Response to reviewers:
On the suitability of the Thorpe-Mason model for calculating sublimation of saltating snow

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A note to all reviewers

Apart from addressing the points raised by of each of the two reviewers individually, we felt that it might be pertinent to write to both the reviewers together especially in view of the fact that the most outstanding issue raised by both is essentially the same - the need to present more data.

At the outset, we would like to thank the reviewers for mostly positive remarks regarding the quality of the submitted manuscript and the core message of the paper, i.e., questioning the well-established, Thorpe-Mason (TM) model for computing sublimation of snow particles in the atmosphere. We are further grateful to their detailed comments regarding the study and clarifications sought. We feel that this has genuinely improved the manuscript and help us convey our ideas more clearly to the prospective reader.

Coming to the common concern raised by both the reviewers, both the reviewers felt that we need to present more data, especially from the large-eddy simulations (LES) in Section 3 and used for Experiments III and IV. As would be apparent from the length of the submitted manuscript, we intended to be extremely focused on the core message - challenging the Thorpe-Mason model - and presented only those results that we felt were *most* relevant to support our result and make it clear to the community that this is a worthwhile challenge to the existing models and estimates for sublimation. We write in the originally submitted quite explicitly that the large-eddy simulations are, in the context of the current study, used for two purposely only; (a) to find the residence time of saltating particles and (b) see if the results from the extremely idealized grain-scale simulations of sublimation are relevant during saltation. These two aspects are covered by Figures 2 and 3 in the original manuscript.

We agree with Reviewer #1 that we need to atleast state the flow speed in the different u_* cases and we have added them in the revised manuscript. However, we humbly state that presenting vertical profiles of various mean and turbulent quantities, although quite interesting, would make the article lose its focus and move the discussion into areas that are far from the core message of the paper. This is especially true because we have 30 simulations in total. Given the immense size of the data-set, presenting it in any which way would certainly make the paper unwieldy, without perhaps adding much to core message of the paper.

Are the vertical profiles of different variables interesting ? Certainly. Indeed, we are currently working towards a manuscript analyzing the LES results using mean and turbulent kinetic energy, heat and moisture budgets. The present round of reviews has in fact motivated us even further about the importance of such an analysis for the community. However, the depth of the analysis necessitates a separate paper. In view of our opinion on this issue we state the following points:

- It seems to us that for both the reviewers, the interest in analyzing vertical profiles from the LES simulations was triggered by a hypothesis presented in the paper to explain the role of increased sublimation and the associated cooling and stabilization of the saltation layer in lowering the residence time of lighter (smaller) particles as opposed to the heavier (larger) particles. This hypothesis is indeed confirmed in our data and can be explained by looking at the total vertical buoyancy flux. However, presenting this quantity would require presenting a host of other associated quantities. Most importantly, this point by itself, although quite interesting and a major motivation for a lot of our current work, is not of principal interest for the core message of the paper. We have remolded the text in the revised manuscript accordingly and touched upon this point in the concluding section of the paper.

- If the reviewers feel quite strongly that this data is absolutely necessary in the current paper, we hope that it is indeed agreeable to the reviewers that it is sufficient to add it to the supplement (as suggested by Reviewer #1). We attempted to add it to the main portion of the manuscript but it was really hard to maintain the flow of the paper and not distract the reader into issues far from the core message of the paper. Thus, the reviewers will find, in what follows, the new additional analysis that we hope can be added to supplement.

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S3.1 Vertical profiles of mean and turbulent quantities

In this section, vertical profiles extracted from the large-eddy simulations in Experiment III are shown to provide additional context for the simulations performed. Note that a detailed analysis of the vertical profiles is out of the scope of the present study and will be presented in a future publication. All the profiles presented below are time-averaged as well as averaged in the horizontal (periodic) directions.

In Fig. 1, the velocity magnitude for the low (UL), medium (UM) and high wind (UH) cases are presented. Influence of initial relative humidity (the RL, RM and RH variants) was not found to be important and thus not presented. Before the snow surface is allowed to be eroded, a fully developed channel flow is allowed to developed. This can be seen in Fig. S2 in the previous section. This also implies the formation of the logarithmic velocity profile as can be seen in Fig. 1. Once the snow surface is allowed to erode, snow transport begins and the particles in the flow cause enhanced drag in the flow. This causes the velocity profile to change with an overall deceleration of the flow. The wind speeds before saltation begins at a height of 1 m above the surface are 11 m/s, 16.33 m/s and 21.86 m/s for the UL, UM and UH cases respectively. Once the snow transport is fully-developed (i.e., when the total mass of snow in the air is constant in Fig. S1), the corresponding wind speeds have reduced to 8.771 m/s (-20%), 11.34 m/s (-30%) and 12.98 m/s (-40%) respectively for the three cases.

The snow drift density is the mass of snow per unit volume present in the air and is shown for the UL-, UM- and UH- cases. Once again, the RL, RM and RH invariants of each of these cases are not found to be significantly different from each other and are thus not presented. Two time points chosen lie during the transient period where increasing snow mass is being entrained into air (profile at 10 seconds) and during fully-developed or steady state snow transport (profile at 240 seconds). The profiles are qualitatively as well as quantitatively (order of magnitude comparison) similar to previous works (see, for example, Gordon et al. 2009). As expected, the amount of

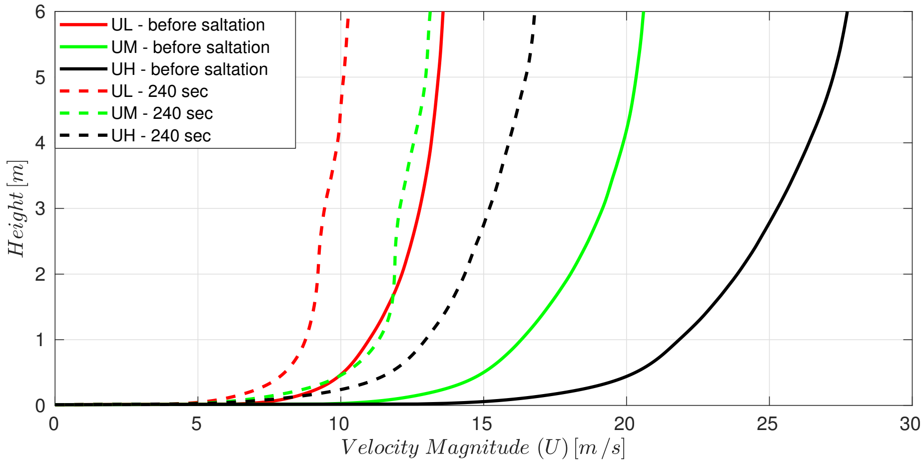


Figure 1: Vertical profiles of mean velocity magnitude for the low (UL), medium (UM) and high wind (UH) cases in Experiment III. For each case, profiles before commencement of saltation and 240 seconds after saltation begins are shown.

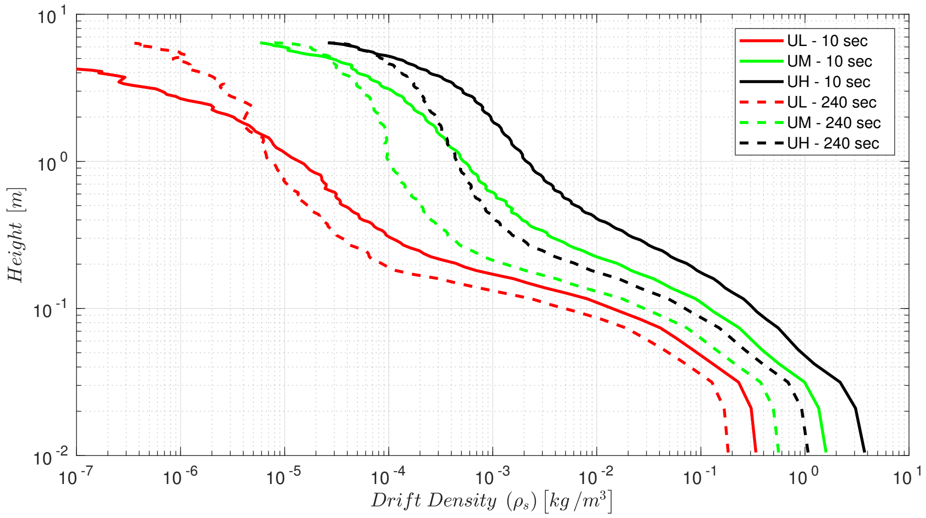


Figure 2: Vertical profiles of snow drift density for the low (UL), medium (UM) and high wind (UH) cases in Experiment III. For each case, profiles 10 seconds and 240 seconds after commencement of saltation are shown.

mass in the air increases with increasing wind speed and is found to be concentrated in the lowest 10 centimetres of air above the surface.

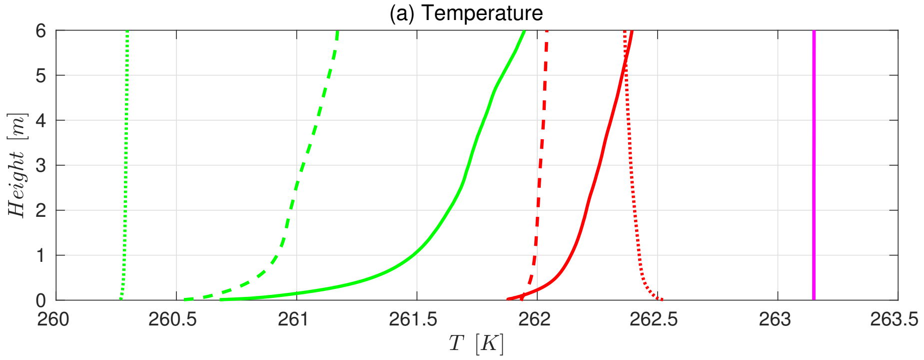
Figure 3 presents an inter-comparison of the evolving thermodynamic state of the air computed using either the NUM or the TM approach, with subfigures a,b and c showing vertical profiles of temperature, specific humidity and relative humidity respectively. Only one of the nine cases in Experiment III, namely the UL-RL case is chosen for illustration. Recall that as per our LES setup, the only source or sink of heat and mass in the atmosphere is through interaction with the particles. First, let's focus on subfigure c which shows the relative humidity (R.H) profiles at 3 different times after saltation begins, along with the initial condition for R.H, which in the UL-RL case was fixed at 30% in the entire domain. As time progresses, the R.H in the air increases due to cooling as well as larger amounts of water vapor, both due to sublimation of particles aloft. The profiles on the extreme right of subfigure c, which are extracted 1000 seconds after the start of saltation are similar for both the NUM and TM approaches with the air is close to saturation in both the cases. In the profiles at earlier time-steps, the R.H is higher near the surface and decreases with height as expected. The near surface air reaches a high saturation-rate (90%) within 100 seconds after saltation begins, but it takes almost 900 seconds more to reach saturation. This can be explained by turbulent mixing which continuously supplies dry air from aloft to the near-surface region.

While Fig. 3c, shows qualitatively a similar behavior for both the NUM and TM approaches as far as R.H evolution is concerned, we have shown in the main text that the TM approach underestimates the mass flux due to sublimation as compared to the NUM approach (see Figure 4 in the main article). The reason for this is the difference in the total cooling of the air between the two cases. This can be observed in the temperature profiles in Fig. 3a. For the TM approach, the cooling is much stronger, with the final temperature being 260.3 K, 2.85 K lower than initial air temperature of 263.15 K. On the other hand, for the final air temperature for NUM approach is 262.4 K, almost 2 K warmer than the TM case. The dynamics of the evolution of air temperature are much more complicated in the NUM case due to the inter-play between the thermodynamics of the air as well as the particles. Further work is needed to establish proper thermodynamic constraints on the coupled air-particle system. Ultimately, the results in Experiment I and II show that even for a solitary ice-grain, the TM approach under-predicts the mass sublimated in comparison to the NUM approach for exactly the same environmental conditions. This is reflected in the profiles of specific humidity in subfigure c. The NUM approach, at each of the three time-steps chosen shows higher flux as compared to the TM approach.

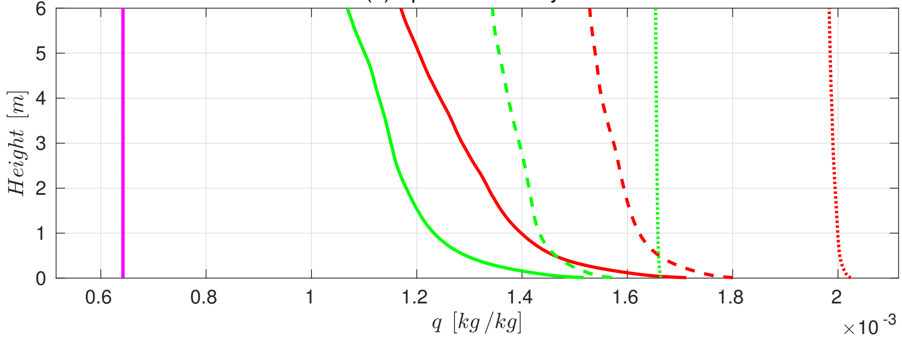
Vertical profiles of streamwise $\left(\sqrt{\overline{u'u'}}\right)$, cross-stream $\left(\sqrt{\overline{v'v'}}\right)$ and vertical $\left(\sqrt{\overline{w'w'}}\right)$ velocity fluctuations are shown in Fig. 4 for the UL-RL case before and during saltation. The TKE is highest near the surface and decreases with distance from the surface. Interestingly, during snow transport, each of the TKE components show a decrease as compared to their respective value before snow transport, upto a height on approximately 2 m above the surface. Above this height, the TKE components actually show an increase.

In the final figure in this section, we compare profiles of vertical buoyancy fluxes $\left(\overline{w'b'} = \left(g/\left\langle\theta_v\right\rangle_{xy}\right)\overline{w'\theta_v'}\right)$ from three cases, UL-RL, UL-RM and UL-RH, from Experiment III. The three subfigures show profiles for three different times after beginning of saltation. The vertical buoyancy flux is an important quantity as it is a term of the budget equation for vertical velocity fluctuations $\left(\sqrt{\overline{w'w'}}\right)$. For each simulation case, the buoyancy flux decreases as time progresses. The UL-RL case is also found to have the largest magnitude of buoyancy flux close to the surface in each of the time-steps shown, followed by UL-RM and finally UL-RH, which has the least buoyancy flux amongst the three cases. Note that this is negative buoyancy flux and thus, in terms of vertical velocity fluctuations, the -RL, -RM and the -RH cases have increasing vertical fluctuations in that order. This could potentially explain the results in Fig. 3a in the main text, where the lighther particles show increasing residence times in the order -RL, -RM and -RH. Further exploration of role of

(a) Temperature



(b) Specific Humidity



(c) Relative Humidity

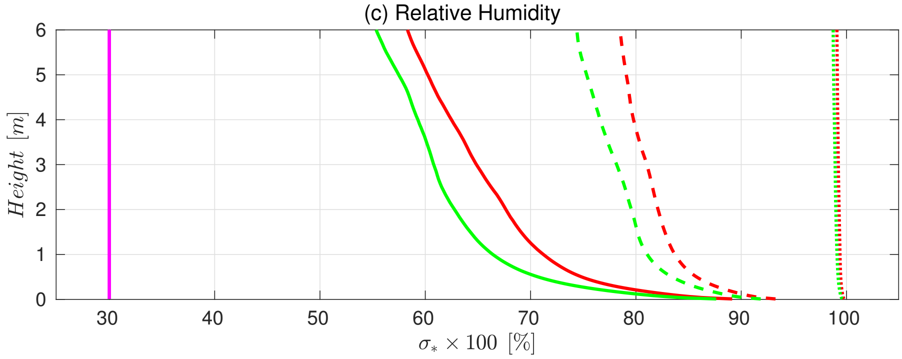


Figure 3: Intercomparison between the NUM (redlines) and TM (green lines) approaches for calculating sublimation of saltating snow in the UL-RL case in Experiment III. The magenta line is the initial condition for temperature, specific humidity and relative humidity. In all the subfigures, the solid, broken and dotted lines are profiles extracted 100, 240 and 1000 seconds after the commencement of saltation respectively.

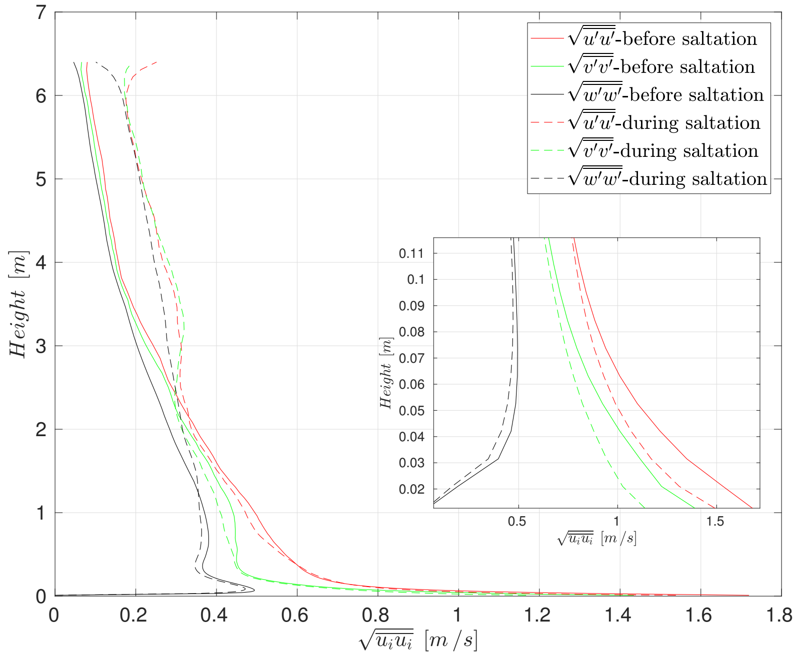


Figure 4: Vertical profiles of the three different constituents of the turbulent kinetic energy before and during saltation (240 seconds after saltation begins) for the case UL-RL in Experiment III.

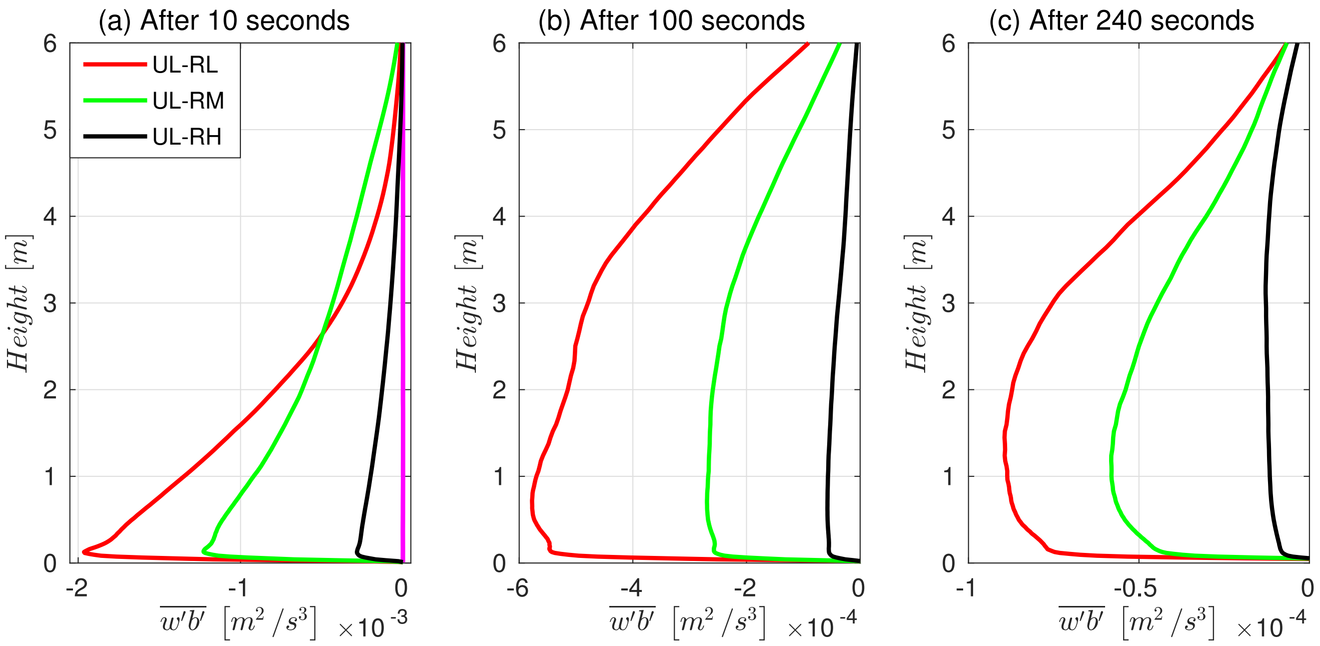


Figure 5: Vertical buoyancy fluxes for three cases, UL-RL, UL-RM, UL-RH at different times after the commencement of saltation.

buoyancy in affecting saltation dynamics is left for future work.

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