We thank both reviewers for their thorough reading of our paper and for the proposed corrections. We deeply considered their remarks on the English quality and agree that our paper may present a more advanced sensitivity test.

If the Editor allows us to submit a new version of this paper, we propose:

1. to more accurately evaluate the model behavior, particularly by adding a new section dedicated to the model sensitivity to the roughness length,
2. to improve the English language by having recourse to a native English speaker before re-submission,
3. to standardize the paper by including the suggestions made by the reviewers and the new analyzes proposed in the following review.

The following paragraph has been added in the conclusion, and is reported here to provide an insight of our approach in the new version of the paper.

The original calibration of z_0 (Gallée et al. 2013) gives satisfactory results for modeled wind speed at D17. This good behavior is not maintained when considering another measurement point located 100 km away (D47). A modification of z_0 considerably improves the simulation at D47, but reduces the agreement between modeled and observed wind speed at D17. This suggests that z_0 might be varying regionally, and implies that the model may account for a spatial distribution of z_0 (because of various feedbacks between aeolian transport of snow and z_0) to allow a consistent representation of the aeolian snow mass fluxes.

All those modifications, mainly related to the model, will induce a change in the authors list with Charles Amory will be the first author. He has greatly contributed to the review and has made new simulations of the MAR to evaluate the roughness length. Alexandre Trouvilliez will be second author.

Our responses are reported hereafter.

Response to reviewer #1

Summary: In this paper, the authors describe a set of simulations performed with the MAR regional climate model for the month of January 2011 over parts of Antarctica. The model is run at high spatial and temporal scales and is validated using observations of meteorological conditions and blowing snow particles at three automatic weather stations in Adélie Land. It is shown that the model generally captures the observed meteorological conditions but underestimates by about a factor of 10 the blowing snow transport rates. The authors end their paper by providing insights on the possible causes for the underestimated snow transport fluxes, including lower wind speeds simulated by MAR when observations are above 10 m s^{-1}.

There are results in this manuscript that will be of interest to the readership of the journal and contribute to the growing body of work on snow transport processes and their simulation. There are some aspects of the comparisons between simulated and observed conditions that are unclear. The language also needs some improvement as described in my report below:

General Comments:

1) Some of the language used in the paper needs improvement. Some language issues are highlighted in the specific comments below. This remark has been taken into account in the

manuscript and the new version of the paper will be corrected by a native English speaker before submission.

2) Although the MAR regional climate model simulations are run at relatively high horizontal resolution (5 km), it is unclear how the simulation data are compared with the in situ point data. Are the simulation data extracted simply from the nearest grid point to the automatic weather stations, or is spatial interpolation performed to do the comparisons? Are there large spatial variations in the model output near the observational sites? We propose to add the following sentence: "Simulation data are extracted from the nearest grid point from the considered automatic weather and snow stations".

The model outputs have been examined at two different sites (i.e., D17 and D47), showing that the MAR model presents accurate results for both locations, which are more than 100 km away from each other. This distance represents roughly 20 grid points in our MAR simulations. In addition, we propose a further evaluation of temperature in Figure 1 for both observation sites. The temperature is not a consistent validation support since Gallée et al. (2013) showed that the model is likely to overestimate the amplitude of the diurnal cycle due to an underestimation of cloud fraction above the study site leading to incorrect downward longwave radiation flux. Moreover, no radiation data are available at both stations, which impedes the evaluation of the corresponding modeled variables. Nevertheless, statistical efficiencies for temperature at both locations are positive (0.05 and 0.48 for D17 and D57, respectively).
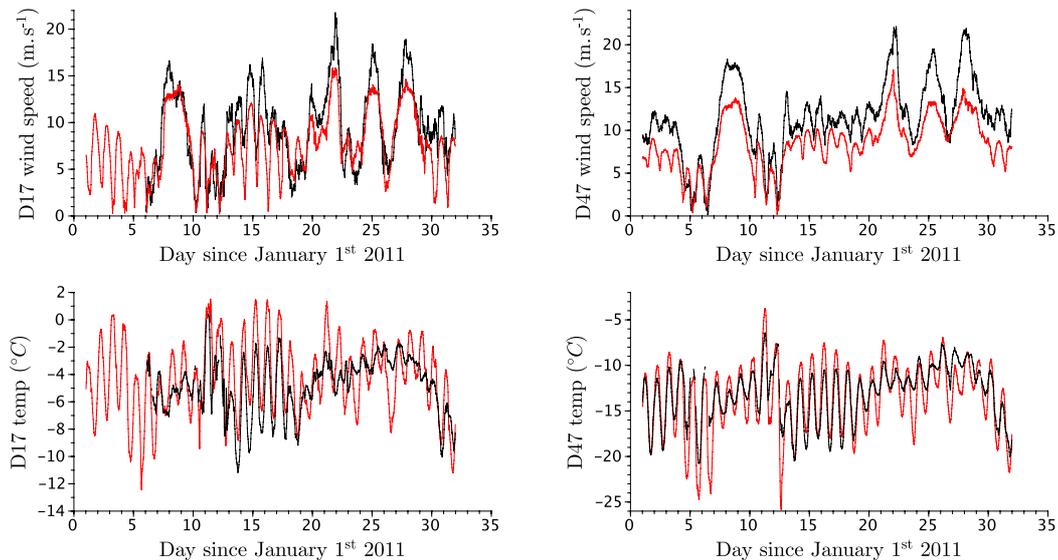

Figure 1. Comparison between simulated and observed temperature at 2 m height for D17 and D47 stations.

3) Is there any advection of the blowing snow from one horizontal grid cell to the next one downwind? If so, how is the advection treated by MAR? We propose to include the following sentence in the text: "Eroded snow particles from the ground are drifted into the atmosphere, and the airborne snow particles are advected from one horizontal grid cell to the next one downwind. More generally airborne snow particles are modeled according to the cloud microphysical scheme described by Gallée (1995)."

4) It is surprising that no spatial plots of blowing snow fluxes over the entire simulation domain (see Figure 1) are presented in the paper. It would be interesting to visualize how the blowing snow transport and sublimation fluxes vary across the simulation domain during the study period, rather than just time series at individual sites. Can the model simulations also be used to identify recurrent zones of snow erosion or deposition? Recurrent zones of erosion and deposition depend on flow convergence or divergence, and on gravity waves of various wavelengths relative to the generating process. The magnitude of transport fluxes does not

influence strongly the snow accumulation distribution. However, modeled accumulation is very sensitive to spatial snow transport variations, which reflect converging or diverging fluxes. This is clearly visible on an accumulation map (Figure 2) over the simulation domain for January 2011. Here, accumulation is computed as deposition minus erosion, and includes divergence of blowing snow fluxes. Please note that the uncertainty resulting from an incorrect representation of the snowdrift process itself is much larger than the one resulting from the absence of data interpolation. As already suggested in our paper, this uncertainty suggests that the model still requires improvements, and further validation based on new observation datasets (see our response to comments n°2a and 2e of reviewer #2). Therefore, the spatial distribution of modeled accumulation should be considered with caution if the magnitude of fluxes is not checked previously using field data. In this context, analyzing spatial plots of blowing snow and/or sublimation fluxes might be premature.
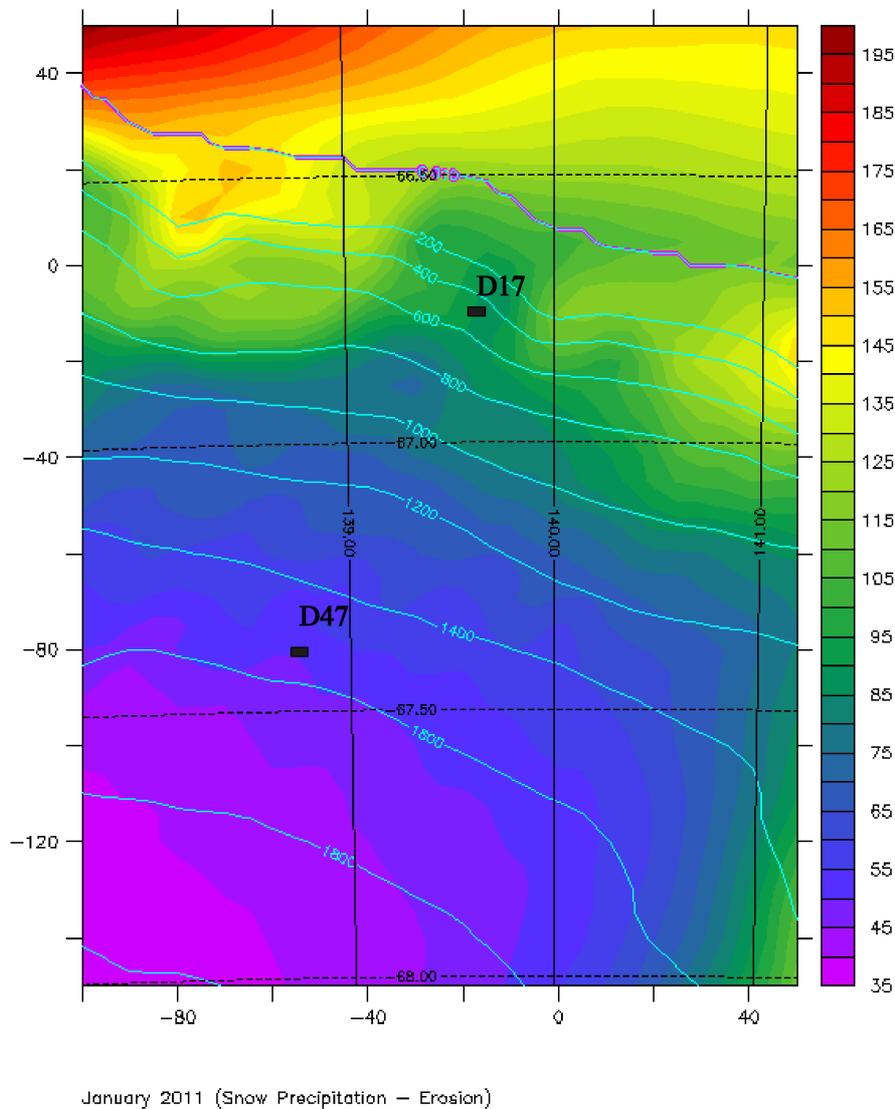

January 2011 (Snow Precipitation — Erosion)

Figure 2. Accumulation map (deposition minus erosion) for January 2011 over a portion of the simulated domain including the two observational sites. X and Y axis are in kilometers, altitude lines are in meters. The vertical colorbar on the right represents the accumulation in mm.w.e.

5) Have any sensitivity tests been conducted with the MAR regional climate model to clearly identify the reason(s) why it simulates less blowing snow transport than observed? The calibration of the MAR model in this paper is the same as the one presented in Gallée et al. (2013). Several sensitivity tests have been performed to assess the impact of surface roughness length variation on final drifting snow flux. We propose to include a new additional section in the paper to present our results. This new section is described hereafter:

4.4 Model sensitivity to roughness length for momentum

MAR significantly underestimates aeolian snow transport, particularly for small drifting snow events when wind-borne particles are only detected in the first meter above the ground. The model also fails at reproducing the large snow mass fluxes (>100 $g.m^{-2}.s^{-1}$) associated with strong wind events (>13 $m.s^{-1}$). Previous evaluation of the MAR in Adélie Land (Gallée et al. 2013) provided similar conclusions for the same model set-up. In the model, z_0 partly depends on the wind speed, whose vertical evolution is in turn controlled by z_0. In Gallée et al (2013), z_0 was calibrated to correctly reproduce the wind minima measured at D17. This configuration was used again in the present work without performing any adjustment, and results in a median z_0 value of about 3 mm at D47 over our period of interest. Although somewhat higher, it is consistent with other millimetric z_0 values retained for realistic simulations of the Antarctic surface wind field (Reijmer 2005, Lenaerts et al. 2012). However, the model exhibits a different behavior for wind speed according to the location (Fig. 3): at D17, the MAR underestimates wind speed maxima, but correctly reproduces observation when wind speed is weaker. The situation is different at D47, where an almost constant underestimation of about 2 $m.s^{-1}$ is observed. A single calibration of z_0 does not allow a consistent representation of the wind speed at both locations.

When the wind speed is stronger, higher snow mass fluxes should inherently be observed, leading to larger relative humidity in the lowest levels as a consequence of the sublimation of additional wind-borne snow particles. Since wind speed is the most relevant forcing for snow erosion (Gallée et al. 2013), we performed a sensitivity test that first aimed at increasing the wind speed towards a better agreement between observations and simulations. We have tuned the model by reducing the z_0 dependence on the wind speed value, which results in a decrease of the modeled z_0. The model evaluation for various median z_0 values is summarized in Table 2. Best results were obtained for a reduction of z_0 by a factor 30 (*i.e.*, a median z_0 value of about 0.1 mm) over the simulated period at D47. Corresponding statistical efficiency for wind speed reaches 0.89, while efficiencies for snow mass flux and relative humidity are both positive. This means that the simulation is significantly improved at D47 if a decrease of one order of magnitude of z_0 is accounted for. The resulting local snow transport is still underestimated but by about one third of the observed one only.

Calibrated z_0 (median value, mm)	Wind Speed	Snow Mass Flux	Relative Humidity
3	0.37	-0.06	-4.77
0.5	0.8	0.2	-0.14
0.2	0.86	0.26	-0.01
0.1	0.89	0.32	0.16

Table 2. Comparison of Nash tests for wind speed, blowing snow flux and relative humidity for D47 at 2 m height relative to various median values of z_0.

Specific Comments:

1) P. 6008, line 4: Write as "one month". Corrected accordingly

2) P. 6008, lines 17-19: The sentence starting with "It will conduct" is incomplete and needs to be revised. The sentence is the same written P. 6020 line. both sentences were corrected: "Our results indicate that the MAR, with this parameterization, will underestimate the effect of the aeolian snow transport on the Antarctic surface mass balance."

3) P. 6009, line 24: Write as "rarer (Lenaerts et al., 2012b) and could" Changed accordingly

4) P. 6010, line 1: Revise to "simulations". Changed accordingly

5) P. 6010, line 3: Write as "one month". Changed accordingly

6) P. 6010, line 10: Perhaps add "instruments" after "FlowCapt"? Changed according to the remark. The word instrument has also been added after "first-generation FlowCapt" P. 6010, line 7.

7) P. 6010, line 22: Replace "described" with "monitored". Changed according to the remark

8) P. 6010, line 24: Should this be "100 km h-1"? The maximum wind speed occurs geographically at the break in slope observed between the plateau and the coast. In Adélie Land, this break is located approximately 250 km inland from the coast. The sentence has been changed for: "The coastal region is characterized by frequent and strong katabatic winds with a maximum wind speed near the break in slope located approximately 250 km inland […]".

9) P. 6012, lines 11 and 14: What is a "classic automatic weather station"? The term classic has been removed. We now describe measurements performed at the AWS: P. 6011 lines 13 to 17: "Automatic weather stations (AWS) measuring wind speed, wind direction, temperature, relative humidity and snow height every 10 s were installed at three different locations along a transect extending from the coastline to 100 km inland (Trouvilliez et al. 2014). […] The combination of an automatic weather station with FlowCapt™ sensors is hereinafter referred to as automatic weather and snow station (AWSS)."

10) P. 6015, line 10: Write as "one month". Changed according to the remark

11) P. 6015, line 11: Write "snowpack" as one word. Idem

12) P. 6016, line 3: Insert "a" before "1-D". Idem

13) P. 6017, line 22: It should read "events". Idem

14) P. 6019, line 19: Rather than "strong" perhaps refer to as "heavy simulated precipitation"? Idem

15) P. 6019, line 22: Change to "speeds". Idem

16) P. 6020, line 2: Write "snowpack" as one word. Idem

17) P. 6020, line 4: Write as "one month". Idem

18) P. 6020, line 14: Delete "And" at the start of the sentence. Idem

19) P. 6020, line 20: Replace "conduct" with "lead". Idem

20) P. 6020, line 28: Write as "Sørensen (1991)". Idem

21) P. 6021, line 1: Here write as "the Sørensen (1991) formulation. Idem

22) P. 6021, line 9: Write as "the Kotlyakov (1961) formulation". Idem

23) P. 6022, line 21: Insert the article number for this reference ("4679"). Idem

24) P. 6022, line 22: Note the spelling mistake in "Equilibrium". Idem

25) P. 6024, line 1: Insert the article number for this reference ("L04501"). Idem

26) P. 6024, line 25: Note the spelling mistake in "forecasting". Idem

27) P. 6024, line 32: Insert the article for this reference ("D16123"). Idem

28) P. 6025, line 24: Note the spelling mistake in "Dordrecht". Idem

29) P. 6026, Table 1: Replace "Localisation" with "Location". Furthermore, degree symbols are missing for the coordinates. Suggestions have been considered and included into Table 1:

Table 1. Location and characteristics of the two automatic weather and snow stations used in the study

	D17	D47
Location	66.7°S, 139.9°E	67.4°S, 138.7°E
Altitude (m)	450	1560
Distance from the coast (km)	10	110
Period of observation	Since February 2010	January 2010 to December 2012
Atmospheric measurements	Wind speed, temperature and hygrometry at 6 levels	Wind speed, temperature and hygrometry at 2 m
Aeolian transport measurements	Second generation FlowCapt™ from 0 to 1 m	Second generation FlowCapt™ from 0 to 1 m and 1 to 2 m

Response to reviewer #2

This paper compares observed blowing snow transport rates with output from a regional climate model for a site in East Antarctica. The authors find a reasonable agreement between model and observations for wind speed, but the model underestimates observed drifting snow fluxes.

Although the subject suits well for The Cryosphere, and the paper is potentially interesting for the glaciological community, I am afraid that it is, in its current state, not suited for publication. The paper contains really little new information (compared to e.g. Gallée et al., 2013 or Trouvilliez et al., 2014), discusses a really short time series (whereas, according to the authors, three years of observations are available), does not discuss model sensitivity to several parameters, and the use of English language is really poor. Therefore, I strongly recommend declining publication in the The Cryosphere. We claim our paper is a great improvement in comparison with our previous papers (Gallée et al., 2013 and Trouvilliez et al., 2014). In Trouvilliez et al. (2014) we were focusing on the description of automatic weather stations designed to survey drifting snow mass fluxes, whereas Gallée et al. (2013) was dedicated to verify that the MAR was able to reproduce drifting snow occurrences.

In more details, in Gallée et al. (2013) the model outputs were compared with measurements performed at only one location (D3), while in the present work, datasets from two observation sites (D17 and D47) located 100 km away from each other are used to evaluate the model. Furthermore, Gallée et al. (2013) only focus on the timing and duration of aeolian snow transport events. In our paper, we propose a quantitative evaluation of the aeolian erosion process at one location (D47) by comparing observed and modeled aeolian snow mass fluxes and relative humidities. We also investigate the influence of the wind speed underestimation on the modeled aeolian snow mass fluxes by comparing observations and simulations for four strong events during January 2011 at D47.

In addition, we propose to study the model behavior in terms of friction velocity and threshold friction velocity (see our response to next comment) at D17 where these variables can be determined experimentally. Although it is restricted to a short period without simultaneous precipitations, such an analyze is not conducted in Gallée et al. (2013). Finally, we propose to add a new section dedicated to the model sensitivity to the roughness length for momentum (see our response to comment n°5 of reviewer#1), showing that the simulation can be significantly improved by use of a different median value of z_0. This suggests that 1) z_0 might be varying

regionally because of various feedbacks between aeolian transport of snow and z_0, and 2) distributed modeling should account for a spatial distribution of z_0 to allow a consistent representation of the aeolian snow mass fluxes.

I have several suggestions for improvement if the authors would like to resubmit the manuscript.

(1) the manuscript needs thorough (!) revision of language. The manuscript contains many language errors and vague statements. A shortlist of language comments is found below, but this list is certainly not complete. I am astonished that with such a large group of well-respected authors, the quality of the text is so poor. The new version of the paper has been red by a native English speaker to meet with the Cryosphere standards.

(2) the analysis needs to be strongly enhanced:

(a) The time series need to be extended, as –apparently- there are much more data available. The model needs to be evaluated in more detail, e.g. surface pressure, temperature, SMB, etc. More stations could/should be used in the evaluation…. In the first version of the paper, the comparison between model and field data was made on:

- wind speed and blowing snow occurrence data recorded at 2 m above the surface, at two geographical location (i.e. at the automatic weather and snow station located at D17 and D47),

- friction velocity at D17,

- snow mass fluxes from 0 to 2 m and relative humidity at D47.

We propose to include a new comparison between simulated and observed threshold friction velocity as shown in the following Figure 4. In this updated figure we show that the MAR gives overestimated threshold friction velocity values for the period over which friction velocities have been evaluated, leading to the absence of drifting snow in the model during this period:
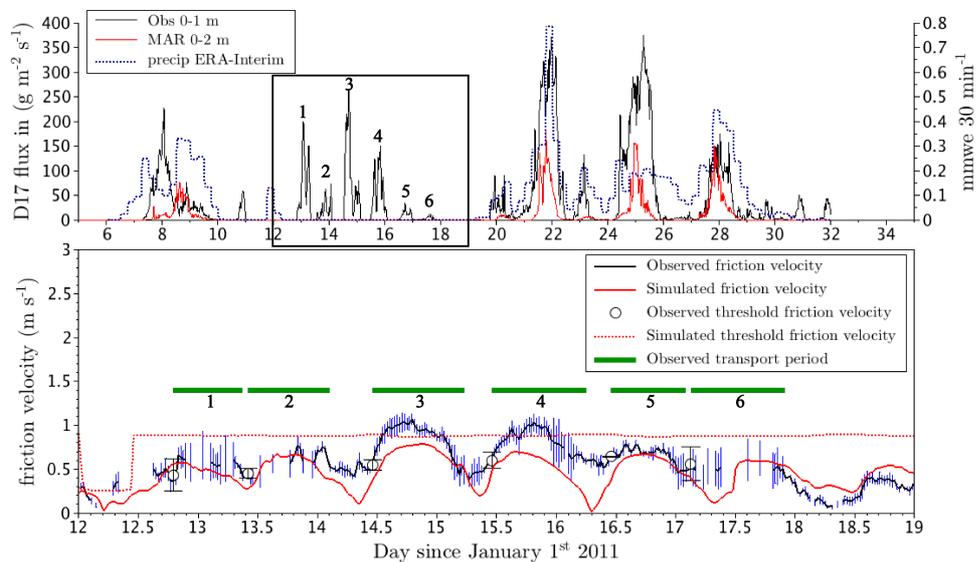

Figure 4. Top panel: Comparison between observed aeolian snow mass fluxes from 0 to 1 m (black), simulated ones from 0 to 2 m (red) and precipitation from ERA-interim at D17. The black rectangle delimits the period without precipitation analyzed in the bottom panel. Bottom panel: Comparison of observed/simulated friction velocity (black line/red line, respectively) and observed/simulated threshold friction velocity (dashed line/black dots, respectively) at D17 for a transport period without simultaneous precipitation. The vertical blue bars represent the 95% confidence limit of the observed friction velocity. The horizontal green bars represent observed aeolian snow transport events numbered from 1 to 6.

Temperature evaluation was initially not included to keep the paper brief and concise. It is now proposed in Figure 1 as presented in our response to reviewer#1 (see general comment n°2). The evaluated fields are now nearly the same as those used in an evaluation of the RACMO 2.3 model done in Greenland at one observation site (Lenaerts et al., 2014): temperature at 2 m, wind speed at 10 m, relative humidity at 2 m, horizontal snow flux at 1 m, friction velocity, threshold friction velocity and frequency of particle diameter. There still subsist small differences in data used for validation because sensors installed at the AWS are different in our study and in Lenaerts et al., (2014). In Greenland, a SPC was installed during the field campaign, allowing to monitor the flux at one height, and to give the particle size distribution. This second variable is not available with the FlowCapt™ instrument.

We believe that the study period is too short (only one month) to offer a robust distribution of accumulation. In other words, the distribution of modeled SMB over the simulation domain may be significantly different from annual SMB distribution. This is an important limitation because stake networks in the area are surveyed only once a year and do not give access to monthly SMB values. Moreover, field SMB data in Adélie Land reflect a strong influence of gravity waves on accumulation/ablation patterns (Agosta et al. 2012, Verfaillie et al. 2012) that cannot be efficiently represented by the model considering both the horizontal resolution and the size of the integrative domain adopted in our simulation. Finally, the use of ultrasonic gauge data may be proposed to roughly estimate the monthly SMB at the AWS sites, but this sensor is extremely sensitive to erosion/building of sastrugi in the immediate vicinity of the sampled surface area and data may not offer a robust information for a validation of aeolian snow mass fluxes. As a consequence, we believe that using SMB values for model validation was complex here.

Conversely, our validation step performed at more than one AWS is sufficiently robust to demonstrate our main conclusions (i.e., a distributed modeling should account for a spatial distribution of z_0 to allow a consistent representation of the aeolian snow mass fluxes). Data from D3 AWS were not included here, because we focused on aeolian snow mass fluxes, and this data is not accurate there because the FlowCapt™ sensors at this station are of the first generation design, which strongly overestimates aeolian snow mass fluxes (Trouvilliez et al. 2014) and then does not allow a relevant evaluation of simulated fluxes.

(b) The explanation of the underestimation of wind speed is extremely poor. It is not clear why the authors do not try to improve the model instead of just remarking its deficiency. Here, we deliberately used the same calibration as in previous publication by Gallée et al. (2013) because we wanted to keep consistency between both publications. In this calibration, the calibrated variable was the roughness length, and its value was tuned to correctly reproduce the observed wind speed 30 min-means minima at the D17 station. We propose to mention the role of this calibration in the underestimation of the wind speed, and to add a new section in the text to describe a sensitivity test that we performed on the roughness length values (see our response to comment n°5 of reviewer#1).

(c) The bias of relative humidity is large, but this is barely discussed in the paper. Conversely, relative humidity could/should be also used as a parameter to tune the blowing snow model and improve the modeled blowing snow! The bias on the relative humidity is caused by underestimation of aeolian snow transport and resulting sublimation of snow particles in the model. As a consequence, the first step in present model calibration is to correctly simulate the horizontal snow mass fluxes because tuning relative humidity would be meaningless without this condition. Sensitivity test on the roughness length lead to a better agreement between observed and simulated variables (see our response to comment n°5 of reviewer#1).

(d) If the model is used, its sensitivity for input parameters needs to be discussed, especially since it underestimates the transport with a factor of 10. Which improvements are necessary to increase correspondence to the observations? Many more model tests are necessary. Equation 5 is used for correction, but the resulting transport is wrong. The equation 5 allows computation of

fluxes in the first meter, which is not possible in the MAR model simulation in which the first level is located at 2 m. This equation was considered to account for the strong decrease of aeolian snow mass fluxes above the first meter. It is based on results of modeling with the 1-D version of the MAR model with the same parameterization as used in our 3-D MAR simulation. It results in a dimensionless correction factor. This correction demonstrates that underestimation of fluxes in the 3-D MAR is not caused by the strong decrease in the first meter. This element is thus important for modelers because it demonstrates that other improvements are necessary. In the paper, we propose to describe the way this equation was obtained as follows:

"Snow mass fluxes were first obtained with the coarse resolution 3D model, in which the first level is located at 2 m. In order to account for the strong decrease in aeolian snow mass fluxes above the first meter, a correction factor was assumed. This factor results from comparison between snow transport fluxes computed in our 3-D Mar simulation and those obtained with a 1-D version of the MAR model using the same parameterization.".

(e) Then, if the model works better, the authors should present and analyse the spatial fields. Blowing snow transport is clearly a spatially homogeneous process, and exactly for that reason you need a model. Otherwise, the reason to use a model in this context is absent. This remark is not clear. If the process is homogeneous, or rather constant, there is no need to use a model. We suppose that the reviewer was actually suggesting that snow transport in "not" a "spatially homogeneous process".

Several studies (Pettré et al. 1986, Agosta et al. 2012, Verfaillie et al. 2012) have shown that SMB heterogeneities are clearly visible down to the kilometric scale in Adélie Land, and these heterogeneities are probably partially related to aeolian redistribution/erosion of snow. As we use a regional climate model with a relative fine horizontal resolution (5 km) over this area, it could be possible to simulate the largest scales of these erosion/deposition patterns, but this is not the purpose of the present paper. The aim here is to perform an evaluation of the model from observations made by observers on the field (*i.e.*, in summer), and we do not have observations in order to evaluate the spatial patterns simulated by the model over this period. Furthermore we show that a one-order decrease in the magnitude of z_0 significantly improves the simulation at D47, but we have no way to affirm that this modified z_0 is closer to its actual value in this area. In other words, getting a better spatial distribution of accumulation, and hence of snow transport does not mean that the modeled roughness length agrees with observation and that the processes governing its behavior are correctly modeled. This may result from error compensations. As a consequence, further investigations on the influence of roughness length on transported snow by the wind in Adélie Land are needed before making a spatial validation.

Language and text (not complete):

P6009

L2: "compared with Aeolian snow mass fluxes". I guess "observed" needs to be added. Changed according to the remark

L17: "It will conduct the MAR". Poor English, I guess the authors mean that "Our results indicate that MAR, with..." Changed according to the remark

L26: 10%. Transport does not contribute to the ASMB. The contribution comes from erosion or sublimation. The sentence has been changed; We now write : "Previous estimations of contribution of aeolian snow erosion and sublimation to the ASMB using numerical models […]".

P6010:

L24: "wind speed of around 100 km inland". Interesting value for wind speed. The maximum wind speed occurs geographically at the break in slope between the plateau and the coast. This break in slope is located in Adélie Land approximately 250 km from the coast. The sentence has been changed to more accurately describe this point: "The coastal region is characterized by frequent and strong katabatic winds with a maximum wind speed near the break in slope located around 250 km inland […]".

P6011

P23-30: it is not clear how the height of the sensors (which of course varies throughout the year) is determined. Variations in the surface elevation are retrieved using an ultrasonic depth gauge installed on the AWS. A description of the automatic weather stations has been added in the text: "Automatic weather stations (AWS) measuring wind speed, wind direction, temperature, relative humidity and snow height every 10 s were installed at three different locations along a transect extending from the coastline to 100 km inland. (Trouvilliez et al. 2014)." We also added the following sentence: "An ultrasonic gauge is installed to survey surface variations, from which the elevation of sensors above the surface is assessed throughout the year.".

P6014 Saltation is described, but how is suspension parameterized? P 6016 Equation 5: If I can do my math, the number in the exponent is just 2.4. L21: "can be associated with the MAR outputs". What does this mean? The exponent has been changed for 2.4. We change the sentence by: "The wind gust diagnostic model from Brasseur et al., (2002) is an adequate tool for […] with high wind speeds. The MAR outputs can serve to force the wind gust model. Although the method […]".

Suspension of snow is represented by the turbulent surface flux of snow particles (see e.g., Gallée et al. 2001, Gallée et al. 2005) and results from the equilibrium between turbulence, vertical advection and sedimentation speed. As exposed in our response to general comment n°3 from reviewer#1, airborne snow particles are treated by the microphysical scheme of MAR (see Gallée 1995, eq. A5 p. 2064).

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Comparison between observed and simulated aeolian mass fluxes in Adélie Land, East Antarctica

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13

Abstract

Using the original set up described in Gallée et al. (2013), the MAR regional climate model including a coupled snowpack/aeolian snow transport parameterization, was run at a fine spatial (5 km horizontal and 2 m vertical) resolution over one summer month in coastal Adélie Land. Different types of feedback were taken into account in MAR including drag partitioning caused by surface roughness elements. Model outputs are compared with observations made at two coastal locations, D17 and D47, situated respectively 10 km and 100 km inland. Wind speed was correctly simulated with positive values of the Nash test (0.60 for D17 and 0.37 for D47) but wind velocities above 10 $m.s^{-1}$ were underestimated at both D17 and D47; at D47, the model consistently underestimated wind velocity by 2 $m.s^{-1}$. Aeolian snow transport events were correctly reproduced with the right timing and a good temporal resolution at both locations except when the maximum particle height was less than 1 m. The threshold friction velocity, evaluated only at D17 for a 7-day period without snowfall, was overestimated. The simulated aeolian snow mass fluxes between 0 and 2 m at D47 displayed the same variations but were underestimated compared to the second-

generation FlowCapt[TM] values, as was the simulated relative humidity at 2 m above the surface. As a result, MAR underestimated the total aeolian horizontal snow transport for the first two meters above the ground by a factor of 10 compared to estimations by the second-generation FlowCapt[TM]. The simulation was significantly improved at D47 if a one-order decrease in the magnitude of z_0 was accounted for, but agreement with observations was reduced at D17. Our results suggest that z_0 may vary regionally depending on snowpack properties, which are involved in different types of feedback between aeolian transport of snow and z_0.

1   Introduction

Measurements of aeolian snow mass fluxes in Antarctica revealed that a large amount of snow is transported by the wind (Budd, 1966; Wendler, 1989; Mann et al., 2000; Trouvilliez et al., 2014). The aeolian transport of snow is probably a significant component of the surface mass balance distribution over the Antarctic ice sheet. Although estimates have been proposed based on remote sensing data (Das et al., 2013), reliable quantifications of the contribution of aeolian snow transport processes to the Antarctic surface mass balance (ASMB) can only be assessed by modeling. Previous estimates using numerical models suggest that erosion and blowing snow sublimation represent around 10% of the net ASMB (Déry and Yau, 2002; Lenaerts et al., 2012a). However, these evaluations were made without considering the complex feedback system between snow surface properties, wind-borne snow particles, and atmospheric conditions. Indeed, aeolian erosion promotes the formation of snow surface structures such as sastrugi, barchans, dunes and megadunes, which, in turn, alter the atmospheric dynamics (Frezzotti et al., 2004). Rougher surfaces reduce the wind speed and the resulting wind-driven erosion of snow (Kodama et al., 1985), but increase turbulence in the near-surface airflow thereby further increasing the aeolian snow mass flux (Frezzotti et al., 2002). Moreover, the presence of airborne snow particles and their subsequent sublimation are both responsible for an increase in air density, which may reduce turbulence in the surface boundary layer and contribute negatively to snow erosion (Bintanja, 2000; Wamser and Lykossov, 1995). On the other hand, the increase in air density strengthens katabatic flows (Gallée, 1998). An overview of the different types of feedback caused by blowing and drifting snow is given in Gallée et al. (2013).

As previously highlighted (Gallée et al., 2001; Lenaerts et al., 2012b), there are few reliable datasets on aeolian snow transport covering a long period with an hourly temporal resolution,

making it difficult to evaluate modelling in Antarctica. One-dimensional (1-D) numerical models have been compared with aeolian snow transport rates in ideal cases (Xiao et al., 2000) and with observations (Lenaerts et al., 2010). Regional climate models have been evaluated against surface mass balance estimates derived from stake networks (Gallée et al., 2005; Lenaerts et al., 2012c). The latter is an integrative method that includes all the components of the surface mass balance: precipitation, run-off, surface and wind-borne snow sublimation, and erosion/deposition of snow. Aeolian snow transport events simulated by regional climate models have been compared with remote sensing techniques (see Palm et al., 2011), and with visual observations at different polar stations (Lenaerts et al., 2012b) or with particle impact sensors (Lenaerts et al., 2012c). Aeolian snow mass flux measurements are even rarer. Lenaerts et al. (2012b) were only able to evaluate their simulations against annual transport rate values estimated at Terra Nova Bay by the first version of an acoustic sensor FlowCapt^{TM} (Scarchilli et al., 2010), which overestimated aeolian snow mass flux (Trouvilliez et al., 2015), and against an extrapolation of optical particle counter sensor measurements performed at Halley (Mann et al., 2000). To improve analyses, model evaluations thus require more detailed and reliable aeolian snow transport measurements in Antarctica.

Here, we present a detailed comparison between outputs of the regional atmospheric model MAR and data collected during an aeolian snow transport observation campaign in Adélie Land, Antarctica (Trouvilliez et al., 2014). We focus on a one-month period, (January 2011) during which the observers were in the field and could visually confirm the occurrence of meteorological events. MAR has already been evaluated over coastal Adélie Land in terms of the occurrence and qualitative intensity of aeolian snow transport events in January 2010 (Gallée et al. 2013). However, model outputs were only compared with a single point of aeolian snow transport measurements using first-generation FlowCapt^{TM} instruments. These sensors are good at detecting aeolian snow transport events but fail to estimate aeolian snow mass fluxes (Cierco et al., 2007; Naaim-Bouvet et al., 2010; Trouvilliez et al., 2015). Second-generation FlowCapt^{TM} instruments were installed at two new locations in February 2010. Unlike its first-generation counterpart, the second-generation sensor is able to provide a lower bound estimate of the aeolian snow mass fluxes (Trouvilliez et al., 2015). It thus allows comparisons not only between the simulated and observed timing of aeolian snow transport events, but also between the simulated and observed aeolian snow mass fluxes, which was previously not the case.

2   Field Data

Observations were performed in Adélie Land, East Antarctica (Fig. 1), where surface atmospheric conditions are well monitored at the permanent French Dumont d'Urville station (Favier et al., 2011). The coastal region is characterized by frequent strong katabatic winds starting at the break in slope located approximately 250 km inland (Parish and Wendler, 1991; Wendler et al., 1997). These katabatic winds are regularly associated with aeolian snow transport events (Prud'homme and Valtat, 1957; Trouvilliez et al., 2014) making Adélie Land an excellent location for observations of aeolian snow transport. Furthermore, a 40-year accumulation dataset is available for Adélie Land and long-term stake measurements are still made along a 150-km stake line (Agosta et al., 2012) and in erosion areas (Genthon et al., 2007; Favier et al., 2011). These datasets give access to the annual SMB in the area.

Several meteorological campaigns including aeolian snow transport measurements have already been carried out in Adélie Land using mechanical traps (Madigan, 1929; Garcia, 1960; Lorius, 1962) and optical particle counter sensors (Wendler, 1989). However, none of the measurements in Adélie Land or elsewhere in Antarctica fulfils all the requirements of an in-depth evaluation of regional climate models. In 2009, a new aeolian snow transport observation campaign started in Adélie Land, which was specially designed to optimally evaluate models as well as possible given the prevailing logistical difficulties and limitations (Trouvilliez et al., 2014). In this context, automatic weather stations (AWS) that measure wind speed, wind direction, temperature, relative humidity and snow height at 10 second intervals were installed at three different locations from the coastline to 100 km inland (Trouvilliez et al., 2014). Half-hourly mean values are stored on a Campbell datalogger at each station. The AWS are equipped with FlowCapt[TM] acoustic sensors designed to quantify the aeolian snow mass fluxes and to withstand the harsh polar environment. The combination of an automatic weather station and FlowCapt[TM] sensors is hereafter referred to as an automatic weather and snow station (AWSS). Two generations of FlowCapt[TM] exist and have been evaluated in the French Alps and in Antarctica (Trouvilliez et al., 2015). Both generations appear to be good detectors of aeolian snow transport events. The first-generation instrument failed to correctly estimate the snow mass flux with the constructor's calibration and even with a new calibration, but the second-generation instrument is capable of providing

1 a lower bound estimate of the snow mass flux and a consistent relationship of the flux *versus*

2 wind speed.

3 At each AWSS, FlowCapt[TM] sensors were set up vertically. When the lower extremity of the

4 sensor is close to the ground or is partially buried, the FlowCapt[TM] is able to detect the onset

5 of an aeolian snow transport event (i.e., initiation of saltation). Although the level of the

6 snowpack changes over the course of the year due to accumulation and ablation processes, the

7 sensor can nevertheless record continuous observations, which is an advantage over single

8 point measurement devices. The FlowCapt[TM] has better temporal resolution than visual

9 observations, which are usually made at 6 h intervals. Moreover, the ability of these sensors to

10 detect events of small magnitude is particularly useful, as satellite measurements can only

11 detect blowing snow events in which the snow particles are lifted 20 m or more of the surface

12 in the absence of clouds (Palm et al., 2011). Trouvilliez et al. (2014) reported that aeolian

13 snow transport events with a maximum particle height < 4.5 m above ground level (agl.)

14 accounted for 17% of the total aeolian snow transport events in the period 2010-2011 at D17

15 coastal site (Table 1). Ground and satellite observations are thus complementary.

16 In early 2010, two AWSS equipped with second-generation FlowCapt[TM] sensors (2G-

17 FlowCapt[TM]) were set up at sites D17 and D47 (Table 1). Because D47 is located in a dry

18 snow zone roughly 100 km inland from D17, the two stations document distinct climatic

19 conditions. At D17, one 2G-FlowCapt[TM] was mounted from 0 to 1 m agl. on a 7-m high mast

20 with six levels of cup anemometers and thermo hygrometers, while at D47 a one

21 measurement level AWS was equipped with two 2G-FlowCapt[TM] installed from 0 to 1 and

22 from 1 to 2 m agl. (Fig. 2). Like the other meteorological variables, the half-hourly mean

23 aeolian snow mass flux is recorded by each 2G-FlowCapt[TM] and stored in the datalogger. An

24 ultrasonic gauge was installed at D47 to monitor surface variations, from which the elevation

25 of sensors above the surface is assessed throughout the year. A detailed description of the

26 equipment at both AWSS can be found in Trouvilliez et al. (2014). Since we focus on the

27 simulated and observed snow mass fluxes, our evaluation is limited to the two stations

28 equipped with 2G-FlowCapt[TM], i.e., D17 and D47.

29

3 The MAR Model

3.1 General Description

MAR is a coupled atmosphere / snowpack / aeolian snow transport regional climate model. Atmospheric dynamics are based on the hydrostatic approximation of the primitive equations using the terrain following normalized pressure as vertical coordinate to account for topography (Gallée and Schayes, 1994). An explicit cloud microphysical scheme describes exchanges between water vapor, cloud droplets, cloud ice crystals (concentration and number), rain drops and snow particles (Gallée, 1995). The original snowpack and aeolian snow transport sub-models are described in Gallée et al. (2001). An improved version is detailed in Gallée et al. (2013) and is used here.

Eroded snow particles drift from the ground into the atmosphere, and the airborne snow particles are advected from one horizontal grid cell to the next one downwind. More generally, airborne snow particles are modeled according to the microphysical scheme. In particular, the sublimation of wind-borne snow particles is a function of air relative humidity. Many different types of feedback that are an integral part of aeolian transport of snow are included in MAR. The parameterization of turbulence in the surface boundary layer (SBL) is based on the Monin-Obukhov similarity theory (MO-theory) and accounts for the stabilizing effect of blowing snow particles, as proposed by Wamser and Lykossov (1995). Turbulence above the SBL is parameterized using the local E - scheme, which consists in two prognostic equations, one for turbulent kinetic energy and the other for its dissipation (Duynkerke, 1988), and includes a parameterization of the turbulent transport of snow particles consistent with classical parameterizations of their sedimentation velocity (Bintanja, 2000). Blowing snow-induced sublimation is computed by the microphysical scheme and influences the heat and moisture budgets in the layers that contain airborne snow particles. Their influence on the radiative transfer through changes in the atmospheric optical depth is taken into account (see Gallée and Gorodetskaya, 2010).

Under near-neutral atmospheric conditions, the MO-theory predicts that the vertical profile of the wind speed within the SBL is semi-logarithmic:

$$u(z) = \frac{u_*}{k} \ln(\frac{z}{z_0}) \tag{1}$$

where u(z) is the wind speed at height z, = 0.4 is the von Kármán constant, z_0 is the

6

1 roughness length for momentum and u_* is the friction velocity that describes the shear stress

2 exerted by the wind on the surface. Aeolian transport of snow begins when u_* exceeds the

3 force required for aerodynamic entrainment of snow surface particles, known as threshold

4 friction velocity (u_{*t}), which depends on the surface properties of the snow (Gallée et al.

5 2001). In MAR, surface processes are modelled using the "soil-ice-snow-vegetation-

6 atmosphere transfer" scheme (SISVAT; De Ridder and Gallée, 1998, Gallée et al., 2001,

7 Lefebre at al., 2005, Fettweis et al., 2005). The threshold friction velocity for a smooth

8 surface (u_{*tS}) depends on dendricity, sphericity, and grain size for snow density below 330

9 $kg.m^{-3}$ (see Guyomarc'h and Mérindol, 1998), and on snow density alone above 330 $kg.m^{-3}$.

10 To account for drag partitioning caused by roughness elements, the threshold friction velocity

11 for a rough surface (u_{*tR}) is calculated as in Marticorena and Bergametti (1995):

$$u_{*tR} = \frac{u_{*tS}}{R_f} \tag{2}$$

12 where both threshold friction velocities are expressed in $m.s^{-1}$ and R_f is a ratio factor defined

13 as:

$$R_f = 1 - \frac{\ln(\frac{z_{0R}}{z_{0S}})}{\ln\left[0.35(\frac{10}{z_{0S}})^{0.8}\right]} \tag{3}$$

14 where z_{0R} and z_{0S} are the surface roughness lengths in meters for rough and smooth surfaces,

15 respectively. Over smooth snow surfaces, the roughness length is generally around 10^{-5}–10^{-4}

16 m (Leonard et al., 2011). In MAR, this value is set to 5.10^{-5} m. In addition to the drag

17 partition, moving particles in the saltation layer transfer momentum from the airflow to the

18 surface. Above the saltation layer, the net effect is similar to that of a stationary roughness

19 element (Owen, 1964). Thus, saltation leads to an increase in roughness length compared with

20 a situation without wind-borne snow, even in the case of a smooth surface. The contribution

21 of blowing snow particles to the roughness length z_{0S} is calibrated using Byrd project

22 measurements (Budd et al., 1966; Gallée et al., 2001):

$$z_{0S} = 5x10^{-5} + \max\left(0.5x10^{-6}, au_*^2 - b\right) \tag{4}$$

23 where a and b are two constants.

1 One of the main surface roughness elements in Antarctica is a kind of snow ridge known as
2 sastrugi. These are meter-scale erosional features aligned with the prevailing wind that formed
3 them. The building of sastrugi may be responsible for an increase in the sastrugi drag
4 coefficient (form drag), leading to an increase in surface roughness and hence to loss of
5 kinetic energy available for erosion. This is negative feedback for the aeolian transport of
6 snow, as an increase in the roughness length reduces wind speed. Andreas (1995) estimated
7 the time-scale for sastrugi formation to be half a day. Sastrugi can be buried if precipitation
8 occurs, thereby reducing surface roughness. All these effects are taken into account in the
9 improved version of the snowpack sub-model concerning the parameterization of z_{0R} (see
10 Gallée et al., 2013). Finally, the modeled roughness length results from a combination of z_{0S}
11 and z_{0R}. MAR also accounts for the influence of orographic roughness (Jourdain and Gallée,
12 2010), but its contribution to the computation of the roughness length was neglected here, as
13 our study is restricted to the coastal slopes of Adélie Land (Fig. 1).

14 Once aeolian transport begins, the concentration of snow particles in the saltation layer (h_s),
15 expressed in kilograms of particles per kilograms of air, is parameterized from Pomeroy
16 (1989):

$$h_S = \begin{cases} 0 & \text{if } u_{*R} < u_{*tR} \\ e_{salt}\left(\dfrac{u_{*R}^2 - u_{*tR}^2}{gh_{salt}}\right) & \text{if } u_{*R} \geq u_{*tR} \end{cases} \qquad (5)$$

17 where u_{*R} is the friction velocity for a rough surface in m.s^{-1}, e_{salt} is the saltation efficiency
18 equal to 3.25, g is the gravitational acceleration in m.s^{-2} and h_{salt} is the saltation height in m, a
19 function of u_{*R} (Pomeroy and Male, 1992).

20 As in Gallée et al. (2013), densification of the snowpack by the wind is included in SISVAT
21 from the work of Kotlyakov (1961), i.e., the density of deposited blown snow particles is
22 parameterized as a function of the wind speed at 10 m agl. (U_{10}):

$$r = 104(U_{10} - 6)^{1/2} \qquad (6)$$

23 where r is the snow density in kg.m^{-3} and $U_{10} > 6$ m.s^{-1}. In turn, an increase in the density of
24 the surface snowpack is responsible for an increase in the threshold friction velocity for
25 erosion. This is negative feedback.

26

3.2 Model Configuration

MAR was run over Adélie Land for the whole month of January 2011. The modeling grid and set up were the same as those described in Gallée et al. (2013): the integrative domain covers an area of about 450-km x 450-km with a 5-km horizontal resolution (Fig. 1). This domain was chosen so as to include the katabatic wind system that develops over the slopes of Adélie Land starting at the break in slope roughly 250 km inland. Since the size of the domain does not significantly influence simulated wind speed (Gallée et al., 2013), we chose a small domain with to limit numerical costs. Lateral forcing and sea-surface conditions were taken from ERA-Interim. Sixty vertical levels were used to simulate the atmosphere, with a first level 2 m in height and a vertical resolution of 2 m in the 12 lowest levels. A spin-up, as described in Gallée et al. (2013), was applied so as to achieve relative equilibrium between the snowpack and the atmospheric conditions: the simulation started on December 1, 2010, that is, one month before the period in which we were interested.

Erosion of snow by the wind is a highly non-linear process. Therefore, a good simulation of the atmospheric flow that drives aeolian snow transport events is a prerequisite to simulate the timing of their occurrence for the right reasons. In the model, the roughness length partly depends on wind speed, whose vertical evolution is in turn controlled by the roughness length in a feedback fashion. In Gallée et al. (2013), z_0 was calibrated to correctly reproduce the wind minima measured at D17. The same approach was used here.

4 Comparison of Field Data and Model Outputs

The aim of this section is to provide a detailed comparison between observed and modeled meteorological variables including aeolian snow mass fluxes. The model performances are assessed using the efficiency statistical test (E) proposed by Nash and Sutcliffe (1970):

$$E = 1 - (RMSE / s)^2 \qquad (7)$$

where s is the standard deviation of the observations and RMSE is the root mean squared error of the simulated variable. An efficiency index of 1 means a perfect simulation (RMSE=0) and a value of 0 or less means that the model is no better than a minimalist model whose output constantly equals the mean value of the modeled variable over the time period concerned. Wind speed and relative humidity were compared at a height of 2 m above the surface. Simulation data were extracted from the nearest grid point to the AWSS concerned.

9

1 Simulated snow mass fluxes were first obtained at the coarse resolution (2 m) of the 3-D

2 model. To account for the marked decrease in aeolian snow mass fluxes within the first two

3 meters, a dimensionless correction factor (A) was applied. This factor results from comparing

4 the snow mass fluxes computed in our 3-D MAR simulation and those obtained with a 1-D

5 version of the MAR model using the same parameterization and a higher vertical resolution

6 with 5 levels describing the first meter above the surface. Corrected snow mass fluxes are

7 calculated as:

$$m_{IC} = m_{IR} A \tag{8}$$

8 where μ_{IC} is the corrected flux for the lowest layer (0-2 m) and μ_{IR} the raw flux from MAR for

9 the lowest layer, both in g.m^{-2}.s^{-1}. μ_{IC} is compared with the mean observed snow mass flux

10 from 0 to 2 m agl. (μ_{0-2m}), which is calculated as:

$$m_{0-2m} = \frac{m_1 h_1 + m_2 h_2}{h_1 + h_2} \tag{9}$$

11 where μ_i is the observed snow mass flux integrated over the emerged length h_i of the

12 corresponding 2G-FlowCapt^{TM} sensor, in g.m^{-2}.s^{-1} and m, respectively.

13 The comparison first focused on wind speed, which is the driving force behind aeolian snow

14 transport. The timing of aeolian snow transport events was then studied, together with an

15 evaluation of both friction and threshold friction velocities for a period with no concomitant

16 precipitation at site D17. The aeolian snow mass fluxes were then analyzed at D47. We also

17 paid attention to relative humidity so as to evaluate the sublimation of wind-borne snow

18 particles, since it plays an important role in the ASMB (Lenaerts et al., 2012a). Model

19 sensitivity to roughness length is analyzed in sub-section 4.4.

4.1 Wind Speed

21 Wind speed was correctly simulated by the model (Fig. 3) with an efficiency of 0.60 and 0.37

22 for D17 and D47, respectively. Variations were correctly represented but wind speeds above

23 10 m.s^{-1} were underestimated, particularly at site D47 where the model consistently

24 underestimated wind speed by about 2 m.s^{-1}. The high efficiency for wind speed at D17

25 suggests that z_0 might be correctly modeled, while the lower efficiency and the systematic

26 negative bias at D47 strongly suggest overestimation of z_0 at this grid point.

1 MAR simulated a median z_0 value of 3.2 mm at D17 for our period of interest. This variable
2 could only be compared to observations at D17 since its determination using the profile
3 method (Garrat, 1992) using Equation (1) requires measurement of wind speed at several
4 levels. During January 2011, atmospheric stratification was mostly near-neutral at D17 owing
5 to mixing caused by katabatic winds. The roughness length z_0 was computed by fitting
6 Equation (1) with the observed profiles using least-square techniques with the four upper cup
7 anemometers (the two lowest cup anemometers were not functioning correctly). The
8 instruments' elevations above the surface were measured manually at the beginning of
9 January 2011, but variations caused by accumulation/ablation processes during the remainder
10 of the month of January are not known. Errors in measurement heights would introduce a
11 curvature to the modeled wind profile given by Equation (1) that could produce erroneous
12 values of z_0. To reduce z_0 uncertainty resulting from this discrepancy, we only considered
13 cases where linear fits was providing determination coefficients above 0.98. This threshold
14 allows removing vertical profiles when wind speed was diverging from logarithmic profiles.
15 The median value of the resulting z_0 was 2.3 mm for the entire month of study, lower but still
16 close to the one simulated by MAR.

17 This comparison suggests a possible overestimation of z_0 by MAR. Nevertheless, this
18 overestimation is not sufficient to explain the tendency of the model to miss wind maxima.
19 This behavior may also be due to the E - turbulent scheme, which is based on the small
20 eddies concept. During strong winds, turbulent eddies have a large vertical extent and are
21 responsible for the deflection of higher air parcels, which represent a source of momentum
22 that can be transported to the surface in gusts. The E - turbulence scheme cannot reproduce
23 these large eddies or the gusts associated with strong wind events. The use of a non-local
24 turbulence scheme would possibly improve this aspect of the simulation.

25 Finally, at D47, the original configuration of Gallée et al. (2013) resulted in a median z_0 value
26 of approximately 3.4 mm for the simulated period. Although somewhat higher, this value is
27 consistent with other millimetric z_0 values used in realistic simulations of the Antarctic
28 surface wind field (Reijmer, 2005; Lenaerts et al., 2012b). However, the model behaved
29 differently with respect to wind speed depending on the location (Fig. 3). Consequently, a
30 single calibration of z_0 would not represent wind speed with the same accuracy at the two
31 locations.

4.2 Occurrence of Aeolian Snow Transport Events

First we compare the observed and simulated aeolian snow transport events in terms of occurrence. The timing of events at D17 and D47 detected by the 2G-FlowCapt[TM] sensor measuring snow particle impacts in the first meter above the surface was correctly simulated by the model except between January 12 and January 19 (Fig. 3). For this period, the field reports mentioned that drifting snow at D17 was limited to less than 1 m above the surface. The same observation was made at D47 as the 2G-FlowCapt[TM] installed from 1 to 2 m above the surface measured negligible snow mass fluxes (Fig. 3). Indeed, MAR failed to reproduce aeolian snow transport events when the maximum particle height was less than 1 m above the surface (Fig. 3). The coarse vertical resolution of the first layers of the MAR (2 m) may explain part of this discrepancy, but corrections of fluxes made with the Equation (9) should partly account for this aspect. The prevention of erosion in the model may, thus, be related to processes involving snowpack properties and/or friction conditions at the surface. This assumption can be investigated by analyzing both modeled friction and threshold friction velocities.

Like for z_0, friction and threshold friction velocities were only compared with observations at D17 using the same determination procedure. The 95% confidence limit of each u_* was calculated to account for statistical errors associated with the logarithmic profile (Wilkinson 1984). The lowest 2G-FlowCapt[TM] was in contact with the ground and allowed the detection of aeolian snow transport events: u_{*t} was computed as the u_* value as soon as the observed flux value exceeded 0.001 g.m^{-2}.s^{-1}. This calculation is only valid without snowfall occurrence. Indeed, when snow falls during windy conditions, the sensor detects the presence of airborne snow particles but does not distinguish between precipitating snowflakes and snow grains that were eroded from the surface by the wind. Accounting for situation with snowfall occurrence would introduce a bias in the u_{*t} values since the detection of an aeolian snow transport event by the 2G-FlowCapt[TM] is not necessarily associated with erosion of snow. Therefore, for an accurate evaluation of u_{*t}, snowfall events need to be removed from the data. For this purpose, we used the ERA-interim reanalysis from the European Center for Medium-range Weather Forecast, which appears to be the most appropriate support for estimating precipitation rates in the study area (Palerme et al., 2014). According to the ERA-interim data, the longest period without precipitation was between January 12 and January 19. During this period, six transport events were identified and six threshold friction velocities

1 were determined (Fig. 4) from observations. Nevertheless, MAR did not simulate any aeolian

2 snow transport event during the entire period. As shown in Figure 4, the simulated u_* is lower

3 than the observed one, while the simulated u_{*t} is overestimated and higher than the simulated

4 u_*. This results in the absence of drifting snow in the simulation of this period. Note the

5 decrease in the simulated u_{*t} in response to the light snowfall that occurred around January 12

6 (Fig. 4).

7 Except for cases of drifting snow presented in the previous paragraph, the 2G-FlowCapt[TM]

8 sensors recorded four aeolian snow transport events, which, this time, were simulated by the

9 MAR. Model behavior can be assessed by comparing the relation between aeolian snow mass

10 fluxes versus wind speed for the four strongest events that occurred in January 2011. It is well

11 known that, at a given height, for a given set of snow particles (i.e., a constant threshold

12 friction velocity value), the amount of snow being transported by the wind can be

13 approximated by a power law of the wind speed (Radok 1977; Mann et al. 2000). This is

14 clearly depicted in Figure 5 for events n°2, 3 and 4. However, observations show that the

15 occurrence of precipitation may impact this basic relationship, and may explain part of the

16 difference between model and observations (see events n°2 and 4). Indeed, unlike the others,

17 the first event was characterized by a hysteresis effect (Fig. 5, upper left panel). A similar case

18 was reported by Gordon et al. (2010), who linked this phenomenon to the occurrence of

19 snowfall. This may be justified assuming a 3-stage process of the snow mass flux–wind speed

20 relationship according to changes in u_{*t} over time: 1) the first stage describes the initiation of

21 the blowing snow event associated with the onset of strong winds: the aeolian snow mass flux

22 increases with wind speed according to the theoretical power law described by Radok (1977),

23 which suggests that u_{*t} stays roughly unchanged; 2) the second stage is characterized by the

24 relative constancy of the wind speed around 17-18 m.s^{-1} while the aeolian snow mass flux

25 decreases gradually, probably in response to a progressive increase in u_{*t} (caused by the

26 exhaustion of easily erodible snow or the exposure of a harder layer); 3) finally, Era-interim

27 estimates predict the occurrence of substantial precipitation amounts leading the same wind

28 speed to be associated with higher aeolian snow mass fluxes than during the two previous

29 stages: precipitating snow particles and subsequently loosened snow particles are added to the

30 previous set of airborne particles which originate from the surface, and are responsible for a

31 considerable decrease in u_{*t} below the value estimated in the first stage. Then, as the wind

32 weakens, the snow mass flux decreases to negligible values, and the event ends.

The influence of snowfall is also evidenced by the model outputs, showing that the largest simulated snow mass fluxes (~90-100 $g.m^{-2}.s^{-1}$) occur at a wind speed of around 13 $m.s^{-1}$, although the model simulates stronger wind speeds. The second and fourth events (Fig. 5, right panels) are particularly concerned. This reflects the decrease in u_{*t} associated with the heavy snowfall events simulated at that time.

4.3   Aeolian Snow Mass Fluxes

Next, we compare the measured aeolian snow mass fluxes and relative humidity with the model outputs in Figure 6. The evaluation is based only on the AWSS at D47, since this station, unlike D17, provides information on the snow mass fluxes from 0 to 2 m agl., allowing a comparison with the first level of the model. As mentioned above, MAR only simulated aeolian snow transport events at D47 when the maximum particle height was above 1 m. Even in these cases, MAR consistently underestimated the aeolian snow mass fluxes measured by the 2G-FlowCapt[TM]. The modeled underestimation is even higher knowing that the 2G-FlowCapt[TM] sensor already underestimates actual snow mass flux (Trouvilliez et al., 2015). An important negative bias between observed and simulated relative humidity appeared, even when the model correctly simulated the timing of the aeolian snow transport events (Fig. 6). This underestimation may result from the underestimation of the sublimation of the blown snow particles, linked to the underestimation of the concentration of blown snow particles in the lower model layer.

Overall, simulated aeolian snow mass fluxes were twice lower than those provided by the 2G-FlowCapt[TM] sensors for equal wind speed values except during snowfall events. The model also failed to reproduce strong aeolian snow transport events with wind speeds above 13 $m.s^{-1}$ and snow mass fluxes in excess of 100 $g.m^{-2}.s^{-1}$. As a result, the simulated horizontal snow transport through the first two meters agl. at D47 in January 2011 was underestimated by roughly a factor 10 compared to observations: the model calculated 5 768 $kg.m^{-2}$ while the 2G-FlowCapt[TM] measured 67 509 $kg.m^{-2}$.

4.4 Model Sensitivity to Roughness Length for Momentum

Since wind speed is the most important force behind snow erosion (Gallée et al. 2013), we performed a sensitivity test to see whether lower z_0 was giving more accurate modeled wind speed values. We tuned the model with different z_0 values to assess wind speed relationship with z_0. According to theory, the higher the wind speed, the higher the snow mass fluxes. As a consequence, larger relative humidity was modeled close to the surface with lower z_0. This resulted from sublimation of additional wind-borne snow particles in the lowest levels of the model. The model evaluation was performed with wind speed values measured at D47 over the entire study period. Results for various median z_0 values are summarized in Table 2. The best results were obtained for a reduction of z_0 by a factor 30 (i.e., a median z_0 value of 0.1 mm) over the simulated period at D47. The corresponding statistical efficiency for wind speed reached 0.89, while the efficiencies of the snow mass flux and relative humidity both became positive. The resulting local snow transport was still underestimated but only by about one third of the observed value. Nevertheless, reducing z_0 did not enable the reproduction of the small drifting snow events that occurred between January 12 and January 19, suggesting that part of the processes leading to surface state evolution is not fully reproduced by the MAR. Therefore, further improvements are still necessary.

5 Discussion

The original calibration of z_0 (Gallée et al. 2013) produced satisfactory results for modeled wind speed at D17, but the same good behavior was not reproduced at D47, another measurement point located 100 km away. We showed that a one-order decrease in the magnitude of z_0 significantly improved the simulation quality at D47, but we cannot affirm that this modification gives a more relevant z_0 for this site. In other words, obtaining a better representation of the evaluated variables did not make modeled roughness length agree with observed length or that the processes governing its behavior were correctly modeled. This may result from error compensations.

Nevertheless, this suggests that z_0 may vary regionally. In particular, D17 and D47 are located on either side of the dry-snow line, and the temperature regime at the two locations is sufficiently contrasted to explain differences in snowpack properties such as internal cohesion, density or aerodynamic resistance, which are involved in different types of feedback between z_0 and snow transport by the wind. In this case, distributed modeling should account for spatial variations of z_0 to allow a consistent representation of the aeolian snow

mass fluxes. Smeets and van den Broeke (2008) showed that z_0 can vary from 2 to 3 orders of magnitude during the ablation season between coastal and inland locations situated on either side of the equilibrium line of West-Greenland. Consequences on wind speed and aeolian snow mass fluxes would be important, as demonstrated at D17, where the agreement between modeled and observed wind speed was significantly reduced assuming a lower z_0 value. Indeed, the modeled wind speed bias increased from -1 to +1.5 m.s^{-1} for the entire simulated period when z_0 was changed from 3.2 mm to 0.2 mm. Further investigations of z_0 and its linkages with snow transport by the wind in Adélie Land are thus required.

Using the original calibration, the simulated horizontal snow transport in the first two meters above the surface at site D47 in January 2011 was about ten times lower than the observed value. This difference could be mainly explained by overestimation of the modeled z_0 and subsequent underestimation of the wind speed. The drag partition dictating the form drag in the MAR is currently parameterized with a qualitative formulation (Gallée et al. 2013) adapted from the work of Andreas and Claffey (1995) on sea ice in the Weddell Sea. Validity of this formulation should be reassessed given the differences in surface drag properties between coastal margins of Adélie Land and sea ice. Indeed, the severe katabatic wind regime characterizing the slopes of Adélie Land may promote aerodynamical adjustment of the snow surface. Thus, the form drag is likely lower than for sea ice, which experiences much lower wind speeds. In particular, overestimation of z_0 in the simulation resulted in a deficit of shear stress available for snow erosion, thus leading to underestimation of the modeled snow mass fluxes. As form drag is the main contributor to surface transfer of momentum (Jackson and Carroll 1978; Andreas 1995; Smeets and van den Broeke 2008) over rough snow/ice fields, a more sophisticated representation of z_0 that accounts for potential spatial and temporal variations in the form drag in the model is needed.

6   Conclusion

The regional climate model MAR, which includes a coupled snowpack/aeolian snow transport parameterization was run at a fine spatial resolution (5 km horizontally and 2 m vertically) for a period of one summer month in coastal Adélie Land, East Antarctica. The study reported here is a step forward in the model evaluation of the aeolian transport of snow. The study by Gallée et al. (2013) focused on checking that the MAR was able to reproduce drifting snow occurrences in January 2010 at one near-coastline location (D3, ~5 km from the coast) in

Adélie Land. In this paper, using the same model set-up, we present a quantitative evaluation of the aeolian erosion process in the same region, by comparing model outputs with 1) observed aeolian snow mass fluxes and relative humidity at D47 (~100 km from the coast) in January 2011, and 2) observed friction velocity and threshold friction velocity for snow transport over a 7-day period without precipitation in January 2011 at D17 (located ~10 km from the coast). This comparison highlighted the model qualities and discrepancies. Firstly, wind speed variations were accurately represented by the MAR although the model underestimated the wind maxima at D17 and more generally the wind speed at D47. This underestimation may be justified by an incomplete representation of z_0 and by the use of a turbulent scheme based on the small eddies concept. Secondly, the occurrence of the aeolian snow transport events was well reproduced except for events when the maximum particle height was less than 1 m above the surface. This probably results from a combination of underestimation of the friction velocity, overestimation of the threshold friction velocity and the too-coarse vertical resolution (2 m) of the MAR near the surface. Thirdly, at the same wind speed, modeled snow mass fluxes were twice lower than those measured by the 2G-FlowCapt^{TM} sensor, while it is known that this sensor already underestimates the snow mass fluxes of aeolian snow transport. Finally, the model underestimated the large snow mass fluxes (>100 g.m^{-2}.s^{-1}) and the associated strong winds (>13 m.s^{-1}). Comparison with measurements from 2G-FlowCapt^{TM} sensors at D47 revealed that the model underestimates the horizontal snow transport over the first two meters above the ground by a factor 10. Our results show that using the original set-up of Gallée et al. (2013), MAR would significantly underestimate the contribution of aeolian snow transport to the ASMB. For that reason, new observations are currently underway to better assess the contribution of the form drag to z_0 in coastal Adélie Land and to develop a more robust calibration process for z_0.

Acknowledgements

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18

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2   Table 1. Location and characteristics of the two automatic weather and snow stations used in

3   the present study

	D17	D47
Location	66.7°S, 139.9°E	67.4°S, 138.7°E
Altitude	450 m	1,560 m
Distance from coast	10 km	110 km
Period of observation	Since February 2010	January 2010 – December 2012
Atmospheric measurements	Wind speed, temperature and hygrometry at 6 levels	Wind speed, temperature and hygrometry at 2 m
Aeolian transport measurements	Second-generation FlowCapt^{TM} from 0 to 1 m	Second-generation FlowCapt^{TM} from 0 to 1 and 1 to 2 m

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1

2   Table 2. Comparison of Nash tests for wind speed, aeolian snow mass flux and relative

3   humidity at D47 for various median values of z_0.

Calibrated z_0 (median value, mm)	Wind Speed	Snow Mass Flux	Relative Humidity
3	0.37	-0.06	-4.77
0.5	0.8	0.2	-0.14
0.2	0.86	0.26	-0.01
0.1	0.89	0.32	0.16

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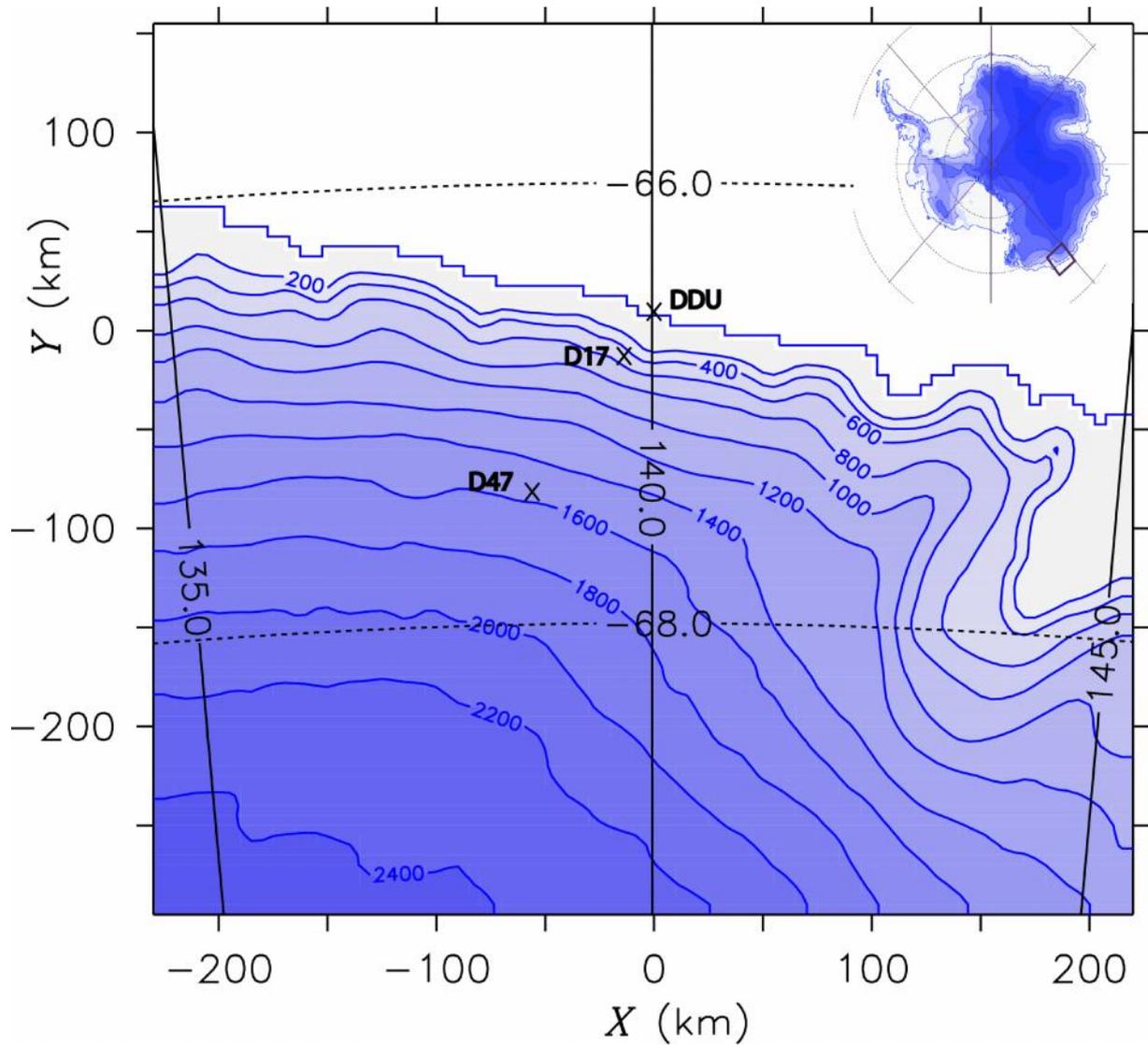
Figure 1. Integrative domain of the MAR in Adélie Land, East Antarctica. The crosses mark
the location of the French Dumont d'Urville base (DDU) and the two automatic weather and
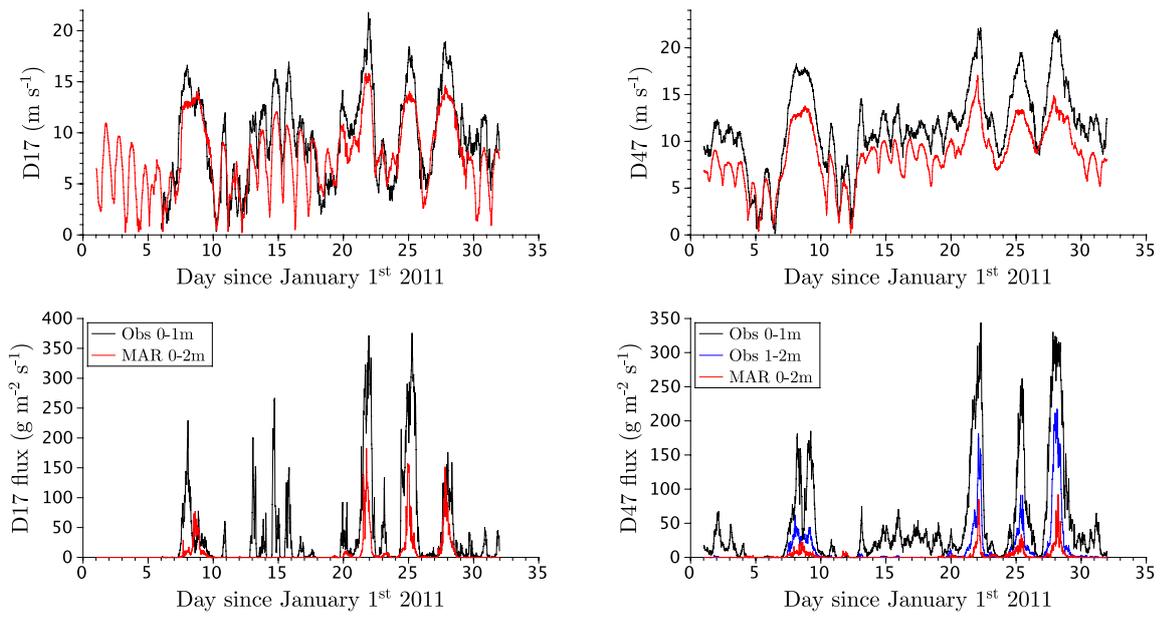snow stations used in this study (D17 and D47).

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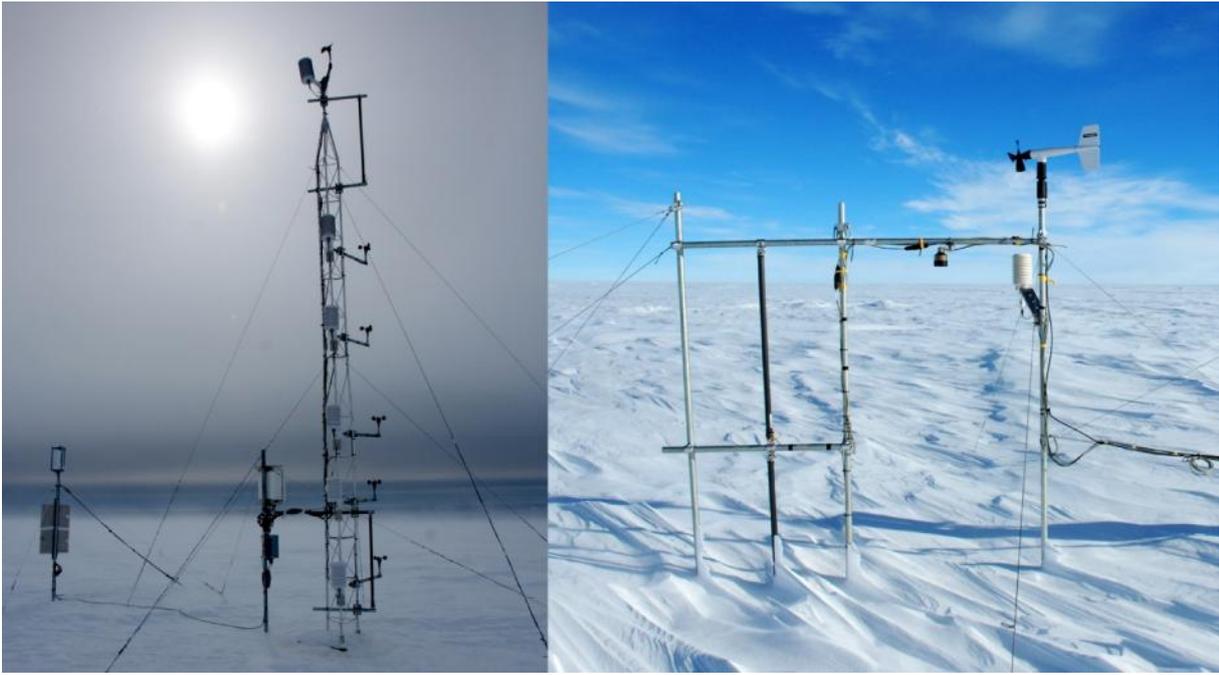
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3   Figure 2. Left: The D17 7-m mast with one second-generation FlowCapt[TM]. Right: The D47

4   automatic weather and snow station with two second-generation FlowCapt[TM] sensors.

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Figure 3. Top: Observed (black) and simulated (red) wind speed at a height of 2 m. Bottom: Aeolian snow transport events: comparison of observed snow mass fluxes from 0 to 1 m (black) and simulated fluxes from 0 to 2 m (red) at the D17 site (bottom left) and at the D47 site (bottom right). Observed snow mass fluxes from 1 to 2 m (blue) are also given for the D47 site.
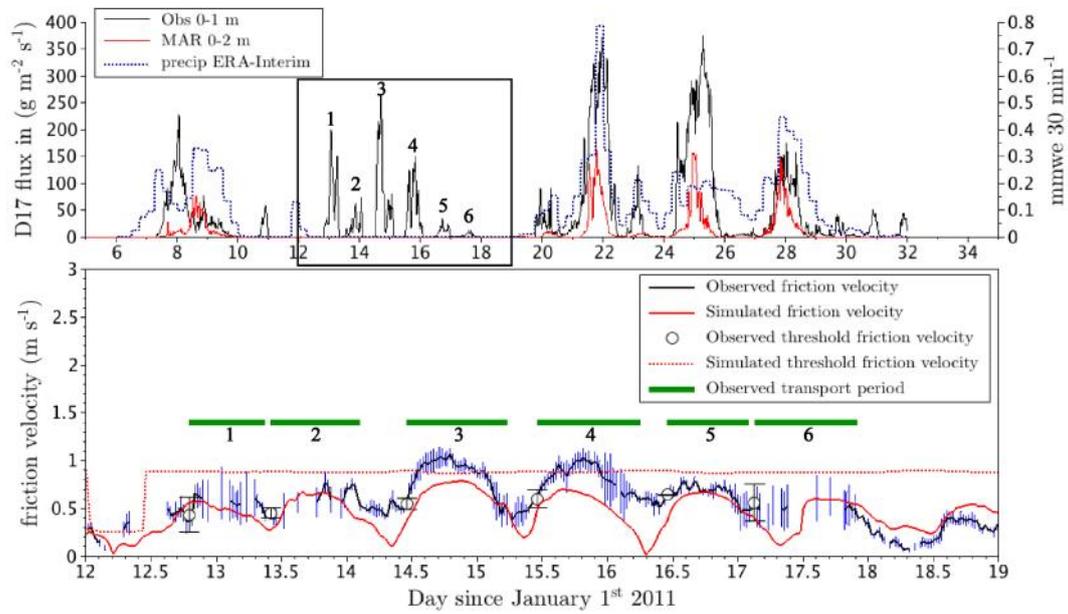
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Figure 4. Top panel: Comparison between observed aeolian snow mass fluxes from 0 to 1 m (black), simulated fluxes from 0 to 2 m (red) and precipitation from ERA-interim at D17. The black frame identifies the period without precipitation analyzed in the bottom panel. Bottom panel: Comparison of observed/simulated friction velocity (black line/red line, respectively) and observed/simulated threshold friction velocity (dashed line/black circles, respectively) at D17 for a transport period with no precipitation. The horizontal green bars represent the observed aeolian snow transport events numbered from 1 to 6.

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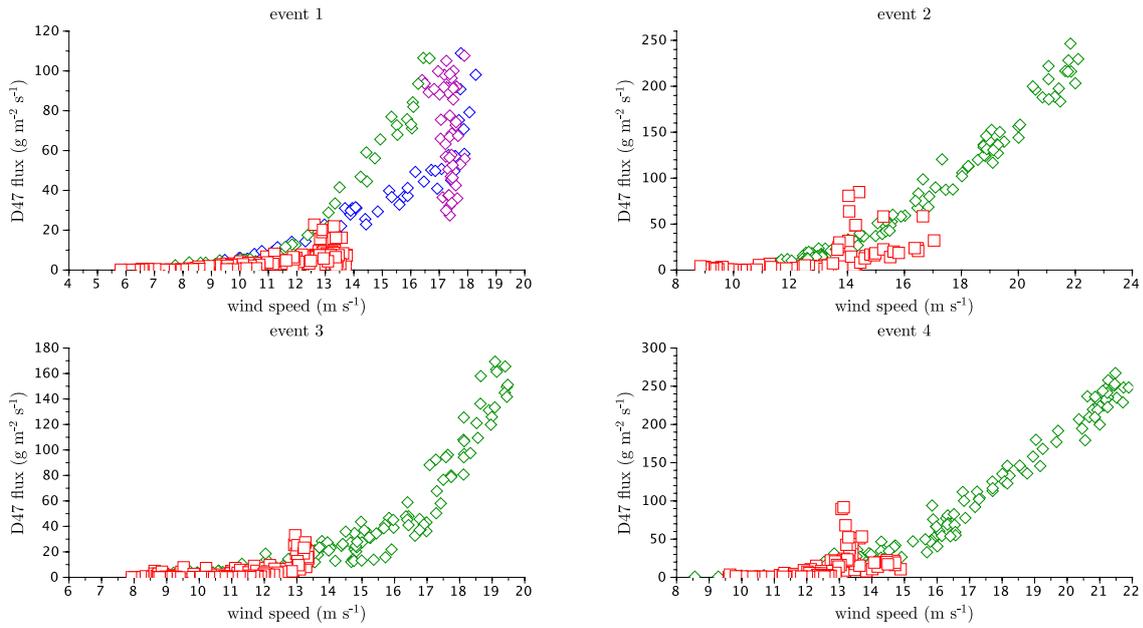
2

3   Figure 5. Observed (diamonds) and simulated (red squares) snow mass fluxes from 0 to 2 m

4   versus the observed (and simulated respectively) wind speed at 2 m in January 2011 for the

5   four strong aeolian snow transport events recorded at D47. Event 1 lasted from the 7th to the

6   10th, event 2 from the 21st to the 22nd, event 3 from the 24th to the 26th and event 4 from the

7   27th to the 29th. For the first event, the observed snow mass fluxes are decomposed in time

8   between a first (blue), an intermediate (purple) and a final relationship (green).

9

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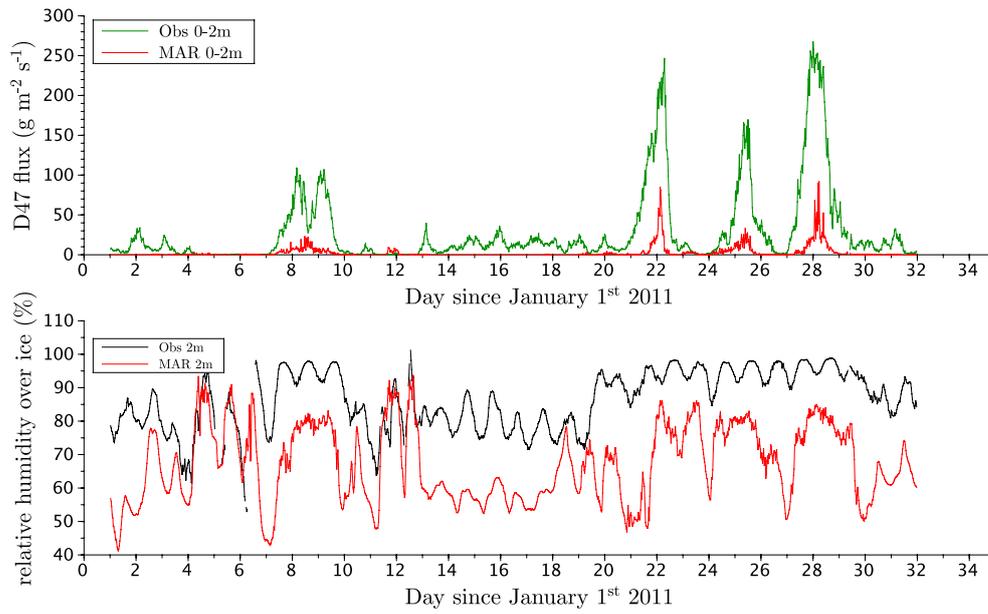
2

3 Figure 6. Top: Observed (green) and simulated (red) snow mass fluxes from 0 to 2 m.

4 Bottom: observed (black) and simulated (red) relative humidity 2 m above the surface.