Estimating the Snow Density using Collocated Parsivel and MRR Measurements: A Preliminary Study from ICE-POP 2017/2018

Wei-Yu Chang[1], Yung-Chuan Yang[1], Chen-Yu Hung[1], Kwonil Kim[2], Gyuwon Lee[3]

[1]Department of Atmospheric Sciences, National Central University, Taoyuan, Taiwan
5 [2]School of Marine and Atmospheric Sciences, Stony Brook University, NY, USA
[3]Department of Atmospheric Sciences, Center for Atmospheric REmote sensing (CARE), Kyungpook National University, Daegu, Republic of Korea

Correspondence to: Wei-Yu Chang (wychang@g.ncu.edu.tw)

Abstract. A new method is developed to derive the hydrometer's bulk density and bulk water fraction from collocated
10 measurements from Micro-Rain Radar (MRR) and Particle Size and Velocity disdrometer (Parsivel). Rigorous particle scattering simulation, namely the T-matrix method, is applied to particle size distribution data of Parsivel to calculate the reflectivity (Z_{HH}). The possible combinations of the particle's ice, air, and water are derived to compare them with the MRR-measured Z_{HH}. The combination of minimum water fraction subsequently determines the bulk density (ρ_{bulk}). The proposed method is applied to the data collected from the International Collaborative Experiments for Pyeongchang 2018 Olympic and
15 Paralympic Winter Games (ICE-POP 2018) Projects and its pre-campaign. The estimated ρ_{bulk} was examined by self-evaluation of reflectivity weighted fall velocity (Vz) of MRR and independent comparison of the liquid-equivalent snowfall rate (SR) of collocated Pluvio. The bias values are adequately low (Vz: -0.27~0.14 m s^{-1}, SR: 0.52~0.74 mm hr^{-1}). The correlation coefficient of calculated SR from estimated ρ_{bulk} and observed SR from Pluvio can be up to 0.74. The results indicate the capability to derive reliable ρ_{bulk} through the proposed method, leveraging the compact and easily deployable
20 designs of MRR and Parsivel. The derived bulk density of the two warm-low cases (28 February and 07 March 2018) shares a similar transition as the systems were decaying. The particles with higher bulk density and bulk water fraction were found in the coastal sites (BKC and GWU: mean ρ_{bulk} values are 0.12 to 0.25 g cm^{-3}), typically accompanied by higher liquid-water constituents (mean values of the top 5% bulk water fraction are 0.33 to 0.50) than the inland sites (YPO and MHS: mean ρ_{bulk} values are 0.09 to 0.08 and mean values of the top 5% bulk water fraction are 0.001 to 0.029) during such synoptic conditions.

1 Introduction

25 The particle size distributions (PSD) and physical properties of hydrometers in winter storms are essential to discriminate among hydrometeor types (e.g., riming and aggregate snow) and develop algorithms (e.g., quantitative precipitation estimation of snow) for estimating the liquid water content of hydrometer with remote sensors (e.g., polarimetric radar and satellite). These physical properties, including terminal fall speed, shape, composition, and density, are crucial to verifying and

30 improving microphysical parameterizations in numerical forecast models (Yuter et al. 2006; Kim et al. 2021). For example,

riming processes led to snowfall velocity and density diversity in the same particle diameter size (Zhang et al. 2021). The supercooled liquid water freezes on snow particles and fills in the holes of snow; therefore, snow's mass and fall velocity increase while size has little changes (Heymsfield 1982; Moisseev et al. 2018). On the other hand, the melting process induces higher fall velocity and density by increasing liquid phase fraction in a warm environment. The dispersed fall velocity caused

35   by particles melted from dry snow to rain leads to higher collision efficiency and facilitates the aggregation and accretion processes (Yuter et al. 2006). Higher snow density is associated with steeper fall velocity and diameter (V-D) relations, which result from stronger riming (Lee et al. 2015) or melting processes (Yuter et al. 2006). To emulate the diverse physical properties of hydrometers, Morrison and Milbrandt (2015) proposed a new bulk method to parameterize ice-phase particles with evolvable density to study the role of density in numerical simulation. Radar-based quantitative precipitation estimation (QPE)

40   of liquid equivalent snowfall rate (SR) from equivalent reflectivity (Ze) inhibits great uncertainty due to the diversity of snow properties (Huang et al. 2010, 2015, and 2019). Pre-assumed snow density in Ze-SR relation is one of the critical factors. The snow density caused by various degrees of riming and melting processes is essential to derive the Ze-SR relation (Huang et al. 2014).

      As the snow density cannot be measured directly, various techniques with diverse measuring principles have been

45   developed to investigate snow density using observational data. Brandes et al. (2007) estimated the bulk snow density from a two-dimensional video distrometer (2DVD) derived precipitation volume and the collocated gauge-measured precipitation mass. A climatological relation of bulk snow density and median volume diameter (D_0) is also obtained. Nevertheless, various factors influence the density of frozen precipitation, which cannot be well illustrated by size-density relation (Roebber et al. 2003); Zhang and Luchs (2011) proposed a terminal velocity–based modification to the density value derived from the equation

50   for terminal fall velocity (Pruppacher and Klett 1997). Several studies have proven that after the differentiation of riming degree, the density of snow can be derived correctly from the corresponding size (Li et al. 2018; Zhang et al. 2021; Lee et al. 2015; Zhang and Luchs 2011). An alternative approach is to use radar reflectivity to constrain the estimated bulk snow density. Huang et al. (2010) utilized a 2DVD to derive snow's particle size distribution (PSD) and a C-band dual-polarimetric radar to obtain the reflectivity on top of 2DVD. The measured reflectivity (Ze) was subsequently used to estimate the snow density by

55   minimizing the measured Ze from radar and calculated Ze from 2DVD. Mroz et al. (2021) proposed an algorithm utilizing triple-frequency (X, Ka, W) radar measurements to retrieve the size, ice water content (IWC), and degree of riming of ice clouds. The results indicate the estimates of the mass-weighted diameters and IWC estimates are adequately accurate. Yet, the degree of riming remains challenging.

      Even though the 2DVD provides state-of-the-art hydrometer particle observation, the 2DVD is challenging to maintain

60   and not ideal for continuous unattended operation (Tokay et al. 2017). A viable alternative method utilizing collocated Micro Rain Radar (MRR, Löffler-Mang et al. 1999) and Particle Size and Velocity (Parsivel, Loffler-Mang and Joss 2000) distrometer is proposed in this study to derive the bulk snow density. Parsivel and MRR are reliable, robust, easy to maintain, and relatively affordable. Hence, they are widely used in the research community and typically collocated. The MRR is a vertically pointing frequency modulated continuous wave (FMCW) radar at 24.23 GHz. The radar transmitted radiation vertically upward, and

65 the hydrometeor above scattered a portion of the energy back to the antenna. The magnitude and frequency of the backscatter signal provide the vertical profiles of Z_{HH} and the Z_{HH} weighted fall velocity (V_Z) (Kneifel et al. 2011). Parsivel is a laser-based optical distrometer for simultaneous particle size and velocity measurements. As the hydrometeor passes through the laser beam generated by the transmitter, particle extinction leads to a decrease in the energy detected by the receiver. The amplitude of the energy reduction determines particle size, and the particle velocity is derived from the reduction duration.

70 Similar to Huang et al. (2010), the measured Z_{HH} from MRR is applied to constrain the probability of volume ratio of ice and liquid water (vi and vw) on the simulated Z_{HH} from particle size distribution (PSD) of Parsivel in the proposed method. The bulk density of snow (ρ_{bulk}) is consequently derived from the vi and vw, corresponding to the most consistently measured and simulated Z_{HH}. Subsequently, the measurement of Z_{HH} weighted fall velocity (V_Z) from MRR, regarded as the self-evaluation of our result, is compared with the calculated V_Z from the derived bulk density and PSD measurement from Parsivel.

75 The consistency between the measured and calculated Vz ensures the reliability of the estimated bulk snow density. Finally, independent measurements of the liquid-equivalent snowfall rate observed by Pluvio evaluate the bulk snow density from the proposed method.

The main objective of this study is to evaluate the algorithm as introduced earlier. The data of the microphysical instruments, namely MRR, Parsivel, and Pluvio, from the International Collaborative Experiments for Pyeongchang 2018

80 Olympic and Paralympic Winter Games (ICE-POP 2018) Projects and its pre-campaign is applied to estimate the bulk density of snow. The performance and applicability of the proposed algorithm are examined using the ICE-POP data. The instruments and data are introduced in section 2. The methodology is detailed in section 3. The results are summarized in section 4. Finally, the conclusion is shown in section 5.

2 Instruments and Data Processing

85 The data of MRR, Parsivel, and Pluvio were collected during the ICE-POP 2018 (2017/2018 winter) and the pre-ICE-POP campaign (2016/2017 winter). The instruments were located in nineteen sites across the Gangwon region on the east coast of Korea (Kim et al. 2021). Five sites with collocated MRR and Parsivel were available for this study. These sites aligned across the Taebaek Mountains from mountain to coast are YPO (YongPyong Observatory), MHS (MayHills Supersite), CPO (Cloud Physics Observatory), BKC (BoKwang 1-ri Community Center), and GWU (Gangneung-Wonju National University),

90 respectively. The YPO, MHS, and CPO sites are in the mountainous region, while GWU and BKC sites are in the coastal area. The data available from these five sites during the pre-campaign and ICE-POP campaign are listed in Table 1.

The snow observation from Parsivel suffers from various issues due to the measuring principle (Battaglia et al. 2010). The minute PSD data was quality-controlled using the fall velocity filtering technique (Lee et al. 2015). The mean fall velocity and standard deviation (σ) for a given diameter were calculated, and the particles that deviate from the mean fall velocity of

95 more than one standard deviation were filtered. The quality-controlled data of Parsivel was subsequently processed for the Z_{HH}

calculation. The third gate of Z_{HH} data from MRR was selected for retrieving snow density since some clutter contamination can be found in the first two gates.

The MRR and Parsivel have different measuring principles and designs. The measurement inconsistency between collocated MRR and Parsivel degrades the accuracy of estimating the bulk density. To ensure the observation consistency between MRR and Parsivel data and to minimize the measurement bias, the pure rain precipitation events (13-14 April 2018 and 22-23 April 2018) were selected to calculate the bias in rainfall rate between MRR and Parsivel. The data was quality controlled by examining the rainfall rate of the MRR, Parsivel, and collocated Pluvio. The rainfall rate measurements from Parsivel and Pluvio (a weighing gauge) were consistent with each other. Thus, the Parsivel PSD data was applied to the T-Matrix simulation to obtain Z_{HH}. The mean bias was derived after excluding one standard deviation outlier data. The mean bias values of each MRR are listed in Table 2. The results indicate that the MRR consistently underestimated the reflectivity from 2.1 to 10.2 dBZ. The MRR data have been bias-corrected by applying the bias values listed in Table 2.

3 Methodology

Hydrometeor is composed of solid ice and liquid water with a density of 0.92 (ρ_{ice}) and 1.0 (ρ_{water}) g cm^{-3}, respectively. Therefore, the hydrometeor bulk density (ρ_{bulk}) can be determined by its volume ratio of solid ice (vi) and liquid water (vw) as follows,

$$\rho_{bulk} = \text{vi} \times 0.92 + \text{vw}; \ \text{g } cm^{-3}. \tag{1}$$

The sum of the values of vi and vw equals one or less than one if it contains air in the particle. Thus, the reflectivity factor (Z_{HH}) can be calculated as follows under Rayleigh scattering assumption (Huang et al. 2010),

$$Z_{HH} = \left(\frac{\rho_{bulk}}{\rho_{ice}}\right)^2 \frac{|K_{ice}|^2}{|K_w|^2} \int D^6 N(D) dD; \ mm^6 \ m^{-3}. \tag{2}$$

The K_{ice} and K_w are the dielectric factors of solid ice and liquid water, respectively. *D* is the particle size, and *N(D)* is the particle size distribution. As shown in (1) and (2), the Z_{HH} is positively correlated to ρ_{bulk}. The higher hydrometer bulk density has a higher value of Z_{HH} for a given PSD. Hence, the Z_{HH}, the factor relating to the vi and vw of hydrometeor, can estimate the bulk density. Huang et al. (2010) utilized the C-band radar measurements on top of a 2DVD. The ρ_{bulk} was derived from (2) by applying the reflectivity from C-band radar and the PSD from 2DVD. However, the sampling size discrepancy of C-band radar resolution volume on top of 2DVD was neglected by Huang et al. (2010).

The bulk density estimation algorithm developed in this study is modified by Huang et al. (2010). Instead of scanning C-band radar and 2DVD, the collocated MRR (Micro Rain Radar, Löffler-Mang et al. 1999) and Parsivel are proposed to minimize the sampling size inconsistency. The estimated density is considered as "bulk" or "equivalent" density since the MRR Z_{HH} measurement is the summation of all hydrometeor within the sampling volume. The procedures of the proposed method are introduced in the following section, and the validation and discussion are described in the next section.

The Z_{HH} values were simulated from each Parsivel PSD measurement. Each Z_{HH} value was calculated using a rigorous T-matrix method with specified vi and vw (Vivekanandan et al. 1991; Bringi and Chandrasekar 2001). The T-matrix method is a fast numerical solution of Maxwell's equations to compute the scattering properties of particles. The shape of the hydrometeor is regarded as a symmetric sphere since the Z_{HH} measurement of the hydrometer was observed from the bottom of the snow

130   particle by vertical pointing MRR. The mean and standard deviation of the canting angle are assumed 0° and 20°, respectively.

An example of simulated Z_{HH} from Parsivel observed snow PSD via T-matrix simulation with different combination of vi/vw and temperature is shown in Fig. 1. The results indicate that the simulated Z_{HH} values remain nearly identical when varying the temperature from -10 to 0 ^{0}C. On the other hand, the simulated Z_{HH} varies significantly when altering the composition of vi/vw. The lowest (highest) value of Z_{HH} was from the combination of vi/vw of 1.0/0.0 (0.0/1.0), which was

135   pure ice (rain) with a density of 0.92 (1.0) g cm^{-3}. The particle temperature was consequently assumed to have a constant value of 0℃ in the following Z_{HH} T-matrix simulation. On the other hand, all possible combinations of vi and vw ranging from 0.0 to 1.0 were included in the T-matrix simulation of Z_{HH}.

A selected example of the simulated Z_{HH} from observed PSD with various combinations of vi/vw is shown in Figure 2. The observed PSD from Parsivel (Fig. 2a) was applied to the T-Matrix backscattering simulation. All possible combinations of

140   vi/vw were used to calculate simulated Z_{HH} (Fig. 2b). The corresponding bulk density was derived via (1) and shown as contour lines in Fig. 2b. The values of simulated Z_{HH} vary from -5 to 35 dBZ (shaded color in Fig. 2b). The simulated Z_{HH} values increase as the increasing of the bulk snow density. In this selected case, the observed Z_{HH} from MRR was 18.49 dBZ (blue dash line in Fig. 2b). The observed Z_{HH} from MRR was thus applied to constrain the possible combination of vi/vw and bulk density. The possible ranges of vi/vw are 0.0/0.02 to 0.3/0.0, shown as a dashed blue line in Fig. 2b. The corresponding bulk

145   density are 0.02 and 0.28 g cm^{-3}, respectively. The higher the fraction of ice (e.g., vi), the higher bulk snow density values can be found in Fig. 2b. To determine the bulk snow density from possible combinations of vi/vw, bulk density with the maximum vi is selected as suggested in Huang et al. (2010). The contour's maximum density, 0.28 g cm^{-3}, is determined as the estimated bulk density by assuming vw is 0.

Moreover, liquid water's dielectric constant value is higher than that of solid ice. Consequently, the magnitude and variation

150   of retrieved density are influenced mainly by vw, as shown in Fig. 2b. The change of vw can be adequately obtained in the proposed method. Consequently, vw can be regarded as "bulk water fraction" which can also be estimated in the proposed method besides the bulk density and will be analyzed in the following section.

This study will use two approaches to evaluate the density derived from the proposed method with collocated MRR and Parsivel measurements. First, the bulk density was self-verified with the reflectivity-weighted fall velocity (V_Z). The fall

155   velocity measurements from MRR (V_Z^{MRR}) and the "density-calculated" fall velocity derived from bulk density ($V_Z^{\rho bulk}$) are compared to ensure the consistency of observed and calculated V_Z.

The terminal fall velocity of particle size D, $V(D)$, was computed from derived bulk density (ρ_{bulk}) as follows (Rogers and Yau 1989),

$$V(D) = \left(\frac{4}{3}\frac{g}{C_d}\frac{\rho_{bulk}}{\rho_{air}}\right)^{0.5} D^{0.5} \quad (3)$$

160 The C_d is the drag coefficient and equals to 0.5 for the sphere hydrometeor assumption. g is the gravity constant (9.81 kg m^{-2}). ρ_{air} is the air density which is assumed as constant ($1.29 \times 10^{-3} g\ cm^{-3}$) in the calculation. Subsequently, the corresponding $V_Z^{\rho bulk}$ can be obtained from $V(D)$ as following,

$$V_Z^{\rho bulk} = \frac{\sum Z(\rho_{bulk}, D)\, V(D)\, N(D)\, dD}{\sum Z(\rho_{bulk}, D)\, N(D)\, dD} \quad (4)$$

The $Z(\rho_{bulk}, D)$ indicates the reflectivity factor from retrieved bulk density (ρ_{bulk}). $N(D)$ represents the number
165 concentration of the particle size D obtained from Parsivel.

The comparison of the $V_Z^{\rho bulk}$ and the V_Z^{MRR} is considered as a quality control procedure of the retrieved bulk density. This procedure utilizes independent measurement, V_Z^{MRR}, which is not used in the bulk density retrieval process. As discussed in the previous section, the proposed retrieval technique requires well-calibrated data from MRR and Parsivel. Nevertheless, the snow observations from Parsivel and MRR suffered various issues due to measuring principles. The V_Z criteria of the five sites
170 are determined as the absolute value of the V_Z mean bias of the sites plus one standard deviation of the bias. The V_Z criteria are applied to each site to remove inadequate bulk density estimation. The corresponding V_Z criteria values are shown in Table 3.

The second approach to evaluating the retrieved bulk density is examining the liquid-equivalent snowfall rate (SR, mm hr^{-1}). The collocated Pluvio was utilized to investigate the performance of the derived bulk density. The SR was calculated with
175 the derived bulk density ρ_{bulk}, fall velocity $V(D)$ and the PSD from Parsivel measurement as shown in (5).

$$SR = 3.6 \sum_{i=1}^{32} \frac{\pi\rho_{bulk}}{6} D^3 \times V(D_i)N(D_i) \quad (5)$$

The measured and calculated SR are integrated into 5 min resolution (Li et al. 2018) to avoid instant fluctuation in the comparison. The SR calculated from the derived density is examined with the Pluvio SR, independent of the Parsivel and MRR observations. In addition, the $\rho_{bulk} - D_0$ relation is also derived for analysis. Once the PSD is obtained from Parsivel, the
180 median-volume diameter (D_0) defined in (6) can be derived (Brandes et al. 2007),

$$\int_{D_{min}}^{D_0} D^3 N(D)dD = \int_{D_0}^{D_{max}} D^3 N(D)dD \quad (6)$$

where one-half of the precipitation volume is contained in particles smaller than D_0 and one-half is contained in particles larger than D_0.

4 Results

185 The bulk density estimation has been applied to all available data during the ICE-POP 2018 and its pre-campaign, as listed in Table 1. There are 17 events: five sites with collocated MRR and Parsivel and four with Pluvio. The density-calculated fall

velocity ($V_Z^{\rho bulk}$) will first examined with MRR measured fall velocity (V_Z^{MRR}). The purpose is to remove inadequate bulk density retrieval due to MRR and Parsivel measurement issues. Subsequently, the liquid-equivalent snowfall rate (SR) will be validated by collocated Pluvio measurements. The statistical performance of retrieved bulk density will be investigated by

190 comparing the SR. Furthermore, the detailed analysis of the two selected events will be illustrated by examining their environmental condition, precipitation type, and the spatiotemporal evolution of retrieved bulk density and bulk water fraction.

4.1 Reflectivity-weighted (V_Z)

The normalized number density function of measured V_Z^{MRR} from MRR and "density-calculated" $V_Z^{\rho bulk}$ from PSD of five sites are shown in Fig. 3. The V_Z^{MRR} and $V_Z^{\rho bulk}$ are in agreement with each other. Most of the fall velocities were less than 2

195 m s^{-1}. In addition, MHS, CPO, and GWU sites had second peak values of about 2.0-3.0 m s^{-1} and showed reasonably consistent values. The BKC sites had the most consistency of velocity. On the other hand, the GWU site had the most discrepancy, which $V_Z^{\rho bulk}$ was sometimes higher than V_Z^{MRR}. The bias and standard deviation values (Table 3) are about -0.27 ms^{-1} to 0.03 ms^{-1} and 0.67 to 0.94 ms^{-1}, respectively. In general, the $V_Z^{\rho bulk}$ values of YPO, MHS, and CPO (BKC and GWU) are slightly lower (higher) than V_Z^{MRR}. The bias and standard deviation values are -0.07 ms^{-1} and 0.80 ms^{-1}, respectively. A more detailed

200 comparison will be shown in the selected case study.

The deviation of the calculated V_Z is partly attributed to the idealized equation of terminal fall velocity in (3) and (4). In the V_Z calculation, particles are assumed to be spheres, and the drag coefficient is 0.5. The various shapes and falling behaviors of ice-phase and mixing-phase particles induce noise and deviation when comparing MRR V_Z measurements. Moreover, various measurement issues of MRR and Parsivel also influence some inconsistency. Subsequently, the V_Z criteria value

205 determined from each site's standard deviation was obtained to remove inadequate bulk density retrieval. The V_Z criteria values are about 0.84 to 1.8 m s^{-1} (Table 3). The retrieval of the difference between $V_Z^{\rho bulk}$ and V_Z^{MRR} greater than V_Z criteria was removed in the following analysis.

4.2 Liquid-equivalent snowfall rate (SR)

After removing the inadequate bulk density retrievals with the V_Z criteria, the density-derived SR is obtained and compared

210 with collocated Pluvio measurements. Fig. 4 demonstrates the normalized number density function of the density-derived and measured SR of four sites. The majority of the SR values are less than 2.0 mm hr^{-1}. Most retrieved and observed SR are around the 1-to-1 line, indicating that the retrieved bulk density SR agrees with the Pluvio SR measurement. Some fractional data scatter away from the 1-to-1. The correlation coefficient values are between 0.52 and 0.74, as shown in Table 3. The bias and standard deviation values of each site are about -0.27 to -0.11 mm hr^{-1} and 0.73 to 1.09 mm hr^{-1}, respectively. The overall

215 mean bias and mean standard deviation values of five sites are -0.18 ms^{-1} and 0.93 mm hr^{-1}, respectively. The results indicate that the density-derived SR is slightly lower than the Pluvio-observed SR. It is postulated that the attenuation effect caused by the accumulated snow atop the MRR antenna induced the underestimation of the reflectivity and thus the retrieved bulk density

and SR. Even though the MRRs deployed in ICE-POP were equipped with heating capability, notes taken during the observation indicates the presence of a significant amount of accumulated snow on the antenna. Thus, some inconsistency
220 between MRR reflectivity and Parsivel PSD can be noticed. More discussion will be shown in the next section.

Two snow events, 28 February 2018 and 7 March 2018, from the ICE-POP 2018, are selected for further investigation. The synoptic pattern of these two events was characterized as warm-low, according to Kim et al. (2021), with the low pressure situated to the south of the polar jet. Most of the precipitation was in the southern and eastern parts of Korea. The warm and moist air was transported from the Yellow Sea and East Sea. This moisture air forms supercooled water as it encounters the
225 steep Taebaek mountain, which benefits the growth of ice-phased particles by riming (Kim et al. 2021). The event on 28 February 2018 had the most intense precipitation rate, and accumulated snowfall during the ICE-POP (Gehring et al. 2020) is investigated comprehensively. The data of the MHS site is examined to understand the pros and cons of the proposed bulk density estimation algorithm. The derived bulk density and the weather factors of the five sites aligned from the Taebaek mountain to the coast (from southwest to northeast are YPO, MHS, CPO, BKC, and GWU) from the event of 7 March 2018
230 are investigated to understand the performance of derived bulk density in different environment condition.

4.3 Case study: 28 February 2018

The time series of observational data from the MHS site on 28 February 2018 is shown in Fig 5, the mid-level precipitation was evaporated and observed by MRR from 00 to 03 UTC (Fig. 5c). Precipitation reached the surface at 03 UTC and continued until 16 UTC (Fig. 5b), the precipitation gradually weakening after 16 UTC (Gehring et al. 2020). Both retrieved bulk density
235 and bulk water fraction decreased gradually from 0.4 to 0.05 g cm^{-3} and 0.5 to 0.0 between 03 and 05 UTC (Fig. 5a), while the temperature slowly dropped from 5°C to 0°C. The derived bulk density between 04 and 16 UTC was low (less than 0.2 g cm^{-3}), and the bulk water fraction was nearly zero. The MASC data show aggregate particles during this period (Gehring et al., 2020). The precipitation gradually weakened after 16 UTC, and the bulk density increased again (0.4 to 1 g cm^{-3}). The graupel and small particles were identified as the temperature continued to drop till the end of the day, according to MASC data
240 (Gehring et al., 2020). The higher retrieved bulk density during the weakening period is consistent with the hydrometeor classification of MASC observation in Gehring et al. (2020).

The velocities from MRR (V_Z^{MRR}) and calculated from retrieved bulk density ($V_Z^{\rho bulk}$) are shown in Fig. 5e. The increasing values of V_Z^{MRR} from 15 UTC to 18 UTC is consistent with the $V_Z^{\rho bulk}$ calculated from bulk density. However, a pronounced discrepancy between the $V_Z^{\rho bulk}$ and the V_Z^{MRR} can be noticed at 06 UTC and between 09 and 14 UTC (Fig. 5e). The fall
245 velocity inconsistency suggests that the retrieved bulk density is not derived adequately. It can be noticed that there was a pronounced Z$_{HH}$ drop in MRR measurement around 06 UTC and 09 to 13 UTC (Fig. 5d), which is inconsistent with PSD measurement (Fig. 5c). This implies that significant snow accumulation on the antenna, particularly associated with large-sized aggregated snow at 06 UTC (Fig. 5c), likely results in strong attenuation. This leads to the degraded performance of the

bulk density retrieval algorithm. The unreasonable retrieval data is identified by V_Z criteria introduced in the previous section and is regarded as less credible (gray area in Fig. 5).

In Fig. 5f, the consistency of the bulk density calculated SR and observed SR from Pluvio can be found from 03 to 08 UTC and 15 UTC to 24 UTC. The underestimation of the bulk density calculated SR from 08 to 15 UTC was caused by the attenuated MRR measurement. The V_Z criteria also identify the underestimated SR. Overall, both the $V_Z^{\rho bulk}$ and SR show good agreement with the MRR and Pluvio, except the period with inadequate bulk density. The result indicates that the algorithm can derive bulk density adequately.

The fall velocity-diameter relation examines the overall microphysical characteristics of the event in Fig. 6. Distinct characteristics of the fall velocity-diameter relation can be noticed before 04 and after 16 UTC. In Figs. 6a and c, most of the hydrometeor size was less than 2 mm (Fig. 5b), and fall velocity was more significant than 1 m s^{-1} (Fig. 5e, close to the fall velocity-diameter relation of rain and graupel) before 04 UTC and after 16 UTC. Before 04 UTC, the fog near the surface and nimbostratus was observed by W-band radar (Gehring et al. 2020). In addition, the temperature was above 0˚C, and the particle size was less than 5 mm. These features suggest possible wet snow, small raindrops, and drizzle. After 16 UTC, the graupel and small particles with near zero environment temperature were identified by MASC (Gehring et al. 2020). From 04 to 16 UTC (Fig. 6 b), the particles were aggregate-like with a lower derivation density. The particle size was 8 to 20 mm (Fig. 5b and Fig. 6b). More particles were found between the lines of graupel and dry dendrites fall velocity-diameter relations.

4.4 Case study: 7 March 2018

Both the 7 March and 28 February events share similar larger-scale conditions. The difference between these two events is that the precipitation on the 7 March was relatively weaker yet persisted for longer than the 28 February event. An east-moving trough from east China became a potential vorticity streamer, which produced prominent precipitation (Gehring et al. 2020). The low-pressure system developed over the Korean peninsula and produced intensive precipitation. Besides the similarity in larger-scale conditions, the microphysical characteristics of precipitation systems share similar behaviors in these two cases. The bulk density rapidly increased in most sites (Fig. 7 to 11) as the nimbostratus weakened and dissipated into the shallow convection (about 03 UTC on 08 March 2018). The bulk density also increased as the temperature decreased in YPO, MHS, and CPO sites (Fig. 7a,c to 9a,c). The five sites share similar tendencies of derived bulk density, bulk water fraction, PSD, Z_{HH} profile, and SR. The intensive precipitation system associated with the low-pressure system started at 10 UTC on 7 March and gradually dissipated near 04 UTC on 8 March. The weakened precipitation with shallow convections can be found from 08 UTC to 19 UTC on 8 March.

The overall bulk density and bulk water fraction in the GWU site (Fig. 11) are the highest in all sites. In contrast, the YPO (Fig. 7) site demonstrates a relatively lower magnitude of bulk density and bulk water fraction, especially after 04 UTC on 8 March. The contrast may be attributed to their geographical environment, as the YPO site is located in the westernmost mountainous area of the five sites. In contrast, the GWU site is located on the east coast, which faces abundant moisture from

the East Sea. Gradual increase of density as well as the liquid water content can also be found in the distribution of fall velocity versus the diameter from MHS, BKC, to the GWU sites (Fig. 12). The distributions of the GWU site mostly feature particles concentrated around the fall velocity-diameter relation of rain. While in MHS and BKC sites, especially the MHS site, data are distributed more discretely and scattered between the relation of rain to the relation of dry dendrites. Overall, the features

285   of sites due to the geographical and synoptic environments are successfully revealed by the retrieved bulk density and bulk water fraction, which are in accord with the distributions of all velocity-diameter relations.

The YPO, MHS, and CPO sites had continual low bulk density and bulk water fraction values (about 0.1 to 0.2 g cm^{-3}, Figs. 7a-9a) at the beginning of the precipitation. They gradually dissipated at 04 UTC on 8 March. The MRR reflectivity profiles indicate an intensive precipitation system up to 5 km (Figs. 7c-9c) from 10 UTC on 7 March to 04 UTC on 8 March. The PSD

290   was featured with large particle size (Figs. 7b-9b) and aggregates-like particles (Gehring et al. 2020). The coastal sites began with nimbostratus cloud and high bulk density values (Figs. 10a,b-11a,b), 10 to 13 UTC for BKC and 10 to 19 UTC for GWU on 7 March, followed by similar low bulk density as other sites till 04 UTC on 8 March. The high-density period in the beginning corresponds to a higher bulk water fraction derived. Hence, it implies more liquid-water constituents, which can confirm the distribution of fall velocity and diameter. More data concentrate near the rain relation from 08 to 19 UTC 7 March

295   (Fig. 12c) than 19 UTC to 03 UTC on 8 March in GWU site (Fig. 12f). The higher density initially in MHS and BKC sites are also confirmed by the alike contrast between 08 to 19 UTC on 7 March (Figs. 12a, b) than 19 UTC to 03 UTC on 8 March (Figs. 12d, e).

After 04 UTC on 8 March, all sites featured high bulk density and bulk water fraction (Figs. 9a-11a). The PSDs were mainly small particles (Figs. 9b-11b). According to MRR measurements, the precipitation systems were weaker and shallower (Figs.

300   9c-11c) compared to the period with low bulk density. The Vz of particles also transited from consistently low values to slightly higher and more noisy values (Figs. 9e-11e), suggesting high-density particles with high fall velocity. Compared to 19 UTC on 7 March to 03 UTC on 8 March (Figs. 12d, e, and f), the velocity-diameter velocity relation from 04 to 12 UTC on 8 March has a more consistent relation of rain (Figs. 12g, h, and i). After 12 UTC, more particles were distributed between the relation of rain and graupel (Fig. 12j, k, and l). Before the dissipation of precipitation (around 12 UTC on 8 March), a sudden decrease

305   of Vz and an increase in particle size were found in YPO, MHS, and CPO sites. Low bulk density in YPO, MHS, CPO, and BKC sites also captured this feature.

Moreover, the good agreements between the Pluvio SR and the derived SR calculated from all sites' bulk density can be noticed in Figs. 7f, 8f, 10f, 11f. The Pluvio is not available at the CPO site. Two distinct types of precipitation structures (according to MRR) and microphysical characteristics (bulk density, bulk water fraction, PSD) can be noticed in Figs. 7-11.

310   One has deeper and more intensive precipitation structures, higher bulk density, and bulk water fraction, and is contained with smaller particles. Overall, the estimation of the bulk density and the bulk water fraction demonstrates the contrast between sites of different geographical locations and captures the evolution of the precipitation system.

4.5 Statistical analysis of bulk density and bulk water fraction

The retrieved bulk density and bulk water fraction are investigated statistically to understand the microphysical
characteristics of the winter precipitation systems from ICE-POP 2018 and its pre-campaign. The number density function of
retrieved bulk density and observed median-volume diameter (D_0) of all sites are shown in Fig. 13. The bulk density decreases
exponentially as D_0 increases. The majority of the particle is consistent with $\rho_{bulk} - D_0$ relation of Brandes et al. (2007), which
utilized the data of 52 storm days from the Front Range in eastern Colorado during October–April 2003 to 2005 of a ground-
based two-dimensional video disdrometer. The data of Brandes et al. (2007) is dominated by almost spherical aggregates
having near-exponential or superexponential size distributions.

On the other hand, the $\rho_{bulk} - D_0$ relation from Heymsfield et al. (2004) shows slightly lower bulk density than this study.
Heymsfield et al. (2004) utilized the aircraft data collected from two field programs, namely the Atmospheric Radiation
Measurement (ARM) program, Cirrus Regional Study of Tropical Anvils and Cirrus Layers (CRYSTAL) Florida Area Cirrus
Experiment (FACE) in southern Florida during July 2002. The ARM data is mostly ice clouds formed primarily through large-
scale ascent, and the CRYSTAL observations are mainly from convectively generated cirrus anvils. The consistent $\rho_{bulk} -$
D_0 relations between ICE-POP 2017/2018 and Brandes et al. (2007) can be attributed to the similar environmental conditions
of the two studies. This results indicate that the proposed bulk density estimation algorithm can derive accurate retrievals with
consistent microphysical characteristics in similar environmental conditions.

To further understand the microphysical characteristics of winter precipitation, each site's retrieved bulk density and bulk
water fractions are divided into warm-low (nine cases) and cold-low (five cases) events according to the synoptic condition
(Kim et al. 2021; Gehring et al. 2020). As shown in Fig. 14a, the mean values of bulk density of warm-low events from the
mountain site (YPO) to the coastal site (GWU) are about 0.09 to 0.25 g cm^{-3}. The GWU site has the highest bulk density. On
the other hand, the mean values of bulk density of cold-low events from YPO to GWU are about 0.07 to 0.12 g cm^{-3} (Fig. 14b).
The overall bulk density values are lower in cold-low events than in warm-low events.

In Fig. 14c and d, more than 90% of bulk water fractions are less than 0.03 for warm- and cold-low events. The YPO site
has the lowest bulk water fraction, especially the cold-low events that remain lower than 0.1. The mean value of the top 5% of
the bulk water fraction of each site is obtained for further investigation. The warm-low event has a relatively higher bulk water
fraction than cold-low events due to warmer and moister environments. The values of bulk water fraction gradually increase
from the mountain site (YPO) to the coastal site (GWU) for both warm- and cold-low events. The mean values of the top 5%
bulk water fraction of MHS to GWU site for warm-low events are 0.02 to 0.50, and the cold-low events are 0.12 to 0.30. The
increasing feature of bulk water fraction from YPO to GWU is the same as that of bulk density. These results indicate that the
winter precipitation systems of coastal sites with warmer and moister environments have higher bulk water fraction than
mountain sites.

5 Conclusion

345   The density of snow, one of the key characteristics, varies with the microphysics processes and imposes weather conditions. The variations inherently involve complex behaviors and require more investigations. In the study, the snow density is derived by compositing collocated MRR and Parsivel data, which can be acquired easily. In the proposed method, the PSD from the Parsivel is applied to T-matrix backscattering simulation and compared with the Z_{HH} from MRR. The bulk density and bulk water fraction are derived from comparing simulated and calculated Z_{HH}. The high sensitivity of Z_{HH} to the liquid portion of

350   the particle led to precise bulk water fraction estimation. It implied better capability of the density variation due to bulk water fraction change (ex. melting) in the proposed method in this study.

The reflectivity-weighted fall velocity (V_Z) of MRR is considered as the self-evaluation of the retrieved bulk density and water fraction. Consistency of measured Vz from MRR and calculated Vz from retrieved bulk density from 09 to 15 UTC on 28 February 2018 is noticed. It is postulated that the attenuation effect mainly causes the Vz discrepancy due to the accumulated

355   snow on the MRR antenna. The Vz criteria is proposed to mitigate uncertainties in bulk density retrieval. The performance of the retrieved bulk density is validated by comparing independent measurements of snowfall rate (SR) from collocated Pluvio and calculated SR from bulk density. The consistency of SR has been greatly improved after applying the Vz criteria. The correlation coefficient values can be up to 0.74, and the mean bias is about -0.18 mm hr^{-1}. General consistency between the measured and the bulk density-calculated SR was found in all available cases of the four sites during the ICE-POP 2018

360   campaign.

The bulk density and bulk water fraction of two events with warm low synoptic patterns (28 February 2018 and 7th to 8th March 2018) were investigated. In these two cases, similar demarcations that separate lower and higher-density periods were found in similar synoptic conditions. During the transition, particles' bulk density and fall velocity rose with decreasing particle size while the convection precipitation dissipated. The microphysical similarity of these two events confirms the dependence

365   of the micro-scale factors on the synoptic conditions.

The contrastive bulk density and bulk water fraction between mountain sites (YPO and MHS, lower bulk density and bulk water fraction) and coastal sites (BKC and GWU, higher bulk density and bulk water fraction) indicates the geographical and synoptic environmental effects on distinct microphysical characteristics of winter precipitation systems of each site. Overall, the derivations demonstrated good accordance with the fall speed, the diameter of the particle, and the V_Z and SR in time series,

370   providing an insightful perspective in microphysics analysis.

375

Competing interests

The contact author has declared that none of the authors has any competing interests.

390

395

400

405

References

Battaglia, A., Rustemeier, E., Tokay, A., Blahak, U., and Simmer, C.: PARSIVEL Snow Observations: A Critical Assessment,
410   J. Atmos. Oceanic Technol., 27, 333-344, https://doi.org/10.1175/2009JTECHA1332.1, 2010.

Brandes, E. A., Ikeda, K., Zhang, G., Schönhuber, M., and Rasmussen, R. M.: A Statistical and Physical Description of
Hydrometeor Distributions in Colorado Snowstorms Using a Video Disdrometer, J. Appl. Meteorol. Climatol., 46, 634–650,
https://doi.org/10.1175/JAM2489.1, 2007.

Bringi, V., and Chandrasekar, V.: Polarimetric Doppler Weather Radar: Principles and Applications, Cambridge: Cambridge
415   University Press, doi:10.1017/CBO9780511541094, 2001.

Chang, W. Y., Lee, G., Jou, B. J. D., Lee, W. C., Lin, P. L., and Yu, C. K.: Uncertainty in Measured Raindrop Size
Distributions from Four Types of Collocated Instruments. Remote Sens. 12, 1167, https://doi.org/10.3390/rs12071167, 2020.

Gehring, J., Ferrone, A., Billault-Roux, A. C., Besic, N., Ahn, K. D., Lee, G., and Berne, A.: Radar and ground-level
measurements of precipitation collected by EPFL during the ICE-POP 2018 campaign in South-Korea, Earth Syst. Sci. Data,
420   13, 417–433, https://doi.org/10.5194/essd-13-417-2021, 2021.

Heymsfield, A. J.: A Comparative Study of the Rates of Development of Potential Graupel and Hail Embryos in High Plains
Storms, J. Atmos. Sci., 39, 2867-2897. https://doi.org/10.1175/1520-0469(1982)039<2867:ACSOTR>2.0.CO;2, 1982.

Heymsfield, A. J., Bansemer, A., Schmitt, C., Twohy, C., and Poellot, M. R.: Effective Ice Particle Densities Derived from
Aircraft Data, J. Atmos. Sci., 61, 982-1003, https://doi.org/10.1175/1520-0469(2004)061<0982:EIPDDF>2.0.CO;2, 2004.

425   Huang, G., Bringi, V. N., Cifelli, R., Hudak, D., and Petersen, W. A.: A Methodology to Derive Radar Reflectivity–Liquid
Equivalent Snow Rate Relations Using C-Band Radar and a 2D Video Disdrometer, J. Atmos, Oceanic Technol., 27, 637-
651, https://doi.org/10.1175/2009JTECHA1284.1, 2010.

Huang, G. J., Bringi, V. N., Moisseev, D., Petersen, W. A., Bliven, L., and Hudak, D.: Use of 2D-video disdrometer to derive
mean density–size and Ze–SR relations: Four snow cases from the light precipitation validation experiment, Atmos. Res., 153,
430   34–48, https://doi.org/10.1016/j.atmosres.2014.07.013, 2015.

Huang, G.-J., Bringi, V. N., Newman, A. J., Lee, G., Moisseev, D., and Notaroš, B. M.: Dual-wavelength radar technique
development for snow rate estimation: a case study from GCPEx, Atmos. Meas. Tech., 12, 1409–1427,
https://doi.org/10.5194/amt-12-1409-2019, 2019.

Kneifel, S., Maahn, M., Peters, G., and Simmer, C.: Observation of snowfall with a low-power FM-CW K-band radar (Micro
435   Rain Radar), Meteorol. Atmos. Phys., 113, 75–87, doi: 10.1007/s00703-011-0142-z, 2011.

Kim, K., Bang, W., Chang, E. C., Tapiador, F. J., Tsai, C.-L., Jung, E., and Lee, G.: Impact of wind pattern and complex
topography on snow microphysics during International Collaborative Experiment for PyeongChang 2018 Olympic and
Paralympic winter games (ICE-POP 2018), Atmos. Chem. Phys., 21, 11955–11978, https://doi.org/10.5194/acp-21-11955-
2021, 2021.

440   Lee, J. E., Jung, S. H., Park, H. M., Kwon, S., Lin, P. L., and Lee, G. W.: Classification of Precipitation Types Using Fall Velocity–Diameter Relationships from 2D-Video Distrometer Measurements, Adv. Atmos. Sci., 32, 1277–1290, https://doi.org/10.1007/s00376-015-4234-4, 2015.

Li, H., Moisseev, D., and von Lerber, A.: How Does Riming Affect Dual-Polarization Radar Observations and Snowflake Shape? J. Geophys. Res., 123, 6070–6081, https://doi.org/10.1029/2017JD028186, 2018.

445   Löffler-Mang, M., Kunz, M., and Schmid, W.: On the performance of a low-cost K-band Doppler radar for quantitative rain measurement, J. Atmos. Oceanic Technol., 16, 379–387, https://doi.org/10.1175/1520-0426(1999)016<0379:OTPOAL>2.0.CO;2, 1999.

Löffler-Mang, M., and Joss, J.: An Optical Disdrometer for Measuring Size and Velocity of Hydrometeors, J. Atmos. Oceanic Technol., 17, 130-139. https://doi.org/10.1175/1520-0426(2000)017<0130:AODFMS>2.0.CO;2, 2000.

450   Morrison, H., Milbrandt, J. A., Bryan, G. H., Ikeda, K., Tessendorf, S. A., and Thompson, G.: Parameterization of Cloud Microphysics Based on the Prediction of Bulk Ice Particle Properties. Part II: Case Study Comparisons with Observations and Other Schemes, J. Atmos. Sci., 72, 312-339. https://doi.org/10.1175/JAS-D-14-0066.1, 2015.

Mroz, K., Battaglia, A., Nguyen, C., Heymsfield, A., Protat, A., and Wolde, M.: Triple-frequency radar retrieval of microphysical properties of snow, Atmos. Meas. Tech., 14, 7243–7254, https://doi.org/10.5194/amt-14-7243-2021, 2021.

455   Pruppacher, H. R., and Klett, J. D.: Microphysics of Clouds and Precipitation, Aerosol Science and Technology, 28:4, 381-382, https://doi.org/10.1007/978-0-306-48100-0, 1997.

Roebber, P. J., Bruening, S. L., Schultz, D. M., and Cortinas , J. V., Jr.: Improving Snowfall Forecasting by Diagnosing Snow Density, Wea. Forecasting, 18, 264-287. https://doi.org/10.1175/1520-0434(2003)018<0264:ISFBDS>2.0.CO;2, 2003.

Rogers, R. R., and Yau, M. K.: A short course in cloud physics, Pergamon Press, Oxford, 1989.

460   Tokay, A., D'Adderio, L. P., Porcù, F., Wolff, D. B., and Petersen, W. A.: A Field Study of Footprint-Scale Variability of Raindrop Size Distribution, J. Hydrometeor., 18, 3165-3179, https://doi.org/10.1175/JHM-D-17-0003.1, 2017.

Yuter, S. E., Kingsmill, D. E., Nance, L. B., Löffler-Mang, M.: Observations of Precipitation Size and Fall Speed Characteristics within Coexisting Rain and Wet Snow, J. Appl. Meteor. Climatol., 45, 1450–1464, https://doi.org/10.1175/JAM2406.1, 2006.

465   Vivekanandan, J., Adams, W. M., and Bringi, V. N.: Rigorous Approach to Polarimetric Radar Modeling of Hydrometeor Orientation Distributions, J. Appl. Meteor. Climatol., 30, 1053-1063, https://doi.org/10.1175/1520-0450(1991)030<1053:RATPRM>2.0.CO;2, 1991.

Zhang, G., Luchs, S., Ryzhkov, A., Xue, M., Ryzhkova, L., and Cao, Q.: Winter Precipitation Microphysics Characterized by Polarimetric Radar and Video Disdrometer Observations in Central Oklahoma, J. Appl. Meteor. Climatol., 50, 1558-1570.

470   https://doi.org/10.1175/2011JAMC2343.1, 2011.

Zhang, Y., Zheng, H., Zhang, L., Huang, Y., Liu, X., and Wu, Z.: Assessing the Effect of Riming on Snow Microphysics: The First Observational Study in East China, J. Geophys. Res., 126, https://doi.org/10.1029/2020JD033763, 2021.

Figures and Tables

Table 1: Data availability of MRR (x), Parsivel (v), and Pluvio (o) for YPO, MHS, CPO, BKC, and GWU site during pre-campaign and ICE-POP campaign.

Site / Dates	YPO	MHS	BKC	GWU	CPO
2017/1/4~2017/1/5	v, x	v, x			v, x
2017/1/8	v, x	v, x			v, x
2017/1/29~2017/1/30	v, x	v, x			v, x
2017/2/21~2017/2/22	v, x	v, x			v, x
2017/3/1~2017/3/2	v, x	v, x			v, x
2017/3/14	v, x	v, x			v, x
2017/12/9~2017/12/10	v, x, o	v, x, o	v, x, o	v, x, o	v, x
2017/12/24	v, x, o	v, x, o	v, x, o	v, x, o	v, x
2018/1/7~2018/1/8	v, x, o	v, x, o	v, x, o	v, x, o	v, x
2018/1/16	v, x, o	v, x, o	v, x, o	v, x, o	v, x
2018/1/22	v, x, o	v, x, o	v, x, o	v, x, o	v, x
2018/1/30	v, x, o	x, o	v, x, o	v, x, o	v, x
2018/2/28~2018/3/1	v, x, o	v, x, o	v, x	v, x, o	v, x
2018/3/4~2018/3/5	v, x, o	v, x, o	v, x, o	v, x, o	v, x
2018/3/7~2018/3/8	v, x, o	v, x, o	v, x, o	v, x, o	v, x
2018/3/14~2018/3/15	v, x, o	v, x, o	v, x, o	v, x, o	v, x
2018/3/20~2018/3/21	v, x, o	v, x, o	v, x, o	v, x, o	v, x

Table 2: MRR bias of YPO, MHS, CPO, BKC, and GWU sites derived from rain events.

site / MRR bias	YPO	MHS	CPO	BKC	GWU
mean	-8.7 dBZ	-10.2 dBZ	-7.4 dBZ	-2.1 dBZ	-5.8 dBZ

16

490 **Table 3: The V_Z criteria of the five sites are determined as the absolute value of the V_Z mean bias of the sites plus one standard deviation of the bias. The V_Z mean bias are the average of the V_Z difference between of MRR measurement and derived density calculation during all events available (Table 1) while the standard deviation of the bias is the standard deviation of the V_Z difference.**

		YPO	MHS	CPO	BKC	GWU	ALL
V_Z	V_Z criteria (m s^{-1})	0.94	0.94	0.89	0.84	1.08	nan
	Mean bias (m s^{-1})	-0.27	-0.16	-0.12	0.03	0.14	-0.07
	Standard deviation (m s^{-1})	0.67	0.78	0.77	0.81	0.94	0.80
SR	Mean bias (mm hr^{-1})	-0.14	-0.11	nan	-0.27	-0.19	-0.18
	Correlation coefficient	0.70	0.52		0.74	0.68	nan
	Standard deviation (mm hr^{-1})	0.73	1.09		0.85	1.01	0.93

495
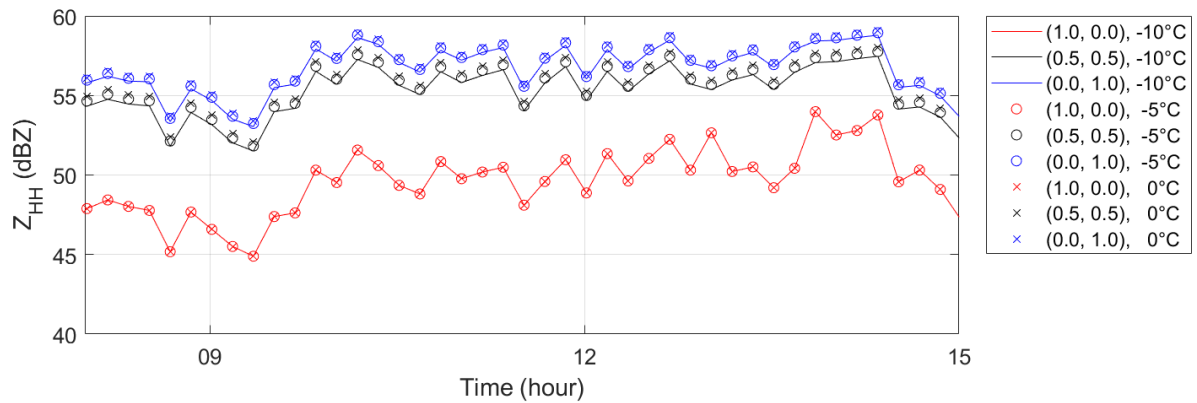
Figure 1: The simulated Z_{HH} with combinations of the volume ratio of solid ice and liquid water (vi, vw) and temperature is demonstrated by a case from the Parsivel observation of MHMS site on 28 February 2018. The combinations of (vi, vw) were (1.0, 0.0) in red, (0.5, 0.5) in black, and (0.0, 1.0) in blue lines. The temperature values were -10, -5, and 0℃ (thick line, circle, and cross marks).
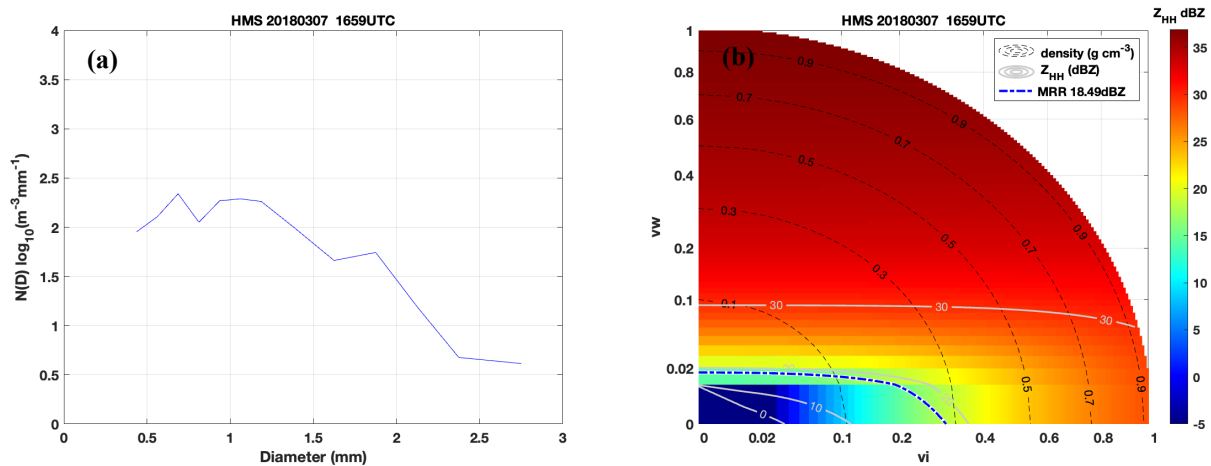
Figure 2: (a) Observed snow size distribution, N(D), from the MHS Parsivel site at 1659 UTC on 7 March 2018. (b) Z_{HH} distribution simulated from the Parsivel DSD. The x- and y-axis are the volume ratio of solid ice (vi) and liquid water (vw), respectively. The shaded color indicates the ZHH magnitude (dBZ), and the black dashed lines are contours of density (g cm^{-3}). Grey solid lines are contours of Z_{HH} (dBZ). The Z_{HH} variation with vw is much less than that with vi on the contours of Z_{HH}. The blue dashed-dot line is the value of the collocated MRR measurement of Z_{HH} (dBZ).
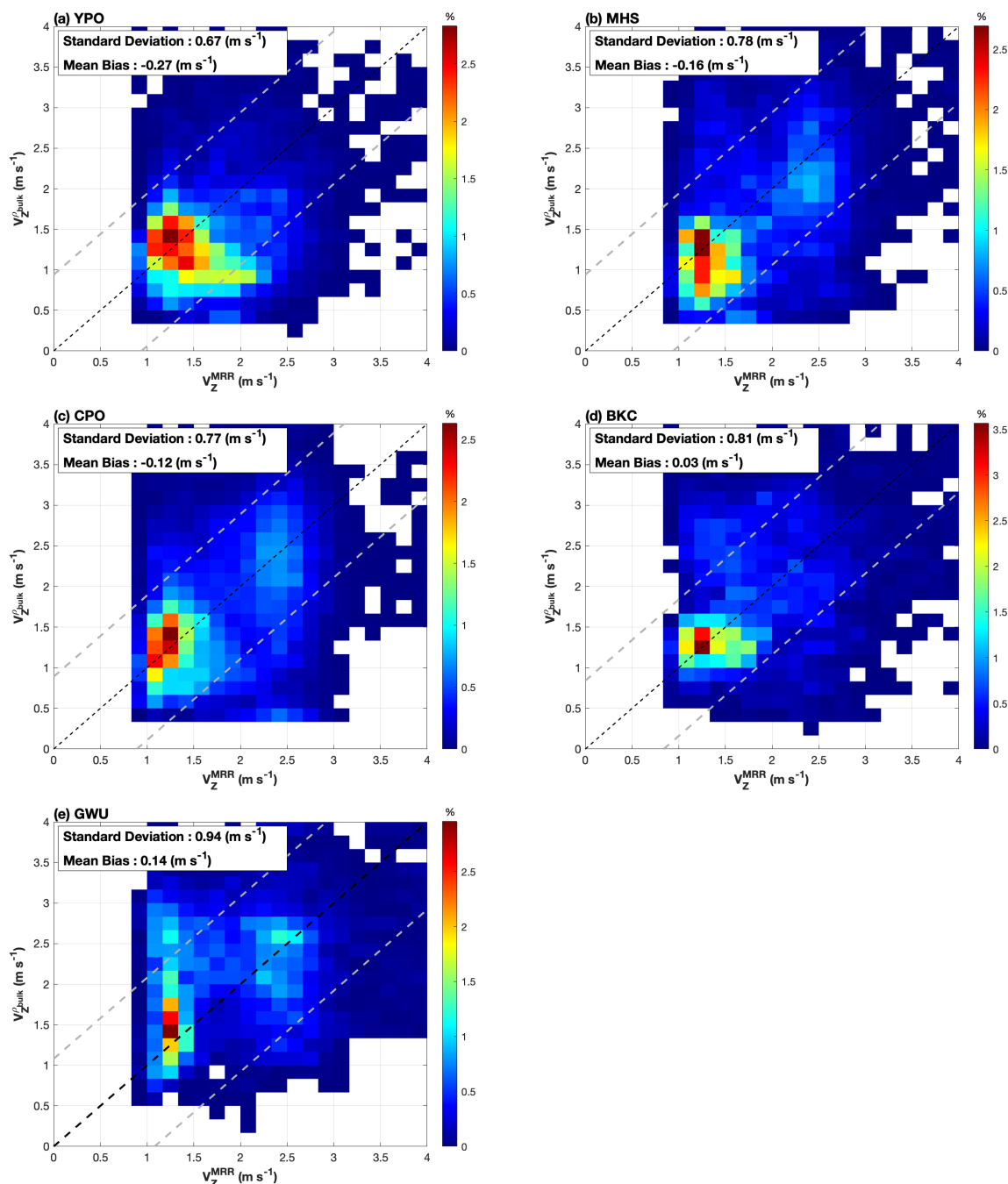
Figure 3: The probability density function of Z$_{HH}$ weighted fall velocity ($V_Z^{\rho bulk}$) calculated from "bulk density" and the MRR measurement (V_Z^{MRR}) in (a) MHS, (b) CPO, (c) BKC, (d) GWU, and (e) YPO site. The gray dash lines are the Vz criteria.
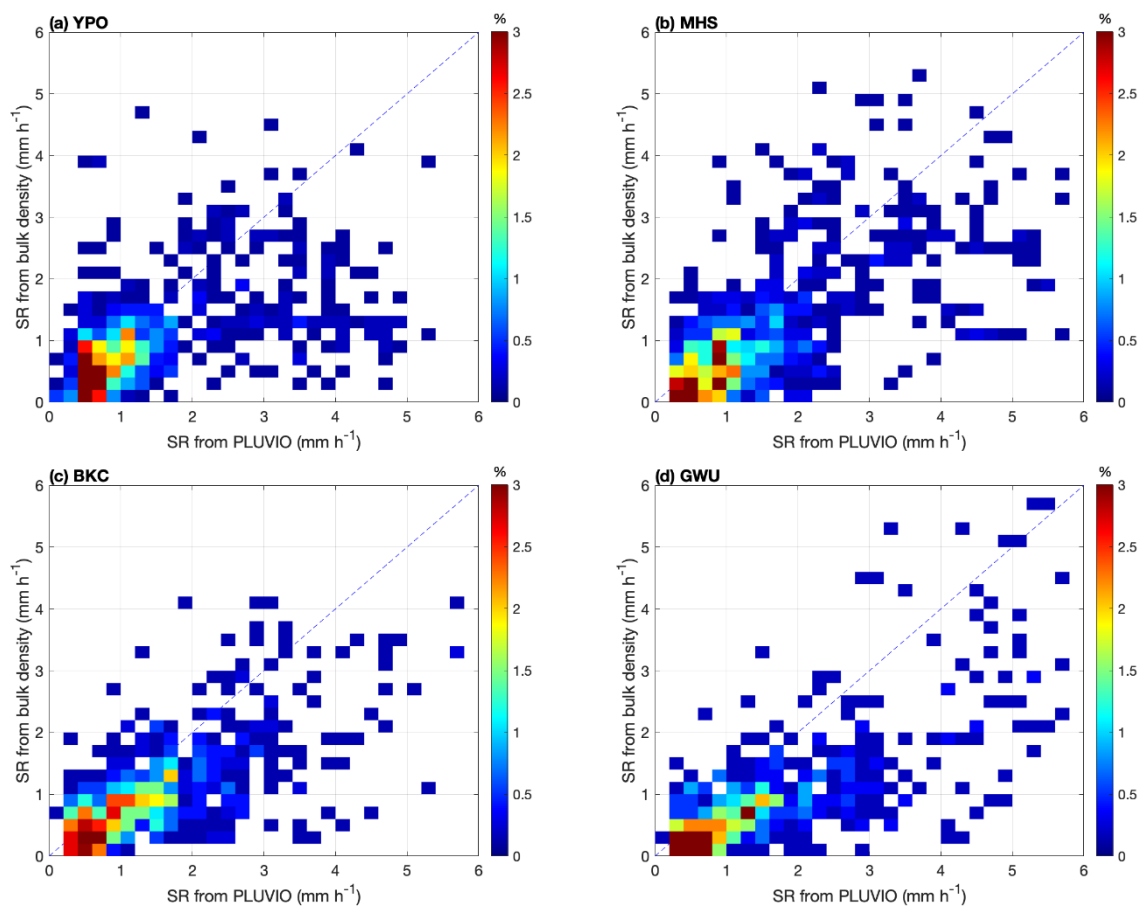
Figure 4: Normalized number density function of SR from density-derived and Pluvio observed SR in (a) YPO, (b) MHS, (c) BKC, and (d) GWU site. The data has been V_Z quality controlled.
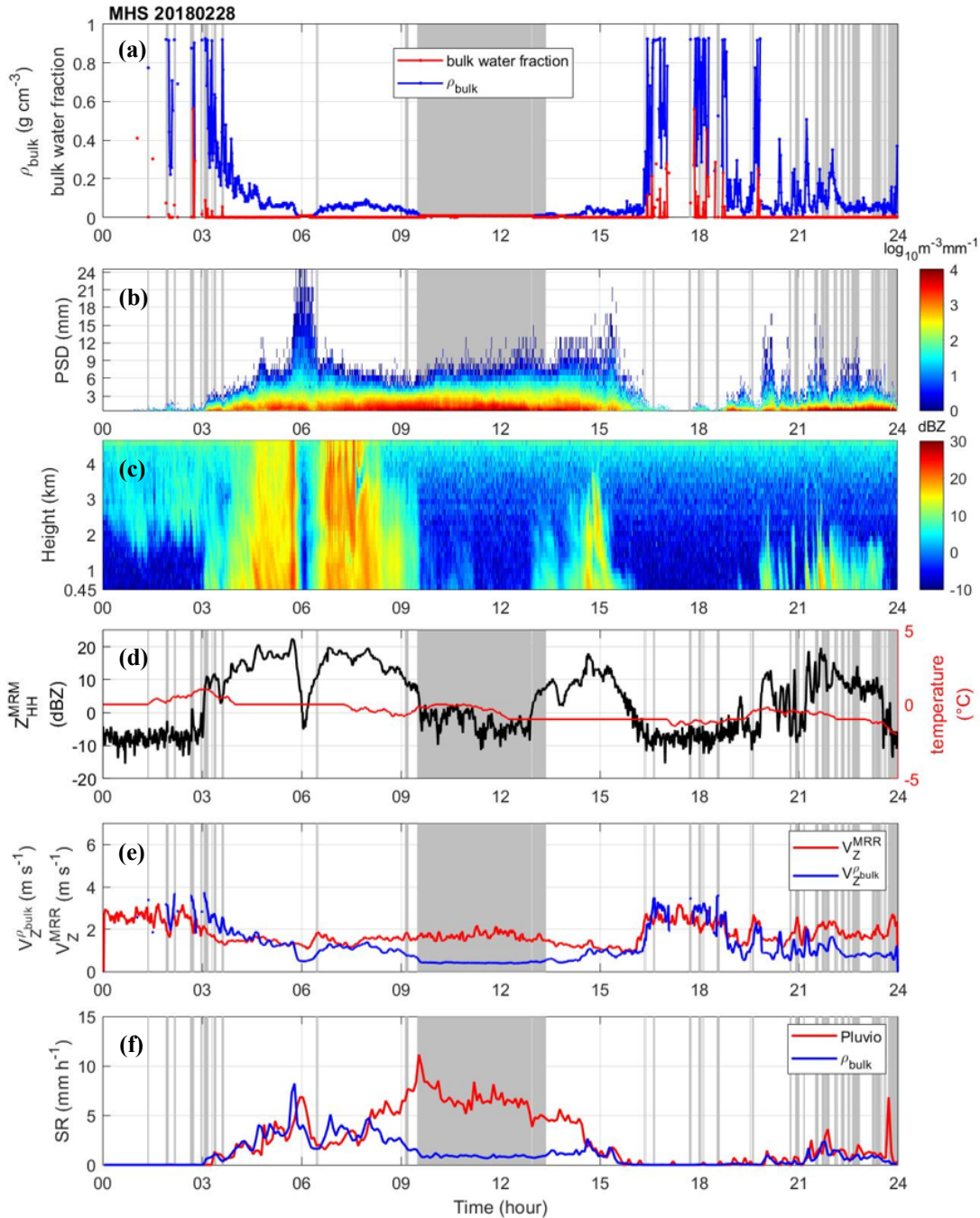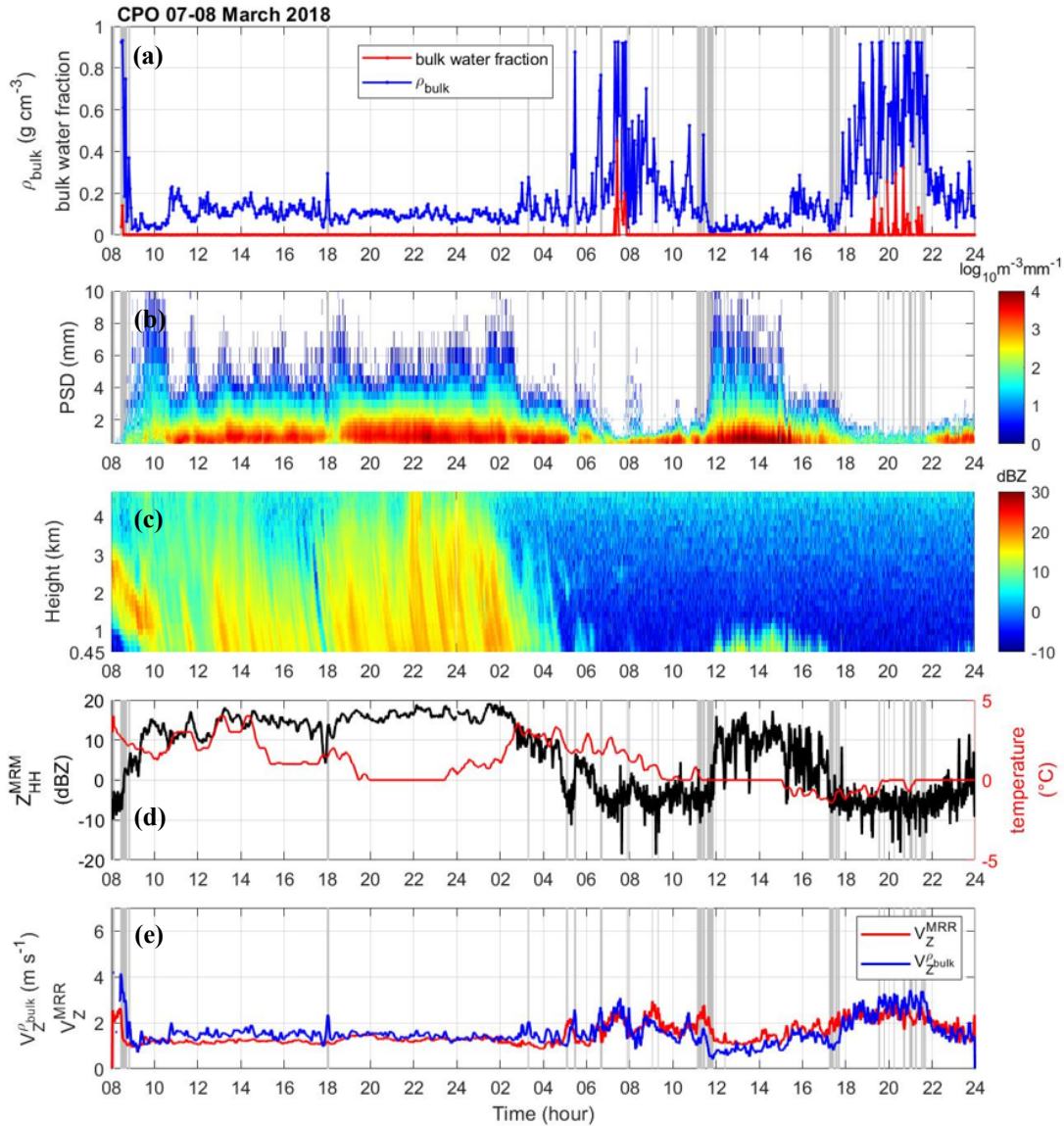
Figure 5: The data from MHS site on 28 February 2018. (a) Derived bulk density (g cm⁻³, blue line), bulk water fraction (red line).
560 **(b) Parsivel PSD in logarithm scale. (c) The vertical profile of Z_{HH} from the third layer (0.45 km) to the top (dBZ, shaded area) of MRR. (d) The temperature (°C, red line) and Z_{HH} from third layer. (e) The velocity (V_Z^{MRR}) of MRR measurement (red line) and the Z_{HH} weighted velocity ($V_Z^{\rho_{bulk}}$) calculated from bulk density (blue line). (f) The liquid-equivalent snow-rate (SR) of Pluvio measurement (red line) and bulk density derived SR (blue line). The inadequate retrieval which the V_Z difference between V_Z^{MRR} and $V_Z^{\rho_{bulk}}$ greater than the V_Z criteria (Table 3) of MHS site are indicated by gray area.**

565

Figure 6: The number density function of fall velocity and diameter from Parsivel (logarithm scale shown in color-shaded) collected from 28 February 2018. The average of fall velocity in each diameter bin (m s^{-1}, black line), relations of fall velocity-diameter of rain, graupel, and dry dendrites (from the upper to lower red line) are derived for (a) 00 to 04 UTC, (b) 04 to 16 UTC, and (c) 16 to 20 UTC in the MHS site. The relation of rain is from Brandes et al. (2002). The relations of graupel and dry dendrites are from Locatelli and Hobbs (1974).

570
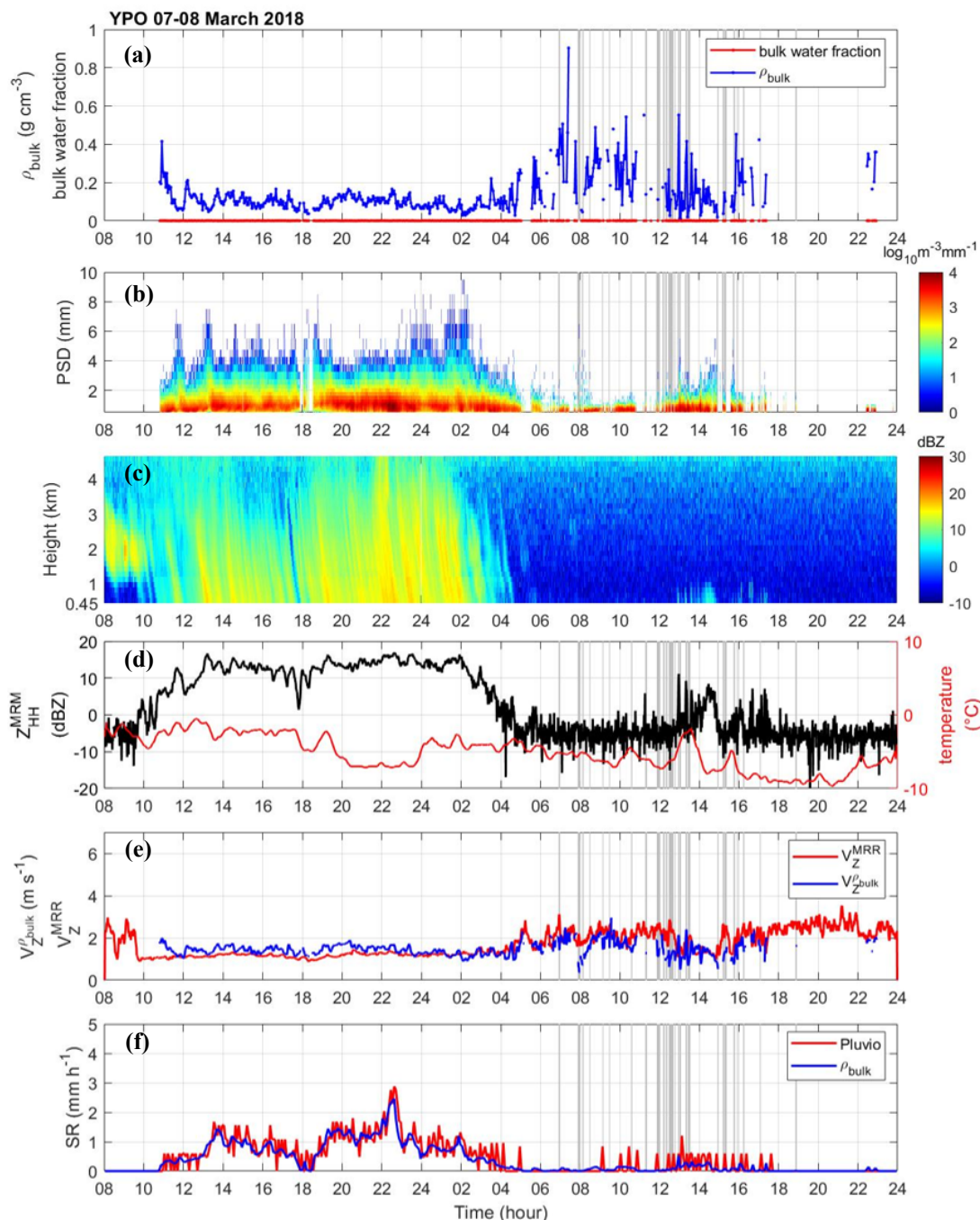
Figure 7: The data from YPO site on 7 March 2018. (a) Derived bulk density (g cm^{-3}, blue line), bulk water fraction (red line). (b)
Parsivel PSD in logarithm scale. (c) The vertical profile of Z_{HH} from the third layer (0.45 km) to the top (dBZ, shaded area) of MRR.
(d) The temperature (℃, red line) and Z_{HH} from third layer. (e) The velocity (V_Z^{MRR}) of MRR measurement (red line) and the Z_{HH}
weighted velocity ($V_Z^{\rho bulk}$) calculated from bulk density (blue line). (f) The liquid-equivalent snow-rate (SR) of Pluvio measurement
(red line) and bulk density derived SR (blue line). The inadequate retrieval which the V_Z difference between V_Z^{MRR} and $V_Z^{\rho bulk}$
greater than the V_Z criteria (Table 3) of MHS site are indicated by gray area.
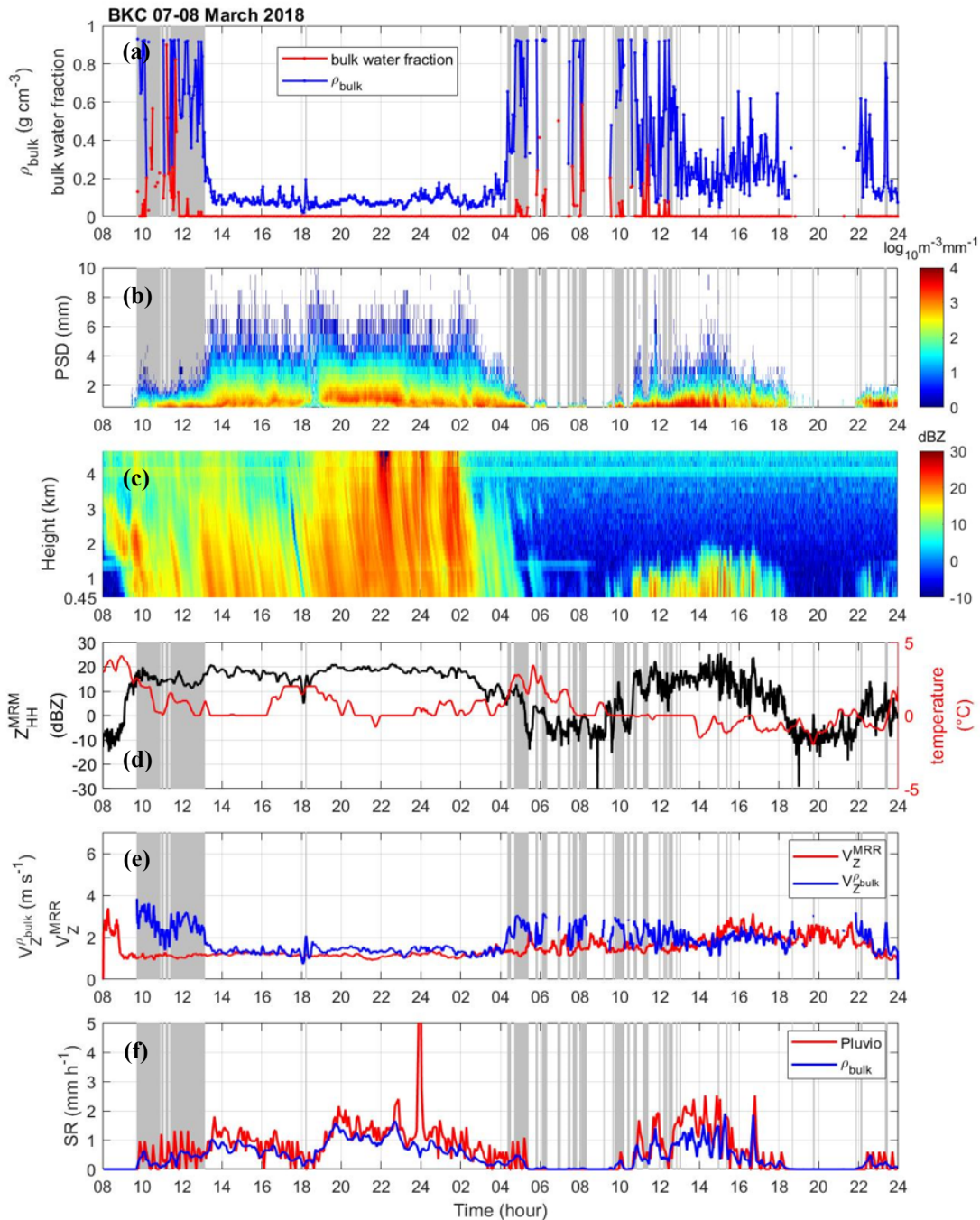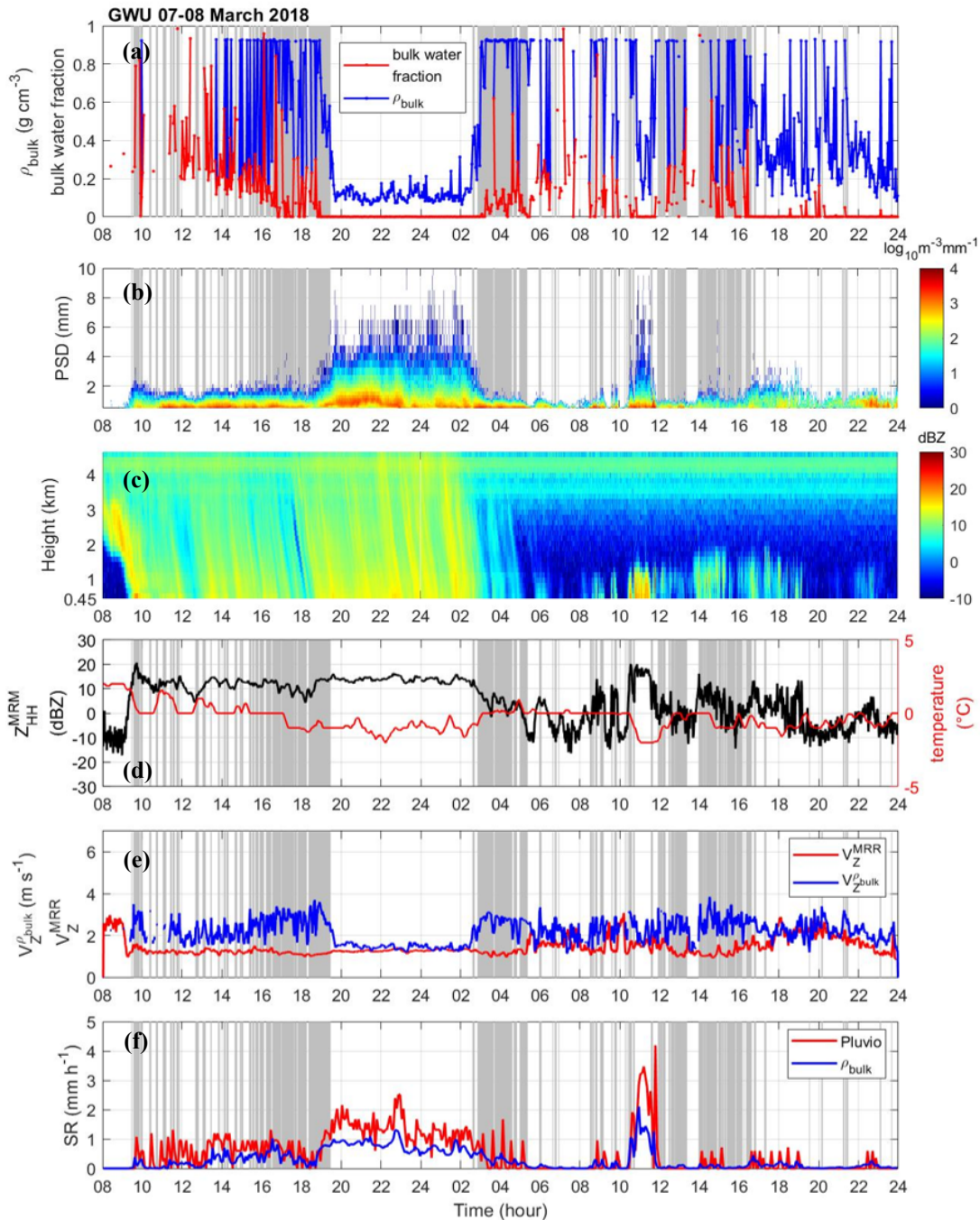
24

Figure 8: The data from MHS site on 7 March 2018. (a) Derived bulk density (g cm⁻³, blue line), bulk water fraction (red line). (b) Parsivel PSD in logarithm scale. (c) The vertical profile of Z_{HH} from the third layer (0.45 km) to the top (dBZ, shaded area) of MRR. (d) The temperature (℃, red line) and Z_{HH} from third layer. (e) The velocity (V_Z^{MRR}) of MRR measurement (red line) and the Z_{HH} weighted velocity ($V_Z^{\rho bulk}$) calculated from bulk density (blue line). (f) The liquid-equivalent snow-rate (SR) of Pluvio measurement (red line) and bulk density derived SR (blue line). The inadequate retrieval which the V_Z difference between V_Z^{MRR} and $V_Z^{\rho bulk}$ greater than the V_Z criteria (Table 3) of MHS site are indicated by gray area.

25

Figure 9: The data from CPO site on 7 March 2018. (a) Derived bulk density (g cm^{-3}, blue line), bulk water fraction (red line). (b) Parsivel PSD in logarithm scale. (c) The vertical profile of Z$_{HH}$ from the third layer (0.45 km) to the top (dBZ, shaded area) of MRR.
590 **(d) The temperature (°C, red line) and Z$_{HH}$ from third layer. (e) The velocity (V_Z^{MRR}) of MRR measurement (red line) and the Z$_{HH}$ weighted velocity ($V_Z^{\rho bulk}$) calculated from bulk density (blue line). The inadequate retrieval which the V$_Z$ difference between V_Z^{MRR} and $V_Z^{\rho bulk}$ greater than the V$_Z$ criteria (Table 3) of MHS site are indicated by gray area. The Pluvio is not available in CPO site.**

Figure 10: The data from BKC site on 7 March 2018. (a) Derived bulk density (g cm⁻³, blue line), bulk water fraction (red line). (b)
Parsivel PSD in logarithm scale. (c) The vertical profile of Z_{HH} from the third layer (0.45 km) to the top (dBZ, shaded area) of MRR.
(d) The temperature (℃, red line) and Z_{HH} from third layer. (e) The velocity (V_Z^{MRR}) of MRR measurement (red line) and the Z_{HH}
weighted velocity ($V_Z^{\rho bulk}$) calculated from bulk density (blue line). (f) The liquid-equivalent snow-rate (SR) of Pluvio measurement
(red line) and bulk density derived SR (blue line). The inadequate retrieval which the V_Z difference between V_Z^{MRR} and $V_Z^{\rho bulk}$
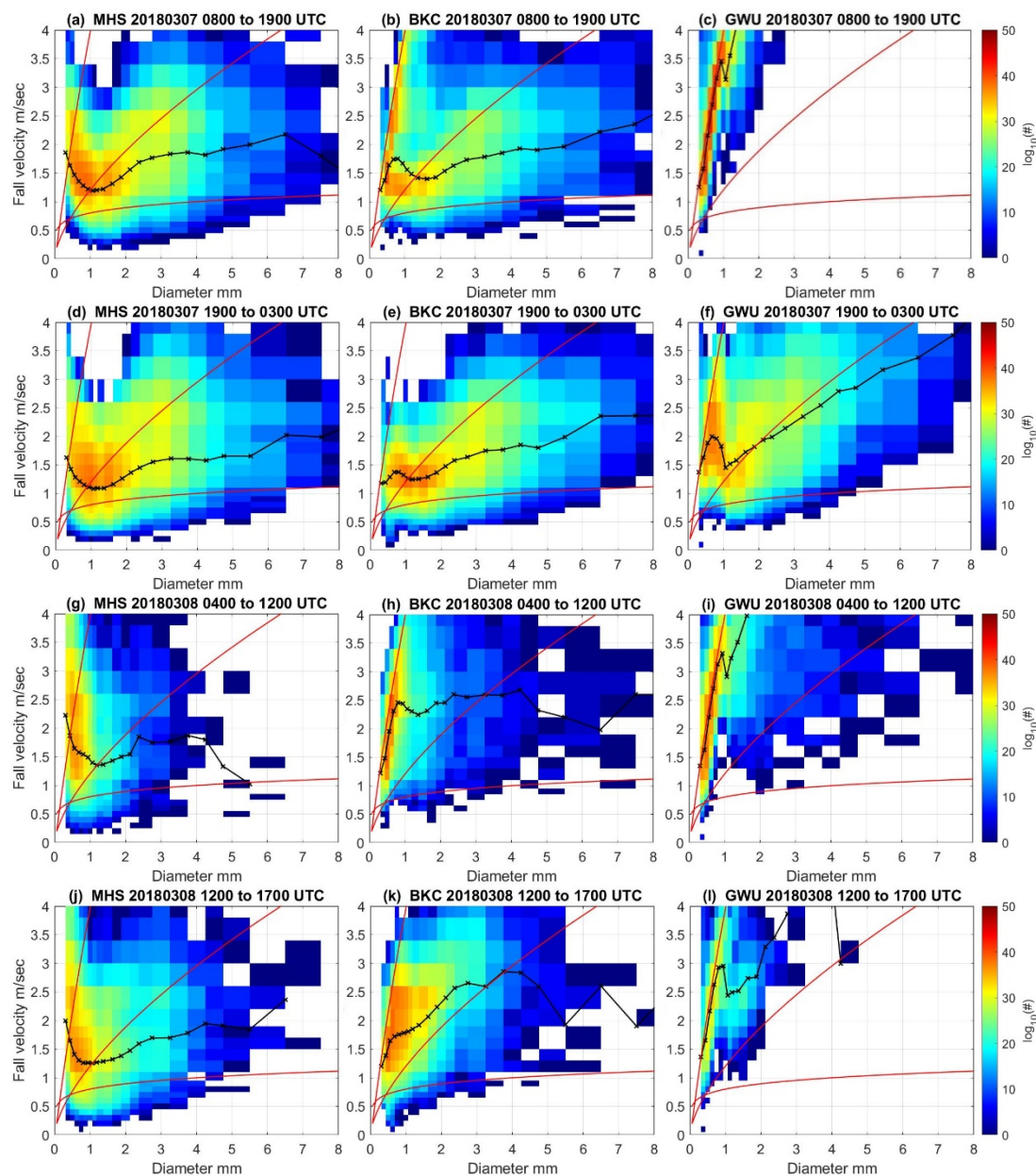**greater than the V_Z criteria (Table 3) of MHS site are indicated by gray area.**

27

Figure 11: The data from GWU site on 7 March 2018. (a) Derived bulk density (g cm⁻³, blue line), bulk water fraction (red line). (b) Parsivel PSD in logarithm scale. (c) The vertical profile of Z_{HH} from the third layer (0.45 km) to the top (dBZ, shaded area) of MRR. (d) The temperature (℃, red line) and Z_{HH} from third layer. (e) The velocity (V_Z^{MRR}) of MRR measurement (red line) and the Z_{HH} weighted velocity ($V_Z^{\rho bulk}$) calculated from bulk density (blue line). (f) The liquid-equivalent snow-rate (SR) of Pluvio measurement (red line) and bulk density derived SR (blue line). The inadequate retrieval which the V_Z difference between V_Z^{MRR} and $V_Z^{\rho bulk}$ greater than the V_Z criteria (Table 3) of MHS site are indicated by gray area.

28

Figure 12: The number density function of fall velocity and diameter from Parsivel (logarithm scale shown in color-shaded) from MHS, BKC, and GWU sites collected from 7-8 March 2018. The average of fall velocity in each diameter bin (m s⁻¹, black line), relations of fall velocity-diameter of rain, graupel, and dry dendrites (from the upper to lower red line) are derived for (a)~(c) 08-19 UTC on 7 March, (d)~(f) 19 UTC on 7 March to 03 UTC on 8 March, (g)~(i) 04-12 UTC on 8 March, and (j)~(l) 12-17 UTC on 8 March in the MHS, BKC, and GWU sites. The relation of rain is from Brandes et al. (2002). The relations of graupel and dry dendrites are from Locatelli and Hobbs (1974).
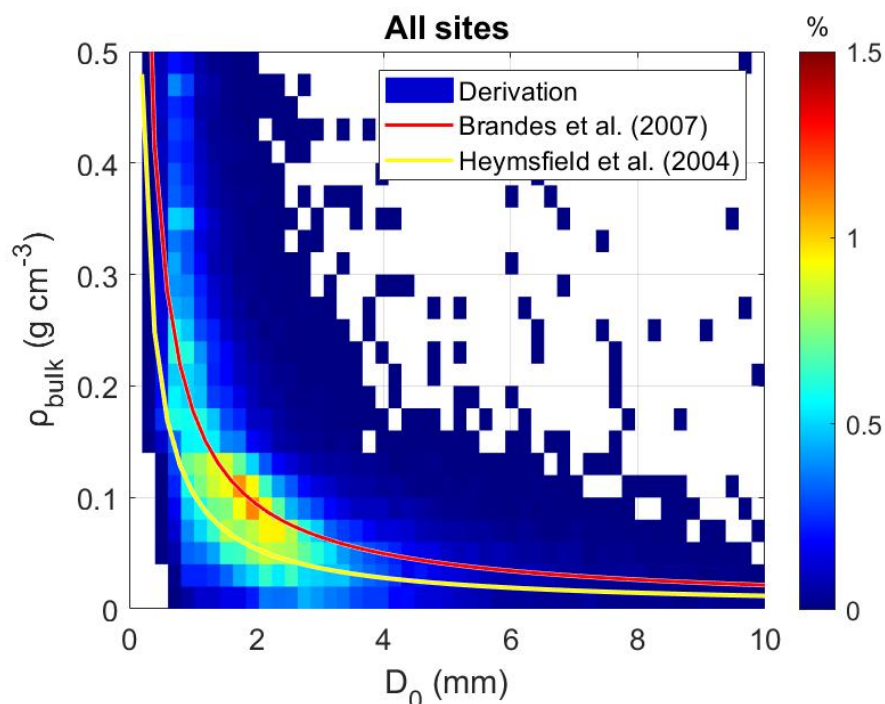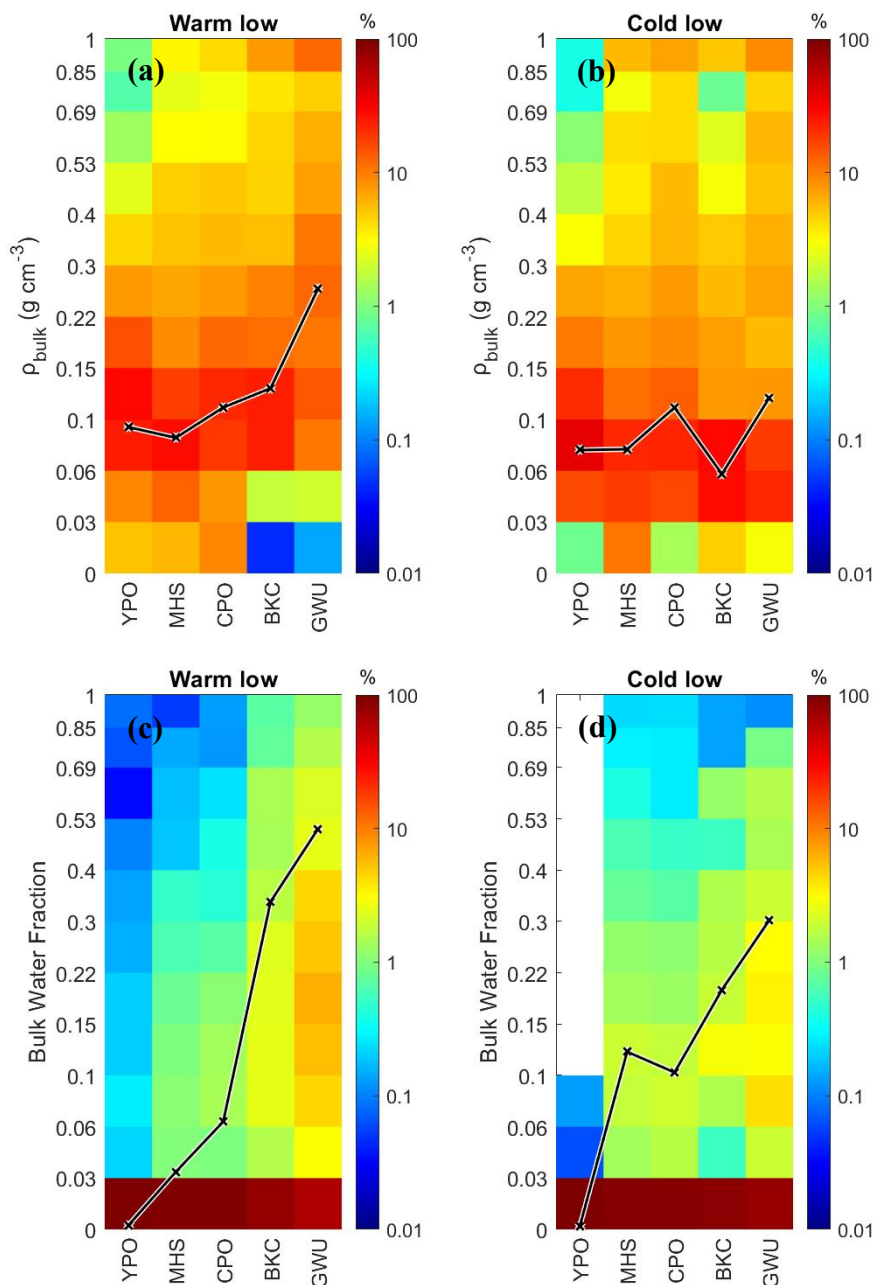
Figure 13: The number density function of retrieved bulk density and observed median-volume diameter (D0) from all sites of entire
625 **ICE-POP 2018 and its pre-campaign is shown in shaded. The red and yellow lines represent the $\rho_{bulk} - D_0$ relation from Brandes**
et al. (2007) and Heymsfield et al. (2004), respectively.

630

Figure 14: (a) The normalized number density function of retrieved bulk density of each site for warm-low events. The black line indicates the mean bulk density of each site. **(b)** Same as in (a), but for cold-low events. **(c)** The normalized number density function of retrieved bulk water fraction of each site for warm-low events. The black line represents the mean values of each site's top 5% bulk water fraction. **(d)** Same as in (c), but for cold-low events. The normalization is individually applied to every site, ensuring that the total sum of the normalized distribution for each site equals 100%.