Estimating the Snow Density using collocated Parsivel and MRR measurements: a preliminary study from ICE-POP 2017

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Abstract

Obtaining the density of ice hydrometeor is long standing challenge due to instrumental limitation. A newly method is developed to estimate the density of ice hydrometeor utilizing collocated Micro Rain Radar (MRR) and Parsivel disdrometer. Ice hydrometeors are composed of water, ice, and air. The fractions of water (vw), ice (vi) and air (va) of hydrometer are obtained by minimizing the difference of calculated reflectivity of drop size distribution (DSD) observed from Parsivel disdrometer and measured reflectivity from MRR. The T-matrix simulation calculates reflectivity from DSD with pre-assumed particle shape and with specified vw, vi and va. The MRR can measure the vertical profile of reflectivity. By comparing the reflectivity measurement from MRR and reflectivity calculation from Parsivel DSD observations via T-matrix simulation, the values of vw, vi and va can be obtained. The density thus can be calculated from estimated water, ice and air fractions.

The newly developed method has been implemented to examine five snowfall events from ICE-POP 2017. Among these events, event5 (2017/03/25) contained various types of precipitation associated with distinct density of hydrometeors (e.g., ice, drizzle, snow graupel). The retrieved density is validated via two approaches. First, the relationship of fall velocity and diameter of hydrometeors is highly related to the density of particles according to the derivation of terminal fall velocity. Therefore, parameters from regression of fall velocities and diameters can be used to validate the density estimated in the study. Second, the reflectivity weighted fall velocity calculated from estimated density is compared to MRR measurements. Overall, the density estimated in the study shows comparable results from the regression parameter and the weighted fall velocity. The results indicate the capability of the ice density estimation method developed in the study.

Keywords: Hydrometeor density, fall velocity

1. Introduction

Understanding the microphysical properties of ice hydrometeors is vital for the quantitative precipitation estimation (QPE) of snow (Huang et al., 2014 and 2019). Density of ice hydrometeor is also fundamental to the characterization of frozen precipitation. Other physical properties, for example, fall speed, drop size distribution (DSD), shape and porosity are crucial for microphysical studies as well. Snow Video Imager yields a size estimate of each particle as a circular equivalent-area diameter which comes from the measured irregular shape (with holes filled). 2D-video disdrometer can measure fall speed from two orthogonal images as well as the DSD. However, density of ice hydrometeor cannot be observed directly. Many factors may contribute to density of ice hydrometeor, including in-cloud (riming and aggregation), and subcloud (melting and sublimation). Snow density is often assumed to be 100 kg m^{-3} or follows other empirical rules when forecasting the snowfall quantity. However, there is considerable case-to-case variability in snow density. Also, even for locations in close proximity, the density of snow can differ substantially due to the different dominant meteorological conditions (Milbrandt et al., 2012 and Roebber et al., 2002). A correct method to estimate density of frozen particles is urgent and need.

In the study, A newly method is developed to estimate the density of ice hydrometeor utilizing collocated Micro Rain Radar (MRR) and Parsivel disdrometer. Five snowfall events from ICE-POP 2017 are presented to demonstrate the capability of the approach.

2. Data from ICE-POP 2017

Five snowfall cases (in local time) used in the study were collated in 2017 for an international collaborative experiment of Pyeongchang 2018 Olympic (ICE-POP):

event1 2017/03/01 1800 ~ 03/02 1800

event2 2017/03/05 2100 ~ 03/06 0400
event3 2017/03/14 1100~1900
event4 2017/03/21 0700~1400
event5 2017/03/25 0800~1800

Generally, the precipitation types of all the five events are dominated by snow. However, event4 and event5 have more various precipitation types than others. There is a transition period (1200~1500) in event5 precipitation type which starts from snow-dominated to several types appear alternately and then return to snow-dominated again.

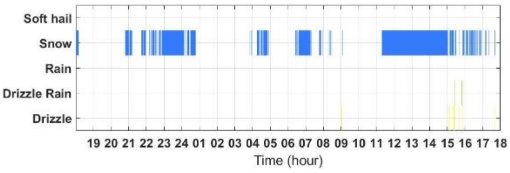

Figure 1. Event 1 precipitation type

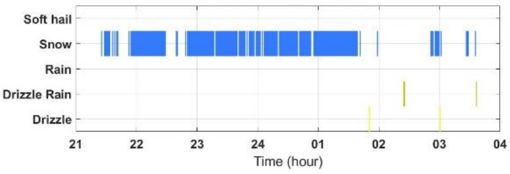

Figure 2. Event 2 precipitation type

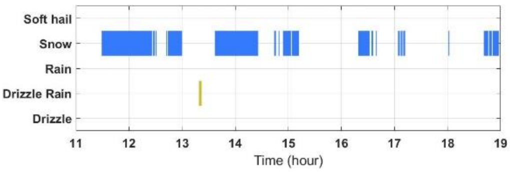

Figure 3. Event 3 precipitation type

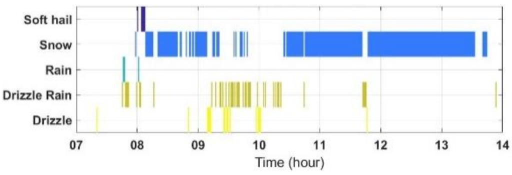

Figure 4. Event 4 precipitation type

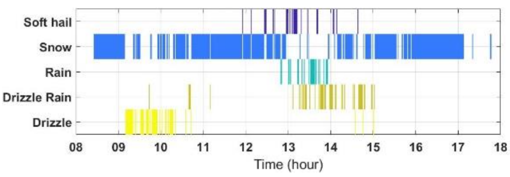

Figure 5. Event 5 precipitation type

The MRR and Parsivel observations used to estimate density were very likely to be contaminated by noise. Total number of particles are calculated from Parsivel DSD as the criteria to make sure most of the data used are reliable. In the study the criteria is set to be 100, when the total number of particles at that time is equal or less than 100, the data are abandoned.

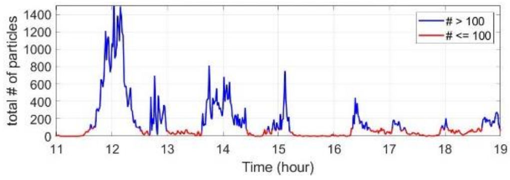

Figure 6. Total number of particles of event 3. Red line indicates abandoned data.

3. Method for estimating the density

Different fractions of ice and water (vi and vw) in particles and different DSD of the particles in the atmosphere would result in different received reflectivity. T-matrix simulation can calculate reflectivity according to the theoretical formula with specified vi, vw, and DSD which can be provided by Parsivel. On the other hand, MRR can observe reflectivity directly. In the study, we simulate the reflectivity with T-matrix and Parsivel DSD with the prescribed range of vi and vw. Range of vi and vw is set from 0 to 100% with vi plus vw equal to or less than 100%. The simulated reflectivities are arranged according to their specified vi and vw in a table form. The reflectivity observed from MRR corresponds to a contour on the table of simulated reflectivity. The coordinates of any point on the contour is represented by (vi, vw). These points which are represented by (vi, vw) are computed into several densities ρ_x, that is, the density distribution we want to derive.

$$\rho_x = \mathrm{vi} \times 0.92 + \mathrm{vw} \times 1.0 \quad \text{unit: } g/cm^2$$

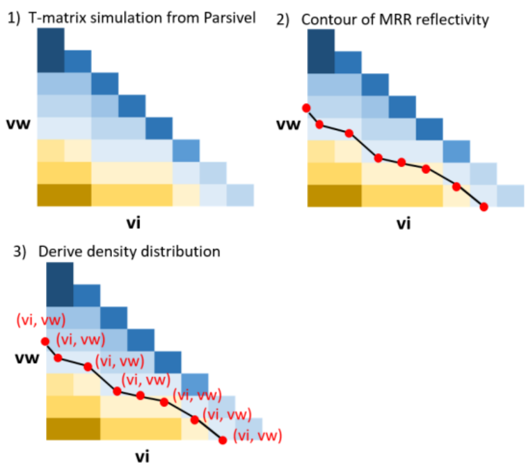

Figure 7. Three steps to estimate the density of hydrometeor

4. Cases study

Five snowfall cases in ICE-POP 2017 are analyzed. Two of them, event4 and event5 correspond to multiple precipitation types compared with others, especially, event5. Three periods can be separated from event5 (2017/03/25 0800~1800) according to their dominated precipitation types:

0800~1200 snow and drizzle
1200~1500 snow, hail, rain, and drizzle
1500~1800 only snow

With the method developed in the study, density distributions for each time can be derived. The median and interquartile range (IQR) of the density distribution is demonstrated in red point and blue line in Figure. Also, the maximum possible vi and vw (orange and blue line) is found from the density contour of MRR reflectivity described in section 3. In event5 0800~1200, the medians and IQRs are about 0.1 g/cm^3. While the maximum possible vw is much less than the maximum vi but still a little bit more than 1%. Event5 1200~1500 has the largest average of median density and maximum vw compare with other periods in event5 and other events (Table 1 and 2). On the other hand, event5 1500~1800 corresponds to the lowest values of median density and maximum vi, vw in the three periods in event5. In 1500~1800, the maximum vw are nearly equal to 1 % which seem to be reasonable since pure snow often has lower fraction of water. While hail, rain, and drizzle happened in 1200~1500 which led to higher maximum vw and density than others. Generally, event1 to 3 are nearly dominated by snow and have lower average of median density and maximum vw. By comparison, event4 and 5 include hail, rain, drizzle, and snow therefore have higher density and maximum vw than event1 to 3 (Table 1).

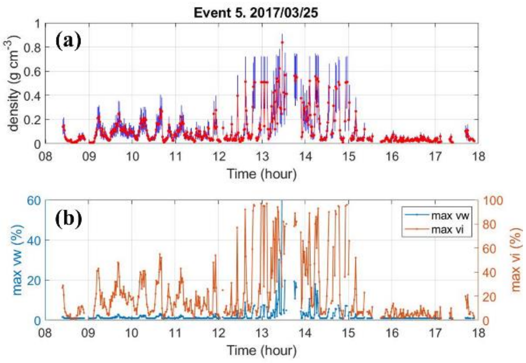

Figure 8. (a) Median (red) and IQR (blue) of density distributions in event5. (b) Maximum probable vi (orange) and vw (blue) in event 5.

Table 1 Average of density and max vw

Event no.	1	2	3	4	5
Density (g/cm^3)	0.0368	0.059	0.0196	0.0581	0.1125
Max vw (%)	0.9834	1.1329	0.9507	1.1538	2.0298

Table 2 Average of density and max vw in event5

Event 5	0800-1200	1200-1500	1500-1800
Density (g/cm^3)	0.0861	0.212	0.0428
Max vw (%)	1.2535	4.0189	1.0344

5. Validation

The terminal fall velocity u_∞ of particles can be derived since the drag force F_D is balanced with the gravity force F_G.

$$F_G = gm = gV(\rho_x - \rho) \cong gV\rho_x = \frac{\pi}{6} gD^3\rho_x$$

$$F_D = AC_d\rho u_\infty^2 = \frac{\pi}{8} D^2 C_d \rho u_\infty^2$$

$$F_D = F_G$$

In the derivation, particles are assumed to be a sphere and the terminal fall velocity u_∞ is approximated to be the fall velocity V which led to the relationship of fall velocity V and diameter D. The exponent of the diameter is 0.5 in the relationship and the parameter "a" is positive correlated with the particle density ρ_x.

$$u_\infty = \left(\frac{4}{3}\frac{gD}{C_d}\frac{\rho_x}{\rho}\right)^{0.5} = \left(\frac{4}{3}\frac{g}{C_d}\frac{\rho_x}{\rho}\right)^{0.5} D^{0.5}$$

$$u_\infty \cong V = aD^{0.5}$$

$$a = \left(\frac{4}{3}\frac{g}{C_d}\frac{\rho_x}{\rho}\right)^{0.5}$$

Parsivel can provide the number distribution of fall velocity and diameter at each time in addition to the DSD. Parameter "a" can be fitted from the number distribution of fall velocity and diameter with the Levenberg-Marquardt algorithm.

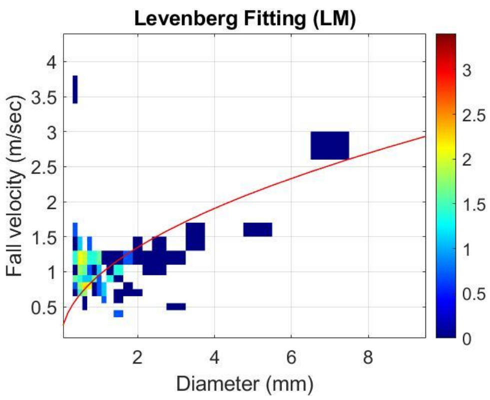

Figure 9. The parameter "a" is fitted from the number distribution of V-D (shaded) with the Levenberg-Marquardt algorithm. Redline is the line of $V = aD^{0.5}$.

In Figure, the fitted parameter "a" in event5 1200~1500 is higher than other periods in event5 which is consistent with the estimated density (the median of the density distribution). The correlation coefficients between "a" and estimated density in five events are shown in Table 3. Event4 and 5 have the highest correlation coefficients compared with other events and is probably caused by their various precipitation types. That is, the magnitude of density transition between different precipitation types is much significant than the density change in snows which probably make the estimated density of event4 and 5 easier to be consistent with the time series of parameter "a".

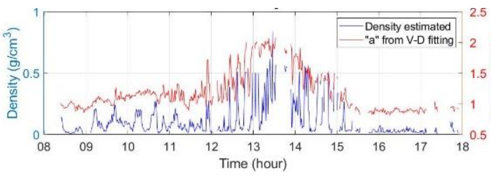

Figure 10. The time series of parameter "a" (red) and the estimated density (blue) in event 5.

Calculating the reflectivity weighted fall velocity is another way to validate the estimated density. MRR observes the reflectivity weighted fall velocity which can be considered as the truth. On the other hand, the reflectivity weighted fall velocity can be calculated from the estimated density. Therefore, by the comparison of the computed and observed fall velocity, the estimated density can be examined.

$$V_{computed} = \frac{\int_{D_{min}}^{D_{max}} Z(D)\, V(D)\, n(D)\, dD}{\int_{D_{min}}^{D_{max}} Z(D)\, n(D)\, dD}$$

Computed (blue line) and observed (orange line) reflectivity weighted fall velocity of event5 are presented in Figure. Overall, the two fall velocities show similar behavior, with 1200~ 1500 corresponds to higher fall velocity than other periods in the event5. Also, correlation coefficients between two fall velocities in five events are demonstrated in Table 3. Again, event4 and 5 show the best correlation than event1 to event3 and may be due to their multiple precipitation types rather than snow-dominated.

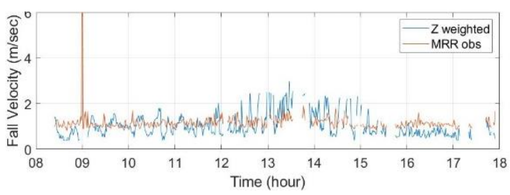

Figure 11. The reflectivity weighted fall velocity from estimated density (blue) and MRR (orange) in event 5.

Table 3 Correlation coefficient

Event no.	1	2	3	4	5
Parameter "a"	0.3709	0.3743	0.3868	0.6246	0.6913
Fall velocity	0.1399	0.2875	0.1041	0.3108	0.3362

6. Summary

In the study, a newly developed method to estimate the density of ice hydrometeor is demonstrated. Five snowfall events in ICE-POP 2017 with collocated MRR and Parsivel measurements are applied. The estimated density distributions and the maximum fraction of water (vw) agree well with the precipitation types from the Parsivel. The validations toward the median of estimated density distributions are executed in two approaches. First, the relationship between fall velocity and diameter of hydrometeors is highly related to the density of particles according to the derivation of terminal fall velocity. Therefore, parameters from the regression of fall velocities and diameters can be used to validate the density estimated in the study. Second, the reflectivity weighted fall velocity calculated from the estimated density is compared to MRR measurements. Event 4 and event 5 show better performance than others according to the correlation coefficients between parameter "a" and estimated density also the computed and observed fall velocity in five events (Table 2, 3). The relatively poor performance of event 1 to 3 may result from their snow-dominated precipitation type. Overall, the density estimated in the study shows comparable results from the regression parameter and the weighted fall velocity. These results indicate the capability of the ice density estimation method developed in the study.

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