

The manuscript describes measurements with the DEID, the Differential Emissivity Imaging Disdrometer. The instrument has been presented by Singh et al. 2021 who explain that it can “measure the mass, size, density and type of individual hydrometeors as well as their bulk properties.” Laboratory and field measurements have been described in that paper, which are very similar to the measurements presented in this manuscript. The authors also cite another study, Rees et al. 2021, which describes mass and density measurements of individual hydrometeors with the DEID in comparison to refined optical imagery data, again like what is presented in this manuscript.

The only new thing with the method is about density estimation. The determination of an effective thickness h allows a different estimation of the volume compared to the estimate based on area equivalent diameter used in Singh et al. 2021 and Rees et al. 2021 (spherical-particle method). Measurement of h is done during a calibration with certain ice particles under certain conditions determining P_0 . This P_0 is then used for h , and thus density estimation.

The field campaign provides new data (compared to Singh et al. 2021 and Rees et al. 2021) and comparison of densities in the field. In this campaign a different optical imaging system is used to provide complimentary data on the frozen hydrometeors. This imaging system uses a laser sheet that illuminates the falling hydrometeors from the side, which are then imaged by an SLR camera. Its optical resolution (judged from the images provided) seems similar or only slightly better than the optical resolution of the thermal camera of the DEID.

METHOD to determine mass m (as in Singh et al. 2021 and Rees et al. 2021):

The melted hydrometeor’s temperature and area are observed during evaporation, in the laboratory also during the initial faster melting.

From these observations, mass is determined using an equation derived from a heat transfer balance assuming that the heat transferred into the melted hydrometeor equals the sum of the heats required to a) increase the temperature of the hydrometeor and b) melt and c) evaporate the hydrometeor.

0) Determine κ (laboratory calibration).

1) Observe during evaporation: $A(t)$, $T_w(t)$. ($T_p(t)$ about const)

2) Determine $T_{p,max}$.

3) Use Eq. (2) to determine m .

METHOD to determine density ρ_{MS} (new in this manuscript):

The density is determined from m divided by V_s , the “volume of a snowflake”.

The volume V_s is estimated as $A_p \cdot h$, where A_p is the “initial snowflake projected area” and h is the “particle’s effective thickness in the direction normal to the hotplate”. This effective thickness h is estimated as the product of a melting speed and the melting duration. The implied definition (or method of determination) of this melting speed v_{melt} is h divided by melting duration. v_{melt} can be determined from ΔT_{melt} (average temperature difference between hotplate and frozen part of melting particle) as the two variables are proportional. The proportionality factor includes, besides κ , the laboratory calibrated coefficient P_0 .

For DEID measurements in the field it is easier to observe evaporation duration (instead of the much shorter melting duration), so ΔT_{melt} and melting duration can be replaced by ΔT_{evap} and evaporation duration. Thus, the volume, and with that the density, is estimated from A_p , ΔT_{evap} , and evaporation duration (Eq. 8).

- 0) Determine P_0 (laboratory calibration)
- 1) Observe during evaporation: $T_w(t)$. ($T_p(t)$ about const)
- 2) Determine ΔT_{evap}
- 3) Use Eq. (8) to determine density ρ_{MS}

The manuscript continues with a method to determine the average density and derive from that the snow water equivalent precipitation rate and snow accumulation rate.

These methods are explained with a series of equations that are derived step by step. All these equations, however, suffer from unclear, implicit, badly motivated (or not at all), or wrong assumptions. This makes it extremely difficult to check the validity of the methods and to understand under which conditions and for which type of hydrometeors they can be applied. None of these assumptions is adequately discussed. That means that uncertainties related to these assumptions cannot be estimated.

Despite these many issues and unclear assumptions, the results are seemingly good. This is both surprising and interesting and needs better and further discussion. In particular it is interesting how DEID estimated well snowpack densities agree with manually measured density despite the fact that average hydrometeor density is wrongly considered to be the snow pack density.

Due to all the issues with the method and validation measurements using a limited variety of very simply-shaped hydrometeors, most of the conclusions should be re-evaluated after addressing these issues.

Before I can accept this manuscript for publication, I would like to see major changes taking into consideration my feedback.

Below follows a detailed description of some issues, including major issues and some others, that I have seen. I have refrained so far from commenting on other smaller issues with for example language and on commenting in detail all the sections.

Issues with Equations

Eq. (1) --- Issues and questions

The term representing the heat required to increase the temperature is $m \cdot C_w \cdot T_{p,\text{max}}$. The specific heat of water C_w is different for ice and for liquid water. This fact seems completely neglected. No value for C_w is given.

Further, I would expect a temperature difference in this term, the amount by which the hydrometeor's temperature is increased. Instead there is $T_{p,max}$, which is explained as "maximum surface temperature of the hotplate". It is unclear what $T_{p,max}$ is and why it is used in this term.

Assuming that $T_{p,max}$ is the temperature difference by which the hydrometeor's temperature is increased, then this implies or assumes that the whole hydrometeor (m) actually increases by this amount. Is this assumption ok, i.e. does most of the evaporation (and consequential decrease in m) happen when the melted hydrometeor reaches its highest temperature?

The temperature $T_w(t)$ is the "temperature of the water droplet at time t ", whereas area $A(t)$ is the "area of each snowflake at time t ". Why does one refer to a droplet and the other to a snowflake?

How is "area" A defined?

The equation includes melting and evaporation. This is clear only from $Le_{qv} = L_v + L_f$ being the sum of the latent heats of fusion and vaporization. The integral in the equation is from time $t=0$ to Δt_{evap} , "the time required to evaporate the water droplet". It is unclear if melting is neglected in this integral or if melting starts at $t=0$, i.e. if the integral includes melting and evaporation. Does evaporation also start at $t=0$ or does it start when melting is finished (at $t = \Delta t_{melt}$)?

κ is determined by evaporating droplets of known mass (in Singh et al. 2021, water droplets of $20\mu\text{L}$). The "empirical calibration coefficient" κ seems to represent the specific heat capacity of the contact area between hotplate and melted hydrometeor. κ is $(k/d)_{eff}$ in Singh et al. 2021, who call this the calibrated value of the term k_w/d_w in their equation for $R2$ (in text; for $R2$ see their Fig 2 and Eq 15) without mentioning anywhere what k_w and d_w are.

κ is determined only for liquid droplets and only for one size. Is κ a constant that can be applied to frozen and liquid hydrometeors as done in Eq. (1)?

Melting neglected in Eq. (1)??

Initially, at deposition at $t=0$, the contact is at a few points only. Most likely it takes a very short time for a liquid layer to form at the hotplate, which provides the contact area needed to apply Eq. (1).

Heat lost from the hydrometeor or melted hydrometeor is neglected. This is not mentioned, motivated or discussed.

Eq. (2) --- Issues and questions

The time varying temperature difference from Eq. (1) is replaced with the constant ΔT_{evap} referring to Rees et al. 2021, who should be demonstrating that this can be done. I could not see that Rees et al. 2021 motivate this in any way, they simply do the same substitution from one equation to the next. As with Eq. (1), it is unclear if the integral starting at $t=0$ includes melting or only shows evaporation. In the former case, Fig2b shows that the temperature difference

cannot be approximated as constant. In the latter case, the integral is over the time range in white in Fig2b and the temperature difference ΔT_{evap} may be approximated as constant.

Eq. (3) --- Issues and questions

The “particle’s effective thickness in the direction normal to the hotplate h ” seems to be defined as the height of the quasi hemispherical “droplet” on the hotplate (Fig1). Why is this called “effective” thickness? The melting speed relates h and the time required to “melt an individual snowflake”. How is h defined for a “frozen hydrometeor”?

Eq. (3) implies that the “volume of a snowflake” is $A_p * h$.

When P_0 is later determined (Sects 3.1/3.2 and Sect 4.1), frozen quasi-hemispherical solid ice pellets are used. As an example, one size is generated from water droplets of $60\mu\text{L}$ volume and stated to have a measured height h of 1.95mm and area A (why is this not called not A_p ?) of 0.502 cm^2 (L278-279). The volume of these ice pellets is thus (according to $A_p * h$) $98\mu\text{L}$. This cannot be explained by the lower ice density and shows that $A_p * h$ is not the volume of these ice particles. However, this volume is what Eq. (3) is based on. This then affects the following equations too, in particular Eqs (7) and (8), which are used to determine the density of a frozen hydrometeor.

Eq (4) --- Issues and questions

L_{ff} should be L_{f} ?

The equation refers only to melting. It seems to implicitly approximate the temperature difference between hotplate and frozen part of hydrometeor as constant ΔT_{melt} . Is this justified? I am not sure when looking at Fig2b (the grey part).

What happens to the integral? Why have an integral over A over a constant 1 and not write out what that is? How you get to that integral is also unclear. There seem to be implicit assumption that are not mentioned.

Eq (5) --- Issues and questions

The concept of “the ‘effective mechanical work rate’ or mechanical power ... required to melt a snowflake” is not adequately introduced, in particular the “constant ‘melting pressure’” P_0 . Apparently P_0 was found to be constant empirically, and these equations (Eq.5) represent the attempt to derive that with some integrals that seem mathematically dubious. It is unclear what integrals over V_s or $A*h$ between $t=0$ and Δt_{melt} as it is mathematically wrong. As with Eq. (4), there seem to be implicit assumptions not mentioned, and the unresolved integral over A appears.

Eq (6)-(9) --- Issues and questions

These equations follow from the above equations, i.e. they are based on the assumptions and approximations of those so that it is difficult to see under which conditions they apply and/or how the density ρ_{MS} is implicitly defined. See also the issues regarding Eq (3) about interpretation of volume and definition of h .

One assumption used to derive Eq. (8) from Eq (7) is the substitution shown in L 108 to replace ΔT_{melt} and Δt_{melt} with ΔT_{evap} and Δt_{evap} .

This is based on Eq (4)/Eq (A1) and Eq (A2) with all their assumptions and issues.

Eq (10)-(13) --- Issues and questions

The accumulated snow water equivalent SWE is simply the snow water equivalent rate of precipitation (from Eq. 10) times Δt_{res} . Why use an integral (in Eq 11) if all that is involved is a single value of Δm and one sampling interval Δt_{res} ?

Eq. (12) defines an average hydrometeor density of an ensemble of hydrometeors as the sum of their masses divided by the sum of their estimated volumes. I do not agree with calling this “average density of a freshly fallen snowpack layer”. If it was the average snowpack density, then Eq. (13) describes the snow accumulation rate, as claimed. But given the definition of this average density, H from Eq. (13) is the height that one would get if all hydrometeors pack exactly (sum of volumes of hydrometeors divided by the surface over which they were collected), i.e. without effectively neither leaving any space in between them nor overlapping. In other words, I don’t agree that one can generally determine the height of the snowpack and the accumulation rate from the volumes of the individual hydrometeors without any knowledge of how efficiently they pack.

DEID laboratory set-up

The DEID is described briefly here, the previous publication about the DEID and its method (Singh et al. 2021) should contain the details.

The set-up, however, is flexible and in this manuscript is described as a hotplate of 9 cm x 6 cm that is thermally imaged using 531 pixels x 362 pixels of the thermal camera yielding a “spatial resolution” of 0.2 mm/pixel. It is, without mentioning this, assumed that the thermal imagery is looking vertically down at the hotplate. What is not mentioned here, neither for the set-up in Singh et al. 2021, is the actual inclination of around 30 degrees (see Fig 3c). Does this, and if so to what extent, affect the determination of A_p and A ?

Fig 3b shows a “Side-view of a surface temperature contour plot of an ice particle obtained using the thermal camera.” Has this been obtained with the configuration shown in Fig 3c?

Sample preparation

L 164-166 describe the sample preparation to manufacture ice particles for laboratory validation. In a freezer, one of eight different known volumes is applied, using a micropipette, to “a flat silicone mold”. Is this a flat silicone sheet rather than a mould suggesting a specific shape? The formed ice particles are referred to as “hemispherical”. I guess they will be close to, but not exactly hemispherical, as can be seen, for example, from the value of A_p of 0.502 cm² (L278-279) for ice particles produced from 60 μL of liquid water (a hemisphere of liquid water would have 0.29 cm²). The shape of these sample ice particles should be better described. See also comments on volume and h regarding Eq. (3).

Sect 3.2/Sect 4.1: what is the ambient temperature in the lab when testing environmental variability? In field evaluations (Sect 4.3) the ambient temperature varies. Do results depend on ambient temperature, which for calibrations was plus 18 degree C?

L 274: “Here, V_{pipette} is volume of the ice particle created by pipetting a known volume of water.” Should V_{pipette} not be the volume of liquid water dispensed from the pipette to generate an ice particle?

Sect. 4.1 last sentence (L 283-285): The “80 ice particles with different shapes and sizes” were presumably all of the same size and same shape. I am assuming this as it is in the same paragraph as the description of test particles as produced from 60 μL of liquid water. Else, what does “different shapes and sizes” refer to?

Tab 3: What is “Percentage of salt”?

Uncertainties

There is no discussion of how measurement uncertainties affect the measurements of mass and density.

Errors in A as determined by thermal imagery?

Micropipette accuracy? L 152: “1.00/1.20 %/μL”, what does that mean? 1% or 1% for each 1.2 μL; 1% or 1.2 μL (when 1% and when 1.2 μL)?

Accuracy of measurements of h?

Accuracy of temperature measurements?

Maybe less important: accuracy of time measurements? With 15 fps I guess error in time is on the order of 1/15 s.

Sect 3.5 --- geometrical volume estimates

The explanation of how volume is determined is not sufficient. The quantities D_{min} , D_{max} , A , $mean(A)$, and D_v are not defined adequately. Planar crystals are approximated as a disc. Is this disc a cylinder (as suggested by Fig 5b) or a column with base A_{max} (as suggested by the definition of A_{max} from the text)?

When referring to “the mean area of all images as illustrated in Fig. 5b”, it is not clear what exactly this refers to. The text and Fig 5b are not sufficient to precisely define D_{min} .

“Dreff” (L 232) should be D_{eff} ?

What is D_v (not clear from Fig 5b)?

D_{min} is likely over-estimating the thickness of Planar crystal particles, as it is difficult to get the thickness from the images. The examples Planar crystal shown in Fig 5a is likely not completely planar but features some 3D structure coming out of a dominant plane.

Some other issues:

The units of c (L270) are not given.

Fig 8b contains the mean density from “manual measurements”. This is not mentioned in the text of Sect 4.4, but likely refers to Eq. (16). Note, that this is not the same as the average density from Eq (12), see my comments regarding Eq (10)-(13).

L344 in Conclusions lists “an estimate of the speed with which the particle thickness on the plate diminishes as it melts” as one of the measured variables without saying that it is the melting speed. This text is not adequate for describing melting speed. Melting speed is h divided by melting time, not the speed at which the thickness h diminishes as that may vary with time.

Fig A1. Plotted times only, not products of times and temperatures ($\Delta T_{melt} \Delta t_{melt}$ and $\Delta T_{evap} \Delta t_{evap}$), as should be done according to Eq (A3)?

Fig B1 shows example images for aggregates. They seem to be cut (not completely imaged). Are these aggregates cut, or is this an effect of cropping when several aggregates are close to each other? It would be good to show examples with the whole hotplate indicating if several particles are observed. Are multiple particles observed falling onto the hotplate closely to each other (observed by SLR imaging) and then thermally imaged?