The Cryosphere Discuss., 9, C382–C396, 2015
www.the-cryosphere-discuss.net/9/C382/2015/

The Cryosphere
Discussions
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Interactive comment on "A 3-D simulation of drifting snow in the turbulent boundary layer" *by* N. Huang and Z. Wang

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Received and published: 10 April 2015

Authors' Responses to the Comments on the Manuscript "A 3-D simulation of drifting snow in the turbulent boundary layer" from reviewer 2

General Response:

According to the suggestions of the referees' comments, we have made a substantial revision to the original manuscript so that a clear description on the research is displayed in the revised version. We deeply appreciate the time and effort you have spent in reviewing our manuscript. The detailed responses to the comments of the referees are as follows:

General comments:

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Comments from Referees:

The paper is of great interest. It introduces a 3D model coupling effects between wind and snow particles. The coupled model is evaluated on a flat erodible snow surface under various wind conditions and is compared to wind tunnel experiments, the results of which are published in the literature. The model takes into account all involved physical processes and allows to better understand behaviors of particles in a boundary layer. The main criticism that can be made is that this paper takes a great inspiration from a paper recently published for drifting sand by Dupont, Bergametti, Marticorena and Simoëns (Modeling saltation intermittency published in Journal of geophysical research: Atmosphere, vol 118, 7109–7128, doi:10.1002/jgrd.50528, 2013). This paper is mentioned in the article, but it is not clearly explained that the presented model is only an adaptation of an existing model. The use of an existing model in itself is not a problem, but it must be mentioned and for example the authors have to avoid to speak about "their model" (p 311 line 13). ... The structure of the numerical model and the chosen hypothesis (for example, but it is not the only, the non inclusion of aerodynamic entrainment) are better explained in the original paper. I would therefore suggest that authors will rewrite the paper, refer to the original model and focus on their own contributions (which are very interesting) and present them in more details. The modifications of the existing model and the reasons of these modifications must be introduced and discussed. The choice of specific parameters for snow must be also better introduced and discussed. For example why choose the same parameters for the splash function initially developed for sand. .. Moreover the obtained results for sand and snow are very similar; this point must be further developed and also discussed in the light of the chosen hypothesis.

Author's response:

Thanks for the reviewer's careful reviewing of the manuscript and his useful suggestions. According to the comments from all the reviewers, a series of simulations with snow entrainment/rebound/splash functions and some completely different simulation conditions are performed. We have made some improvements and adaptations for drifting snow.

Author's changes in manuscript:

1. The aerodynamic entrainment (Clifton and Lehning, 2008; Groot et al., 2014) that used for drifting snow is included in the simulation, which is described in line 131-150 of the revised manuscript.

2. The revised rebound / splash formulations for drifting snow are introduced into the model and the choice of parameters are discussed in detail (Kok and Renno, 2009; Groot et al., 2014) and compared with other works in line 151-201 of the revised manuscript.

3. The simulation details, including computation domain, boundary conditions and other simulation details, are modified to a more reasonable case based on the comments from all the reviewers and present in line 203-244 of the revised manuscript.

Subsequently, the results were reanalyzed based on the reviewer's suggestions and the manuscript was rewritten in a clearer way. The expressions of "our model" have been avoided in the revised manuscript. The work of Dupont et al. (2013) has been introduced in line 68-71 of the revised manuscript as follow: 'In this paper, based on the model of Dupont et al. (2013) that developed for blown sand movement, the Advanced Regional Prediction System (ARPS, version 5.3.3), which is a middle-scale meteorological model, is applied in a small-scale for drifting snow and a series of adaptations are made for drifting snow simulation'.

In the results part, our results are compared with blown sand movement (Greeley et al., 1996; Dupont et al., 2013) and some discussions are made for the difference and similarity between blown sand movement and drifting snow.

Simulations details:

Comments from Referees:

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- It is written that the initial wind database is obtained from the experimental results of wind tunnel: which experiments are these? Did the authors perform their own experiments?

Author's response:

The reviewer is right. We performed some experiments in the wind tunnel of our lab (Multi-function environmental wind tunnel of Lanzhou University) to obtain the initialization data as well as to compare that with part of the simulation results (e.g. figure 3 and 6 in the revised manuscript).

Author's changes in manuscript:

We have add some descriptions in line 203-205 of the revised manuscript as follows: 'In this paper we have performed some wind tunnel experiments to obtain the initialization data for the simulation as well as to compare the simulated results with experiment results.'.

Comments from Referees:

- It is not clearly written that the boundary conditions are periodic also for particle motion in order to simulate an infinite erodible soil and to obtain a well developed saltation layer. It is probably true on the basis of the obtained results. But in this case, I did not understand why the cycle location is set up on meter upstream the particle layer. Thus we get successive bands with and without particles on the ground, which is not representative of a real case.

Author's response:

Thanks for the reviewer's useful suggestions. According to the suggestions of the reviewer, the simulation details, including computation domain, boundary conditions and instructions have completely revised.

Author's changes in manuscript:

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The detailed description of the simulation in line 203-227of the revised manuscript is as follows:

‘In this paper we have performed some wind tunnel experiments to obtain the initialization data for the simulation as well as to compare the simulated results with experiment results. The computational region is set as 16m*1.0m*1.5m and divided into two sections, as show in Figure 1. The first zone extending from x=0m to x=5m is used to develop a turbulent wind field and provide a steady turbulent boundary layer. In this simulation, the turbulent characteristics separating from our wind tunnel results are added on the initial logarithmic velocity profile at beginning and the inlet velocity of fluid will be equal to the wind velocity at the location of x=5m after 5 seconds, which realizes a long distance development of the turbulent boundary layer. The second zone is the blowing snow region from x=6m to x=16m, where a loose snow layer is set on the ground.

In this model, the grid has a uniform size of dx=dy=0.05m in the horizontal direction, and the average mesh size of dz=0.03m in the vertical direction. The grid is stretched by cubic function to acquire detailed information of the surface layer and the smallest grid is dzmin=0.002m.

The actual computation time is 30 seconds, in which the first 10s and the second 10s are respectively used for the development of turbulent boundary layer and the drifting snow, and the last 10s for data statistics. The dynamic Smagorinsky-Germano subgrid-scale (SGS) model is used in this simulation. For the flow field, we apply the rigid ground boundary condition at the bottom, the open radiation boundary in the top, the periodic boundary condition in the spanwise direction, the open radiation boundary condition at the end of the domain along the streamwise direction. The forced boundary is applied in the inflow as mentioned above. Additionally, the snow particles have circulatory motion in the lateral boundary and they will disappear when moving out of the outlet in the end of the domain.’

Comments from Referees:

- Figure 2: I suppose that the size distribution of snow particles is the particle size distribution at the ground (It is a an initial condition, isn't it ?). But the gamma distribution (Schmidt, 1980) is representative of particle size distribution in the boundary layer during drifting snow event. Similarly the particles trapped in the Faraday's cage (Omiya et al., 2011) were particle in the saltation layer. Gunn and Marshall (1958) first reported that size distributions on the ground were approximately exponential in form, such that ND=N0exp(-λD) where D is the melted diameter of a snow particle, ND dD is the number of snow particles with a melted diameter between D and D + dD in a unit volume of air, N0 is the intercept, and λ is the slope (see for example Harimaya T., Kodama H., Muramoto K., 2004, Regional differences in snowflake size distribution, Journal of the Meteorological Society, 82(3), 895-903). What are the values of α and β? What is the number 2617: is it the number of numerically resolved particles? What is the ratio between the real number of particles and the number of numerically resolved particles?

Author's response:

Thanks for the reviewer's careful reviewing of the manuscript. We are sorry for the confusing expression. Actually, every particle ejected or entrained from surface to the air will be given a random size from the size distribution by Schmidt (1984) and will be tracked separately.

Author's changes in manuscript:

The expression of this part has changed to:

'The size distribution of snow particles in the air in this paper is fitted to the experiment results obtained from field observations of SPC (Schmidt, 1984), that is equation (15) in the revised manuscript where alpha and beta are the shape and scale parameters of gamma-function distribution and we choose a value of 4.65 and 75.27, respectively. Every new ejection or entrainment particle will be given a random size from above distribution and will be tracked separately. A large amount of snow particles in the air are stochastic collected during drifting snow and the size distribution is presented in Figure 2. Every particle ejected or entrained from surface to the air will be given a random size from above distribution and will be tracked separately. The size of snow particles in the air are stochastically collected and the size distribution is presented in Figure 2.The mean diameter is dp=350 micrometer. The results are in consistence with those observational results of the natural snow (Omiya et al., 2011).' in the line 228-237 of revised manuscript.

Comments from Referees:

- What is the sensitivity of the numerical model to temperature and humidity? Which model parameters are affected? Indeed, experiments carried out in cold wind tunnel were performed at different temperatures.

Author's response:

Thanks the reviewer for his attention to detail in reviewing this manuscript. The temperature and humidity are just used for the initialization of the flow field (Xue et al., 2000). The effects of temperature and humidity on snow particles (e.g. sublimation and viscous force) are not included at this stage.

Author's changes in manuscript:

The sentence 'The processes of snow blowing with the wind velocity of Ue=5∼10 m/s are performed at environmental temperature of -10 degree centigrade and initial relative humidity of 90%.' has changed to 'The processes of snow blowing with the friction wind velocity of u*=0.179∼0.428 m/s are performed with the environmental temperature of -10 degree centigrade and initial relative humidity of 90%. And we found the lower bound of friction velocity for a drifting snow is approximately 0.18 m/s for this situation.' in line 241-244 in the revised manuscript.

Results and discussion:

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Comments from Referees:

- The source of the experimental data must be clearly quoted in the references. I suppose that the data introduced in Figure 7 and 9 come from : T. Okaze, A. Mochida, Y. Tominaga, M. Nemoto, T. Sato, Y. Sasaki, K. Ichinohe, Wind tunnel investigation of drifting snow development in a boundary layer Journal of Wind Engineering and Industrial Aerodynamics, Volumes 104–106, May–July 2012, Pages 532–539. Sugiura, K., Nishimura, K., Maeno, N., Kimura, T., Measurements of snow mass flux and transport rate at different particle diameters in drifting snow, Cold Regions Science and Technology, Volume 27, Issue 2, April 1998, Pages 83-89 Y. Tominaga, T. Okaze, A. Mochida, Y. Sasaki, M. Nemoto, T. Sato, PIV measurements of saltating snow particle velocity in a boundary layer developed in a wind tunnel? Journal of Visualization, May 2013, Volume 16, Issue 2, pp 95-98. The date of publication of the previous article is 2013 instead of 2012 as written on the figure.

Author's response:

Thanks for the reviewer's careful reviewing of the manuscript. The sources of the experimental results have been listed in the references and the corresponding figure has been modified in the revised manuscript.

Comments from Referees:

- What are the references of the papers of Lv (2012) and Sedmit (1984) cited in Figure 4. It is impossible to have a general picture of the relevance and quality of conclusions without having access to data and experimental conditions.

Author's response:

Thanks for the reviewer's careful reviewing of the manuscript. We are sorry for the confusing expression. According to the reviewer, this figure has been modified in the revised manuscript. The simulation conditions are consistent with the actual situation of the wind tunnel experiments.

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Author's changes in manuscript:

The figure has changed in the revised manuscript. Additionally, the observation results of Sedmit (1984) have removed the Figure 4.

Comments from Referees:

- As previously said there is a lot of similarity between results presented in Dupont et al. and in this paper. For example, we can compare Figures 3 and 6 in this paper and Figure 9 in Dupont et al. Some conclusions are also very close. "for μ 1< 100 μ m, the gravity force becomes much lower than the drag force, and so, particles start to be transported higher by turbulence structures of the flow, reaching the limit between saltation and suspension motions (Dupont et al. 2013)" should be compared with "It can be seen that turbulence can significantly affect the trajectory of snow particles with diameter smaller than 100 μ m (this paper)"..."The high sand concentration patterns correlate mostly with the high wind speed patter ns . . .the correlation between sand concentration and the wind velocity field is hardly visible motions (Dupont et al. 2013)" should be compared with " By comparing the concentration and corresponding cloud map, it can be found that the particle concentration shows a direct proportional relationship with the local wind velocity (this paper))". . .. Throughout the analysis, similarities and differences must be set out and analysed.

Author's response:

Thanks for the reviewer's useful suggestions. Following the reviewer's suggestion, the comparisons between snow and sand results (Dupont et al. 2013) are made in the revised manuscript.

Author's changes in manuscript:

The sentences 'It can be seen that turbulence can significantly affect the trajectories of snow particles with diameter smaller than 100 μm, and may drive snow particles with diameter of 100 μm moving 5$\sim$6 m during one saltation process. By contrast,

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the trajectories of larger snow particles are less affected by the turbulent fluctuation, showing only slight influence on the saltation height, saltation distance and landing position of snow particles.' have changed to 'It can be seen from figure 9 that turbulence can significantly affect the trajectories of snow particles with diameter smaller than 100 μm, and may drive these snow particles moving up to 5$\sim$6 m during one saltation process. By contrast, the trajectories of larger snow particles are less affected by the turbulent fluctuation. These results are consistent with that of the sand saltation in the turbulent boundary layer performed by Dupont et al. (2013). On the other hand, we can be seen from figure 10 that the wind velocity is significantly decreased in the drifting snow region due to the reaction force of the snow particles, while the TKEs are obviously enhanced during snow drifting. This result is attributed to the fact that velocity gradient is obviously changed when the drifting snow formed (Okaze et al., 2012).' in the line 324-333 of revised manuscript.

The explanation 'By comparing the concentration and corresponding velocity cloud map, it can be found that the particle concentration shows a direct proportional relationship with the local wind velocity, that is, only few snow particles present in the low-speed streaks.' has change to 'By comparing the concentration and corresponding velocity cloud map, it is hard to decide the relationship between particle concentration and local wind velocity, which is just like the sand streamers reported by Dupont et al. (2013). This may be due to the complex motion of the snow particles and hysteretic change of local wind. However, the shapes of snow streamers are quite different from that of sand streamers. For example, the snow streamers trend to be longer and thinner in the turbulent boundary layer.' in the line 348-355 of the revised manuscript.

Comments from Referees:

- Figure 7 / In the experiments of Okaze, three different velocities have been tested: 5m/s, 7 m/s and 9 m/s. It corresponds roughly to u*=0,22 m/s, 0,37 m/s and 0,55 m/s (see figure 9 in the paper). I cannot recognize these measurement points in figure 7 b. The transport rate of drifting snow in the saltation layer is calculated by integrating over

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the vertical mass flux profile of the drifting snow within saltation layer. The integration range was from 0 to 0.03 or 0.05 m in the case of Okaze et al.. But which height did you chose? And what about Sugiura? To compare between themselves the results, heights of integration must be the same.

Author's response:

Thanks for the reviewer's carefully reviewing of the manuscript. The experiment result of Okaze in figure 9 has been replaced by a set of more suitable data (see figure 4 and its instructions in the revised manuscript). And the integration range of our simulation can be adjusted (16 to 61mm for Sugiura) to consistent with the experiment set in the revised results.

Author's changes in manuscript:

The experiment results of Okaze et al. (2012) have replaced by the model results of Nemoto and Nishimura (2004).

Comments from Referees:

- Figure 9 / Others recent data are available in the literature (u*=0,37 m/s in Nishimura et al., 2014, Snow particle speeds in drifting snow, J. Geophys. Res. Atmos., 119, doi:10.1002/2014JD021686.

Author's response:

Following the reviewer's suggestion. The new experiment results in the literature are adopted and compared with the simulation results in the revised manuscript.

Author's changes in manuscript:

The experiment data of Nishimura et al. (2014) is included in the figure 6(a) in the revised manuscript.

Comments from Referees:

- Figure 12 / Experiment by Gromke: In this paper it is also written that Nishimura and others (1998) and Sugiura and others (1998), both using a SPC (Sato and others, 1993), report an increase in the share of small particles over height within the saltation layer. The data of Sugiura and others (1998) show a less pronounced increase in the share of small particles at lower heights for larger free stream and friction velocities . . .their results imply a decrease of the mean snow particle diameter with height, whereas our results indicate a fairly constant mean particle diameter with only a slight tendency to decrease with height. This may be due to the resolution of the CMOS chip (0.05mm) in combination with the image processing and evaluation which does not allow resolution of the smallest particle sizes in such detail as the SPC, and to the different snow particle characteristics in the experiments" Do you have any comments on it ?

Author's response:

Thanks the reviewer for his attention to detail in reviewing this manuscript. The drifting snow processes have been recomputed with new computation domain and boundary conditions as well as modified bed surface process. This result has been reanalyzed and compared with experiment results. The difference between simulation and experiment was reconsidered as well.

Author's changes in manuscript:

The changes can be seen in figure 7 and its explanations in line 297-307 of revised manuscript as:

'Finally, figure 7 shows the mean size of snow particles along height in the air at different friction velocities and compared with the experimental result of Gromke et al. (2014). All the data have been normalized to the average diameter of overall snow particles. It is clearly that the mean diameter of snow particles in the saltation layer slightly decreases with the height increasing, which is also consistent with the observation of previous works (Nishimura and Nemoto, 2005). However, it appears that the mean diameter increase with increasing height above the saltation layer. The main reason may be that the small particle trends to carry smaller inject velocity, while the larger particle is just the opposite due to the stronger inertia. The rebound velocity is proportional to the incident velocity and thus larger snow particle will rebound with a bigger initial velocity.'

Comments from Referees:

- p 312 line 4 : How is estimated the length λ x and λ y (from time average spatial autocorrelation of Cp?)

Author's response:

Thanks. Here, we are aimed at giving the quantitative macroscopic statistical of the snow streamers and the method that used to estimate the length λ x and λ y is as follows:

The grid with concentration large than 0.5*Cmax (where Cmax is the maximum of concentration in the domain) will be count and a cloud map of snow streamers will be made. Based on these cloud maps at different time, we can obtain the approximately snow streamer shapes through an average statistics.

Comments from Referees:

- p 312 line 27 : "It can be seen that the STR increases rapidly and reaches a dynamic equilibrium state in a short time". It is probably due to the choice of the splash function parameters (equations 8 and 11) which were not determined for snow particles (Kok and Renno, 2009), (Anderson and Haff (1991]. In the study of OKaze et al., 2012, the saltation layer nearly attained equilibrium in the downstream region from x=9 m to x=11,5 m. Okaze also remind that Takeuchi (1980) and Tabler (2003) indicated that the total transport rate of drifting snow, suspension, reached equilibrium around several hundred meters.

Author's response:

Following the reviewer's suggestion. A new simulation study was performed with new computation domain and boundary conditions described in the simulation details. The grain-bed interactions are also reconsidered and compared with other drifting snow studies. The results are rearranged and reanalyzed in the revised manuscript.

Author's changes in manuscript:

The sentence 'It can be seen that the STR increases rapidly and reaches a dynamic equilibrium state in a short time' has changed to 'It can be seen that the STR per width increases along with the streamwise and gradually reaches a steady state, which is basically consistent with the observation in the wind tunnel by Okaze et al. (2012). And it appears that the distance needed to reach the state is increase with the increasing of friction wind speed.' in line 250-256 of the revised manuscript.

References :

Comments from Referees:

- Some references must be added in order to illustrate the influence of drifting snow on mass balance of the Antarctic ice sheets. One proposal: Gallee et al., 2012 DOI: 10.1007/s10546-012-9764-z) but other references can be proposed by the authors. - The reference (Michaux et al., 2012) is written in French. It is not easily accessible and this reference can be replaced by another one written in english Michaux et al., 2001, Drifting-snow studies over an instrumented mountainous site: II. Measurements and numerical model at small scale, Annals of Glaciology. - All papers introducing experimental data, which are used to evaluate the numerical model, must be cited.

Author's response:

Following the reviewer's suggestion. These references have been added in the revised manuscript or replaced by others that are easily accessible.

Author's changes in manuscript:

The reference Gallee et al. (2012) has added in line 32 of the revised manuscript.

The reference (Michaux et al., 2012) is replaced by (Michaux et al., 2001).

All the used papers are cited in the reference.

Reference:

Nishimura, K., and Nemoto, M.: Blowing snow at Mizuho station, Antarctica, Phil. Trans. R. Soc. A, 2005, 363, doi: 10.1098/rsta.2005.1599, 2005.

Okaze, T., Mochida, A., Tominaga, Y., Nemoto, M., Sato, T., Sasaki, Y., and Ichinohe, K.: Wind tunnel investigation of drifting snow development in a boundary layer, J. Wind Eng. Ind. Aerodyn., 104(106), 532-539, 2012.

Xue, M., Droegemeier, K. K., and Wong, V.: The advanced regional prediction system (ARPS)-A multiscale nonhydrostatic atmospheric simulation and prediction model. Part I: model dynamics and verification, Meteorol. Atmos. Phys., 75, 161-193, 2000.

Please also note the supplement to this comment:
http://www.the-cryosphere-discuss.net/9/C382/2015/tcd-9-C382-2015-supplement.pdf

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Interactive comment on The Cryosphere Discuss., 9, 301, 2015.