~~Multi-year precipitation characteristics based~~ Impact of weather systems on ~~in-situ and remote sensing observations~~ observed precipitation at Ny-Ålesund ~~,~~ (Svalbard)

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Abstract.

~~Accurate precipitation data are essential for understanding the Arctic climate, yet estimates from satellite, re-analysis, or climate models remain uncertain.~~ Ground-based ~~observations, which~~ precipitation observations are sparse in the Arctic ~~, are needed for a better understanding of~~ but are needed to better understand precipitation processes and ~~, as reference points, can help to characterize uncertainties and improve precipitation estimates. We present extended precipitation measurements~~ to provide reference data sets for numerical models and satellite products. This study presents new, temporally highly resolved precipitation measurements from a Pluvio precipitation gauge and a Parsivel disdrometer at the Arctic research station AWIPEV ~~in~~ part of the Ny-Ålesund Research Station, Svalbard. Using the information on the precipitation phase by Parsivel, ~~Svalbard, consisting of a Pluvio precipitation gauge, a Parsiveldisdrometer, and a micro rain radar. Analyzing~~ we also derived a temperature-dependent separation of precipitation into liquid and solid mass. The Pluvio precipitation amount and the Parsivel/temperature-based precipitation type were analyzed for four years of data (August ~~2017–December~~ 2017–December 2021) ~~, we characterized precipitation by amount, type, and frequency and also focused on extreme events. Monthly precipitation at Ny-Ålesund varied widely, from 1 to 155 mm. We also associated the contribution of~~ and related to the presence of synoptic-scale weather systems, i.e., ~~of~~ atmospheric rivers (ARs), cyclones ~~,~~ and fronts, ~~to precipitation amount. Though ARs (separated or co-located with other weather systems) occur~~ detected from ERA5 reanalysis data. ARs occurred only 8% of the time at Ny-Ålesund ~~, 43~~but contributed to about 42% of the total precipitation amount ~~is measured during these events and 22%when only ARs are present. Cyclones contributed 40% (21%) of the total precipitationamount if all (separated)cyclone events are considered. Extreme precipitation events were largely associated with ARs, i.e. in 11 out of 12 cases. Determining precipitation occurrence depends very much on the observation method and the temporal resolution, from 1% (Pluvio at 1-minute resolution) to 21% (micro rain radar) and increased to 38% with daily resolved Pluvio data. Identifying precipitation type solely through Parsivel remains challenging, and a more detailed evaluation using in-situ methods is needed.~~ with a high liquid mass fraction (72%). Cyclones occurred 20% of the time and were associated with 39% of the precipitation, mainly in

solid form (62%). Frontal systems play a minor role in the precipitation amount at Ny-Ålesund. The days with the highest 2% of daily precipitation sums contribute 18% of the total precipitation. All of these extreme precipitation events are related to enhanced water vapor transport, often in the form of ARs and in combination with fronts, and with a high liquid mass fraction. Also, liquid precipitation in winter is mainly connected to ARs. These new measurements will help to better characterize uncertainties in gauge-based precipitation observations and the local variability of precipitation.

1 Introduction

Precipitation is a key climate variable ~~that is~~ crucial to the Arctic climate system. It is an integral part of the hydrological cycle and has a direct impact on the Arctic Ocean and land freshwater budget (e.g. Serreze et al., 1995; Cullather et al., 2000; Prowse et al., 2015; Vihma et al., 2016). In the Arctic, most of the precipitation falls as snow (Bintanja and Andry, 2017), altering the surface albedo (Box et al., 2012; Riihelä et al., 2019) and thus the surface energy budget. Snow also directly contributes to the surface mass balance of the cryosphere~~: e.g.~~. For example, precipitation is the major positive contribution to the mass balance of the Greenland ice sheet (Bring et al., 2016; van den Broeke et al., 2009), as well as to ice caps and glaciers in the Arctic. Snow on sea ice also affects sea ice growth and decay via different snow-sea ice interactions (Serreze and Hurst, 2000).

In the last decades, the Arctic has experienced a rapidly changing climate with a substantial increase in near-surface air temperature, known as Arctic amplification (Serreze and Francis, 2006; Serreze and Barry, 2011; Wendisch et al., 2023). ~~A recent study by Zhou et al. (2024) revealed that the Arctic warming between 1979 and 2001 is three~~ Recent studies have shown that Arctic warming during the last decades was four times higher than ~~the global warming~~ global warming (Zhou et al., 2024; Rantanen et al., 2

. In particular, the Svalbard archipelago is located in the warmest region of the Arctic and ~~reveals~~ has experienced the highest temperature increase (Dahlke and Maturilli, 2017). The potential causes for Arctic amplification are central questions in Arctic research (Wendisch et al., 2023). In this context, various local feedback mechanisms (e.g., albedo, ~~lapse-rate~~lapse rate, water vapor, Planck ~~,~~ and cloud feedback), as well as remote ones (e.g., oceanic heat and meridional heat and moisture transport) are discussed ~~(e.g. Goosse et al., 2018; Pithan and Mauritsen, 2014; Wendisch et al., 2023; Mewes and Jacobi, 2019)~~(e.g., Goosse et al., 2018; Pi

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The increase in Arctic temperature and the associated mechanisms mentioned before also affect the hydrological cycle of the Arctic climate system and, thus, precipitation. ~~For example, climate models~~ Observations (Serreze et al., 2024; Champagne et al., 2024; Ha

, reanalyses and climate models (Serreze et al., 2024; Cai et al., 2024) reveal a substantial increase in precipitation in the Arctic ~~(McCrystall et al., 2021; Bintanja and Andry, 2017; Bintanja et al., 2020) with rain becoming the most dominant precipitation type in future (Bintanja, 2018; Bintanja and Andry, 2017). Recent studies have shown that not only the Arctic mean precipitation will increase in the 21st century but also its interannual variability (Bintanja et al., 2020; Hartmuth et al., 2023). Thus, extreme precipitation is also becoming more likely. The increase in precipitation is likely caused by different reasons, i.e., a higher local moisture supply (Bintanja and Selten, 2014; Kopec et al., 2016), increased poleward transport of atmospheric moisture from lower latitudes (Bengtsson et al., 2011; Bintanja et al., 2020; McCrystall et al., 2021; Pettersen et al., 2022), but also by a stronger radiative loss of energy to space as shown in a recent study by Pithan and Jung (2021).~~

~~Precipitation in Svalbard is highly variable in space and time and strongly influenced by the orography and the large-scale atmospheric circulation and associated transport routes of air masses (Vikhamar-Schuler et al., 2019; Dobler et al., 2020). Highest precipitation amounts are typically found at the windward sides of the western mountainous regions (Vikhamar-Schuler et al., 2019) . Vikhamar-Schuler et al. (2019) analyzed downscaled reanalysis data and found that in these regions, annual mean precipitation is more than 1000 mm per year, while in more sheltered valleys and areas in the central and eastern parts of Svalbard, yearly precipitation amount can be below 400 mm. These regional differences are also reflected in the precipitation gauge time series for different stations in Svalbard. At Longyearbyen airport, the yearly mean precipitation amount is lowest (<200 mm) and about twice as large in Barentsburg and Ny-Ålesund. The different stations show a similar seasonal cycle in precipitation amount with a minimum in late spring/early summer and a maximum in September/October (Hanssen-Bauer et al., 2019; Vikhamar-Schuler . For most stations (including Ny-Ålesund), a second maximum can be seen in March. For all stations in Svalbard, a~~ in the last decades. For example, all precipitation gauges in Svalbard show a positive trend in annual precipitation~~amount has been observed~~, with significant trends for Bjørnøya, Hopen and Ny-Ålesund (Hanssen-Bauer et al., 2019). However, since gauge data in Hanssen-Bauer et al. (2019) have not been corrected for undercatch, trends are also uncertain due to the shift to more liquid precipitation, which is more efficiently collected by precipitation gauges. ~~This issue~~ The significant observed positive trend for Ny-Ålesund has also been ~~raised by Førland and Hanssen-Bauer (2000) and addressed in more detail by Champagne et al. (2024).~~ confirmed by Champagne et al. (2024), who also distinguished between solid and liquid precipitation amounts and applied different correction functions to 12 hourly precipitation gauge data. The authors pointed out that correcting for undercatch is crucial in trend detection since it significantly impacts the trend magnitude, particularly for snowfall and ~~, thus also ,~~ thus also for total precipitation. ~~In addition to~~ Although both solid and liquid precipitation amounts at Ny-Ålesund show positive trends, only the liquid one was found to be significant (independently of the correction method). Also, future projections reveal an increase in Arctic precipitation (Cai et al., 2024; McCrystall et al., 2021; Bintanja and Andry, 2017; Bintanja et al., 20 . And also here, the increasing importance of rain has been demonstrated as it will become the most dominant precipitation type in the future in the Arctic (Dou et al., 2022; Bintanja, 2018; Bintanja and Andry, 2017).

The discrimination of the precipitation phase is thus crucial to accurately describe Arctic precipitation changes. For precipitation gauge measurements, it is critical since correction functions often depend on precipitation type. As direct observations on the precipitation phase are usually not available, temperature is often used as a proxy to differentiate between solid and liquid (Champagne et al., 2024; Kochendorfer et al., 2017; Førland and Hanssen-Bauer, 2000; Kneifel et al., 2022). In this way, precipitation amounts from gauge measurements, for example, can be divided into solid and liquid. For example, Champagne et al. (2024) regarded all precipitation as solid for 2 m temperatures $<1°C$ and as liquid otherwise. In numerical weather prediction and climate models, parameterizations of precipitation processes and thus phase discrimination heavily depend on temperature (e.g., ECMWF, 2016; Seifert and Beheng, 2005). Also, in land surface models, a temperature threshold and/or a temperature range in which both rain and snow occur is often assumed (Jennings et al., 2018; Harpold et al., 2017; Feiccabrino et al., 2015) . However, the assumed temperature dependencies and applied thresholds are very uncertain.

Recent simulation studies have shown that not only the Arctic mean precipitation will increase in the 21st century but also its interannual variability (Bintanja et al., 2020; Hartmuth et al., 2023). Thus, extreme precipitation is also becoming more likely.

The increase in precipitation is caused by different reasons, i.e., a higher local moisture supply (Bintanja and Selten, 2014; Kopec et al., 201 , increased poleward transport of atmospheric moisture from lower latitudes (Bengtsson et al., 2011; Bintanja et al., 2020; McCrystall et al. , but also by a stronger radiative loss of energy to space (Pithan and Jung, 2021). Also, observations have shown an overall observed increase in precipitation amount, an increase in the frequency of extreme precipitation events has been found (e.g., Vikhamar-Schuler et al., 2016; Serreze et al., 2015). Based on precipitation gauge data, Serreze et al. (2015), for example, revealed a significant increase in frequency and intensity for extreme precipitation events at Ny-Ålesund in winter. Vikhamar-Schuler et al. (2016) further showed that the rate occurrence of melt daysin winter in Svalbard and the associated precipitation sums have increased . These rain-on-snow , i.e. days with temperature >0°C, and the accumulated precipitation during these events have increased in Svalbard in winter. Rain-on-snow events, which have implications for the cryosphere, ecosystem , and infrastructure, have also been studied in further detail (e.g., Hansen et al., 2014, 2019; Peeters et al., 2019; Xie et al., 2024). Such extreme winter events are connected to warm and moist air masses being advected and are also related to cyclones whose number has been found to increase in the last decades (Wickström et al., 2020; Rinke et al., 2017). In particular, atmospheric rivers (ARs; Ralph et al., 2020) are an essential mechanism for the poleward transport of moisture (Guan and Waliser, 2015). They can significantly impact the Arctic via enhanced precipitation, concurrent heat advection , and increased longwave downward radiation , and subsequent snow and ice melt (e.g., Mattingly et al., 2018, 2020; Bresson et al., 2022). In a recent study by Lauer et al. (2023), the impact of ARs and associated weather systems on Arctic precipitation has been analyzed in detail. Based on ERA5 reanalysis data, precipitation was attributed to ARs, cyclones , and /or and fronts for two campaign periods in early summer 2017 and early spring 2019. Lauer et al. (2023) found that for the early spring campaign, precipitation was dominated by cyclone-related weather systems, while for the early summer period, both ARs and fronts contributed by 40% and 55%, respectively. Furthermore, Dobler et al. (2020) investigated atmospheric circulation types, their future changes , and their impact on precipitation over Svalbard. Based on future climate projections using a regional climate model, they found a distinct increase in precipitation over Svalbard in the period 2071–2100 compared to 1971–2000. This increase is not related to changes in circulation type frequencies but rather due to changes in atmospheric conditions, in particular particularly during cyclonic circulation patterns.

Even though many studies addressed precipitation in the Arctic and in Svalbard in particular, observing and modeling Arctic precipitation is still very challenging and associated with quite some uncertainties. To gain an Arctic-wide picture of precipitation properties, satellite or model data, i.e., from numerical weather prediction models, reanalyses, or climate simulations, have to be used. However, precipitation is still one of the most uncertain variables in models (Boisvert et al., 2018; Behrangi et . Also, precipitation estimates from satellite measurements are challenging due to uncertainties in retrieval methods, limited observation capabilities close to the surface, and coarse temporal resolution (e.g., von Lerber et al., 2022; Maahn et al., 2014) . Continuous, highly temporally resolved ground-based observations of precipitationare , which are still sparse in the Arctic, are thus necessary to better understand precipitation and precipitation-related processes in the Arctic and serve better and to act as a reference for satellite and model data . In addition to the classical precipitation gauge observations, ground-based remote sensing has been proven beneficial for precipitation observations. In particular, measurements of the micro rain radar have been widely used to analyze precipitation in the polar regions (Maahn and Kollias, 2012; Shates et al., 2021; Schoger et al., 2021).

~~In~~ data set. In this study, we ~~thus~~ therefore present a new ~~comprehensive~~ data set of ground-based precipitation observations at Ny-Ålesund, Svalbard, which includes an OTT Pluvio2L weighing gauge ~~,~~ and an OTT Parsivel2 disdrometer~~and a METEK MRR-2 micro rain radar (MRR)~~. While the Pluvio ~~and the Parsivel provide information on~~ measures surface precipitation amount~~and type, the MRR includes information on the vertical structure of precipitation up to a height of 1 km. These complementary observational records~~ , precipitation type is provided by the Parsivel. Compared to classical manual precipitation gauge data, Pluvio measurements rely on the weighing principle and are available in a high temporal resolution, i.e., 1 min~~, which enables more detailed analyses of precipitation processes, in particular in combination with the further cloud remote sensing instruments at Ny-Ålesund (Chellini et al., 2022). This data set will thus extend and add to the already existing surface precipitation observations in Svalbard, e.g., the long-term precipitation gauge observations of the~~ . The precipitation bucket is combined with a weighing mechanism including a stainless steel load cell and a temperature sensor that accounts for temperature changes. Since the whole bucket is weighed, there are no losses due to wetting of the inner walls. Due to the high temporal sampling, uncertainties due to evaporation are avoided. With a high manufacturer-declared accuracy, i.e., the larger value of 0.01 mm or ±1%, trace precipitation can be in principle better captured. Of course, wind-induced undercatch still affects the measurements as this is the case for all precipitation gauges. While manual 12 hourly precipitation measurements have been performed by the Norwegian Meteorological Institute (MET Norway) with a standard precipitation gauge already since 1975, automatic hourly resolved precipitation measurements with a Geonor T-200 only started in 1997 by MET Norway. However, the recorded Geonor data can not be directly used as more sophisticated data corrections and noise filtering must be applied first (Mareile Wolff, Norwegian Meteorological Institute~~.~~

~~In this paper, we~~ , pers. comm 19 Jan 2025). With the Parsivel precipitation type classification, temperature-independent information on the precipitation phase is now available, further facilitating mass separation into liquid and solid precipitation. In this way, Pluvio and Parsivel complement the existing MET Norway precipitation observations at Ny-Ålesund. This paper will present the results of data from more than four years of ~~data and focus on some general precipitation characteristics at Ny-Ålesund but also on individual precipitation events. We also~~ Pluvio and Parsivel. As previous studies have highlighted the importance of large-scale circulation patterns for precipitation, we link the precipitation amount to specific weather systems on the synoptic scale, i.e., here, ARs, cyclones ~~,~~ and frontal zones ~~,~~ following the methodology by Lauer et al. (2023). In ~~the~~ this paper, we will thus focus on the following research questions:

- Can the Parsivel constrain a temperature-based mass separation of precipitation into solid and liquid precipitation? How do phase occurrence and mass separation depend on temperature?
- How are precipitation amount and type related to large-scale synoptic systems like ARs, cyclones and fronts?
- Which role do these systems play in extreme precipitation events?

In the next section, the different data sets and methods are introduced. In section 3, ~~four main questions are addressed: How much precipitation falls at Ny-Ålesund, and how is it related to the previously mentioned weather systems? What type of precipitation occurs? How often does it precipitate? Here, we will focus mainly on daily and monthly precipitation~~

Figure 1. a) Parsivel ~~,~~ and b) ~~MRR, and c)~~ Pluvio of the University of Cologne at Ny-Ålesund. The Parsivel ~~and MRR are~~ is located on the roof platform of the AWIPEV atmospheric observatory (~~Fig. 1,~~ location A), while Pluvio is installed in the field about 180 m away (~~Fig~~location B). ~~1~~In addition, the MET Norway precipitation gauge (c) located in the center of Ny-Ålesund (location ~~B~~C) is shown. The map of Ny-Ålesund and the map inlet showing the location of Ny-Ålesund in northwestern Svalbard are taken from https://toposvalbard.npolar.no by courtesy of the Norwegian Polar Institute.

~~statistics. In section~~ the performance of the Pluvio and Parsivel measurements is assessed. This includes a comparison of the Pluvio precipitation amount to the MET Norway manual observations (with and without undercatch correction applied) and a discussion on how precipitation type is attributed. Section 4 ~~, individual precipitation events are analyzed in more detail with a focus on extreme events. Conclusions and an outlook~~ deals with the impact of ARs, cyclones and fronts on precipitation at Ny-Ålesund. Conclusions are presented in section 5.

2 Data and methods

The core instruments used in this analysis are a ~~micro rain radar, a Parsivel ,~~ Parsivel and a Pluvio operated ~~of~~ by the University of Cologne within the Transregional Collaborative Research Centre (TR 172) "Arctic Amplification: Climate Relevant Atmospheric and Surface Processes ~~,~~ and Feedback Mechanisms (AC)^3" (http://www.ac3-tr.de; Wendisch et al., 2017). ~~All three~~ The instruments were installed in 2017 at the German-French AWIPEV research base (78.92308°N, 11.92108°E; 11 m above mean sea level; Fig. 1) that is operated jointly by the Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research (AWI) and the French Polar Institute Paul Emile Victor (IPEV) and is part of the Ny-Ålesund Research Station, Svalbard. In this work, the data for the years 2017-2021 is considered. A more detailed description of the instruments and the additional data used in this study is given below. ~~We also present auxiliary information included in the analysis.~~

2.1 Pluvio

The Pluvio2L 400 ~~(in the following Pluvio)~~ manufactured by the OTT Hydromet GmbH is an automated weighing gauge with a collecting area of 400 cm^2. The Pluvio has been installed in the measurement field about 180 m away from the Parsivel ~~and micro rain radar~~ (Fig. 1). Precipitation falling into the bucket is weighed every 6 s. The difference between the ~~current bucket content and the previously recorded one~~ bucket content at time step $t+1$ and at time step t gives the precipitation amount during the integration time. The OTT software provides different outputs in a 1 min resolution. In this study, the ~~so-called~~ non-real-time output of the OTT software is used, which is particularly suited for daily and monthly totals (OTT, 2016b). The non-real-time output is delayed by 5~~minutes~~ min and provides a more precise precipitation sum due to better filtering: fine precipitation is collected over one hour and output after reaching the threshold of 0.05 mm within that hour. There will be no output if the fine precipitation does not reach the threshold within an hour. The resolution of the precipitation values is 0.01 mm. The measurement uncertainty is the larger value of $\pm$0.1 mm or $\pm$1% (OTT, 2016b). The Pluvio data are available from 2 August 2017 onward (Ebell et al., 2023b). The data availability in each month is generally larger than 90% (Fig. A1a). Months with longer data gaps are March and August 2019, July 2019, October and November 2020 ~~,~~ and November 2021. The data gaps are only critical for the monthly precipitation sums of March and July 2019 and October 2020 since significant precipitation has been reported by the ~~micro rain radar and/or the~~ MET Norway precipitation data during the missing periods. Thus, the yearly precipitation sums for 2019 and 2020 are most likely underestimated.

The Pluvio data used in this work were filtered according to the instrument status provided by the OTT software. The software indicates if the instrument ~~runs properly~~ operates correctly or if an event associated with a "warning" or an "alarm" occurred. All times where the instrument status is associated with an alarm, i.e., an unstable or incorrect weight measurement, have been excluded from the analysis.

Uncertainties in the precipitation amount also arise due to an undercatch of precipitation, particularly of solid precipitation and when wind speed is high. Also, blowing snow can affect the measurements. To reduce this uncertainty, the Pluvio is surrounded by a single Alter wind shield, which has been shown to substantially improve the detection of precipitation and reduce the undercatch of precipitation (Nitu et al., 2018): within the WMO Solid Precipitation Intercomparison Experiment (SPICE) project it has been found that overall a shielded gauge improved the catch efficiency by 0.1 to 0.2 compared to an unshielded gauge. We also applied an empirical correction function by Wolff et al. (2015) to the ~~1-minute~~ 1 min precipitation data to ~~further consider~~ correct for wind-induced precipitation losses. This correction function has been developed based on gauge measurements in southern Norway and depends on temperature and wind speed at gauge height (see Eq. 12 in Wolff et al., 2015). The advantage of this correction function is that it can be directly applied to the total precipitation amount and does not require a mass separation of the precipitation into liquid and solid first. As this paper does not focus on evaluating correction functions, we made a choice here but want to point out that the estimated undercatch strongly depends on the chosen correction function (Champagne et al., 2024).

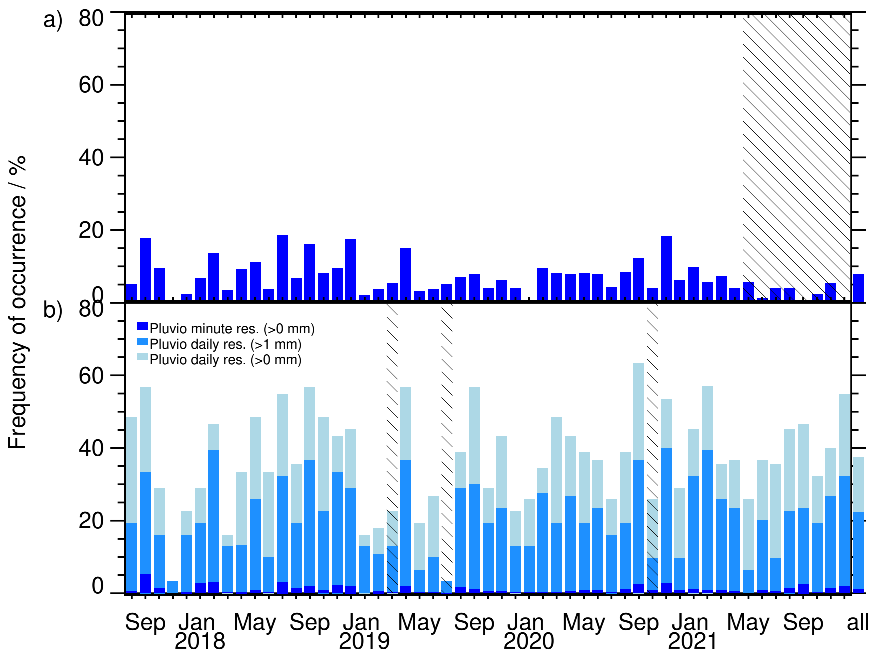

Figure 2. Monthly frequency of precipitation occurrence for a) Parsivel and b) Pluvio. The monthly values have been calculated from the 1 min resolved data (dark blue in all panels). For Pluvio, monthly precipitation occurrence has also been calculated based on daily precipitation amounts >1 mm (medium blue) and >0 mm (light blue), respectively. Hatched areas indicate months when the monthly values are unknown/unreliable due to missing measurements. The last column shows the frequency of precipitation occurrence for the whole time period considered (1 August 2017 – 31 December 2021

Fig. 2b shows the frequency of detected precipitation by Pluvio. Using the 1 min resolved Pluvio time series results in monthly precipitation frequencies of up to 5% only and in all-time average values of 1%. Using daily accumulated Pluvio data increases the monthly precipitation frequency to 4%–63% and, if a threshold of 1 mm is applied, to 4%–46%.

2.2 Parsivel

The OTT present weather sensor Parsivel^2 ~~(in the following Parsivel)~~ is an optical laser disdrometer. It provides information on fall speed, size ~~,~~ and type of precipitating particles in 1 min temporal resolution. The Parsivel consists of two sensor heads with a 30 mm wide, 180 mm long ~~,~~ and 1 mm high laser light strip in-between (OTT, 2016a). The output voltage of the Parsivel is reduced when a precipitation particle falls through the laser beam. The reduction of output voltage is proportional to the particle size. The particle speed is determined by the duration of the voltage signal, i.e., the time the particle needs to enter and leave the laser beam. Measurable size ranges are between 0.2 mm and 8 mm for liquid precipitation and between 0.2 and 25 mm for solid precipitation, with 32 size classes in total. Measured fall speeds are in the range of 0.2 $\mathrm{ms^{-1}}$ and 20 $\mathrm{ms^{-1}}$ with 32 particle speed classes. The OTT Parsivel software also retrieves the type of precipitation particles, namely "drizzle", "drizzle with rain", "rain", "rain~~, ~~/drizzle with snow", snow", "snow grains", "~~soft hail~~graupel" ~~, ~~and "hail". The actual retrieval of the precipitation type is proprietary, but in principle, it relies on the fact that different particle types have different fall speed-size relationships. OTT reports that the differentiation of the precipitation types drizzle, rain, hail ~~, ~~and snow corresponds to the observations of a weather observer in more than 97% of the cases (OTT, 2016a).

At AWIPEV, the Parsivel has been installed on the western roof platform of the atmospheric observatory (Fig. 1). Data are available since 29 April 2017 (Ebell et al., 2023a). Until May 2021, data coverage is generally ~~quite ~~high (Fig. A1b). From June 2021 onward, longer measurement gaps occurred ~~, ~~and the OTT Parsivel software quality flag often indicated problems with the glass cover/laser. This was related to humidity condensing inside the instrument. Opening and drying the instrument helped in the short term. Still, the problem re-emerged~~such that valid measurements are only available to a very limited extent~~, such that the number of valid Parsivel measurements was strongly reduced until the end of 2021. ~~Only ~~In this study, only data for which the quality flag indicated reliable measurements were used. In June 2022, this instrument has been replaced by a new Parsivel.

2.3 ~~MRR~~

~~The Micro Rain Radar (MRR; type MRR2), manufactured by Meteorologische Messtechnik GmbH (Metek), is a vertically pointing frequency modulated continuous wave (FM-CW) Doppler radar operating at 24.1 GHz (K band). It was installed at Ny-Ålesund at the end of April ~~Compared to the 1 min resolved Pluvio measurements, the precipitation signal occurrence is much higher for Parsivel (Fig. 2). For the whole period (August 2017 ~~next to the Parsivel on the roof platform of the AWIPEV atmospheric observatory (Fig. 1), with data being available since 28 April 2017 (Ebell et al., 2023c). The MRR measures the backscattered signal by falling hydrometeors at 32 range gates. At Ny-Ålesund, the vertical resolution was set to 30 m. Measurements are reported for the height levels (indicating the lower boundary of the radar bin) from 30 m to 930 m.It should be highlighted that the lowest 2-3 radar bins are affected by near-field effects and also the uppermost radar bin is very noisy. Data at these heights should thus not be used. The temporal resolution of the final data products is 60 s. In the standard data processing of the Metek software, the particle size distribution $N(D)$ is calculated from the spectral reflectivity density with respect to velocity, namely the Doppler spectrum, using an idealized size-fall velocity relation $v(D)$ for rain by Atlas et al. (1973) and Mie theory (Peters et al., 2002; Maahn and Kollias, 2012). Combining $N(D)$ with $v(D)$ and integration over the drop size distribution results in the rain rate and integration over $N(D)$ in the radar reflectivity factor Z. While this method works very well for liquid precipitation, it is unsuitable for snow (Maahn and Kollias, 2012; Kneifel et al., 2011), which often occurs at Ny-Ålesund. Thus, we used the Improved MRR Processing Tool (IMProToo) by Maahn and Kollias (2012), which includes an improved sensitivity, a correction for aliased data, and reliable values of equivalent radar reflectivity Z_e, Doppler velocity, and spectral width. From this point forward, when mentioning reflectivity, we will be referring specifically to the equivalent radar reflectivity factor Z_e. In contrast to the Metek processing, the radar moments are directly calculated from the radar Doppler spectrum. To retrieve a quantitative estimate of precipitation from the MRR, Z_e–S or Z_e– R relations for snowfall S and rain rate R could be applied. However, this involves prior knowledge of the precipitation phase to decide if S or R must be~~

retrieved. Also the choice of a Z_e–$S(R)$ relation introduces further uncertainties in the snow- and rainfall amount. Since this study focuses not on the evaluation of S and R from MRR (see e.g., Schoger et al., 2021), we only make use of the MRR radar reflectivity as the primary measurement of the instrument for the detection and vertical structure of precipitation. The absolute calibration of the MRR was evaluated with details given in Appendix **??**. We found that the instrument systematically underestimates reflectivity by 0.6 dB. However, this calibration offset is not applied to the data as it is within the instrument uncertainty. The MRR is very robust in operation (Fig. A1c) with a 100% data coverage in most of the months. – December 2021), it is 8% (compared to the 1% of Pluvio). This is due to the fact that the Parsivel already detects a few precipitating particles whose mass might not be large enough to be measured by the Pluvio.

2.3 Additional observational data sets

For the analysis of precipitation type and the correction of precipitation undercatch, we also use the 2 m temperature (T_{2m}) and 2 m wind speed measured as part of the Baseline Surface Radiation Network (BSRN) station at Ny-Ålesund (Maturilli, 2020). The data is provided in 1 min resolution. In general, daily mean T_{2m} values are above 0°C in summer and to most extent in from September and rarely exceed 10°C (Fig. A2). The lowest temperatures are found in March. This is in line with the long-term observations at Ny-Ålesund (Dahlke et al., 2020; Maturilli et al., 2013). Fig. A2 also reveals a large variability of daily mean T_{2m} in the cold season with even positive values in winter, indicating the potential for liquid precipitation.

Furthermore, we use the daily precipitation sums provided by the Norwegian Meteorological Institute (MET Norway, https://seklima.met.no) performed manually with an used precipitation measurements taken with the old Norwegian precipitation gauge with a windshield of MET Norway located in the center of the village of Ny-Ålesund and thus about 300290 m away from the Pluvio (Fig. 1). In particular, we use the data set published by Jacobi and Champagne (2024), which includes the original 12-h precipitation sums of MET Norway always reported at 06 and 18 UTC and corrected precipitation sums based on different correction methods as described in Champagne et al. (2024). The corrections applied include corrections due to wetting and evaporation losses within the 12 h period, i.e., constant values of 0.075 mm for rain and 0.05 mm for snow, as well as losses due to aerodynamic effects. To correct for the latter, six different correction functions have been applied by Champagne et al. (2024). Two of the corrections (Adam and Lettenmaier, 2003; Kochendorfer et al., 2017) are only valid for snow. The proposed corrections by Hanssen-Bauer et al. (1996) and Førland et al. (1996) have separate correction functions for solid and liquid precipitation. Thus, the total precipitation that the MET Norway gauge has measured had to be separated into a liquid and solid component first. Champagne et al. (2024) used here the 12 hourly average temperature and a corresponding snow-to-total precipitation ratio that has been derived from hourly temperature data and assuming that all precipitation is solid for temperatures lower than 1°C and liquid for temperatures equal or larger than 1°C. This allocation of liquid and solid precipitation is not needed for the correction functions by Wolff et al. (2015) and Kochendorfer et al. (2017) which have been applied as well to the total precipitation sums. All correction functions use temperature (except for the correction functions for solid only) and wind speed information, typically at gauge height. Some correction functions also have an additional version that uses wind speed at 10 m height. In the present study, we use the original (uncorrected) MET Norway data, as well as the corrected precipitation values based on the ensemble mean of all corrections analyzed in Champagne et al. (2024), which is also provided in the data set by Jacobi and Champagne (2024). ~~The measurements are quality controlled but not corrected for undercatch (Hildegunn D. Nygård, Norwegian Meteorological Institute, pers. comm 11 May 2023). Daily precipitation totals are always valid for 0600 UTC to 0600 UTC the next day, with the time stamp indicating the end of the measurement period.~~

2.4 Atmospheric river, cyclone and front detection

To associate precipitation to synoptic scale weather events, we analyzed ERA5 reanalysis (Hersbach et al., 2020) data as in Lauer et al. (2023) from 1 August 2017 to 31 December 2021. To this end, ARs, cyclones ~~, and fronts~~ (CYs) and fronts (FRs) were detected north of 60°N. The details of the weather event detection methods are provided in Lauer et al. (2023) ~~,~~ and we give only a summary here. The AR detection algorithm applied is the second version (Guan et al., 2018) of the original method by Guan and Waliser (2015)~~(Guan et al., 2018)~~. It is based on thresholds in integrated water vapor transport (IVT) and its geometry. The IVT must exceed the monthly 85th percentile of IVT that has been calculated for each grid cell based on ERA5 data from 1979-2020. Also the lower limit of 50 $\mathrm{kg\,m^{-1}\,s^{-1}}$ must be exceeded. In addition, the IVT direction has to be along the detected AR axis within 45°. The length of the AR has to be larger than 2000 km and the length-to-width ratio needs to be higher than two. If the direction and geometric criteria are not fulfilled, the same checks are repeated for the 87.5th percentile. If the direction and geometric criteria are still not fulfilled, checks are repeated for the 90th, 92.5th and 95th percentiles, respectively. An example of a detected AR on 13 Jan 2018 is shown in Fig. 3. Cyclones are detected based on mean sea level pressure (MSLP) following Sprenger et al. (2017) who ~~use~~ used a refined version of Wernli and Schwierz (2006). In principle, grid points with a minimum in MSLP are detected and for every local MSLP minimum, the outermost closed MSLP contour is determined. Cyclones that occur over regions with surface elevations higher than 1500 m are excluded. Finally, frontal systems are calculated from a threshold in the horizontal gradient of equivalent potential temperature ~~(Jenkner et al., 2010; Schemm et al., 2015).~~ at 700 hPa, i.e., 4 K 100 $\mathrm{km^{-1}}$ (Jenkner et al., 2010; Schemm et al., 2015). Precipitation occurring within a distance of up to 200 km of the frontal line is assumed to be associated with the front.

Each reanalysis data grid point (0.25° x 0.25° resolution) is thus classified in terms of the (non-)occurrence of an AR, cyclone (CY) ~~, and /or~~ and front (FR). Like the reanalysis data, this weather system classification data set has an hourly temporal resolution. A weather event is then detected for Ny-Ålesund if the grid box in which Ny-Ålesund is located is part of the region of the weather event. In total, seven different combinations are thus possible: The weather systems can occur separately, i.e., only ARs (O-AR~~, O-FR,~~), only CYs (O-CY) and only fronts (O-FR), or simultaneously in different combinations (AR-FR, AR-CY, AR-CY-FR, CY-FR). ~~For one case study (section 4), we also looked at the temporal development of the different measurements at Ny-Ålesund and also incorporated the integrated water vapor (IWV) from the microwave radiometer HATPRO having a temporal resolution of about 2-3 s (Rose et al., 2005; Nomokonova et al., 2019; Nomokonova et al., 2019).~~

3 ~~General precipitation characteristics~~

~~First, we~~

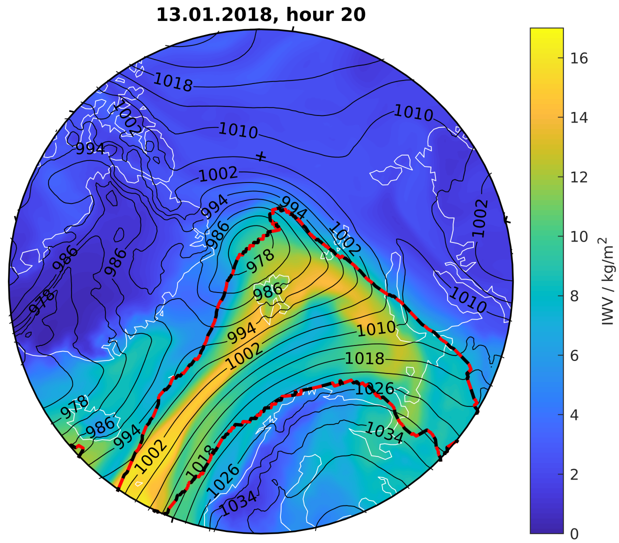

Figure 3. Integrated water vapor (IWV, in kg m^{-2}; colors) and mean sea level pressure (in hPa; black contours) on 13 January 2018 at 20 UTC from the ERA5 reanalysis. The dashed black-red line indicates the boundaries of the detected atmospheric river.

3 Instrument and method assessment

Before we analyze the impact of different weather systems on precipitation at Ny-Ålesund, we first look at the ~~general precipitation characteristics from Pluvio , Parsivel, and MRR, i.e., precipitation amount, frequency, and type for the period from August 2017 to December 2021, with a focus on monthly statistics. We also relate precipitation amounts to the presence of ARs, CYs, and FRs~~performance of Pluvio and Parsivel. For Pluvio, we can compare the measurements to the MET Norway precipitation data (sec.3.1). The Parsivel measurements are indirectly assessed by relating them to the observed temperature and wind speed (sec. 3.2). Based on these findings, a new separation of precipitation mass into liquid and solid precipitation is proposed.

3.1 Precipitation amount from different sensors and correction methods

Figure 4 depicts the monthly precipitation amount of the uncorrected Pluvio data, the corrected Pluvio data following Wolff et al. (2015) ~~,~~ and the MET Norway uncorrected and ensemble-mean corrected precipitation sums. Monthly ~~precipitation sums~~ corrected precipitation sums from Pluvio show a large variability ranging from 1 mm (October 2017) to 155 mm (September 2017). There is no apparent seasonality in precipitation amount from this relatively short period. Other studies with long-term precipitation measurements have found a seasonal cycle in precipitation amount at different stations in Svalbard with a minimum in late spring/early summer and a maximum in September/October (Hanssen-Bauer et al., 2019; Vikhamar-Schuler et al., 2016) . For most stations (including Ny-Ålesund), also a second maximum in March is typical.

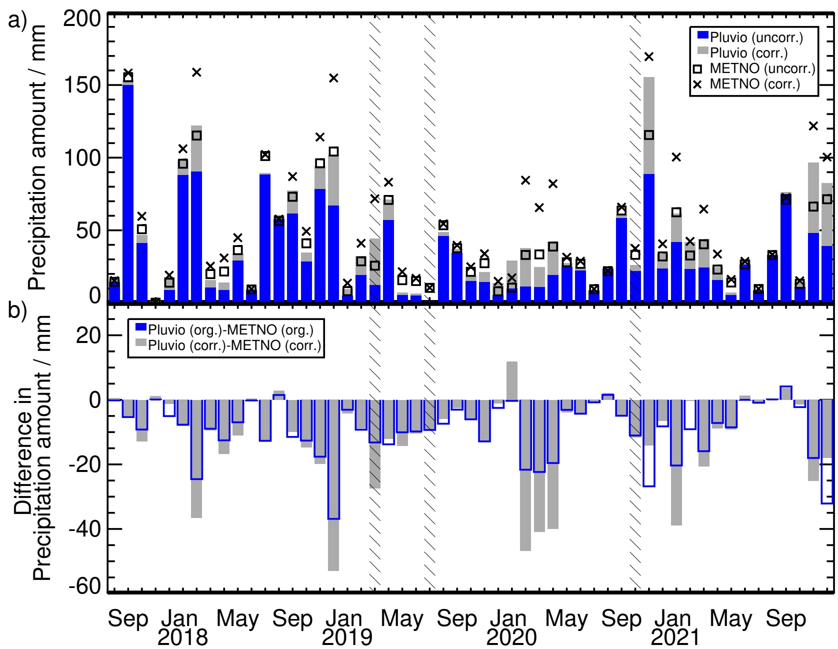

Figure 4. a) Monthly precipitation amount (in mm) from Pluvio based on the uncorrected (blue) and ~~undercatch~~ corrected ~~(see text)~~ data following Wolff et al. (2015) (gray)~~as well as from MET Norway rain gauge~~. The uncorrected (squares) and the ensemble-mean corrected (x symbols) precipitation measurements of the MET Norway precipitation gauge from Champagne et al. (2024) are shown as well. Hatched areas indicate months for which the monthly precipitation sums from Pluvio are underestimated due to measurement gaps. b) Differences in monthly precipitation amount between Pluvio and MET Norway for uncorrected (blue) and corrected values (gray).

Table 1. Annual precipitation amount (in mm) of the uncorrected and corrected Pluvio and MET Norway ~~rain~~ precipitation gauge data. For the corrected MET Norway data, the results of the ensemble mean of all corrections of Champagne et al. (2024) are shown.

	2018	2019	2020	2021
Pluvio uncorr.	~~618~~ 619	~~220*~~ 222*	325*	~~330~~ 353
Pluvio corr.	752	311*	495*	520
MET Norway uncorr.	~~749~~ 770	~~313~~ 322	~~434~~ 446	~~453~~ 464
MET Norway corr. (ensemble mean)	941	426	655	639

* underestimated due to measurement gaps

Considering effects due to wind-induced undercatch adds 0.5% to ~~442~~257% to the uncorrected monthly ~~value~~values of Pluvio. In absolute terms, the largest correction is found for November 2020 with an additional ~~66~~67 mm. The large variability in monthly precipitation sums is also reflected in the large range of yearly precipitation sums (Table ~~??).~~ 1). With 752 mm of precipitation, 2018 was a very wet year~~(750 mm)~~. The MET Norway time series since 1975 (not shown) reveals that 2018 was even a record year with the largest annual precipitation amount, while the long-term annual average of the manual (uncorrected) precipitation measurements is 436 mm. In contrast, 2019 was a relatively dry year with a corrected Pluvio precipitation amount of about ~~300~~311 mm (Table ~~??~~1). As mentioned before, the estimates of annual precipitation amounts from Pluvio are likely underestimated for 2019 and 2020 due to measurement gaps during some precipitation periods. However, the MET Norway data also indicate a relatively low annual precipitation amount for 2019. ~~The values of monthly precipitation amount derived from Pluvio agree reasonably well with the manual MET Norway observations.However,a direct comparison is difficult due to the different measurement systems, locations, and thus, different wind conditions having a different impact on precipitation undercatch. For some months, the (uncorrected) MET Norway measurements show even higher values than the corrected ones from Pluvio . A detailed comparison of the instruments would also require a precipitation correction of~~

When comparing the monthly and yearly precipitation sums of the Pluvio to the MET Norway precipitation measurements, we find quite some differences for both the corrected and uncorrected values (Figs. 4,A3, Table 1). For most of the months, Pluvio has smaller precipitation amounts. For the uncorrected monthly data, this results in a bias of -9.4 mm and a standard deviation of 9.1 mm (Fig. A3a). The negative bias is also reflected in the uncorrected daily precipitation sums with a corresponding value of -0.3 mm and a standard deviation of 1.1 mm (Fig. A3c). When comparing the corrected data, i.e. the Wolff et al. (2015) correction for the Pluvio data and the ensemble mean correction from (Champagne et al., 2024) for the MET Norway data, differences are even larger (Figs. 4,A3). These differences accumulate to a difference in the yearly corrected precipitation sums of 189 mm (2018) and 119 mm (2021). Several reasons likely contribute to the differences between the different data sets. For the ~~MET Norway time series, which is not the scope of this paper. However, Jacobi et al. (2019)~~ uncorrected data, the smaller precipitation sums of Pluvio hint at a stronger wind-induced loss at the location of the Pluvio. Due to the surrounding buildings, the MET Norway precipitation gauge seems more shielded and less exposed to wind effects than the Pluvio. However, even the corrected monthly Pluvio values are in some months smaller than the uncorrected MET Norway gauge data. This means that, most likely, the Wolff et al. (2015) correction still underestimates the wind-induced precipitation loss. The combined impact of the chosen correction function and the way it has been applied (i.e., 12 hourly vs. 1 min resolved data, assumed liquid/solid mass separation in Champagne et al. (2024)) can be seen from the difference between the gray and blue bars in Fig. 4b. Of course, different correction functions result in different precipitation amounts, but the temporal resolution of the data also plays a role. Jacobi et al. (2019), for example, have compared the manual MET Norway precipitation observations, the Pluvio measurements ~~as well as~~ and the automatic precipitation measurements of ~~a Geonor T-200 weighing gauge (also operated by MET Norway)~~ the Geonor for a full hydrological year (Sep 2017–Sep 2018) at Ny-Ålesund and also took different correction methods and temporal resolutions into account. The Geonor is located in the same field as the Pluvio, about ~~100~~140 m apart. ~~An excellent agreement between Pluvio and Geonor annual precipitation sums had been found, while the manual precipitation observations revealed much higher values for both uncorrected and corrected data. The same tendency can also be seen in the present study, which underlines the challenge of precipitation correction and its uncertainty.~~

~~Moving to shorter temporal scales, we also analyzed daily precipitation sums of the corrected Pluvio data (Fig. ??). 50% of the daily precipitation sums have values lower than 1.3 mm (gray line in Fig. ??) and contribute only about 5% to~~

the total precipitation at Ny-Ålesund (black line in Fig. ??). Very small precipitation amounts or trace precipitation, i.e., small but immeasurable daily precipitation events, are still challenging for observations and models. Boisvert et al. (2018) , who defined trace precipitation as days with less than 1 mmprecipitation, showed large differences in the occurrence and annual amount of trace precipitation over the Arctic Ocean between eight reanalyses. At Ny-Ålesund, trace precipitation (i.e., non-zero daily precipitation amount < 1 mm) is reported from the corrected Pluvio data for about 44% of the analyzed period. Trace precipitation is thus a common feature of the atmospheric state at Ny-Ålesund. The annual trace precipitationamounts for the years 2018-2021 are between 20 to 30 mm. Compared to the annual precipitation amount, these values are rather small. E.g. for 2021, the annual trace precipitation amount is 5.5% of the total precipitation amount at Ny-Ålesund. In particular, in other dry Arctic regions, trace precipitation can make up a substantial proportion of the total precipitation amount (Boisvert et al., 2018). Trace precipitation could be associated with the frequent occurrence of low-level mixed-phase clouds in conjunction with katabatic winds (Gierens et al., 2020), with the dry katabatic flow leading to the sublimation of a large portion of the precipitating mass. Only 5% of the days with precipitation measured by Pluvio have a daily precipitation amount larger than 13.3 mm. These 5% of precipitation days contribute about 45% to the total precipitation at Ny-ÅlesundJacobi et al. (2019) showed that the correction was higher for the daily resolved data. For example, using Pluvio hourly and daily data and applying the Wolff et al. (2015) correction resulted in 673 mm and 731 mm, respectively. They concluded that this is mainly due to a larger correction of solid precipitation. Also, in their study, the yearly precipitation sums of both Pluvio and Geonor were lower than the manual MET Norway measurements. However, an excellent agreement between Pluvio and Geonor annual precipitation sums had been found, giving trust in the Pluvio measurements. For the following analyses, we stick to the corrected Pluvio data using the Wolff et al. (2015) method. However, we are aware that in the future, a more detailed analysis of correction functions is needed to find an optimal correction function for the Pluvio at this location.

Cumulative relative occurrence of daily precipitation sums (grey) and cumulative relative contribution of daily precipitation sums to total precipitation amount (black) based on the corrected Pluvio data for the time period 1 August 2017 to 31 December 2021. The inlet is a zoom-in for daily precipitation sums below 10 mm.

As discussed earlier, large-scale weather patterns substantially impact Arctic precipitation . We thus related the measured precipitation amount by Pluvio with the presence of ARs, cyclones, and fronts. Fig. ?? depicts the monthly occurrence of these weather systems based on the methodology by Lauer et al. (2023) and the corrected precipitation amount from Pluvio associated with these. ARs (separated and co-located) typically occur less than 15% of the time in a month. A higher occurrence has been found for Sep 2017 (49%) and July 2018 (37%). Front occurrence (separated and co-located) shows yearly maxima of more than 20% in summer or late summer, which might be related to

3.2 Precipitation type attribution

The Pluvio provides precipitation amount but the question of how much of the differential heating of the Arctic Ocean and the snow-free land as well as coastal orography which supports baroclinicity (Serreze and Barry, 2014). Separated and co-located cyclones occur all year long with a mean value of 20%. When looking at the contribution of these weather systems to the monthly precipitation amount (mass is solid and how much is liquid remains. Here, the Parsivel can provide independent information and help to constrain a temperature-based mass separation which is useful for cases when no Parsivel measurements are available. To analyze this in more detail, we focused on the period from August 2017 to December 2020, i.e., the period when the data coverage of Parsivel is very good (see Fig. ??b,c), we find that the largest contributions are from the AR and cyclone classes. In particular, in the very wet month Sep 2017, almost all precipitation, i.e., 145 mm, can be related to the (co-)occurrence of ARs. For the month with the highest precipitation amount, i.e., November 2020, both AR and cyclone classes contribute together to about 80% of the total precipitation amount, with the only-cyclone class even dominating. The monthly precipitation amount from fronts (separated and co-located) is, on average, less than 9 mm and shows a distinct contribution to monthly precipitation in only a few months, e.g., August 2020 (O-FR: 35%). Quite some precipitation cannot be attributed to any of these weather patterns with a mean monthly value of 33%. This residual is generally larger from early autumn to early spring. The annual and whole-time statistics (Table ??) show that separated ARs (O-AR) and cyclones (O-CY) each contribute about 20% to the total precipitation with quite some variability from year to year. E.g., in 2018, O-ARs (co-located ARs) contributed almost 30% (49%). Fronts only seem to play a minor role in the precipitation amount at Ny-Ålesund: separated fronts contribute only about 4% to the total precipitation. Only in combination with ARs and cyclones the value increases to 20%.

a) Relative monthly occurrence (in %) of weather systems at Ny-Ålesund. Atmospheric rivers (AR), cyclones (CY), or fronts (FR) can be separated (only O) or co-located. Monthly precipitation amount associated with different weather types in b) absolute and c) relative values with respect to the total monthly precipitation amount. Precipitation, which is not associated with any of these weather types, is denoted as "residual". Note that the different classes are stacked in the plots.

Contribution of atmospheric rivers (AR), cyclones (CY), and fronts (FR) to the precipitation amount (in %) of the different years and of the whole time period considered (1 August 2017 - 31 December 2021). Weather systems can be separated (only, O) or co-located. 2018 2019 2020 2021 whole timeO-AR 29 24 11 15 22 AR-FR 7 2 6 3 6 AR-CA 8 5 9 5 8 AR-CY-FR 5 9 8 2 6 O-CY 18 26 26 24 21 CY-FR 3 3 4 6 4 O-FR 3 4 5 5 4 residual 27 27 30 40 29

3.3 Precipitation type

Information on surface precipitation type is provided by the Parsivel. In this study, the Parsivel types A1b). We took all corrected 1 min resolved Pluvio precipitation values larger than 0 mm into account, for which also the Parsivel had detected a precipitation signal within ±10 min. The Pluvio precipitation signal was then declared as solid if the classes "snow", "snow grains", "soft hailgraupel" and "hail" are summarized in a "solid were the dominating precipitation types within the ±10 min interval. We included "precipitation class , graupel" and the types "hail" in the solid class even though the microphysical processes might be quite different in these cases. However, the occurrence of these two classes is very low (<1.9% for graupel and <0.001% for hail) and does not impact the key findings. If the liquid Parsivel classes "drizzle", "drizzle with rain", and or "rain" in the "liquid " precipitationclass. was dominating, the Pluvio precipitation amount was associated with liquid precipitation. In a few cases (0.7% of all cases), mixed-phase precipitation ("Rainrain, drizzle with snow"is the only Parsivel class that is of "mixed"-phase precipitation. In fact, this "mixed"-phase class occurs very rarely with a mean monthly occurrence of 0.12% only and a maximum occurrence of 1.5% in Sep 2017. Before discussing the precipitation type occurrence in more detail, we will first have a closer look at the Parsivel performance. Since no reference data for precipitationtype is available, we have combined the Parsivel with the 2 m temperature measurements to check for consistency of the retrieved precipitation type and plotted the) was dominating the Parsivel signal. Here, half of the Pluvio precipitation amount was attributed to solid and half to liquid precipitation. However, since these cases contribute only 0.7% to the total precipitation amount they do not significantly affect the results.

The occurrence of liquid , solid, and mixed precipitation from Parsivel data and solid precipitation was then analyzed as a function of 2 m temperature T_{2m} using the 1 min resolved data (Fig. ??). This makes sense since temperature is often used as a proxy for the discrimination of solid and liquid precipitation (Champagne et al., 2024; Kneifel et al., 2022). Fig. ?? shows that the transition between solid to liquid precipitation occurs between 0°C to 3°C with an equal occurrence of solid and liquid precipitation around 2°C. When using all Parsivel data 5a). When taking all cases into account (dotted lines in Fig. ??5a), liquid precipitation is detected by Parsivel even for temperatures far below 0°C and solid precipitation even for temperatures larger than 5°C. Wind and turbulence can affect the particle velocity when passing through the Parsivel laser beam such that the measured velocity does not correspond to the true fall speed of the precipitation particles. Subsequently, this effect will result in a misclassification of the measured particles. Filtering the data by removing cases with 2m 2 m wind speeds larger than 5 ms^{-1} (solid lines in Fig. ??5a) results in a smoother transition from solid to liquid precipitation removing liquid occurrence at very low temperatures and almost all solid precipitation at temperatures larger than 3°C. Even after filtering, the Parsivel data shows an unexpectedly higher liquid occurrence around -3 to -2°C. Looking at these cases in more detail reveals that all these situations are occur during periods when solid precipitation only has been detected by Parsivel as well in other minutes (not shown). Detected particle sizes during these cold "liquid" events are relatively small, with a mean volume equivalent diameter of 1.3 mm only. A possible temperature inversion resulting in positive temperatures in upper height levels could be excluded from radiosonde profiles. We also checked similar cases for more recent dates for which measurements by a video-in video in situ snowfall sensor (VISSS; Maahn et al., 2024) at Ny-Ålesund are available. The VISSS has been was installed at Ny-Ålesund in September 2021 and is operated in the measurement field about 140 m northwest of Pluvio. Visual inspection of the pictures of the particles taken by VISSS for a case on 5 May 2023 clearly showed that only solid precipitation was present (Max Maximilian Maahn, University of Leipzig, pers. comm personal communication 25 August 2023). We thus assume that the Parsivel algorithm falsely classifies the signal as "rain" or "drizzle" for this temperature regime. Interestingly, in this temperature regime, Interestingly, Chellini et al. (2022, 2023) found that low-level mixed-phase clouds at Ny-Ålesund produce small fast-falling ice particles in this temperature regime, which could potentially be misinterpreted as drizzleby Parsivel . The detected Parsivel particle sizes are relatively small during these cold "liquid" events, with a mean volume equivalent diameter of 1.3 mm only. We thus assume that the Parsivel algorithm falsely classifies these smaller solid particles in this temperature regime as "rain" or "drizzle".

According to the discussion of the previous paragraph, we refined the precipitation classification for the following analyses: precipitation is assumed to be purely solid for $T_{2m} <$ -2The transition temperature regime, where both liquid and solid occur, is roughly between 1 °C and purely liquid for $T_{2m} >$ 43 °C . For -2°C $\leq T_{2m} \leq$ 4°C, we use the Parsivel information even though we can not rule out completely wind effects and uncertainties due to the OTT classification algorithm. In (see Fig. 5b). If we

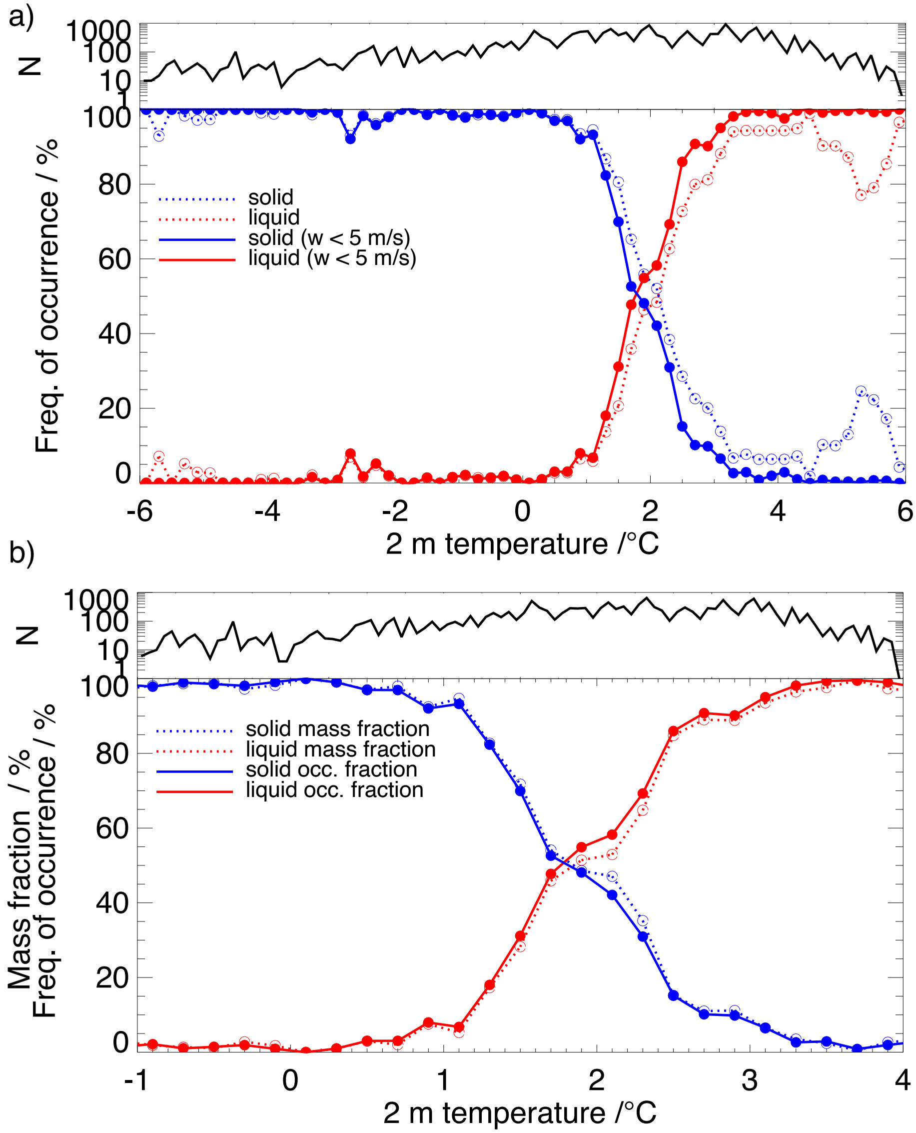

Figure 5. a) Frequency of occurrence of solid (blue) and liquid (red) precipitation as a function of 2 m temperature. Solid and liquid precipitation was determined from the Parsivel measurements at all times when the Pluvio detected a measurement signal for the period August 2017 to December 2020. See also sec. 3.2 for more details. Note that liquid and solid precipitation can occur at the same time such that the sum of liquid and solid occurrence can be >100%. Temperature bin size is 0.2°C, e.g., [0.2,0.4), [0.4,0.6), etc., with N the number of cases within a temperature class. Results for all cases (dotted lines) and cases with 2 m wind speeds w <5 ms^{-1} only (solid lines) are shown. b) Zoom into the temperature range of -1°C and 4°C. The solid (blue) and liquid (red) occurrence fractions for cases with 2 m wind speeds w <5 ms^{-1} are shown (solid lines). The dotted lines indicate the corresponding mass fractions as a function of temperature. See also Table 2.

look at the solid and liquid mass fractions (dotted lines in Fig. ??, the fraction of monthly precipitation occurrence being solid, liquid and mixed-phase with respect to all cases with a precipitation signal from Parsivel is shown. Typically, solid precipitation dominates from October to May and liquid precipitation from June to September, with May/June and October/November being the transition months. January and November 2018 reveal an exceptionally high fraction of liquid precipitation 5b), we find that the temperature dependency of the mass separation follows the phase occurrence frequency. This shows that the occurrence of 50% which is connected to positive temperatures on a few days in these months.

In section 3.1, the total monthly and yearly precipitation amount has been discussed, but the question remains: how much solid (liquid) precipitation at a specific temperature can also be used as a proxy for the separation into the corresponding mass. At about 1.8 °C, half of the precipitation amount can be attributed to solid , liquid, or mixed precipitation ? We thus combined the Pluvio, Parsivel, and temperature information to allocate the precipitation amount to a precipitation phase. Also, here, mass is solid and half is liquid.

To split precipitation into solid and liquid for the whole period August 2017 to December 2021, we applied a combined Parsivel/temperature-based mass separation (TMS) method: for temperatures <0.2°C, we assume all precipitation to be solid. All precipitation is assumed to be purely solid for $T_{2m} < -2$liquid for temperatures ≥3.6°C and purely liquid for $T_{2m} > 4$°C. For -2°C ≤ T_{2m} ≤ 4°Cthe temperature range in-between, we check the Parsivel classification within a time window of first if Parsivel detected precipitation within ±10 min . This is reasonable since the instruments are not located directly next to each other. If only solid (liquid) precipitation has been detected within this time interval, the and if wind speeds are <5 ms^{-1}. If this is the case, we use the Parsivel classification, as explained earlier, to discriminate between liquid and solid and attribute the precipitation mass correspondingly. If precipitation phase information is not available from Parsivel due to missing or erroneous Parsivel data (in particular in 2021; cf. Fig. A1b), due to no detected precipitation amount is assumed to be solid (liquid). If both phases have been detected by Parsivel, or due to wind speeds ≥5 ms^{-1}, the 2 m temperature is used for the mass separation as shown in Fig. 5b) (for the exact values see Table 2). In some cases, no temperature measurements were available, so the precipitation amount is attributed to a "mixed-phase" type.If the Parsivel does not detect any precipitation or no Parsivel measurements are available, the precipitation phase is "unknown". Allocation of precipitation amount to a certain precipitation phase is actually quite challenging at Ny-Ålesund because a substantial amount of precipitation occurs in the transition regime between -2°C and 4°C, i.e. about 47% of the total precipitation amount during August 2017 and December could not be determined for the corrected Pluvio precipitation amounts. However, this affected less than 2 mm of the whole precipitation amount in the period from August 2017 to December 2021.

The resulting monthly liquid precipitation amount and liquid mass fraction are shown in Fig. ?? (filled contours) shows the fraction of monthly precipitation amount in each phase. Generally, the precipitation amount of each phase class follows the monthly fraction of precipitation type occurrence. Since the mixed-phase precipitation type, as detected by Parsivel, only seldom occurs, most of the mixed-phase precipitation amount is because both solid and liquid precipitation occur within the ±10 min time window considered. Since the data coverage of Parsivel is very poor from June 2021 onward (see Section 2.2) , much of the measured precipitation amount by Pluvio can not be allocated a precipitation type, resulting in higher numbers of the "unknown" class. More than 50% of the monthly precipitation amount is purely solid from October to April except for

Table 2. Liquid mass fraction as a function of 2 m temperature derived from corrected Pluvio precipitation amount and Parsivel precipitation type for the period August 2017 to December 2020. For temperatures <0.2°C (≥3.6°C), all precipitation is assumed to be solid (liquid). For the temperature range between 0.2°C and 3.6°C, the liquid mass fraction corresponds to the values shown in Fig. 5b.

T range / °C	Liquid mass fraction / %	T range / °C	Liquid mass fraction / %
<0.2	0	[2.0,2.2)	53
[0.2,0.4)	1	[2.2,2.4)	65
[0.4,0.6)	2	[2.4,2.6)	85
[0.6,0.8)	3	[2.6,2.8)	89
[0.8,1.0)	8	[2.8,3.0)	89
[1.0,1.2)	5	[3.0,3.2)	94
[1.2,1.4)	17	[3.2,3.4)	96
[1.4,1.6)	28	[3.4,3.6)	98
[1.6,1.8)	46	≥3.6	100
[1.8,2.0)	51		

October 2017, January and November 2018, and April 2019. Only for a few months during late summer/early autumn, the monthly precipitation amount is almost entirely liquid. Nevertheless, liquid 6a and the yearly liquid and solid precipitation sums in Table 3. Liquid precipitation typically dominates the total precipitation amount from April to September. However, a substantial amount of liquid precipitation can also be found in January, February, November, and mixed-phase precipitation can also dominate precipitation amounts in other months, e.g., in January December 2018with nearly 90% and in November , as well as November 2020. For 2018and May 2019 with about 60%. When looking at the annual precipitation amount, about 22% to 30% is found to be purely liquid, with another 4 to 27% being of mixed-phase type , this results in a high liquid precipitation fraction of 52%, while in 2021, the liquid fraction is only 29%. We also analyzed the effect of using a simple temperature threshold (T1°C) assuming all precipitation to be solid for temperatures <1°C as in Champagne et al. (2024) (Fig. 6b). For some months, this significantly increases liquid precipitation (by up to 53 mm) resulting in generally higher yearly liquid precipitation fractions with an additional six to 15 percentage points (Table 3). Using only the temperature-based mass separation (TS) as derived from the Parsivel observations (and thus no direct Parsivel observations at all), has a smaller effect, even though for some months differences are several millimeters showing still the uncertainty related to phase attribution. However, the yearly liquid mass fraction of the TMS method is similar to the combined Parsivel/TMS method (Table ??3).

The previously mentioned rain-on-snow (ROS) events are of particular interest since they can have severe implications for wildlife and Arctic communities. We investigated ROS events using daily precipitation sums during the cold season months November to March. A ROS event is defined as a day with the sum of liquid and mixed-phase daily precipitation exceeding

Since Champagne et al. (2024) applied the 1°C temperature threshold to hourly mean 2 m temperature values, we also calculated hourly liquid and solid precipitation sums from the 1 mm. The partitioning into liquid and mixed-phase precipitation

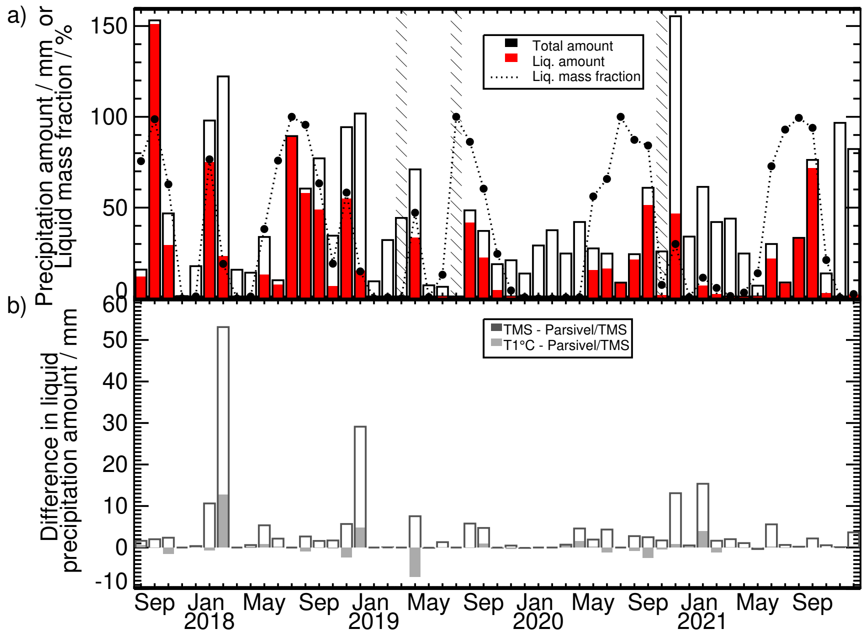

Figure 6. a) Total monthly precipitation (in mm) from corrected Pluvio data (black bars). The corresponding liquid precipitation amount (in mm) from the combined Parsivel/temperature-based mass separation (Parsivel/TS; red bars) and the monthly liquid fraction (in %, dotted line) are shown as well. b) Differences in monthly liquid precipitation amount (in mm) if the temperature-based mass separation (TMS; dark gray bars) or a simple temperature threshold of 1°C (T1°C; light gray bars) is used.

Table 3. Annual liquid precipitation amount (in mm) and liquid fraction of the total annual precipitation amount (in %; brackets) based on the combined Parsivel/temperature-based mass separation (TMS) method, the TS method only and based on a simple temperature threshold of 1°C (T1°C).

	2018	2019*	2020*	2021
Liquid Parsivel/TMS	392 (52)	106 (34)	162 (33)	152 (29)
Liquid TMS	406 (54)	99 (32)	160 (32)	155 (30)
Liquid T1°C	504 (67)	125 (40)	194 (39)	185 (35)

* yearly values underestimated due to measurement gaps

follows the same strategy as the monthly sums. Except for the relatively cold 2019min resolved liquid and solid values of the combined Parsivel/2020 winter TMS method and set those in context to hourly mean 2 m temperatures (Fig. A2), for which no ROS event has been found, 5-6 ROS events have been detected for each Nov-Dec period, i.e., 16 in total for the whole analysis

Table 4. ~~Fraction~~ Contribution of ~~monthly precipitation occurrence~~ atmospheric rivers (~~black lines/dots~~AR), cyclones (CY) and ~~monthly~~ fronts (FR) to the precipitation amount (~~filled contours~~in %) ~~being~~ and their frequency of ~~a~~occurrence (in %) ~~solid, b) liquid, c) mixed,~~ for different years and ~~d~~the whole time period considered (1 August 2017 – 31 December 2021)~~unknown type~~. ~~The precipitation type was determined using Parsivel and 2 m temperature~~ Weather systems can occur separately (~~see text for more details~~O-AR, O-CY, O-FR) or at the same time in different combinations. ~~The fraction of monthly precipitation occurrence is given with respect to~~ "All" includes all cases with a ~~precipitation signal from Parsivel. In contrast, the fraction~~ certain system regardless of ~~monthly precipitation amount is given with respect to all cases with a precipitation signal from Pluvio~~whether the other two systems are present or not.

~~Annual precipitation amount (in mm) of Pluvio and separated into precipitation phase. Numbers in parentheses are the percentages relative to the total annual precipitation (in %). See text for more details.~~

	2018		2019		2020		2021		08/2017 – 12/2021	
~~Pluvio corr~~	precip. fraction	system occurr.	precip. fraction	system occurr.	precip. fraction	system occurr.	precip. fraction	system occurr.	precip. fraction	system occurr.
~~liquid~~ all AR	~~229~~ 50	~~(30)~~ 10	~~75~~ 40	~~(~~5	34	9	25	6	42	8
all CY	34	22	43	16	48	22	38	21	39	20
all FR	18	13	18	13	24 ~~)~~	~~127~~ 16	~~(26)~~16	~~114~~ 13	~~(~~20	14
O-AR	29	5	24	2	11	4	15	3	22 ~~)~~	4
~~solid~~ AR-FR	~~285~~ 7	~~(38)~~2	~~174~~ 2	~~(56)~~ 1	~~300~~ 6	~~(61)~~ 2	~~243~~ 3	~~(47)~~2	6	2
~~mixed~~ AR-CY	~~206~~ 8	~~(27)~~2	~~42~~ 5	~~(14)~~ 1	~~43~~ 9	~~(~~1	5	1	8	1
AR-CY-FR	5	1	9 ~~)~~	~~23~~ 1	~~(4)~~8	1	2	1	6	1
~~unknown~~ O-CY	~~32~~ 18	~~(~~17	26	12	26	16	24	15	21	15
CY-FR	3	3	3	2	4 ~~)~~	~~18~~ 3	~~(~~6 ~~)~~	~~25~~ 3	~~(~~4	3
O-FR	3	7	4	8	5 ~~)~~	~~141~~ 9	~~(~~5	7	4	8
residual	27 ~~)~~	63	27	72	30	63	40	68	29	66

~~period~~ A4). Also, for hourly averaged 2 m temperatures and hourly accumulated liquid and solid precipitation sums, we find a similar temperature dependency for the mass separation as shown in Fig. 5b.

4 Impact of atmospheric rivers, cyclones and fronts on precipitation at Ny-Ålesund

To better understand the impact of large-scale weather systems on precipitation at Ny-Ålesund, we set the local precipitation observations in context to the occurrence of ARs, cyclones and frontal systems, which have been detected using ERA5 reanalysis data and the methods explained in section 2.4. The monthly occurrence of these systems is depicted in Fig. 7 and also listed for the different years as well as for the entire study period (1 August 2017 – 31 December 2021) in Table 4.

4.1 ~~Precipitation frequency~~

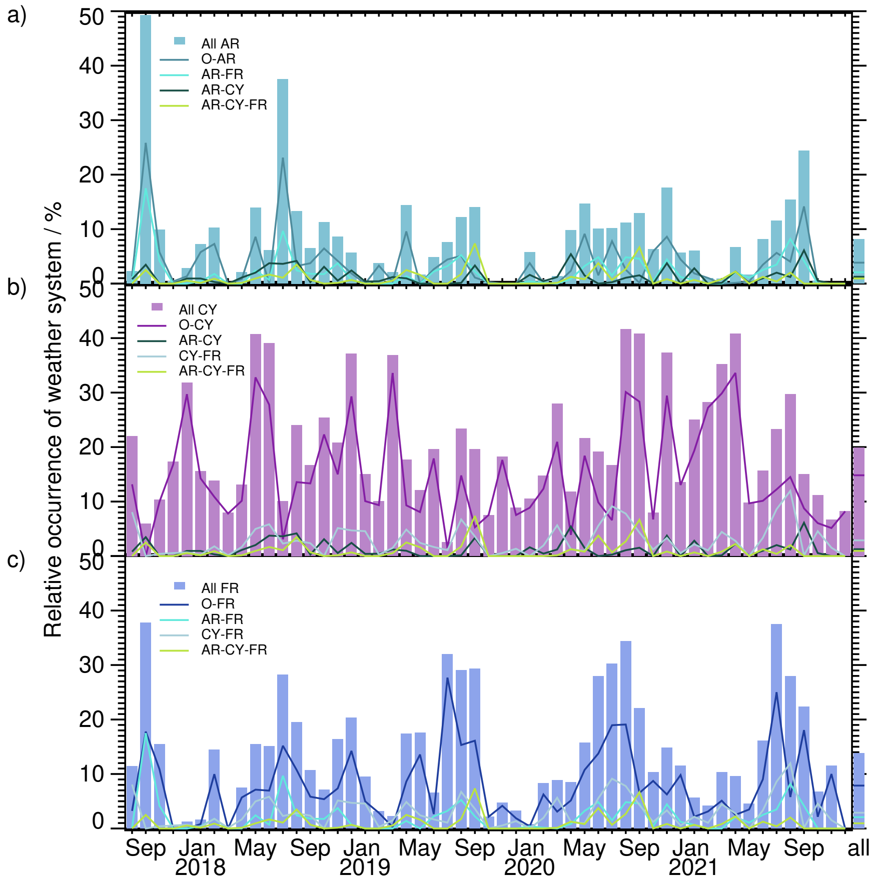

Figure 7. ~~Frequency of~~ Monthly occurrence (in %) of ~~liquid~~ weather systems related to a) atmospheric rivers (~~red~~AR), ~~solid~~ b) cyclones (~~blue~~CY) ~~,~~ and ~~mixed~~ c) fronts (~~gray~~FR)~~precipitation derived from Parsivel as a function of 2 m temperature~~. ~~Results are shown for all data~~ Weather systems can occur separately (~~dotted line with circles~~O-AR, O-CY, O-FR) ~~and data when 2m wind speed <5 ms^{-1}~~ or at the same time in different combinations (~~solid line with filled circles~~colored lines, see legends). ~~The values have been normalized~~ "All" (colored bars) includes all cases with ~~the total number~~ a certain system regardless of ~~observations within each temperature class~~whether the other two systems are present or not. The ~~temperature bin size is~~ last column shows the occurrence of weather systems for the whole time period considered (1 ~~°C~~August 2017 – 31 December 2021).

~~From the previous sections, it became clear that determining precipitation amount and type is challenging. However, even the detection of precipitation and, thus, the determining precipitation frequency are subject to great uncertainty and are very~~

sensitive to the method applied. This can be seen in the monthly precipitation frequency determined by Parsivel, Pluvio, and MRR (Fig. **??**) . Monthly precipitation frequency has been determined from the times when a signal has been recorded by the corresponding instruments relative to the total number of measurements. To this end, we used all 1 min resolved data within a month. Since precipitation amount is often available on a daily basis only, we also calculated the monthly precipitation frequency based on daily Pluvio values with a precipitation amount >Weather systems can occur separately (O-AR, O-CY, O-FR) or at the same time in different combinations ("co-located" in the following). On average, ARs (separated and co-located) occur 8% of the time with a high variability in the monthly values ranging from 0 mm and >1 mm. For the MRR, we took the measured radar reflectivity Z_e at the lowest height bin with valid measurements, i.e., at 120 m. We counted all cases with $Z_e >$ -10 dBZ which corresponds to the sensitivity of the instrument at that height (Fig. **??**) . To account for the sensitivity of the results to the Z_e threshold applied, the corresponding values for a more conservative threshold of -5 dBZ are also shown. To understand which rain or snowfall rate a value of -5 or -10 dBZ actually represents, $Z_e - R$ and $Z_e - S$ relationships must be applied. If we exemplarily use the $Z_e - R$ relation by Tokay et al. (2009) ($Z_e = 129R^{1.5}$), -10 dBZ (-5 dBZ) corresponds to a rain rate of about 0.01 mm h^{-1} (0.02 mm h^{-1}). If we use for example the three bullet rosette $Z_e - S$ relationship by Kulie and Bennartz (2009) ($Z_e = 24.04S^{1.51}$), which was also used in the study by Maahn et al. (2014) , corresponding snowfall rates are 0.03 mm h^{-1} and 0.06 mm h^{-1}% in some months to an exceptionally high occurrence of 49% and 37% in September 2017 and July 2018, respectively. In principle, only a few mm sized snowfall particles (aggregates) per cubic meter are sufficient to be detected by the MRR. Half of the ARs occurred without the presence of cyclones or fronts directly at Ny-Ålesund. Cyclones occur in each month at Ny-Ålesund with a generally higher frequency (whole-time average of 20%) compared to ARs. 75% of these cyclones occur separately from the other two weather systems. Front occurrence (separated and co-located) shows monthly maxima of more than 20% in summer or late summer. This enhanced frontal activity in summer might be related to the differential heating of the Arctic Ocean and the snow-free land as well as coastal orography which supports baroclinicity (Serreze and Barry, 2014). On average, fronts occur 14% of the time at Ny-Ålesund. At least for the four years considered, it seems that the yearly AR occurrence is more variable than the cyclone or front occurrence. However, a longer time series needs to be analyzed to draw a conclusion here.

The monthly precipitation frequency from the MRR ranges from 1% to 38%. Averaging over the whole measurement period results in a mean value of 21%. From the short time series, no seasonality can be deduced. The more conservative threshold of -5 dBZ slightly reduces the monthly values, typically about 2 to 4 percentage points, and the whole time mean precipitation frequency to 18%.

Since the Parsivel is also sensitive to single precipitation particles, the derived precipitation frequency is also high, with maximum values of about 18%. However, these numbers are generally lower than those from MRR, which also has a much larger sampling volume: e.g., with a beam width of 1.5°, the observed volume between 120 m and 150 m, for example, is about 300 m^3. Also, the time series of monthly precipitation frequency differs between Parsivel and MRR, resulting in a correlation coefficient (May 2017 - May 2021) of 0.72 only.

Surface precipitation, i.e., any signal in the Pluvio measurements, is recorded only in very few cases. Using the 1 min resolved Pluvio time series to determine precipitation frequency results in monthly values of up to 5% only. Using daily

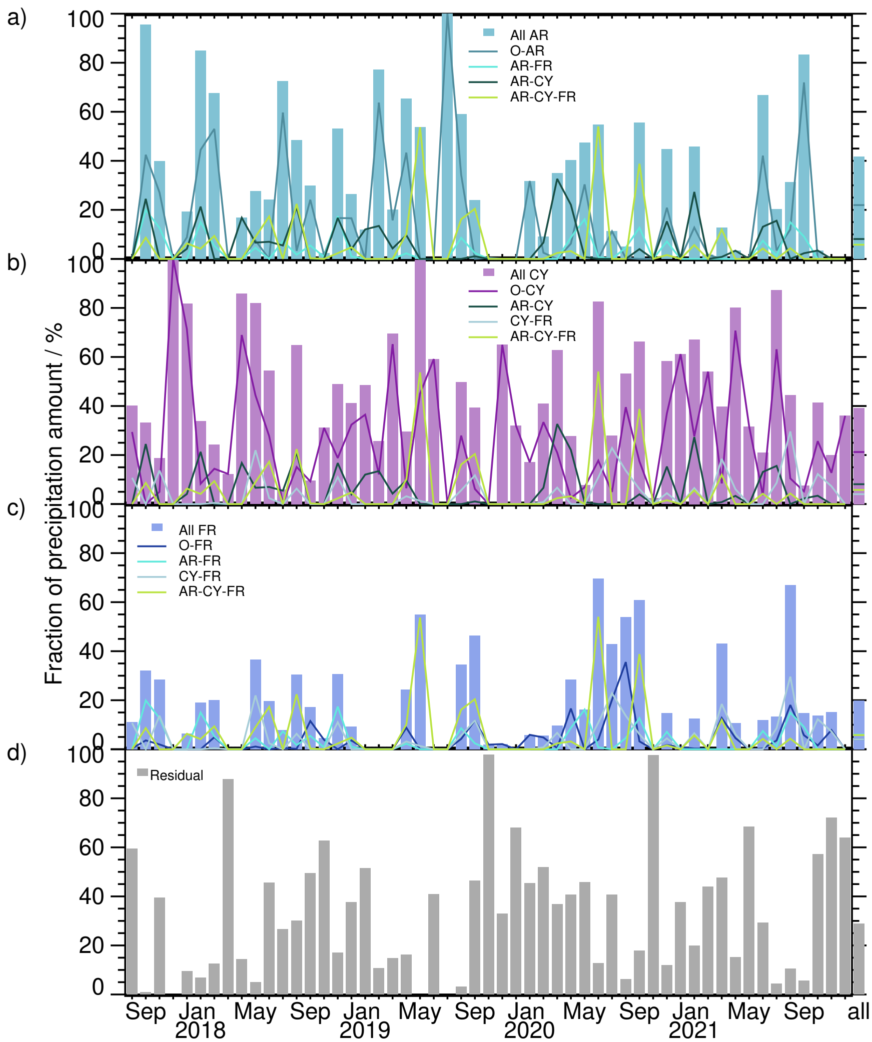

Figure 8. Relative contribution (in %) of a) atmospheric rivers (AR), b) cyclones (CY) and c) fronts (FR) to monthly precipitation amount. Weather systems can occur separately (O-AR, O-CY, O-FR) or at the same time in different combinations (colored lines, see legends). "All" (colored bars) includes all cases with a certain system regardless of whether the other two systems are present or not. Precipitation that can not be attributed to any of these systems is denoted as "residual" (see panel d). The last column shows the relative contribution to the total precipitation amount of the whole period considered (1 August 2017 – 31 December 2021).

~~resolved Pluvio data increases the monthly precipitation frequency to~~ By combining the corrected Pluvio measurements with the detected weather systems over Ny-Ålesund, we can assess how much of the precipitation is related to ARs, cyclones or fronts. Precipitation that can not be attributed to any of these systems is denoted as "residual". The monthly absolute and relative precipitation amounts are summarized in Figs. A5 and 8, respectively, and the yearly and whole time contributions in

Table 4. The largest contributions to monthly and yearly precipitation can be found for the AR and cyclone classes. Even if the occurrence of ARs is rather low on average (4% –63% and , if a threshold of 1 mm is applied, to 4%–46% Considering the months August 2017 to May 2021, for which all instruments provide sufficiently large data coverage, the mean precipitationfrequency is O-AR, 8% for all ARs), they contribute 22% (Parsivel), O-AR) and 42% (all AR) to the total precipitation, respectively. The relatively rare combined classes AR-FR (2%), AR-CY (1%(Pluvio,) and AR-CY-FR (1 min resolution), 38% (Pluvio, daily resolution, >0 mm), 22% (Pluvio, daily resolution, >1 mm), and 21% (MRR with -10 dBZ threshold), respectively.

We want to emphasize that we do not evaluate the derived precipitation frequency of each method. Depending on the individual scientific question, %), contribute together 20% of the total precipitation amount. However, the precipitation frequency by one or the other method might be more relevant. For example, for hydrological applications, year-to-year and month-to-month variability of the precipitation fraction associated with ARs is large, with only 25% in 2021 and even 50% in 2018. In particular, in the very wet month of September 2017, almost all precipitation, i.e., 145 mm (Fig. A5), can be related to the (co-)occurrence of ARs. For the month with the highest precipitation amount, i.e., November 2020, both AR and cyclone classes contribute together to about 80% of the total precipitation amount, with the O-CY class even dominating. Cyclones, which occur more often (20%) than ARs, contribute similarly to the total precipitation amount, i.e., 21% for O-CY and 39% for all CY. Fronts seem to play a minor role in the precipitation occurrence based on Pluvio measurements might be of more interest. Still, precipitation occurrence as detected by the MRR is relevant for analyzing the microphysical processes of clouds and precipitation.

In contrast to Parsivel and Pluvio, the MRR also provides information on vertical precipitation structure. Fig. **??**a depicts the 2D histogram of MRR Z_e for the whole analysis period. Here, we plotted the data of all height levels included in the IMProToo data set. From the 2D histogram, it becomes clear that measurements are unreliable below 120 m and above 900 m and should not be used for these levels. Looking at the other height levels, we find a median Z_e profile with a vertically constant value of about 6 dBZ. The same feature has also been found for MRR measurements taken at the Sverdrup Research Station at Ny-Ålesund from March 2010 to March 2011 (Maahn et al., 2014) as well as for X band radar observations at Iqaluit in the Canadian Arctic (Henson et al., 2011).When looking more closely at the signal frequency for different Z_e thresholds amount at Ny-Ålesund: a distinct contribution of separated fronts (O-FR) to monthly precipitation amount can only be found in a few months, e.g., August 2020 (O-FR: 35%). Regarding the whole time period, separated fronts contribute only about 4% to the total precipitation. Only in combination with ARs and cyclones the value increases to 20%. Quite some precipitation cannot be attributed to any of these weather patterns with an overall value of 29%. This residual is generally larger from early autumn to early spring, both in terms of absolute (Fig. A5d) and relative precipitation amounts (Fig. **??**b), we can see that, in particular, higher Z_e values are equally distributed in the vertical. For lower Z_e thresholds, a maximum in signal frequency is found for a height of about 540 m. The decrease of signal frequency below, i.e., about 2 percentage points, is likely related to sublimation effects. By simply counting cases where no MRR signal has been reported at 120 m but in any other height layer above (Z_e >-10 dBZ), we find a mean "sublimation" occurrence of 7%. This number should be taken as an upper estimate since we do not consider advection and wind effects, as well as tilted fall streaks. 8d).

Monthly frequency of precipitation occurrence for a) MRR, b) Parsivel, and c) Pluvio. For the MRR, precipitation is assumed to occur if Z_e at 120 m height is larger than -10 dBZ (-5 dBZ; x symbols). The monthly values have been calculated from the 1 min resolved data (dark blue in all panels). For Pluvio, monthly precipitation occurrence has also been calculated based on daily precipitation amounts >0 mm (light red) and >1 mm (light blue). Hatched areas indicate months when the monthly values are unknown/unreliable due to missing measurements.

a) 2D histogram of MRR Z_e as a function of height for May 2017 to December 2021. The occurrence has been normalized by the total number of MRR profiles. The black solid line indicates the median Z_e profile. b) Signal frequency of each height layer for May 2017 to December 2021. Each line represents the signal frequency with different dBz thresholds ranging from -10 to 30 dBz.

5 Event-based precipitation analysis and extreme events

For the synergetic analysis of all three instruments, it is useful to consider individual precipitation events. In the last part of this study, we would like to address the following questions: what kind of precipitation events contribute most to the precipitation amount at Ny-Ålesund, what is the duration of precipitation events, and which role do extreme precipitation events play in this respect? As a first step, "precipitation event" has to be defined. Here, we take the following approach: based on the 1 min resolved data, we first check when MRR Z_e at 120 m height is greater than -10 dBZ. Periods with Z_e greater than -10 dBZ need to be more than These results are not directly comparable to the study by Lauer et al. (2023), as they focused on four months only (May/June 2017, March/April 2019) and on the Arctic North Atlantic and Kara and Barents Seas. However, they also found that fronts were of higher importance for precipitation in the summer period and that residual precipitation made up about 30 min apart to be counted as two individual MRR events. In this way, we allow for short interruptions in precipitation since precipitation might still be associated with the same larger-scale cloud% of the total precipitation.

With the combined Parsivel/temperature-based mass separation method (sec. 3.2), we also analyzed the phase partitioning for the different weather systems (Table 5). Regarding the precipitation of all ARs from 1 August 2017 and – 31 December 2021, only 645 of them (∼21%) contained precipitation measured by Pluvio. For 162 MRR events (∼5.2%), no information on precipitation amount is available. The 645 precipitation events will be analyzed in more detail in the following. 2021, 72% of the precipitation amount is liquid. For all fronts and all cyclones, the liquid fraction is 63% and 38%, respectively. The corresponding values for the different years vary, but the tendency of a higher liquid fraction for ARs and fronts is visible. The highest liquid fraction occurs when ARs and fronts are co-located (86%). The high liquid fraction of precipitation related to fronts is also due to the fact that front occurrence has a maximum in summer. Residual precipitation, which predominantly occurs in autumn and winter, consists mainly of solid precipitation (79%) with yearly values ranging from 63% to 89%. The importance of ARs for rain was also found by Lauer et al. (2023), as well as the higher contribution to snowfall of the residual precipitation class.

The high temporal resolution of the Pluvio and Parsivel measurements allows precipitation rates to be analyzed for shorter time intervals. When looking at the hourly precipitation sums (Fig. 9a), 50% of the sums have values lower than 0.4 mm and

Table 5. Fraction of liquid precipitation (in %) relative to the total precipitation amount of the different weather systems for different years and the whole time period considered (1 August 2017 – 31 December 2021). Atmospheric rivers (AR), cyclones (CY) and fronts (FR) can occur separately (O-AR, O-CY, O-FR) or at the same time in different combinations. "All" includes all cases with a certain system regardless of whether the other two systems are present or not. Precipitation that can not be attributed to any of these systems is denoted as "residual". The precipitation amount is taken from the corrected Pluvio data and phase information is obtained using the combined Parsivel/temperature-based method.

	2018
all AR	71
all CY	46
all FR	60
O-AR	69
AR-FR	79
AR-CY	78
AR-CY-FR	62
O-CY	27
CY-FR	33
O-FR	36
residual	37

~~min is somewhat arbitrary, and the sensitivity of the results to this threshold will be discussed later. A further criterion for a~~

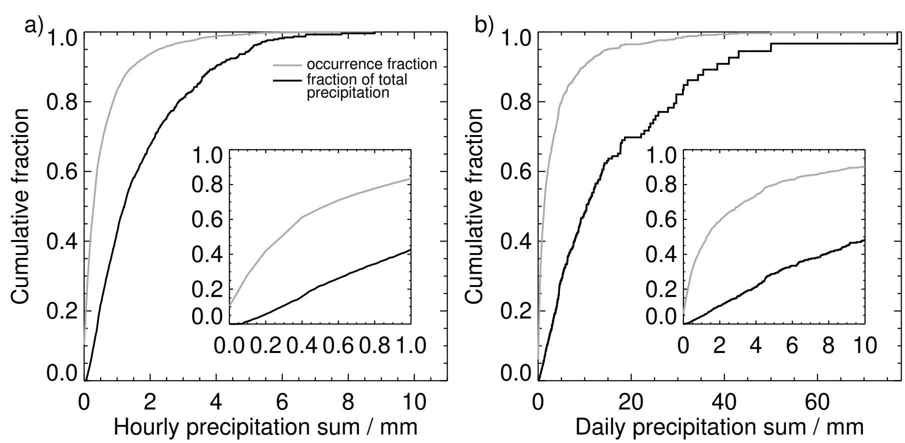

Figure 9. Cumulative relative occurrence of a) hourly and b) daily precipitation sums (gray) and cumulative relative contribution of these precipitation sums to total precipitation amount (black) based on the corrected Pluvio data for the time period 1 Aug 2017 to 31 December 2021. The inlets are a zoom-in for hourly (daily) precipitation sums below 1 mm (10 mm).

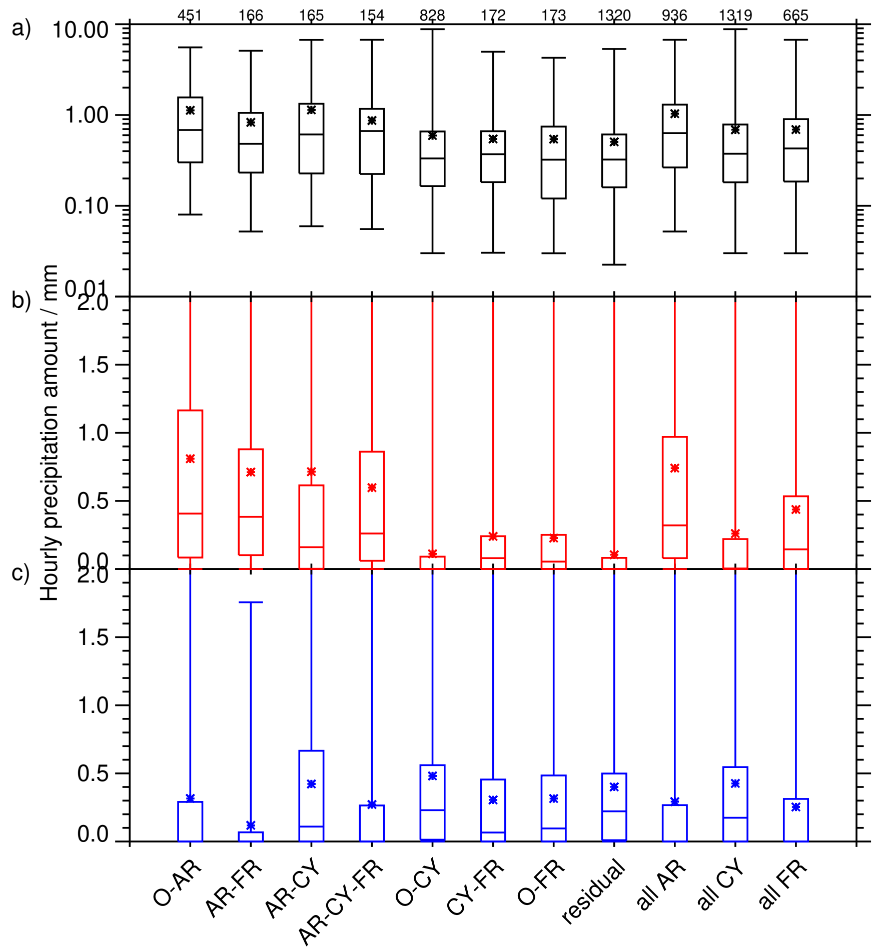

Figure 10. ~~Relative occurrence~~ Boxplots of ~~a) maximum and b) median Z_e for all MRR~~ hourly precipitation ~~events from~~ amounts of the different weather systems during 1 August 2017 ~~to~~ and 31 December ~~2021 with~~ 2021. a) Total (black), b) liquid (red) and ~~without~~ c) solid (~~gray~~blue) precipitation~~measured by~~. Atmospheric rivers (AR), cyclones (CY) and fronts (FR) can occur separately (O-AR, O-CY, O-FR) or at the same time in different combinations. "All" includes all cases with a certain system regardless of whether the other two systems are present or not. Precipitation that can not be attributed to any of these systems is denoted as "residual". Precipitation amount is taken from the corrected Pluvio data and phase information from the combined Parsivel/temperature-based method. The whiskers indicate the maximum/minimum value and the star the mean value. The numbers on top show the sample size.

90% lower than 1.5 mm. The latter contributes only about 57% to the total precipitation at Ny-Ålesund. Hourly precipitation amounts larger than 3.6 mm make up only 2% of all non-zero hourly precipitation sums.

As seen from Differentiating between different weather systems (Fig. ??, the MRR is quite sensitive for detecting precipitating particles. The question, therefore, arises for which Z_e values precipitation is actually detected on the ground. For each event, we thus calculated the maximum and median Z_e at 120 m height. Figure **??** depicts the relative occurrence of maximum and median Z_e for all precipitation events and for all MRR events (without the surface precipitation criterion applied). We find that maximum Ze values during a precipitation event 10) reveals that the largest hourly precipitation amounts are associated with the occurrence of ARs with median hourly values between 0.5 mm and 0.7 mm. In 85% of the hours with ARs, liquid precipitation occurs. Hourly liquid precipitation amounts are typically between 10 to 40 dBZ, and median values centered around 5 dBZ. These results are independent of 0.1–1.0 mm (25th and 75th percentiles). At the same time, hourly solid precipitation amounts during ARs are relatively small since solid precipitation occurs only in 42% of all hours with ARs. Only for the AR-CY class, both liquid and solid precipitation are common with median values of 0.2 mm and 0.1 mm, respectively. Apart from this, cyclones (all CY) are rather associated with solid precipitation (median hourly solid precipitation sum of 0.2 mm), while the opposite is found for fronts (median hourly liquid precipitation sum of 0.1 mm). However, a closer look reveals that the liquid precipitation during fronts mainly occurs when they are colocated with ARs. As mentioned earlier, the temporal separation threshold of 30 min, and the same numbers are found for thresholds of 15 min and 60 min (not shown) residual precipitation is rather related to solid precipitation which is also reflected in the hourly precipitation amounts with a median value for solid of 0.2 mm and 0 mm for liquid.

Cumulative relative occurrence of all precipitation events from 1 August 2017 to 31 December 2021 (gray) and cumulative relative contribution of precipitation events to total precipitation amount (black) as a function of a) event duration (in min) and b) event precipitation amount (in mm). Results for precipitation events with a 15 min (60 min) separation threshold are indicated with dashed (dashed-dotted) lines.

When looking at the cumulative relative occurrence of event duration (Fig. **??**a), one can see that, as expected, the distribution of event duration is sensitive to the temporal separation threshold applied: using a 15 min threshold results in a higher occurrence of shorter events. In contrast, a 60 min threshold shifts the distribution to more extended events. Depending on the event separation criterion, 50% of all precipitation events have a duration of less than 4.2 h to 9.6 h and maximally contribute to the total precipitation amount with 11%. Events shorter than one hour rarely occur, i.e. less than 6% of all events, and have a negligible contribution to the total precipitation Moving to daily temporal scales (<1%). Events covering more than one day represent only about 5% to 15% of all events but contribute to the total precipitation by about 37% to 60%.

If we analyze the events in terms of their precipitation amount (Fig. **??**9b), we can see that the cumulative distribution is less sensitive to the event separation criterion. About 54% (85find that 50% (90%) of all precipitation events have a precipitation amount of less than 1the daily precipitation sums have values lower than 1.3 mm (510 mm) . They contribute to about 6% (27%) of and contribute only about 5% (47%) to the total precipitation amount. Events with a precipitation amount of more than 20 mm rarely occur, i.e., only 3% of all events but make up 41% at Ny-Ålesund. Very small precipitation amounts or trace precipitation, i.e., small but immeasurable daily precipitation events, are still challenging for observations and models. Boisvert et al. (2018), who defined trace precipitation as days with less than 1 mm precipitation, showed large differences in the occurrence and annual amount of trace precipitation over the Arctic Ocean between eight reanalyses. However, trace

Table 6. Upper 2% of ~~events~~ the days between 1 August 2017 and 31 December 2021 with the highest precipitation amount ranked in ~~terms of their precipitation amount~~descending order. In addition to the daily precipitation amount ~~and duration of~~ from the ~~precipitation event~~corrected Pluvio data, the liquid fraction based on the combined Parsivel/temperature-based method and the weather systems detected at least once during the event are reported, i.e., atmospheric river (AR), cyclone (CY) ~~,~~ and front (FR).

#	~~Period~~ Date ~~(Date/Time UTC)~~	Amount (in mm)	~~Duration~~ Liquid fra[…] (~~h~~in %)
1	~~12~~ 13 Jan 2018 ~~, 20:37 - 14 Jan 2018, 02:00~~	~~79~~ 77	~~29~~ 89
2	~~26 Feb 2018, 10:25 - 27 Feb 2018, 16:37~~9 Nov 2021	~~71~~ 50	~~30~~ 1
3	~~09 Nov 2021, 00:56 - 10 Nov 2021, 17:09~~28 Nov 2020	~~61~~ 43	~~40~~ 0
4	~~01 Sep 2017, 19:58 - 03 Sep 2017, 17:35~~18 Nov 2018	~~57~~ 41	~~46~~ 93
5	~~18 Dec~~ 26 Feb 2018 ~~, 01:31 - 20 Dec 2018, 05:02~~	~~55~~ 38	~~52~~ 44
6	~~17 Nov 2018, 19:21 - 19 Nov 2018, 14:24~~4 Dec 2021	~~50~~ 35	~~43~~ 0
7	~~14 Nov 2020, 05:36 - 17 Nov 2020, 00:25~~3 Sep 2017	~~50~~ 34	~~67~~ 100
8	27 ~~Nov 2020, 18:02 - 29 Nov 2020, 01:34~~Feb 2018	~~48~~ 32	~~AR CY –~~ 9
~~10~~ 9	~~30 Aug 2018, 06:08 - 31 Aug 2018, 07:46~~25 Sep 2017	~~42 26 AR CY FR 11 09 Jul 2018, 14:~~31 ~~- 11 Jul 2018, 02:45~~	~~34~~ 100
~~12~~ 10	~~24~~ 23 Sep 2017 ~~, 20:47 - 26 Sep 2017, 00:44~~	~~32~~ 31	~~28~~ 100

precipitation can make up a substantial proportion of the total precipitation amount ~~. Focusing on extreme events, i.e.~~over the central Arctic Ocean (Boisvert et al., 2018; Barrett et al., 2020). The question of whether these small amounts of precipitation that numerical models frequently generate occur also in reality has not yet been completely answered. This is also due to missing accurate reference observations. At Ny-Ålesund, trace precipitation (i.e., non-zero daily precipitation amount <1 mm) is reported from the corrected Pluvio data for about 16% of the time of the analyzed period. It accounts for 44% of the days with precipitation recorded. Trace precipitation is thus a common feature of the atmospheric state at Ny-Ålesund. The annual trace precipitation amounts for 2018-2021 are between 20 to 30 mm. Compared to the annual precipitation amount, ~~here the upper 2% of events with the highest precipitation amounts (12 events in total), we find that all these events exceed 31.7 mmand contribute 28% to the total precipitation amountof all events (Table ??). In terms of duration, they vary between 25 and 67 h. Interestingly, almost all events(except for one)are~~ these values are rather small. For example, for 2021, the annual trace precipitation amount is 5.5% of the total precipitation amount at Ny-Ålesund. Days with trace precipitation can be mainly related to the residual class (43%) followed by cyclone-related events, in particular with the O-CY class (18%). Focusing more on processes on the local scale, trace precipitation could also be associated with the ~~occurrence of an AR. However, also cyclones and fronts are typical accompanying features for these extreme events~~frequent occurrence of low-level mixed-phase clouds in conjunction with katabatic winds (Gierens et al., 2020), with the dry katabatic flow leading to the sublimation of a large portion of the precipitating mass.

~~Extreme precipitation event on 12 - 14 January 2018. a) Occurrence of weather systems as described in Fig. ??, b) MRR radar reflectivity (in dBZ), c) hourly accumulated precipitation (grey bars) and accumulated precipitation during the event~~

~~(black line) (in mm), d) Parsivel precipitation type, e) 2 m temperature (black line, in °C) and 2m wind speed (grey line, in m/s), and f) integrated water vapor (IWV) from HATPRO (in kg/m^2). The vertical dashed lines indicate the start and end time of the precipitation event.~~

~~IWV (colors) and MSLP (black contour lines) on 13 Jaunuary 2018 at 20 UTC from the ERA 5 reanalysis. The dashed black-red line indicates the detected AR.~~

~~The high temporal resolution of the precipitation observations allows for a more detailed analysis of the temporal development of these extreme events. While the thorough analysis of all extreme precipitation cases listed in Table **??** is beyond the scope of this paper and will be addressed in a follow-up study, we will exemplarily have a closer look at event #1 having the maximum precipitation amount of 79 mm within 29 h. Figure **??** depicts the time series of the different precipitation observations, the measurements of 2 m temperature, wind speed, and IWV, as well as the occurrence of weather systems detected from ERA5. The precipitation event was accompanied by a substantial increase in water vapor on 12 January 2018 from about 5 kg/m^2 to more than 12 kg/m^2. With the onset of the precipitation at the end of that day, the HATPRO microwave radiometer measurements became unreliable due to the wet radome of the instrument, and no information on IWV is available for the following hours. This strong increase in IWV was due to an AR arriving at Ny-Ålesund on 12 January 2018 around 16 UTC. This~~ When focusing on the right tail of the distribution of the daily precipitation amounts, in particular on the 2% of the days with the highest precipitation amounts (Table 6), we find that all of these events are related to enhanced water vapor transport from the North Atlantic ~~was stirred by a high-pressure system over Scandinavia and a cyclone developing off the coast of northeastern Greenland (Fig. 3). With the cyclone moving northeastwards, water vapor was transported along its eastern flank to Ny-Ålesund. Continuous, intense precipitation signals of more than 30 dBZ, which only occur less than 1% of the time at Ny-Ålesund (Fig. ??), were observed by the MRR from 22 UTC on 12 January 2018 to 21 UTC on~~ or Eurasia, often in the form of ARs and in combination with fronts. In these situations, the liquid fraction is also often high. Exemplarily, the ERA5 integrated water vapor and the detected AR for the day with the highest precipitation sum, 13 January ~~2018. With the arrival of the North Atlantic air mass, the 2 m temperature also increased to above 2 °C, resulting in liquid precipitation as indicated by the Parsivel data. For some times during this event, the Parsivel data also indicates solid precipitation. However, these solid precipitation cases are correlated to situations with higher wind speeds and are thus likely misclassified liquid precipitation situations as discussed earlier. With the cyclone slowly moving further northeastwards and polar air being advected at its backside, temperature and IWV decreased again on 14 January~~ 2018, ~~and precipitation stopped.~~

~~Even though a detailed analysis of all extreme precipitation cases will be presented in a future study, we would already like to highlight common features of these precipitation events.~~is shown in Fig. 3. Visual inspection of the ERA5 output ~~revealed that all these events are related to enhanced water vapor transport from the North Atlantic or Eurasia, often in the form of ARs. The~~ for the other days with extreme precipitation revealed that the prevailing general circulation patterns ~~feature a high MSLP~~ are a high surface pressure system over Scandinavia/the Barents Sea and/or a ~~low-pressure~~ low surface pressure system located over the North Atlantic near Iceland (not shown). In the case of a (blocking) high-pressure system over Scandinavia, enhanced water vapor transport into the Arctic is realized along its western flank. In the majority of the extreme precipitation cases, cyclones also developed in the Fram Strait or off the coast of northeastern Greenland, which also drive the water vapor

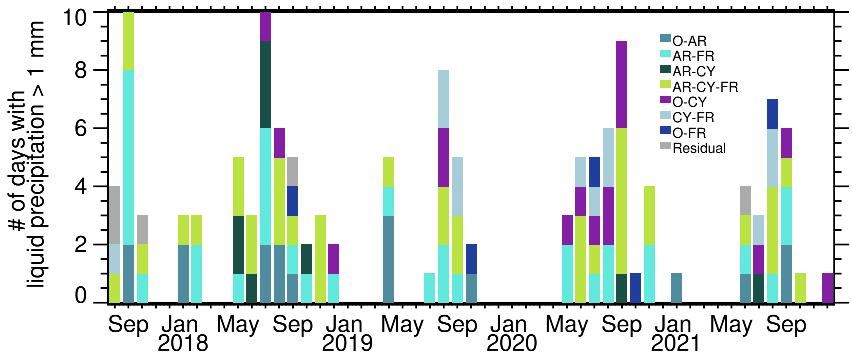

Figure 11. Number of days with liquid precipitation >1 mm and relation to atmospheric rivers (AR), cyclones (CY) and fronts (FR). Weather systems can occur separately (O-AR, O-CY, O-FR) or at the same time in different combinations.

transport from the North Atlantic to Ny-Ålesund: water vapor is then advected along their eastern flank, resulting in enhanced precipitation at the site. Additional precipitation might also occur when polar air that is advected on the backside of these cyclones hits the warm and humid North Atlantic air. These findings are generally consistent with the composite analysis of extreme precipitation events at ~~Spitsbergen~~ Svalbard by Serreze et al. (2015), who analyzed station and MERRA reanalysis data from 1979 to 2014. They showed that the general synoptic situation is linked to low ~~MSLP~~ surface pressure systems off the southeast coast of Greenland and between Greenland and ~~Spitsbergen~~Svalbard, with positive anomalies in 500 hPa height over Scandinavia and the Barents Sea and negative anomalies centered over Greenland. These conditions favored a southerly flow with advection of water vapor from the North Atlantic. ~~The strong~~ Strong uplift in the regions of low ~~MSLP also favored the formation of precipitation.~~ surface pressure caused precipitation formation.

Another type of "extreme" precipitation event is liquid precipitation during the cold season. As mentioned before, rain-on-snow events are of particular interest since they can have severe implications for wildlife and Arctic communities. We investigated the number of days with liquid precipitation >1 mm in each month and connected it to the occurrence of the different weather systems (Fig. 11). As expected, most of these days can be found from May to September when temperatures are predominantly above 0°C (Fig. A2). However, except for the relatively cold 2019/2020 winter (Fig. A2), liquid precipitation days are also common from November to April. Almost all liquid precipitation days are connected to at least one of the weather systems and all liquid precipitation days from November to April (22 in total). 91% of these days are connected to ARs with a median liquid precipitation amount of 5 mm. 64% and 45% of these days are related to fronts and cyclones, respectively.

5 Summary and conclusions

Surface observations of precipitation are very scarce in the Arctic. This makes the few locations where continuous precipitation measurements are available even more important. In mid-2017, a ~~MRR, a Parsivel ,~~ Parsivel and a Pluvio were added to the instrument suite at AWIPEV, Ny-Ålesund, providing temporally highly resolved (1 min) information on precipitation amount and type. Their measurements thus ~~contribute to~~ complement the existing precipitation observations at Ny-Ålesund, e.g., the long-term precipitation records by MET Norway with the 12 hourly manual precipitation gauge and hourly Geonor observations. In particular, with the new automatic measurements on precipitation phase another important variable linked to precipitation is now available. ~~The information of MRR, Parsivel, and Pluvio complement each other so that an overall picture of precipitation amount, type, and vertical structure is achieved.~~ This study has addressed the potential of these ~~observations to characterize precipitation in terms of long-term statistics and individual precipitation events using~~ new observations for discrimination of the precipitation phase and the corresponding mass separation. By combining the precipitation observations of more than four years ~~of data.~~

~~The monthly precipitation totals exhibit a large variability ranging from~~ (1 ~~mm to 155 mm. Considering the effect of undercatch is crucial since it can add more than 100% to the originally measured precipitation value. While a first comparison of Pluvio precipitation amount to the manual daily precipitation measurements by MET Norway revealed a reasonable agreement, an extended comparison including also the Geonor precipitation gauge is planned for the future. Such an analysis could shed further light on the uncertainties in the determination of quantitative precipitation estimates from precipitation gauges in the Arctic. In this respect, the correction functions applied to the precipitation gauge measurements are crucial as pointed out in Champagne et al. (2024). Following Champagne et al. (2024), a best estimate for the Pluvio data record will be derived. Another aspect is the local variability of precipitation at this complex site. Here, the comparison with the measurements from the Bayelva site (Boike et al., 2018) about 3 km southwest of Ny-Ålesund would be interesting.~~ August 2017–31 December 2021) with ERA5 reanalysis data, we also assessed the impact of synoptic-scale weather systems, namely ARs, cyclones and fronts, on precipitation characteristics at Ny-Ålesund.

~~Daily precipitation amounts at Ny-Ålesund are typically very small with~~ Based on the Parsivel precipitation type classification, we found that almost all precipitation is solid below 0.4°C and liquid above 3.6°C. In-between, liquid precipitation occurrence increases with increasing temperature with a 50~~% being smaller than 1.3 mm. Large-scale weather events like ARs and cyclones are common features at Ny-Ålesund and strongly impact the precipitation amount. While ARs (separated or co-located with other weather systems) occur only 8% of the time at Ny-Ålesund), 43% of the total precipitation amount is measured during these events and 22% during AR events only. Cyclones also play a crucial role, contributing 40% (21%)of the total precipitation amount if all cyclone events (separated cyclone events) are considered.~~ % occurrence at 1.8°C. The temperature dependency of the mass separation follows the temperature relation of the phase occurrence. This mass separation–temperature relation does not change when moving from minute to hourly accumulated/averaged data. To discriminate liquid and solid precipitation amounts for the whole period considered, we used the Parsivel precipitation type information in combination with the derived temperature-based mass separation (when no Parsivel information was available). Differences in liquid (and correspondingly solid) precipitation sums of corrected Pluvio data can be quite large compared to a simple temperature threshold method of 1°C. The latter leads to increased annual liquid precipitation sums by six to 15 percentage points, highlighting the importance of a more precise phase discrimination.

~~Determining precipitation type and, thus, the attribution of precipitation amount still poses challenges as well. As no reference data exists, we related the retrieved precipitation type from Parsivel to temperature~~ Since no reference precipitation phase measurements are available in high temporal resolution, the Parsivel classification could only be checked for consistency with 2 m temperature data. Some inconsistencies could be identified with an increased liquid precipitation frequency at -2°°C and an increased solid precipitation frequency at around 5°°C. While the latter is related to cases with higher wind speeds affecting the assumption of the fall speed of the particles, the liquid occurrence at low temperatures could not be explained completely. With the measurements of the video in-situ in situ snowfall sensor, which has been was installed in September 2021, these cases can be analyzed in more detail in the future. This might allow for a more refined detailed evaluation of precipitation type from Parsivel or even help to establish an improved (and open source) retrieval method for precipitation type, which could also directly incorporate temperature information as a further constraint. In many studies, precipitation type is often based solely on a threshold in temperature. However, as indicated by the Parsivel measurements, both solid and liquid precipitation occurs in the temperature regime of -2°C and 4°C. For now, we combined the February 2025, a Thies disdrometer was operated by the University of Leipzig close to the balloon hall about 30 m away from the Parsivel. A comparison of the detected precipitation and precipitation type provided by the Parsivel software and phase will shed further light on the accuracy of the measured 2 m temperature information to allocate precipitation amount to precipitation type. We found that about 22% disdrometer-derived precipitation phase classification. The observed precipitation phase – temperature dependency can subsequently also be used to assess the phase partitioning in numerical models.

The occurrence of ARs, cyclones and fronts has a distinct impact on the precipitation characteristics at Ny-Ålesund. Although ARs occurred only 8% of the time at Ny-Ålesund, they contributed to about 42% to the total precipitation amount of the corrected Pluvio measurements in the time period 1 August 2017 to 30% of the annual precipitation amount is purely liquid with another 31 December 2021 considering all cases, i.e., with or without colocated cyclones and fronts. Even for the low presence of ARs only (O-AR; 4to 27%being mixed-phase. The high amount of liquid/mixed-phase precipitation (in total 57%)in 2018 seems unusual% of the time), their contribution to total precipitation is 20%. Similar precipitation fractions can be found for cyclone (CY)-related classes with 21% for O-CY and 39% for all cyclones. However, a more extended time series is needed to assess the year-to-year variability in the future. Since the performance of the Parsivel degraded in mid-2021, a new instrument was installed in June 2022.

The frequency of precipitation occurrence strongly depends on how precipitation occurrence is defined and on which measurements it is based. While the MRR is very sensitive to cyclones are in general more frequent than ARs (20%). Except for a few months in summer, precipitation associated with fronts seems to play a minor role at Ny-Ålesund. In general, a few precipitation particles, resulting in a precipitation occurrence of 21% (-10 dBZ threshold, higher liquid mass fraction is found for precipitation during ARs and fronts (72% and 63%, respectively) than for cyclones (38%). Residual precipitation, i.e., precipitation that is not associated with any of the weather systems, is mainly solid (79%). Consistently, hourly precipitation rates are generally larger for precipitation during AR-related weather types with the highest hourly liquid precipitation sums. Both large liquid and solid hourly precipitation sums can only be found when ARs and cyclones occur at the same time. If cyclones and fronts occur separately, solid hourly precipitation rates dominate. For fronts, hourly liquid precipitation sums are notably larger if ARs are present as well.

Daily precipitation amounts at Ny-Ålesund are typically very low with 50% of the daily sums being smaller than 1.3 mm. While trace precipitation with daily precipitation amounts <1 min resolved values), Parsivel and Pluvio detect only precipitation during 8% and 1% of the time, respectively. If daily precipitation totals from Pluvio with precipitation amounts larger than 0 mm(1 mm) are considered, precipitation occurrence is 38% (22%).

When looking at individual precipitation events , i.e., times with a MRR signal and precipitation detected by the Pluvio, radar reflectivity values are can make up a substantial proportion of the total precipitation amount in the central Arctic, it plays a minor role in the total precipitation at least Ny-Ålesund, where it is mainly related to the residual and O-CY classes. 50% of the total precipitation in the analysis period is attributed to daily precipitation amounts of >10 dBZ at some time during the event. This radar reflectivity threshold corresponds roughly to a rain (snowfall) rate of 4.6 mm h^{-1} (0.6 mm h^{-1}). While the quantitative precipitation estimate from the MRR reflectivities was outside the scope of this study, more detailed analyses of radar-based precipitation retrievals will be performed in the future. For example, different $Z_e - R$ and $Z_e - S$ relations, including the proposed method by Schoger et al. (2021) mm. The days with the highest 2% of daily precipitation sums (10 days in total) contribute 18% of the total precipitation. All of these extreme precipitation events are related to enhanced water vapor transport from the North Atlantic or Eurasia, often in the form of ARs and in combination with fronts. In these situations, the liquid fraction is also often high. Almost all days with liquid precipitation >1 mm are associated with at least one of the three weather systems. In the months of November to April, 91% of these days are connected to ARs.

Still, a few points should be noted regarding the presented analysis. The absolute values of the precipitation amount are still uncertain. As seen from the comparison with the uncorrected Geonor data, the corrected Pluvio measurements (using the algorithm by Wolf are likely still underestimated. Following Champagne et al. (2024), different correction functions will be applied , and the performance of radar-based precipitation retrievals for Ny-Ålesund will be assessed. The VISSS measurements could also help to constrain the $Z_e - S$ relations further. Such a data set will be valuable for evaluating satellite-based precipitation estimates, e.g., from CloudSat (Stephens et al., 2002) and the EarthCARE (Wehr et al., 2023) mission, as the MRR also includes vertical precipitation information.

As already seen from the daily precipitation amounts of Pluvio, also the precipitation amountsof the individual precipitation eventsas defined by MRR and Pluvio are often small, with 50% of these events having a precipitation amount of less than 0.8 mm. Extreme precipitation events, i.e., here the upper 2% of the precipitation events with the highest precipitationamount during August 2017 and December 2021 contribute 28% to in the future to better account for the uncertainties of the Pluvio data record. An extended comparison with the processed Geonor precipitation data will provide further insight into the measurement uncertainties. Since the hourly resolved Geonor data have been available since 1997, the study could be expanded to a longer time series to look also into potential changes in precipitation characteristics and their relation to the total precipitation amount of all events considered. All the extreme events analyzed coincide with weather systems. The precipitation measurements from the Bayelva site about 3 km southwest of Ny-Ålesund (Boike et al., 2018) could also be incorporated to better understand the local precipitation variability at this complex location. This is also relevant when setting the measurements in context with simulation results of numerical models. As these models often produce a lot of small, potentially artificial precipitation amounts, it would be interesting to look more into the trace precipitation events. While these events are probably the most challenging ones for precipitation gauge observations, in particular for classical manual gauges, the higher sensitivity of the Parsivel might be beneficial. Also, additional observations from the cloud and micro rain radar will be helpful in identifying blowing snow events that might be falsely interpreted as precipitation.

To connect precipitation at Ny-Ålesund to ARs, cyclones and fronts, we applied a very straightforward approach following Lauer et al. (2023). One criterion was that the weather systems have to be detected over the Ny-Ålesund model grid box. This excludes cases when Ny-Ålesund is already under the influence of a certain weather system that is not directly located above the site. Also, the occurrence and shape of a weather system depend very much on the applied definition and thresholds used (Lauer et al., 2023). We have seen that enhanced water vapor~~transport into the Arctic, with 11 out of 12 cases related to atmospheric river events. The~~ , as highlighted already in other studies, is important for the precipitation at Ny-Ålesund. Instead of using very strict geometric criteria as applied for the detection of ARs, percentiles of water vapor amount or transport might be a more suitable variable to look at. At Ny-Ålesund, the long-term, temporally highly resolved ~~precipitation observations by Pluvio, MRR, and Parsivel can capture the temporal development of these events in more detail. Combining the~~ (2-3 s) microwave radiometer observations of water vapor can be exploited here (Nomokonova et al., 2019). Also, combining the temporally highly resolved precipitation measurements with the additional ~~information from the other in-situ and~~ remote sensing observations at AWIPEV will ~~thus~~ further shed light on the precipitation processes, e.g., precipitation formation, sublimation, and evaporation. Here, the combination with the cloud radar and micro rain radar will be exploited further in the future so that precipitation characteristics can be described in more detail and also be linked to cloud microphysics (e.g., with dual-frequency and polarimetry approaches; Chellini et al., 2023). ~~In addition to detailed case studies, the multi-year data set, which is continuously growing, can be analyzed by exploiting machine learning techniques. These could be used to identify and characterize different precipitation regimes, which are also likely linked to the large-scale synoptic forcing.~~

~~Thus, the data set will be very beneficial for evaluating reanalyses, numerical weather prediction, and climate models regarding precipitation in the Arctic. While the strong local scale variability of precipitation at Svalbard might complicate the comparison of the point measurements with coarser resolved precipitation data sets, the high-resolution simulations with ICON-LEM that have been established for Ny-Ålesund (Schemann and Ebell, 2020; Kiszler et al., 2023) allow for a more direct evaluation and will support the interpretation of the measurements in the future.~~

Data availability. The Pluvio (Ebell et al., 2023b) and Parsivel data (Ebell et al., 2023a) have been published on PANGAEA. The 12 hourly precipitation sums of the precipitation gauge of the Norwegian Meteorological Institute (MET Norway) and the corrected precipitation estimates have been taken from Jacobi and Champagne (2024). 2 m temperature and wind observations at AWIPEV are from Maturilli (2020). The ERA5 reanalysis datasets were provided by ECMWF (Hersbach et al., 2023b, a). The global atmospheric rivers catalog for ERA5 reanalysis is available on PANGAEA (Lauer et al., 2023). The detected weather systems (atmospheric rivers, cyclones, fronts) at Ny-Ålesund for 2017–2021 are available in Lauer (2024).

Appendix A: ~~MRR calibration evaluation~~

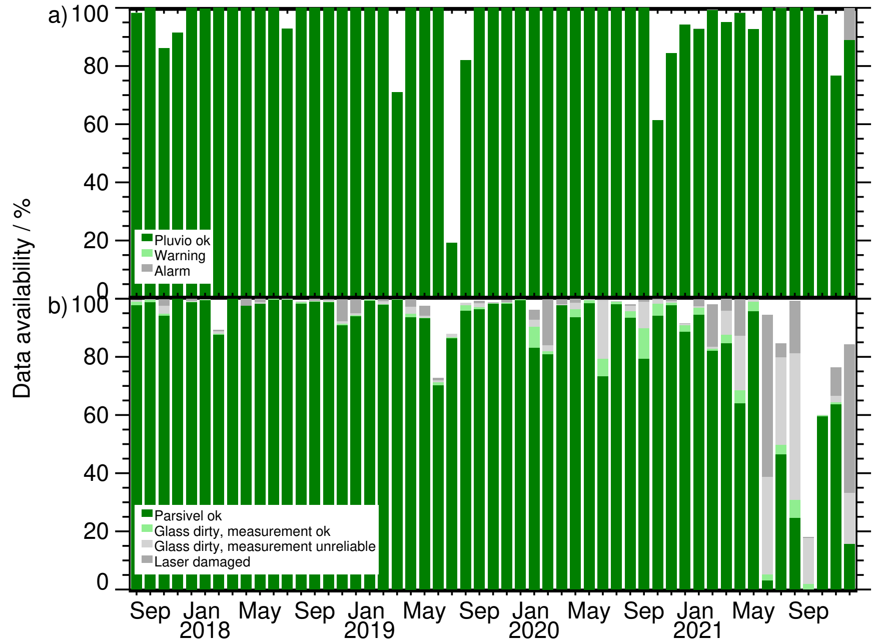

Figure A1. Data availability and status of a) Pluvio ~~,~~ and b) Parsivel ~~, and c) MRR data (based on measurements at 120 m)~~ from May 2017 to December ~~2020.~~ 2021. Green (~~grey~~gray) colors indicate data that should (not) be used. See legend for more details.

~~The absolute calibration of the MRR was evaluated against Parsivel observations of drop size distributions (DSDs) in rain collected during July-September 2022. Radar reflectivity was forward simulated based on the observed DSDs, and compared against values observed by the MRR, following the approach described in Chellini et al. (2022). The calibration offset was estimated to be +0.6 dB, with the positive sign indicating that the instrument underestimates reflectivity. The calibration evaluation was performed based on data recorded outside of the period analyzed in the current study since we noticed biases in the Parsivel data. We observed a systematic underestimation of total accumulated precipitation by Parsivel when compared to Pluvio, which might, in turn, lead to biases in the forward-simulated reflectivity used in the calibration. At the same time, we believe that such bias does not affect the precipitation classification used in the analysis. Parsivel was replaced with a new identical instrument in June 2022, which did not display the bias. It is for this reason that we estimate the MRR offset based on data recorded in July–September 2022.~~

Author contributions. KE, RG and MM conceptualized the manuscript. KE and CB analyzed data and prepared the plots. GC and AW worked on processing instrument data. PK took care of the instrument operation, data collection and basic processing. ML provided the

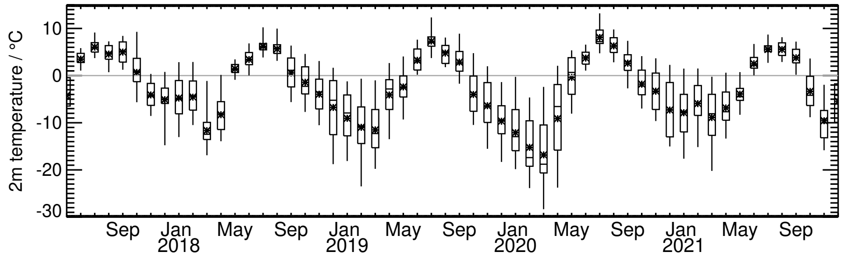

Figure A2. Monthly ~~box plots~~ boxplots of daily mean 2 m temperature at Ny-Ålesund. The extent of the whiskers indicates the minimum/-maximum value. A star indicates the mean value.

atmospheric river, cyclone and front detection and helped interpret the results. SD provided visualizations of the reanalysis data and analyzed the figures. KE is the main author of this paper. All co-authors contributed to discussions and reviewed the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

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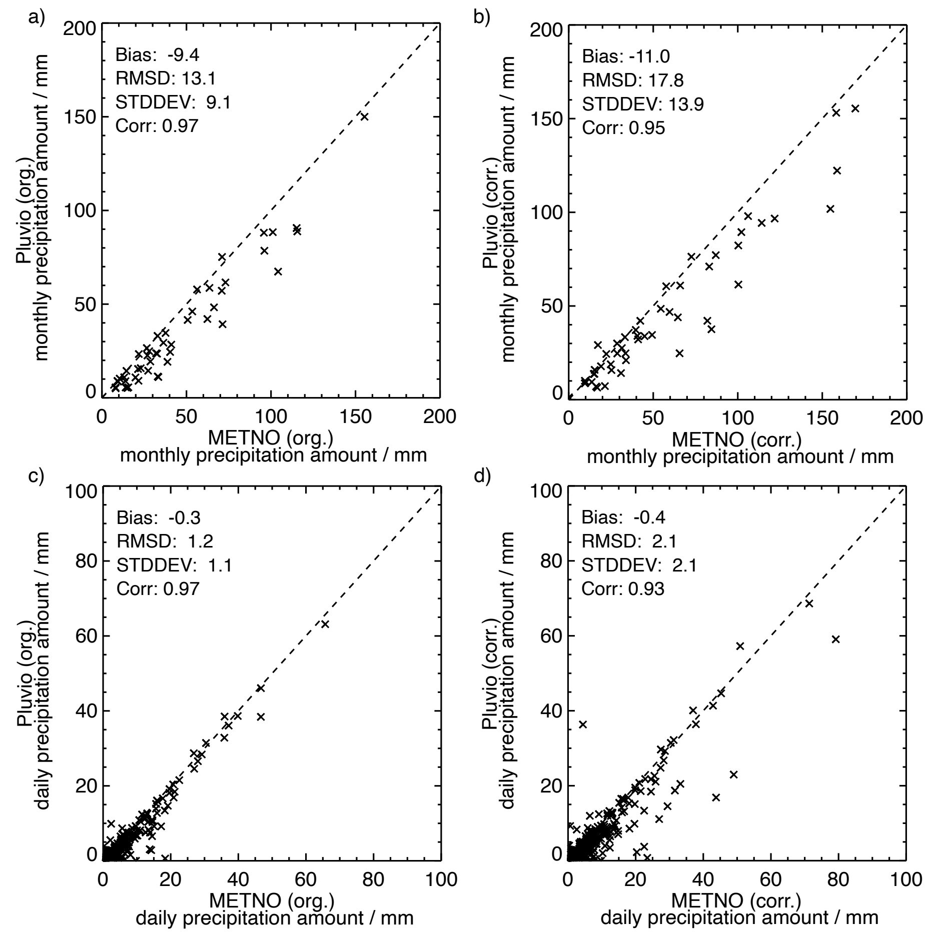

Figure A3. Scatter plots of monthly and daily precipitation sums at Ny-Ålesund for 1 August 2017 – 31 December 2021. a) Monthly uncorrected precipitation amount of MET Norway precipitation gauge vs. Pluvio. b) Corrected monthly precipitation amount of MET Norway precipitation gauge (ensemble mean correction by Champagne et al., 2024) vs. Pluvio (with correction from Wolff et al., 2015). c) Same as a) but for daily data. d) Same as b) but for daily data. The bias, root-mean-squared difference, the standard deviation and the correlation are shown as well.

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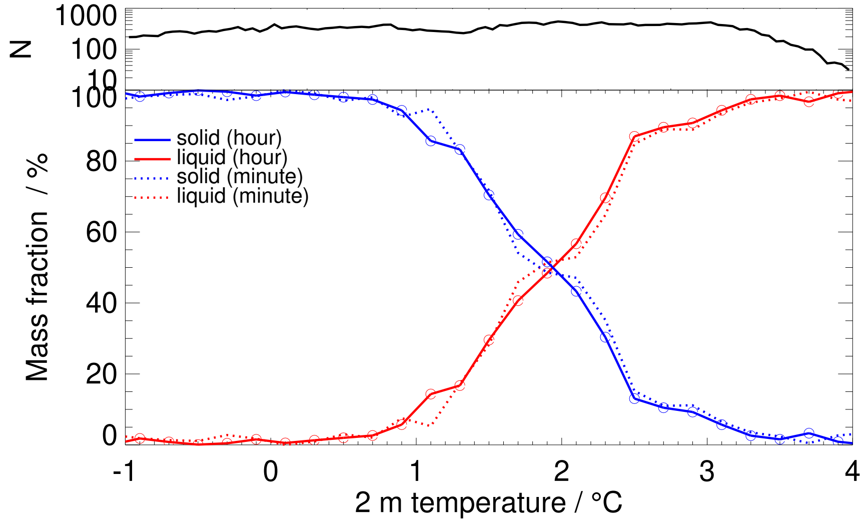

Figure A4. Solid (blue) and liquid (red) mass fractions (in %) as a function of 2 m temperature (in °C) based on the 1 min resolved data (dotted lines, same as in Fig. 5b) and the hourly averaged 2 m temperature and hourly accumulated liquid and solid precipitation values (solid lines), respectively. The hourly precipitation values are derived from the 1 min resolved corrected Pluvio measurements together with the combined Parsivel/temperature-based mass separation method. See text for more details. Temperature bin size is 0.2°C, e.g. [0.2,0.4), [0.4,0.6), etc., with N the number of cases within a temperature class.

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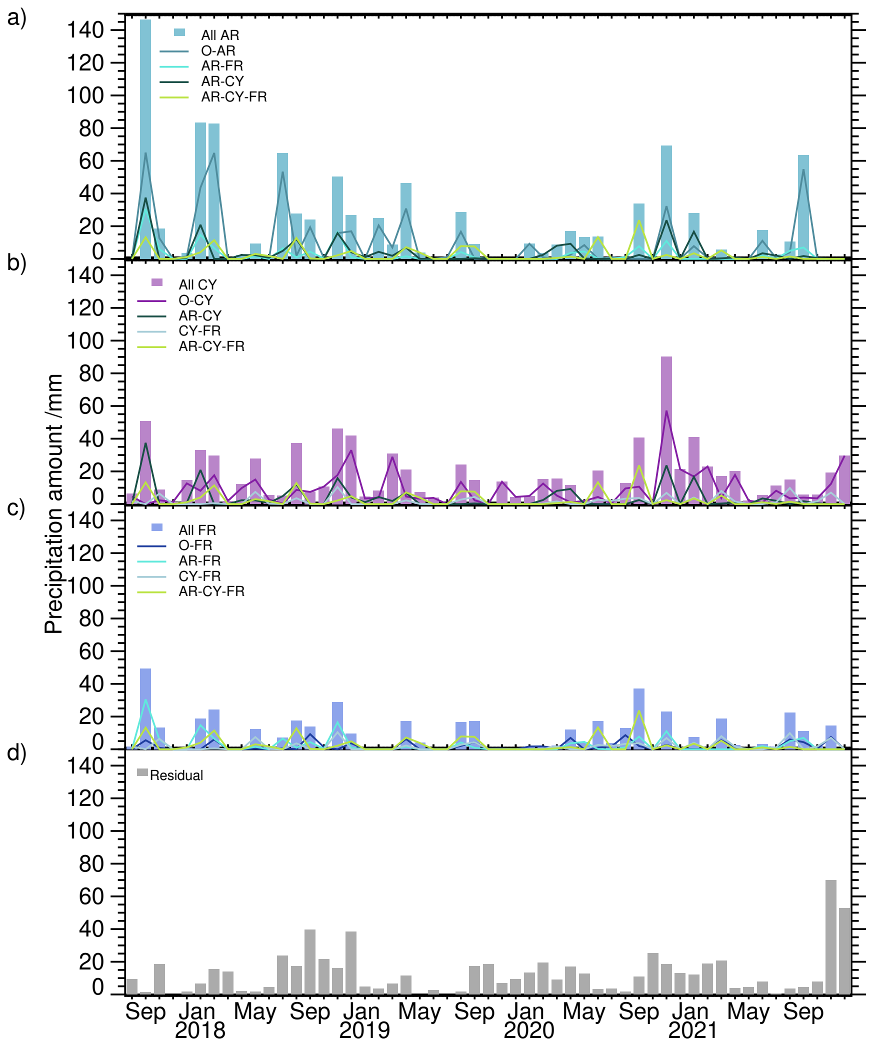

Figure A5. Monthly precipitation amount (in mm) related to a) atmospheric rivers (AR), b) cyclones (CY) and c) fronts (FR). Weather systems can occur separately (O-AR, O-CY, O-FR) or at the same time in different combinations (colored lines, see legends). "All" (colored bars) includes all cases with a certain system regardless of whether the other two systems are present or not.

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