https://doi.org/10.5194/egusphere-2025-5195
Preprint. Discussion started: 28 January 2026

Proposed improvement of the detection and measurements of light precipitation in the Canadian Arctic

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https://doi.org/10.5194/egusphere-2025-5195
Preprint. Discussion started: 28 January 2026

Abstract. Snowfall during the extended cold season experienced in Arctic regions is the primary contributor to snowpack evolution, terrestrial components of the water cycle, and many melt-season hydrologic phenomena. Despite this importance, solid precipitation measurements in the Arctic are challenging; frequent periods of light precipitation are often difficult to measure with existing gauge networks, and result in under-estimations of total snowfall during a winter season. This study analyzes the measurement of solid precipitation at the Trail Valley Creek Research Station in the Canadian Northwest Territories, using a weighing precipitation gauge, and micro rain radar. The study period runs from 4 November 2023 to 30 April 2024, with an intensive observation period from 16 March to 2 April 2024, during which detailed manual observations improved our understanding of instrument performance in arctic conditions. The already established weighing gauge was used as the reference for the study and measured a total snowfall (snow water equivalent) during the study period of 68 mm, which increased to 190 mm after corrections for wind and snowfall intensity. Manual observations coupled with radar, however, confirm the difficulty of measuring light precipitation. We present a method of on-site calibration for the reflectivity-snowfall relationship for the micro rain radar, that we use to estimate the low-rate (< 0.2 mm hr^{-1}) snowfall amounts that are commonly missed by weighing gauges. Adding these trace amounts of precipitation, the total snowfall amount increased by another 24%. While more work is required to confirm these methods in Arctic environments, this study contributes to a better understanding of current measurement systems and can be used to enhance snowfall estimations.

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1 Introduction

The high-latitude regions of the world are of great interest in the context of climate change, however, they are poorly understood and surveyed due to their remote location and harsh climate (Brunet and Milbrandt, 2023, Souverijns et al., 2017). These areas are also the most impacted by global warming, with effects such as enhanced changes in near-surface air temperature being observed due to arctic amplification (Previdi et al., 2021). Snow in the Arctic plays a major role in the local permafrost and hydrology, and in regional and global energy balances (Marsh and Pomeroy, 1996; Chen et al., 2021; O'Neill and Burn, 2017). Total snowfall measurement, however, is challenging; with end of winter snow on the ground often being larger than measured snowfall (Woo et all, 1983). Such errors are due to frequent periods of trace amounts of snow being often difficult to measure, with many existing gauge networks having a minimum detectable precipitation rate higher than what has been observed in polar regions (Colli and Rasmussen, 2015; Gultepe et al., 2016, Matrosov et al., 2022, Mariani et al., 2024). These periods of light precipitation (rates from 0.1 to 0.5 mm hr^{-1}, depending on the study), can be missed by conventional gauges designed for mid and low latitudes. Light precipitation can nonetheless significantly contribute to the snowpack throughout the winter, representing 80% of the precipitation over arctic regions in terms of duration, and up to 45 to 50% in terms of amount (Gultepe et al., 2016, Matrosov et al., 2022).

Depending on the type of hydrometeor, wind speed, and gauge design, many precipitation gauges have shortcomings when measuring snowfall rate and amount (Rasmussen et al., 2012, Mariani et al., 2024). Underestimated snowfall can be adjusted using transfer functions that include wind speed, temperature, particle fall speed (Leroux et al., 2021), and snow intensity (Colli et al., 2020). Even with such adjustments, the total precipitation measured by a weighing precipitation gauge with a single-Alter windshield may be incorrect by as much as 54% to 123% when compared to a Double Fence Automated Reference (DFAR), (Smith et al., 2020).

More advanced instruments, such as laser and video disdrometers and hotplate precipitation gauges have been developed to address some of the shortcomings of weighing precipitation gauges, and to enhance analysis of precipitation characteristics (see Leroux et al., 2021; Thériault et al., 2021). Challenges such as access to reliable AC power, data storage and recovery, and accuracy in harsh environments, remain. Optical disdrometers, for example, are known to have issues characterizing the precipitation rate during periods of snow due to border effects, one-dimensional size characterization of particles, and shadow effect for simultaneous particles (Battaglia et al., 2010; Kochendorfer et al., 2022).

Experimentation to retrieve solid precipitation measurements in polar regions has recently evolved with the use of vertically pointing radars. Beyond identifying precipitation formation processes aloft, techniques have been developed to retrieve snowfall rates (Matrosov et al., 2022). Schoger et al. (2021), and Souverijns et al. (2017), both used micro rain radars (MRRs) in Svalbard Norway, and Princess Elizabeth, Antarctica, respectively, in combination with W-band cloud radars and optical disdrometers. Using the relationship between radar reflectivity and snowfall rate removes the necessity to catch and weigh precipitation or rely on particles being intercepted within a small footprint at the surface. Snowfall studies in Antarctica differ from this research however, due to the small number of large snowfall events across the southern hemisphere continent that are driven by large-scale process such as atmospheric rivers (Gorodetskaya et al., 2014, as cited in Souverijns et al., 2016). To enrich meteorological measurements in the Canadian arctic, two federally funded supersites have been established in Whitehorse and Iqaluit, which make use of an array of radar, lidar, and remote sensing instrumentation (Mariani et al., 2022; also see Mariani et al., 2024). These instruments are primarily used to support operational forecasting

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and numerical weather prediction models, and both sites are located near population centers and upper air observations stations. Neither site currently has an MRR in operation.

For this study, an established meteorological station at a high-latitude site in the western Canadian Arctic, Trail Valley Creek Research Station (TVC), was supplemented with an optical disdrometer, MRR, and hotplate for the 2023-2024 winter. Accompanying manual observations were made during March-April 2024. The catchment hosts an assortment of hydrological research activities that began and 1991 (Marsh et al., 2004), with recent studies ranging from the water balance of thermokast lakes (Wilcox et al., 2023), to tundra snowpack modelling (Meloche et al., 2022). Outside the catchment, research includes studies of the region's biodiversity, hydrological regimes (Morse et al., 2012), and permafrost (O'Neill and Burn, 2017). Difficulties in the closure of catchment water balances, however, are exacerbated when total winter snowfall amounts are at best underestimated where measured and missing where data are sparse. While snow surveys are carried out each spring in the catchment to record total snow depth and snow water equivalent (SWE) on the ground, it is the accurate measurement of snowfall throughout the winter that remains a challenge at TVC.

Accordingly, the goal of this study is to propose a method to improve the estimation of light precipitation. To do so, we use a combination of in situ measurements from the federally operated weighing precipitation gauge, the MRR, and manual observations. Technical issues and reliable power for the disdrometer and hotplate prevent us from utilizing data from these instruments during the study period.

The manuscript is organized as follows: Section **Error! Reference source not found.** details the site, instruments, and methods used in the study, and in Section 3 we present the results of the 2023 – 2024 data collected at TVC. In Section 4 we discuss the results, the reliability of the instruments in the Canadian Arctic, the performances of various corrections, and the added value of the intensive observation period. Section 5 provides a summary and conclusions.

2. Methods

2.1 The study site

Trail Valley Creek Research Station (TVC) (68°44'31.2"N, 133°29'55.3"W) (Fig.1), first established in 1991, lies 50 km north of Inuvik, Northwest Territories, and ~75 km south of the Arctic Ocean coastline. It is a continental location with a subarctic climate, and Inuvik climatology from 1965 to 1995 indicates a mean annual precipitation of ~340 mm, with ~207 mm being snow (Environment and Climate Change Canada, 2023). Marsh et al. (2010) described long term changes in snowfall at Inuvik and at TVC. Precipitation trends in the region, however, have been positively correlated with the warming of the Arctic in recent years (Przybylak, 2002).

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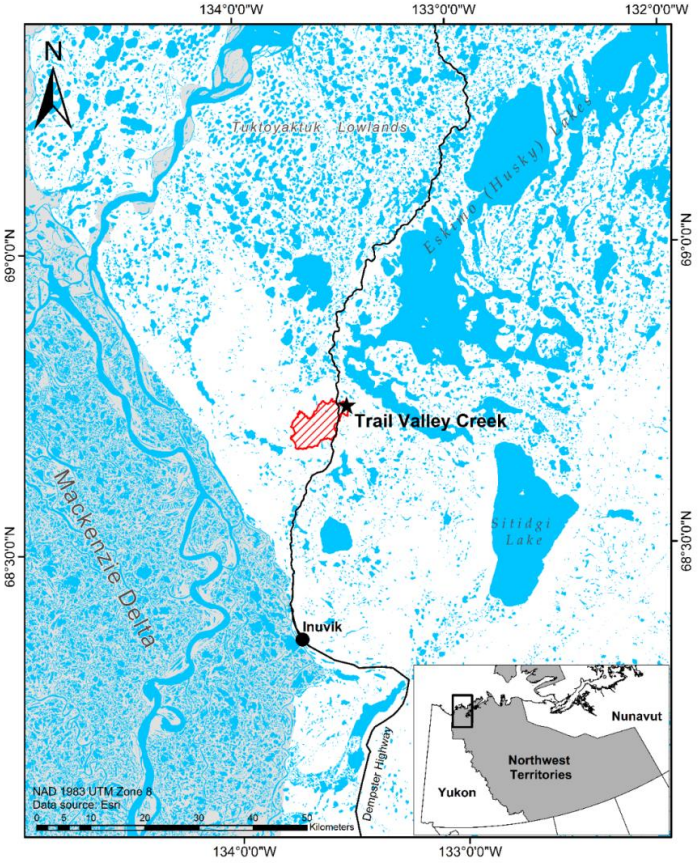

Figure 1. Trail Valley Creek and northwestern Northwest Territories. Shown is the Mackenzie Delta, the town of Inuvik (center bottom), and the Dempster and Inuvik to Tuktoyaktuk highways (black line). Also displayed is the weather station used in this study (black star), and the Trail Valley Creek watershed (red polygon) (adapted from Walker and Marsh, (2019)).

The station operates on solar power and battery for as much of the arctic summer as possible, with a backup generator charging the battery bank at all other times. The selection of instrumentation therefore is limited as power consumption is a continuous concern. Regardless of this, the station manages a broad array of hydrometeorological instruments and camp facilities, considering it is 5 and 8 degrees north of the federally funded supersites in Iqaluit and Whitehorse, respectively. The instruments used in this study are shown in Fig. 2.

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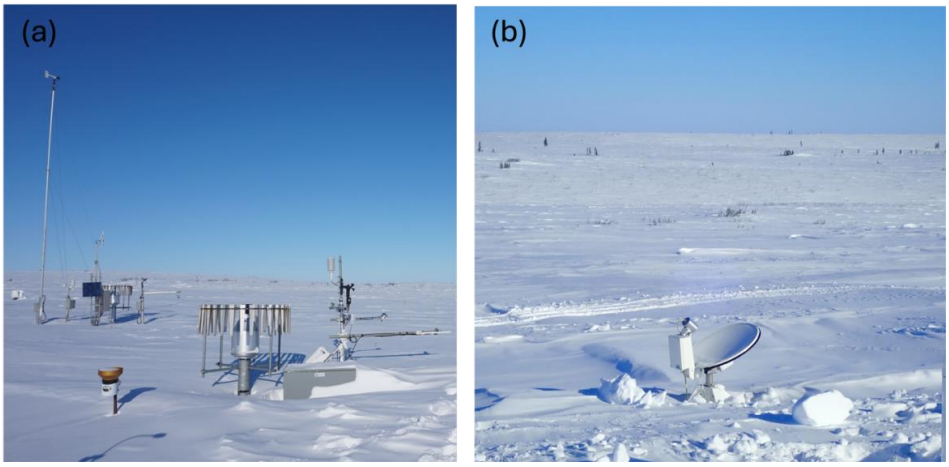

Figure 2: Instruments used at Trail valley Creek. (a) The Environment and Climate Change Canada 10 m mast, Geonor weighing precipitation gauge (furthest gauge to the left), and temperature, pressure, and humidity sensors. In the foreground, Wilfrid Laurier University instruments with another Geonor, anemometer, radiometer, and a snow depth sensor. Only data from the ECCC instruments were used in this analysis. (b) The METEK micro rain radar MRR2. All images taken April 2024, with snowpack depth being near the seasonal maximum for the 2023 – 2024 winter.

2.2 Instruments and data

The Environment and Climate Change Canada (ECCC) station at TVC (Climate ID: 220N005; WMO ID: 71683) comprises a Geonor weighing precipitation gauge with single Alter wind shield (henceforth referred to as the Geonor), a 10 m mast with an RM Young wind monitor, and pressure, temperature, and humidity sensors (Fig. 2a). Hourly data are available from 1998, making it a valuable resource in this data-sparse region. Data for this study were downloaded from November 2023 to May 2024 from ECCC's historical data website. A similarly instrumented weather station operated by Wilfrid Laurier University (WLU) is collocated with the ECCC station, however, the WLU instruments are configured for research purposes, as opposed to the operational ECCC station. Hourly ECCC data is also the typical resource the wider hydrometeorological community uses for precipitation measurements in the area.

The ECCC Geonor is equipped with a single alter shield to decrease wind-induced precipitation undercatch; however, even with this shield this gauge is known to still under estimate solid precipitation (Leroux et al., 2021). As a result of multiple studies (e.g., Kochendorfer et al. 2017, 2018; Pierre et al. 2019), several collection efficiency (CE) equations have been developed using different meteorological parameters. The measured precipitation rate ($P_{measured}$) can then be adjusted ($P_{adjusted}$) using CE with:

$$P_{adjusted} = \frac{P_{measured}}{CE} \quad (1)$$

Despite having a disdrometer, there were too many data gaps to use methods developed in Leroux et al. (2021); therefore we use in this study the transfer function developed by Colli et al. (2020) referred to as $f_{(U,SI)}$, using:

$$CE = e^{-a(U_w)\left(1-\left[\tan^{-1}(b(SI)+c)\right]\right)} \quad (2)$$

With U_w the wind speed at 2-m height and SI the unadjusted snowfall intensity (SI) in mm h^{-1} from a single-Alter Geonor gauge. Equation 1 is based on data collected at Marshall in Colorado, Centre for Atmospheric Research Experiments in Canada (CARE), and Haukelister in Norway from fall 2013 to spring 2015. Each site has different

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weather conditions and therefore uses different coefficients. We use coefficients from the Marshall measurement site (a = 0.4156, b = 8.7795, and c = -0.7062). Similarly to Colli et al., (2020), we use wind speed measured at 10 m height (U) and employ adjustment $U_w = 0.71 * U$ to obtain the 2 m wind speed. We limit the maximum wind speed to 10 m s^{-1} (Colli et al., 2020).

Regardless of the transfer function used, adjustments to precipitation amounts can only be performed when the hourly values are greater than zero. Configurations for Geonor (and similar) gauges vary depending on the location and network. For the Geonor located at TVC, the minimum measurement threshold was set to 0.2 mm per hour.

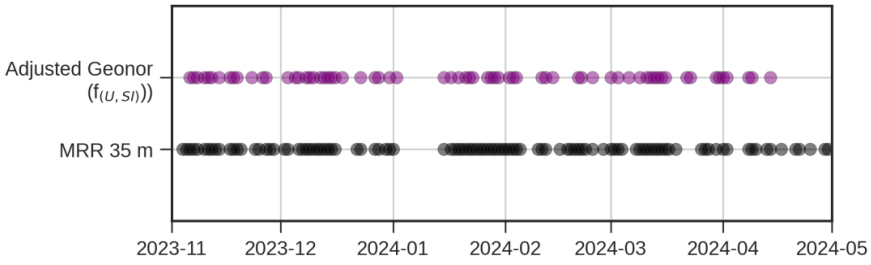

Figure 3. Time series (daily resolution) of snowfall signals recorded at Trail Valley Creek Research Station by the Geonor weighing precipitation gauge (purple circles), and the METEK MRR2 (black circles).

2.3 Micro rain radar

The MRR (Fig. 2b) is a vertically orientated, continuously transmitting, 24 GHz meteorological radar using a 2° wide beam reflected from a ~70 cm parabolic dish. The dish is heated to avoid snow and ice buildup during precipitation events. The resulting data include information on particle reflectivity and the vertical velocity of hydrometeors aloft (Metek, 2009). The 32 range gates can be set to a vertical resolution between 35 m and 200 m. To capture the greatest range, we employed a novel method of switching between 35 m and 200 m vertical resolutions every ~30 seconds using a function in the manufacturer-supplied software. This allowed for the finer details of near-surface precipitation to be observed, down to 70 m above ground level, while maintaining an understanding of the mid-level source of the precipitation particles (i.e., most cloud tops are above the 1120 m maximum height observed when using only the 35 m resolution). Data from both resolutions were post-processed using Maahn and Kollias, (2012), which increases the instrument's sensitivity to light solid precipitation (Thériault et al., 2021). The timing of precipitation detected from the MRR agrees well with the Geonor precipitation gauge (Fig. 3), a benifit of the instrument being located on a (relatively) reliable electrical circuit.

2.4 Intensive observation period

An Intensive Observation Period (IOP) took place from 2300 UTC 16 March until 1700 UTC 2 April 2024, and followed the same structure described in Thériault et al. (2019) and Thompson et al. (2023). The aim of the IOP in this study was to confirm the atmospheric conditions during periods of light precipitation and blowing snow, and to evaluate instrument performance during these events. This also removed some of the guesswork when analysing data after the field campaign. While the IOP was relatively short, conditions during the polar winter at TVC prevent any substantial observation period earlier than March each year. During the IOP, weather observations were taken every hour indicating either no precipitation, light precipitation, snow event, or blowing

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snow event (or a combination of conditions). Sky conditions were also reported, as well as the primary and secondary particle types in cases of precipitation.

An ice-fishing tent was installed to provide shelter for photography equipment in the hope of replicating the macrophotography protocol used in previous mid-latitude experiments (e.g., Thériault et al., 2019) (Fig. 4). Sporadic snowfall and low precipitation rates, however, prevented the routine photography of hydrometeors every 10-minutes as the collection pad was often not sufficiently covered with particles. This did provide an opportunity for the field participants to delineate between *snow* and *light precipitation* in their observations: if the collection pad was covered enough for a series of images to be taken then the precipitation type for the 10-minute period was classed as snow; if snow or ice crystals were present but there were not enough hydrometeors on the pad to photograph, then the precipitation type was classed as light precipitation. This method became more reliable than using a snow board to estimate trace amounts of snow, as the board was usually stripped bare of snow by wind. All observations used World Meteorological Organization standards (e.g., WMO, (2021)). The observations do not cover most of local nighttime nor the period from 1700 UTC 26 March to 0300 UTC 28 March due to a resupply trip to Inuvik.

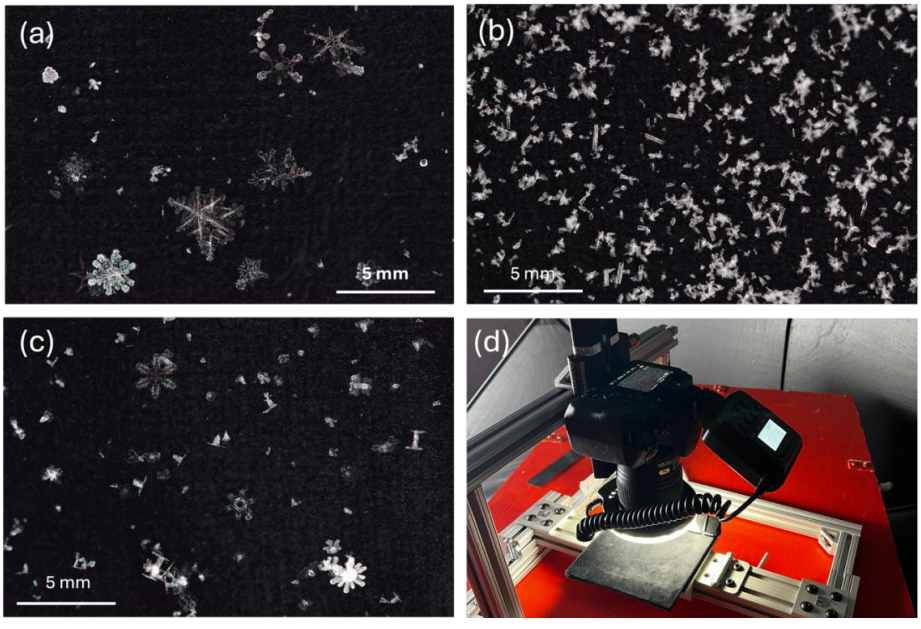

Figure 4. Macrophotographs and the photography equipment used during the intensive observation period (IOP). (a) taken on 30 March 2024, contains a collection of dendrites between 3-5 mm in size; (b) and (c) taken on 1 April 2024 ~2 hours apart, shows the transition of snow crystal type from columns, bullets, and ice particles ~1-2 mm in size, to capped columns, plates, and dendrites 2-4 mm in size.

2.5 Z-S estimation reflectivity

Using the manual observations, a Z-S relationship was derived to determine the occurrence of light precipitation. Snowfall (S) amount at the surface is related to the MRR reflectivity (Z_e) using:

$$S = \left(\frac{1}{a_{ZS}} Z_e\right)^{1/b_{ZS}} \quad (3)$$

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with Z_e the effective reflectivity of the MRR, a_{ZS} the prefactor, and b_{ZS} the exponent value. We follow methods used by Schoger et al. (2021) by taking the average backscattered signal Z_e every five minutes for the heights 105 m, 140 m, and 175 m, using the 35 m resolution data. There were no days of missing data during the study period; however, the post-processing algorithm can struggle to dealiase all 10 second data, depending on noise in the signal, which leads to the 5-minute averaging.

The range of values for a_{zs} and b_{zs} from previous studies highlights the complexity of the S-Ze relationship, which is a function of particle size and shape, liquid water content, and precipitation type, in addition to other environmental and microphysical properties. Despite previous studies warning against using a fixed climatological S-Ze relationship (e.g., Rasmussen et al., 2003), and improvements being made using variable a_{zs} values, in this study we are constrained to a fixed S-Ze relationship due to the mismatch in temporal resolution between the MRR (1-minute) and Geonor (hourly), which is a situation we envision other hydrometeorological groups may encounter. An attempt was made to replicate methods used by Rasmussen et al. (2003) and Schoger et al. (2021) using data from the disdrometer; however, our dataset appears to be too noisy to obtain accurate estimates for b_{zs} and a_{zs}. Values for b_{zs} for example, were a magnitude larger than expected (Rasmussen et al., 2003) and therefore unphysical. We suspect this is due to very low rates of snowfall, yet high number of small particles observed (i.e. below the size range of the disdrometer). To select the appropriate coefficients to use in this study, we first use the average values from Schoger et al. (2021) ($a_{zs} = 77.61$, $b_{zs} = 1.22$), however this resulted in a gross underestimation (~50%) of total snow accumulation compared to the adjusted Geonor values during the season. Conversely, using Souverijns et al. (2017) ($a_{zs} = 18$, $b_{zs} = 1.10$), overestimated snow accumulation by a factor of 2. Taking these bounds into consideration, we conducted a linear regression analysis that iterated Eq. (3) 10,000 times with incremental steps for a_{zs} between 10 to 100, and b_{zs} between 1.0 and 2.0, using 206 hours of concurrent measurements between the MRR and Geonor. From this, the linear regression model with the lowest RMSE and closest total seasonal precipitation amount provided coefficients for Eq. (3) of $a_{zs} = 64.55$, $b_{zs} = 1.72$.

3. Total accumulated precipitation: November 2023 – April 2024

We constrain our analysis to data obtained from 4 November 2023 to 30 April 2024, when all instruments were installed and configured as described in Section 2. TVC does experience snowfall outside of these months, therefore total accumulation mentioned here does not represent total seasonal snow-on-the-ground at the site. Additionally, we maintain the native resolution of the MRR in our analysis as the higher frequency of measurements is a key feature in the increased sensitivity of these instruments to snowfall in this experiment. For direct comparisons to the Geonor, we have accumulated the individual 1- or 5-minute precipitation amounts to obtain hourly accumulation. We make these hourly comparisons sparingly, however, due to suspected dumps of snow into the Geonor from capping (a build-up on snow and/or ice on the instrument housing) that resulted in the timing of accumulation appearing to be misaligned.

During the study the temperature remained below 0°C during all episodes of precipitation, and only solid precipitation was observed. The Geonor observed a total of 246 hours (Fig. 3) with 0.2 mm or more of precipitation, with a maximum hourly amount of 2.0 mm (unadjusted) observed on 23 March 2024, and a daily maximum of 4.5 mm (unadjusted) on 18 November 2023. Of the 71 days during the study period that precipitation was observed by the Geonor, 49 of those days had < 1 mm (unadjusted) of total accumulation (Fig. 4). The total unadjusted accumulation for the study period from the Geonor was 62.3 mm (Figure 5), with ~50% of the total accumulation

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falling in November and December 2023 (not shown). Adjusting the Geonor data using $f_{(U,SI)}$ (Eq. (3)), the total observed accumulation increases 276% to 172 mm, with hourly accumulations increasing between 6.9% and 1409%, and the maximum daily accumulation becoming 28 mm on 27 December 2023.

The Geonor data exhibit a discontinuity at the lower ends of both the hourly and daily accumulation distributions, i.e., no values below 0.2 mm (not shown); a fact that is exacerbated at this Arctic site due to the high frequency of low-rate precipitation events during the study period. The Geonor therefore underestimates precipitation not only due to gauge under catch, but also due to instrument sensitivity more so in the arctic than in the mid-latitudes.

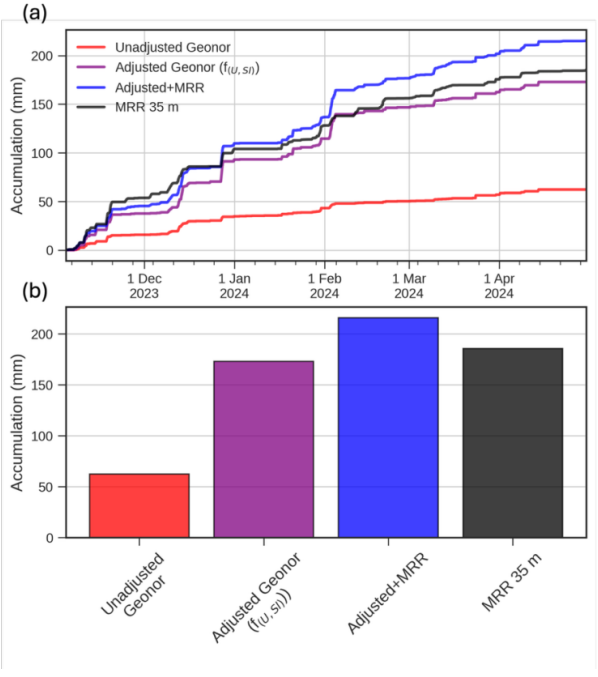

Figure 5. Total precipitation accumulation for instruments and adjustments used in this study. (a) The time series from 4 November 2023 to 30 April 2024 for each instrument, and (b) total cumulative accumulation. Colors represent the Unadjusted Geonor accumulation (red), adjusted Geonor accumulation, f(U, SI), using Colli et al. (2020) (purple); Geonor-MRR adjusted (adjusted Geonor amount with additional MRR detected accumulation, see Section 3.3) (blue); total accumulation using the MRR signal and Eq. (3) (black).

Summing the 5-minute precipitation amounts from the MRR data using Eq. (3) resulted in a total accumulation of 185 mm. The instrument detected precipitation for 1188 hours, with 5-minute average reflectivity ranging from 0.0678 dBz to 408.5 dBz, which equates to precipitation rates ranging from 0.018 to 2.92 mm hr^{-1}. This is in line with the minimum threshold of 0.01 mm hr^{-1} stated by Mahn and Kollias (2012). The daily maximum MRR accumulation of 11.5 mm was recorded on 27 December 2023 (correlating with the Geonor).

Differences in the total accumulations between the MRR and the Geonor are primarily explained by the choice of a_{ZS} and b_{ZS} in Eq. (2), and the fact that they are not explicitly defined for TVC and this study. Regardless, the amount measured by the MRR is a realistic first-order estimation. Other sources of error include sublimation of particles between the measurement heights aloft and the surface, and horizontal transport of hydrometeors away from the MRR location after the reflectively measurements were made. It would also be conceivable for the MRR total to be greater than the Geonor due to the MRR method being immune to issues associated with weighing

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gauges such as wind undercatch, instrument capping, and sublimation; problems that were noted by both Schoger et al. (2021) and von Lerber et al. (2017) but that were not accounted for.

4. Intensive Observation Period: March – April 2024

Weather conditions during the IOP from 16 March 2024 to 4 April 2024 are shown in Figure 6. During this period, the hourly manual observations comprised of 9 snow, 19 light precipitation, and 32 blowing snow observations. There were 158 hourly observations of no precipitation (Table 1). The minimum and maximum temperatures recorded during the IOP were -38°C and -3°C, respectively. (Fig. 6).

Table 1. Instrument performance during the Intensive observation period hourly observations

Instrument	Snow	Light precipitation	Blowing snow
Observed	9	19	32
Geonor	5	0	0
MRR	9	13	1

The Geonor recorded at least 0.2 mm precipitation for 5 of the 9 hours of snow (**Error! Reference source not found.**), but none of the light precipitation or blowing snow observations. Precipitation rates from the MRR signal could be calculated during the 9 hours of snow, one hour of blowing snow, and during 13 of the 19 hours of light precipitation. For the 4 hours of snow that the Geonor failed to detect precipitation, the MRR data indicates precipitation rates < 0.2 mm hr-1. Notably, the Geonor recorded the maximum hourly accumulation during the IOP on 23 March 2024 (2 mm). The manual observations and MRR signal indicate no precipitation occurring during that time; however, warming (> 1°C hr^{-1}) at the surface towards 0.0°C for several hours preceding the measurement suggests a dump from capping (a build-up on snow and/or ice) of the instrument housing. Furthermore, sublimation of snow from inside the housing is not considered in this study but could play a minor role in underestimating total accumulation.

From the IOP observations, we confirm there are frequent small amounts (< 0.2 mm) of precipitation at the surface without being detected by conventional precipitation gauges. From here, we propose a method to quantify these amounts and analyse their contribution to seasonal snow totals at Trail Valley Creek.

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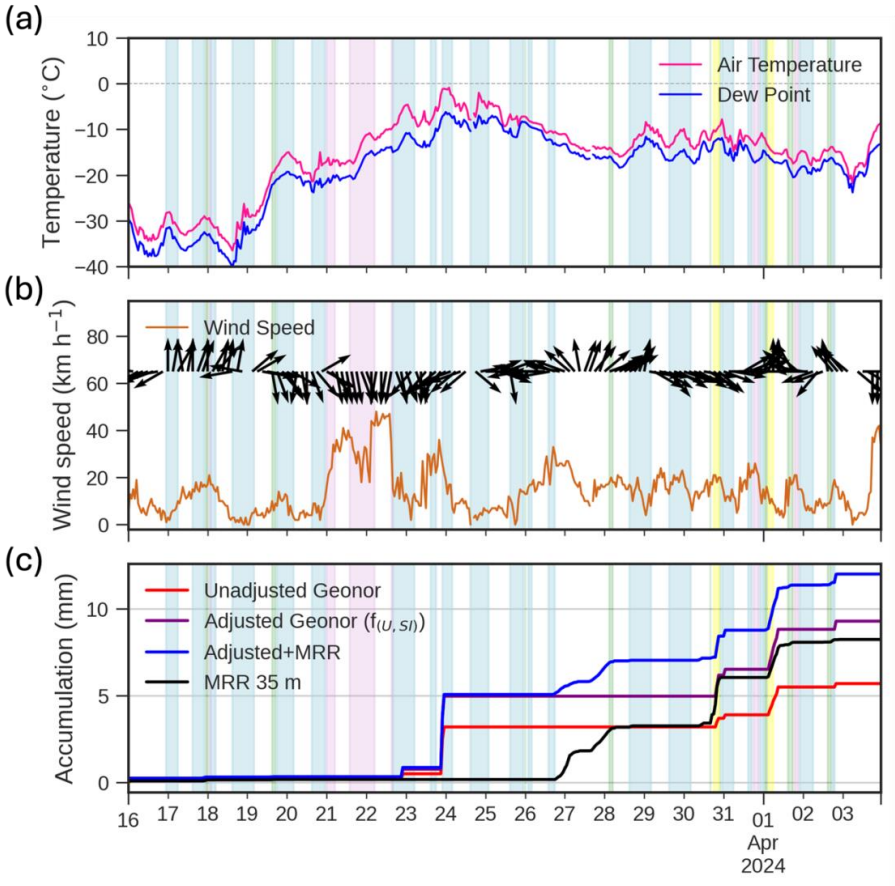

Figure 6. Overview of the intensive observation period (IOP) from 16 March to 4 April 2024. (a) Air temperature (pink) and dew point (blue); (b) wind speed (orange) with wind direction indicated by arrows; (c) cumulative precipitation accumulation from the instruments described in the text, including unadjusted Geonor (red), adjusted Geonor (purple), adjusted Geonor combined with MRR (blue), and MRR at 35 m (black). Vertical shading denotes observed weather conditions: snow (yellow), blowing snow (pink), light precipitation (green), and no precipitation (blue). Unshaded areas indicate periods with no observations.

5. Contribution of the light precipitation

Using the manual observations of light precipitation, snow, and no precipitation, we extract the corresponding subset of MRR data to determine precipitation rates and amounts observed during the hourly observations. During the periods of light precipitation and snow that the Geonor did not detect, hourly MRR totals were less than 0.2 mm, with a one hour maximum of 0.14 mm. MRR-derived 5 minute precipitation rates during these periods were up to ~1.8 mm hr^{-1}; however, the interquartile range of 5-minute rates from the MRR were 0.03 – 0.3 mm hr^{-1}, with a mean of 0.27 mm hr^{-1}. No discernible signal was detected during periods of no precipitation. An example of vertical profiles obtained from the MRR during the IOP is presented in Fig. 7.

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Despite the extended sensitivity of the MRR, using rate alone to fill in missing precipitation is not suitable due to the disparity in temporal resolutions between the MRR (5-minute) and the Geonor (hourly). We therefore select all occurrences during the study period (4 November 2023 – 30 April 2025) where the hourly precipitation amount recorded by the MRR is between 0.01 and 0.2 mm then exclude hours that the Geonor already detects at least 0.2 mm (i.e., records a non-zero amount). We also amend our working definition of *light precipitation* from this point onward to match. The total accumulation of light precipitation between 4 November 2023 and 30 April 2024 using this method is 43 mm, spread over 903 hours. Adding this to the adjusted Geonor increases the total adjusted accumulation 24% to 215 mm, a 248% increase from the unadjusted amount. We term the combination of these amounts as *Geonor-MRR adjusted* (Fig. 5). This increases the number of days during the study period that precipitation was observed from 71 (39% of the study period) to 112 (62%), with 66 days measuring < 1mm (Fig. 8b), a mean daily precipitation amount of 1.91 mm day^{-1} for days with precipitation and 1.20 mm day^{-1} for the entire study period.

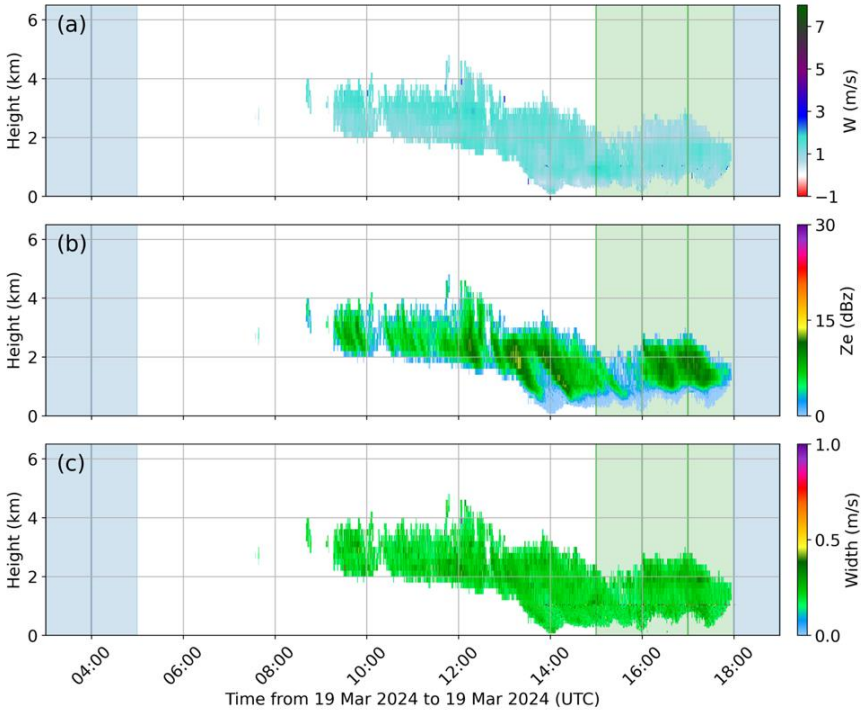

Figure 7. Time series of MRR profiles for an observed snow event in March. The three panels represent (a) Doppler velocity of particles (W), (b) effective reflectivity (Ze), and (c) the Doppler spectral width (s). For all profiles, under 1120 m above ground level represents data from the 35 m resolution while above 1120 m are the data from the 200 m resolution. The background vertical shading corresponds to weather observations: no precipitation observed (blue), and light precipitation (green). For hours without shading, observations were not available.

The largest uncertainty in this method arises from the use of a constant prefactor in Eq. (3), yet Schoger et al. (2021) illustrate that the largest swing in values for a time-varying a_{ZS}, between 500 – 2000 mm$^{6\text{-}bZS}$ h^{bZS} m^{-3}, are associated with greater amounts of liquid water in the atmosphere, a condition that is unlikely supported at TVC when light precipitation is observed. We attempt to minimize the error by only employing the MRR adjustment when necessary (i.e., for periods the Geonor is not sensitive enough) and using a constant a_{ZS} appropriate for the

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conditions. Therefore, the advantage of this method is to add what was confirmed by manual observations to be missing from the Geonor measurements, rather than perform an additional correction or adjustment. The inclusion of MRR derived light precipitation increases the number of days with low precipitation amounts (e.g., 0 – 1 mm, 1 – 2 mm), and those days' contribution to the total seasonal accumulation (Fig. 8a).

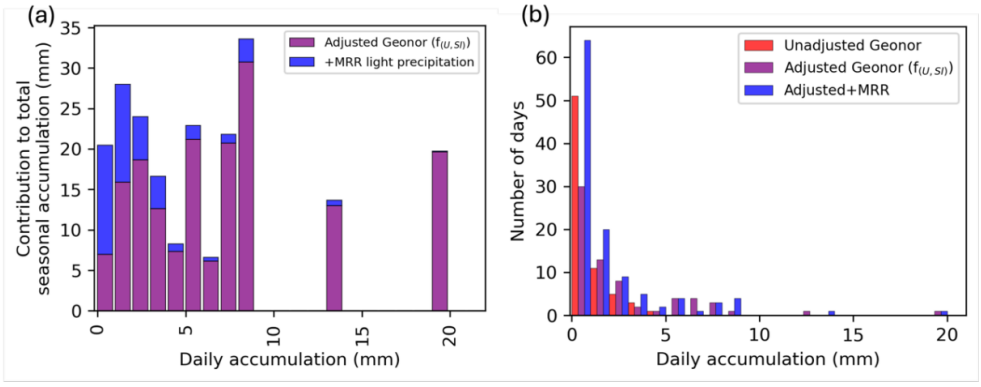

Figure 8. Histograms for total accumulation for Geonor-MRR adjusted accumulation. (a) Number of days for observed daily accumulation amounts, and (b) total accumulation over 4 November 2023 to 30 April 2024 for observed daily accumulation amounts. Histogram bins go from 0.0 mm to 30 mm in 1 mm increments.

6 Concluding Remarks

6.1 Conclusions

In this study, we have proposed a new method for quantifying the frequent, light precipitation amounts observed at Trail Valley Creek (TVC) research station by adding low-intensity snowfall detected using a micro rain radar (MRR) to the measurements made by a long-running, federally operated Geonor weighing gauge.

At TVC, the Geonor gauge records at a minimum hourly resolution of 0.2 mm, which misses low-intensity events. After applying wind and snowfall corrections, recorded totals increased by 204%, underscoring the importance of post-processing. It is unclear, however, whether such corrections are consistently applied by hydrology or ecology users outside the meteorology community.

The MRR revealed that light precipitation below the Geonor threshold accounted for ~24% of the seasonal snowpack. Events with intensities of 0.01 – 0.2 mm hr^{-1} and daily totals <1 mm, though easily overlooked, proved essential to winter accumulation. This demonstrates the importance of small, frequent snowfalls in Arctic environments and highlights the value of complementary manual observations. To bridge these gaps, we used a simple regression model to relate radar reflectivity to snowfall rate. Although less sophisticated than other methods, this approach provides a practical first order estimate and minimizes error by using MRR data only where Geonor records fall short. This strategy is well suited to hydrology focused groups seeking to fill in missing low-rate precipitation within existing networks. The continued operation of these instruments at TVC provides opportunities for refinement, including the use of time-varying regression coefficients, and the fine-tuning of equipment towards finer detection thresholds. Such upgrades would further improve Arctic snowfall measurement and support both scientific and applied uses.

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6.2 Limitations

This study reflects a single site and season, limiting its generalizability across Arctic regions. While broader campaigns are common at lower latitudes, reliable data from high latitudes remain scarce, making site-specific results valuable despite this constraint.

Geonor measurements consistently underestimate snowfall, and correction factors strongly influence adjusted totals. The coarse hourly resolution and snow/ice buildup on the housing create timing uncertainties relative to higher-resolution radar and disdrometer data. Sublimation and wind-driven advection further complicate the radar–snowfall relationship.

The IOP's short duration restricted the range of conditions observed. Heavier snowfall events, such as that of 27 December 2023, were missed, precluding evaluation of instrument performance under such conditions. Likewise, limited data on blowing snow prevented analysis of how the instrumentation respond during these periods.

6.3 Implications

Light snowfall, often below the detection limit of conventional gauges, contributes significantly to Arctic snowpack. This finding challenges the adequacy of standard networks and highlights the risk of underestimating water inputs in cold regions.

For hydrology, more accurate low-rate snowfall estimates improve snowpack modelling, runoff forecasts, and predictions of streamflow timing – critical for water supply, flood risk, and permafrost stability. For ecology, capturing subtle snowfall inputs refines the understanding of snow-vegetation interactions, soil insulation, and habitat conditions for Arctic species. For climate science, the results provide ground-based evidence that frequent, light snowfall is an important but underrepresented component in Earth system models. Incorporating these processes will improve climate projections in polar regions, where precipitation feedback is key to sea-ice decline, permafrost thaw, and global circulation changes.

Finally, this study underscores the importance of communication between disciplines. Hydrologists and ecologists often rely on gauge data but may be unaware of correction requirements or the sensitivity of the instrumentation, leading to systematic underestimation. Improved knowledge exchange between atmospheric scientists and data users will help ensure precipitation records are applied correctly and consistently, strengthening the reliability of Arctic research in support of climate adaptation.

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Data availability

Data from the ECCC station at Trail Valley Creek can be found using the ECCC Historical data website, https://climate.weather.gc.ca/historical_data/search_historic_data_e.html (Station name: Trail Valley; Climate ID: 220N005). All other data and code used are part of the ongoing *Improved measurements of Arctic snowfall using a novel interdisciplinary approach (A-Snow)* project, and currently available by request from the authors. A publicly accessible dataset is planned for the cumulation of the project.

Author contributions

PM and JMT designed the study, with input from HDT. HDT deployed the instruments, and HDT and JD participated in the field campaign and data analysis. JD and HDT prepared the manuscript with supervision from JMT and PM. All authors have read and agree to the final version of the published manuscript.

Competing interests

The authors declare that they have no conflict of interest.

Acknowledgments

This study was conducted under the Northwest Territories Scientific research license #17453, and we thank the Aurora Research Institute in Inuvik, Northwest Territories, for their administrative and logistical support. Many thanks to the staff of the Trail Valley Creek research station for assisting with fieldwork and field logistics.

Funding sources

Funding for this research was provided by the Government of Canada's New Frontiers in Research Fund (NFRFE-2022-00669), Canada Research Chairs Program (CRC-2022-00292), and the Natural Sciences and Engineering Research Council of Canada Discovery Grants Program (RGPIN-2019-06654.) Support is also provided from the Canadian Foundation of Innovation's grant for servers and instruments (#37720 and #36146).

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