	-5- -4.1	4.0- -3.1	3.0- -2.1	2.0- -1.1	1.0- -0.1	0-0.9	1-1.9	2-2.9	3-3.9	4-4.9	5-5.9	6-6.9	7-7.9	8-8.9	9-9.9	>10.0	No. of cases	%
Drizzle	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	1.1	2.4	12.1	28.9	38.0	49.8	51.3	53.5	52.7	51.5	37.2	30.8	25.0	60.3	16.5
Rain	0.4	0.0	0.2	0.2	0.2	0.2	0.1	0.0	0.9	0.4	1.1	14.3	50.9	58.9	49.1	48.2	46.0	47.0	48.5	62.8	69.2	75.0	72.7	19.9
Sleet	0.0	0.0	0.0	0.4	0.4	0.4	0.6	0.6	0.9	2.7	9.8	33.0	14.4	2.3	0.6	0.1	0.4	0.0	0.0	0.0	0.0	0.0	20.2	5.5
Snow	94.5	98.5	96.3	96.7	96.3	95.8	95.9	95.8	94.0	91.5	80.1	37.0	4.6	0.5	0.3	0.3	0.2	0.3	0.0	0.0	0.0	0.0	201.8	55.3
Freezing rain/drizzle	0.1	0.0	0.0	0.0	0.0	0.2	0.1	0.6	0.2	0.8	2.1	0.6	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.3	0.4
Hail, snowcrystals	5.0	1.5	3.5	2.7	3.1	3.4	3.2	3.0	3.6	3.4	4.3	3.0	1.1	0.2	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	8.8	2.4
No. of cases	36.5	8.9	9.8	11.2	12.6	11.6	17.8	19.4	20.6	26.0	28.0	32.4	32.2	28.5	23.0	17.6	12.6	8.4	4.7	2.2	0.9	0.3	365.2	100.0

99840 Svalbard Airport

Temperature (degC)	<-10	-10- -9.1	-9- -8.1	-8- -7.1	-7- -6.1	-6- -5.1	-5- -4.1	4.0- -3.1	3.0- -2.1	2.0- -1.1	1.0- -0.1	0-0.9	1-1.9	2-2.9	3-3.9	4-4.9	5-5.9	6-6.9	7-7.9	8-8.9	9-9.9	>10.0	No. of cases	%
Drizzle	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	1.1	4.0	5.5	16.0	14.8	17.4	25.5	15.9	15.9	3.8	3.8	0.0	11.1	3.9
Rain	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.4	5.9	26.5	56.3	79.9	80.6	74.1	84.1	84.1	96.2	96.2	100.0	47.6	16.5
Sleet	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.6	1.8	7.6	20.1	28.6	18.1	4.4	1.6	0.0	0.0	0.0	0.0	0.0	0.0	11.6	4.0
Snow	95.4	99.6	100.0	98.1	98.6	98.4	98.1	97.6	98.3	94.3	87.4	69.2	38.8	9.6	0.7	0.0	0.5	0.0	0.0	0.0	0.0	0.0	212.7	73.6
Freezing rain/drizzle	0.1	0.4	0.0	0.4	0.0	0.0	0.6	0.9	0.3	0.5	1.7	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.3
Hail, snowcrystals	4.5	0.0	0.0	1.5	1.4	1.6	1.3	1.2	0.8	3.1	0.8	0.5	0.6	0.0	0.3	0.4	0.0	0.0	0.0	0.0	0.0	0.0	5.2	1.8
No. of cases	74.8	9.7	11.4	11.0	11.5	12.9	13.0	13.8	14.7	15.8	14.6	15.3	13.3	13.6	12.2	10.1	8.7	6.4	3.4	1.1	1.1	0.7	289.0	100.0

99910 Ny-Alesund (Number of cases per year adjusted to 4 obs/day)

Temperature (degC)	<-10	-10- -9.1	-9- -8.1	-8- -7.1	-7- -6.1	-6- -5.1	-5- -4.1	4.0- -3.1	3.0- -2.1	2.0- -1.1	1.0- -0.1	0-0.9	1-1.9	2-2.9	3-3.9	4-4.9	5-5.9	6-6.9	7-7.9	8-8.9	9-9.9	>10.0	No. of cases	%
Drizzle	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.1	5.0	11.9	23.0	36.6	35.5	31.3	34.2	31.3	8.0	12.5	22.2	25.5	8.6
Rain	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	1.8	8.0	20.9	52.6	60.9	64.1	68.7	65.8	68.8	92.0	87.5	77.8	50.1	17.0
Sleet	0.2	0.0	0.0	0.0	0.0	0.0	0.8	0.7	1.7	1.3	6.2	24.1	38.1	15.1	1.9	0.4	0.0	0.0	0.0	0.0	0.0	0.0	17.2	5.8
Snow	92.7	97.3	97.4	97.9	97.8	95.6	94.6	95.9	94.2	94.9	86.1	57.8	26.0	7.1	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	192.6	65.2
Freezing rain/drizzle	0.0	0.0	0.0	0.0	0.0	0.4	0.4	0.3	0.0	0.0	0.3	1.1	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.2
Hail, snowcrystals	7.1	2.7	2.6	2.1	2.2	4.0	4.2	2.7	4.1	3.9	3.6	4.0	2.5	2.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.6	3.2
No. of cases	48.2	10.0	10.4	12.7	12.3	12.0	13.9	15.7	15.6	16.6	18.0	20.1	18.9	18.8	16.9	13.2	11.3	6.2	2.6	1.3	0.4	0.5	295.6	3.2

99950 Jan Mayen

Temperature (degC)	<-10	-10- -9.1	-9- -8.1	-8- -7.1	-7- -6.1	-6- -5.1	-5- -4.1	4.0- -3.1	3.0- -2.1	2.0- -1.1	1.0- -0.1	0-0.9	1-1.9	2-2.9	3-3.9	4-4.9	5-5.9	6-6.9	7-7.9	8-8.9	9-9.9	>10.0	No. of cases	%
Drizzle	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.2	0.2	2.1	7.3	21.1	32.3	40.1	49.1	51.4	55.0	52.9	39.2	37.9	19.4	11.5	91.5	20.1
Rain	0.0	0.0	0.2	0.0	0.3	0.4	0.0	0.2	0.4	0.3	2.0	11.3	35.2	51.4	49.3	48.3	44.8	46.9	60.8	62.1	80.6	88.5	88.8	19.5
Sleet	0.0	0.2	0.3	0.1	0.1	0.1	0.4	0.4	1.5	2.6	5.6	22.6	20.4	6.4	1.3	0.2	0.1	0.0	0.0	0.0	0.0	0.0	23.9	5.2
Snow	97.4	97.7	97.6	97.8	97.9	96.7	94.8	91.4	90.6	84.7	75.7	41.2	10.9	1.6	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	236.3	51.8
Freezing rain/drizzle	0.0	0.0	0.0	0.1	0.1	0.8	1.0	1.6	1.9	3.5	4.9	0.8	0.2	0.1	0.0	0.1	0.0	0.2	0.0	0.0	0.0	0.0	4.5	1.0
Hail, snowcrystals	2.6	2.1	1.9	1.9	1.5	2.9	3.6	6.1	5.4	6.8	4.4	3.0	1.0	0.4	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.0	11.0	2.4
No. of cases	31.3	11.7	14.0	16.5	16.4	18.0	18.3	20.8	22.5	28.1	36.9	44.0	39.5	30.8	29.5	26.3	24.0	15.1	8.2	2.8	0.8	0.6	455.9	100.0

5.2 *Fractions of snow and rain as a function of air temperature*

For water-balance considerations, it is important to know the probability of getting precipitation as rain or snow at different air temperatures. The fractions of number of events with various precipitation types within different temperature intervals are included in Table 4. The table shows e.g. that for air temperature in the interval 1-2 °C, 26% of the precipitation events in Ny-Ålesund are reported as snow, 38% as sleet, 21% as rain and 12% as drizzle. For the temperature interval –1 to 0 °C, the similar figures are snow: 86%, sleet: 6%, rain: 2% and drizzle: 2%.

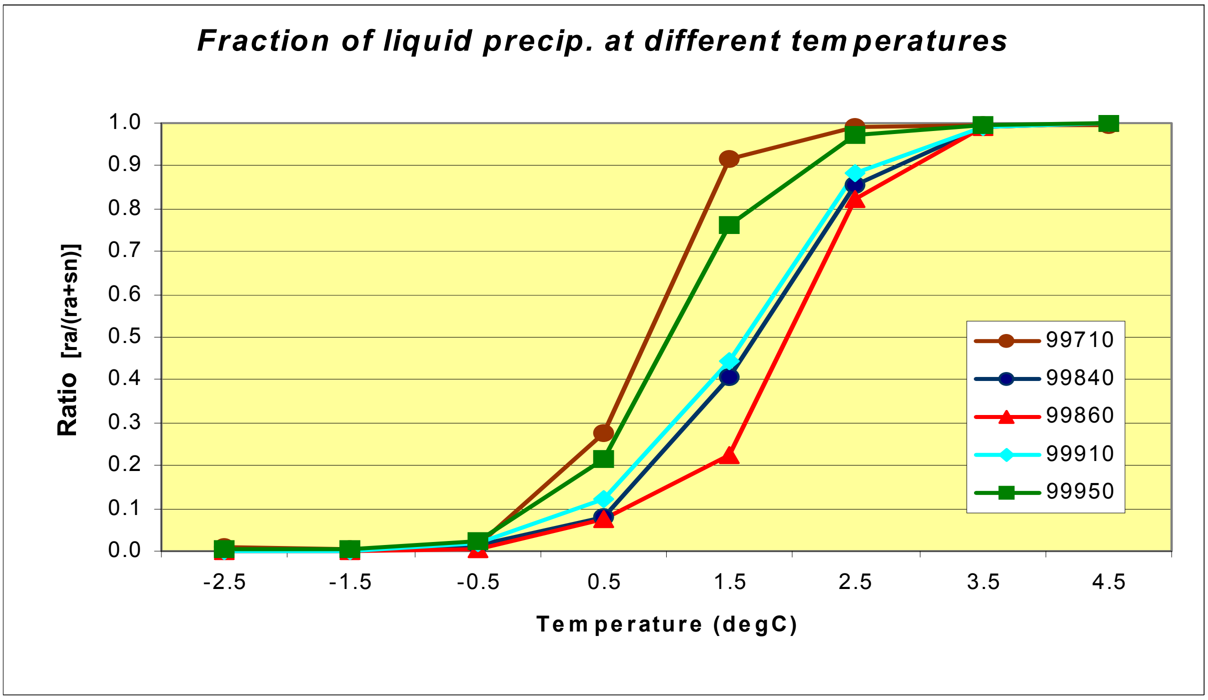

Figure 4. Fractions of observations classified as liquid precipitation for different temperatures. (Stations: 99710 Bjørnøya, 99840 Svalbard Airport, 99860 Longyearbyen, 99910 Ny –Ålesund, 99950 Jan Mayen)

Figure 4 demonstrates that there are distinct geographical differences in fractions of liquid/solid precipitation as a function of air temperature. For near zero temperatures at Bjørnøya and Jan Mayen, the fraction of liquid precipitation is generally higher than at the Spitsbergen stations. For air temperatures above 1.5°C, the precipitation at Bjørnøya is liquid in more than 90% of the events, while in Longyearbyen this fraction is just ca. 20%.

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

St.no	St.name	Period	Threshold temperature (°C)	Events/year
99710	Bjørnøya	1956-1999	0.84	3.0
99840	Svalbard Airport	1975-1999	1.70	1.1
99860	Longyearbyen	1957-1977	1.96	1.0
99910	Ny-Ålesund II	1975-1999	1.62	1.0
99950	Jan Mayen	1956-1999	1.03	8.5

Also the "threshold" temperature where the probability for liquid and solid precipitation is equal, is different at the Arctic stations (Table 5). At Bjørnøya this threshold temperature is 0.8°C, and at Jan Mayen it is close to 1.0°C. At the Spitsbergen stations however, this threshold temperature is higher than 1.6°C, and in Longyearbyen even close to 2.0°C. The same feature is also found for mixed precipitation (cf. Table 4), where the median temperature is lower at Bjørnøya and Jan Mayen than at the Spitsbergen stations. This indicates that, at the same 2m air temperature, the air-mass aloft is colder over Spitsbergen than over Bjørnøya and Jan Mayen, at least during precipitation events. No obvious physical explanation for this is suggested.

5.3 Frequencies of liquid precipitation at air temperatures below zero

Wild animals and particularly the reindeers at Spitsbergen are vulnerable to events with snow crust or icy conditions. Extensive starving and death of reindeers were e.g. reported after severe crust and ground ice formation in November and December of 1993. Table 5 shows that episodes with rain or drizzle falling at temperatures below 0 °C are rather infrequent at Spitsbergen; both in the Longyearbyen and in Ny-Ålesund in average just once a year. At Jan Mayen it is more frequent, with nearly 10 cases per year.

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

6. 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 (Table 6). At Svalbard Airport and Ny-Ålesund the similar figures were ca. 45 and 25%, while ca. 25 % was falling as sleet or a mixture of rain and snow. At Bjørnøya and Jan Mayen the amounts of snow, rain and mixed precipitation were quite equal. The fractions in Table 6 are based on semi-daily measurements of precipitation amounts, and the precipitation types reported by the observers. No correction for gauge undercatch has been performed, and accordingly the fraction of solid precipitation is underestimated.

Table 6. Changes in precipitation amounts and types during 1975-2001.

P_m is mean measured annual precipitation, Frc is fraction of P_m falling as liquid, solid and mixed precipitation, mean correction factor is ratio between corrected (P_c) and measured (P_m) precipitation, Chg is difference between levels in 1975 and 2001, based on linear regression. Chg for measured and corrected precipitation (rightmost columns) are given both in millimetres and as a percentage per decade of the 1975 level.

											Precipitation change			
	P_m	Liquid		Solid		Mixed		Corr.factor		P_c	Measured		Corrected	
	(mm)	Frc(%)	Chg	Frc(%)	Chg	Frc(%)	Chg	Mean	Chg	(mm)	Chg(mm)	Chg(%)	Chg(mm)	Chg(%)
Bjørnøya	396	31.4	-2.6	36.6	-2.4	32.0	5.0	1.52	0.00	602	129	15.0	198	15.2
Hopen	469	21.1	4.5	57.6	-8.5	21.3	4.0	1.64	-0.05	767	-65	-5.0	-119	-5.6
Svea Gruver	271	16.3	11.9	62.7	-15.8	21.0	3.9	1.66	-0.10	451	-40	-5.2	-100	-7.6
Svalbard Ap.	192	27.9	6.1	45.4	-12.9	26.7	6.8	1.56	-0.07	299	10	2.1	5	0.7
Ny-Ålesund	403	24.9	-5.3	45.3	-3.0	29.8	8.3	1.56	0.01	631	88	9.4	142	9.8
Jan Mayen	680	34.5	8.6	29.4	-19.0	36.1	10.4	1.48	-0.10	1007	-97	-5.2	-203	-7.2

Table 6 demonstrates that the fraction of solid precipitation has diminished at all stations during the latest decades, and particularly at Svalbard Airport and Jan Mayen. Based on linear regression, the fraction of solid precipitation at 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.

7. 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 (cf. section 2). 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 and Hanssen-Bauer, 2000). The potential for such artificial trends is at maximum in areas with strong winds and where a large percentage of the annual precipitation is solid, as e.g. in the Norwegian Arctic.

By applying the rough correction factors (section 2.2) 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 are applied to all the Arctic stations, and no consideration is taken to differences in wind and temperature conditions at the stations. The measured values are not corrected for evaporation and wetting effects. The rough estimates of P_c presented in Table 6 indicates 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 still illustrate the importance of correcting Arctic precipitation series for undercatch.

By referring to measured values, the increase in the annual precipitation at Svalbard Airport during the period 1975-2001 is 2.1% per decade (Table 6, rightmost columns). However, by correcting for gauge undercatch, the increase in the resulting estimates for "true" precipitation is 0.7% per decade. The present scenarios (Table 3) indicate an increase in annual temperature from present up to 2050 of 3°C in the Svalbard region. 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.

8. Conclusions

- Annual temperatures in the Longyearbyen/Svalbard Airport area has increased by more than 1°C since 1910, but because of the large inter-annual 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 (20-30%) during the last 7-8 decades. Both 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 the latest decades. This leads to a reduced annual undercatch in the precipitation gauges, and consequently a fictitious positive trend in measured precipitation.

- The relative increase in measured precipitation at Svalbard Airport is nearly three times the increase in "true" precipitation. 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 crucial for water balance assessments in the Arctic

- Suggestion for future studies: The present procedures for correction for gauge undercatch under Arctic weather conditions are based on rather crude extrapolations. No measurements of "true" precipitation in the Norwegian Arctic are available. As reliable correction procedures for undercatch are essential both for monitoring long-term variations in precipitation as well as for water balance assessments, a "Double Fence Intercomparison Reference, DFIR" for direct measurement of "true" precipitation should be installed at the weather station in Ny-Ålesund. Detailed WMO recommendations how to establish and run parallel measurements in national gauges and DFIR to establish correction procedures is given by Goodison et al. (1998). The DFIR-measurements should be evaluated by field measurements of the water equivalent in the snow magazine in the Ny-Ålesund area.

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