A point-by-point response to the reviews

Dear reviewers,

We sincerely thank you for the efforts you have made in reviewing our manuscript. Your insightful comments and positive evaluation of our work are really appreciated. We have studied your comments carefully and have revised and improved the manuscript accordingly. A point to point responds to the reviewer's comments are listed as following:

Reponses to RC1

Item 1: The authors present a relatively comprehensive snow drift model, taking into consideration of vertical diffusion of humidity. The results are compared with published data. It is shown that the results are at least qualitatively consistent with the observations and in some aspect also quantitatively consistent. I see considerable value in the further development of the model to a full scale comprehensive model. This model is a very good starting point, as it already has all the ingredients.

Response: Thanks for the positive comments. Our goal is to develop a more comprehensive model considering the sublimation of both saltating and suspended particles in the atmospheric turbulent boundary layer in the future, which is depicted in line 389-395 of page in the revised manuscript.

Item 2: The introduction can be shorter. The very first sentence in the abstract is a very long sentence trying to say too much. Also, the model formulation can be made more concise, e.g., Equation (1). It is unnecessary to write it in such a complex way.

Response: Following the reviewer's suggestion, we have simplified the introduction in line 7-10 of page 1 and model formations in line 104-105 of page 4 in the revised manuscript.

Item 3: The discontinuity of the model results is somewhat surprising, like in Figure 2a. The authors should explain what makes the model to behave like that and how it can be improved.

Response: The discontinuity is at a height of about 0.1m in Fig.2a. It can be seen from Fig. 10a that 0.1m is approximately equal to the maximum height of the saltating particles, and snow particles near the height of 0.1m is rare. Therefore the randomness of snow particles' number and their sizes at 0.1m is relatively large, which leads to the discontinuity of snow mass concentration. This problem is more serious in case the wind speed is smaller, for the smaller the wind speed is, the fewer number of snow particles in the air (See Fig.2a). It's much improved when the wind speed is higher (see Fig.2c). We have explained this phenomenon in the revised manuscript in line 235-241 of page 10 in the revised manuscript.

Item 4: I hope the authors can give a critical assessment of their model and point out the potential for further development.

Response: For the future development of the model, we will: (1) extend the model to three dimensions and take into consideration of the effects of turbulence on the sublimation of both saltating and suspended particles in the atmospheric turbulent boundary layer, which will lead to a more accurate and realistic model; (2) propose a parametric model of the blowing snow sublimation, which will provide parameterized values for the mesoscale climate model of the polar ice sheet, the alpine glacier, snowy with the high latitude and so on. We have added this content in line 389-395 of page 15 in the revised manuscript.

Item 5: In general, I find the work very interesting and represents a very useful contribution to snow drift modelling. As it has been revised and many question from the earlier review reports have been considered, I think the paper is now of good quality.

Response: Thanks you the positive comments.

Reponses to RC2

Item 1: This work deals with an important topic, and is one of the few studies that deal with the blowing snow sublimation over near-surface region. The results show that the sublimation will still exist in near-surface region in the fully developed blowing snow, and the mass of sublimation in near-surface region could account for even more than half of the total. The manuscript is laid out in a clear and straightforward manner and adds something new to the physical understanding of the behavior of the snow distribution and transport of snow in the polar, glacier and snowfields etc.. This kind of manuscript is very rare and always of interest, and should be published.

Response: Thanks for the positive comments. Our results in this paper show that the sublimation of blowing snow particles can't be ignored. We wish that the blowing snow sublimation near surface can be taken seriously in the future study.

Item 2: Does the snow sublimation in near-surface region have an impact on the mass and movement of snow particles? That is, Does the change in m also go into equations (4)- (6)?

Response: Thanks for the comment. We do have calculated the impact of sublimation on the snow particles, and the results show that the loss in mass of a single particle due to sublimation during its whole movement process is less than 0.1% of its own mass. Thus, the change in m didn't go into equations (4)-(6).

Item 3: According to the authors, the blowing snow sublimation will reduce the air temperature. It is not clear how the effects of temperature change and the flow field are related in your simulation.

Response: The temperature drop caused by snow sublimation is generally very small and does not exceed 2K. We verified that the temperature change of 2K has little effect on the wind field and it was ignored in our simulation.

Item 4: Usually the snow particles in the air are divided into suspension and saltation particles, and you seem to distinguish them simply by height. Please explain the reason.

Response: In Aeolian study, scientists usually define the particles jumping near surface, as saltation particles, which are mainly composed of large particles; define the particles whose movement distance in the air is long, as suspension particles, which are mainly composed of small particles. For simplicity's sake, a critical height is given. That is, particles fly higher than the critical height are regarded as suspension, while particles move below the height are considered as saltation. Furthermore, some scientists believed that the blowing snow sublimation in the near-surface region cloud be ignored, so they assumed that relative humidity below the critical height, which was used to distinguish the saltating and suspended particles. In this paper, we chose three heights defined by other scientists (see Table 3), and calculated the blowing snow sublimation masses below these heights. The results show that all the sublimation masses below the three heights, account for more than half of the total sublimation mass (see Fig. 12).

Because the difference of the critical height defined by different scientists very greatly (see Table 3), which made the simulation results produce a big difference. In this manuscript, we distinguish the saltation and suspending particles (Eq.2) based particles' flowing ability of the wind field. The diffusion equation was applied to describe the motion of suspended particles for small snow particles follow the wind field well. The Lagrangian particle tracing method was used to trace the motion of every large snow particle saltating in the near-surface region.

Item 5: Fig. 12 shows that snow sublimation occurs mainly in the near-surface region. It seems contradictory that in Fig. 13 the water vapor flux in the upper air is larger than that in the near-surface region.

Response: Because snow sublimation occurs mainly in the near surface, the humidity will decrease with the height. The water vapor produced by sublimation will be transferred from the higher humidity area to the lower one, and the amount of water vapor flux is determined by the concentration gradient of water vapor, not by the amount of sublimation. Therefore, it is possible that the water vapor flux in the upper air is larger than that in the near-surface region.

Item 6: All the results in Figure 4 don't include the results of saltation particles sublimation, but why the results of this paper is larger than that of xiao et al..

Response: In the simulation of Xiao et al., they considered that the water vapor in the near-surface region was saturated. That is, the humidity in the near-surface region was assumed to be 100%. In our simulation, the humidity in the near-surface region would not attain to 100% because of the vertical transportation of water vapor. Thus, the calculated humidity of this paper is smaller than that of Xiao et al., and the sublimation result of this paper is larger than that of Xiao et al. accordingly.

Item 7: This manuscript refers that there is a negative feedback effect in the blowing snow sublimation. Actually Figure 9 shows that the saltation particles sublimation does have a significant negative feedback effect, but you did not take into consideration of the feedback effect of sublimation of the suspended snow particles?

Response: It can be seen from Fig10a, 11a that the mass concentration as well as sublimation rate of the saltating snow particles is very high, so the saltating snow particles sublimation will strongly affect the temperature and humidity of the surrounding air. Therefore, it has a very strong negative feedback effect. However, it can be seen from Fig. 10b, 11b that both the mass concentration and sublimation rate of the suspended snow particles are much lower, so the effects of suspended snow particles sublimation on air temperature and humidity are very small. Therefore, its negative feedback effect is negligible.

Item 8: The writing proficiency of this manuscript need to improve because there are some writing errors in this paper. For example, the friction wind speeds in Figure 7 and Figure 8 are not expressed by the same symbol. In the first sentence of the abstract "Drifting snow sublimation is a physical process containing phase change and heat change. . .", the words "of the drifting snow" should be deleted.

Response: Following the reviewer's suggestion, we have corrected these writing errors in Fig. 7 in page 25 and in the revised manuscript in line 7-10 of page 1. A native English speaker, who is an English teacher in my university, has revised the English of this manuscript so that a clear description on the research has been displayed in the revised version. All revised sentences are marked by green.

Reponses to SC1

Item 1: Prof. Huang and his team made a very interesting job in analyzing drifting snow sublimation. Their results indicate that blowing snow sublimation is 3-4 orders of magnitude higher than at 10m. It is amazing and very useful, because this phenomenon has not been involved in any land surface model, as I know. I believe this job can fill the gap.

Response: Thanks. In this paper, we just verify the importance of blowing snow sublimation in near-surface region. In further work, we will propose a parametric model, which can be applied to the land surface models.

Item 2: One minor opinion: more explanation in figure captions may be better for readers.

Response: Following the Dr. Li's suggestion, we have added some explanation in figure 1, 2, 3, 4 in page19-22 in the revised manuscript.

Reponses to RC3

Item 1: The objectives of the paper are clear. However the connections between equations are not always clear to the reader.

Response: Thanks for the comment. Following your suggestion, we have added the calculation process, where the connections between equations are clearly described in line 202-218 of page 9 in the revised manuscript.

Item 2: Also, I understand the challenge of finding ground-based observations to valide simulation of the sublimation. But the limited number of observations used here weakens the conclusion made by the authors. In other words the lack of sufficient validation data makes it impossible to say for certain if this model constitute an improvement over the previous models.

Response: Thanks. Just as you said, ground-based sublimation observations are very few. However, we still found some experimental results that could be used to validate our model. For example, we compared our simulated snow sublimation rate with that of Schmidt's observational results (see Fig. 3) in page 21 in the revised manuscript. We also compared the simulated snow mass concentration with that of Pomeroy and Male (1992) to indirectly validate our model (see Fig. 2) in page 20 in the revised manuscript.

Item 3: Line 7 : instead of "drifting snow sublimation" the authors could clear state "sublimation of blowing snow" or "sublimation of transported snow particles".

Response: Thanks for your useful suggestion. We have replaced the phrase drifting snow sublimation with sublimation of blowing snow in the revised manuscript.

Item 4: Line 10: by "snow sublimation near surface " Do the authors mean the sublimation during the saltaion phase or the turbulent suspension phase of the blowing snow or both?

Response: In this manuscript, "snow sublimation near surface" includes the sublimation of both saltation particles and turbulent suspension particles in the region which is close to the snow bed.

Item 5: Line 10 -11: I would say that the statement is not exactly correct. There are a few models that take this sublimation of blowing snow into account (see for example Liston and Sturm, 1998, Essery et al., 1999).

Response: Thanks for the comment. You are right. Although in most of models snow sublimation near surface was ignored, some models did consider the sublimation of near bed. But in these models the value of sublimation near surface is only a rough estimate by some empirical formula based on assumptions. We have added some comments on previous work with more precise sentences in line 10-12 of page 1 in the revised manuscript.

Item 6: Line 15: the sentence is not clear.

Response: Thanks for your suggestion. We have modified the sentence in line 18 of page 1.

Item 7: Line 17: How small?

Response: From Fig. 12, we can see that the mass of snow sublimation near surface accounts for even more than half of the total when the friction wind velocity is less than about 0.55 m/s. We have added the specific value of wind velocity in line 21-22 of page 1 in the revised manuscript.

Item 8: Line 20: this sentence need rewording

Response: Following your suggestion, we have reworded this sentence in line 25-28 of page 1 in the revised manuscript.

Item 9: Line 42: need to cite references : "Many researchers….(references)"

Response: Thanks for your carefully reviewing of the manuscript. We have added some relevant references in line 56 of page 2 in the revised manuscript.

Item 10: Line 43: is "violently" the appropriate scientific word to use here?

Response: Thanks. As your suggestion, the sentences in line 43-45 have been modified in line 56-60 of page 2 in the revised manuscript as: Many researchers (Déry et al., 1998; Bintanja, 2001a; Mann et al., 2000) believed that the sublimation of snow particles near surface would be significant at the early stage of drifting snow process. However, the high concentration of snow particles near surface would result in a rapid air temperature decrease and humidity increase. Therefore, the humidity near surface would quickly reach saturation, leading to sublimation ceasing in the layer with saturated humidity.

Item 11: Line 48: I would state this: "However, some researchers (references) found that humidity near surface not to reach saturation in the drifting snow in the field, ….."

Response: Thanks. Following your suggestion, we have added some references in line 66-67 of page 2 in the revised manuscript.

Item 12: Line 68: "But this model can not describe snow particles suspending in upper air." The sentence is awkward and need rewording.

Response: Thanks. Following your suggestion, we have modified this sentence in line 89-90 of page 3 in the revised manuscript.

Item 13: Line 85: Authors should explain why use Flows equation instead of Blowing snow equation in for example Liston et Sturm, 1998.

Response: In order to accurately calculate the sublimation mass of snow particles, we need to know detailed information of each snow particle in the air (including particle size, relative velocity of particles to the wind speed, etc.). These data can't be directly obtained from the blowing snow equation. But they can be calculated by combine the flow equation and the snow particle motion equation. Therefore the Flows equation is used by many scientists, and we added such a reference in line 104-105 of page 4 in the revised manuscript.

Item 14: Line 94: judging criterion?? Do the authors mean "Threshold".

Response: "judging criterion" is the criterion for judging whether a particle is a saltating particle or a suspended particle.

Item 15: line 97: the authors should show the connection between this equation and the previous ones (eqs 1and 2).

Response: Thanks. This equation is used to calculate the final sedimentation velocity of the particles, which is a parameter in Equation 2. We have explained it in line 121-122 of page 5, and further explained the connections of all the equations in the calculation processes in line 202-218 of page 9 in the revised manuscript.

Item 16: Line 121: Please add reference.

Response: Thanks. As your suggestion, we have added some references in line 149 of page 6 in the revised manuscript.

Item 17: Line 171: Which particles, please explain.

Response: Thanks. The snow particle size distribution is that we used in the blowing snow model. We have explained it in line 200-201 of page 9 in the revised manuscript.

Item 18: Line 185: This conclusion is based on only 4 observations of field is a little bit of a stretch. For example, there is no observations on the figures 2 a, b, c.

Response: The reviewer is right. Because of the limited observational conditions, only a few observations are generally available to validate our model.

Item 19: Line 189: What are those environmental conditions? Can the authors explain why the difference What is the difference between the authors approach and that o schmidt?

Response: The conditions used in our simulations are the same as those reported by Schmidt. And we have added the environmental conditions in figure caption of Fig.3 in page 21 in the revised manuscript. Actually the conditions in the field are much complex and changing fast. Therefore it is almost impossible that the results of numerical simulation and field observation results are exactly the same. Nevertheless, it can be seen from Fig. 3 that the two results are relatively consistent, so we think that our model is reliable.

Item 20: Line 195: What are the difference between the 4 models apart from that the all neglect sublimation?

Response: The differences among these four models mainly include their structures, numerical methods, meteorological field treatment and the parameterization schemes although they are based on common physical concepts. Detailed information can be found in the paper by Xiao et al. (2000).

Item 21: Lines 200: - 205: this section is not clear and need to be reworded

Response: Thanks. As your suggestion, we have reworded this sentence in line 257-263 of page 11..

Item 22: Line 206: "suspended particles versus various friction velocities" IT should be "for various …" instead of "versus, …"

Response: Thanks. As your suggestion, we have modified this word in line 266 of page 11.

Item 23: Line 209: "reach stead" what does that mean? do you mean "plateau" = constant value?

Response: Yes, it means that the values of parameters, such as mass of saltating particles and suspended particles will not change with time.

Item 24: Line 214-216: This sentence is incomprehensible

Line 219: Need rewording

Line 221: Need rewording too

Line 227: "reach steady" is not an appropriate phrase to use in my view.

Line 230: need rewording

Line 246: The sencence need rewording

Response: As your suggestion, we have reworded these sentences in 273-279 of page 11, line 281-286 pages 11-12, line 285-288 of page 12, line 294-296 of page 12, line 298-301 of page 12, line 315-317 of page 13. Actually, we asked a native English speaker, who is an English teacher in my university, have revised the English of this manuscript.

Item 25: Line 270: I don't think this statement is true. Many models do take the sublimation into account

Response: Thanks for the comment. You are right. Although in most of models snow sublimation near surface was ignored, some models did consider the sublimation of near bed. But in these models the value of sublimation near surface is only a rough estimate by some empirical formula based on assumptions. We have made some comments on previous work with more precise sentences in line 343-344 of page14 in the revised manuscript.

Item 26: Line 275: Pomeroy et Male (1992)??? Vionnet et al. (year???)

Response: Thanks for your comment. We have added the year in line 351 of page 14 in the revised manuscript.

Item 27: Line 284: Could the authors cite the study that neglected the saltation?

Response: Thanks. As your suggestion, we have added the references in line 361-362 of page 14 in the revised manuscript.

Item 28: Figure 13: The smaller figure is not readable

Response: Thanks for your comment. The data of the small figure and the lager one in Fig. 13 are same. The only difference between the small figure and the larger one in Fig.13 is that the small one uses the logarithmic coordinates as x coordinates, and the large one use the linear coordinates as x coordinates. We have deleted it in page 31 in the revised manuscript.

Item 29: Line 307: "Bellowing snow" what does that need?

Response: Thanks for your comment. We have modified this word in line 387 of page 15.

Once again, thank you very much for your comments and suggestions.

Best regards

Ning Huang and Guanglei Shi

a list of all relevant changes made in the manuscript

In the Title:

'Snow' has been rewritten as 'snow'.

Line 3-4 of page 1:

The Superscript "1" is deleted.

Line 7-23 of page 1:

'Drifting snow sublimation is a physical process containing phase change and heat change of the drifting snow, which is not only an important parameter for the studying of polar ice sheets and glaciers, but a significant one for the ecology of arid and semi-arid lands, where snow cover is the main fresh water resource. However, in the previous studies drifting snow sublimation near surface was ignored. Herein, we built a drifting snow sublimation model containing vertical moisture diffusion equation and heat balance equation, to study drifting snow sublimation near surface. The results showed that though drifting snow sublimation near surface was strongly reduced by negative feedback effect, relative humidity near surface didn't reach the saturation state caused by vertical moisture diffusion. Therefore, the sublimation near surface will not stop in drifting snow near surface. The sublimation rate near surface is 3-4 orders of magnitude higher than that at 10 m. And the mass of snow sublimation near surface accounts for even more than half of the total if the wind velocity is small. Therefore, drifting snow sublimation near surface can't be neglected.'

has been rewritten as

'Sublimation of blowing snow is an important parameter not only for the studying of polar ice sheets and glaciers, but also for maintaining the ecology of arid and semi-arid lands. However, sublimation of blowing snow near surface is often ignored in the most of previous studies. To study sublimation of blowing snow near surface, we established a sublimation of blowing snow model containing both vertical moisture diffusion equation and heat balance equation. The results showed that although sublimation of blowing snow near surface was strongly reduced by negative feedback effect, due to vertical moisture diffusion, the relative humidity near surface doesn't reach 100%. Therefore, the sublimation of blowing snow near surface will not stop. In addition, the sublimation rate near surface is 3-4 orders of magnitude higher than that at 10 m above the surface and the mass of snow sublimation near surface accounts for even more than half of the total snow sublimation when the friction wind velocity is less than about 0.55 m/s. Therefore, sublimation of blowing snow near surface should not be neglected.'.

Line 25-43 of page 1-2:

‘The polar ice sheets, mountain glaciers, snowy area in high latitude of Northern Hemisphere (such as North of Canada, Greenland, etc), whose main source is snow, have profound influence on the global hydrologic cycle, climate change and ecological system. Extensive researches showed that drifting snow sublimation was an important method to change the snow distribution, especially in the polar ice sheets, highland mountains and high latitude of Northern Hemisphere. For example, Pomeroy and Jone (1995) found that the mass of drifting snow sublimation was equal to 18.3% of annual precipitation in coastal Antarctica; while Liston and Sturm (2004) found that it was equal to 22% of winter precipitation in Arctic Alaska. Pomeroy and Essery (1999) found that blowing snow sublimation fluxes during blowing snow return 10±50% of seasonal snowfall to the atmosphere in North American prairie and arctic environments. MacDonald et al. (2010) found that the mass of drifting snow sublimation was equal to 17%-19% of annual precipitation in Rocky Mountains, Canada. Zhou et al. (2014) pointed out that the mass of drifting snow sublimation was equal to 24% of annual precipitation in western Chinese mountains. These results indicate that drifting snow sublimation is very important to the study of global and polar hydrological systems.’

has been rewritten as

‘Blowing snow is the main source of polar ice sheets and mountain glaciers at snowy area with high latitude in the Northern Hemisphere (such as north of Canada, Greenland, etc), which have profound influence on the global hydrologic cycle, climate change and ecological system. Extensive studies have showed that sublimation of blowing snow is an important method to change the snow distribution, especially in the polar ice sheets, highland mountains and areas with high latitude in Northern Hemisphere. It has been shown the mass of sublimated blowing snow was equal to 18.3% of annual precipitation in coastal Antarctica (Pomeroy and Jone, 1995), 22% of winter precipitation in Arctic Alaska (Liston and Sturm, 2004), 17%-19% of annual precipitation in Rocky Mountains, Canada (MacDonald et al. 2010), and 24% of annual precipitation in western Chinese mountains (Zhou et al. 2014). In addition, the fluxes of sublimated blowing snow sublimation fluxes during blowing snow returned 10±50% of seasonal snowfall to the atmosphere in North American prairie and arctic environments (Pomeroy and Essery, 1999). These results indicate that sublimation of blowing snow is very important for studying of global and polar hydrological systems.’.

Line 44-50 of page 2:

‘Some scientists directly measured drifting snow sublimation using eddy covariance, but this method can only obtain a few points of information, and it is difficult to predict the whole sublimation in snowy areas (Pomeroy and Essery, 1999; Cullen et al., 2007; Marks et al., 2008; Reba et al., 2012). Therefore, there is a high demand of studying the sublimation of snow using numerical model. ’

has been rewritten as

‘Some scientists (Pomeroy and Essery, 1999; Cullen et al., 2007; Marks et al., 2008; Reba et al., 2012) used eddy covariance to directly measure sublimation of blowing snow. However, since this method can only obtain information from a few points, it is difficult to be used to predict the whole sublimation in snowy areas (Pomeroy and Essery, 1999; Cullen et al., 2007; Marks et al., 2008; Reba et al., 2012). Therefore, studying the sublimation of snow using numerical model is highly demanded.’

Line 51-60 of page 2:

‘The sublimation of snow particles in the drifting snow is normally accompanied with heat absorption and water vapor production, which will cause a decrease in the ambient air temperature and an increase in humidity. The increased humidity will in turn inhibit the sublimation of snow particles; while the lower temperature will lead to a decrease in the air saturated vapor pressure, which will also inhibit the snow sublimation. Many researchers believed that the sublimation of snow particles near surface would occur violently at the early stage of drifting snow process, since the high concentration of snow particles near surface would result in a rapid air temperature decrease and humidity increase. Then the humidity would reach saturation quickly near surface, and the sublimation would stop at the saturated layer of humidity.’

has been rewritten as

The sublimation of blowing snow particles is normally accompanied with heat absorption and water vapor production, which will lead to decreased ambient air temperature and increased in humidity. The latter will in turn inhibit snow sublimation, and the former will decrease the saturated vapor pressure in the air, and subsequently inhibit the snow sublimation. Many researchers (Déry et al., 1998; Bintanja, 2001a; Mann et al., 2000) believed that the sublimation of snow particles near surface would be significant at the early stage of drifting snow process. However, the high concentration of snow particles near surface would result in a rapid air temperature decrease and humidity increase. Therefore, the humidity near surface would quickly reach saturation, leading to sublimation ceasing in the layer with saturated humidity.

Line 66-69 of page 3:

‘However, some researchers found that humidity near surface didn’t reach saturation in the drifting snow in the field or wind tunnel experiments, which they thought was caused by water transport (convection and diffusion) (Schmidt, 1982; Groot Zwaadtink et al., 2011).’

has been rewritten as

‘However, some researchers (Schmidt, 1982; Groot Zwaadtink et al., 2011) found that humidity near surface didn’t reach saturation in the drifting snow in the field or wind tunnel experiments and believed that caused by water transport (convection and diffusion).’.

Line 70 of page 3:

‘they simulated’ has been rewritten as ‘simulating’.

Line 71-72 of page 3:

‘They found that the time-integrated values of sublimation increased 14% than the results which fix the relative humidity at 100%,’

has been rewritten as

‘and found that the time-integrated values of sublimation increased by 14% than at 95% relative humidity at compared with that at 100% relative humidity.’.

Line 73 of page 3:

‘so’ has been rewritten as ‘So they believed that’.

Line 74 of page 3:

‘blowing sublimation’ has been rewritten as ‘blowing snow sublimation’.

Line 75 of page 3:

‘, taking’ has been rewritten as ‘by taking’.

Line 76 of page 3:

the” Drifting snow sublimation” have been written as “Sublimation of blowing snow” in the revised manuscript.

Line 79 of page 3:

‘grassland covered by snow’ has been rewritten as ‘snow-covered grassland’.

Line 83-86 of page 3:

‘, which can describe the movement of small particles well. But the diffusion equation is difficult to describe the movement of large snow particles which are mainly distributed in the near surface area (Déry et al., 1998; Xiao et al., 2000; Vionnet et al. 2014).’

has been rewritten as

‘. Although the equation is good on describing the movement of small particles well, but it is difficult to describe the movement of large snow particles which are mainly distributed in the near surface area (Déry et al., 1998; Xiao et al., 2000; Vionnet et al. 2014).’.

Line 88 of page 3:

‘saltation’ has been rewritten as ‘saltating’.

‘on’ has been rewritten as ‘with’.

Line 89-90 of page 3:

‘But this model can not describe snow particles suspending in upper air.’

has been rewritten as

‘But this model did not take into consideration of to turbulent suspension of snow particles.’.

Line 90 of page 3:

‘all above’ has been rewritten as ‘all the above’.

Line 93-101 of page 4:

‘Therefore, a drifting snow model has firstly been built to describe the movement of snow particles of both saltating near surface and suspending in the higher region. Then, a drifting snow sublimation model has been built the combination of the drifting snow model, a vertical moisture diffusion equation and a heat balance equation. Then drifting snow sublimation with three wind speeds was calculated. The temporal evolution and vertical profiles of temperature, relative humidity, mass concentration of snow particles, snow sublimation rate were analyzed in details. Meanwhile, the proportions of the sublimation mass of saltation snow grains and saltation layer to the total sublimation mass were also given.'

has been rewritten as

'In this study, a drifting snow model was first established to describe the movement of snow particles of both saltating snow particles near surface and suspended snow particles in the higher region. Then, a sublimation model of blowing snow was built in combination of the drifting snow model, a vertical moisture diffusion equation and a heat balance equation. Next, sublimation of blowing snow at three different wind speeds was calculated and the temporal evolution and vertical profiles of temperature, relative humidity, mass concentration of snow particles and snow sublimation rate were analyzed in details. At last, the proportions of the sublimation mass of snow particles near surface to the total sublimation mass were also given.'.

Line 102 of page 4:

'Method' has been rewritten as 'Methods'

Line 103 of page 4:

'Basic Equations of the Flows' has been rewritten as 'Basic flow equations'.

Line 105 of page 4:

The reference '(Nemoto and Nishimura, 2004)' has been added in.

Line 105-108 of page 4:

'Considering a fully developed steady flow field on an infinite polar ice sheet where the changes of wind field in the lateral and flow direction are negligible, the fully developed horizontal direction flow field equation can be obtained according to the theory of mixing length by Prandtl.' has been deleted.

Line 113 of page 4:

‘saltation’ has been written as ‘saltating’.

Line 115 of page 4:

‘saltation’ has been written as ‘saltating’.

Line 116 of page 5:

‘suspension’ has been written as ‘suspended’.

Line 118 of page 5:

‘saltation’ has been written as ‘saltating’.

Line 119 of page 5:

‘saltation’ has been written as ‘saltating’.

Line 121-122 of page 5:

‘ w_s is the final sedimentation velocity of the particles which can be calculated by the following equations (Carrier, 1953):’

has been changed to

‘ w_s is the final sedimentation velocity of the particles which can be calculated by the following equations (Carrier, 1953):’.

Line 124 of page 5:

‘densities’ has been modified to ‘density’.

Line 125 of page 5:

‘particle’ has been modified to ‘particles’.

Line 126 of page 5:

‘saltation’ has been written as ‘saltating’.

Line 127-128 of page 5:

‘Saltation particle motion equation is as follows (Huang et al., 2011):’

has been written as

‘The motion equation of the saltating particles is as follows (Huang et al., 2011),’

Line 134 of page 5:

‘respectively’ has been added in this line.

Line 135 of page 6:

‘respectively’ has been added in this line.

Line 135-136 of page 6:

‘relative velocity of movement’ has been rewritten as ‘movement relative velocity’.

Line 136 of page 6:

‘and’ has been rewritten as ‘in’.

Line 137 of page 6:

‘respectively’ has been added in this line.

Line 146 of page 6:

‘respectively’ has been added in this line.

Line 147 of page 6:

‘Basic Equations of Suspended particles’ has been written as ‘Basic equations of suspended particles’.

Line 148 of page 6:

‘suspension’ has been written as ‘suspended’.

Line 149 of page 6:

The reference ‘Déry and Yau, 1999’ has been added in.

Line 152 of page 6:

‘grain.’ has been rewritten as ‘particles, and’

Line 154 of page 6:

‘ $w^{'}$ is the turbulent fluid velocity in the vertical’

has been rewritten as

‘ $w^{'}$ is the vertical turbulent fluid velocity’.

Line 155 of page 6:

The word ‘and’ has been added in.

Line 156 of page 7:

‘Aerodynamic Entrainment’ has been rewritten as ‘Aerodynamic entrainment’.

Line 159 of page 7:

‘causing by’ has been rewritten as ‘due to’.

Line 165 of page 7:

‘relative humidity of air’ has been rewritten as ‘relative air humidity’.

Line 166 of page 7:

‘thermal conductivity of air’ has been rewritten as ‘air thermal conductivity’.

Line 169 of page 7:

‘respectively’ has been added in this line.

Line 172 of page 7:

‘equation’ has been rewritten as ‘equations’ .

Line 173 of page 7:

‘The heat and humidity equations of air’ has been rewritten as ‘The air heat and humidity equations’.

Line 178 of page 8:

‘respectively’ has been added in this line.

Line 179 of page 8:

‘and’ has been added in this line.

Line 183 of page 8:

‘Where’ has been rewritten as ‘where’.

‘,’ has been rewritten as ‘and’.

Line 194 of page 8:

‘saltation’ has been written as ‘saltating’.

‘and’ has been added in this line.

Line 195 of page 8:

‘saltation’ has been written as ‘saltating’.

Line 196 of page 8:

‘saltation’ has been written as ‘saltating’.

Line 197 of page 8:

‘saltation’ has been written as ‘saltating’.

Line 200-201 of page 9:

‘The snow particle size distribution fits the results of Schmidt (1982) field observations (Fig. 1).’

has been written as

‘The size distribution of snow particles used in this paper fits the results of Schmidt’s (1982) field observations (Fig. 1).’.

Line 202-218 of page 9:

‘2.6 Calculation process

The calculation process of our model is as follow,

(1) We set a logarithmic wind field as the initial wind field, and give the first take-off particle with random particle size and vertical velocity $\sqrt{2GD}$.

(2) All the snow particles in the air are divided into saltating particles and suspended particles by Eq. 2-3. The movement of saltating particles is calculated by Eq. 4-7 and the movement of suspended particles is calculated by Eq. 11-12.

(3) If the snow particles fall on the bed, they will rebound and eject other particles which are on the bed. This process will be calculated by Eq. 8-9.

(4) 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 can be calculated by Eq. 13.

(5) The reaction force of the snow particles to the flow field is calculated by Eq.4-5 due to Newton's third law, and then the new flow filed is calculated by Eq.1.

(6) The air temperature and humidity are calculated by Eq. 16-19.

(7) The sublimation of snow particles is calculated by Eq. 14-15.

(8) The step (2)-(7) will be recycled until the end of the simulation.’

has been added in.

Line 220 of page 9:

‘eq. 2’ has been written as ‘Eq. 2’.

Line 221 of page 9:

‘eq. 16’ has been written as ‘Eq. 16’.

Line 223-225 of page 9:

‘and the particle diameter $D_{99\%}$ was recorded. $D_{99\%}$ and threshold particle diameter D_{th} calculated by eq.2 were compared, and the results is shown in Table1.’

has been written as

‘recorded the particle diameter $D_{99\%}$ and compared it with the threshold particle diameter D_{th} calculated by Eq.2. The results are shown in Table1.’.

Line 226 of page 10:

‘which are’ has been written as ‘with diameter’ .

‘Particle’ has been written as ‘diameter’.

Line 228 of page 10:

‘eq. 2’ has been written as ‘Eq. 2’.

Line 230 of page 10:

‘that’ has been written as ‘those’.

‘ rot’ has been written as ‘rots’.

‘is’ has been written as ‘are’.

Line 231-232 of page 10:

‘And’ has been written as ‘and’.

Line 232 of page 10:

‘with’ has been written as ‘in’.

Line 233 of page 10:

‘filed’ has been written as ‘field’.

Line 233-235 of page 10:

'It is shown that our simulation results are basically consistent with those observed in the field, which demonstrates the reliability of our simulations.'

has been written as

'It is clear from Fig.2 that our simulation result is basically consistent with those observed in the field, demonstrating the reliability of our simulations.'.

Line 235-241 of page 10:

'It can be seen from Fig. 2 that there are some discontinuities in our results, and the discontinuity is at a height of about 0.1m, which is approximately equal to the maximum height of the saltating particles (Fig. 10a) for snow particles near the height of 0.1m is rare. Therefore the randomness of snow particles' number and their sizes at 0.1m is relatively large, which leads to the discontinuity of snow mass concentration. This problem is more serious in case the wind speed is smaller, for the smaller the wind speed is, the fewer number of snow particles in the air (See Fig.2a). It's much improved when the wind speed is higher (see Fig.2c).' has been added in.

Line 232-249 of page 10:

'We also compared our sublimation results with that of the field observations to verify their reliability (Fig.3). The red lines in Fig. 3 are the results gotten from the observed data by Schmidt (1982) in Wyoming, U.S.A, in 1982. The black line was the simulated results using the same environmental conditions as those of Schmidt's. It can be seen that the total sublimation rates calculated by the model of this paper (black line) are approximately the same as Schmidt's results, and the sublimation rate at 0.01 m was two orders of magnitude larger than that at 0.1 m. These results demonstrate that our snow sublimation results are reliable too.'

has been written as

'We also verify the reliability of our simulation by comparing our sublimation results with that of the field observations (Fig.3). The red lines in Fig. 3 are the observation results of Schmidt (1982) in Wyoming, U.S.A, in 1982. The black line represents the simulated results obtained at the same environmental conditions as those of Schmidt's. It can be seen that the total sublimation rates calculated using our model (black line) are approximately the same as Schmidt's results, and the sublimation rate at 0.01 m is two orders of magnitude larger than that at 0.1 m. These results demonstrate that our results are reliable too.’.

Line 251-252 of page 10:

‘The black line in Fig. 4 is the result of the suspension particles sublimation rate calculated by our model ($u_* = 0.89, T = 253.15K$).,

‘The black line in Fig. 4 represents the result of the sublimation rate of suspended particles calculated by our model ($u_* = 0.89, T = 253.15K$).’.

Line 254 of page 10:

‘saltation’ has been written as ‘saltating’.

Line 255 of page 11:

‘all the rates of suspension particle’

has been written as

‘sublimation rates of suspended particle’.

Line 256-257 of page 11:

‘and then start to decrease, and the peak is at about 0.1 m. The results of this paper are higher than that of Xiao et al. (2001).’

has been written as

‘reaching peak at about 0.1 m. Our results are higher than those of Xiao et al. (2001).’.

Line 257-264 of page 11:

‘The peaks of total sublimation rate using our model and Schmidt (1982) are all at a height about 0.01 m, which is lower than that of the four blowing snow models in Fig. 4. But the values of peak in this paper and Schmidt (1982) are two orders of magnitude larger than that of the four blowing snow models. This is because the sublimation of saltation particles is neglected in the four models, which is the main movement of snow particles near surface.’

has been written as

‘The sublimation rate of the four models is zero below at height 0.05 m, which is different with the result of our model and Schmidt (1982) in Fig. 3. This is because the relative humidity below height of 0.05 m is set to 100% in the above-mentioned four models, but not in our model.’.

Line 265 of page 11:

‘saltation’ has been written as ‘saltating’.

Line 266 of page 11:

‘versus’ has been written as ‘for’.

‘mass’ has been written as ‘masses’.

‘saltation’ has been written as ‘saltating’.

Line 267 of page 11:

‘finally’ has been written as ‘eventually’.

‘saltation’ has been written as ‘saltating’.

Line 268 of page 11:

‘larger’ has been written as ‘higher’.

‘suspension’ has been written as ‘suspended’.

‘in’ has been written as ‘at’.

Line 269 of page 11:

‘saltation’ has been written as ‘saltating’.

‘and’ has been written as ‘while that is’.

Line 271-279 of page 11:

‘Fig. 6 shows the curves of temperature and humidity with height in the near-surface region of saltation particles and they are compared with their initial conditions. It is shown that drifting snow sublimation changes air temperature and relative humidity, and the change amplitude increases with the friction velocity. This is because the larger the friction velocity is, the more snow particles in the air are, and the more sublimation will occur, which makes a greater impact on temperature and humidity.’

has been written as

‘Fig. 6 shows the changes of temperature and humidity with height at initial state and at 1500 s. It is shown that air temperature and relative humidity are changed by sublimation of blowing snow particles, and the amplitude of these changes increase with the friction velocity. The greater wind velocity will lead to more snow particles into the air and undergoing sublimation and subsequently more dramatic changes in air temperature and relative humidity.’.

Line 280-293 of page 11-12:

‘We compared the temperature and humidity with height. It is shown in Fig. 7 and 8 that the change amplitude of temperature and relative humidity increases while the height decreases. Combined with the results from Fig. 10, the mass concentration of snow particles increases while height decreases, which can make a stronger sublimation.

It is shown in Fig. 8 that the time for humidity to reach steady is about 2 s at 0.01 m, which is consistent with the stability time of saltation snow particles; and at 10 m is about 300 s, which is consistent with the stability time of suspension snow particles. This is because the main part of snow particles near surface is saltation particles, opposite to that in upper air which is mainly suspension particles (Fig. 10).’

has been written as

‘Fig. 7 and Fig. 8 show the temporal evolution of temperature and relative humidity at various heights. It is clear from in Fig. 7 and 8 that the amplitude changes of temperature and relative humidity decrease with height increasing and sublimation becomes weaker with height increasing while the relative humidity becomes constant of about 2 s at 0.01 m and about 300 s at 10 m, consistent with the corresponding values for suspended snow particles. This is because the main part of snow particles near surface is saltating particles, while that in upper air is mainly suspended particles (Fig. 10).’.

Line 294-297 of page 12:

‘Fig. 8 shows that the relative humidity near surface with three kinds of friction velocities does not reach saturation when the blowing snow reaches steady, which indicates that the snow sublimation does not stop. It also shows that the vertical diffusion of water vapor can reduce the negative feedback effect effectively.’

has been written as

‘Fig. 8 also shows that the relative humidity near surface with three friction velocities does not reach saturation when the blowing snow particles saturate, indicating that the snow sublimation does not stop. Moreover, the vertical diffusion of water vapor can effectively reduce the negative feedback effect.’

Line 298-301 of page 12:

‘It can be seen from Fig. 9a that the sublimation rate of saltation particles increases with time first, then starts to decrease, in which the peak is at about 2 s and finally reaches stability at about 300 s.’

has been written as

‘It can be seen from Fig. 9a that the sublimation rate of saltating particles shows a trend of first increasing then decreasing with time. Its peaks at 2s and gradually decreases and reaches a steady state at about 300 s.’.

Line 301 of page 12:

‘saltation’ has been written as ‘saltating’.

Line 302-304 of page 12:

‘Because the mass of saltation particles increases with time during the first 2 s, and the increasing amplitude of which is larger than that of relative humidity’

has been written as

‘Because the mass of saltating particles increases with time during the first 2 s, with a greater amplitude than that of relative humidity’.

Line 305 of page 12:

‘saltation’ has been written as ‘saltating’.

‘stay’ has been written as ‘stays’.

Line 307 of page 12:

‘which results’ has been written as ‘resulting’.

Line 308 of page 12:

‘saltation’ has been written as ‘saltating’.

Line 309 of page 12:

‘change amplitude’ has been written as ‘amplitude change’.

‘which results’ has been written as ‘resulting’.

Line 310 of page 12:

‘saltation’ has been written as ‘saltating’.

Line 313-317 of page 13:

‘The mass of suspension particles increases with time during the first 300 s, which the increase amplitude of is larger than that of relative humidity, so the suspension sublimation rate increases with time. Then the mass of suspended particles and relative humidity both reach stable, which leads to the sublimation rate of suspended particles reaching stable.’

has been written as

‘The mass of suspended particles increases with time during the first 300 s with an amplitude larger than that of the relative humidity. So the suspended sublimation rate increases with time. Then the mass of suspended particles and relative humidity both reach their steady states, leading to the sublimation rate of suspended particles becomes constant.’.

Line 318 of page 13:

‘change amplitude’ has been written as ‘amplitude change’.

Line 319 of page 13:

‘the negative feedback effect on suspended particles is not strong.’

has been written as

‘therefore, the negative feedback effect on suspended particles is also weak.’.

Line 320 of page 13:

'saltation' has been written as 'saltating'.

'than' has been written as 'than that on'.

Line 321 of page 13:

'saltation' has been written as 'saltating'.

Line 322 of page 13:

'saltation' has been written as 'saltating'.

Line 325 of page 13:

'saltation' has been written as 'saltating'.

Line 326 of page 13:

'saltation' has been written as 'saltating'.

Line 327 of page 13:

'distribute' has been written as 'distribute at height'.

Line 329-333 of page 13:

'Sublimation rates of saltation and suspended particles increase with height first, then start to decrease. The peak of saltation particles is at about 0.01 m, and that of suspended particles is at about 0.1 m.'

has been written as

'The sublimation rates of saltating and suspended particles show a trend of decrease after increasing, reaching peak at about 0.01 m for saltating particles, and about 0.1 m for suspended particles.'.

Line 333 of page 13:

'snow' has been written as 'snow particles'.

Line 334 of page 13:

‘saltation’ has been written as ‘saltating’.

Line 335 of page 13:

‘suspension’ has been written as ‘suspended’.

Line 336 of page 13:

‘saltation’ has been written as ‘saltating’.

Line 338 of page 13:

‘which is same as’ has been written as ‘consistent with’.

Line 343-346 of page 13:

‘In the previous studies the snow sublimation near surface was ignored. That is, to define a wind velocity related height, below which saltation particles move.’

has been written as

‘The snow sublimation near surface was ignored in most previous studies (Déry et al., 1998; Xiao et al. 2000; Vionnet et al. 2014). That is, to define a wind velocity related height, below which saltating particles move, saltating particles are moved due to wind velocity below certain height.’.

Line 343-346 of page 14:

‘Then assumed that moisture in the region was saturated and therefore the snow sublimation would not be counted (Déry et al., 1998; Xiao et al. 2000; Vionnet et al. 2014).’

has been written as

‘Assuming that moisture below the height is saturated, therefore the snow sublimation would not be counted in the region (Déry et al., 1998; Xiao et al. 2000; Vionnet et al. 2014).’.

Line 351 of page 14:

The years ‘2014’ and ‘192’ have been added in.

Line 352 of page 14:

‘shown’ has been written as ‘clear’.

Line 353 of page 14:

‘three’ has been written as ‘the three’.

Line 354 of page 14:

‘saltation’ has been written as ‘saltating’.

Line 355 of page 14:

‘And although’ has been written as ‘Although’.

Line 356 of page 14:

‘of’ has been written as ‘in’.

Line 358 of page 14:

‘which results’ has been written as ‘resulting’.

‘of’ has been written as ‘in’.

Line 358-359 of page 14:

‘mass of sublimation’ has been written as ‘sublimation mass’.

Line 359 of page 14:

‘saltation’ has been written as ‘saltating’.

Line 359-362 of page 14:

‘and the previous methods neglecting blowing snow sublimation near surface is not appropriate.’

has been written as

‘Thus, it is not appropriate to neglect blowing snow sublimation near surface in previous reports methods (Déry et al., 1998; Xiao et al. 2000; Vionnet et al. 2014).’.

Line 364-365 of page 14:

'which will lead to decreasing proportion of snow particles near surface, the proportion of the mass of sublimation near surface will decrease as well.'

has been written as

'which will lead to decrease in proportion of snow particles near surface, the proportion of the sublimation mass near surface will decrease as well.'.

Line 366 of page 14:

'shown' has been written as 'clear'.

Line 367 of page 14:

'saltation' has been written as 'saltating'.

'then' has been written as 'and'.

Line 368 of page 14:

'For' has been written as 'Because'.

Line 370-372 of page 14-15:

'From Fig. 13 it can also be seen that vapor flux increases with friction velocity, for humidity (Fig.5) and moisture diffusion coefficient (eq.17) increase with friction velocity.'

has been written as

'It also can be seen from Fig. 13 that vapor flux increases with friction velocity, similar to that for humidity (Fig.5) and moisture diffusion coefficient (Eq.17).'.

Line 374 of page 15:

'which includes' has been written as 'with consideration of'.

Line 376-379 of page 15:

'The simulation results showed that the blowing snow sublimation decreased air temperature and increased humidity of air. Meanwhile, the snow sublimation was reduced by the negative feedback effect of temperature and humidity, especially for near surface, which is in agreement of previous researches.’

has been written as

‘The simulation results showed that the blowing snow sublimation decreases air temperature while increases air humidity. Meanwhile, the snow sublimation is reduced by the negative feedback effect of temperature and humidity, especially at near surface region, in agreement with previous researches.’.

Line 380 of page 15:

‘was’ has been written as ‘is’.

Line 381 of page 15:

‘continued’ has been written as ‘is a continuous process’.

‘was’ has been written as ‘is’.

Line 382 of page 15:

‘was’ has been written as ‘is’.

Line 384-386 of page 15:

‘Furthermore, when the wind speed was low, the mass of sublimation near surface accounted for more than half of total mass of sublimation, and could not be neglected.’

has been written as

‘Furthermore, at low wind speed, the mass of sublimation near surface accounts for more than half of the total sublimation mass, and could not be neglected.’.

Line 386 -387of page 15:

‘bellowing’ has been written as ‘blowing’.

‘form’ has been written as ‘from’.

Line 389-395 of page 15:

‘We will continue to develop our model in the future. Two possible improvements in the future are that:

(1) extend the model to three dimensions and take into consideration of the effects of turbulence on the sublimation of both saltating and suspended particles in the atmospheric turbulent boundary layer, which will lead to a more accurate and realistic model; (2) propose a parametric model of the blowing snow sublimation, which will provide parameterized values for the mesoscale climate model of the polar ice sheet, the alpine glacier, snowy area with the high latitude and so on.' has been added in.

Table 2 in page 18

'Table 2: Sublimation rate at 1500s for various heights (*: friction velocity (m/s); **: height (m); ***: sublimation rate ($kgm^{-3}s^{-1}$))'

has been written as

'Table 2: Sublimation rate at 1500s for snow particles at various heights (*: friction velocity (m/s); **: height (m); ***: sublimation rate ($kgm^{-3}s^{-1}$))'.

Table 3 in page 18

'Table 3: Height which most of saltation particles distributed below for various friction velocities'

has been written as

'Table 3: Height of most of saltating particles distributed below at various friction velocities'.

Fig.1 in page 19

'Figure 1: Particle size distribution'

has been written as

'Figure 1: Particle size distribution used in this paper, which fits the results of Schmidt's (1982) field observations.'.

Fig.2 in page 20

'Figure 2: Comparison of mass concentration for this paper and field observation (a: $u_* = 0.35ms^{-1}$; b: $u_* = 0.41ms^{-1}$; c: $u_* = 0.54ms^{-1}$)'

has been written as

'Figure 2: Comparison of mass concentration for this paper and field observation (a: $u_* = 0.35ms^{-1}; T = 268.65K$; b: $u_* = 0.41ms^{-1}; T = 268.65K$; c: $u_* = 0.54ms^{-1}; T = 268.65K$). The results of red dot are from near Saskatoon, Canada in 26 January 1987.'.

Fig.3 in page 21

'Figure 3: Comparison of sublimation rate for this paper and Schmidt (1982) (a:

$u_* = 0.632ms^{-1}, T = 267.45k$; b: $u_* = 1.072ms^{-1}, T = 265.65K$)'

has been written as

'Figure 3: Comparison of sublimation rate obtained this paper and by Schmidt (1982) (a:

$u_* = 0.632ms^{-1}, T = 267.45k$; b: $u_* = 1.072ms^{-1}, T = 265.65K$). The results of red line are from the data observed by Schmidt (1982) in Wyoming, U.S.A, in 1982.'.

Fig.4 in page 22

'Figure 4: Comparison of sublimation rate for this paper and four blowing snow's models (Xiao et al., 2000)'

has been written as

'Figure 4: Comparison of sublimation rate for this paper and four blowing snow's models (Xiao et al., 2000). The friction velocity is set to 0.89m/s, and the temperature is set to 253.15K. '.

Fig.5 in page 23

'Figure 5 : Temporal evolution of mass of saltation particles and suspension particles (a: saltation particles; b: suspended particles)'

has been written as

'Figure 5 : Temporal evolution of mass of saltating particles and suspended particles (a: saltating particles; b: suspended particles)'.

Fig.7 in page 25

The written error in Fig. 7 has been modified.

Fig.9 in page 27

'Figure 9: Temporal evolution of saltation sublimation rate and suspension sublimation rate(a: saltation particles; b: suspended particles)' has been written as

'Figure 9: Temporal evolution of saltation sublimation rate and suspension sublimation rate (a: saltating particles; b: suspended particles)'.

Fig.10 in page 28

'Figure 10: Vertical profiles of mass concentration for saltation and suspension (a: saltation particles, b: suspended particles)'

has been written as

'Figure 10: Vertical profiles of mass concentration for saltation and suspension (a: saltating particles, b: suspended particles)'.

Fig.11 in page 29

'Figure 11: Vertical profiles of sublimation rate for saltation and suspension (a: saltation particles; b: suspended particles)'

has been written as

'Figure 11: Vertical profiles of sublimation rate for saltation and suspension (a: saltating particles; b: suspended particles)'.

Fig.12 in page 30

'Figure 12: The ratio of sublimation mass below three heights to the total (the sublimation mass below a height is the sublimation mass that was ignored by other's model , such as Déry et al. (1998), Pomeroy and Male (1992), and Xiao et al. (2000).)'

has been written as

'Figure 12: The ratio of sublimation mass below three heights to the total. Sublimation mass below a certain height is the sublimation mass that was ignored by other's models (Déry et al. 1998; Pomeroy and Male, 1992, and Xiao et al., 2000).'.

Fig.13 in page 31

The small figure has been deleted.

The significance of vertical moisture diffusion on drifting ~~Snow~~ snow sublimation near snow surface

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Abstract. ~~Drifting snow sublimation~~ Sublimation of blowing snow ~~is a physical process containing phase change and heat change of the drifting snow, which~~ is ~~not only~~ an important parameter not only for the studying of polar ice sheets and glaciers, but also for maintaining ~~a significant one for~~ the ecology of arid and semi-arid lands.~~, where snow cover is the main fresh water resource.~~ However, ~~in the most of previous studies drifting snow sublimation~~sublimation of blowing snow near surface ~~was~~ is often ignored in the most of previous studies. To study sublimation of blowing snow near surface, ~~Herein,~~ we establishedbuilt ~~-~~a ~~drifting snow sublimation~~ sublimation of blowing snow model containing both vertical moisture diffusion equation and heat balance equation~~, to study drifting snow sublimation near surface~~. The results showed that although ~~drifting snow sublimation~~sublimation of blowing snow near surface was strongly reduced by negative feedback effect, due to vertical moisture diffusion, the relative humidity near surface ~~didn't~~ doesn't reach ~~the saturation state~~100% ~~caused by vertical moisture diffusion~~. Therefore, the sublimation of blowing snow near surface will not stop. ~~in drifting snow near surface.~~ In addition, ~~The~~ the sublimation rate near surface is 3-4 orders of magnitude higher than that at 10 m above the surface and~~. And~~ the mass of snow sublimation near surface accounts for even more than half of the total snow sublimation when the friction wind velocity is less than about 0.55 m/s.~~if the wind velocity is small.~~ Therefore, ~~drifting snow sublimation~~sublimation of blowing snow near surface ~~can't~~ should not be neglected.

1 Introduction

Blowing snow is the main source ~~The~~ of polar ice sheets~~,~~ and mountain glaciers~~,~~ at snowy area ~~in~~ with high latitude ~~of~~ in the Northern Hemisphere (such as ~~North~~ north of Canada, Greenland, etc), ~~whose main source is snow, have~~which have profound influence on the global hydrologic cycle, climate change and ecological system. Extensive ~~researches~~ studies have showed that ~~drifting snow sublimation~~sublimation of blowing snow ~~was~~ is an important method to change the snow distribution, especially in the polar ice sheets, highland mountains and areas with high latitude ~~of~~ in Northern Hemisphere. It has been shown~~For example, Pomeroy and Jone (1995) found that~~ the mass of ~~drifting snow sublimation~~sublimated blowing snow was equal to 18.3% of annual precipitation in coastal

Antarctica (Pomeroy and Jone, 1995),~~;~~ ~~while Liston and Sturm (2004) found that it was equal to~~ 22% of winter precipitation in Arctic Alaska (Liston and Sturm, 2004),~~.~~ 17%-19% of annual precipitation in Rocky Mountains, Canada (MacDonald et al. 2010), and 24% of annual precipitation in western Chinese mountains (Zhou et al. 2014). In addition, the fluxes of sublimated~~Pomeroy and Essery (1999) found that~~ blowing snow sublimation fluxes during blowing snow returned 10±50% of seasonal snowfall to the atmosphere in North American prairie and arctic environments (Pomeroy and Essery, 1999).~~ MacDonald et al. (2010) found that the mass of drifting snow sublimation was equal to 17%-19% of annual precipitation in Rocky Mountains, Canada. Zhou et al. (2014) pointed out that the mass of drifting snow sublimation was equal to 24% of annual precipitation in western Chinese mountains.~~ These results indicate that ~~drifting snow sublimation~~sublimation of blowing snow is very important ~~to the~~for studying of global and polar hydrological systems.

Some scientists (Pomeroy and Essery, 1999; Cullen et al., 2007; Marks et al., 2008; Reba et al., 2012) used eddy covariance to directly measure~~d~~ ~~drifting snow sublimation~~sublimation of blowing snow~~ using eddy covariance,~~. However, since~~but~~ this method can only obtain information from a few points~~ of information~~, ~~and~~ it is difficult to be used to predict the whole sublimation in snowy areas (Pomeroy and Essery, 1999; Cullen et al., 2007; Marks et al., 2008; Reba et al., 2012). Therefore, studying the sublimation of snow using numerical model is highly demanded~~there is a high demand of studying the sublimation of snow using numerical model~~.

The sublimation of blowing snow particles ~~in the drifting snow~~ is normally accompanied with heat absorption and water vapor production, which will lead to~~cause~~ ~~a~~ decreased ~~in the~~ ambient air temperature and ~~an~~ increased in humidity. The ~~increased humidity~~latter will in turn inhibit ~~the~~ snow sublimation~~ of snow particles;~~, ~~while~~ and the former ~~lower temperature~~ will ~~lead to a~~ decrease~~ in~~ the ~~air~~ saturated vapor pressure in the air, and subsequently~~which will also~~ inhibit the snow sublimation. Many researchers (Déry et al., 1998; Bintanja, 2001a; Mann et al., 2000) believed that the sublimation of snow particles near surface would be significant at the early stage of drifting snow process. However, the high concentration of snow particles near surface would result in a rapid air temperature decrease and humidity increase. Therefore, the humidity near surface would quickly reach saturation, leading to sublimation ceasing in the layer with saturated humidity. ~~Many researchers believed that the sublimation of snow particles near surface would occur violently at the early stage of drifting snow process, since the high concentration of snow particles near surface would result in a rapid air~~

~~temperature decrease and humidity increase. Then the humidity would reach saturation quickly near surface, and the sublimation would stop at the saturated layer of humidity.~~ Therefore, the ~~snow~~ sublimation of snow particles near surface was negligible in the fully developed drifting snow (Déry et al., 1998; Bintanja, 2001a; Mann et al., 2000). However, some researchers (Schmidt, 1982; Groot Zwaadtink et al., 2011) found that humidity near surface didn't reach saturation in the drifting snow in the field or wind tunnel experiments and believed that~~, which they thought was~~ caused by water transport (convection and diffusion)~~ (Schmidt, 1982; Groot Zwaadtink et al., 2011)~~. Déry and Yau (1999) fix the relative humidity at 95% instead of 100% at the surface when ~~they simulated~~ simulating the blowing snow sublimation~~. They~~ and found that the time-integrated values of sublimation increased by 14% than at 95% relative humidity compared with that at 100% relative humidity~~the results which fix the relative humidity at 100%,~~. ~~so~~ So they believed that humidity near surface is very important for the simulations of blowing snow sublimation. Huang et al. (2016) calculated the snow sublimation in the saltation layer~~, ~~ by taking into consideration of the effect of horizontal moisture convection on the non-homogeneous snow cover. Their results showed that ~~drifting snow sublimation~~sublimation of blowing snow in the saltation layer could not be neglected in the presence of horizontal moisture convection. But they did not discuss the sublimation near surface of areas such as polar ice sheets, snow-covered grassland~~ covered by snow~~, etc., where the snow cover was very large and the water convection was very weak. Therefore, studies on the snow-sublimation in these regions are of great significance for the understanding of global hydrological systems and ecosystems.

However, in the previous blowing snow sublimation model, the diffusion equation was often used to describe the movement of snow particles~~,~~. Although the equation is good on describing ~~which can describe~~ the movement of small particles well~~.~~, ~~But~~ but ~~not the diffusion equation~~it is difficult to describe the movement of large snow particles which are mainly distributed in the near surface area (Déry et al., 1998; Xiao et al., 2000; Vionnet et al. 2014). Huang et al. (2016) used the Lagrangian particle tracing method to describe the movement of near-surface snow particles, and for the first time calculated the sublimation of ~~saltation~~ saltating particles in near surface region ~~on~~ with non-uniform snow cover. But this model did not take into consideration of ~~can not describe~~ turbulent suspension of snow particles~~snow particles suspending in upper air~~. Furthermore, all the above exiting models did not take into consideration of the effects of vertical moisture diffusion on the sublimation.

In this study,Therefore, a drifting snow model was first establishedhas firstly been built to describe the movement of snow particles of both saltating snow particles near surface and suspendingsuspended snow particles in the higher region. Then, a drifting snow sublimationsublimation model of blowing snow model has beenwas built the in combination of the drifting snow model, a vertical moisture diffusion equation and a heat balance equation. Then Next, drifting snow sublimationsublimation of blowing snow with at three different wind speeds was calculated. The and the temporal evolution and vertical profiles of temperature, relative humidity, mass concentration of snow particles, and snow sublimation rate were analyzed in details. MeanwhileAt last, the proportions of the sublimation mass of saltation snow grains particles near and saltation layersurface to the total sublimation mass were also given.

2 Methods

2.1 Basic flow Equations equations of the Flows

The horizontal wind field satisfies the Navier–Stokes equation at the atmospheric boundary layer (Nemoto and Nishimura, 2004). Considering a fully developed steady flow field on an infinite polar ice sheet where the changes of wind field in the lateral and flow direction are negligible, the fully developed horizontal direction flow field equation can be obtained according to the theory of mixing length by Prandtl.

$$\frac{\partial}{\partial z}(\rho_a \kappa^2 z^2 \left|\frac{du}{dz}\right|\frac{du}{dz}) + F = 0 \qquad (1)$$

where κ is the von Karman constant, ρ_a is air density, u is the horizontal wind speed and F is the reaction force of the snow particles on the flow field.

2.2 Snow particle motion equation

The snow particles jumping from the bed are divided into saltation saltating and suspended particles when calculating snow particle movement. These two types of particles are distinguished based on the particle size and flow field conditions. Then the saltation saltating particles are calculated by Lagrange particle tracing method, and the suspension suspended particles are calculated by diffusion equation.

2.2.1 Judging criteria of saltation saltating and suspended particles

The judging criterion of saltation saltating and suspended particles is as follows (Scott, 1995):

$$\begin{cases} w_s/(ku_*) > 1, & saltation\ particle \\ w_s/(ku_*) \le 1, & suspension\ particle \end{cases} \quad (2)$$

where u_* is the friction velocity and w_s is the final sedimentation velocity of the particles which can be calculated by the following equations (Carrier, 1953):

$$\begin{aligned} w_s &= -\frac{A}{D} + \sqrt{\left(\frac{A}{D}\right)^2 + BD} \\ A &= 6.203\upsilon_a \\ B &= \frac{5.516\rho_p}{8\rho_a} g \end{aligned} \quad (3)$$

where D is diameter of snow particle, υ_a is air viscosity coefficient, ρ_p is the densities density of snow particles, g is the acceleration of gravity.

2.2.2 Basic equations of saltation saltating particles

Saltation The particle motion equation of the saltating particles is as follows (Huang et al., 2011):).

$$m\frac{dU_p}{dt} = F_D\left(\frac{U_a - U_p}{V_r}\right) \quad (4)$$

$$m\frac{dV_p}{dt} = -G + F_B + F_D\left(\frac{V_a - V_p}{V_r}\right) \quad (5)$$

$$\frac{dx_p}{dt} = U_p \quad (6)$$

$$\frac{dy_p}{dt} = V_p \quad (7)$$

where m is the mass of snow particle, G is the gravity of snow particle, U_a and V_a are the horizontal and vertical velocity of air, respectively, U_p and V_p are the horizontal and vertical velocities of snow particle, respectively, $V_r = \sqrt{(U_p - U_a)^2 + (V_p - V_a)^2}$ is the movement relative velocity ~~of movement~~ of the snow particles ~~and~~ in the flow field, F_B and F_D are the buoyancy and traction forces of snow particles, respectively, x_p and y_p are the horizontal and vertical positions of snow particles.

The splash function fitted by Sugiura and Maeno (2000) according to the observations of the low temperature wind tunnel experiment was chosen,

$$S_v(e_v) = \frac{1}{b^a G(a)} e_v^{a\text{-}1} \exp\left(-\frac{e_v}{b}\right) \tag{8}$$

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

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

where $S_v(e_v)$, $S_h(e_h)$ and $S_e(n_e)$ are the probability distribution functions of the vertical restitution coefficient e_v, horizontal restitution coefficient e_h, and the number of grains ejected n_e ~~,~~ respectively.

2.2.3 Basic ~~Equations~~ equations of ~~Suspended~~ suspended particles

The movement of ~~suspension~~ suspended particles is described by the following vertical diffusion equation according to horizontal uniformity condition (Déry and Yau, 1999),

$$\frac{\partial q}{\partial t} = \frac{\partial}{\partial y}\left(K_s \frac{\partial q}{\partial y} + w_s q\right) + S \tag{11}$$

where q is the snow particle mass concentration, K_s is the vertical diffusion coefficient, S is the volume sublimation rate of snow ~~grain~~particles~~.~~, and $K_s = \delta\kappa u_* z$, δ is as follows (Csanady, 1963),

$$\delta = \frac{1}{\sqrt{1 + \frac{\beta^2 f^2}{w_a^2}}} \tag{12}$$

where β is the proportionality constant, w' is the vertical turbulent fluid velocity ~~in the vertical~~, and we set $\beta = 1$, and $\overline{w'^2} = u_*^2$.

2.2.4 Aerodynamic ~~Entrainment~~entrainment

The aerodynamic entrainment equation of Shao and Li (1999) is chosen,

$$N_a = Vu_* \left(1 - \frac{u_{*t}^2}{u_*^2} \right) D^{-3} \tag{13}$$

where N_a is the number of snow particles taking off ~~causing by~~due to aerodynamic entrainment, ς is a non-dimensional coefficient, approximately equal to 1×10^{-3}, u_* is the friction velocity, and u_{*t} is the threshold friction velocity.

2.3 Sublimation formula

The sublimation formula is as follows (Thorpe and Mason, 1966),

$$\frac{dm}{dt} = \frac{\pi D(RH-1)}{\frac{L_s}{KNuT_a}(\frac{L_s}{R_v T_a}-1)+\frac{R_v T_a}{ShK_l e_s}} \tag{14}$$

where RH is the relative air humidity~~ of air~~, T_a is air temperature, L_s is the latent heat of sublimation (equal to 2.84×10^6 J kg^{-1}), K_a is the air thermal conductivity~~ of air~~, R_v is the gas constant of water vapor (equal to 461.5 J kg^{-1} K^{-1}), K_l is the molecular diffusion of water vapor of atmosphere, e_s is the saturated vapor pressure relative to the ice surface. Nu and Sh are the Nusselt and Sherwood numbers, respectively (Thorpe and Mason, 1966; Lee, 1975),

$$Nu = Sh = \begin{cases} 1.79 + 0.606\,\mathrm{Re}^{0.5} & 0.7 < \mathrm{Re} \le 10 \\ 1.88 + 0.580\,\mathrm{Re}^{0.5} & 10 < \mathrm{Re} < 200 \end{cases} \tag{15}$$

where $R_e = \frac{DV_r}{\upsilon_a}$ is Reynolds number.

2.4 Heat and humidity equations

The air heat and humidity equations ~~of air~~ are as follows (Déry and Yau, 1999; Bintanja，2000),

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left(K_\theta \frac{\partial\theta}{\partial z} \right) - \frac{L_s S}{\rho_f C} \tag{16}$$

$$K_\theta = \kappa u_* z + K_T \tag{17}$$

$$\frac{\partial h_u}{\partial t} = \frac{\partial}{\partial z}\left(K_q \frac{\partial h_u}{\partial z}\right) + \frac{S}{\rho_f} \quad (18)$$

$$K_h = \kappa u_* z + K_V \quad (19)$$

where K_T and K_V are the molecular diffusion coefficients of heat and water vapor, respectively, and C is the specific heat of air.

2.5 Initial and boundary conditions

The initial potential temperature $\theta_0 = 263.15K$, and the initial absolute temperature is

$$T_0 = \theta_0 \left(\frac{p}{p_0}\right)^{0.286} \quad (20)$$

~~Where~~ where p is atmospheric pressure~~, ~~ and its initial value is

$$p = p_0 \exp\left(-\frac{yg}{R_d \theta_0}\right) \quad (21)$$

where $p_0 = 1000hpa$, $R_d = 287 JKg^{-1}K^{-1}$ is the gas constant for dry air.

The initial relative humidity profile is

$$RH = 1 - R_S \ln(z / z_0) \quad (22)$$

where z_0 is the surface roughness, and its value is $3\times10^{-5} m$ at snow bed (Nemoto and Nishimura, 2001), and $R_S = 1.9974\times10^{-2}$.

The conversion relationship of relative humidity and specific humidity is

$$q = 0.622 \cdot \frac{e_s}{p - e_s} \cdot RH \quad (23)$$

where $e_s = 610.78 \exp\left[21.87(T - 273.16)/(T - 7.66)\right]$.

The calculation area is set to 1 m in length, 10 m in height, and 0.01 m in width. The time step is 10^{-5} s for ~~saltation~~ saltating particles, 10^{-2} s for suspended particles, and 10^{-3} s for wind, and the calculation time is 1500 s. The motion of ~~saltation~~ saltating particles is only calculated for 10 s in consideration of the practical simplicity, since ~~saltation~~ saltating particles will stabilize within a few seconds. The data of ~~saltation~~ saltating particles in the air and the jumping particles from bed are then replaced by the data averaged in 10 s. The threshold friction velocity is 0.21 m/s ~~-~~(Nemoto and Nishimura, 2001).

The ~~snow particle~~ size distribution of snow particles used in this paper fits the results of Schmidt's (1982) field observations (Fig. 1).

2.6 Calculation process

The calculation process of our model is as follow,

(1) We set a logarithmic wind field as the initial wind field, and give the first take-off particle with random particle size and vertical velocity $\sqrt{2GD}$.

(2) All the snow particles in the air are divided into saltating particles and suspended particles by Eq. 2-3. The movement of saltating particles is calculated by Eq. 4-7 and the movement of suspended particles is calculated by Eq. 11-12.

(3) If the snow particles fall on the bed, they will rebound and eject other particles which are on the bed. This process will be calculated by Eq. 8-9.

(4) 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 can be calculated by Eq. 13.

(5) The reaction force of the snow particles on the flow field is calculated by Eq.4-5 due to Newton's third law, and then the new flow filed is calculated by Eq.1.

(6) The air temperature and humidity are calculated by Eq. 16-19.

(7) The sublimation of snow particles is calculated by Eq. 14-15.

(8) The step (2)-(7) will be recycled until the end of the simulation.

3 Results and Discussion

In order to verify the judging criteria in ~~eq~~Eq.2, we divided the particles into sets varied by 10 μm (1-600 μm), and used ~~eq~~Eq.16 to simulate all the jumping particles. Then we accumulated the mass of snow particles in the air from small to large particles until the mass was equal to 99.9% of the total mass of snow particles in the air, recorded~~and~~ the particle diameter $D_{99\%}$ ~~was recorded.~~ and compared it with the ~~$D_{99\%}$~~ ~~and~~ threshold particle diameter D_{th} calculated by ~~eq~~Eq.2. ~~were compared, and t~~The results ~~is~~ are shown in Table1.

As shown in Table 1, particles with diameter~~which are~~ larger than the threshold diameter~~particle~~ do not enter into air according to the vertical diffusion, indicating that these particles can not be described by the diffusion equation. Thus, the judging criteria in ~~eq~~Eq.2 are reliable.

In order to verify the reliability of the blowing snow model in this paper, we compared our mass concentration results with ~~that~~ those of the field observations (Fig.2). The red dots in Fig. 2 ~~is~~ are the field observation results near Saskatoon, Canada in 26 January 1987 (Pomeroy and Male, 1992)~~. And~~ and the black line in Fig.2 is our numerical simulation results using the same conditions ~~with~~ in the above ~~filed~~ field observation results. It is clear from Fig.2~~shown~~ that our simulation result~~s~~ ~~are~~ is basically consistent with those observed in the field, ~~which demonstrates~~ demonstrating the reliability of our simulations. It can be seen from Fig. 2 that there are some discontinuities in our results, and the discontinuity is at a height of about 0.1m, which is approximately equal to the maximum height of the saltating particles (Fig. 10a) for snow particles near the height of 0.1m is rare. Therefore the randomness of snow particles' number and their sizes at 0.1m is relatively large, which leads to the discontinuity of snow mass concentration. This problem is more serious in case the wind speed is smaller, for the smaller the wind speed is, the fewer number of snow particles in the air (See Fig.2a). It's much improved when the wind speed is higher (see Fig.2c).

We also verify the reliability of our simulation by ~~compared~~ comparing our sublimation results with that of the field observations ~~to verify their reliability~~ (Fig.3). The red lines in Fig. 3 are ~~the~~ the observation results ~~gotten from the observed data by~~of Schmidt (1982) in Wyoming, U.S.A, in 1982. The black line represents~~was~~ the simulated results obtained at~~using~~ the same environmental conditions as those of Schmidt's. It can be seen that the total sublimation rates calculated ~~by~~ using ~~the~~ our model ~~of this paper~~ (black line) are approximately the same as Schmidt's results, and the sublimation rate at 0.01 m ~~was~~ is two orders of magnitude larger than that at 0.1 m. These results demonstrate that our ~~snow sublimation~~ results are reliable too.

We further compared our results with corresponding results of other models under the same conditions. The black line in Fig. 4 ~~is~~ represents the result of the ~~suspension particles~~ sublimation rate of suspended particles calculated by our model ($u_* = 0.89, T = 253.15K$). The other four lines are the results calculated by Xiao et al. (2001) using four existing blowing snow sublimation models, in which the sublimation of ~~saltation~~ saltating particles near surface was neglected. It is shown from Fig.

4 that all the sublimation rates of ~~suspension~~ suspended particle increase with height first, and then start to decrease, ~~and the~~reaching peak ~~is~~ at about 0.1 m. ~~The~~ Our results~~ of this paper~~ are higher than ~~that~~ those of Xiao et al. (2001). The sublimation rate of the four models is zero below at height 0.05 m, which is different with the result of our model and Schmidt (1982) in Fig. 3. ~~The peaks of total sublimation rate using our model and Schmidt (1982) are all at a height about 0.01 m, which is lower than that of the four blowing snow models in Fig. 4. But the values of peak in this paper and Schmidt (1982) are two orders of magnitude larger than that of the four blowing snow models.~~ This is because ~~the sublimation of saltation particles is neglected~~the relative humidity below height of 0.05 m is set to 100% in the above-mentioned four models~~,~~, but not in our model.~~ which is the main movement of snow particles near surface.~~

Fig. 5 is the temporal evolution of the mass of ~~saltation~~ saltating particles and suspended particles ~~versus~~ for various friction velocities. It is shown that the masses of ~~saltation~~ saltating and suspended particles increase with time, and eventually~~finally~~ reach steady. The mass of ~~saltation~~ saltating particles is much ~~larger~~ higher than that of ~~suspension~~ suspended particles ~~in~~ at the steady state. The time for ~~saltation~~ saltating particles to reach steady state is about 2 s, while that is~~and~~ about 300 s for suspended particles.

Fig. 6 shows the ~~curves~~ changes of temperature and humidity with height at initial state and at 1500 s~~in the near-surface region of saltation particles and they are compared with their initial conditions~~. It is shown that air temperature and relative humidity are changed by sublimation of blowing snow particles~~drifting snow sublimation changes air temperature and relative humidity~~, and the ~~change~~ amplitude of these changes increases with the friction velocity. ~~This is because the larger the friction velocity is, the more snow particles in the air are, and the more sublimation will occur, which makes a greater impact on temperature and humidity.~~The greater wind velocity will lead to more snow particles into the air and undergoing sublimation and subsequently more dramatic changes in air temperature and relative humidity.

Fig. 7 and Fig. 8 show the temporal evolution of temperature and relative humidity at various heights.~~We compared the temperature and humidity with height.~~ It is clear from~~shown~~ in Fig. 7 and 8 that the ~~change~~ amplitude changes of temperature and relative humidity decrease with height increasing and sublimation becomes weaker with height increasing while the~~increases while the~~

~~height decreases. Combined with the results from Fig. 10, the mass concentration of snow particles increases while height decreases, which can make a stronger sublimation.~~ relative humidity becomes constant of about 2 s at 0.01 m and about 300 s at 10 m, consistent with the corresponding values for suspended snow particles. This is because the main part of snow particles near surface is saltating particles, while that in upper air is mainly suspended particles (Fig. 10).

~~It is shown in Fig. 8 that the time for humidity to reach steady is about 2 s at 0.01 m, which is consistent with the stability time of saltation snow particles; and at 10 m is about 300 s, which is consistent with the stability time of suspension snow particles. This is because the main part of snow particles near surface is saltation particles, opposite to that in upper air which is mainly suspension particles (Fig. 10).~~

Fig. 8 also shows that the relative humidity near surface with three ~~kinds of~~ friction velocities does not reach saturation when the blowing snow ~~reaches~~ particles saturate~~steady~~, ~~which indicates~~ indicating that the snow sublimation does not stop. Moreover,~~It also shows that~~ the vertical diffusion of water vapor can effectively reduce the negative feedback effect ~~effectively~~.

It can be seen from Fig. 9a that the sublimation rate of ~~saltation~~ saltating particles shows a trend of first increasing then decreasing with time. Its peaks at 2s and gradually decreases and reaches a steady state~~increases with time first, then starts to decrease, in which the peak is at about 2 s and finally reaches stability~~ at about 300 s. The negative feedback effect on ~~saltation~~ saltating particles is very obvious and the time to reach a steady state is about 300 s. Because the mass of ~~saltation~~ saltating particles increases with time during the first 2 s, with a greater amplitude~~and the increasing amplitude of which is larger~~ than that of relative humidity, and the saltation sublimation rate increases with time. However, the mass of ~~saltation~~ saltating particles basically stays unchanged after 2 s, while the relative humidity near surface gradually increases. Therefore, the sublimation rate decreases with time. The relative humidity near surface also reaches steady after 300 s, ~~which results~~ resulting in the stability of sublimation rate. The ~~saltation~~ saltating particles distribute mainly near surface, where the amplitude change ~~amplitude~~ of relative humidity is strong, ~~which results~~ resulting in a strong negative feedback effect on ~~saltation~~ saltating particles.

It is shown in Fig. 9b that sublimation rate of suspended particles increases with time and finally reaches steady at about 300 s. The negative feedback effect on suspended particles is not obvious. The mass of ~~suspension~~ suspended particles increases with time during the first 300 s with an, ~~which the increase amplitude of is~~amplitude larger than that of the relative humidity~~,~~. ~~so~~ So the ~~suspension~~ suspended sublimation rate increases with time. Then the mass of suspended particles and relative humidity both reach their steady states~~reach stable~~, ~~which leads~~ leading to the sublimation rate of suspended particles becomes constant~~reaching stable~~. Since the suspended particles mainly distribute in upper air where the ~~change~~ amplitude change of relative humidity is weak, therefore, the negative feedback effect on suspended particles is also weak.~~not strong.~~

Although the effect of negative feedback on ~~saltation~~ saltating particles is stronger than that on suspended particles, the sublimation rate of ~~saltation~~ saltating particles is still greater than that of suspended particles, indicating that the sublimation of ~~saltation~~ saltating particles is very strong even under the effect of negative feedback.

Fig. 10 shows that the mass concentration of snow particles increases with friction velocity and decreases with height, and the mass concentration of ~~saltation~~ saltating particles is much higher than that of suspended particles. It can be seen from Fig. 10a that ~~saltation~~ saltating particles mainly distribute at height below 0.1 m, which is consistent with the previous experimental results (Takeuchi, 1980).

Fig. 11 shows that sublimation rates increases with friction velocity. The ~~Sublimation~~ sublimation rates of ~~saltation~~ saltating and suspended particles show a trend of decrease after ~~increase~~ increasing~~with height first, then start to decrease. The peak of saltation particles is~~, reaching peak ~~-~~at about 0.01 m for saltating particles, and ~~that of suspended particles is at~~ about 0.1 m for suspended particles. This is because the mass concentration and relative humidity of snow particles decrease with height, while temperature increases. However, mass concentration of ~~saltation~~ saltating particles changes more strongly than that of ~~suspension~~ suspended particles with height. Therefore, sublimation rate of ~~saltation~~ saltating particles reaches peak at lower height.

Table 2 shows that the sublimation rate at 0.01 m is two orders of magnitude faster than that at 0.1 m, consistent with~~which is same as~~ the experimental results in Fig. 3, and it's 3-4 times faster than that at 10 m, although the negative feedback effect near surface is stronger than other regions. Because the mass concentration of snow particles near surface is much higher than that in other regions (Fig. 8), and water vapor near surface is not saturated, the sublimation rate near surface is much faster than that in other regions.

~~In the previous studies the~~ The snow sublimation near surface was ignored in most previous studies (Déry et al., 1998; Xiao et al. 2000; Vionnet et al. 2014). That is, to define a wind velocity related height, below which saltating particles move.~~Therefore~~, saltating particles are moved due to wind velocity below certain height.~~That is, to define a wind velocity related height, below which saltation particles move.~~ ~~Then assumed~~ Assuming that moisture ~~in the region~~ below the height ~~was~~ is saturated, ~~and~~ therefore the snow sublimation would not be counted in the region (Déry et al., 1998; Xiao et al. 2000; Vionnet et al. 2014). Three heights at several wind velocities proposed by Déry et al. (1998), Pomeroy and Male (1992), and Xiao et al. (2000) were respectively given in Table 3 (The height by Vionnet et al. (2014) was the same as that of Pomeroy and Male (1992)). Fig. 12 shows the actual ratio of our simulated sublimation mass below the three heights to the total. It is ~~shown~~ clear that all the sublimation masses below the three heights account for more than half of the total sublimation mass. This is because the main part of snow particles is ~~saltation~~ saltating particles (Mellor, 1965), which mainly distribute in near surface region. ~~And a~~Although sublimation near surface leads to significant changes ~~of~~ in temperature and humidity, which have a strong inhibition effect on sublimation, moisture near surface does not reach saturation due to the vertical diffusion of water vapor, ~~which results~~ resulting in continuous snow sublimation. Therefore, the main part of the ~~mass of~~ sublimation mass is sublimation of ~~saltation~~ saltating particles~~,~~. Thus, it is not appropriate to neglect blowing snow sublimation near surface in previous reports methods~~and the previous methods neglecting blowing snow sublimation near surface is not appropriate~~ (Déry et al., 1998; Xiao et al. 2000; Vionnet et al. 2014). Fig. 12 also shows that the proportion of the sublimation mass near surface decreases with friction velocity. Because more snow particles can enter into upper air with increased wind velocity, which will lead to ~~decreasing~~ decrease in proportion of snow particles near surface, the proportion of the ~~mass of~~ sublimation mass near surface will decrease as well.

Fig.13 shows the vertical profiles of vapor flux. It is ~~shown~~ clear that vapor flux increases rapidly in near surface region, where most of ~~saltation~~ saltating particles move, ~~then~~ and slows down greatly after reaching a certain height. ~~For~~ Because there is no horizontal flux of water vapor，the water vapor flux at any height must be equal to the total amount of water vapor generated per second below the height. So most of the water vapor is coming from near surface regions. It also can be seen from~~From~~ Fig. 13 ~~it can also be seen~~ that vapor flux increases with friction velocity, similar to that for humidity (Fig.5) and moisture diffusion coefficient (~~eq~~Eq.17) ~~increase with friction velocity~~.

4 Conclusions

We have established a blowing snow sublimation model~~,~~ with consideration of~~which includes~~ vertical moisture diffusion and heat balance, to study the snow sublimation near surface in large snow cover area in this paper. The simulation results showed that the blowing snow sublimation ~~decreased~~ decreases air temperature ~~and~~ while ~~increased~~ increases air humidity ~~of air~~. Meanwhile, the snow sublimation ~~was~~ is reduced by the negative feedback effect of temperature and humidity, especially at near surface region~~for near surface~~, ~~which is~~ in agreement ~~of~~ with previous researches. However, moisture near surface ~~was~~ is not saturated due to the vertical moisture diffusion, so snow sublimation near surface is a continuous process~~continued~~. The sublimation rate near surface ~~was~~ is even larger than that in the upper air, because mass concentration of snow particles near surface ~~was~~ is much higher than that in other regions. The sublimation rate at 0.01 m is two orders of magnitude greater than that at 0.1 m, and is 3-4 orders of magnitude greater than that at 10 m. Furthermore, ~~when the~~at low wind speed ~~was low~~, the mass of sublimation near surface ~~accounted~~ accounts for more than half of the total ~~mass of~~ sublimation mass, and could not be neglected. Most of the air vapor in ~~bellowing~~ blowing snow is ~~form~~ from near surface region. Therefore, blowing snow sublimation near surface should be taken seriously in the study of snow sublimation and water vapor transport in the future.

We will continue to develop our model in the future. Two possible improvements in the future are that: (1) extend the model to three dimensions and take into consideration of the effects of turbulence on the sublimation of both saltating and suspended particles in the atmospheric turbulent boundary layer, which will lead to a more accurate and realistic model; (2) propose a parametric model of the blowing snow sublimation, which will provide parameterized values for the mesoscale climate model of the polar ice sheet, the alpine glacier, snowy area with the high latitude and so on.

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Table 1: Comparison of D_{th} and $D_{99\%}$

	$u_* = 0.35ms^{-1}$	$u_* = 0.41ms^{-1}$	$u_* = 0.54ms^{-1}$
D_{th}	80.55μm	87.84μm	102.61μm
$D_{99\%}$	≤80μm	≤90μm	≤110μm

Table 2: Sublimation rate at 1500s for snow particles at various heights (*: friction velocity (m/s); **: height (m); *: sublimation rate ($kgm^{-3}s^{-1}$))**

	$u_* = 0.35ms^{-1}$	$u_* = 0.45ms^{-1}$	$u_* = 0.55ms^{-1}$
h=0.01****	3.71E-04***	4.05E-04	4.21E-04
h=0.05	1.22E-05	2.31E-05	3.18E-05
h=0.1	6.11E-07	3.08E-06	5.37E-06
h=1	1.68E-07	1.12E-06	2.29E-06
h=5	2.93E-08	2.88E-07	7.52E-07
h=10	8.44E-09	1.09E-07	3.31E-07

Table 3: Height ~~which~~ of most of ~~saltation~~ saltating particles distributed below ~~for~~ at various friction velocities

	$u_* = 0.35ms^{-1}$	$u_* = 0.45ms^{-1}$	$u_* = 0.55ms^{-1}$
Déry et al. (1998)	0.0196m	0.0253m	0.0316m
Pomeroy and Male(1992)	0.0222m	0.0306m	0.0395m
Xiao et al.(2000)	0.05m	0.05m	0.05m

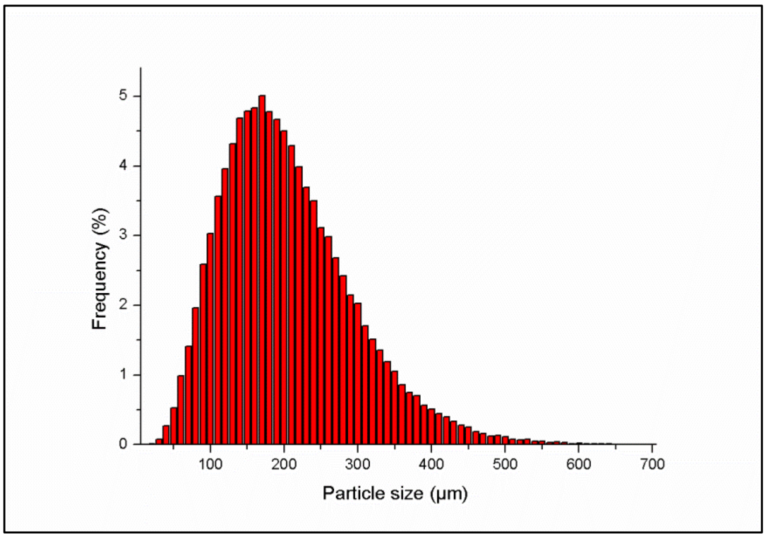

Figure 1: Particle size distribution used in this paper, which fits the results of Schmidt's (1982) field observations.

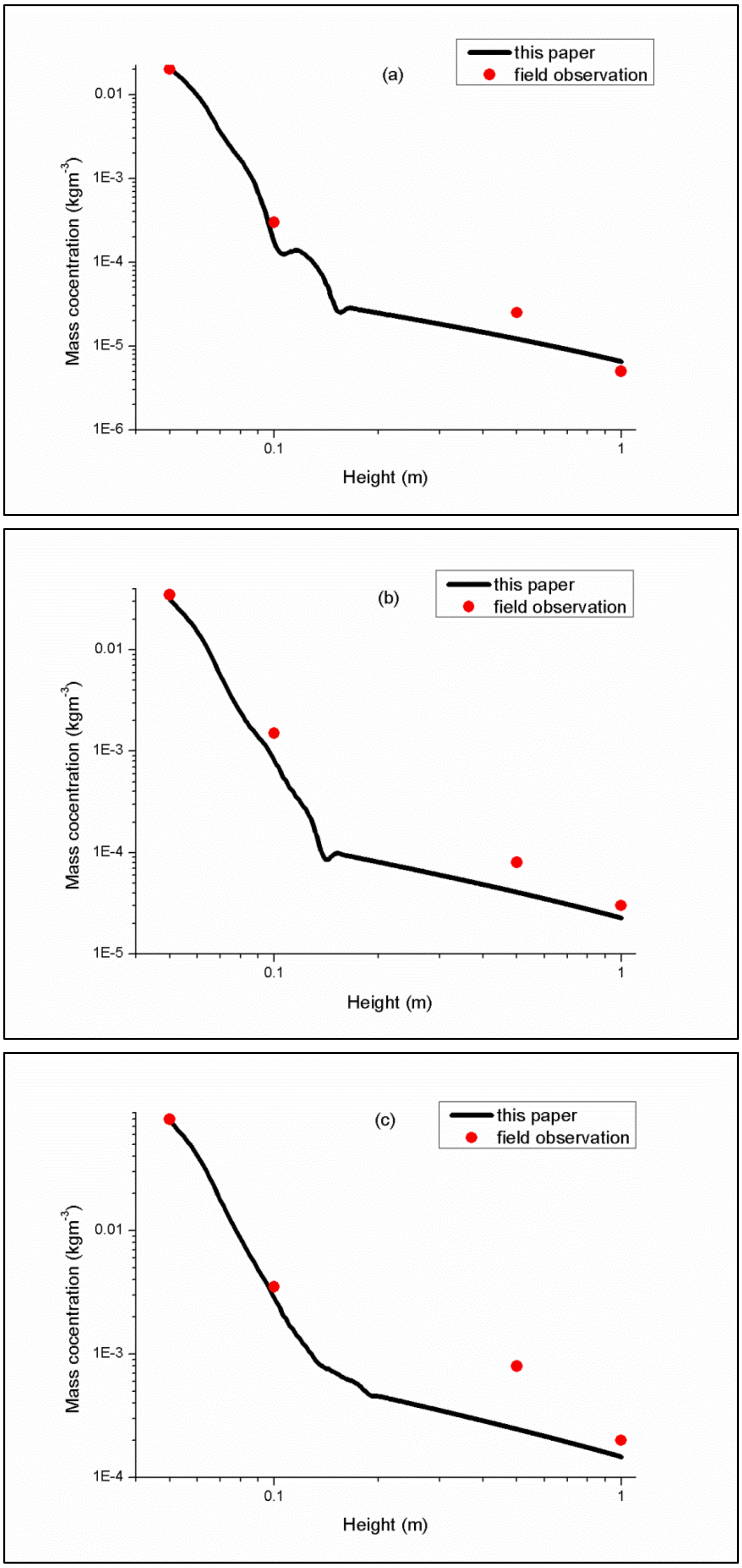

Figure 2: Comparison of mass concentration for this paper and field observation (a:
$u_* = 0.35ms^{-1}; T = 268.65K$ **; b:** $u_* = 0.41ms^{-1}; T = 268.65K$ **; c:** $u_* = 0.54ms^{-1}; T = 268.65K$ **). The results of red dot are from near Saskatoon, Canada in 26 January 1987.**

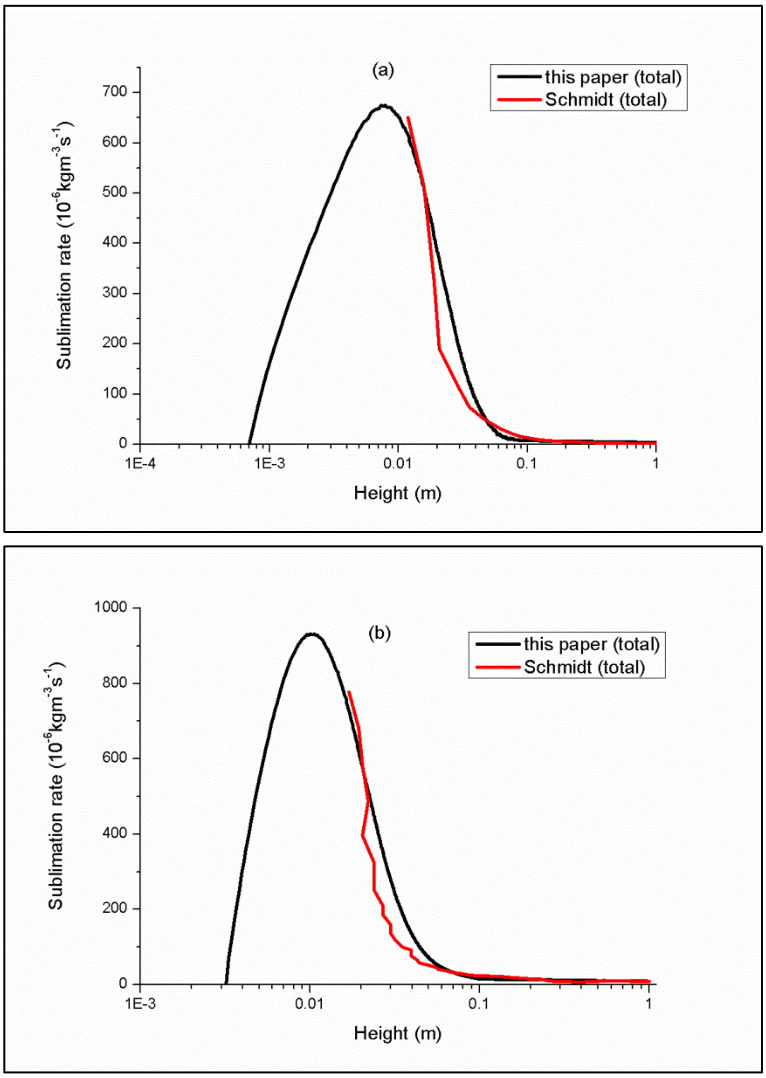

Figure 3: Comparison of sublimation rate ~~for~~ obtained this paper and by Schmidt (1982) (a: $u_* = 0.632ms^{-1}, T = 267.45k$ **; b:** $u_* = 1.072ms^{-1}, T = 265.65K$ **). The results of red line are from the data observed by Schmidt (1982) in Wyoming, U.S.A, in 1982.**

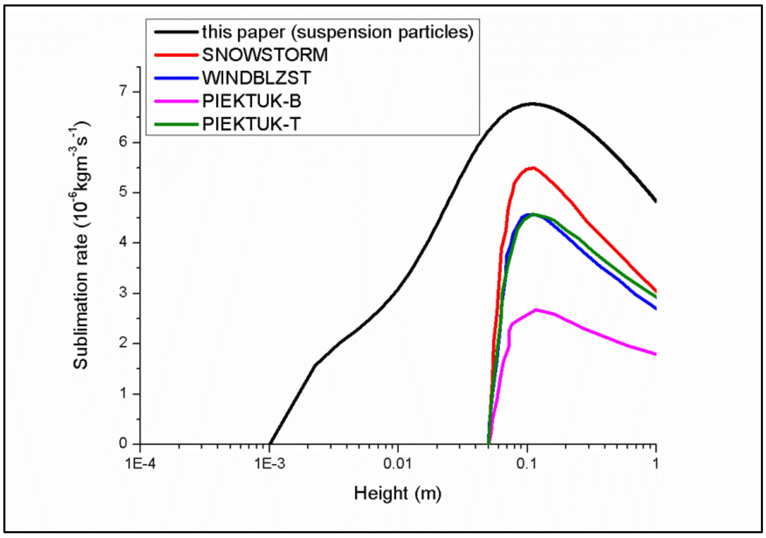

Figure 4: Comparison of sublimation rate for this paper and four blowing snow's models (Xiao et al., 2000).

The friction velocity is set to 0.89m/s, and the temperature is set to 253.15K.

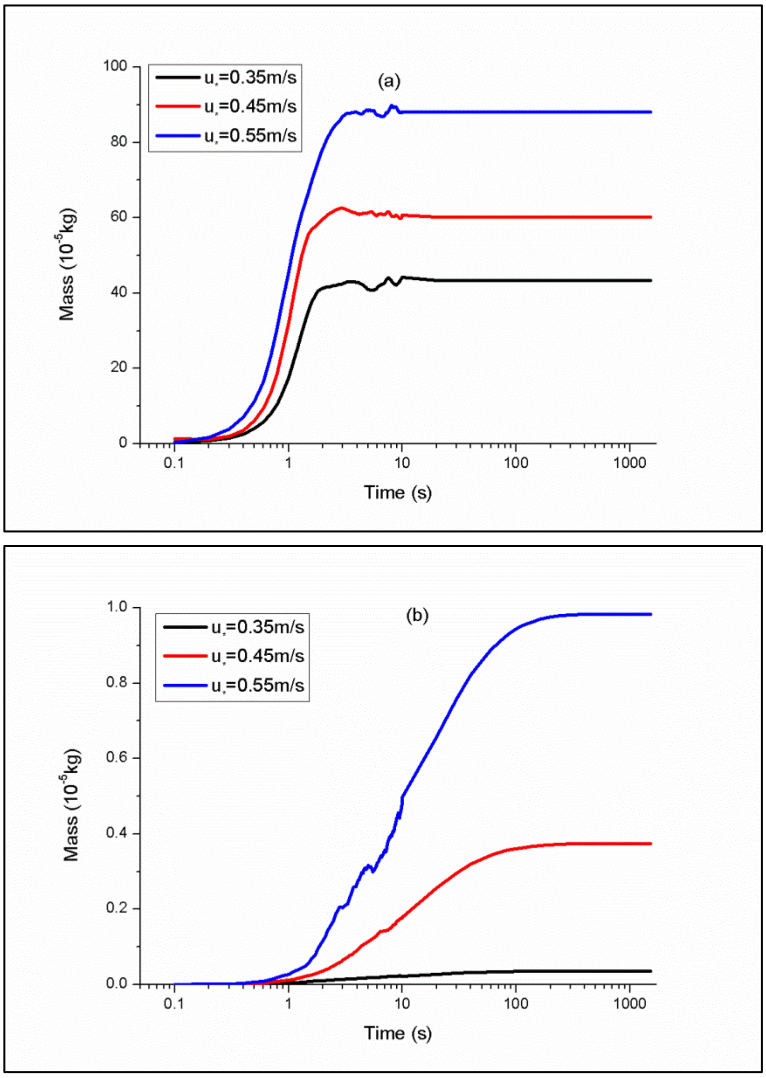

Figure 5 : Temporal evolution of mass of ~~saltation~~ saltating particles and ~~suspension~~ suspended particles (a: ~~saltation~~ saltating particles； b: suspended particles)

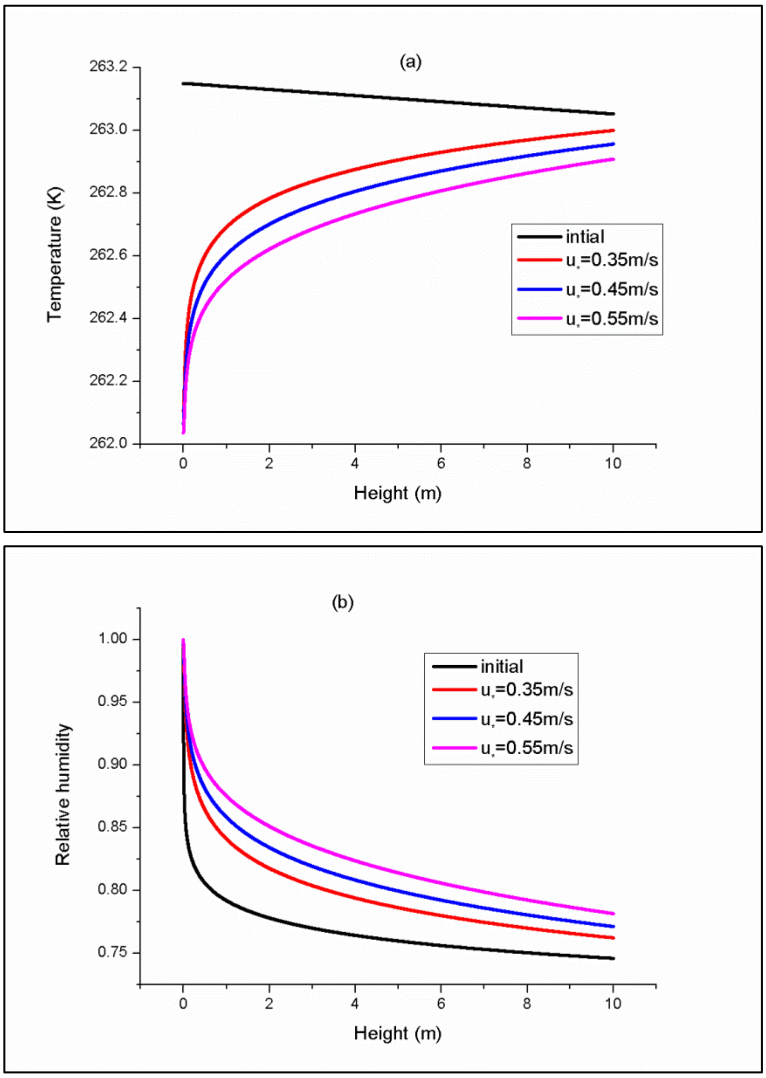

Figure 6: Vertical profiles of temperature and relative humidity

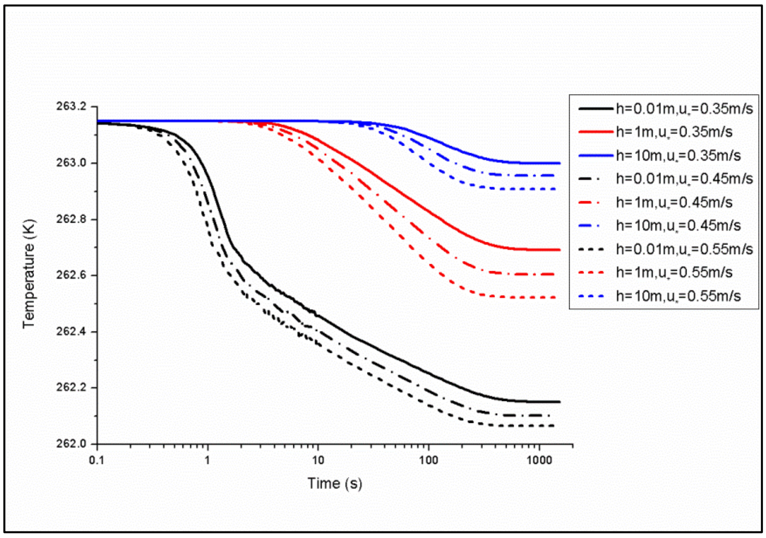

Figure 7: Temporal evolution of temperature for various heights

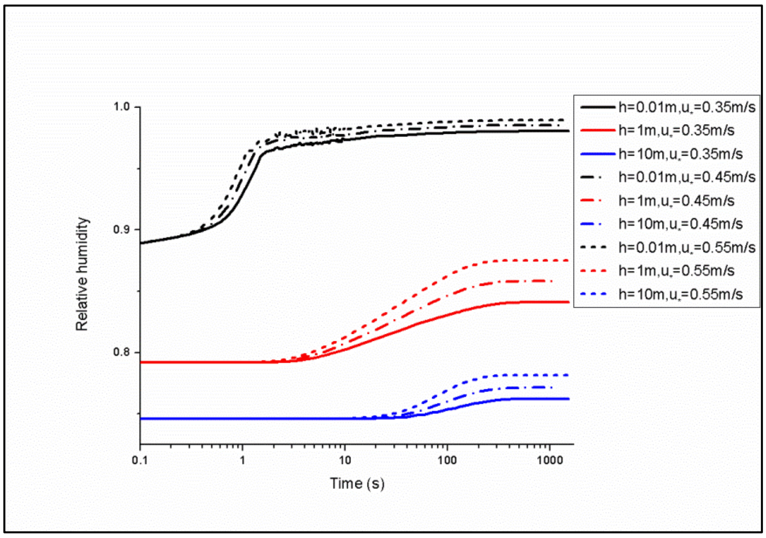

Figure 8: Temporal evolution of relative humidity for various heights

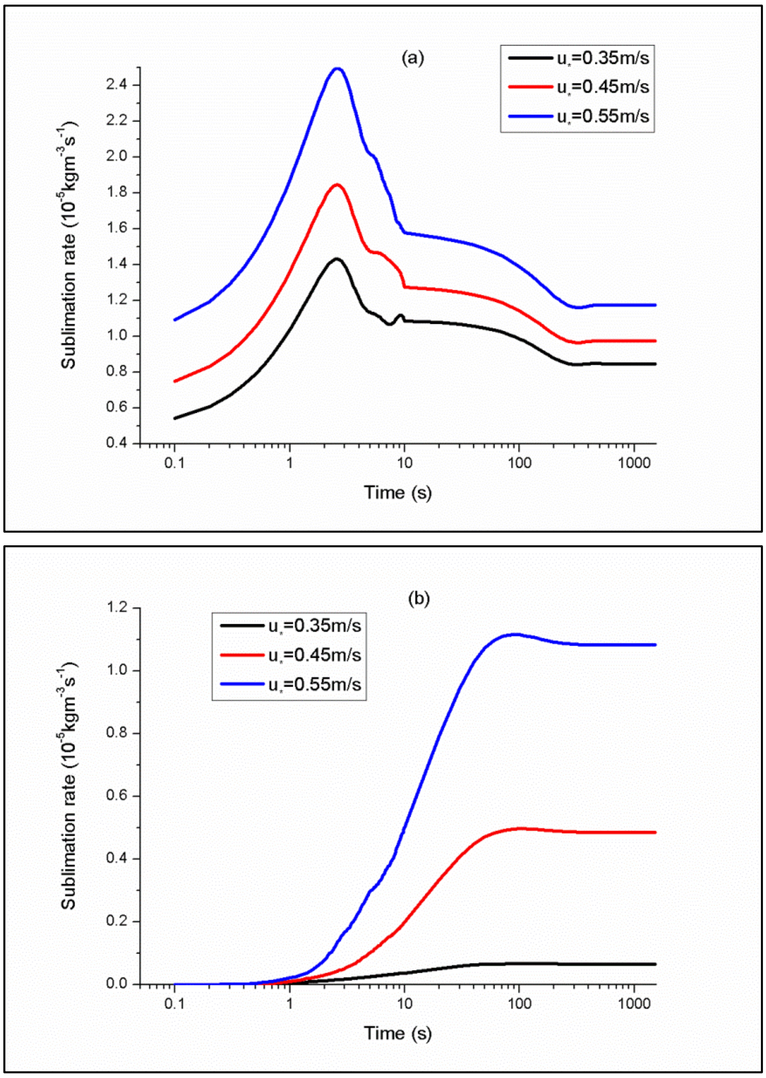

Figure 9: Temporal evolution of saltation sublimation rate and suspension sublimation rate (a: ~~saltation~~ saltating particles; b: suspended particles)

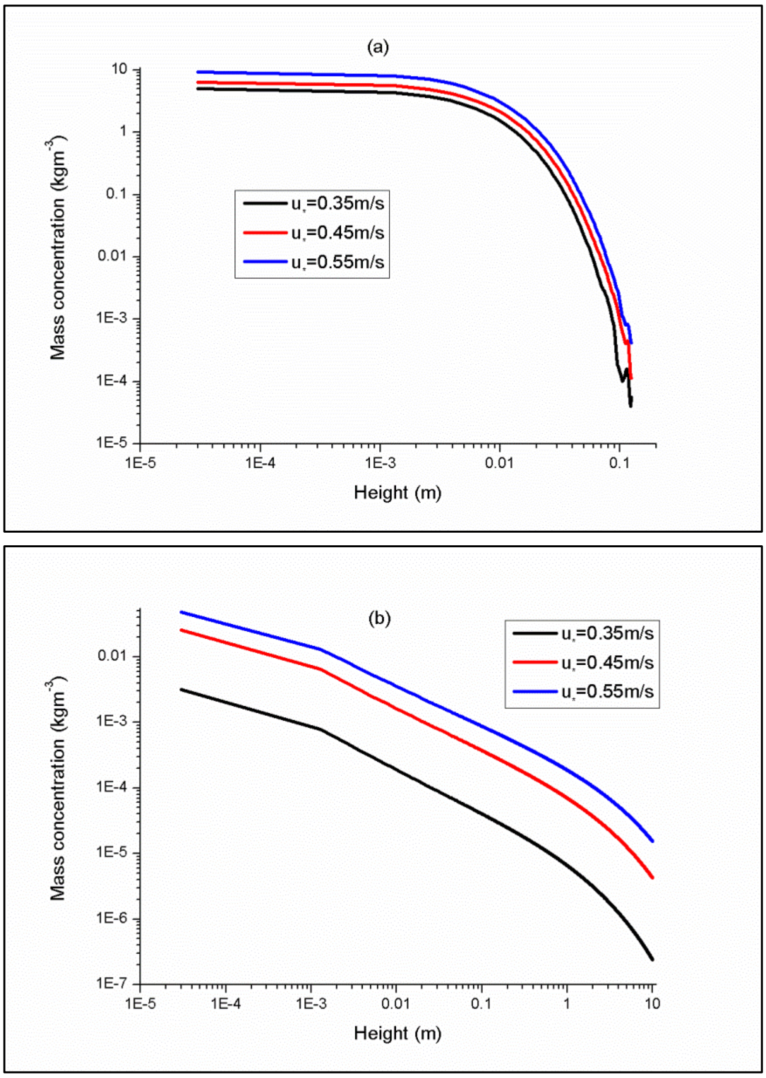

Figure 10: Vertical profiles of mass concentration for saltation and suspension (a: ~~saltation~~ saltating particles, b: suspended particles)

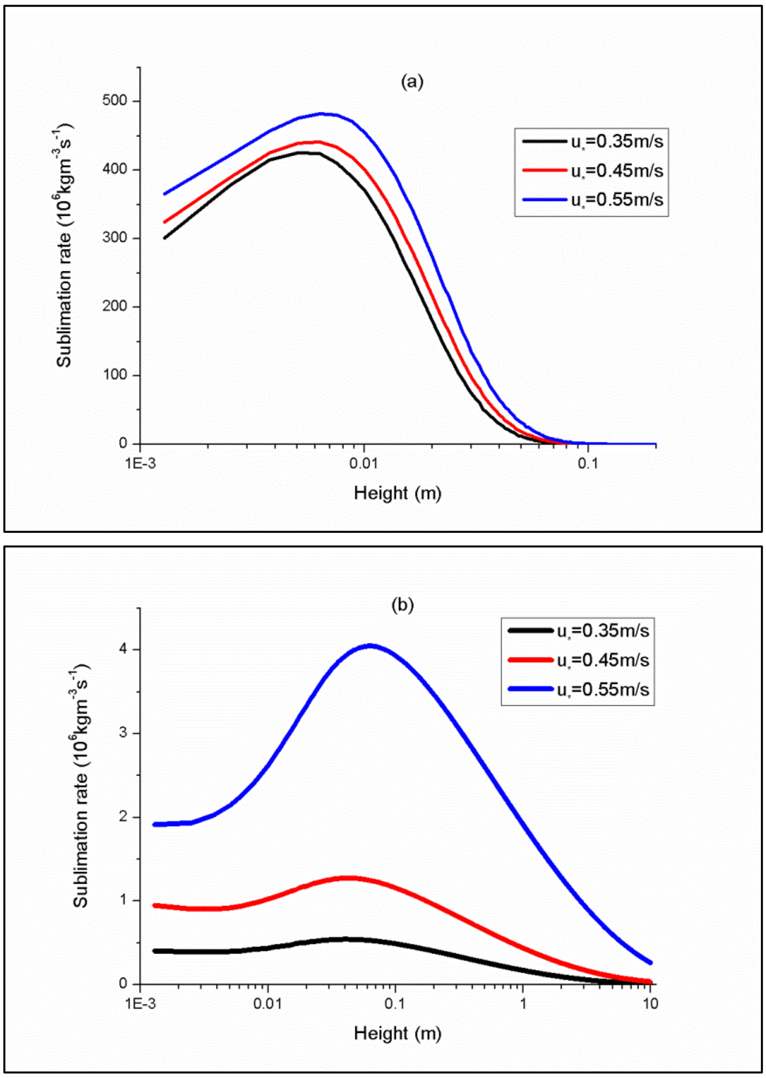

Figure 11: Vertical profiles of sublimation rate for saltation and suspension (a: ~~saltation~~ saltating particles; b: suspended particles)

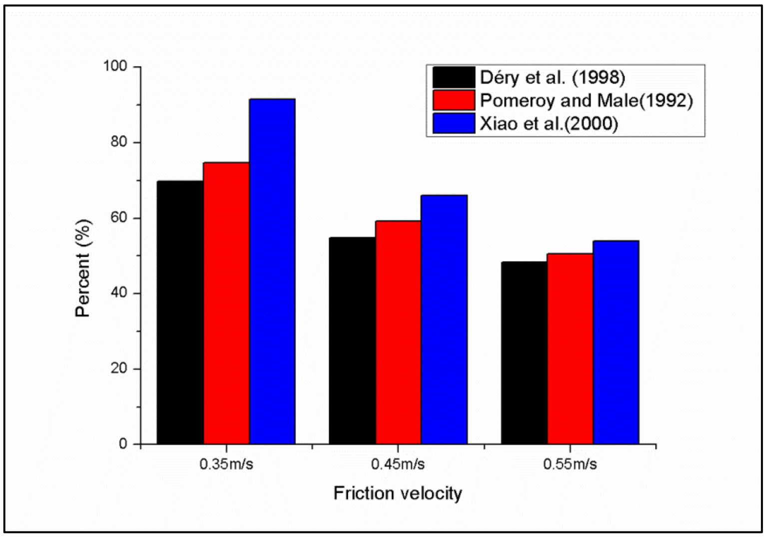

Figure 12: The ratio of sublimation mass below three heights to the total. Sublimation mass below a certain height is the sublimation mass that was ignored by other's models (Déry et al. 1998; Pomeroy and Male, 1992, and Xiao et al., 2000).

~~**(the sublimation mass below a height is the sublimation mass that was ignored by other's model , such as Déry et al. (1998), Pomeroy and Male (1992), and Xiao et al. (2000).)**~~

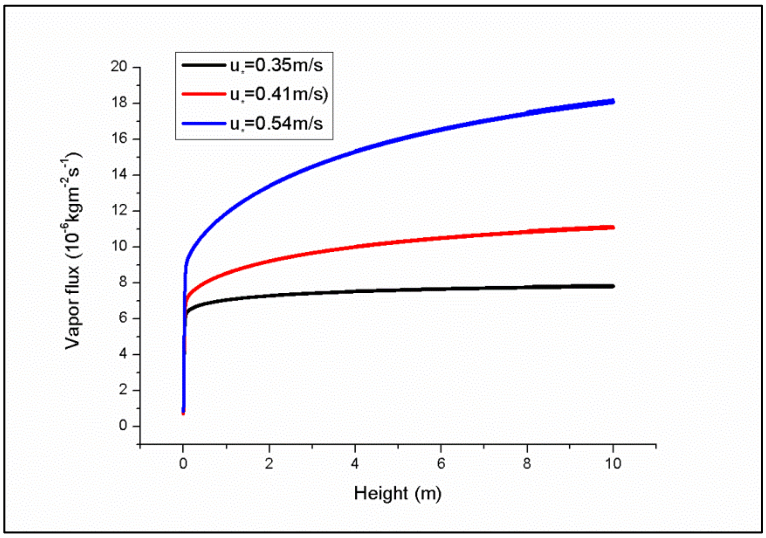

Figure 13: Vertical profiles of vapor flux