We'd like to thank Referees for the insightful comments and positive evaluation of our work. We have studied the comments carefully and did our best to revise and improve our manuscript. The comments by the reviewer are repeated in bold font and the responds are as follows.

Referee #1

This contribution addresses an important problem, which is globally unresolved namely how much snow mass is lost back to the atmosphere during drifting and blowing snow. The contribution now tries to quantify snow sublimation in the saltation layer, which is typically regarded as insignificant because of quick saturation. The authors present a concise and well-written article, which nicely discusses her main hypothesis that continuous transport of moisture out of the saltation layer may play a significant role.

Reply: Thanks for the reviewer's recognition of the importance and the writing of our manuscript.

However, their model assessment is fundamentally flawed and the paper must therefore be rejected. In the quantitative model assessment, the authors introduce (p.7 l.11) a completely arbitrary sink of moisture due to "advective" transport, which is contradicting the model set-up as a boundary layer model. The rest of the model uses the assumption of an equilibrium boundary layer in which forces or sinks/sources are balanced by vertical turbulent transport. By superimposing an artificial and completely unjustified horizontal moisture transport term, you can produce any number for sublimation. The calculation results are therefore not a scientifically sound basis for the conclusion that "DSS rate in the saltation layer can be several orders of magnitude greater than that of the suspended particles".

Reply: As we know，the term (i.e. Q in our paper) described the advection of total moisture by the wind basically exists in the moisture conservation equation (Roland B. Stull, 1988). Normally, this term is ignored under the hypothesis of horizontal homogeneity, which leads to the condition mentioned by the referee "an equilibrium boundary layer in which forces or sinks/sources are balanced by vertical turbulent transport". Although it is an effective way to simplify the moisture conservation equation for an infinite planar snow cover, this hypothesis is sometimes hard to be satisfied because of some common phenomena, such as patchy mosaic of snow or heterogeneous snow drifting over rough surface (Liston, 1999). In the paper, we did not artificially add the horizontal moisture transport term, but took into account of the ignored term under more complex situation. Actually, the effect of advection is considered via the setups of the entrance boundary and the egress boundary of moisture for the simulated region in our paper. Two typical conditions were discussed: 1), q_{in}=q_{out} , which neglects the effect of advection and be corresponding to condition of infinite and homogeneous snow cover; 2), to consider advection effect at the edge of snow surface, q_{in} represents moisture of dry air and q_{out} equals to the moisture of air affected by the snowdrift sublimation in the simulated region. Although these two cases may not correspond to the really situation exactly, it is an acceptable and useful way to discuss the possible influence of horizontal advection. Similar method was employed by other researchers, such as Richard Bintanja (2001). Anyway we honestly appreciate the referee for the suggestions and we also found there are some irrelevant descriptions which may cause misunderstanding in our paper. Relevant modifications are shown as following:

We described two extreme cases, 1) neglecting the effects of moisture transport; 2) considering moisture transport due to both moisture diffusion and advection. And also a common situation, i.e. considering only moisture diffusion, was studied to explore the interaction between snow sublimation and moisture transport in the revised manuscript. Moreover, we derived the prognostic equations of potential temperature and specific humidity (Eqs. (13) and (14)) from the basic convection diffusion equation (Eqs. (11) and (12)).

There are a (small) number of minor comments such as a missing discussion on surface sublimation or a splash function description on p.9 l.18, which appears to not match the corresponding equations but these are not important compared to the erroneous model set up described above.

Reply: In this manuscript, the initial relative humidity profile is set as $RH = 1 - R_S \ln(y / y_0)$, therefore there will be a saturated layer adjacent the surface. In this case, surface sublimation will not occur. When moisture transport is considered, it is still nearly saturated. Thus, we didn't take surface sublimation into consideration. For splash function, some improvements of description are made here, including: the definition of the vertical restitution coefficient e_v and the horizontal restitution coefficient e_h .

Short comment #1

In this study, a 2-D snow drift model is introduced. A saltation model is coupled with a treatment of moisture and temperature changes associated with snow drift. Much emphasis is placed on the description of the model, and it is relatively short on discussion of the model results. The paper is reasonably well written. A somewhat disappoiting aspect of the paper is that it does not have measurements for comparison or even published data for comparison. May be this can be improved.

Reply: Thanks for the insightful comments and positive evaluation of our work. As mentioned in our manuscript, previous studies on drifting snow sublimation mainly concentrated on the suspended snow. Whereas the sublimation of salating particles was generally ignored due to the consideration that sublimation will soon vanish in the saltation layer for the feedback of drifting snow sublimation (DSS) may lead to a saturated layer near the surface. Therefore, there are very few existing studies and published data on snowdrift sublimation in the saltation layer. In this manuscript, we only give a comparison of snowdrift sublimation between saltating and suspended snow to clarify the importance of drifting snow sublimation in the saltation layer.

Just like Prof. Yaping Shao, we also think that some measurements are necessary for validation of our simulation results. However, the measurement of snowdrift sublimation in the saltation layer is very difficult to conduct at the present stage. We have tried our best to make our results comparison with the published studies. Unfortunately, suitable data for comparison were not found.

The self-limiting nature of snow drift process is clearly revealed. This self-limiting process is similar to saltation of sand with no sublimation, but appears to be more complex, as it involves the moisture process. It is not clear however how the modified stability of the flow influences the self-limiting process.

Reply: Thanks for the insightful comments. In this study, a wind-blown snow model, balance equations for heat and moisture of an atmospheric boundary layer, and an equation for the rate of mass loss of a single ice sphere due to sublimation were combined to study the sublimation rate of drifting snow by tracking each saltating particle in drifting snow. Therefore, the influence of flow on the snow sublimation is mainly evaluated by influencing the processes of saltation movement (equation 5) and the horizontal advection of moisture (equation 12). Because the maximum mass loss of the sublimation for a single snow particle is less than one thousandth of the particle' mass during a process of saltation movement under the conditions of this study, we didn't evaluate mass change of the particle on the air flow.

The authors did not consider the effect of turbulence. While including turbulence may be more difficult, the authors may wish to discuss what might happen if turbulence is included. This is also important, because the stability of the saltation layer also affects the profile of the mean wind. Indeed, I do not see where thermal stability is included in the model.

Reply: Thanks. We acknowledge the comment that some studies (Jasper F. Kok and Nilton O. Renno, 2009; Yaping Shao, 2010) did include the effects of turbulent in their saltation model and it was found that turbulent flow substantially affects the saltation movement of sand particles, mainly the movement of small particles. But the effect of turbulence on larger saltating particles is much less pronounced for their larger inertia and thus smaller susceptibility to fluid velocity perturbations. For example, Shao (2010) showed the effect of turbulence flow for 200 μm particles in a logarithmically-profiled airflow ($u_* = 0.5$ m/s) is small. In our simulations, the diameter of the snow particles is 200 μm. Furthermore, this study concentrates on the time-averaged contributions of saltating snow particles to snow sublimation. Therefore we didn't take into consideration of the effect of turbulence in this manuscript. Perhaps we need to include turbulent effects in our future work.

There are minor writing problems which the authors should carefully check again, for example, DSS is not defined.

Reply: Thanks for the comment. We have modified the writing problems. Following the reviewer's comment, we have defined DSS as drifting snow sublimation in the first sentence of the abstract in the revised manuscript.

Referee #2

In this study the authors used a 2D model for studying snow sublimation in regards to its

capacity to impact saltation layer evolution. For this aim they used a solid particle transport modeling combined with transport equations for potential temperature and specific humidity. The modeling mimics splash and take-off processes as usual. The two way coupling between sublimation and velocity is acted via a rough term inside longitudinal velocity field evolution equation. No four way coupling is introduced. The paper described clearly how all processes are accounted for.

Reply: We thank the reviewer for the positive evaluation of our work. In this study, a wind-blown snow model that takes into consideration of the coupling effect between wind and snow particles is established to simulate the saltating process of snow particles. Then balance equations for heat and moisture of an atmospheric boundary layer, and an equation for the rate of mass loss of a single ice sphere due to sublimation were combined to study the sublimation rate of drifting snow by tracking each saltating particle in drifting snow. The splash functions for drifting snow used in this manuscript was proposed by Sugiura and Maeno (2000) based on their experiments, which is used to determine the number and motion state of the splashed particles as usual.

Some important points are the following:

The two way coupling has to be more deeply discussed as it is proposed: what are the hypothesis leading to this formulation?

Reply: Thanks. In the manuscript, we have stated that the initial wind field is logarithmic and the mean horizontal wind velocity u satisfies the Navier-Stokes equation. For a stable wind blowing over an infinite plane bed, according to Prandtl's mixing length theory we derived the coupling equation (5) to describe the interactive effect between the snow particles and wind field. For details, please see Lines 13-15 of Page 5 in the revised manuscript.

Furthermore even if variation of temperature are low it could be discussed if it could induced some effects on velocity field particularly where there is a large concentration of snow particles. It is relatively easy to add in such modeling these effects.

Reply: Thanks for the insightful comment. The reviewer is right. The variation of temperature could induce some effects on velocity field. However, we found that this effect can be ignored by testing (Fig. 1.1). In our study, the variation of temperature due to snow sublimation is below 2 K, which is relatively low. From Figure 1.1 we can see that the effect of such variation of temperature on velocity field is very small. Thus, we didn't take this effect into consideration.

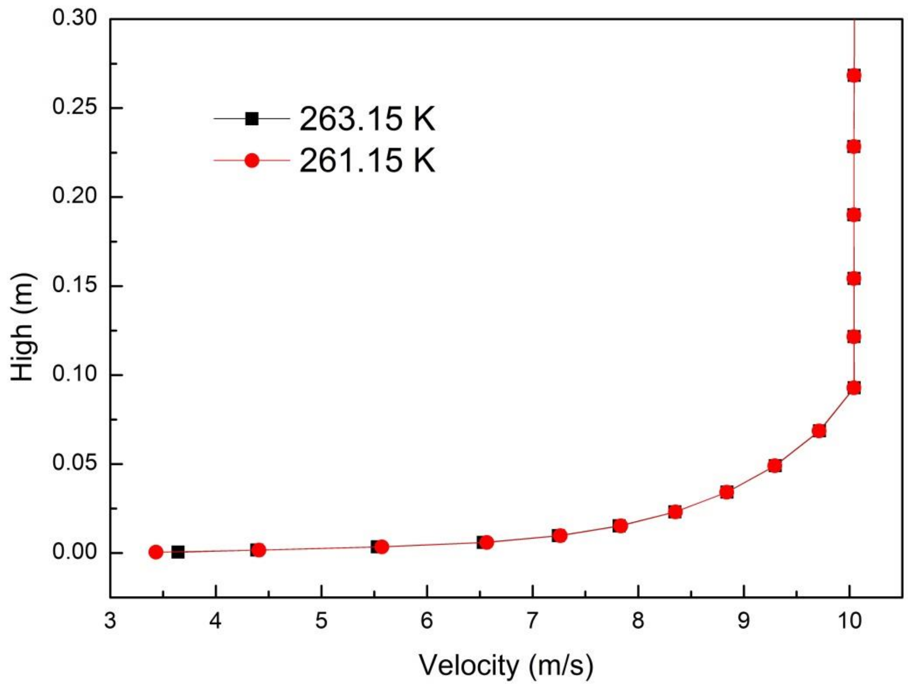

Figure 1.1 Wind velocity profile at different temperature

Concerning the four way coupling and contrarily to sand it could probably modifies significantly the budget close to the ground. As writen by the authors such modeling is not time consuming in so it would be interesting to time increase the computational runs to observe if the various time evolutions of the shown quantities are stabilised.

Reply: Thanks. From Fig. 3, we can see that DSS has reached steady state with moisture diffusion and advection considered. But when only moisture diffusion is included, it is hard to reached steady state. As we state in our manuscript, DSS has an inherent self-limiting nature due to the feedback associated with the heat and moisture budgets. On one hand, snow sublimation absorbs heat, which decreases the temperature of the ambient air and the saturation vapor pressure; on the other hand, it will induce the increment in the moisture content of the ambient air. Both of the above two points can increase the relative humidity of ambient air. It may lead to a saturated layer near the surface finally, and thus sublimation may vanish.

Concerning results it would be interesting to plot snow particles concentration profile evolutions.

Reply: Thanks. Following the reviewer's suggestion, we added a Figure to show the temporal evolution of snow transport rate and the profile of snow particle number density at the steady state for three wind force levels in the revised manuscript.

I agree that it would be interesting to account for turbulence and to compare with experimental results.

Reply: Thanks for the insightful comment. We acknowledge the comment that some studies (Jasper F. Kok and Nilton O. Renno, 2009; Yaping Shao, 2010) did include the effects of turbulent in their saltation model and it was found that turbulent flow substantially affects the saltation movement of sand particles, mainly the movement of small particles. But the effect of turbulence on larger saltating particles is much less pronounced for their larger inertia and thus smaller susceptibility to fluid velocity perturbations. For example, Shao (2010) showed the effect of turbulence flow for 200 μm particles in a logarithmically-profiled airflow ($u_* = 0.5$ m/s) is small. In our simulations, the diameter of the snow particles is 200 μm. Furthermore, this study concentrates on the time-averaged contributions of saltating snow particles to snow sublimation. Therefore we didn't take into consideration of the effect of turbulence in this manuscript. Perhaps we need to include turbulent effects in our future work.

Just like the reviewer and Prof. Yaping Shao, we also think that some measurements are necessary for validation of our simulation results. Unfortunately, the measurement of snowdrift sublimation in the saltation layer is very difficult to conduct at the present stage.

could you check equation (14) (or may be I did a mistake but molecular weight of water have to be taken into account in the first term of the denominator) ? Some details concerning some threshold or constant as the one for take-off have to be given as they are crucial.

Reply: Thanks. Indeed, the first term of the denominator in the sublimation rate given by Thorpe and Mason is related to the molecular weight of water M (kg mol^{-1}), as well the universal gas constant R (J mol^{-1} K^{-1}). But in our study, the gas constant for water vapor R_V (=R/M) is defined with the value of 461.5 (J kg^{-1} K^{-1}). According to the experiments and numerical simulation of Nemoto and Nishimura (2001, 2004), we set the threshold friction velocity of snow to be 0.21 m s^{-1}.

However the aim of this work is interesting and also the way to treat it.

Reply：Thanks for the positive evaluation of our work.

Referee #3

In this study, the authors present an interesting research to evaluate the effect of drafting snow sublimation in the saltation layer, which is rarely studied, but important for the hydrological balance of snow cover. A snowdrift model with considering the coupling effects of snow sublimation, temperature, humidity and moisture transport is established to address their ideas and research. They describe their models and methods concisely and clearly and analyze the results reasonably.

Reply: We thank the reviewer for the positive evaluation of our work.

They present a well-written article, but the Results section seems a little short and has no comparison with the measurements or published data.

Reply: Just like the reviewers and Prof. Yaping Shao, we also think that some measurements are necessary for validation of our simulation results. However, the measurement of snowdrift sublimation in the saltation layer is very difficult to conduct at the present stage. We have tried our best to make our results comparison with the published studies. Unfortunately, suitable data for comparison were not found. We demonstrated the importance of snowdrift sublimation in the saltation layer from numerical simulation and honestly suggest relevant measurement should be carried out in future work.

The authors need to carefully check their manuscript again to do a better job of defining the parameters they use for the controlling equations, for example, the definition of the sublimation rate S.

Reply: Thanks. The sublimation rate S at each height is calculated by summed over the mass loss of all particles at each height above the surface. Theoretically, it is negative, but here taken as positive for illustration purposes. We have pointed that in the revised manuscript.

The prognostic equations of potential temperature and specific humidity (Eqs. 11 and 12) seem to be different from the reference, which may lead to misunderstandings (just as the comments of reviewer 1). In order to express the calculation of temperature and humidity more clearly, it would be better to derive the prognostic equations from the basic convection diffusion equation.

Reply: Thanks for the insightful comment. Following the reviewer’s suggestion, we have derived the prognostic equations of potential temperature and specific humidity (Eqs. (13) and (14)) from the basic convection diffusion equation (Eqs. (11) and (12)) in the revised manuscript. In addition, we stated that three cases considered in our study to explore the interaction between snow sublimation and moisture transport, i.e. two typical cases, neglecting the effects of moisture transport and considering moisture transport due to both moisture diffusion and advection, and a common situation, considering only moisture diffusion.

Why each calculation takes 60 s and doesn't show the sublimation rate when it tends to be stabilized?

Reply: Thanks for the insightful comment. By considering of the required time of drifting snow development and the capability of computer, the simulated time was set as 60s, which is significantly surpass drifting snow development time (about 2-3 s) and could be actualized easily on PC. From Fig. 3, we can see that DSS has reached steady state with moisture diffusion and advection considered within 60 s, but it is not true for only moisture diffusion considered. That is indeed that, the sublimation rate is hard to be stabilized in this 60s in this case, but our results could expose the issues that we care about. Theoretically, the snow sublimation may vanish finally with the development of time. As we state in our manuscript, DSS has an inherent self-limiting nature due to the feedback associated with the heat and moisture budgets. On one hand, snow sublimation absorbs heat, which decreases the temperature of the ambient air and the saturation vapor pressure; on the other hand, it will induce the increment in the moisture content of the ambient air. Both of the above two points can increase the relative humidity of ambient air. It may lead to a saturated layer near the surface finally, and thus sublimation will vanish. Here, we show the temporal evolution of drifting snow sublimation within 60 s to compare our results with the previous study.

I agree that it could be discussed if the variation of temperature could induce some effects on velocity field. The evolutions of snow particles concentration should be discussed.

Reply: Thanks. Indeed, the variation of temperature could induce some effects on velocity field. However, we found that this effect can be ignored by testing (Fig. 1.1). In our study, the variation of temperature due to snow sublimation is below 2 K, which is relatively low. From Figure 1.1, we can see that the effect of variation of temperature on velocity field is very small. Thus, we didn't take this effect into consideration. In addition, following the reviewer's suggestion, we added a figure to show snow particles concentration profile evolution in the revised manuscript.

On the whole, this work is a fundamental research and obviously focusing on science

common topics, which is interesting and well present.

Reply: Thanks for the positive evaluation of our work.

List of changes

Page 1

Line 4: "N. Huang and X. Dai" is changed to "N. Huang[1, 2], X. Dai[1] and J. Zhang[1, 2]".

We add J. Zhang as the third author for his contribution on program test and improvement of the revised manuscript.

Line 7: "[2]School of Civil Engineering and Mechanics, Lanzhou University, Lanzhou 730000, China" is added before "Corresponding to".

Page 4

Line 14: "we followed previous researches to assume relative humidity adjacent to snow surface is saturated and ignored surface sublimation. But the particle sublimation in saltation layer is considered by taking into account of moisture transport in different typical cases, including 1) neglecting the effects of moisture transport; 2) considering moisture transport due to both moisture diffusion and advection, and 3) considering only moisture diffusion. Here," is added after "In this study".

Page 5

Line 14: "is" is changed to "satisfies".

Page 6

Line 15: "(the ratio of vertical ejection velocity and vertical impact velocity)" is added after "e_v".

Line 18: "(the ratio of horizontal ejection velocity and horizontal impact velocity)" is added after "e_h".

Line 23- Line 12 (Page 7): "following prognostic equations…with l being the length of the domain." is changed to "conservation equations (only consider two-dimension)

$$\frac{\partial\theta}{\partial t}+u\frac{\partial\theta}{\partial x}+v\frac{\partial\theta}{\partial y}=\frac{\partial}{\partial x}\left(K_{\theta'}\frac{\partial\theta}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{\theta}\frac{\partial\theta}{\partial y}\right)+R_1 \tag{11}$$

$$\frac{\partial q}{\partial t}+u\frac{\partial q}{\partial x}+v\frac{\partial q}{\partial y}=\frac{\partial}{\partial x}\left(K_{q'}\frac{\partial q}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{q}\frac{\partial q}{\partial y}\right)+R_2 \tag{12}$$

where u is the mean horizontal wind velocity which could be calculated by Eq. (5) and v the vertical wind velocity is assumed to be zero here; $K_{\theta'}$, K_θ, $K_{q'}$ and K_q are the heat and moisture diffusivities due to molecular motion and eddy diffusivity, respectively ; R_1 and R_2 are the source terms due to snow sublimation. In this study, the wind speed is parallel to the horizontal direction, moreover, we hypothesize that the temperature and specific humidity is linearly distributed along this direction. Thus, potential temperature and specific humidity will satisfy the following prognostic equations

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial y}\left(K_\theta \frac{\partial \theta}{\partial y}\right) - u\frac{\partial \theta}{\partial x} - \frac{L_s S}{\rho_f C} \tag{13}$$

$$\frac{\partial q}{\partial t} = \frac{\partial}{\partial y}\left(K_q \frac{\partial q}{\partial y}\right) - u\frac{\partial q}{\partial x} + \frac{S}{\rho_f} \tag{14}$$

where $K_\theta = \kappa u_* y + K_T$ and $K_q = \kappa u_* y + K_V$ (the sum of eddy diffusivity and molecular diffusivity, respectively); S is the sublimation rate summed over all particles at each height above the surface, here taken as positive for illustration purposes; L_s is the latent heat of sublimation (2.835×10^6 J kg^{-1}); C is the specific heat of air; $\frac{\partial \theta}{\partial x}$ and $\frac{\partial q}{\partial x}$ represent the horizontal gradient in temperature and specific humidity. At the edge of snow surface, we considered the effect of advection and hypothesized that the specific humidity in the study domain is linearly distributed along the horizontal direction from entrance with q_{in} to outlet with q_{out}. Thus, the horizontal advection of moisture can be simplified to $u(q_{out} - q_{in})/l$, with l being the length of the domain. Except for snow surface edge, the above setup may be (or partly) suitable for some heterogeneous snow surfaces, such as patchy mosaic of snow cover. And these reasons encourage us to discuss the effect of advection. For the case of infinite and homogenous snow surface, we set $q_{in} = q_{out}$ to avoid advection and considered moisture transfer via molecular motion and eddy diffusivity. Besides, we set $q_{in} = q_{out}$ and $K_q = K_\theta$ to ignore effect of advection and eddy diffusivity, as a reference case. Correspondingly, similar process was actualized for θ. The variation of temperature will induce some effects on velocity field, which, however, can be ignored by testing. In our study, the variation of temperature due to snow sublimation is relatively low and its effect on velocity field is very small. Thus, we didn't take this effect into consideration."

Page 7

Line 15: "(13)" is changed to "(15)".

Line 18: "radius r " is changed to "diameter D ".

Line 19: Eq. (14) is changed to " $\frac{dm}{dt} = \frac{\pi D\delta}{\frac{L_s}{KTNu}(\frac{L_s}{R_v T} - 1) + \frac{R_v T}{D_v She_s}}$ (16)".

Page 8

Line 4: "(15)" is changed to "(17)".

Line 8: "(16)" is changed to "(18)".

Line 11: "(17)" is changed to "(19)".

Line 15: "(18)" is changed to "(20)".

Line 18: "(19)" is changed to "(21)".

Page 9

Line 3- Line 4: "(16) - (19)" is changed to "(18) - (21)".

Line 6- Line 7: The sentence "The threshold friction velocity of snow is 0.21 m s^{-1} and the snow bed roughness is 3.0×10^{-5} m (Nemoto and Nishimura, 2001)." is changed to "According to the investigation of Nemoto and Nishimura (2001) in a cold wind tunnel, the threshold friction velocity of snow is set to be 0.21 m s^{-1} and the snow bed roughness 3.0×10^{-5} m".

Line 24: "(13) - (15)" is changed to "(15) - (17)".

Page 10

Line 1: "3.1 Relative Humidity and Temperature" is changed to "3.2 Relative Humidity and Temperature", "Wind-blown snow has a self-regulating feedback mechanism between the saltating particles and the wind field, i.e. snow particles are entrained and transported by the wind, while the drag force associated with particle acceleration reduces the wind velocity in the saltation layer, thus limiting the entrainment of further particles. Figure 1 illustrates the evolution of saltating snow particles in air and also the profile of snow particle number density at steady state. The results show that the transport rate of particles in air increases rapidly and reaches a steady state after 2-3 seconds. In steady condition, the number of snow particles decreases with height and follows a negative exponential law. Except for the particle in air, the ambient relative humidity and temperature are also important factors concern to DSS." is added before "3.2 Relative Humidity and Temperature".

Line 3: “Fig. 1a” is changed to “Fig. 2a”.

Line 4: “Fig. 1b” is changed to “Fig. 2b”.

Line 6: “continually” is deleted.

Line 8: “Fig. 1” is changed to “Fig. 2”.

Line 10: “when moisture diffusion is included” is added after “increase”, “Fig. 1a” is changed to “Fig. 2a”.

Line 18: “Fig. 2” is changed to “Fig. 3”.

Line 19: “When the advection of moisture and heat are considered as well, the temperature and relative humidity will reach a steady state finally. In this case, the transport of moisture and heat balances the change of temperature and relative humidity due to DSS.” is added at the end of the paragraph.

Line 20: “3.2” is changed to “3.3”.

Line 21: “Fig. 2” is changed to “Fig. 3”, “From Fig. 2, we can see that DSS has reached steady state with moisture diffusion and advection considered within 60 s, but it is not true for only moisture diffusion considered. By considering of the required time of drifting snow development and the capability of computer, the simulated time was set as 60s, which is significantly surpass drifting snow development time (about 2-3 s) and could be actualized easily on PC. Furthermore, the results are enough to expose the issues that we care about.” is added at the beginning of the paragraph.

Line 27: “and will reach steady state” is added after “reduced”.

Line 30: “0.61×10^{-5}” is changed to “0.88×10^{-5}”.

Line 32: “0.96×10^{-5}” is changed to “1.6×10^{-5}”, “0.83” is changed to “1.38”.

Page 11

Line 2: “Fig. 2” is changed to “Fig. 3”.

Line 7: “saturation” is changed to “unsaturation”.

Line 10: “Fig. 3” is changed to “Fig. 4”.

Line 12: “(Figure 1)” is added after “heights”.

Line 14: “number” is added before “density”.

Line 19: “Fig. 3” is changed to “Fig. 4” and “10^{-4}” is changed to “10^{-4} - 10^{-3}”.

Page 16

A new figure is added.

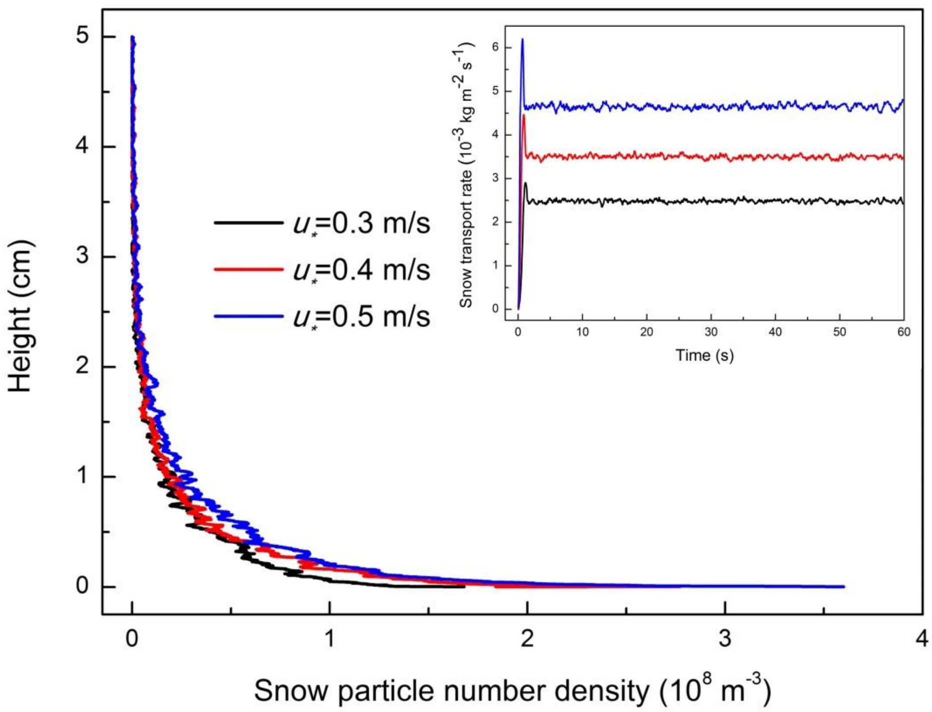

Figure 1. Temporal evolution of snow transport rate (the inset figure) and the profile of snow particle number density at the steady state for three wind force levels.

The original “Figure 1”is changed to “Figure 2”.

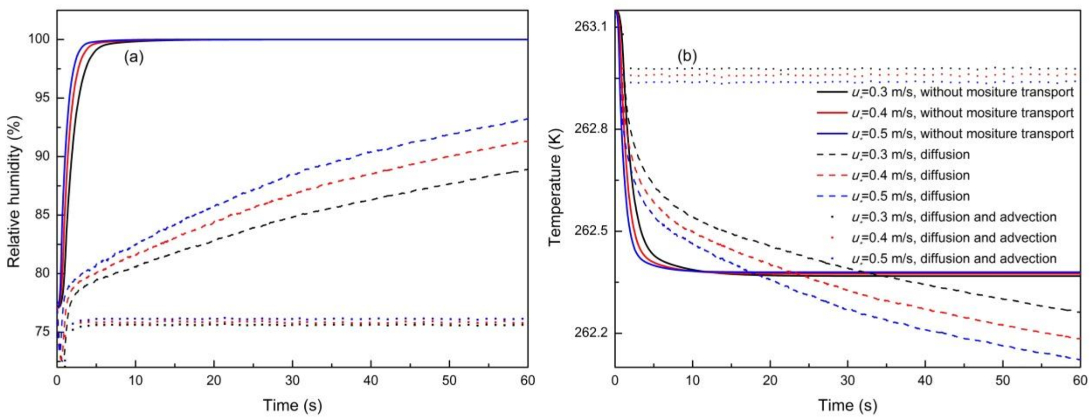

Figure 2. Temporal evolution of relative humidity (a) and temperature (b) at 1 cm above the surface for three wind force levels neglecting the effects of moisture transport, considering only moisture diffusion, and both moisture diffusion and advection.

Page 17

The original “Figure 2”is changed to “Figure 3”.

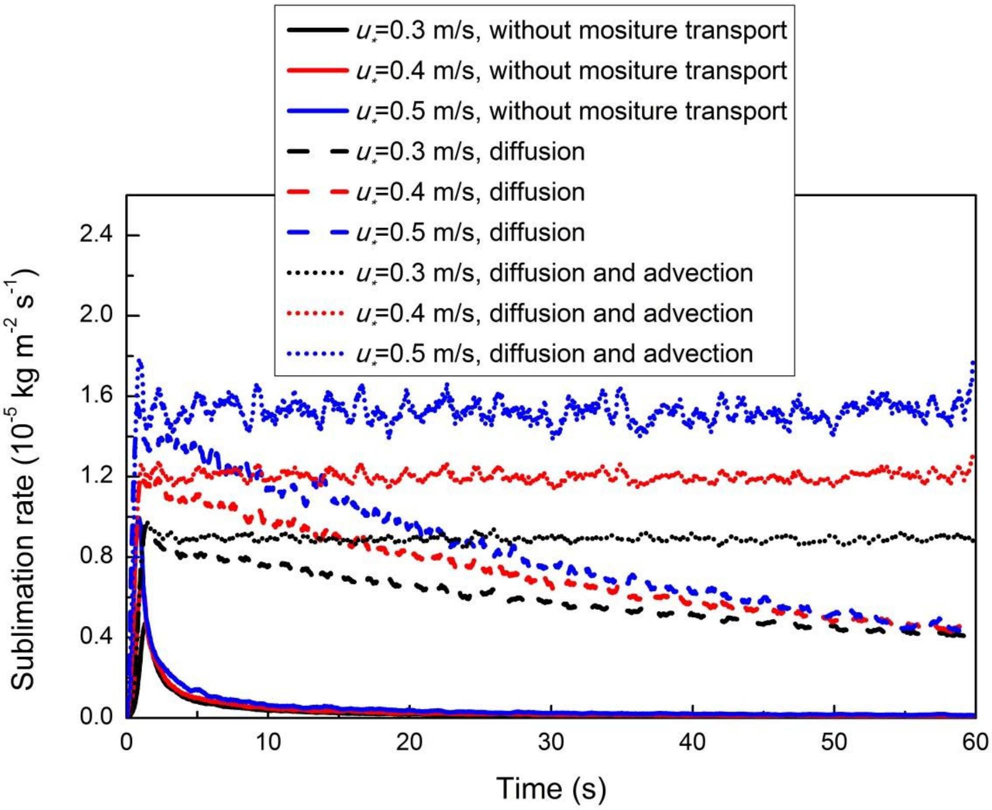

Figure 3.Temporal evolution of drifting snow sublimation rate for three wind force levels neglecting moisture transport, considering only moisture diffusion, and both moisture diffusion and advection.

Page 18

The original “Figure 3”is changed to “Figure 4”.

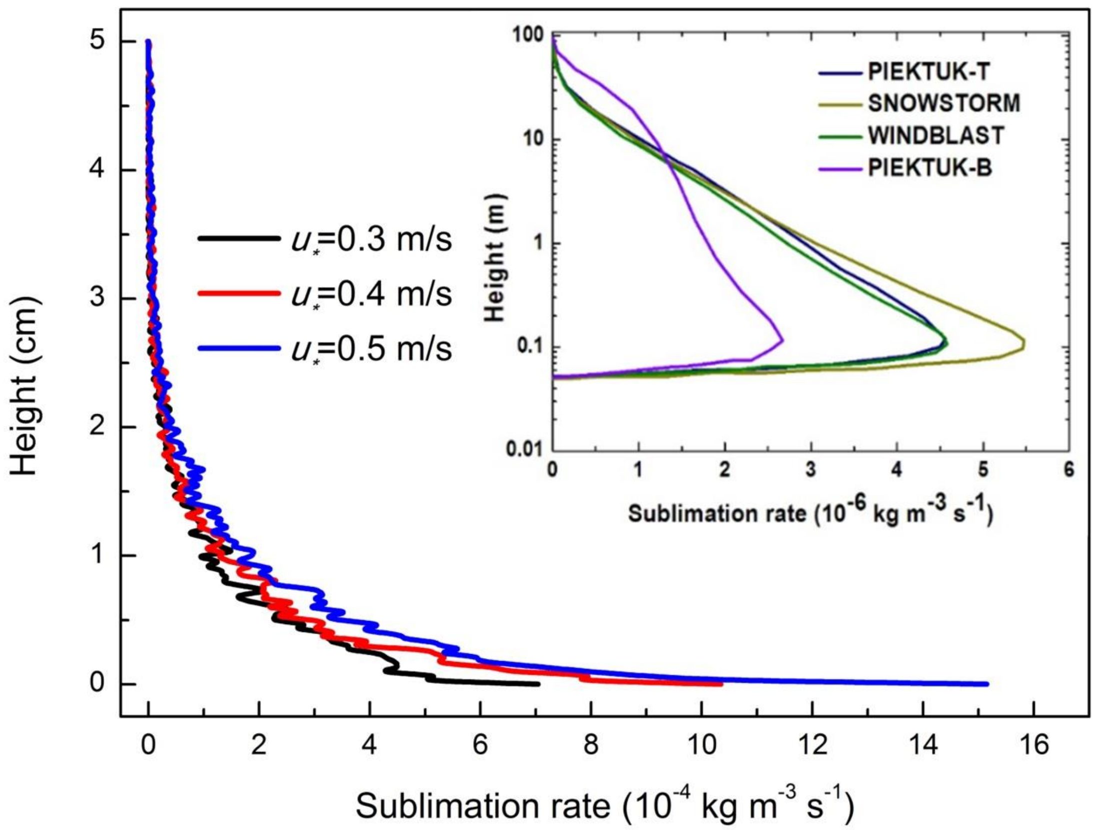

Figure 4. Comparison of the sublimation rate for the saltation layer and suspension layer (the inset figure) at 60 s as a function of height. The inset figure shows the sublimation rate of four models for the suspension layer with initial friction velocity of 0.87 m s^{-1} reported in Xiao et al. (2000). Our results for the sublimation rate in the saltation layer are obtained for three wind force levels (<0.87 m s^{-1}) with moisture diffusion and advection included with the same initial temperature (253.16 K) and relative humidity as Xiao et al. (2000).

The impacts of moisture transport on drifting snow sublimation in the saltation layer

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Abstract

Drifting snow sublimation (DSS) is an important physical process related to moisture and heat transfer that happens in the atmospheric boundary layer, which is of glaciological and hydrological importance. It is also essential in order to understand the mass balance of the Antarctic ice sheets and the global climate system. Previous studies mainly focused on the DSS of suspended snow and ignored that in the saltation layer. Here, a drifting snow model combined with balance equations for heat and moisture is established to simulate the physical DSS process in the saltation layer. The simulated results show that DSS can strongly increase humidity and cooling effects, which in turn can significantly reduce DSS in the saltation layer. However, effective moisture transport can dramatically weaken the feedback effects. Due to moisture advection, DSS rate in the saltation layer can be several orders of magnitude greater than that of the suspended particles. Thus, DSS in the saltation layer has an important influence on the distribution and mass-energy balance of snow cover.

1 Introduction

Drifting snow is a special process of mass-energy transport in the hydrological cycle of snow. It not only changes the snow distribution but also results in phase changes of ice crystals into water vapor, which is known as DSS. Snow sublimation not only significantly influences the mass-energy balance of snow cover (e.g., Zhou et al., 2014) by changing surface albedo (Allison, 1993) and the runoff of snowmelt in cold regions (Marks and Winstral, 2001), but also has a pivotal status on moisture and heat transfer in the atmospheric boundary layer (Pomeroy and Essery, 1999; Anderson and Neff, 2008). Thus, it is of glaciological and hydrological importance (Sugiura and Ohata, 2008). In high cold area, the reduction of snow cover may cause the surface temperature to increase in the cold season (Huang et al., 2008, 2012). The thickness of seasonally frozen ground has decreased in response to winter warming (Huang et al., 2012). On the other hand, both dust and biomass burning aerosols may impact the surface albedo when deposited on snow; soot in particular has large impacts on absorption of radiation (Huang et al., 2011). In addition, a large, but unknown, fraction of the snow that falls on Antarctica is removed by the wind and subsequently sublimates. Therefore, a detailed knowledge of DSS is also essential in order to understand snow cover distribution in cold high area as well as the mass balance of the Antarctic ice sheets, and further the global climate system (Yang et al., 2010).

In drifting snow, snow particles can experience continuous sublimation, which induces a heat flux from the surrounding air to the particle and a moisture flux in the opposite direction (Bintanja, 2001a). Thus, DSS can cause increases in humidity and cooling of the air (Schmidt, 1982; Pomeroy et al., 1993) and has an inherent self-limiting nature due to the feedback associated with the heat and moisture budgets (Déry and Yau, 1999; Groot Zwaaftink et al., 2011, 2013). On one hand, snow sublimation absorbs heat and decreases the temperature of the ambient air, which in turn reduces the saturation vapor pressure and hence the sublimation rate; on the other hand, the increment in the moisture content of the ambient air decreases the sublimation rate of drifting snow, as it is proportional to the under-saturation of the air.

Saltation is one of the three modes of particle motion, along with suspension and creep. Among the three modes, saltation is important and the DSS in the saltation layer may constitute a significant portion of the total snow sublimation (Dai and Huang, 2014). Previous studies of DSS mostly focused on the sublimation of suspended snow, which was mainly due to the consideration that sublimation will soon vanish in the saltation layer because the feedback of DSS may lead to a saturated layer near the surface (Bintanja, 2001b). However, the field observation data of Schmidt (1982) showed that relative humidity only slightly increases during snowdrift events and the maximum humidity was far below saturation. Further studies (Groot Zwaaftink et al., 2011; Vionnet et al., 2013) also showed that the relative humidity does not reach saturation even at the lowest atmosphere level after DSS occurs. Some scientists argued that it was caused by moisture transport, such as diffusion and advection of moisture, which inevitably accompany the drifting snow process (Vionnet et al., 2013). Therefore, it is necessary to study the feedback mechanism of DSS in the saltation layer and the effect of moisture transport on it.

In this study, we followed previous researches to assume relative humidity adjacent to snow surface is saturated and ignored surface sublimation. But the particle sublimation in saltation layer is considered by taking into account of moisture transport in different typical cases, including 1) neglecting the effects of moisture transport; 2) considering moisture transport due to both moisture diffusion and advection, and 3) considering only moisture diffusion. Here, a wind-blown snow model, balance equations for heat and moisture of an atmospheric boundary layer, and an equation for the rate of mass loss of a single ice sphere due to sublimation were combined to study the sublimation rate of drifting snow by tracking each saltating particle in drifting snow. Then, the effects of DSS on the humidity and temperature profiles, as well as the effects of diffusion and advection of moisture on DSS in the saltation layer, were explored in detail.

2 Methods

2.1 Model Description

Saltation can be divided into four interactive sub-processes, i.e., aerodynamic entrainment, particle trajectories, particle-bed collisions, and wind modification (Huang et al., 2011).

The motion equations for snow particles are (Huang et al., 2011)

$$m_p \frac{dU_p}{dt} = F_D \left(\frac{U_f - U_p}{V_r} \right), \tag{1}$$

$$m_p \frac{dV_p}{dt} = -W_g + F_B + F_D \left(\frac{V_f - V_p}{V_r} \right), \tag{2}$$

$$\frac{dx_p}{dt} = U_p, \tag{3}$$

$$\frac{dy_p}{dt} = V_p. \tag{4}$$

where m_p and W_g are the mass and weight of the snow particle, respectively; U_f, V_f, U_p and V_p are the horizontal and vertical velocities of the airflow and snow particle, respectively; $V_r = \sqrt{(U_f - U_p)^2 + (V_f - V_p)^2}$ is the relative velocity between the airflow and snow particle; x_p and y_p are the horizontal position and vertical height of the snow particle, respectively; $F_B = \frac{1}{6}\rho_f \pi D^3 g$ and $F_D = \frac{1}{8} C_D \rho_f \pi D^2 V_r^2$ are the buoyancy force and the drag force applied on the snow particle, respectively; ρ_f is the air density; D is the diameter of the snow particle; g is the acceleration of gravity; and C_D is the drag coefficient.

Within the atmospheric boundary layer, the mean horizontal wind velocity u satisfies the Navier-Stokes equation (Werner, 1990). According to Prandtl's mixing length theory for the steady flow fully developed over an infinite planar bed, u ~~is~~ satisfies

$$\frac{\partial}{\partial y}(\rho_f \kappa^2 y^2 \left| \frac{du}{dy} \right| \frac{du}{dy}) + F_x = 0, \tag{5}$$

Where x is the coordinate aligned with the mean wind direction, y is the vertical direction, κ is the von Karman constant, and F_x is the force per unit volume that the snow particles exert on the fluid in the stream-wise direction and can be expressed as

$$F_x = \sum_{i=1}^{n} m_p a_i. \tag{6}$$

where n is the number of particles per unit volume of fluid at height y, and a_i is the horizontal acceleration of particle i.

When the bed shear stress is greater than the threshold value, snow particles begin lifting off the surface. The number of aerodynamically entrained snow particles N_a is (Shao and Li, 1999)

$$N_a = \varsigma u_* \left(1 - \frac{u_{*t}^2}{u_*^2}\right) D^{-3}. \tag{7}$$

where ς is a dimensionless coefficient (1×10^{-3} in our simulations), u_* is the friction velocity, and u_{*t} is the threshold friction velocity. Following the previous saltation models (McEwan and Willetts, 1993), the vertical speed of all aerodynamically entrained particles is $\sqrt{2gD}$.

The following three splash functions for drifting snow proposed by Sugiura and Maeno (2000) based on experiments are used to determine the number and motion state of the splashed particles.

$$S_v(e_v) = \frac{1}{\beta^\alpha \Gamma(\alpha)} e_v^{\alpha-1} \exp\left(-\frac{e_v}{\beta}\right), \tag{8}$$

$$S_h(e_h) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left[-\frac{(e_h-\mu)^2}{2\sigma^2}\right], \tag{9}$$

$$S_e(n_e) = {}_mC_{n_e} p^{n_e} (1-p)^{m-n_e}. \tag{10}$$

In Eq. (8), S_v is the probability distribution of the vertical restitution coefficient e_v (the ratio of vertical ejection velocity and vertical impact velocity), $\Gamma(\alpha)$ is the gamma function, and α and β are the shape and scale parameters for the gamma distribution function. In Eq. (9), S_h is the probability distribution of the horizontal restitution coefficient e_h (the ratio of horizontal ejection velocity and horizontal impact velocity), and μ and σ are the mean and variance, respectively. In Eq. (10), S_e is the probability distribution function of the number of ejected particles n_e, a binomial distribution function with the mean mp and the variance $mp(1-p)$.

The potential temperature θ and specific humidity q of the ambient air satisfy the conservation equations (only consider two-dimension) ~~following prognostic equations (Déry and Yau, 1999)~~

$$\frac{\partial \theta}{\partial t}+u\frac{\partial \theta}{\partial x}+v\frac{\partial \theta}{\partial y}=\frac{\partial}{\partial x}\left(K_{\theta'}\frac{\partial \theta}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{\theta}\frac{\partial \theta}{\partial y}\right)+R_1 \qquad (11)$$

$$\frac{\partial q}{\partial t}+u\frac{\partial q}{\partial x}+v\frac{\partial q}{\partial y}=\frac{\partial}{\partial x}\left(K_{q'}\frac{\partial q}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{q}\frac{\partial q}{\partial y}\right)+R_2 \qquad (12)$$

where u is the mean horizontal wind velocity which could be calculated by Eq. (5) and v the vertical wind velocity is assumed to be zero here; $K_{\theta'}$, K_{θ}, $K_{q'}$ and K_q are the heat and moisture diffusivities due to molecular motion and eddy diffusivity, respectively ; R_1 and R_2 are the source terms due to snow sublimation. In this study, the wind speed is parallel to the horizontal direction, moreover, we hypothesize that the temperature and specific humidity is linearly distributed along this direction. Thus, potential temperature and specific humidity will satisfy the following prognostic equations

$$\frac{\partial \theta}{\partial t}=\frac{\partial}{\partial y}\left(K_{\theta}\frac{\partial \theta}{\partial y}\right)-u\frac{\partial \theta}{\partial x}-\frac{L_s S}{\rho_f C} \qquad (13)$$

$$\frac{\partial q}{\partial t}=\frac{\partial}{\partial y}\left(K_{q}\frac{\partial q}{\partial y}\right)-u\frac{\partial q}{\partial x}+\frac{S}{\rho_f} \qquad (14)$$

where $K_{\theta}=\kappa u_* y+K_T$ and $K_q=\kappa u_* y+K_V$ (the sum of eddy diffusivity and molecular diffusivity, respectively); S is the sublimation rate summed over all particles at each height above the surface, here taken as positive for illustration purposes; L_s is the latent heat of sublimation (2.835×10^6 J kg^{-1}); C is the specific heat of air; $\frac{\partial \theta}{\partial x}$ and $\frac{\partial q}{\partial x}$ represent the horizontal gradient in temperature and specific humidity. At the edge of snow surface, we considered the effect of advection and hypothesized that the specific humidity in the study domain is linearly distributed along the horizontal direction from entrance with q_{in} to outlet with q_{out}. Thus, the horizontal advection of moisture can be simplified to $u(q_{out}-q_{in})/l$, with l being the length of the domain.

Except for snow surface edge, the above setup may be (or partly) suitable for some heterogeneous snow surfaces, such as patchy mosaic of snow cover. And these reasons encourage us to discuss the effect of moisture advection. For the case of infinite and homogenous snow surface, we set $q_{in} = q_{out}$ to avoid advection and considered moisture transfer via molecular motion and eddy diffusivity. Besides, we set $q_{in} = q_{out}$ and $K_q = K_\theta$ to ignore effect of advection and eddy diffusivity, as a reference case. Correspondingly, similar process was actualized for θ. The variation of temperature will induce some effects on velocity field, which, however, can be ignored by testing. In our study, the variation of temperature due to snow sublimation is relatively low and its effect on velocity field is very small. Thus, we didn't take this effect into consideration.

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial y}\left(K_\theta \frac{\partial \theta}{\partial y}\right) - \frac{L_s S}{\rho_f C}, \qquad (11)$$

$$\frac{\partial q}{\partial t} = \frac{\partial}{\partial y}\left(K_q \frac{\partial q}{\partial y}\right) + \frac{S}{\rho_f} - Q. \qquad (12)$$

where $K_\theta = \kappa u_* y + K_T$ and $K_q = \kappa u_* y + K_V$ are the heat and moisture diffusivities (the sum of eddy diffusivity and molecular diffusivity), respectively, S is the sublimation rate summed over all particles at each height above the surface, L_s is the latent heat of sublimation (2.835×10^6 J kg^{-1}), C is the specific heat of air, $Q = u\frac{\partial q}{\partial x}$ is the horizontal advection of moisture at each height above the surface, and $\frac{\partial q}{\partial x}$ represents the horizontal gradient in specific humidity. When the external dry air with specific humidity q_{out} enters into the study domain, we hypothesize that the specific humidity in the study domain is linearly distributed along the horizontal direction and possesses the value of q_{in} at the exit. Thus, the horizontal advection of moisture can be simplified to $Q = u(q_{in} - q_{out})/l$, with l being the length of the domain.

The total DSS rate Q_S (kg s^{-1}) of the saltation layer within the computational domain is obtained by summing the mass loss of all saltating particles in the domain.

$$Q_S = \sum_i \left(\frac{dm}{dt} \right)_i , \qquad \text{(1~~3~~5)}$$

where $\left(\frac{dm}{dt} \right)_i$ is the mass loss rate corresponding to the *i*-th particle. At the air temperature T and undersaturation $\delta\,(=1-RH)$, the rate of mass change of a single particle with ~~radius r~~ diameter D due to sublimation is (Thorpe and Mason, 1966)

~~$$\frac{dm}{dt} = \frac{2\pi r \delta}{\frac{L_s}{KTNu}\left(\frac{L_s}{R_v T} - 1\right) + \frac{R_v T}{D_v She_s}} , \qquad (14)$$~~

$$\frac{dm}{dt} = \frac{\pi D \delta}{\frac{L_s}{KTNu}\left(\frac{L_s}{R_v T} - 1\right) + \frac{R_v T}{D_v She_s}} \qquad (16)$$

where RH is the relative humidity of air, K is the molecular thermal conductivity of the atmosphere (0.024 J m^{-1} s^{-1} K^{-1}), D_v is the molecular diffusivity of water vapor in the atmosphere, R_v is the gas constant for water vapor (461.5 J kg^{-1} K^{-1}), e_s is saturated vapor pressure with respect to an ice surface, and Nu and Sh are the Nusselt number and the Sherwood number, respectively, both of which are dimensionless and depend on the wind velocity and particle size (Thorpe and Mason, 1966; Lee, 1975).

$$Nu = Sh = \begin{cases} 1.79 + 0.606\,\mathrm{Re}^{0.5} & 0.7 < \mathrm{Re} < 10 \\ 1.88 + 0.580\,\mathrm{Re}^{0.5} & 10 < \mathrm{Re} < 200 \end{cases} . \qquad \text{(1~~5~~7)}$$

where $\mathrm{Re} = DV_r / \upsilon$ is the Reynolds number and υ is the kinematic viscosity of air.

For the purpose of comparison with the sublimation of suspended particles, the initial relative humidity profile in accordance with that of Xiao et al. (2000) is

$$RH = 1 - R_S \ln(y / y_0) , \qquad \text{(1~~6~~8)}$$

where y_0 is roughness length and $R_S = 0.039469$.

The conversion relation between relative humidity and specific humidity is

$$q = 0.622 \cdot \frac{e_s}{p - e_s} \cdot RH , \qquad \text{(1~~7~~9)}$$

where $e_s = 610.78\exp[21.78(T-273.16)/(T-7.66)]$.

The constant initial potential temperature θ_0 is 263.15 K (but is 253.16 K in the comparison with Xiao et al. (2000)) and the initial absolute temperature is

$$T_0 = \theta_0 \left(\frac{p}{p_0} \right)^{0.286}, \qquad (~~18~~20)$$

where p is the pressure and its initial distribution is based on the hypsometric equation

$$p = p_0 \exp(-\frac{yg}{R_d \theta_0}). \qquad (~~19~~21)$$

where p_0 is taken as 1000 hPa and R_d is the gas constant for dry air (287.0 J kg^{-1} K^{-1}).

2.2 Calculation Procedure

The procedure for the calculations is enumerated below.

1. The length, width and height of the computational domain sampled from the saltation layer above the surface are 1.0 m, 0.01 m, and 1.0 m, respectively. The initial and boundary conditions of temperature and humidity are set from Eqs. (168)-(~~19~~21).

2. Snow particles are considered as spheres with diameter of 200 μm and density of 910 kg m^{-3}. According to the investigation of Nemoto and Nishimura (2001) in a cold wind tunnel, ~~The~~ the threshold friction velocity of snow is set ~~is~~ to be 0.21 m s^{-1} and the snow bed roughness ~~is~~ 3.0 $\times 10^{-5}$ m ~~(Nemoto and Nishimura, 2001)~~.

3. The initial wind field is logarithmic. If the bed shear stress is greater than the threshold value, particles are entrained from their random positions on the snow surface at vertical speed $\sqrt{2gD}$ and the number of aerodynamically entrained snow particles satisfies Eq. (7).

4. The snow particle trajectory is calculated using Eqs. (1) - (4) every 0.00001 s in order to obtain the velocity used in the calculation of sublimation rate and the new location of each drifting snow particle to determine whether the snow particle falls on the snow bed.

5. As the snow particles fall on the snow bed, where they impart their energy to other snow particles and splash or eject other snow particles, the velocity and angle of the ejected particles satisfy the splash functions, i.e., Eqs. (8) - (10), according to the motion state of the incident particles and the actual wind field at that time. The number of snow particles is re-counted every 0.00001 s.

6. The reactive force F_x that the snow particles exert on the wind field induces wind modification according to Eq. (5).

7. Based on the process above, the velocity and location of each drifting snow particle are derived and then used in Eqs. (135)-(157) to calculate their sublimation rate every 0.00001 s. Under the effect of DSS, potential temperature and specific humidity at different heights under the diffusion or advection moisture transport are calculated every 0.00001 s.

8. The new values of wind field calculated in step 6 are used in step 3, and then steps 4 to 7 are recalculated. Such a cycle is repeated to finish the calculation of DSS under thermodynamic effects. Each calculation takes 60 s.

3 Results and Discussion

3.1 Wind-blown Snow Development and the Structure of Snow-drifting

Wind-blown snow has a self-regulating feedback mechanism between the saltating particles and the wind field, i.e. snow particles are entrained and transported by the wind, while the drag force associated with particle acceleration reduces the wind velocity in the saltation layer, thus limiting the entrainment of further particles. Figure 1 illustrates the evolution of saltating snow particles in air and also the profile of snow particle number density at steady state. The results show that the transport rate of particles in air increases rapidly and reaches a steady state after 2-3 seconds. In steady condition, the number of snow particles decreases with height and follows a negative exponential law. Except for the particle in air, the ambient relative humidity and temperature are also important factors concern to DSS.

3.12 Relative Humidity and Temperature

The relative humidity at 1 cm height for different defined wind velocities generally reaches saturation within 10 s when moisture transport is not included (Fig. ~~1a~~2a). Snow sublimation will not occur, and the temperature will not change (Fig. ~~1b~~2b). However, when moisture transport is included, the snow sublimation occurs throughout the simulation period, and temperature decreases~~ continually~~. Moreover, under the same moisture transport mechanism, the greater the wind friction velocity, the higher the relative humidity and temperature change (Fig. ~~1~~2). The relative humidity at 1 cm shows a trend of rapid decrease, then rapid increase, and finally a slow increase when moisture diffusion is included (Fig. ~~1a~~2a), but does not reach saturation in the simulation period of 60 s. Early in the wind-blown snow stage, the sublimation rate is smaller as only a few saltating particles sublime and the moisture at the lower height largely moves outwards due to the effect of moisture transport, resulting in relative humidity decrease. With continuing wind-blown snow, more snow particles leave the surface, which increases the sublimation rate and hence the relative humidity. When it reaches a steady state, the amount of snow particles in the saltation layer will no longer increase, but fluctuate within a certain range. Thereafter, because of the increase in humidity and cooling, DSS weakens (Fig. ~~2~~3). The results indicate that DSS in the saltation layer has a self-limiting nature. When the advection of moisture and heat are considered as well, the temperature and relative humidity will reach steady state finally. In this case, the transport of moisture and heat balances the change of temperature and relative humidity due to DSS.

3.~~2~~3 Sublimation Rate

From Fig. 3, we can see that DSS has reached steady state with moisture diffusion and advection considered within 60 s, but it is not true for only moisture diffusion considered. By considering of the required time of drifting snow development and the capability of computer, the simulated time was set as 60 s, which is significantly surpass drifting snow development time (about 2-3 s) and could be actualized easily on PC. Furthermore, the results are enough to expose the issues that we care about.

Moisture transport could remove some moisture, attenuating the increase of relative humidity and thus negative feedback, leading to higher sublimation rates with moisture transport than without (Fig. ~~2~~3). With moisture removal only by diffusion, the sublimation rate at 60 s is roughly the same at 3 wind velocities, meaning that sublimation still shows obvious negative feedback. However, with moisture transport by diffusion and advection, the sublimation rate increases significantly as the negative feedback effect is effectively reduced and will reach steady state. Moreover, the sublimation rate increases with the friction velocity and can be even greater than that at the highest wind velocity without advection. For example, the sublimation rate at 60 s with advection is ~~0.61~~0.88×10^{-5} kg m^{-2} s^{-1} at a friction velocity of 0.3 m s^{-1}, greater than that of 0.44×10^{-5} kg m^{-2} s^{-1} at a friction velocity of 0.5 m s^{-1} without considering advection. The sublimation rate even reaches ~~0.96~~1.6 ×10^{-5} kg m^{-2} s^{-1}, equaling the ~~0.83~~ 1.38 mm d^{-1} snow water equivalent (SWE) at a friction velocity of 0.5 m s^{-1} with advection included (Fig. ~~2~~3). Furthermore, sublimation continues to occur. Thus, it can be seen that effective moisture transport can weaken the negative feedback of sublimation, hence significantly affecting DSS. Because the occurrence of wind-blown snow must coincide with the airflow, DSS in the saltation layer is not negligible, and the assumption that the saltation layer is a saturation boundary layer is inadvisable.

Air temperature decreases with decreasing height, along with air unsaturation degree during wind-blown snow, which is adverse to sublimation in contrast to higher heights above the surface. Nevertheless, the volume sublimation rate increases with decreasing height (Fig. ~~3~~4). This is in agreement with the vertical profiles of the horizontal mass flux of snow particles (Huang et al., 2011). That is, there are more snow particles that can participate in sublimation at lower heights (Figure 1), leading to higher sublimation rates even in environments adverse to sublimation. The results indicate that the particle number density is an important controlling factor for sublimation rate, which is consistent with a previous study (Wever et al., 2009). A comparison between our simulated results and that of four models for suspended snow, i.e., PIEKTUK-T, WINDBLAST, SNOWSTORM and PIEKTUK-B, shows that the local sublimation rate of the suspended snow at 60 s can reach 10^{-6} kg m^{-3} s^{-1} at most (Xiao et al.,2000) (Fig. ~~3~~4), smaller than that of our calculated results (10^{-4} - 10^{-3} kg m^{-3} s^{-1}) by 2-3 orders of magnitude at the same initial temperature and relative humidity. This result shows that the assumption that sublimation in the saltation layer can be ignored by considering it a saturation boundary layer is inadvisable. Therefore, DSS in the saltation layer is of non-negligible importance and requires further detailed study.

4 Conclusions

In this study, we established a wind-blown snow model and balance equations for heat and moisture to study the effect of different moisture transport mechanisms on DSS in the saltation layer. As has been reported (e.g., Schmidt, 1982), DSS could lead to strong increases in humidity and cooling, which in turn can significantly reduce the DSS rate, i.e., DSS has an inherently self-limiting nature. Moreover, the relative humidity in the saltation layer quickly reaches saturation when moisture transport is not considered. However, effective moisture transport, such as advection, can dramatically weaken the negative feedback of sublimation and prolong the duration of the higher DSS rate and hence has a profound effect on DSS. Because of the presence of advection, DSS rate increases with the friction velocity and the volume sublimation rate of saltating particles is several orders of magnitude greater than that of the suspended particles due to the higher particle density in the saltation layer. Thus, DSS in the saltation layer plays an important part in the energy and mass balance of snow cover and needs to be further studied.

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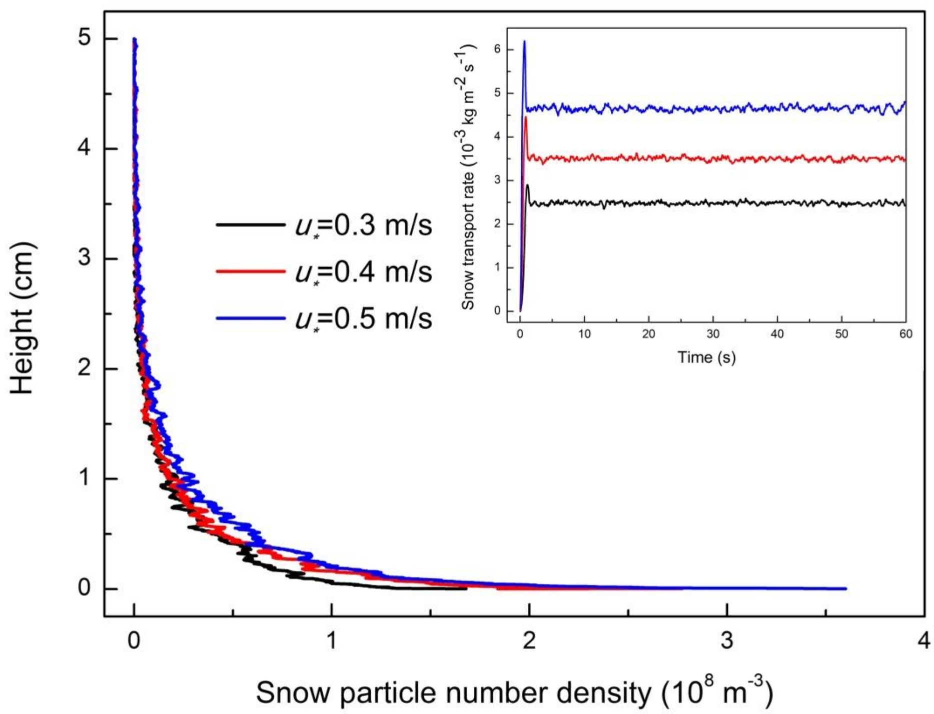

Figure 1. Temporal evolution of snow transport rate (the inset figure) and the profile of snow particle number density at the steady state for three wind force levels.

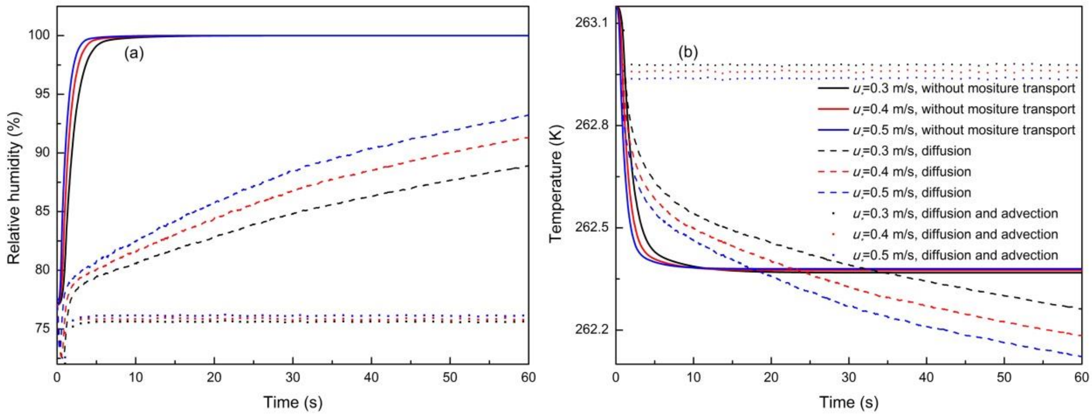

Figure ~~1~~ 2.Temporal evolution of relative humidity (a) and temperature (b) at 1 cm above the surface for three wind force levels neglecting the effects of moisture transport, considering only moisture diffusion, and both moisture diffusion and advection.

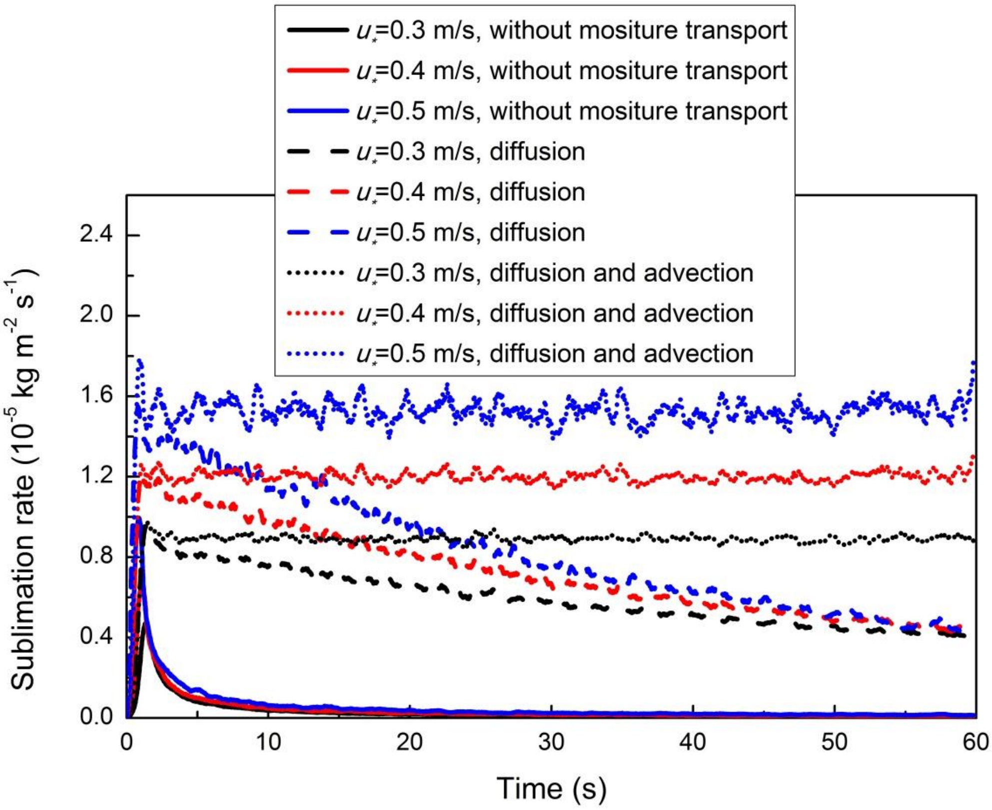

Figure ~~2~~ 3.Temporal evolution of drifting snow sublimation rate for three wind force levels neglecting moisture transport, considering only moisture diffusion, and both moisture diffusion and advection.

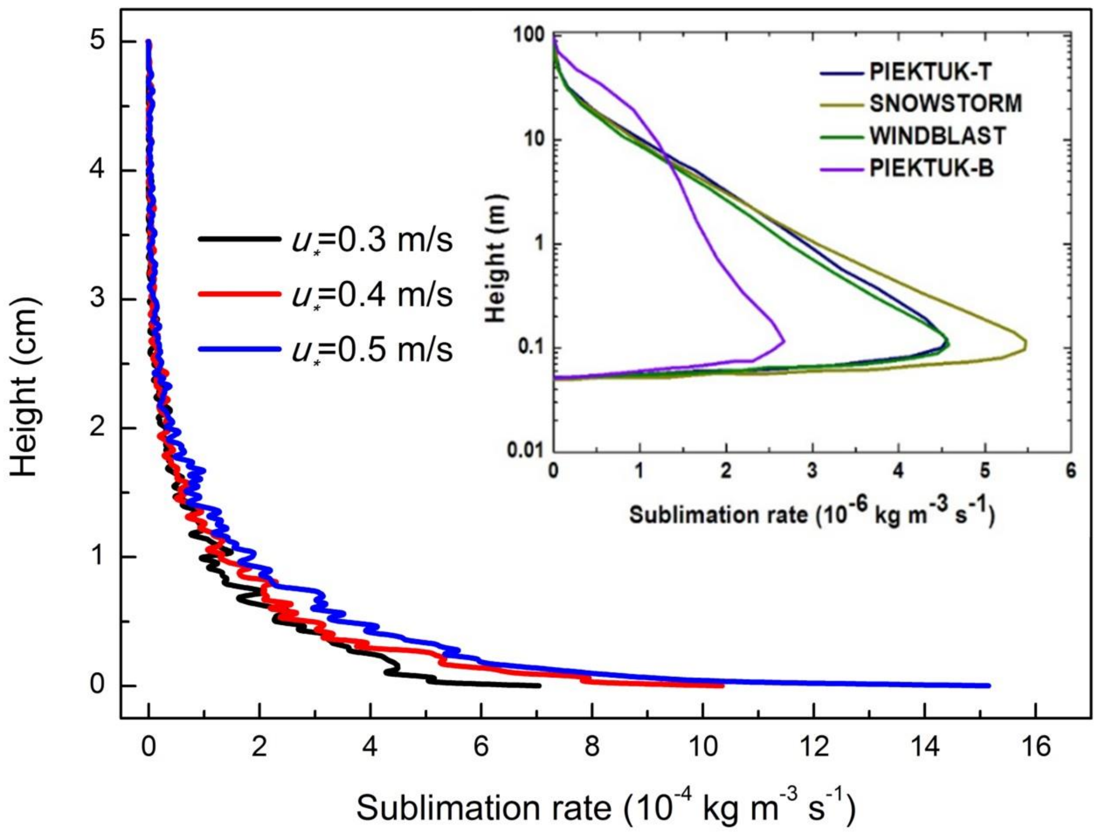

Figure ~~3~~ 4. Comparison of the sublimation rate for the saltation layer and suspension layer (the inset figure) at 60 s as a function of height. The inset figure shows the sublimation rate of four models for the suspension layer with initial friction velocity of 0.87 m s^{-1} reported in Xiao et al. (2000). Our results for the sublimation rate in the saltation layer are obtained for three wind force levels (<0.87 m s^{-1}) with moisture diffusion and advection included with the same initial temperature (253.16 K) and relative humidity as Xiao et al. (2000).