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Comparison of historical and modern precipitation measurement techniques in Sweden

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Abstract— Precipitation gauges used for observations in the 19th century are reconstructed and pairs of gauges are installed at two, climatologically different, regular weather observation sites (Norrköping and Katterjåkk). Norrköping is a quite well sheltered site with a low degree of frozen precipitation, while Katterjåkk is an open site with a high degree of frozen precipitation. One of the gauges at each site is equipped with a wind shield. Parallel observations are conducted from November 2016 through May 2021. Regular observations are also conducted manually with modern gauges and with automatic gauges at the sites.

The wind shield effects (larger observed precipitation sums due to the inclusion of a wind shield) for the sheltered (Norrköping) and the open (Katterjåkk) sites are 7% and 16% for snow and 2% and 1% for rain, respectively.

The modern gauges generally collect more precipitation than the historical shielded gauges, the difference is 0–8% for rain and almost up to 50% for snow. However, these differences can, in part, be ascribed to micrometeorological conditions at the sites.

The differences between observation methods are larger for snow and sleet than for rain. There are also larger differences in the open site than in the sheltered site.

The most closely placed modern gauge relative to the historical gauges (automatic gauge in Norrköping, manual gauge in Katterjåkk) gives the most similar precipitation sums, suggesting that micrometeorology is more important than the observation method.

The undercatch due to lacking wind shields in historical observations can probably not explain more than 20% of the increased observed precipitation in the late 19th and early 20th century.

The question of potential influence on climatological precipitation series due to the transition from historical to modern observation methods remains unconcluded.

Key-words: pecipitation, observations, climate, meteorology, windshield

1. Introduction

The strengthening of the hydrological cycle following the ongoing climate change implies increases in precipitation at mid to high latitudes such as in Sweden. Based on observations from a national network, *Schimanke et al.* (2022) reports a long-term increase of Swedish precipitation starting in the late 19th century. Specifically, from the period 1961–1990 to the period 1991–2020, mean annual precipitation has increased by 8% with considerable seasonal and regional variations. Climate simulations suggest continued future increases in precipitation intensity and total amount in Sweden (*Kjellström el al.,* 2018; *Lind et al.,* 2022). To put future projected precipitation changes into a historical perspective and to assess impacts of changes in precipitation including extremes, long accurate observational time series are key. The homogeneity of long observational time series must be considered as "homogeneous time series data are essential to analyze climate variability and change" (*Venema et al.*, 2020).

Precipitation has been observed regularly over a network of stations in Sweden since the late 19th century, as described below. These observations indicate low amounts of precipitation in the period 1880–1930; similar periods with relatively dry climate are also reported for other European regions (*Metzger* and *Jacob-Rousseau*, 2020; *Haslinger et al.,* 2019; *van der Schrier et al.*, 2007; *Kendon et al.,* 2022). However, long-time observations of river flow do not support the magnitude of a dry anomaly in Sweden suggested by the precipitation observations (*Lindström*, 2002). The discrepancy between observations of precipitation and river flow may be related to changes in evaporation or other environmental factors changing conditions for runoff. Also, it cannot be excluded that errors in precipitation observations (such as neglection of small precipitation amounts) may play a role.

Traditionally, precipitation has been collected in gauges for which the height of the water column has been measured (*Mill,* 1901). This method is still in practice today (*WMO*, 2021). Early automated precipitation observations include the siphoned rainfall recorder (*Rácz*, 2021), in which the water column height of the collected precipitation is recorded on tape. Modern automatic gauges based on the collection principle usually weighs the collected precipitation rather than measure the water column height (*Førland et al.*, 1996). Other automatic methods include the tipping-bucket-type gauge, in which small precipitation sums are counted and summed up, as well as optical methods (*WMO,* 2021).

A particular problem with precipitation observations relates to undercatch, which is most pronounced in winter, as solid precipitation is more strongly influenced (*Førland et al.*, 1996). The efficiency of the gauges to collect precipitation depends on their design but also on ambient conditions. In general, too little precipitation is sampled due to wind and/or evaporative loss, hence the term undercatch. Methods for correcting observed precipitation have been developed using constant, often monthly, correction factors (*Legates* and *Wilmott*, 1990). It has, however, been pointed out that such simple monthly factors may differ between different years, and that factors derived on large national/regional scales may not be appropriate on the local scale. For example, *Stisen et al.* (2012) promoted the idea of time-space varying correction factors for Denmark. Consequently, dynamic methods involving different correction factors considering synoptic weather conditions have been put forward (e.g., *Ehsani* and *Behrangi*, 2022). By applying a dynamic correction method on 4 000 rain gauges in the Baltic Sea region, *Rubel* and *Hantel* (2001) derived correction factors having maximum in February (observed precipitation to be multiplied by 1.25–1.50) and minimum in August (1.02–1.05). It is obvious that changes in observation equipment may impact the undercatch and the need for correction factors, thereby adding one dimension to the homogenization issue.

Potential inhomogeneities at Swedish weather stations include the introduction of wind shields and changes of observation gauges for precipitation observations starting in the late 19th century. These changes in instrumentation implies that it is not clear whether the large increase of precipitation sums observed in Sweden is real or partly an artefact of inhomogeneous observations caused by changing instruments and thereby different degree of undercatch.

To address the potential role of measurement equipment in the historical changes in observed precipitation in Sweden, the performance of historical precipitation gauges relative to modern ones is evaluated. Pairs of historical precipitation gauges are reconstructed (see *Fig. 1*) and installed at two climatologically dissimilar weather observation sites (see *Fig. 2*). One gauge of each pair is equipped with a wind shield. The goals of the study are to:

1. Estimate the *wind shield effect*, i.e., larger observed precipitation sums due to the inclusion of a wind shield, of the precipitation observations with a historical precipitation gauge;
2. Estimate the difference of the precipitation observations with historical gauges and modern gauges (both automatic and manual);
3. Estimate the differences (1–2) in snowy and rainy conditions,
4. Examine how the differences (1–2) vary with air temperature and (mean and gust) wind speed,
5. Estimate the wind shield effect for sub-zero and super-zero temperatures and examine the difference between shielded and unshielded observations for specific months;
6. If possible, estimate the effect of evaporation in the historical observations;
7. Estimate the network-wide undercatch due to lack of wind shields in historical observations; and
8. Determine if it is possible to conclude from the results of the study, whether the transition from the historical to the modern observations method could constitute homogeneity breaks in the observational time series.

Fig. 1. The four precipitation gauges included in this study, the historical unshielded gauge (top left), the historical shielded gauge (top right), the modern manually operated SMHI-gauge (bottom left), and the GEONOR automatic gauge (bottom right).

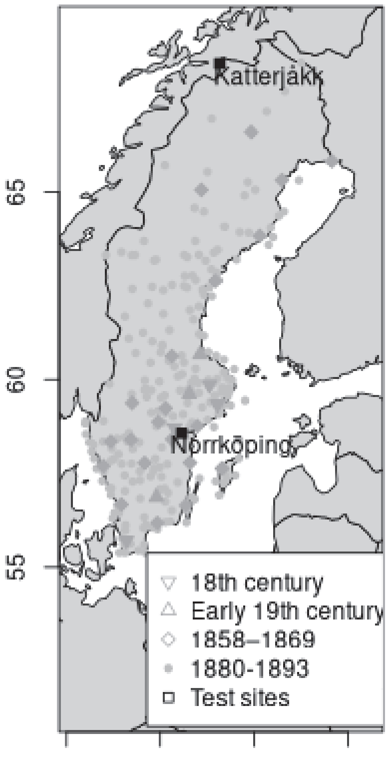

Fig. 2. Map of Sweden with the geographical positions of the test sites and the historical weather observation stations marked out, the symbols refer to the initial date of the stations.

A central question is if correction factors could be derived for the historical measurements. Note that the object of this study is to increase the homogeneity of the historical precipitation observation time series, not an effort to recreate true precipitation. Therefore, no full correction method, including aerodynamic, evaporation, and wetting correction factor for the different gauges, is considered.

2. The history of precipitation observations in Sweden

Regular precipitation observations in Sweden started in the mid-18th century at the astronomic observatories in Uppsala (1723), Lund (1748), and Stockholm (1786). In the digital archives there is also a short precipitation series (1730–1741) from a rural site (Risinge) in Östergötland. In the early 19th century, observations were also conducted at five additional locations (in the cities of Växjö, Strängnäs, Västerås, Gävle, and in a rural site in northern Hälsingland which is not yet digitally available), and in 1858–1860 a small network of about 20 additional meteorological station was set up on the initiative of the Royal Swedish Academy of Sciences (*Eriksson*, 1983). These first stations were unevenly distributed around the country with Jokkmokk being the northernmost station (66.6 °N) and Lund the southernmost (55.7 °N), see *Fig. 2*.

The precipitation measurements were mainly conducted by the collection of precipitation in zinc gauges with a mouth of 1 206.5 cm^2 (*Alexandersson*, 2002) corresponding to 1 Swedish square foot (*Hamberg*, 1911). Following the establishment of "Meteorologiska centralanstalten" (MCA), a precursor of the Swedish Meteorological and Hydrological Institute (SMHI), a gauge with a 1 000 cm^2 mouth was introduced in 1873 as an adaptation to the metric system. This gauge is reconstructed under the current study and is henceforth referred to as the "unshielded gauge", see *Fig. 1.* In 1878, a network of more than 300 precipitation observation stations were set up with the aid of the agricultural organization Kungliga Hushållningssällskapen (*Hamberg*, 1881). From around 1880 precipitation observations conducted at lighthouses where taken over by "Nautisk-meteorologiska byrån" (the Nautical Meteorological Bureau, which later became a part of the precursor of SMHI). The observation method was identical to that of MCA (*Nautisk-meteorlogiska byrån*, N.D.)

In the period from 1893 to 1935, cone shaped Nipher wind shields were introduced to the vast majority of precipitations gauges. The 1 000 cm^2 mouth zinc gauge with wind shield is henceforth referred to as the "shielded gauge", see *Fig. 1*. However, exactly when the first wind shields were installed and when the entire network of precipitation gauges was equipped with wind shields is unknown, due to insufficient documentation. In 1930, most of the precipitation stations had a wind shield (*Alexandersson*, 2003). In the mid 20th century, the 1 000 cm^2 mouth gauges were successively replaced with gauges with a mouth of 200 cm^2. This size of gauges is currently used at SMHI's manual observation stations. In the 1960s, the zinc gauge was replaced by a light metal gauge (henceforth “SMHI-gauge”, see *Fig. 1*), which is easier to handle and not as sensitive to frost weathering as the zinc gauge. Potential losses both due to spillage and leakages were thus restricted (*Eriksson*, 1983). The current SMHI-gauges have a Nipher wind shield.

Automatic observations are currently conducted with a GEONOR instrument (henceforth “automatic gauge”, see *Fig.1.*), equipped with an Alter wind shield. Presently, SMHI operates more than 600 precipitation observation stations, out of which 120 are automatic.

A summary of the types of precipitation gauges historically used in the Swedish observation network is listed in *Table 1.*

Table 1. List of rain gauges used in the Swedish observation network

Approximate time of appearance	**Area of mouth/cm^2**	**Material**	**Wind shield**	**Type**
1723	1 206.5	Zinc	–	Manual
1873	1 000	Zinc	–	Manual[1]
1893	1 000	Zinc	Nipher	Manual[2]
~1950	200	Zinc	Nipher	Manual
~1960	200	Aluminum alloy	Nipher	Manual[3]
1995	200	Aluminum alloy	Alter	Automatic[4]

[1] “Unshielded gauge” ; [2] “Shielded gauge”; [3] “SMHI-gauge”; [4] “Automatic gauge”

3. Previous studies of Swedish precipitation measurement methods

The arguably largest source of error in precipitation measurements is the turbulence around the mouth of the gauge (*Alexandersson*, 2003). *Hamberg* (1911) cited field studies in the years 1890–1895, where the loss in measurements without a wind shield from May through October was found to be on average 12% compared to a pit-gauge. For strong winds the average loss was evaluated to be up to 34%. The difference between gauges with and without wind shield at 1.5 m height was up to 6%, even up to 20% for strong winds. From November through April, 10–35% more precipitation was measured with the shielded gauge compared to the unshielded one, in very windy conditions differences were 60–70%.

In a field study in Särna in 1907–1910 (*Hamberg*, 1911), a gauge with a wind shield on average collected 11% more precipitation than a gauge without a wind shield. The largest departure was found for winter (DJF), when the shielded gauge collected 35% more than the unshielded gauge. The corresponding departure in summer (JJA) was 3%. Winter precipitation being mainly in the form of snow is mentioned as possibly contributing to this seasonal difference.

Hamberg (1881, 1911) speculates that a correction for the annual precipitation for a windswept station with considerably long winter should be about 20%. For summer months the corrections should not exceed 10%, but for winter months a correction of up to 100% could be required.

Bergsten (1954) studied the difference in observed precipitation between the periods 1901–1930 and 1921–1950 for two sets of stations; stations that were equipped with a wind shield in both periods (homogeneous) and stations where the screen was introduced in the latter period (inhomogeneous). The wind shield was estimated to increase observed precipitation by 10–15% with some regional differences. The wind shield effect on the measurements in northern Sweden was less clear than in the south, a result *Bergsten* (1954) considered to be counter-intuitive.

Eriksson (1983) studied the observational time series 1931–1980 and argued that 1951–1980 probably is more homogeneous than 1931–1960 due to the more complete use of wind shields, however did not give any quantitative estimate.

Eriksson et al. (1989) estimated a wind related error in precipitation measurements of 2–15% for rain and 5–50% for snow. *Eriksson et al.* does not explicitly state whether these estimates refer to observations with or without wind shield, however, the standard method of precipitation observations at the time included wind shield. *Alexandersson* (2002) estimated an increase in measured precipitation of 5–10% following the introduction of wind shields.

Fredriksson and *Ståhl* (1994) conducted parallel measurements at the former observation site of SMHI’s headquarter (located a couple of hundred meter southwest of the current observation site)"with three different automatic precipitation gauges alongside the regular manual precipitation measurements from October 1993 to March 1994 as a part of the preparation for the transfer to automatic measurements in the autumn of 1995 (*Alexandersson*, 2000). The automatic gauges generally recorded less precipitation than the manual measurements, with largest monthly departures of about 15%. The GEONOR gauge, currently used at SMHI weather observation stations (here referred to as the “automatic gauge”), delivered results closest to the manual measurements with an average departure of about 5% over the six months.

In their report from the extensive intercomparison study of Nordic precipitation gauges at the Jokioinen Observatory, *Førland et al.* (1996) cited a number of studies on the ratio between precipitation measured in shielded and unshielded gauges. Ratios are listed for rain (1.00–1.09), snow (1.21–1.75), and mixed (1.08–1.26). From the data of the Jokioinen observatory it could be concluded, that the shielded SMHI-gauge caught 68.6% of the weight of the snow caught by the reference double-fenced gauge and 95.6% of the weight of the rain.

Alexandersson (2000) found, by comparing all simultaneously active automatic and manual stations in Sweden, that the automatic gauges observe on average 16% less precipitation than the corresponding manual measurements. The difference is largest wintertime when the automatic gauges observe 22% less precipitation than the manual measurements. The corresponding value for summer is 12%. The difference between manual and automatic measurements at the sites, where these were conducted in parallel, was found to vary considerably between individual stations, but the difference between manual and automatic measurements was also found to be smaller when the whole network of stations was considered. *Alexandersson* (2000) argues that difference in wind exposure probably is the main factor of the discrepancy.

Alexandersson (2003) used a correction factor for the SMHI-gauge between 1.5% and 12% for rain and between 4% and 36% for snow depending on how windswept the station is. The stations were divided into seven wind classes. Correction factors are for example applied in the estimation of true precipitation used in the gridded climate data product PTHBV (*Johansson* and *Chen*, 2003).

While the effect of the introduction of the wind shield and the automation has been object of the above mentioned studies, the potential inhomogeneity due to the shift to the smaller SMHI-gauge has thus far not been studied.

4. Climatology and description of the measurement sites

For the current project, two observation sites were selected: Norrköping and Katterjåkk, see *Fig. 2.* The climatology of these sites are briefly described below.

4.1. Norrköping

Norrköping lies at the end of Bråviken bay in the northeastern part of the region of Östergötland. The weather station is located at the SMHI headquarters about 2 km southwest of the city center, see *Fig. 3.* The area is slightly hilly with mostly lower buildings. The historical gauges were placed inside the fenced area of the official automatic station. The SMHI office buildings are found 60–100 m to the south. Additionally, there are some trees around the site. Unofficial manual measurements were conducted just outside the observations site.

Fig. 3. Map of a part of Norrköping with the observation site marked with a red/dark grey dot. The marked location is approximate. 1:10 000. (*Lantmäteriet*, 2023)

The weather stations in Norrköping (station number 86340) is considered to have a wind class 3 of 7, with the general criteria: "Quite well shielded site, where there can be a minor opening towards a larger field or lake. Well shielded site if it is situated in a generally windswept region". The corresponding wind correction is 3.5% for rain and 8.5% for snow (*Alexandersson*, 2003).

The mean annual observed precipitation (without corrections) in Norrköping (1991–2020) is 536 mm. The driest month is March (27 mm), the wettest month is July (65 mm), see *Fig. 4*. The average daily maximum temperature in July is 23 °C, the average daily minimum temperature in January is −4 °C. In the period for which observations of precipitation form is available (between 2000 and 2010), frozen precipitation (snow, hail, graupel, ice needles) was reported at least once for all months from October (about 3% of the precipitation occasions were reported as frozen) through April (13%). About 60% of the precipitation occasions in February was reported as frozen precipitation.

Preliminary calculations of the average monthly maximum snow depth (1981–2010) in Norrköping show that the deepest average maximum snow depth is in February with 21 cm, see *Fig. 5*. In this period, a measurable snow cover on the 15th each month was more common than not from December through March.

The dominant wind direction in Norrköping over the last twenty years (2004–2023) was west-southwest, and the annual mean wind speed was 2.2 ms^{-1}. The windiest season was winter (DJF) with at mean wind speed of 2.5 ms^{-1}, the least windy season was summer (JJA) with a mean wind speed of 2.0 ms^{-1}.

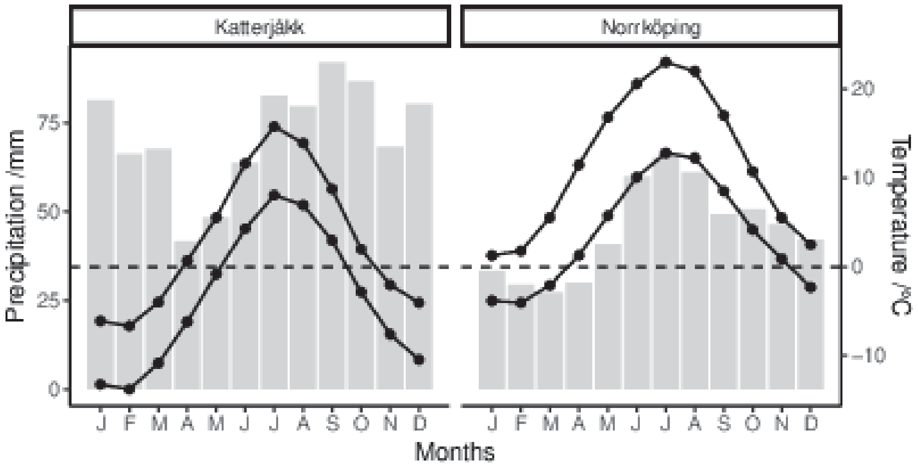

Fig. 4. Average monthly precipitation (bars), daily maximum and minimum temperatures (black lines) 1991–2020.

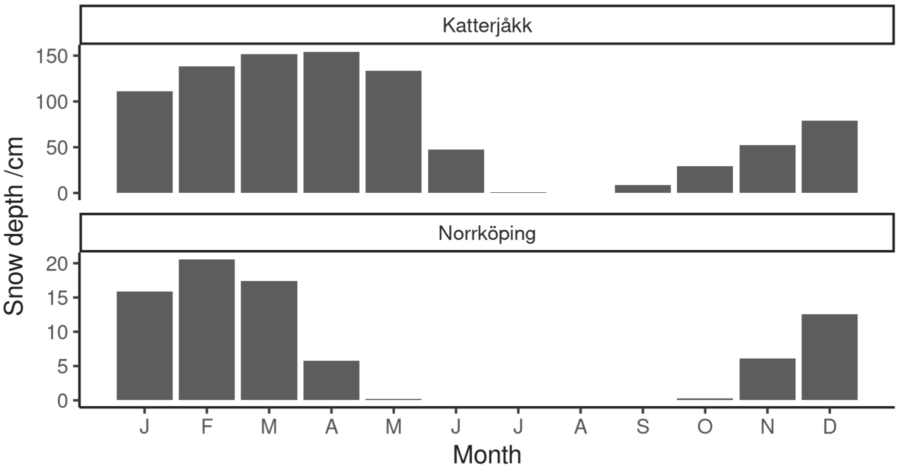

Fig. 5. Average maximum monthly snow depth (1981–2010) in Norrköping and Katterjåkk.

4.2. Katterjåkk

Katterjåkk is situated in the mountainous region in the northwestern part of the province of Lappland in northern Sweden. Within a radius of 10 km, the mountain peaks reach up to 1 100 m above the station height. The weather station lies on a southern hillside, east of a ravine where the Katterjåkk creek runs, see *Fig. 6*. In Katterjåkk, there was both an automatic (station number 18850) and a manual (station number 18820) weather observation station, separated by about 50 m with the automatic station to the south of the manual station. The mast for wind measurements is placed on a small hill 40 m further to the south of the automatic station. The automatic station lies in a slight depression, while the site of the manual station is rather plain and is therefore quite windswept. An office building offers some shelter in the sector southeast to south-southwest and a small birch grove in the sector north to north-northeast. The historical gauges were placed close to the regular precipitation gauge of the manual observation site.

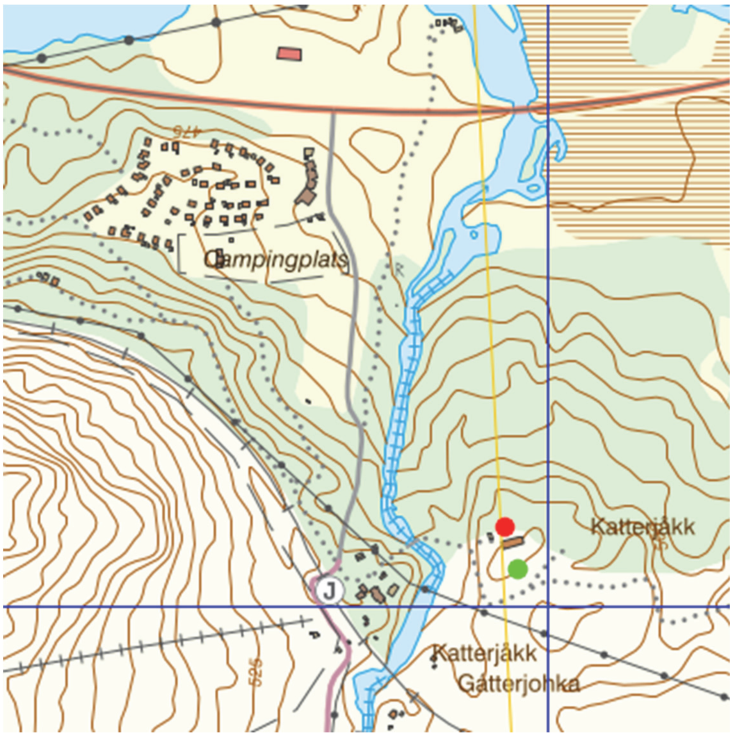

Fig. 6. Map of Katterjåkk with the observation site marked with a red/darkgrey dot, the automatic station is marked with a green/light grey dot. The marked locations are approximate. 1:10 000. (*Lantmäteriet*, 2023)

The weather stations in Katterjåkk is considered to have a wind class 5 of 7, with the general criteria "Open site with only partial protection from buildings or trees, sites on a hill or hillside in the inland". The corresponding wind correction is 6% for rain and 17% for snow (*Alexandersson*, 2003).

The average annual observed precipitation (without corrections) in Katterjåkk (1991–2020) is 859 mm. The driest month is April (42 mm), the wettest month is September (94 mm), see *Fig. 4*. The average daily maximum temperature in July is 16 °C, the average daily minimum temperature in February is −14 °C. Between 1991 and 2020, the highest share of precipitation occasions was reported as frozen in February (94%). The lowest share occurred in July (1%).

Preliminary calculations of the average monthly maximum snow depth (1981–2010) in Katterjåkk show that the deepest average monthly maximum snow depth is in April with 154 cm, see *Fig. 5.* In at least fifteen of these thirty years, there was a measurable snow cover on the 15th of the month from October through May.

The dominant wind direction in Katterjåkk over the last twenty years (2004–2023) was west-northwest, and the mean wind speed was 3.3 ms^{-1}. The windiest season was spring (MAM) with at mean wind of speed of 3.8 ms^{-1}, the least windy season was summer (JJA) with a mean wind speed of 3.0 ms^{-1}.

5. Methods

5.1. Measurements

Parallel daily precipitation observations were conducted with the newly produced historical 1 000 cm^2-mouth gauge (referred to as historical gauges) with and without the wind shield (shielded and unshielded gauge, respectively) in Norrköping and Katterjåkk from November 2016 through May 2021. The mouth of the gauges was about 1.5 m over the ground in Norrköping, which is common practice (*WMO*, 2021). The gauges in Katterjåkk were placed slightly higher, about 2.3 m, in anticipation of large snow depths in Katterjåkk. In Norrköping, the observations were conducted every day approximately at 08:00 local time, in Katterjåkk at 07:00. The water in the gauge was poured into a 1 liter glass container, which was weighted. Snow was melted in room temperature for about one hour before measuring. Two pairs of gauges were used for each of the observation sites (with and without wind shield) to make sure that one pair of gauges was always open for precipitation, even when the measurements were ongoing or snow was being melted. In the seasons when precipitation mainly falls as rain, a funnel was installed in the mouth of the gauge to limit loss due to evaporation. Since snow would block the mouth of the funnel, the funnel was removed under the colder seasons when there is chance for snow and the loss due to evaporation is substantially smaller. All forms of precipitation (rain, snow, hail, graupel) were measured along with condensed water from fog, frost, and dew.

Occasionally, especially over weekends, the gauges were not emptied daily, which means that some values in the series correspond to accumulated precipitation over longer time periods than the ideal 24 h. For frequency of different accumulation times, see *Fig. 7.*

Especially in Katterjåkk, snow cover can change the local wind environment around the gauge, as the snow cover shift the effective height of the precipitation observations and the roughness of the surrounding terrain. The observed snow cover over the test period is described in *Fig. 8.* The deepest observed snow depth in Katterjåkk was 229 cm, in the end of March 2020.

Air temperature and wind speeds were observed at the official automatic weather stations. Precipitation values are available at 15-minute resolution, while 2 m air temperatures and wind speeds are available at hourly resolution.

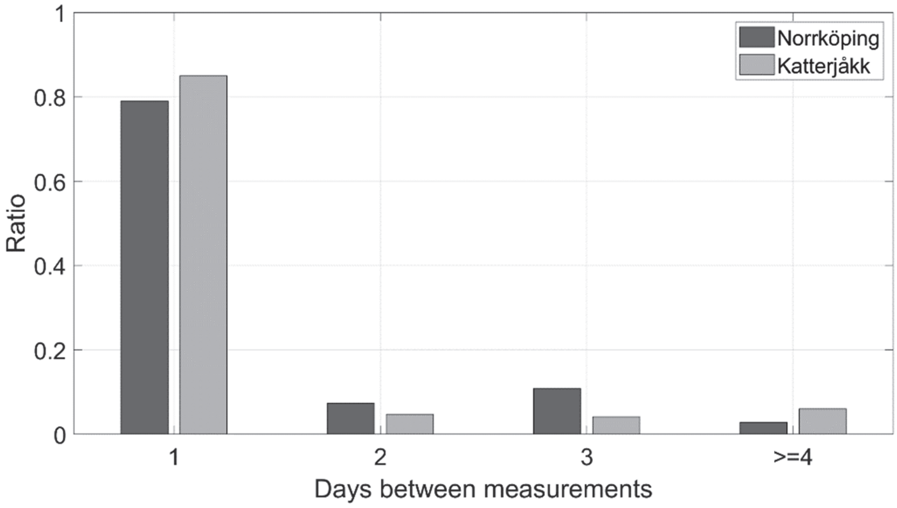

Fig. 7. The frequency of different accumulation times for the measurements with the historical gauges.

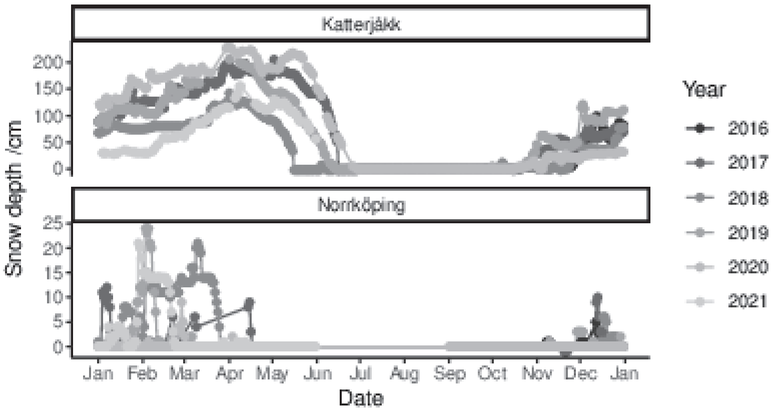

Fig. 8. Observed snow depth in Norrköping and Katterjåkk during the test period.

5.2. Calculations

Precipitation of three types (rain, sleet, and snow) observed in Norrköping and Katterjåkk with the automatic gauge (a), manual SMHI-gauge (m), jointly referred to as modern gauges, and with the unshielded (u) historical gauge are compared with corresponding observations with the shielded (s) historical gauge. Ordinary least squares regression, forced through the origin, is applied. Regression slopes for method *i* (β_{is}), with shielded gauge data as target variables, are obtained. Mean absolute error (MAE) between the precipitation observed, e.g., with the SMHI-gauge and the respective output of the linear regression models are calculated:

$$\mathrm{MAE}_i = \Sigma\ \mathrm{abs}(x_i - [x_\mathrm{s} \times \beta_{i\mathrm{s}} + \alpha_{i\mathrm{s}}])\ /\ N, \qquad (1)$$

where x_i is the observed value with method i (s refers to the observational method with the shielded historical gauge), α is the intercept, and N is the number of observations. The MAE is thus a metric of how well the linear regression generally reproduces the individual observed values. Note that in order to convert these regression slopes to correction factors to make observations with method i homogeneous with method j (a_{ij}) at least one of the three methods, regression slopes must be inverted as homogenization of historical time series either seeks to recreate the conditions of the earliest (e.g., *Moberg et al.*, 2002) or, as it is most common, the latest observation (*Venema*, 2020). Thus, for most applications the correction factors to make unshielded historical gauge observations homogeneous with shielded historical gauge observations are identical to the corresponding regression slope ($a_\mathrm{us} = \beta_\mathrm{us}$), while the correction factors to make shielded historical gauge observations homogeneous with modern methods observations are the inverse of the corresponding regression slopes obtained here ($a_\mathrm{sm} = \beta_\mathrm{ms}^{-1}$, $a_\mathrm{sa} = \beta_\mathrm{as}^{-1}$).

The *wind shield effect* is defined here as the deviation from the regression slope ($\beta_\mathrm{us} - 1$). A positive wind shield effect indicates that larger sums are observed with the wind shield. Since precipitation types for historical observations are not easily accessible, the wind shield effect is also calculated for sub-zero and super-zerotemperatures, where temperature thus is a proxy for precipitation types.

For the irregular measurements with accumulation times more than one day, sums for the corresponding observations of the modern gauges were used.

For the Katterjåkk series, the classification of precipitation type is gathered from information in the observers notes. For Norrköping it is instead deduced from the automatic weather station categorization of present weather. This is due to missing information of precipitation type in the observes notes in Norrköping.

To evaluate the sensitivity of the undercatch due to lacking wind shield on wind speed and temperature, series of ratios between precipitation observed with the unshielded gauges and other methods are calculated and compared with calculated averages of air temperature, mean wind speed (10-minute), and wind gust speed for the accumulation time.

For occasions when the gauges were not emptied daily, the ratio between total daily sums for the period from the automatic gauge and the accumulated precipitation in the historical gauge was calculated and binned according to the number of days of accumulation. Differences between the two were taken as a measure of evaporative loss.

For all calculations, only precipitation sums equal to or larger than 1 mm are used.

To estimate the undercatch due to lacking wind shields in historical observations, all digitally available daily precipitation observations prior to the year with the first installed wind shield at the Swedish weather observation stations (1893) are studied. Only precipitation observations where concurrent mean daily temperature data are available are considered. The precipitation data are multiplied by the wind shield effect correction factor a_{us} according to whether the corresponding mean daily temperature was sub-zero (a^-) or super-zero (a^+). The ratio of the corrected and uncorrected sums is calculated. From the study correction factors for wind classes 3 (a_3) and 5 (a_5) can be deduced. As a raw and conservative estimate, precipitation is corrected according to the stations wind class (*Alexandersson*, 2003). Stations with wind class 1 are not corrected ($a^-_1 = a^+_1 = 1$). Stations with wind class 3 are corrected according to the correction factors that can be deduced from the Norrköping test series (a^-_3, a^+_3). Stations with wind class 5 to 7 are corrected according to the correction factors that can be deduced from the Katterjåkk test series (a^-_5, a^+_5). Stations with wind class 2 are corrected with the averages of corrections factors 1 and 3 ($a_2 = [a_1 + a_3] / 2$), stations with wind class 4 are corrected with the averages of corrections factors 3 and 5 ($a_4 = [a_3 + a_5] / 2$). Stations that were closed prior to *Alexandersson's* work, and therefore, do not have a windclass ascribed to them are treated as class 3 stations, since class 3 stations have the median correction factor.

The precipitation time series prior to the installation of the first wind shield (as those used in the analysis described above), are each compared with corresponding observations from the same station in an equally long period starting in 1930, where most precipitation station were equipped with a wind shield (*Alexandersson*, 2003). The dates are matched such that only data where the same day of year is available both in the late and the early period are considered. The total difference in accumulated precipitation between the early and late periods are 16%.

The results are also compared with the mean difference between the first consecutive standard normal period (*WMO*, 2017) of SMHI's climate indicator annual precipitation (*SMHI*, 2023, *Sturm*, 2024) 1881–1910, and first standard normal period 1931–1960, where wind shields were legio. The mean annual precipitation for the entire network increased by 8% from the period 1881–1910 to 1931–1960 according to this estimate.

6. Results

6.1. Norrköping

The wind shield effect for the historical gauges in Norrköping is about 7% for snow and 2% for rain, see *Table 2.* The rain observation results, for which the MAE between the regression model output and the observed values is smallest of all the regression models presented in this study, are shown as an example in *Fig. 9.* The MAE for all precipitation types is 0.06 mm. The wind shield effect for sub-zero and super-zero temperatures is 2% and 9%, respectively.

Table 2. Regression slope (*β*) and mean absolute error (MAE) for linear regression models for precipitation observed in Norrköping with the unshielded historical, modern (SMHI), and automatic gauges, respectively, all with the precipitation observed with the shielded historical gauge as the target variables

Precipitation types	**Without wind screen**		**SMHI**		**Automatic**	
	β	**MAE/mm**	***β***	**MAE /mm**	***β***	**MAE /mm**
All	1.02	0.06	0.96	0.94	1.00	0.39
Rain	1.02	0.04	0.95	0.91	1.00	0.36
Sleet	1.01	0.07	0.95	1.00	0.99	0.74
Snow	1.07	0.08	0.98	1.03	1.01	0.35

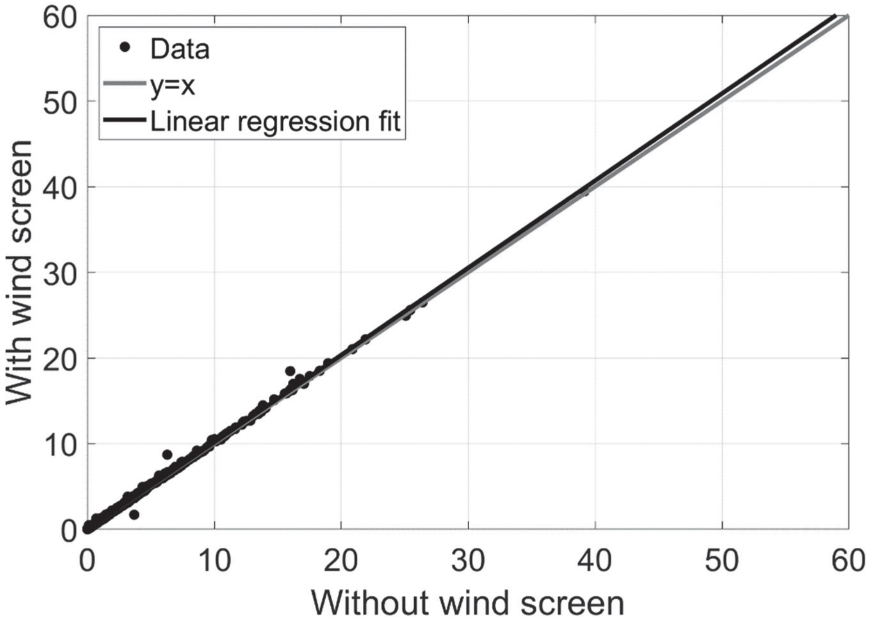

Fig. 9. Linear regression (black line) for daily precipitation sums observed in Norrköping with the shielded historical gauge with precipitation sums observed with the unshielded historical gauge as the explanatory values, the 1:1 relationship is depicted as a grey line.

The automatic gauge collects on average similar sums as the shielded gauge. The uncertainty is on average 0.4 mm, though higher for sleet (0.7 mm). The SMHI-gauge collects on average 4% more precipitation than the shielded gauge with an uncertainty of 0.9 mm. The snow observations are closer than rain and sleet between the SMHI-gauge and the shielded gauge, however, the uncertainty of the linear model is somewhat larger for snow observations than for rain and sleet.

Wind speed and temperature was not found to correlate significantly with the difference of precipitation sums between the methods. For example, for the ratio of the measurements with the unshielded gauge and the automatic gauge, the correlation with air temperature was $\rho = 0.19$, with mean wind speed $\rho = -0.10$, and with maximum wind gust speeds $\rho = -0.07$ (not shown).

There is a significant variation in the amount of mean precipitation between different months between the historical gauges, see *Fig. 10.* In winter and spring (December–May), the shielded gauge collects 6% more precipitation as a median, which is larger than the median (2%) for the summer and autumn months (June–November).

No clear signal of evaporation could be concluded from the study of observations with longer accumulation times (not shown).

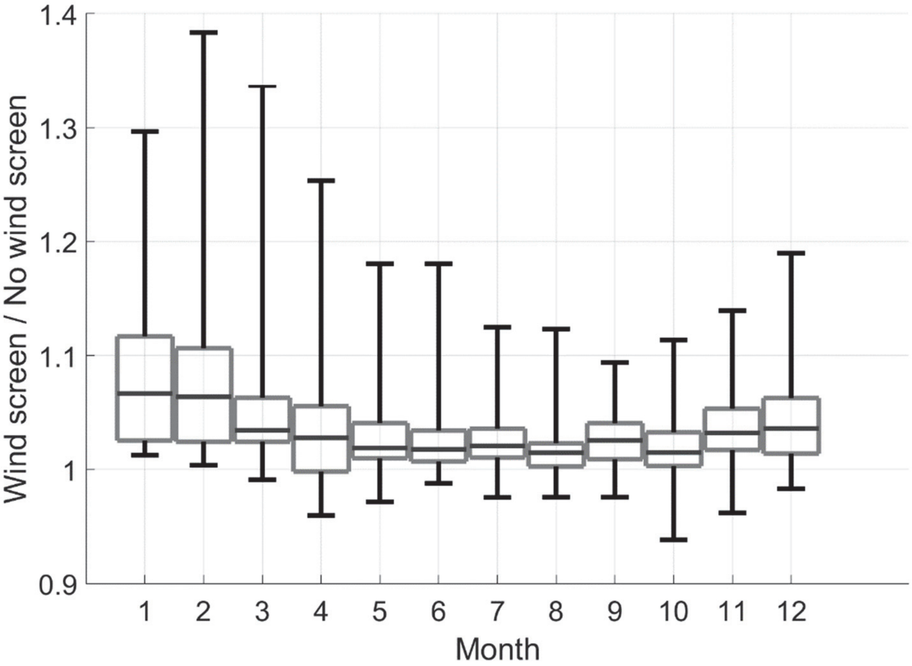

Fig. 10. Ratio of daily precipitation sums observed in Norrköping with the shielded and unshielded gauges for specific months. Horizontal black lines indicate the median, the boxes covers the 25- and 75-percentiles, the whiskers spans over the entire range.

6.2. Katterjåkk

The wind shield effect of the historical gauges in Katterjåkk is on average 11%, see *Table 3.* The effect is larger for snow (16%) than for rain (1%). The larger wind shield effect for snow is also reflected in the MAE, which is 0.4 mm for snow and 0.08 mm for rain. The wind shield effect for sub-zero and super-zero temperatures is 4% and 15%, respectively.

Table 3. Regression slope (*β*) and mean absolute error (MAE) for linear regression models for precipitation observed in Katterjåkk with the unshielded historical, modern (SMHI), and automatic gauges, respectively, all with the precipitation observed with the shielded historical gauge as the target variables

	Without wind screen		**SMHI**		**Automatic**	
Precipitation types	***β***	**MAE /mm**	***β***	**MAE /mm**	***β***	**MAE /mm**
All	1.11	0.47	0.88	0.75	0.66	1.84
Rain	1.01	0.08	0.98	0.19	0.92	1.36
Sleet	1.08	0.59	0.88	0.71	0.64	3.87
Snow	1.16	0.42	0.74	0.98	0.51	1.29

The SMHI-gauge and the automatic gauge collect on average 12% and 34% larger sums than the shielded gauge. Again, the departures are larger for snow (26% and 49% larger sums, respectively) than for rain (2% and 8%, respectively). The uncertainty of the regression model is larger for the automatic gauge measurements (1.8 mm) than for the SMHI-gauge (0.8 mm). The results of the sleet measurements with the automatic gauge, for which the MAE is largest of all the regression models presented in *Tables 2.* and *3,* is shown as an example in *Fig. 11.*

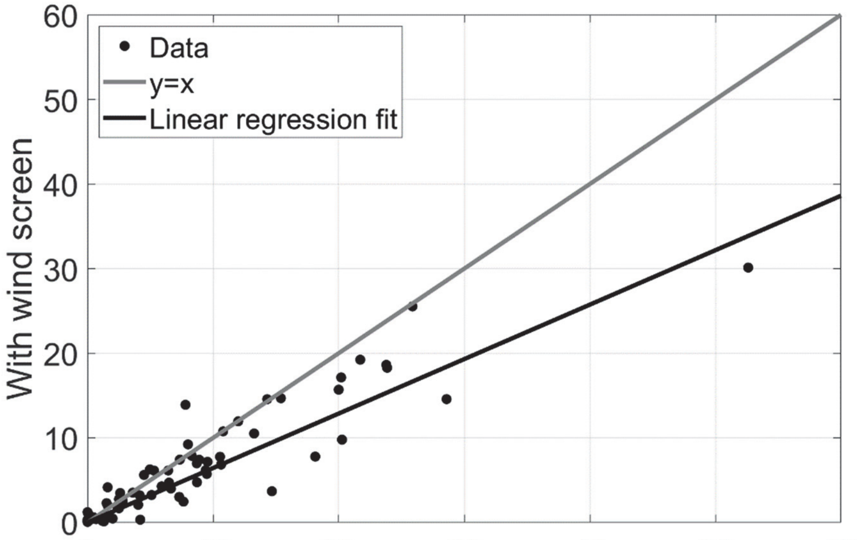

Fig. 11. Linear regression (black line) for daily sleet observed in Katterjåkk with the shielded historical gauge with sleet observed by the automatic gauge as the explanatory values, the 1:1 relationship is depicted as a grey line.

The difference between observations with the unshielded gauge and SMHI-gauge does not significantly depend on air temperature, mean wind speed, or wind gust speed.

There is no clear month to month signal of the ratio of the historical gauge observations, see *Fig. 12.* In winter and spring (December–May), the shielded gauge collects 43% larger sums than the unshielded gauge as a median, in summer and autumn (June–November) this number is 11%.

No clear signal of evaporation could be concluded from the study of observations with longer accumulation times (not shown).

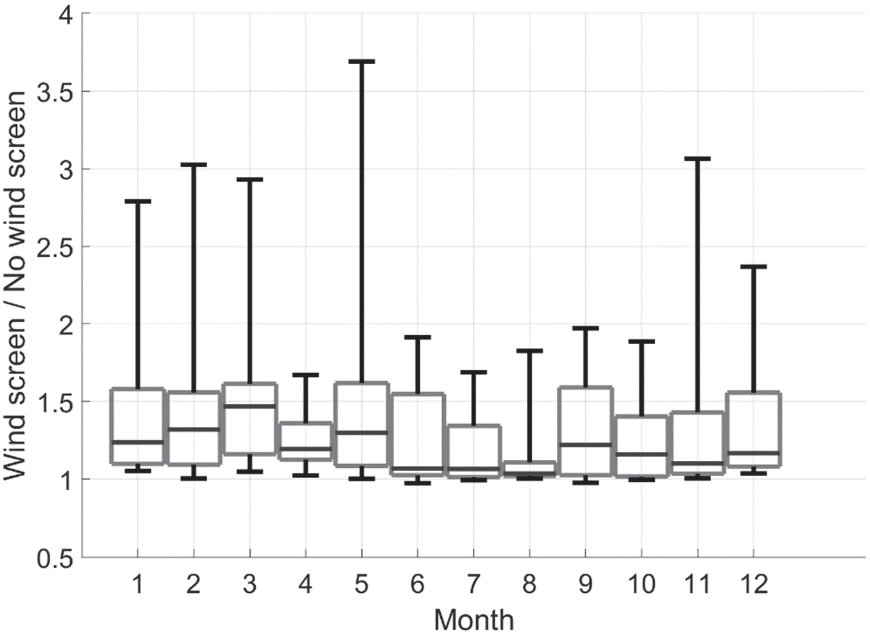

Fig. 12. Ratio of daily precipitation sums observed in Katterjåkk with the shielded and unshielded gauges for specific months. Horizontal black lines indicate the median, the boxes covers the 25- and 75-percentiles, the whiskers span over the entire range.

6.3. Evaluation of undercatch of historical observations

The earliest digitally available daily precipitation observations are from 1836 (Uppsala). In total, 49 weather stations have concurrent daily precipitation and mean temperature data in the period 1836–1893. More than 400 000 observations were included which corresponds to on average 23 years of data per station.

Precipitation observed during days with sub-zero temperatures (28% of the studied days) and super-zero temperatures (72%) were multiplied with correction factors according to the stations' windclass, see *Table 4.* In total, the corrected precipitation was 3% larger than the uncorrected precipitation. The difference was largest in winter (6%) and smallest in summer (2%). In spring the difference was 4%, in autumn 3%.

Table 4. Correction factors used to estimate the undercatch of historical precipitation observations according to the stations' windclass (*Alexandersson*, 2003). Sub-zero (-) and super-zero (+) temperatures are used as a proxy for precipitation form

Wind class	**Formula**	a^-	a^+	**Number of historic stations***	**Modern station****
1	a_1	1	1	1	4%
2	$a_2 = [a_1 + a_3]/2$	1.045	1.01	8	24%
3	a_3	1.09	1.02	14	35%
4	$a_4 = [a_3 + a_5]/2$	1.12	1.03	10	24%
5	a_5	1.15	1.04	3	9%
6	$a_6 = a_5$	1.15	1.04	2	3%
7	$a_7 = a_5$	1.15	1.04	0	0.5%
Not defined	$a_{\mathrm{ND}} = a_3$	1.09	1.02	12	

* Stations with digitally available concurrent daily precipitation and temperature observations prior to 1893

** Share of stations listed in *Alexandersson* (2003)

7. Discussion

For the measurements in Norrköping, the wind shield effects of the historical gauges are on the low end of previous estimates of the wind shield effect (*Hamberg*, 1911; *Bergsten*, 1954; *Eriksson et al.*, 1989). For the measurements in Katterjåkk, the wind shield effect corresponds well to the value discussed by *Hamberg* (1911).

In general, snow gives more diverse observations between methods than rain, which is consistent with previous results. There are larger discrepancies between the parallel observations in Katterjåkk compared to Norrköping. This may partly be explained by the longer distance between the official automatic station and the location of the historical measurements. The more variable snow depth, and thereby, aerodynamic conditions around the site may also play a role.

In Katterjåkk, the observations with the historical gauges are better correlated with the modern manual SMHI-gauge observations than the automatic observations. In Norrköping, observations with the historical gauges resulted in observations closer to those of the automatic gauges. Micrometeorology (i.e., proximity in the location of two parallel observations) thus appears to be more important than the observation method, a similar conclusion was previously drawn by *Alexandersson* (2000).

The MAE of the linear regression models for "sleet" is higher than for snow and rain, probably partly due to the fewer observations and partly due to the more diverse nature of the precipitation types classed as "sleet".

The amplitude and the variability of the ratio between shielded and unshielded observations is larger in winter than in summer, probably due to the larger contributions of frozen precipitation. This pattern is not as clear for the Katterjåkk observations. The lag between the seasonal cycles of snow depth, and the share of frozen precipitation could perhaps explain the weak signal.

No estimate of loss due to evaporation could be deduced from the results. The study was not primarily designed to estimate evaporation loss, and the rather simple method employed proved insufficient. More detailed analysis of precise timing of precipitation and dewpoint deficits in the longer accumulation periods is suggested for a future study.

The estimated undercatch from lacking wind shields in historical observations (1836–1893) is smaller than the network-wide difference of precipitation between periods before 1893 and after 1930, as described above, and that of the two standard normal periods in the climate indicator (1881–1910 and 1931–1960). The undercatch should be considered to be a rough estimate, as estimates of wind shield effects are only obtained for Norrköping (windclass 3) and Katterjåkk (windclass 5) which can be converted to correction factors. Correction factors for stations with other wind classes can only be approximated. It is also not known, how representative these wind shield effects are for other stations within same wind class. The Katterjåkk wind shield effect for snow is for example afflicted by relatively large uncertainty. However, since most stations have a windclass between 2 and 4, the Norrköping wind shield effects have relatively small uncertainties and compares well with literature values, the estimate is still useful. It is also not straightforward to make an estimate of the difference in precipitation before and after the installation of wind shields as early observations are sparse. The climate indicator is produced with the EOF method, where the total precipitation of the entire network over the period from 1880 is estimated by combining the spatial signal of a period of complete coverage with the temporal signal of the available observations. The undercatch due to missing wind shields might therefore be indirectly compensated for to some extent in this product.

On the question whether the historical transition from the 1 000 cm^2-mouth gauges to the modern gauges has influenced the climatological precipitation series, the results are somewhat ambiguous. The test series in Norrköping show no or small deviations between the shielded historical gauge and the neighboring modern gauge (automatic), while the Katterjåkk test series show quite large deviations between the modern and historical observations, and the linear regression models are also afflicted with large uncertainties.

8. Conclusion

The wind shield effect, i.e., larger observed precipitation sums due to the inclusion of a wind shield, is larger for the open site (Katterjåkk) than for the quite well shielded site (Norrköping), and larger for snow than for rain. The wind shield effect was found to be 7% for Norrköping and 16% for Katterjåkk for snow compared to 1% and 2% for rain, respectively.

The undercatch of the shielded historical gauges compared to the modern gauges is also larger for snow (up to 50%) than for rain (0–8%). There are larger differences between the methods in Katterjåkk than in Norrköping. This is probably partly due to the considerable differences in local terrain between the test site and the automatic weather station, partly due to the more windswept and more snowy conditions in Katterjåkk.

The mean average error (MAE) of linear regression models (i.e., how suitable it is to apply correction factors derived from simple linear models to the data) are smallest between the historical gauges, especially for the Norrköping series. The uncertainties are larger for snow and sleet than for rain. The most closely placed modern gauge relative to the historical gauges (automatic gauge in Norrköping, manual gauge in Katterjåkk) gives the most similar precipitation sums, suggesting that micrometeorology is more important than the observation method.

Wind speeds observed at the respective automatic weather station show no simple relationship on the undercatch of the historical gauges.

The wind shield effect is larger and varies more in the winter months than in the summer months, especially for the Norrköping observations. For the Katterjåkk observations, the month-to-month variations of the wind shield effect are difficult to interpret.

The estimated network-wide undercatch due to missing wind shields in historical observation is smaller than the total difference in precipitation between periods without and with wind shields. The study indicates that the installation of wind shields in the late 19th century and early 20th century is probably not the main contribution to the increasing trend in precipitation in this period.

From the results of the study, it cannot be concluded that the transition from historical to modern observations method have had an important influence on the observational time series.

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