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Artificial Trends or Real Changes? Investigating Precipitation Records in Ny-Ålesund, Svalbard



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ABSTRACT

The Svalbard archipelago, in the Atlantic-Arctic region, has been affected by a strong increase in precipitation in the last decades, with major potential impacts for the cryosphere, bio-geochemical cycles, and the ecosystems. Ny-Ålesund (79°N), in the northwest part of Svalbard, hosts invaluable meteorological records widely used by many researchers. Among the observed parameters, the amount of precipitation is subject to large biases, mainly due to the well-known precipitation gauges undercatch during windy conditions. The purpose of this study is to investigate if the observed trend of precipitation in Ny-Ålesund in the 1975-2022 period was real and how it was impacted by the gauge undercatch. We applied several correction factors developed in the last decades, based on local wind speed and temperature. We forced these corrections with 12-hourly precipitation data from the Ny-Ålesund weather station. Taking the period 1975-2022, the trend of precipitation increased from 3.8 mm/year in the observations to 4.5 mm/year (± 0.2) after the corrections, mainly due to enhanced snowfall in November to January months. Taking the most recent 40 years period (1983-2022), the amount of precipitation still increased by 3.8 mm/year in the observations, but only by 2.6 mm/year (± 0.5) after the corrections. The recent observed trend of precipitation stays large due to an increase of wet snowfall and rainfall that are measured more efficiently by the precipitation gauge. This result shows the need of applying corrections factors when using precipitation gauge data, especially in regions exhibiting large inter-annual changes of weather conditions.

SIGNIFICANCE STATEMENT

The purpose of this study is to investigate if the observed trend of precipitation in Ny-Ålesund in the 1975-2022 period was real and how it was impacted by the gauge undercatch. The results show that the observed trend of precipitation was overestimated when calculated in the most recent 40 years period (1983-2022). This overestimation was large due to an increase with time of wet snowfall and rainfall that were measured more efficiently by the precipitation gauge. This result shows the need of applying corrections factors when using precipitation gauge data, especially in regions exhibiting large inter-annual changes of weather conditions.

1. Introduction

The Arctic is the region of the world experiencing the fastest warming (Previdi et al. 2021) with major implications for the hydrological cycle and the ecosystems (Vincent 2020). The Svalbard archipelago is facing a particularly alarming winter warming, reaching 3°C per decades (Hanssen-Bauer et al. 2019). In the last years, several episodes of rain-on-snow have been reported in the middle of the winter, which has a large implication for the cryosphere, favoring avalanches (Eckerstorfer and Christiansen 2011), degrading the permafrost (Hansen et al. 2014), and impacting glacier heat fluxes (Łupikasza et al. 2019; Van Pelt et al. 2016). Moreover, the refreezing of liquid water after rain-on-snow events negatively impact the ecosystem, lowering the productivity of plants (Bjerke et al. 2014) and preventing herbivores from accessing food (Descamps et al. 2017; Forbes et al. 2016). The decrease of snowfall and the resulting reduction of the snowpack may also reduce ecosystem respiration (Morgner et al. 2010). In recent years, rain is becoming more frequent due to an increase of precipitation and a higher rainfall to total precipitation ratio associated to the strong warming (Førland et al. 2011; Łupikasza and Cielecka-Nowak 2020; Peeters et al. 2019). Ny Ålesund, in Northwest Spitsbergen, known as the northernmost town in the world, hosts numerous research stations aiming to document Arctic amplification and its impacts on the cryosphere and the ecosystem (Pedersen et al. 2022). Many of these research projects use the precipitation data observed at the Ny Ålesund meteorological station. However, these precipitation measurements are subject to large uncertainties, mainly due to the well-documented undercatch of precipitation by standard precipitation gauges (Førland and Hanssen-Bauer 2000).

Many correction methods have been developed in the past to obtain true precipitation. The corrections introduced by Hanssen-Bauer et al. (1996) for Norwegian gauges use wind speed, temperature, and precipitation intensity to correct rain and snow separately. This correction method has been used in the Alps (Morin et al. 2012), Russia (Helbig et al. 2013), Finland (Taskinen and Söderholm 2016), Columbia (Ramírez et al. 2017), Canada (Lemieux et al. 2020), Japan (Niwano et al. 2021b), Greenland (Niwano et al. 2021a) or at a global scale (Fuchs et al. 2001). This correction was further modified based on the comparison with a Tretyakov precipitation gauge located in Ny Ålesund (Førland and Hanssen-Bauer 2000). Another correction method, applied only to snow and using solely wind speed data in the correction (Adam and Lettenmaier 2003), was used to correct data in the northern hemisphere (Yang et al. 2005). More recently, correction methods adapted to automatic weather stations were developed (Wolff et al. 2015; Kochendorfer et al. 2017). Wolff et al., (2015) created

integrated correction functions for solid and liquid precipitation using temperature and wind speed. Kochendorfer et al., (2017) developed different correction functions for unshielded and one-shielded automatic gauges. This method has been used in the Alps (Gugerli et al. 2020; Di Mauro et al. 2019), China (Zhao et al. 2021), Tibet (Zhang et al. 2022), Nepal (Kirkham et al. 2019), Arctic Canada (Domine et al. 2021; Lackner et al. 2022), and for the Canadian prairies (Pavlovskii et al. 2019). Other studies combined the methods using separate correction methods for liquid and solid precipitation (Dahri et al. 2018).

Even though correction methods exist, they are often not used in studies using Ny Ålesund precipitation data (Maturilli et al. 2019; Nuncio et al. 2020; Osuch and Wawrzyniak 2017; Pramanik et al. 2019; Wickström et al. 2020), although this bias in the observations can significantly alter the results (Køltzow et al. 2020). The studies based on non-corrected precipitation measurements found an increase in precipitation in Ny Ålesund (Førland et al. 2011; Hanssen-Bauer et al. 2019; López-Moreno et al. 2016; Serreze et al. 2015), mainly for fall and winter rainfall (Łupikasza and Cielecka-Nowak 2020; Peeters et al. 2019). The increase in precipitation accelerated in the 2010s (Hanssen-Bauer et al. 2019) in line with the increase of the winter cyclonic activity (Rinke et al. 2017; Rudeva and Simmonds 2015; Wickström et al. 2020; Zahn et al. 2018). However, Førland and Hanssen-Bauer (2000) argued that the observed trend of precipitation could be biased because the undercatch is higher for snow that became less frequent in the last decades. The interannual change of wind gusts that are modulating this undercatch, may also have an impact on precipitation trends. A study of Førland and Hanssen-Bauer (2003) showed no significant difference of trends between corrected and uncorrected precipitation. In a more recent study, Førland et al. (2020) corrected the precipitation data in several stations in Svalbard using average correction factors for different precipitation types. They found a trend less pronounced than in non-corrected data in the period 1979-2018.

The significance of the trends can also be altered by the choice of the first and last years of the calculation. For instance, Førland et al. (2011) derived a non-significant trend for the period 1969-2011, while López-Moreno et al. (2016) found a significant trend for the longer period 1969-2013 that includes the wet years 2012 and 2013.

In this study we used different methods to correct precipitation measured in Ny Ålesund in the period 1975-2022. Temperature and wind speed are the variables required for the correction that were also measured at Ny-Ålesund. Since the correction methods are very

sensitive to the wind speed (Førland et al. 2020) and the observed wind speed are not homogeneous due to changes in the instrumentation, we also used wind speed from ERA5 reanalysis data (Hersbach et al. 2020). The corrections methods are then compared in their representation of precipitation trends in the 1975-2022 period. The trends are computed for 9 periods of 40 years (1975-2014 to 1983-2022) to consider the impact of a strong interannual variability on the trends.

The main objectives of the study are (i) to generate a corrected precipitation data set using different correction methods for Ny-Ålesund that can be used in future scientific studies, (ii) to evaluate the change of trends in precipitation at Ny-Ålesund before and after applying the different correction methods, and (iii) to explain the factors contributing to the misrepresentation of the trends from measured data. This work provides an assessment of correction methods that can be applied to Ny-Ålesund observations in future works and initiate a method of comparison between correction factors that can be applied to other stations affected by gauge undercatch.

2. Data and methods

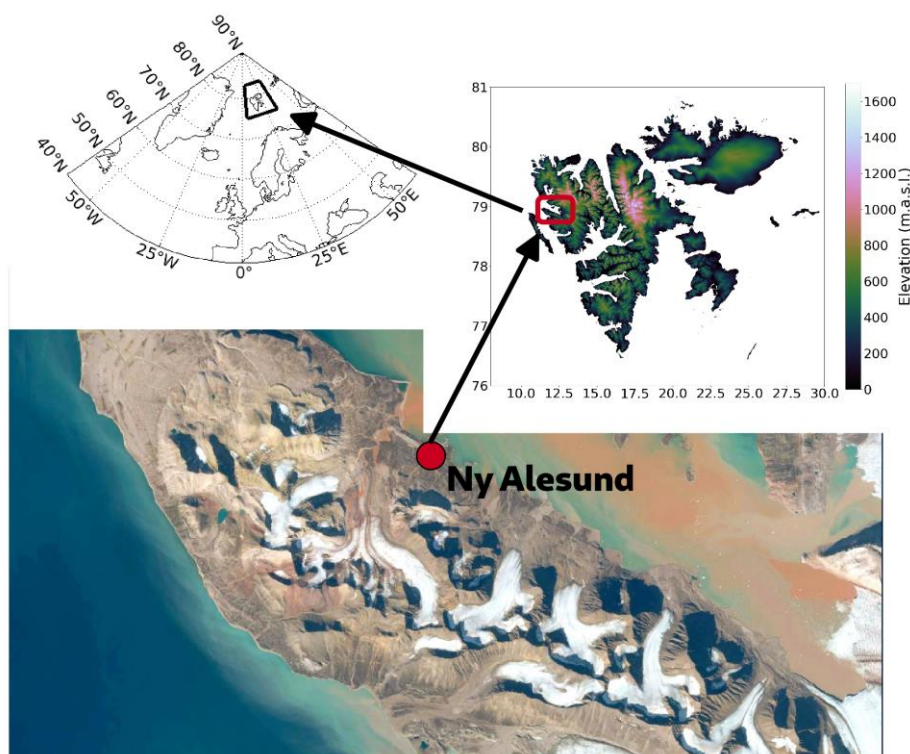


Fig. 1. Location of Ny-Ålesund on the Brøgger peninsula, Svalbard and the North Atlantic Ocean. The lower panel is a Sentinel-2 image from ESA-Copernicus taken on 31 August 2017. The image on the top right represents the elevation from the Global Multi-Resolution Topography (GMRT) synthesis data set.

a. Meteorological measurements in Ny Ålesund

Ny Ålesund is a research village at 79°N latitude, located in northwestern Spitsbergen south of the Kongsfjorden on the Brøgger peninsula (Fig. 1). The temperatures at Ny Ålesund are relatively mild, remaining almost always above 0°C between June and September and reaching a seasonal average of 4°C (Førland et al. 2011). In winter, the average temperature is -12°C, however, the variability of the temperature is higher with occasionally positive temperatures. In this study the meteorological data were retrieved for the period 1975-2022 (THE NORWEGIAN METEOROLOGICAL INSTITUTE, 2023). The change of location of the meteorological instruments is detailed in the Supplemental material (Section S1). Precipitation was measured manually at 06:00 and 18:00 UTC every day from 1 August 1974 using a Norwegian gauge equipped with a Nipher wind shield. Temperature and wind speed were also measured at the same period at 06:00, 12:00 and 18:00 UTC. The anemometer was changed and moved several times during this period. In 1982, the anemometer Mi 250/48 was moved 100 m away from its previous position. In 1984, the anemometer was replaced by a Fues 90z and moved 30 m south-east. An automatic station was installed in 1995 measuring precipitation, wind speed, and temperature at hourly time steps. The wind speed was measured with a Vaisala WAA 151 and were placed 30 meters further from the village compared to the previous measurement. The precipitation gauge, a Geonor T-200 with an Alter windshield, was first placed at the manual location and then moved close to the anemometer in 1997. In 2000, the precipitation gauge and the anemometer were moved again 100 meters further from the previous location. The anemometer location changes had possibly an impact on measurements in the 1975-1980 period as discussed in section 3.a.

For calculation purposes, the wind speed at gauge elevation (w_g) was calculated from the 10 m wind speed measurements (w_{10}) using the following equation:

$$w_g = \frac{\ln\left(\frac{h}{z_0}\right)}{\ln\left(\frac{H}{z_0}\right)} \cdot (1 - 0.024 \cdot \alpha) \cdot w_{10} \quad (1)$$

With h the height of the gauge (2 m), H the height of the wind speed measurements (10 m), z_0 the roughness length, and α the average vertical angle of obstacles around the gauge. Here we used $z_0=0.02$ m corresponding to a yearly average as previously used by Førland et

al. (1996) and $\alpha = 12$ corresponding to an intermediate value between exposed and protected area (Førland et al. 1996) since the area around the anemometer is composed of a few houses.

Hourly wind speed at 10 m from ERA5 reanalysis (Hersbach et al. 2020) were also retrieved and used to calculate ERA5 wind speed at 2 m using equation (1).

b. Precipitation corrections

Although higher resolution precipitation data is available for certain periods, we use here the 12-hourly manual precipitation data to keep a consistent dataset for the entire analyzed period. Similarly, even though the temperature measurements have been recorded hourly since 1995, temperature and wind speed data at 06:00, 12:00 and 18:00 UTC, as measured before 1995, were used for the entire period.

The true precipitation P_c can be obtained from the observed snow P_s and rain P_r by equation (2.1). This equation is adapted from equation 2.2 in Førland et al. (1996):

$$(2.1) \quad P_c = k_s \cdot (P_s + \Delta P_w + \Delta P_e) + k_l \cdot (P_r + \Delta P_w + \Delta P_e)$$

With k_s the correction factor due to aerodynamic effects for snow, k_l the correction factor due to aerodynamic effects for rain, ΔP_w the precipitation lost by wetting, and ΔP_e the precipitation lost by evaporation from the gauge. Wetting loss (ΔP_w) and evaporation loss (ΔP_e) from Eq 2.1 were estimated to be 0.15 mm per day for rain and 0.1 mm per day for snow in Ny Ålesund according to Førland and Hanssen-Bauer (2000). Because our correction is applied for 12-hourly data we use 0.075 mm per case for rain and 0.05 mm per case for snow.

The true precipitation was calculated separately for snow (solid) and for rain (liquid). We did not calculate specifically mixed precipitation as some correction methods do not consider this type of precipitation. Solid and liquid precipitation were separated according to the 12-hourly average temperature and the corresponding snow to total precipitation ratio (Table 1). This ratio was estimated using the automatic hourly precipitation and hourly temperature available in the period 1995-2022. For each hour, all precipitation data were considered as snow when temperature of the same time was strictly lower than 1°C and considered as rain when temperature was higher or equal to 1°C. The ratio of snow to precipitation was then calculated for periods of 12 hours, corresponding to the time-steps of the manual precipitation

measurements in the 1975-2022 period. The average snow to total precipitation ratio was then calculated for each 0.5°C increment class between -2°C and 3°C of the corresponding 12-hourly temperature measured manually (Table 1). The limits of the classes are -2°C and 3°C because below a 12-hourly average of -2°C, more than 99.5% of the precipitation are in form of snow and above a 12-hourly average of 3°C, more than 99.5% of the precipitation are rain. Therefore, below -2°C all precipitation is considered as snow and above 3°C all precipitation is considered as rain. These ratios, calculated for the period where hourly precipitation was recorded (1995-2022), were then applied to the entire manual precipitation dataset (1975-2022) to calculate the amount of snow and rain for each 12-hourly increment.

12-hourly temperature	Ratio of Snow to total precipitation
[-2 - -1.5]	98%
[-1.5 - -1]	97%
[-1 - -0.5]	95%
[-0.5 - 0]	89%
[0 - 0.5]	88%
[0.5 - 1]	70%
[1 - 1.5]	39%
[1.5 - 2]	15%
[2 - 2.5]	5%
[2.5 - 3]	2%

Table 1. Ratio of snow to total precipitation calculated from the hourly automatic data for the corresponding 12-hourly average temperature from manual measurements.

The value of the aerodynamic correction factor for solid (k_s) and liquid precipitation (k_l) were taken from four different methods that are described below and summarized in Table 2.

1) FØRLAND METHODS

To correct the precipitation measured with a so-called Norwegian gauge, the method of Førland et al., (1996) was developed using precipitation data from Jokioinen (Finland). This method is referred to as ‘Førland Norwegian method’ in this manuscript and gives the following correction factors for snow (k_s) and rain (k_l):

$$(2.2) \quad k_s = \exp(-0.12159 + 0.18456 \cdot w_g + 0.006918 \cdot T_g - 0.005254 \cdot w_g \cdot T_g)$$

$$(2.3) \quad k_l = \exp(-0.042303 - 0.00101 \cdot \ln(r_g) + 0.034331 \cdot w_g - 0.012177 \cdot w_g \cdot \ln(r_g))$$

With r_g the observed rainfall from the gauge, T_g the temperature at the gauge elevation (2m), and w_g the wind speed at the gauge elevation (2m).

Another method proposed by Hanssen-Bauer et al. (1996) is used in this study using the aerodynamic factor for Tretyakov gauges identified in Førland et al. (1996) and modified for Norwegian gauges. A Tretyakov gauge was installed in Ny-Ålesund from July 1993 to August 1995 next to the Norwegian gauge, which allowed to determine a relationship between a Tretyakov gauge and a Norwegian gauge (Hanssen-Bauer et al. 1996). Because the aerodynamic correction factors from the Tretyakov gauge are known to be of very high quality, the aerodynamic factors from the Tretyakov gauge and the relationships between a Tretyakov and a Norwegian gauge were used to create new correction factors (Hanssen-Bauer et al., 1996). These factors are site-specific as they were built using data from Ny Ålesund only. This method will here be referred to as the 'Førland Ny Ålesund' method and can be considered as the reference method. The correction factors are calculated according to equations 2.4 and 2.5:

$$(2.4) \quad k_s = \exp(-0.04816 + 0.14883 \cdot w_g + 0.009064 \cdot T_g - 0.007147 \cdot w_g \cdot T_g)$$

$$(2.5) \quad k_l = \exp(-0.042303 - 0.00101 \cdot \ln(r_g) - 0.018177 \cdot w_g \cdot \ln(r_g) + 0.043931 \cdot w_g)$$

2) ADAM METHOD

Adam and Lettenmaier (2003), developed a correction factor for solid precipitation only and for different types of precipitation gauges. For Norwegian gauges, the correction was built using precipitation from Jokioinen (Finland) and corresponds to equation 2.6:

$$(2.6) \quad k_s = \frac{100}{(99.18 - 11.27 \cdot w_{10})}$$

With w_{10} the wind speed at 10m. Wind speed higher than $6.5 \text{ m}\cdot\text{s}^{-1}$ are always set to $6.5 \text{ m}\cdot\text{s}^{-1}$, limiting the maximum correction factor k_s . This method is referred to as the Adam method.

3) WOLFF METHODS

More recently, Wolff et al., (2015) developed a new integrated correction factor for rain and snow (referred to as Wolff method). They built this correction factor using an automatic Geonor precipitation gauge at the high altitude Haukelister Norwegian site. The correction factor is calculated according to equation (2.7):

$$(2.7) \quad k = \left(\left(0.82 - \frac{0.81 \cdot e^{\left(\frac{T_g - 0.69}{1.15}\right)}}{1 + e^{\left(\frac{T_g - 0.69}{1.15}\right)}} \right) \cdot e^{-\left(\frac{W_g}{8.41}\right)^{1.58}} + \frac{0.81 \cdot e^{\left(\frac{T_g - 0.69}{1.15}\right)}}{1 + e^{\left(\frac{T_g - 0.69}{1.15}\right)}} + 0.18 \right)^{-1}$$

Wolff et al., (2015) also developed a correction factor that allows to use directly wind speed at 10 meters height, which is an advantage given that the wind speed is generally measured at 10 meters. This correction factor corresponds to equation (2.8):

$$(2.8) \quad k = \left(\left(0.82 - \frac{0.81 \cdot e^{\left(\frac{T_g - 0.66}{1.07}\right)}}{1 + e^{\left(\frac{T_g - 0.66}{1.07}\right)}} \right) \cdot e^{-\left(\frac{W_{10}}{4.24}\right)^{1.81}} + \frac{0.81 \cdot e^{\left(\frac{T_g - 0.66}{1.07}\right)}}{1 + e^{\left(\frac{T_g - 0.66}{1.07}\right)}} + 0.18 \right)^{-1}$$

4) KOCHENDORFER METHODS:

Kochendorfer et al., (2017) also identified an integrated correction factor for rain and snow for automatic OTT pluvio2 and Geonor precipitation gauges with single Alter shields (referred to as the K2017 method) using data from multiple locations. The correction factor for 2m and 10m wind speed measurements are shown in equations 2.9 and 2.10:

$$(2.9) \quad k = \left(\exp\left(-0.0348 \cdot w_g \cdot \left(1 - \arctan(1.366 \cdot T_g) + 0.779\right)\right)\right)^{-1}$$

$$(2.10) \quad k = \left(\exp\left(-0.0281 \cdot w_{10} \cdot \left(1 - \arctan(1.628 \cdot T_g) + 0.837\right)\right)\right)^{-1}$$

Another function (referred to as the K2017bis method) was also introduced by Kochendorfer et al., (2017). It does not include temperature and is valid only for solid precipitation. The corresponding correction factors for 2 and 10 m wind speed measurements are given in equations 2.11 and 2.12:

$$(2.11) \quad k_s = \left(0.728 \cdot e^{-0.230 \cdot w_s} + 0.336\right)^{-1}$$

$$(2.12) \quad k_s = \left(0.742 \cdot e^{-0.181 \cdot w_{10}} + 0.322\right)^{-1}$$

The correction methods identified by Wolff et al. (2015) and Kochendorfer et al., (2017) are based on automatic precipitation gauges. In this study, the correction is applied to manual precipitation data from a Norwegian gauge installed since 1975, allowing calculation of long-term trends. The manual Norwegian gauges and the automatic Geonor gauges are both available since 1995. The annual amount of precipitation in the 1995-2022 period shows a similar interannual variability between both products (Supplement material section S2) and the average ratio of the automatic Geonor gauge to the Norwegian gauge in Ny Ålesund is satisfactory (0.94). Before the correction, the Norwegian gauge data could have been first transformed to match the Geonor gauge data. However, the difference between both gauges cannot be strongly related to other variables such as wind speed, temperature, or precipitation intensity and a transformation of Norwegian gauge data to match the statistics of the automatic gauge data would introduce uncertainties. Therefore, the correction methods were applied directly to the observations obtained with the Norwegian gauge.

Name	Locations used	Precipitation type	Variables	Reference
Førland Ny Ålesund	Jokioinen (Finland) and Ny Ålesund	Solid and liquid separately	Temperature, wind 2m	Hanssen-Bauer et al, 1996
Førland Norwegian	Jokioinen (Finland)	Solid and liquid separately	Temperature, wind 2m	Førland et al, 1996
Adam	Jokioinen (Finland)	Solid only	Wind 10m	Adam and Lettenmaier, 2003
Wolff	Haukelister (Norway)	Solid and liquid together	Temperature, wind 2m & 10m	Wolff et al, 2015
K2017	Multiple locations	Solid and liquid together	Temperature, wind 2m & 10m	Kochendorfer et al, 2017
K2017 bis	Multiple locations	Solid only	Temperature, wind 2m & 10m	Kochendorfer et al, 2017

Table 2: Summary of the applied correction methods.

The precipitation was corrected using the correction factors described above (Table 2) and using the wind speed measured at Ny Ålesund or the wind speed from ERA5 reanalysis, giving two sets of corrections for each correction method. ERA5 wind speed were used to

compare with the results using Ny Ålesund measurements because Ny Ålesund wind speed measurements are suspicious in the period 1975-1980 (see section 3.a for further details).

c. Calculations of trends

The trends of precipitation were calculated for the observed precipitation data, precipitation corrected using wind speed observations, and precipitation corrected using ERA5 wind speed. For each of these precipitation datasets the trends were calculated for 9 periods of 40 years (from 1975-2014 to 1983-2022). The significance of these trends was tested by the Spearman's rank correlation test (Lehmann and D'Abrera 2006).

3. Results.

a. Trends in observed meteorological variables.

The annual values of the meteorological data used in this study to correct precipitation are depicted in Fig. 2. The wind speed increased by almost $1 \text{ m}\cdot\text{s}^{-1}$ in total in the period 1975-2022 representing an increase of 31 %. This trend of wind speed is in the 95 % confidence interval under the Spearman rank correlation test, but the wind speed values are suspicious in the period 1975 to 1980 since they are very low compared to the remaining period. These very low values may be associated to the location of the instruments before 1982 (Supplemental material section S1). However, the wind speed from ERA5 and the measured wind speed at Longyearbyen, Svalbard (not shown) were also low in the period 1975-1978 and a further study using data from stations and reanalyses shows generally an increase of wind speed in Svalbard (Pilguy et al. 2019). These results suggest that regional atmospheric anomalies potentially contributed to the observed anomalies of the wind speed in 1975-1980, but the role of the change in wind measurement cannot be excluded. Because wind speed measurements are critical to correct the precipitation data from gauge undercatch, the corrections of the precipitation were performed using wind speed from ERA5 or wind speed from station measurements.

Regarding the other meteorological variables, the temperature increased significantly (99 % confidence interval) by 4.3 K on average in the period 1975-2022 and the observed precipitation increased by 50 % (99 % confidence interval) from 370 to 530 mm in the same period. This increase of precipitation was mainly driven by the increase of rainfall from 130 to 276 mm (+113%) while the increase of snowfall from 240 to 267 mm (+11 %) was not

significant (Fig. 3a). This result suggests not only an increase in the amount of precipitation, but also an increase in the rainfall to total precipitation ratio from 36% to 50% in the period 1975-2022. The large increase of precipitation as well as the increase of rainfall to total precipitation ratio was previously reported for Ny Ålesund (Førland et al. 2020; Łupikasza and Cielecka-Nowak 2020).

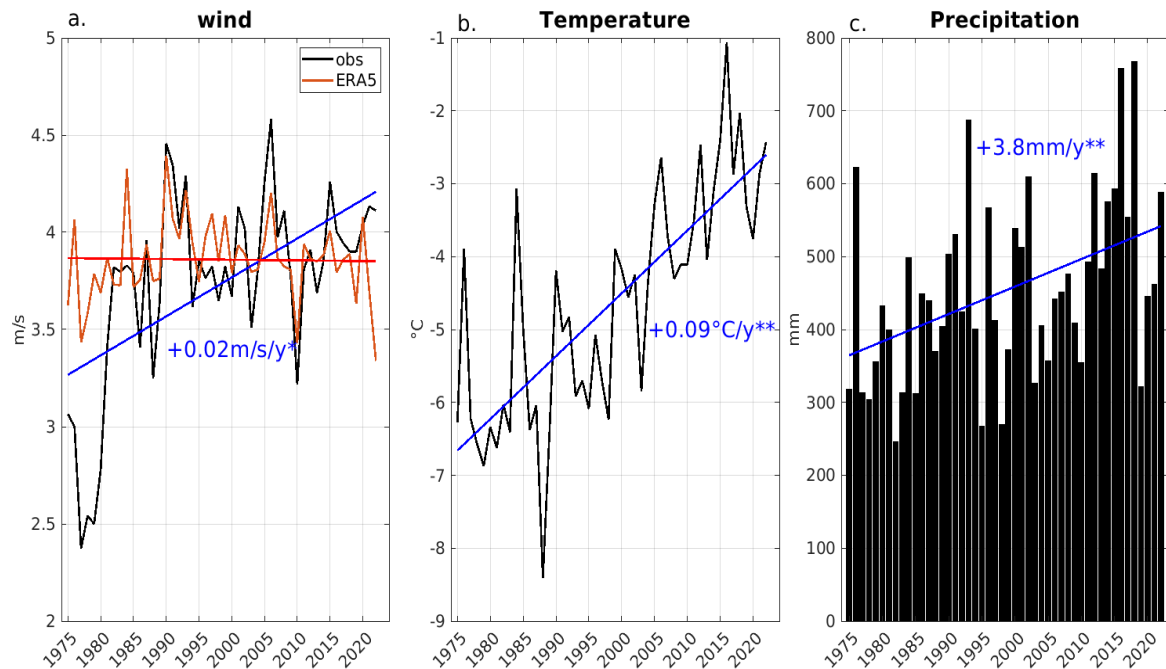


Fig. 2. Time series of annual a. wind speed, b. temperature, and c. precipitation from Ny Ålesund meteorological station (black line), and ERA5 reanalysis (red line). The line in blue shows the linear regression of each data series and the numbers in blue show the associated average increase per year with one (two) star(s) indicating a significant trend at 95% (99%) confidence interval.

b. Trends in corrected precipitation data

The evolution of annual precipitation data from the different corrections are depicted in Fig. 3. The precipitation is decomposed in rain and snow and shown for each correction method. All correction methods show a significant increase according to the Spearman's rank correlation test. Most of the correction methods lead to a similar trend of precipitation (4.2-4.7 mm/year) exceeding the observed absolute trend (3.8 mm/year). The method from Wolff (Wind 10 m) and Adam show highest trends with 5.4 and 5.7 mm/year respectively. The absolute trend in rainfall is very close to the observed data (3.1 mm/year) reaching at most 3.4 mm/year for the methods of Wolff and K2017 (Wind 10 m). The trend in rainfall is significant (99% confidence interval) according to the Spearman's rank correlation test for all

corrected time series. As expected, the differences between the observed and the corrected precipitation data are larger for snowfall with an observed increase of 0.7 mm/year and a corrected increase ranging from 1 mm/year to 1.4 mm/year for most methods. The trend in snowfall is again larger for the method of Wolff (Wind 10m) reaching 2.1 mm/year and the method of Adam reaching 2.6 mm/year. None of these increases of snowfall are significant according to the Spearman's rank correlation test.

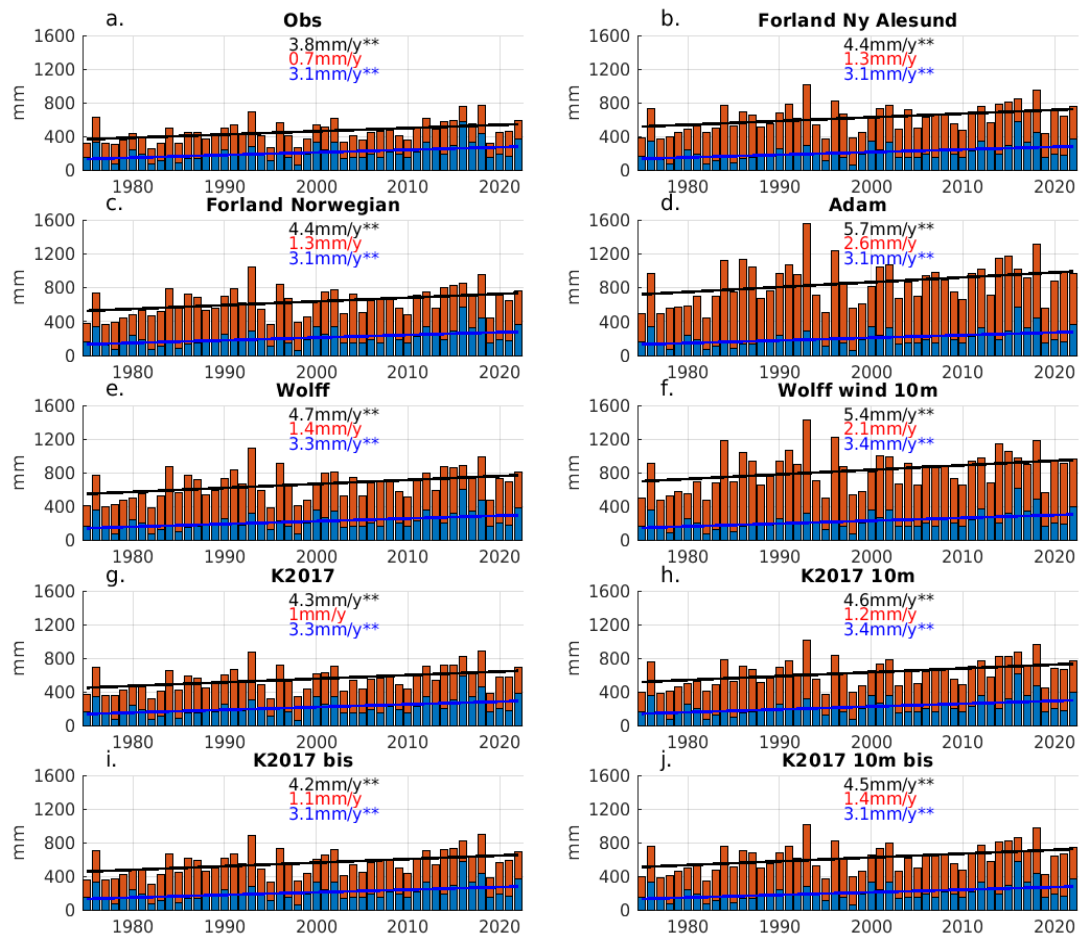


Fig. 3. Annual amount of rain (blue) and snow (red) for the different correction methods. The lines in blue (black) depict the linear regression of rain (total precipitation). The numbers show the associated average increase per year for precipitation (black), rain (blue), and snow (red). The stars next to the numbers indicate a trend significant at 99% confidence interval.

c. Sensitivity of the correction factors to wind and temperature

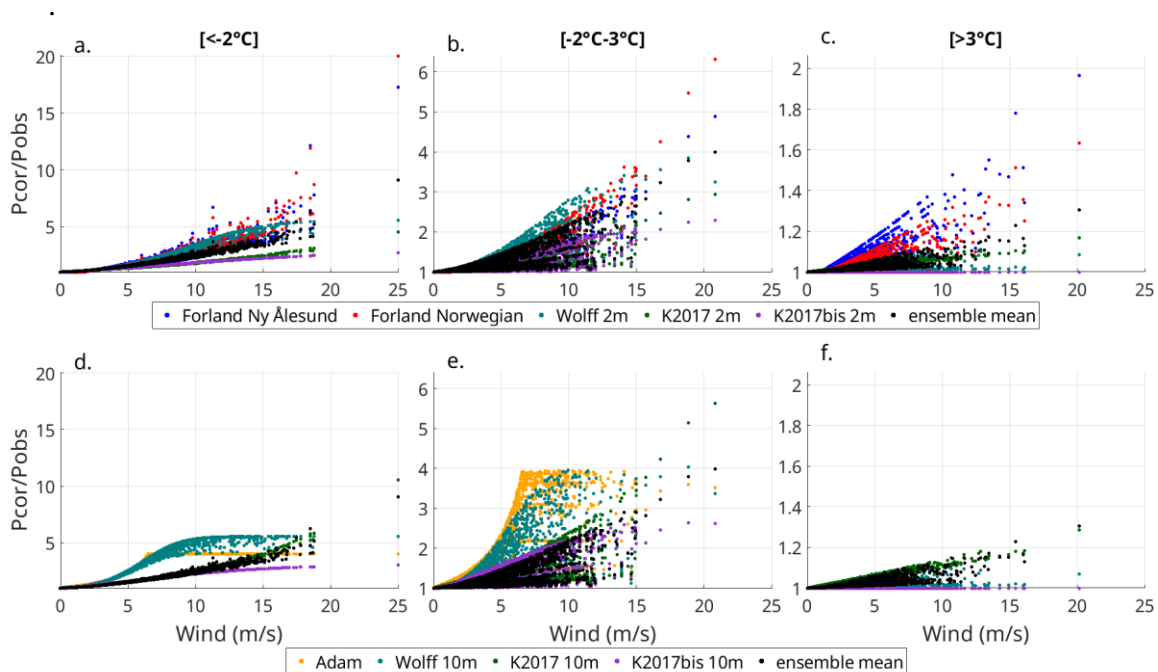


Fig. 4. Calculated correction factors as a function of wind speed for solid (a. and d.), mixed (b. and e.) and liquid (c. and f.) precipitation, for the methods using the wind speed at 2 m (upper panels) and the methods using wind speed at 10 m (lower panels). The ensemble mean appears in black in all panels. Please note the different scales for the y axes.

The evolution of the corrected data is directly driven by the temperature and wind speed that modulate the correction factor. The correction factor can be estimated by dividing the corrected precipitation (P_{cor}) by the observed precipitation (P_{obs}). The sensitivity of the different derived correction factors related to wind speed and temperature is presented in Fig. 4. The correction factors as a function of wind speed for different temperature ranges corresponding to solid ($<-2^{\circ}\text{C}$), mixed ($-2^{\circ}\text{C} - 3^{\circ}\text{C}$), and liquid precipitation ($>3^{\circ}\text{C}$) are shown. This classification on phases is justified by consistent ranges of corrections factors for different temperature values inside these classes (Fig. S3). The change of temperature around 0°C , i.e. the change of precipitation phase, is an important parameter to explain the change of correction factors (Fig. S3), but for the same precipitation phase it is the change of wind speed that creates large differences between methods (Fig. 4). For snow, the methods using 2 m wind speed (Fig. 4a) follow a similar pattern for the Wolff and Førland methods, but with a smaller variability in the correction factors derived with the Wolff method. The Kochendorfer methods show smaller correction factors and also a reduced spread compared to the Førland methods. For the methods using 10 m wind speed (Fig. 4d), Wolff 10m and Adam show very strong increases of the snow correction factors already for low wind speed. On the other end, the Kochendorfer methods using 10 m wind speed show results closer to the Førland methods

than the Kochendorfer methods using 2 m wind speed (Fig. 4d). These results explain the higher corrected values and higher trends of snow and precipitation with the Wolff 10m and Adam methods, but lower trends with the Kochendorfer methods (Fig. 3). For rain, the Førlund methods show clearly higher correction values (Fig. 4c), but the correction factors for rain are low with less impact on precipitation trends. Interestingly, in cases of mixed precipitation, the Wolff method shows higher correction factors compared to the Førlund methods, even using the wind speed at 2 m (Fig. 4b and 4e). This is probably due to separate correction equations for rain and snow in the Førlund method that lead to a quick decrease in the correction factors between snow and rain. In contrast, with the Wolff method the correction factors slowly decrease with increasing temperature.

d. The ensemble mean

Given the very different results from the Adam and Wolff 10m methods compared to the other methods (Fig. 3 and 4) and taking into account the suggestion by Wolff et al. (2015) to use preferably wind speed at gauge height, a so-called ensemble mean, build from an average of all methods, was calculated without these two methods. This ensemble mean, for which the correction factors for the different precipitation types are also shown in Fig. 4, is considered here as the currently optimum corrected precipitation dataset that will be used for further analyses in this study. This ensemble mean is recommended to be applied in further studies using precipitation data from Ny Ålesund.

As expected, the ensemble mean of rainfall from the corrections is very close to the observations (Fig. 5a) with a similar trend ($+3.2 (\pm 0.1)$ mm/year). The ensemble mean trend from corrected snowfall ($+1.2 (\pm 0.1)$ mm/year) and from overall precipitation ($+4.4 (\pm 0.1)$ mm/year) are higher compared to the observations that are respectively 0.7 mm/year and 3.8 mm/year (Fig. 5b and 5c).

The accumulated anomalies in the amount of rainfall, snowfall, and precipitation with respect to the average for the period 1975-1984 are also represented (Fig. 5b,5d,5f). The accumulated precipitation almost constantly increased in the period 1990-2022 suggesting that most years in that period have a larger value than the 1975-1984 average. Two periods show a very large increase of precipitation: 1990-1995 associated mostly to an increase in snowfall (Fig. 5d) and 2010-2018 associated mainly to an increase in rainfall (Fig. 5b). The total anomaly at the end of the period is close to 3500 mm representing an average anomaly

in the period 1986-2022 of almost 100 mm per year (for 37 years) with respect to 1975-1984. The accumulated anomalies of precipitation amounts for the correction methods have a temporal evolution similar to the observed values but a larger total anomaly reaching 5500 mm (± 518). The differences between observed and corrected precipitation are exclusively due to snowfall, the accumulated rainfall reaching 2000 mm for both observed and corrected values (Fig. 5b), with a standard deviation between the different methods reaching 120 mm. These results suggest a clear and consistent increase of precipitation whatever correction method used.

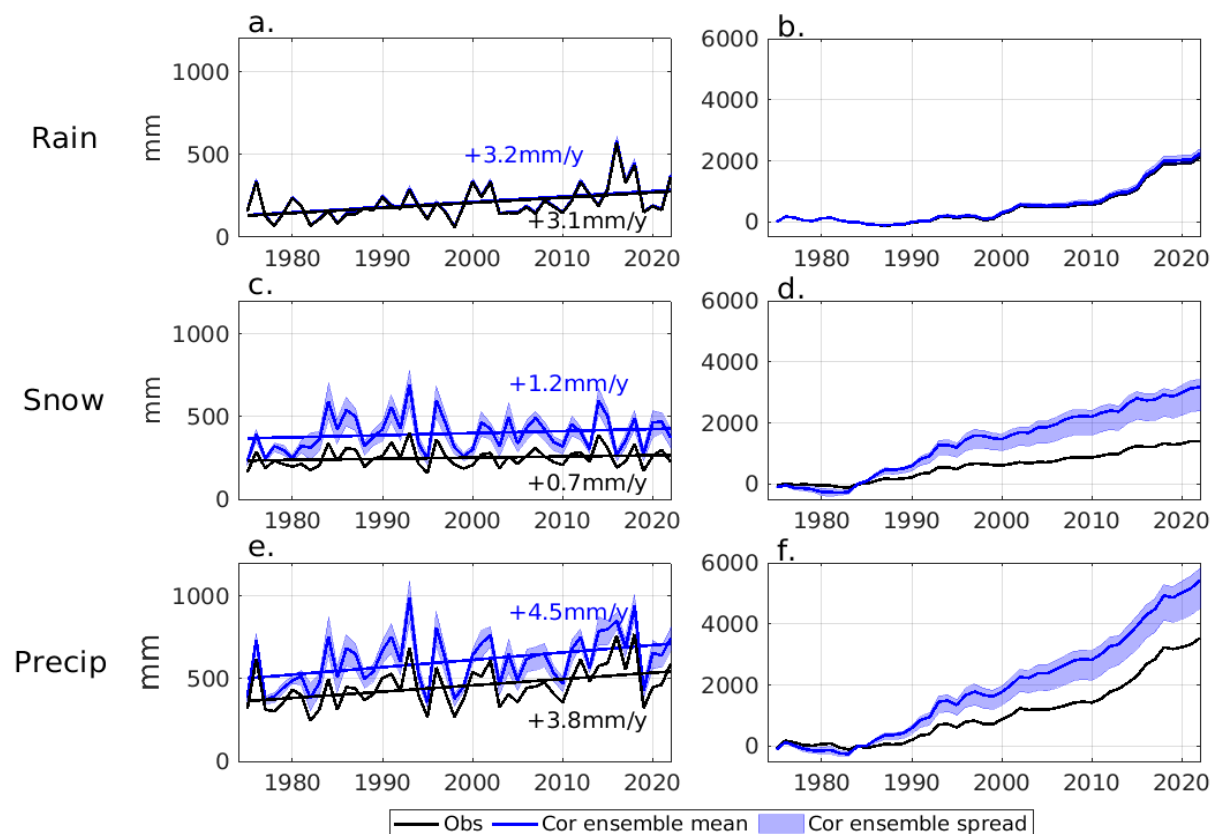


Fig. 5. Yearly amount (left) and accumulated amount anomalies with respect to the period 1975-1984 (right) for a,b: rain, c,d: snow and e,f: total precipitation. The solid blue lines represent the ensemble mean (interannual and linear regression in a., c., and e.) and the limits of the blue shades represent the lowest and highest value from the corrections used to construct the ensemble mean.

e. Robustness in precipitation trends

The corrections of precipitation shown in the last figures were performed using the wind speed and the temperature from the Ny Ålesund meteorological station. To increase the confidence in the trend result, the corrections were also performed using ERA5 wind speed. Moreover, the trends were calculated for 9 periods of 40 years from 1975-2014 to 1983-2022

because one or few years of strong precipitation anomalies at the beginning or the end of the analyzed periods can drastically change calculated trends. Fig. 6 shows the rainfall, snowfall, and precipitation trends for all corrections methods using observed and ERA5 wind speed. The results show a significant increase of rainfall whatever the period chosen and for all correction methods. The trend is lower for the first two 40-year periods 1975-2014 and 1976-2015 (2 mm/year) compared to all later periods (4 mm/year on average) because 1976 was a year with above-average precipitation (Fig. 2), strongly impacting trends that include the year 1976. The snowfall shows an interesting evolution of the trend that is largely positive in the first periods and decreases slowly to become even negative after 1979-2018. The observations also show such an evolution of the trends, but with a lower amplitude and a trend remaining stable in the recent periods. The same results were obtained using ERA5 wind speed for the corrections.

The precipitation trends, as a combination of rainfall and snowfall trends, show the highest increase for the periods 1977-2016 to 1979-2018, after the extreme year 1976 and before the very recent periods that include drier years (2019-2022). Interestingly, in the recent periods (1982-2021 and 1983-2022) the trend in observations remains significant, while the trends become low and insignificant after applying the correction methods. In terms of the absolute value of trends, the observations show a change of the trend from 5.4 mm/year to 3.8 mm/year between 1979-2018 and 1983-2022, while after correction the average trends (standard deviation) drop from 5.2 (± 0.3) to 2.6 (± 0.5) mm/year. Using ERA5 wind speed, the trends similarly drop from 5.3 (± 0.2) mm/year in 1979-2018 to 2.4 (± 0.5) mm/year in 1983-2022. These results suggest that precipitation trends calculated with uncorrected gauge observations calculated in the period 1983-2022 overestimate the real trends by approximately 35 %. In terms of relative trend in the 1979-2018 period we found similar results compared to Førland et al (2020) with an increase relative to 1975-2004 of 13% per decade in the observations dropping to 9% ($\pm 0.9\%$) per decade after corrections. By shifting the period to 1983-2022 the relative trend in the observations (9%) becomes twice the trend from corrected data (4.5 % \pm 0.9%).

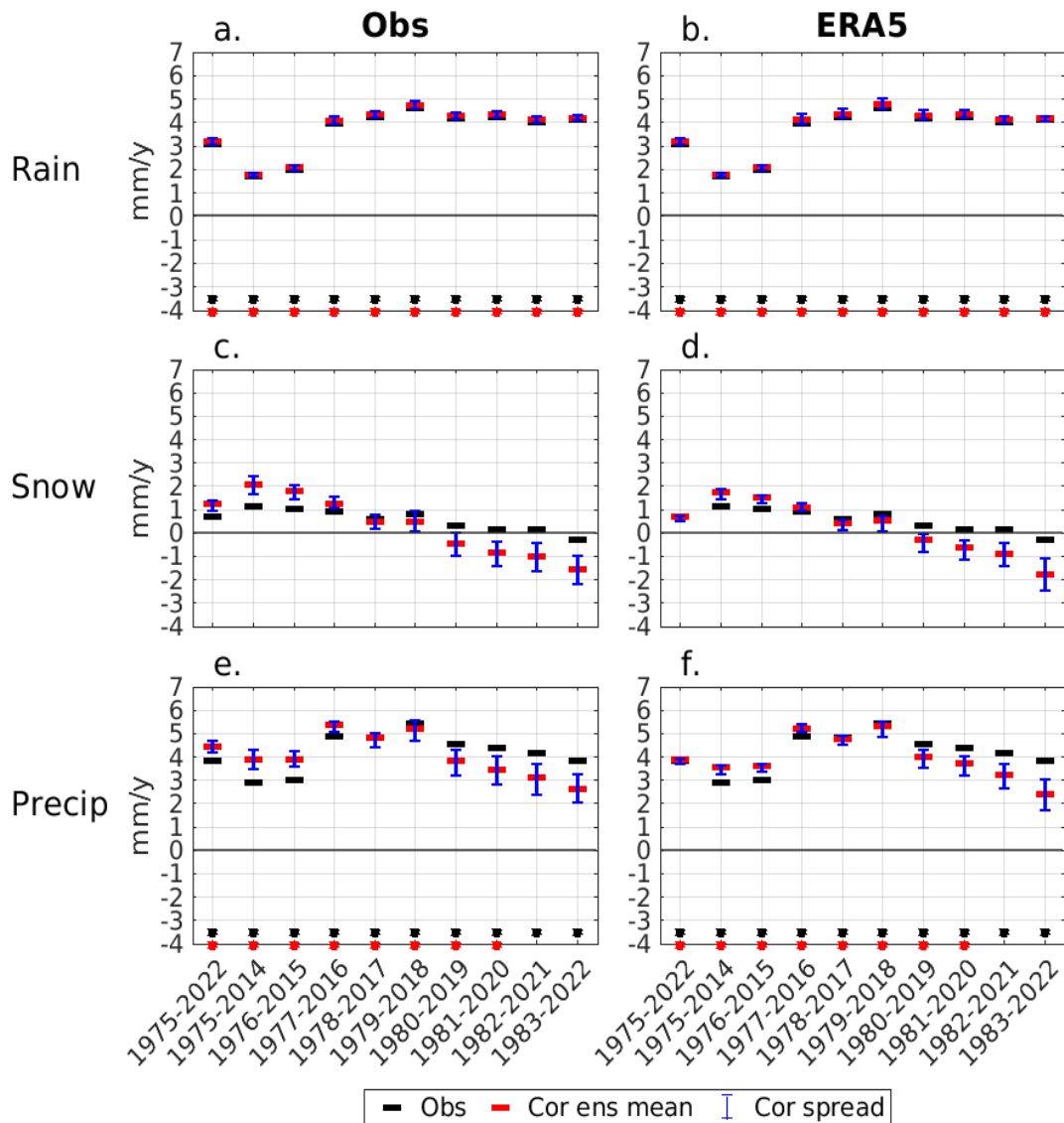


Fig. 6. Calculated linear trends of rainfall (a. and b.), snowfall (c. and d.) and total precipitation (e. and f.) for the observed (black horizontal markers) and the ensemble mean (red horizontal markers) time series using either wind speed from observations (left) or from ERA5 (right) for the period 1975-2022 and 9 different 40-year periods from 1975-2014 to 1983-2022. The blue bars represent the total spread of the corrected data series used for the ensemble mean. Filled circles at the bottom of each plot show significant trends according to the Spearman rank's correlation test with 95% confidence interval.

f. Evolution of correction factors

The average annual correction factors from all methods used to calculate the ensemble mean and the spread are shown for snow, rain, and precipitation in Fig. 7. As expected, the correction for rain is very low with an overall average ratio (standard deviation) of 1.03 (± 0.01) and an annual all-methods mean always lower than 1.1. Some correction methods show larger values, but they remain below 1.2 in all cases. The amplitude of correction for

snowfall is larger with an overall mean (standard deviation) of 1.58 (± 0.15) and an annual all-methods mean ranging from 1.25 in 1980 to 1.92 in 2004. Some annual correction factors occasionally exceed a value of 2. Regarding precipitation data, the average ensemble mean is 1.35 (± 0.12) ranging from 1.12 to 1.63 depending on the year. Using ERA5 wind speed in the calculation of the corrections, the interannual variability of the snow and precipitation correction factors are lower with a standard deviation close to 0.1.

These correction factors are generally lower than the single correction factors of 1.85 for snowfall and 1.15 for rainfall used in Fjørland et al. (2020). The correction factors of Fjørland et al. (2020), based on the method of Fjørland Ny Ålesund, are estimated with data of a very short period (1994-1995) while the correction factors can greatly vary from a year to another (Fig. 7). Mainly, the years 1975-1980 show a low correction factor especially when using measured winds. Removing these first few years from the calculation of the trend, the correction factors follow a negative and significant trend for both ERA5 and observed winds (Table 2). Interestingly the decrease of precipitation correction fraction is enhanced compared to the sum of the trends for snow and rain correction factors. This result shows the effect of the changing phase from snowfall to rainfall, the correction factors from rainfall having more weight in recent years. However, in recent periods (1980-2019 onward), the trend of correction factor from snowfall itself (-0.19 in 1983-2022) represents a large part of the trend of precipitation correction factor (-0.24 in 1983-2022), likely because the correction factor of snow is lower with warmer temperature. This result suggests that consecutive to the warming the efficiency of the precipitation gauge to catch snow is increasing, which has a significant impact on the artificially increasing observed precipitation trend in recent years.

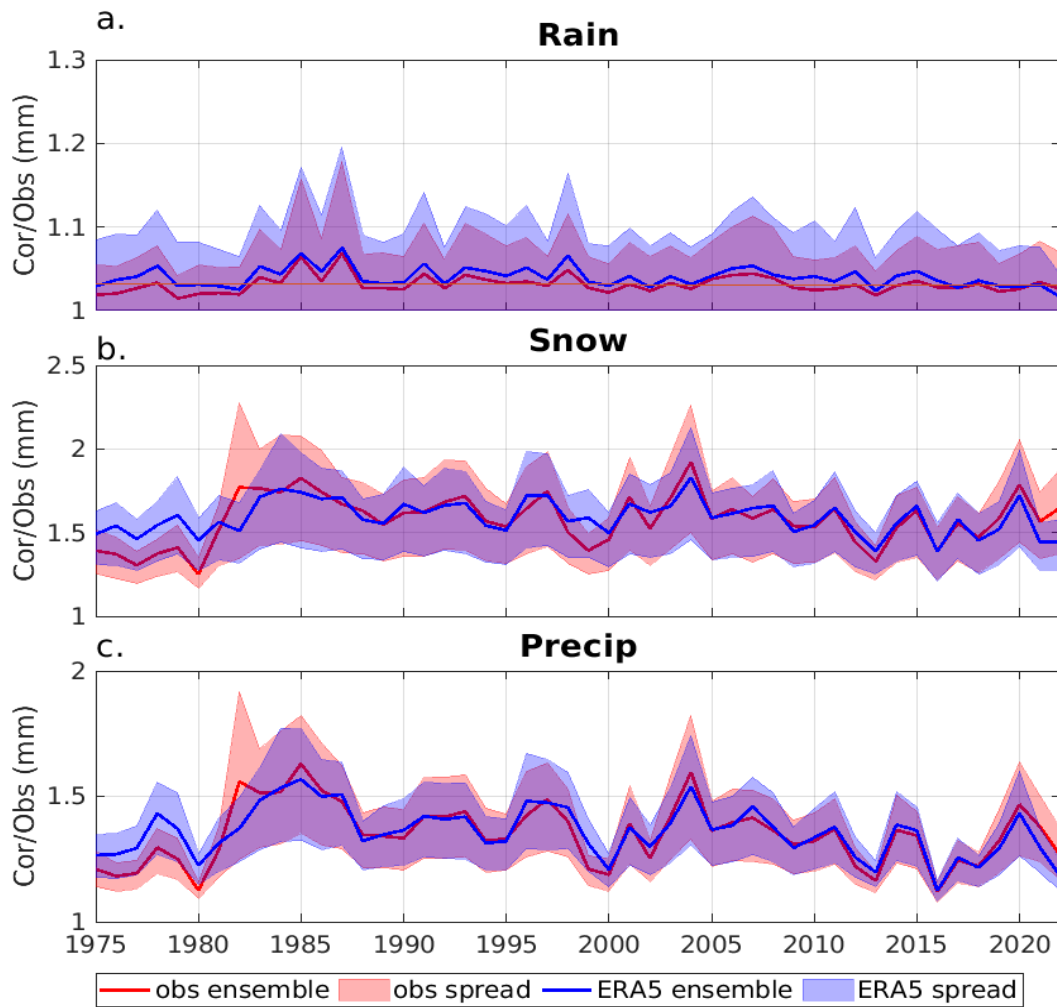


Fig. 7. Annual correction factors (Pcor/Pobs) for rain (a.), snow (b.), and precipitation (c.) for corrections using observed wind speed (red) and ERA5 wind speed (blue). The solid lines represent the average and the shades the total spread of all corrections. Please note the different scales of the y axis.

		1975- 2014	1976- 2015	1977- 2016	1978- 2017	1979- 2018	1980- 2019	1981- 2020	1982- 2021	1983- 2022
Rain	OBS	0.003	0.001	-0.002	-0.004	-0.004	-0.009	-0.012	-0.014	-0.018
	ERA5	-0.001	-0.002	-0.004	-0.007	-0.006	-0.010	-0.014	-0.018	<i>-0.026</i>
Snow	OBS	0.082	0.057	-0.016	-0.073	-0.134	-0.169	-0.201	-0.225	-0.190
	ERA5	0.005	-0.006	-0.058	-0.088	-0.126	-0.142	-0.148	-0.186	-0.232
Precip	OBS	0.005	-0.025	-0.101	-0.153	-0.190	-0.217	-0.242	-0.257	-0.242
	ERA5	-0.036	-0.058	-0.123	-0.159	-0.176	-0.189	-0.203	-0.227	-0.260

Table 3. Calculated trends in annual correction factors. The numbers in bold are in the 95 % confidence interval, and in bold italic in the 99 % confidence interval according to the spearman's rank correlation test.

g. Monthly trends of precipitation

Fig. 6 shows an increase of annual rainfall largely superior to the increase in snowfall when the trend was calculated after 1977. Such a change in the annual rainfall to total precipitation ratio can be caused by a transformation of snowfall to rainfall due to enhanced temperatures or by a larger increase of precipitation in a season more prone to rainfall, such as summer. Therefore, we assessed the precipitation trends for each month. Fig. 8 shows the monthly trends of total precipitation, rainfall, and snowfall calculated for the different periods for the observed values and the ensemble mean of the corrected values using observed (Cor Obs) and ERA5 wind speed (Cor ERA5). The increase of precipitation occurred mainly between September and January in observed and corrected precipitation independently of the considered periods. In September, the increase of precipitation is driven exclusively by the increase of rainfall, while for winter months both rain- and snowfall increased, with the trend of rainfall remaining higher (Fig. 8a, 8c, 8e). These results suggest that both, the increase of rainfall in September and the rainfall to total precipitation ratio in winter contributed to the yearly increase of rainfall to total precipitation ratio. With the correction, the 1975-2022 trend is enhanced, mostly due to an increase of snowfall between November and January. A similar pattern is observed when taking the years 1975 and 1976 in the 40 years trends calculations. The precipitation trend reaches a maximum in the period 1979-2018 in observed and corrected data and concerns mostly September to December as well as July. This positive trend is associated to an increase of rainfall. The reduced trends of precipitation from the period 1980-2019 onward in the corrected data is driven by a reduction of snowfall in January and March. This reduction of snowfall is less obvious in the observations, likely because the recent warmer temperature improves the precipitation gauge efficiency. This increase efficiency is caused by a shift from solid to liquid precipitation and dry snow to wet snow, which are more efficiently collected by the gauge. The increase of gauge efficiency is also shown by the decrease in the snowfall correction factors (section 3.f.).

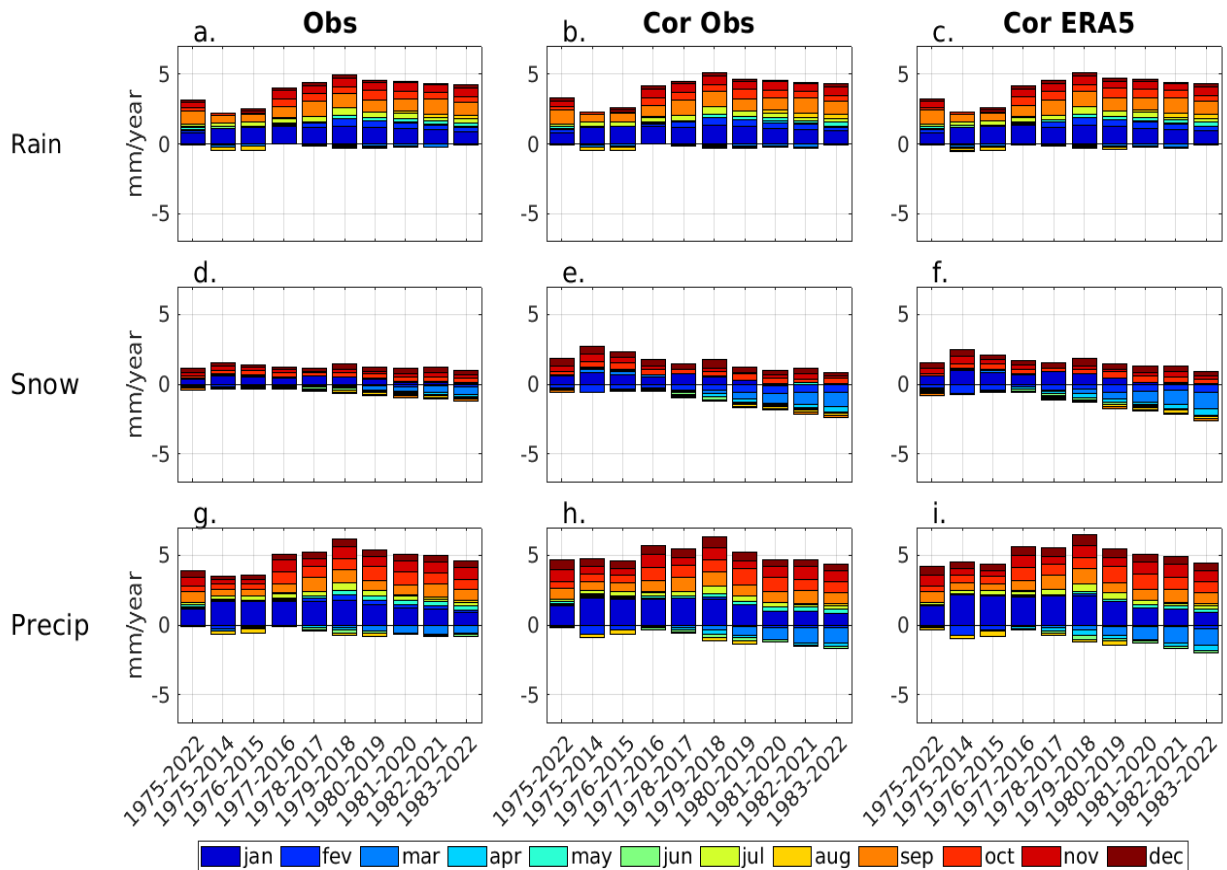


Fig. 8. Trend of rain (a. to c.), snow (d. to f.), and total precipitation (g. to i.) in mm/year for each month (colors) from observations (left) and the ensemble mean using observed wind speed (center) and using ERA5 wind speed (right) in the 1975-2022 period.

4. Discussion and conclusion

In this study, several correction methods, using wind speed and temperature measurements, were applied to Ny-Ålesund precipitation in the period 1975-2022. Assuming that the here constructed ensemble mean of the corrected time series represents best the real liquid and solid precipitation, we demonstrate that using the observed data for trend analysis overestimates the actual trends. The relative observed trends calculated for 1975-2022 are more than 15 % higher than the trends after correction and this difference is further increasing when using only the most recent years for the trend calculations. In 1979-2018 the observed trend (+13 % per decade) was about 40 % higher than the corrected trend (9 % per decade). By shifting the period to 1983-2022 we find that the observed trend (9 % per decade) deviates even more and is twice as high as the corrected trend (4.5 % per decade (± 0.9 %)). Taking the absolute values, this difference is smaller, but still reaches 35 % (± 13 %). The fact that even the absolute trend of observed precipitation is higher than for the corrected precipitation shows the significant difference between both datasets. Indeed, the

absolute trend is automatically higher after corrections even when the relative trend is the same for the observed and corrected precipitation. This mismatch between corrected and observed data is likely due to wetter snow in recent years, which tends to decrease the gauge undercatch (Section 3.f.). These results suggest that the strong warming contributed to an artificial overestimation of the existing positive trend of observed precipitation in the recent years.

Our study confirms the results by Førland et al. (2020), who also showed that the overestimation of the precipitation trend derived from observed precipitation gauge data in Svalbard was amplified in the recent years. Førland et al. (2020) used constant correction factors for liquid and solid precipitation for the entire period, which is apparently sufficient to study long-term trends since the constant correction factors seem to cancel out the high frequency variability of the correction factors due to varying temperatures and wind speed (Fig. 4). However, the recommended dynamical correction methods from our study furnish individually corrected 12-h precipitation data required for studies needing corrected data of solid and liquid precipitation at higher temporal resolution and for individual precipitation events. For example, the here generated corrected precipitation data set appears better suited for snowpack and runoff modeling in cryospheric and hydrological applications or for the analysis of specific events related to precipitation like Rain-on-snow events or avalanche warnings. Using the dynamical correction factors allows further to show that the overestimation in observed trends is partly due to a change to wetter snow and not only a shift of the rainfall to total precipitation ratio. The method used in Førland et al. (2020) cannot detect a trend of snowfall correction factors due to a trend of wind speed or temperature, but takes only into account a trend of the correction due to a change in the occurrence of snowfall and rainfall.

A previous study attempted to compare dynamical correction to results obtained with fixed correction factors (Ehsani and Behrangi 2022). They show a higher correction with the dynamical correction in Northern Canada and western Greenland while in Siberia or eastern Greenland it was higher using constant factors. They also show a higher trend of precipitation with the dynamical correction due to a trend of variables such as temperature and winds. Rather the corrections use fixed or dynamical correction methods, most studies found that one consequence of the warming is a reduction of the trend in the corrected precipitation (Li et al. 2023; Wang et al. 2017; Zhang et al. 2020). The correction methods with fixed constants such as used by Førland et al. (2020) have the main advantage of being easier to use

and being independent of variables that are also subject of errors in the measurements. The possible error of the observed wind speed in the period from 1975 to 1980 from our study is a good example, while further uncertainties also arise from the extrapolation of wind speed observed at 10 m height to the gauge height. However, in this study, the impact of biases in the wind speed measurements appear relatively small since replacing observed wind speed by ERA5 data does not significantly change the results. Finally, the correction factors in Førland et al. (2020) were only determined using data during a limited period (i.e. July 1993 to August 1995) and depend, therefore, on the meteorological conditions during the precipitation events that occurred within this specific period. Considering that temperature and wind speed, which determine the undercatch of the used gauges, have changed considerably since that period (Fig. 2) it appears very likely that the uncertainty of these corrections factors is higher when they are applied to more recent observations.

All correction methods used in this study delivered consistent results and most of the corrected data sets have even a similar amplitude, giving high confidence in these correction methods. The method that was specifically tested in Ny Ålesund, called the Førland Ny Ålesund method (Hanssen-Bauer et al. 1996) was very close to methods that were recently widely recognized such as the K2017 and K2017bis methods (Kochendorfer et al. 2017). These corrected datasets were used in this study to create the ensemble mean of the corrected precipitation data. Only two corrected data sets were excluded from this ensemble mean due to their extreme factors: the Adam and Wolff 10m methods. This ensemble mean can be used in further applications. Since the corrections are larger for snowfall, we recommend using this corrected data set in studies using solid precipitations, for example for snowpack modeling in the Ny-Ålesund area. However, we also recommend using the corrected data for other applications such as glacier mass balance calculations or hydrology models that are also highly dependent on the amount of snowfall. The use of true precipitation data series should also improve the validation of precipitation in reanalysis data or in climate models. Finally, the dynamic correction of the precipitation is also necessary for more detailed studies of meteorological events and the impact of climate changes, for example concerning the analysis of extreme precipitation events or studies of the role of cyclones and atmospheric rivers on moisture transport and precipitation in the Arctic (Migala et al. 2022; Papritz et al. 2021; Viceto et al. 2022).

The evolution of the corrected precipitation shows mainly a period of high snowfall in the 1980-1990s and a period of high rainfall in the 2010s (Fig. 5). The higher snowfall in the

1980s appears not to be in line with what is observed on the entire Svalbard peninsula (Van Pelt et al. 2016). This result is corroborated by the study of Serreze et al. (2015) showing that heavy precipitation events in Ny Ålesund are not simultaneously occurring at other stations in Svalbard. However, similar atmospheric conditions, mostly southerly and southwesterly winds, favor higher precipitation events at different locations in Svalbard (Arażny et al. 2022; Dobler et al. 2019; Migala et al. 2022). The periods of higher precipitation amounts were not directly associated to a change in wind directions, but the period of higher snowfall in the early 1990s was associated to a higher number of deep cyclones (Neu et al. 2013). In recent years, the cyclonic activity increased in winter (Zahn et al. 2018), which can be at the origin of the larger precipitation amounts (Hanssen Bauer et al, 2019) and an increase in the number of heavy rainfall (Serreze et al 2015). Based on a preliminary comparison of the first and second half of the analyzed period (1975-1998 vs. 1999-2022) the increase of precipitation at Ny-Ålesund was due to both an increase in the number of rain events as well as an increase in the average rate of precipitation of these rain events (not shown). However, further detailed investigations of the link between the precipitation amount and frequency at Ny-Ålesund or other stations in Svalbard and the synoptic situation including cyclonic activity are needed.

The change of rain- and snowfall has large implications for the cryosphere, the hydrology, and the ecosystem of this region. The amount of snow is for instance an important parameter for snow modeling (Jacobi et al. 2010, 2019), but also to analyze avalanches and estimate associated risks (Eckerstorfer and Christiansen 2011; Indreiten and Svarstad 2016). On glaciers, winter rainfall that refreezes generally contribute to the winter accumulation but also contributes to icy snow that accelerates summer ice melting (Łupikasza et al. 2019; Van Pelt et al. 2016). The change from snow- to rainfall can also have important implications for the hydrological regimes and the runoff. According to Tang and Lettenmaier (2012), the elasticities of runoff related to mean annual precipitation, which correspond to the fractional change in runoff per fractional change in local precipitation, generally range from 1.0 to 1.8 in basins in cold climates. Therefore, it can be estimated that the runoff in the basins around Ny-Ålesund has significantly increased in the last 50 years with potential impacts on permafrost as well as terrestrial and marine biogeochemical cycles in this sensitive region. Moreover, the large increase of rainfall in the fall created a second peak in the hydrographs and the increase of rainfall to total precipitation ratio prolonged the hydrological year (Nowak, Aga et al. 2021; Osuch et al. 2022). The increase of rainfall in January may contribute to an increase of rain-on-snow events that have large impacts on the local

ecosystem (Bjerke et al. 2014; Descamps et al. 2017; Morgner et al. 2010). For example, a large rainfall instead of a snowfall event can cause the formation of an important ice layer on the ground making activities of animals and humans very challenging (Hansen et al. 2014) as well as decreasing the food availability for herbivores in winter and spring (Descamps et al. 2017; Forbes et al. 2016; Rennert et al. 2009).

Overall, this study shows the need of correcting observed precipitation data to obtain more accurate trends of precipitation and true data series especially when using precipitation for further applications. Most correction methods show consistent results suggesting that a correction method can be chosen depending on the availability of wind and temperature data. The method the most suitable to be used in future studies is likely the K2017 method (Kochendorfer et al. 2017), correcting solid and liquid precipitation using a single equation. We advise also to use the correction method using 10 m wind speed to be in line with the measurements heights often used. We propose further to test the methods used here at other stations in the Arctic, to verify if similar results on changing trends can be observed, increasing the confidence in corrected precipitation time series in the Arctic.

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Data Availability Statement.

The observed meteorological data used in this study are available for download through the Norwegian Meteorological Institute platform [frost.met.no](https://met.no). The corrected data can be accessed at the Earth system Data Repository EaSy Data (www.easydata.earth). Two data sets are available: only the observed and the ensemble mean of the corrected precipitation (<https://doi.org/10.57932/a3d7b9e6-9626-4d43-bb83-623900eb1053>) and the observed, all corrected, and the ensemble mean of the corrected precipitation

(<https://doi.org/10.57932/86e7a148-54cf-4d02-af11-39eb1ab417fe>). All MATLAB scripts used for the analyses and for creating the figures are available on request.

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