

## Responses to Reviewer 2

We thank the reviewer for their efforts and all the comments that helped improve the paper's clarity and manuscript writing.

### Comment 1: Seemingly good results:

**Comment 1:** In my previous review I have noted that despite many 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 used as proxy of the snowpack density.

**Response 1:** We agree that snowpack density estimated by DEID using the average density of snowflakes is surprising. The following statements may help explain these results:

- (1) The fresh snowpack minimally settles during the short interval of 12 hours between manual measurements. That is, comparisons are made with 12-hour storm boards.
- (2) There may be minimal overlap of snowflakes in snowpack. That is, the sum of the heights of the snowflakes is equal to the total depth.
- (3) In reality, there is overlap, but on "average," overlap is minimal.
- (4) Our results imply that the density of the snowpack is equal to the average density of individual snowflakes, which means that the snowflakes "pack" with a density similar to the density of the snowflake. We note that sometimes this is not true, for example, with errors of 15%.

This discussion has been added to the paper in the Conclusions.

**Comment 2:** Validation measurements and calibrations ( $v_{melt}$ ,  $\kappa$ ,  $c$ ,  $c_{melt}$ ) are using a limited variety of very simply-shaped hydrometeors. Is  $\kappa$  the same for ice and liquid (melting and evaporation)? How/why can these then be used for real snow particles, why are the results so good? This is not obvious and should be briefly discussed.

**Response 2:** Indeed,  $\kappa$  was calibrated in the lab with water droplets and idealized ice particles (Singh et al. 2021), and the  $\kappa$  value that we found is valid for both water droplets and ice particles. To deal with complex snowflake shapes, an alternative validation method was needed. Hence, as presented in section 4.3, individual snowflake densities were measured using the SLR camera-laser system (for volume) and the DEID (to obtain mass). This method agrees well with the  $v_{melt}$  densities, which indicates  $\kappa$  is suitably applied to all snowflake types.

We believe that the results the high level of agreement is because all reported measurements are based on the evaporation method (liquid phase), i.e. it is based upon Eq. (8) (previously Eq. (3)). SWE measured for seventeen storms shows excellent agreement with manual measurements (see Figure 9a), with a coefficient of determination of 0.99. The implication is that that  $\kappa$  is well

suited for all types of snow after melting. The parameters  $v_{melt}$ ,  $c$ , and  $c_{melt}$  all depend on  $\kappa$  and  $\Delta T_{melt}$ . Hence, we can use  $v_{melt}$ ,  $\kappa$ ,  $c$ , and  $c_{melt}$  for all types of snowflakes. The results are promising because a similar assumption/uncertainty (e.g. error in temperature, area, time, temporal and spatial averaging) was made during  $\kappa$  calibration.

**Area not properly defined:**

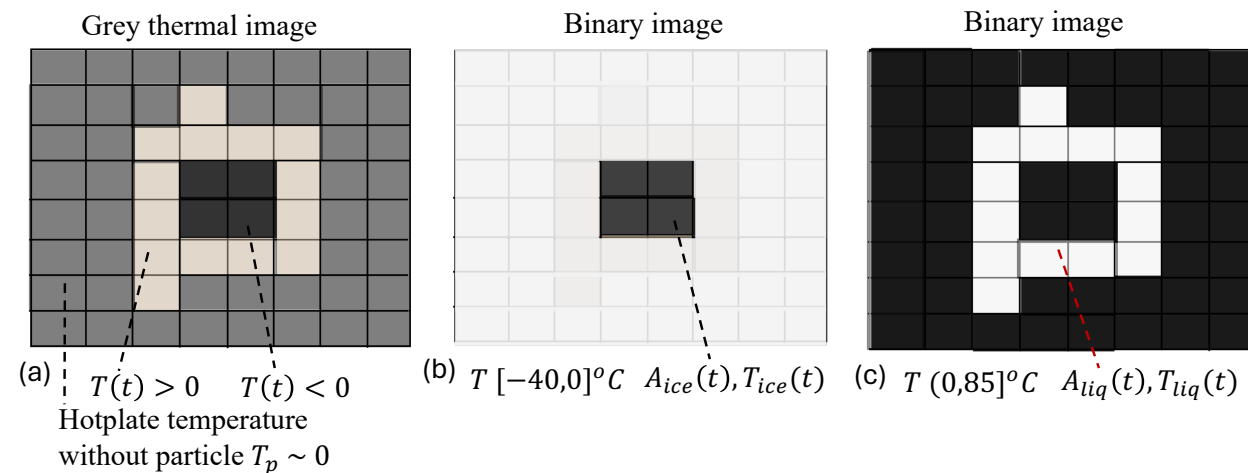
**Comment 3:** Area  $A(t)$  (and  $A_{ice}$  and  $A_{liq}$ ) is still not properly defined. You simply state that it is the area of the ice particle, melted hydrometeor ...

Formulations like " $A(t)$  is the area of each frozen hydrometeor and water droplet at time  $t$ ," are ambiguous. This is ambiguous and may for example refer to the total surface area.

Regarding the heat transfer, it should be a contact area between hydrometeor and hot plate (or some sort of effective contact area).

Regarding your measurement method, it should be cross-sectional area as seen on your 2D images ( $A_p$  you call projected area).

**Response 3:** We agree with the reviewer and have updated the area definition in the manuscript.  $A_p$  is defined as a contact area of the droplet associated with conductive heat transfer from the hotplate to the hydrometeor in the vertical direction. We have added this in Lines 85-90. At any time during melting and evaporation, the temperatures of some portions of the hydrometeor area are less than freezing and others greater than freezing. The contact area of a hydrometeor on the hotplate with a temperature less than or equal to zero is  $A_{ice}$  (the sum of all pixels with temperatures less than or equal to zero). The contact area of a hydrometeor on the hotplate with a temperature greater than zero is  $A_{liq}$  (the sum of all pixels with a temperature greater than zero). We may write  $A(t) = A_{ice}(t) + A_{liq}(t)$ . We count pixels to obtain  $A_{ice}$  and  $A_{liq}$  using different temperature



ranges as detailed in Figure R1 and also added in Appendix E.

**Figure R1.** Schematic illustrating the measurement area (contact area) and temperature of ice and liquid separately. (a) Thermal image of the frozen hydrometeor on the hotplate. The temperatures less than or greater than zero show the frozen hydrometeor's unmelted and melted portions, respectively. The temperature recorded by the thermal camera for the hotplate is around zero due to the low emissivity of the plate, where the actual temperature is 85 °C. (b) In post-processing the data, the temperature range was set  $[-40,0]^\circ\text{C}$ , which allows one to “see” only the area of the unmelted portion (temperature less than and equal to zero) of the frozen hydrometeor, and the area of the melted portion (temperature greater than zero) is zero.

$T_{ice}(t)$  is the mean temperature of all pixels with a temperature less than or equal to zero, and those pixels have a good contrast with the background which allows them to be easily counted. (c) In post-processing the data, the temperature range was set  $(0,85] ^\circ\text{C}$ , allowing us to see only the area of the melted portion (temperature greater than zero) of the hydrometeor.  $T_{liq}(t)$  is the mean temperature of all pixels with a temperature greater than zero, and those pixels have a good contrast with the background that allows them to count.

### **Errors in Eq. (1)-(3):**

**Comment 4:** In Eq. (1), it looks like  $T_h(t)$  is the temperature of the whole hydrometeor (having a cross-sectional area  $A(t)$ ).

This is a simplification hiding details that you likely consider in your algorithms. In addition to the integral over time, there should be an integral over the area and  $T_h(t)$ , as well as  $T_{ice}(t)$  and  $T_{liq}(t)$ , is evaluated at each location. Presumably in your algorithm you do this double integral as two sums, one over all hydrometeor pixels of the image and one over all time steps (images) during melting and evaporation.

Without a double integral, I don't see how you can go from Eq. (1) to Eq. (2) only using  $A(t) = A_{ice}(t) + A_{liq}(t)$ . (In your algorithm, a pixel is either ice or liquid, thus you can split the area integral in the two parts you indicate in Eq (2). However, just as Eq. (1), Eq. (2) is wrong (over-simplified).

**Response 4:** We agree that certain details were omitted and as a result have added Eqs. (1) to (6), where double integration over time and area is explained step-by-step.

Specifically, the mass  $m$  of an individual hydrometeor is obtained by applying conservation of energy to a control volume surrounding each hydrometeor on the hotplate (see Fig. 1). The heat gained by a snowflake from the heated plate is assumed to be equivalent to the heat required to increase the snowflake's internal energy plus the heat lost during melting and evaporation,

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which may be described as follows

$$Q_{in} - Q_{out} = \Delta Q_{st}. \quad (1)$$

Here,  $Q_{in}$  is the conductive heat gained by a hydrometer from the hotplate,  $Q_{out}$  is the heat loss from a hydrometeor to the surrounding,  $\Delta Q_{st}$  is the energy stored in a hydrometer during melting and evaporation. Neglecting convection and radiation losses from the hydrometer (which was shown to be a good approximation in Singh et al. (2021)), Eq. (1) can be written

$$\int_{t_{pc}} \int_{A_c} k(\partial T / \partial z) dA_c dt - \int_{\mathcal{V}} \rho L_{eqv} d\mathcal{V} = \int_{t_{pc}} \int_{\mathcal{V}} \rho C_p (\partial T / \partial t) d\mathcal{V} dt. \quad (2)$$

Here,  $k$  is the thermal conductivity of the aluminum plate,  $A_c$  is the contact area of the hydrometeor on the hotplate,  $t_{pc}$  is time it takes to melt or evaporate a droplet (phase change),  $\partial T / \partial z$  is temperature gradient related to conduction from the hotplate into the hydrometeor,  $\rho$  is density of hydrometeor,  $\mathcal{V}$  is volume of hydrometeor,  $L_{eqv} = L_f + L_v$  is the combined latent heat of fusion ( $L_f$ ) and vaporization ( $L_v$ ),  $C_p$  is the specific heat of hydrometeor,  $z$  is the vertical direction normal to the hotplate. Using  $m = \int_{\mathcal{V}} \rho d\mathcal{V}$ ,  $\partial T / \partial z \approx \Delta T(x, y, t) / \Delta z$ , and by separating the energy stored in hydrometeor during melting and evaporation, Eq. (2) can be modified as

$$\int_{t_{pc}} \int_{A_c} (k / \Delta z)_{eff} \Delta T(x, y, t) dA_c dt - m(L_f + L_v) = mC_{ice}(T_0 - T_{ice}) + mC_{liq}(T_p - T_0). \quad (3)$$

Here,  $C_{ice}$  is the specific heat of ice,  $T_p$  is the hotplate surface temperature during melting and evaporation; it is constant with time,  $T_{ice}$  is initial temperature of a frozen hydrometer,  $T_0 = 0^\circ\text{C}$ ,  $L_f = 3.34 \times 10^5 \text{ J kg}^{-1}$  is the latent heat of fusion of water, and  $L_v = 2.32 \times 10^6 \text{ J kg}^{-1}$  is the latent heat of vaporization of water (see Appendix A1),  $C_{liq} = 4.18 \times 10^3 \text{ J kg}^{-1} \text{ K}^{-1}$  is the specific heat of liquid water,  $(k / \Delta z)_{eff} = \kappa$  is an empirical device-specific calibration coefficient related to the amount of heat that passes through the metal plate into individual hydrometeors per unit time through a unit area with a temperature gradient of one degree, determined to be  $7.01 \pm 0.01 \times 10^3 \text{ W m}^{-2} \text{ K}^{-1}$  (see Singh et al. (2021) for details), which is independent of particle size and environmental conditions. In practice, to numerically calculate the mass of a hydrometeor using images from a thermal camera on 'pixel-by-pixel' basis we suppose that  $n_x$  is the total number of pixels making up hydrometeor in  $x$ -direction at time  $t$  and  $n_y$  is the total number of pixels associated with hydrometeor in  $y$ -direction at time  $t$ . The total number of pixels at time  $t$  is  $N(t) = n_x(t)n_y(t)$ . Eq. (3) can be modified and rearranged for a pixel-by-pixel implementation of Eq. (3) as

$$mC_{ice}(T_0 - T_{ice}) + mL_f + mC_{liq}(T_p - T_0) + mL_v = \kappa \int_0^{\Delta t_{evap}} \sum_i^{n_x} \sum_j^{n_y} (T_p - T_{ij}(t)) A_{ij}(t) dt. \quad (4)$$

Here,  $\Delta t_{\text{evap}}$  is the time required to melt and evaporate a hydrometeor,  $A_{ij}(t)$  is the area of  $ij^{\text{th}}$  pixel at time  $t$ ,  $T_{ij}(t)$  is the temperature of  $ij^{\text{th}}$  pixel at time  $t$ . Assuming all pixels have the same area (e.g.,  $A_1$ ) then  $\sum_i^{n_x} \sum_j^{n_y} A_{ij}(t) = n_x n_y A_1(t)$  is the total contact area of the hydrometeor at time  $t$  (i.e.,  $n_x n_y A_1(t) = A_c(t)$ ). Substituting  $A_c(t)$  into Eq. (4) yields

$$mC_{\text{ice}}(T_0 - T_{\text{ice}}) + mL_f + mC_{\text{liq}}(T_p - T_0) + mL_v = \kappa \int_0^{\Delta t_{\text{evap}}} A_c(t) \left( T_p - \frac{1}{n_x n_y} \sum_i^{n_x} \sum_j^{n_y} T_{ij}(t) \right) dt. \quad (5)$$

85 Here,  $\frac{1}{n_x n_y} \sum_i^{n_x} \sum_j^{n_y} T_{ij}(t) = T_h(t)$ .  $T_h(t)$  is the spatial mean temperature over all frozen hydrometeor and/or water droplet pixels at time  $t$  on the hotplate. Substituting the spatial mean temperature  $T_h(t)$  into Eq. (5) yields

$$mC_{\text{ice}}(T_0 - T_{\text{ice}}) + mL_f + mC_{\text{liq}}(T_p - T_0) + mL_v = \kappa \int_0^{\Delta t_{\text{evap}}} A_c(t) (T_p - T_h(t)) dt. \quad (6)$$

**Comment 5:** To say that the camera doesn't see ice, and therefore  $A_{\text{ice}}=0$  is wrong. If starting with ice, then of course neither is  $A_{\text{ice}}$  zero, nor the terms  $m \cdot C_{\text{ice}} \cdot (T_0 - T_{\text{ice}}) + m \cdot L_f$ . You seem to assume that heat transfer through  $A_{\text{ice}}$  goes exclusively into temperature increase of ice and melting of ice (and heat transfer through  $A_{\text{liq}}$  does not go into these ice terms). So I would clearly state this assumption (important since during part of the time integral in Eq. (3) ice is still present) and directly introduce Eq. (3), i.e. skipping Equations (1) and (2), making sure the integral is properly formulated. It is worth already

here mentioning that when the camera is set to only see hydrometeors after melting, this is done in post-processing only.

**Response 5:** We agree with the reviewer regarding the confusing sentence "the camera doesn't see ice" as neither  $A_{\text{ice}}$  is zero, nor the expression  $m \cdot C_{\text{ice}} \cdot (T_0 - T_{\text{ice}}) + m \cdot L_f$ . First, we assume that heat transfer through the area  $A_{\text{ice}}$  exclusively increases the temperature of the ice leading to ice melting, and that heat transfer through  $A_{\text{liq}}$  does not go into these ice portions (added on Lines 100-105). We justify this since the temperature gradients between the ice and water are much smaller than the temperature gradients between the plate and hydrometeor. Furthermore, the thermal conductivity of aluminum is much higher than ice or water. Note that in post-processing data, the thermal camera can be adjusted selectively to "see" particles on the hotplate in specific temperature ranges (see section 3) as detailed in Appendix E. "In post-processing data, the temperature range of the thermal image was set such that only one phase, either ice or liquid, could be seen on the hotplate. Figure E1a shows a grey thermal image where the temperature of some portions is less than or equal to zero, and some are greater than zero. In post-processing data, only

the ice portion is visible when the temperature range  $[-40,0]$  °C is used, as seen in Fig. E1b. The sum of all visible areas is  $A_{ice}(t)$ , and the spatial mean temperature over all those pixels is called  $T_{ice}(t)$ . Similarly, when the temperature range  $(0,85]$  °C is used, only the liquid portion is visible, as seen in Fig. E1c. The sum of all visible areas is  $A_{liq}(t)$ , and the spatial mean temperature over all those pixels is called  $T_{liq}(t)$ .

**Comment 6:** Be consistent, e.g, if using  $A_{liq}$ , then use it also in Eq. (3).

Reformulate "Note that the initial and final temperature of all frozen hydrometeors is  $T_0 = 0$  degC and  $T_p$ , respectively, during evaporation", which is confusing as you refer to a "frozen hydrometeor" (during part of the evaporation part of the hydrometeor is frozen and below  $T_0$ ).

In Eq. (3) it is wrong to use  $C_{liq} * T_p$ . The specific heat  $C_{liq}$  needs a temperature difference (i.e.  $T_p - T_0$ ). The same applies to Equations (B1) and (B2).

**Response 6:** This has been corrected. We have added the following on Lines [109-111]: Note that all liquid droplet's initial and final temperature during evaporation is  $T_0 = 0$ °C and  $T_p$ , respectively. In Eq. (3), the temperature difference is  $T_p - T_0$ , equal to  $T_p$ .  $T_0 = 0$  for all liquid droplets.

## Sect 2.2 Particle density

### Unclarities remain about h and volume estimate:

**Comment 7:** Fig. 1 is not "illustrating" well a heat transfer rate and control volume. They need to be better explained in the text and equations.

That  $m * L_{ff}$  is "the sum of the internal energy per unit mass of a frozen hydrometeor and its latent heat of fusion" is another example of a wrong/sloppy formulation.

**Response 7:** Fig. 1 has been updated with a side and top view of the control volume and heat transfer balance across the control volume.  $mL_{ff}$  is the sum of internal energy and its latent heat of fusion (energy received by ice to increase temperature and melt completely). We also added Lines 130-135.

**Comment 8:** What is the reason or motivation behind hypothesis Eq. (5)?

Explaining  $\Delta T_{melt}$  below Eq. (5), you have  $T_p(t)$ . But earlier you stated that  $T_p$  was constant. You refer to the wrong Appendix (should be B not A).

$\Delta T_{evap}$  is not defined. Equation (8) is wrong.

**Response 8:** In Eq. (5) (now it is Eq. (9)),  $v_{melt}$  is associated with conductive heat flux from the plate to the ice particle, which is a function of  $\Delta T_{melt}$ . We corrected  $T_p(t)$  to  $T_p$ . Also corrected is Appendix B.  $\Delta T_{evap} = \overline{T_p - T_{liq}(t)}$  temporal and spatial mean during evaporation is added in lines 145-150 and Eq. (8) (now it is Eq. (13)) has been corrected.

**Comment 9:** Without your explanation in the response, one needs some guessing to understand the reasoning behind the "simple height relationships like  $h = 2R/3$ ".  $R$  is (only in the caption of Fig. 1 introduced as "radius of the hydrometeor",  $h$  as the "effective thickness of the hemisphere". You should (more clearly) refer to the special case of a hemispherical ice particle here. You still need a general definition of  $h$  in the text. This is important for clarity of course, but also as the definition of  $v_{\text{melt}}$  seems to be based on  $h$ . It is unclear how, in the laboratory, you can use Eq. (9) with its term  $h_{ij}$ . How can you determine all  $h_{ij}$ ?

"...used Eq. (9) to calibrate laboratory ice particles and compare snowflake habits." What do these refer to?

Line 137: "Note that are impacted by variability..." Something is missing.

In caption of Fig. 2 "(a) Time series of the area of the ice particle (dashed black line) and the melted portion of the ice particle (solid black line)" is another example of a wrong/sloppy formulation.

**Response 9** This has been added in the text lines 150-155: "Snowflakes of complex shapes do not have simple height relationships like  $h = 2R/3$  as shown in Fig. 1a. Hence, a method is required to determine the height and volume of every pixel within a snowflake." We added a general definition of effective thickness,  $h = (1/N)\sum_i \sum_j h_{ij}$  for frozen hydrometeor on Line 135. Eq. (9) (now it is Eq. (14)) provides pixel-by-pixel volume without simplification, which gets a more accurate value and is used for calibrating laboratory ice particles and comparing snowflake habits. Eq. (10) (now it is Eq. (15)) has some simplification, as you can see in Eq. (15), which adds around 2% additional uncertainties. Eq. (15) was used for bulk (many particles) measurements that save computational time. Line 137 (now it is Line 165) is corrected. Fig. 2(a) caption is updated as a time series of the area of the ice particle,  $A_{\text{ice}}(t)$  (dashed black line), and the liquid,  $A_{\text{liq}}(t)$  (solid black line).

### **Sect 2.3 bulk snowpack-derived quantities**

**Comment 10:** The assumption "... by assuming neither leaving any space between snowflakes nor overlapping" is wrongly placed, it is not needed for the average density defined by Eq. (12). The snow accumulation rate in Eq. (13) needs the above assumption. The assumption, however, seems unmotivated and Eq. (13). Link your text "Note that the bulk..." to that assumption.

**Response 10:** It has been corrected on Line 190. The average density of snowflakes (we deleted the average density of freshly fallen snowpack layer) and assumption "assuming no space between snowflakes nor overlapping snowflakes" added in Eq. (18) (previously, it was Eq. (13)).

### **Sect 3.1: ice particle height vs effective height**

**Comment 11:** You don't seem to refer to Fig. 3 (only to Fig. 3d).

Fig. 3b, Fig. 3d, and in text related to Fig 3d, the height  $h$  seems to be a height rather than the effective height  $h$ . Also, in Tab. 1,  $h$  seems to be close to  $R$  derived from  $A_p$  (not to  $2/3 \cdot R$  as I would expect) if the ice particle were a hemisphere. In Fig. 3b, the ice particle doesn't look hemispherical (max height is less than  $R$ ).  $Deff$  in that figure is not explained. L. 376-377 also talk about height rather than effective height. Check for consistency. If the side view in Fig. 3b is taken with the thermal camera shown in Fig. 3b, i.e. from above (Response 19), then I am not sure how it can be a side view.

You should be clearer and more detailed in your description of preparing ice particles in Sect.s 3 and 4 and resulting shapes and contact angles. I am wondering about the role of the silicone mold and didn't understand earlier that it has a certain shape (circular deepening or flat or other shapes deepenings as suggested by Line 315?).

**Response 11:** Figure. 3 is cited in the paper now at the beginning of section 3.1. Figure. 3b is updated. In Figure. 3b,  $h$  is replaced by  $R$ . In Table 1, the maximum height, which is the radius of a hemisphere, is corrected ( $h$  is replaced by  $R$ ). we are not using  $Deff$  in this figure. Lines 376-377 are also corrected. For Fig. 3b, the thermal camera was recorded from the side of the ice particle (added in the caption of Fig. 3b.). The contact angle between silicon flat mold and water droplet is about  $90^\circ$  and a sample of water droplet on silicon flat mold and random surface is shown in Fig. F1.

## Fig. 5

**Comment 12:** In the text related to Fig.5 explaining the geometrical volume estimates, it is unclear what  $D_v$  is (column III aggregates).

**Response 12:** We have added text on Lines 295-300 to address this.  $D_{max}$ ,  $D_{min}$ , and  $D_v$  are the lengths of three mutually perpendicular ellipsoid axes.

## Approximations in Appendix B

**Comment 13:** As you equate  $(B1)=(B2)$  you need to relate Equations (B1) and (B2) to the whole mass (that is melted completely in B1 and then evaporated completely in B2). You need to specify over which part of the area  $A$  (or pixels) you effectively integrate in each of these equations (see comments on integrals in Equations (1) and (2) above). Explain what the "averaging approximation" means. Note that you already use an approximation when using an average  $\Delta T_{melt}$  and  $\Delta T_{evap}$  that should be explained (or refer to somewhere in the paper). (See your Response 10, for example)



**Response 13:** We equated Eq. (B1) for complete melting and Eq. (B2) for complete evaporation for a single pixel (m changed to  $m_{ij}$ ). Based on experimental tests, we assume that  $\Delta t_{ij,melt} \approx \Delta t_{melt}$  and  $\Delta t_{ij,evap} \approx \Delta t_{evap}$  ("averaging approximation") in Eq. (B4) that yields the relation Eq. (B5). All details are included in Appendix B. Please see Eqs. (1) to (6), where double integration over time and area is explained step-by-step.

**Appendix D errors:**

**Comment 14:** An error of only 1.4% for the area measurement seems very good. Can you describe briefly how this was determined or estimated?

Uncertainties in h: are these based on the laser measurements or the indirect method involving assumptions and approximations around  $\Delta T_{evap} \cdot \Delta t_{evap}$ ?

**Response 14:** Uncertainty in area measurement is estimated using the following equation

$$Error\ in\ A = \frac{\Delta A}{A} 100$$

Uncertainties in h were reported based on uncertainty in  $c_{melt}$ ,  $\Delta T_{evap}$ , and  $\Delta t_{evap}$ .