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Wind-packing of snow in Antarctica

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Abstract. The snow surface in polar and mountainous regions is mobile and this mobility determines surface mass balance and isotopic composition before final deposition, which is poorly understood thus far. During a field campaign in Antarctica, a snowfall and subsequent drifting snow event was recorded by meteorological and snow drift stations. Associated surface topology changes and snow hardness changes were measured by terrestrial laser scanning and with a SnowMicroPen. The polar field measurements show that drifting snow is necessary for wind-packing and that the hardening is more efficient at wind-exposed surfaces than in wind-sheltered areas. Furthermore, it is quantitatively demonstrated for the first time how fresh snow gets organized in barchan dunes during subsequent drifting events with significant increases in surface hardness at all locations on the dune. These results form a crucial step in understanding how drifting snow links precipitation to deposition via snow hardening.

1 Introduction

Wind packing of snow is the process through which wind hardens snow and forms wind crusts and slabs at the surface. Fierz et al. (2009) describes a wind crust as a hard, thin, irregular layer and a wind slab as thicker, dense layer on leeward slopes. Wind packing and its results have been described qualitatively in many studies especially in Antarctic literature (e.g. Benson, 1967; Endo and Fujiwara, 1973; Kotlyakov, 1966; Schytt, 1958; Seligman, 1936). The hardening of the snow is also related to the formation of surface features such as dunes and zastrugi as described in Filhol and Sturm (2015). Wind-packing in Antarctica is relevant because of its influence on the mass balance. In fact, snow is often only permanently deposited through wind hardening. Without it, the snow remains mobile and may be redeposited elsewhere (Groot Zwaaftink et al., 2013).

Recently, we conducted wind tunnel experiments to study wind-packing in more detail (Sommer et al., 2017, 2018). We found that no crust forms without drifting snow, that erosion had no hardening effect on fresh snow and that deposition only led to hardening in wind-exposed areas. A Microsoft Kinect sensor (Mankoff and Russo, 2013) was used to quantify erosion and deposition. Two parameters derived from these data, the wind-exposure parameter Sx (Winstral and Marks, 2002) and the deposition rate, could explain almost half of the observed variability of snow hardness. Sx is defined as the upwind slope angle between the point of interest and the shelter-giving point, which is the point that maximizes this upward angle. Sx describes how sheltered or exposed a position is based on the upwind terrain. The hardness of snow was measured with a SnowMicroPen (SMP), a precise, constant-speed penetrometer (Schneebeli and Johnson, 1998; Proksch et al., 2015).

In December 2016 and January 2017 we were able to capture a snowfall and subsequent drifting snow event in Antarctica which resembled our wind tunnel experiments. Comparable measurements to those in the wind tunnel were performed. The Antarctic event is presented in this paper and we show how the observations compare to the wind tunnel results. An event as described below has not yet been observed in such detail. To our knowledge, simultaneous SMP and terrestrial laser scanning measurements of a barchan dune have never been performed. The results are expected to give new insight into how snow accumulation may happen in polar environments.

2 Data and Methods

The event was observed close to the Princess Elisabeth Station, which is located about 220 km inland in Queen Maud Land at an elevation of 1392 m above sea level (71°57' S and 23°21' E). Meteorological data is provided by two identical blowing snow stations 350 m apart. Each station is equipped with two Young wind monitors (HD, Alpine Version, model 05108-45), a Campbell Scientific (CS) CSAT3B sonic anemometer, a CS SR50A ultrasonic snow depth sensor, a CS CS215 temperature and relative humidity probe, an Apogee Instruments SI-111 infrared radiometer to measure the snow surface temperature and a Niigata Electric Snow Particle Counter (SPC, model SPC-95) measuring the number and size of saltating particles. The stations are each powered by a solar panel and a small wind turbine. Here, only mass flux and wind speed data are used. The mass flux measured by the two SPCs was averaged and then integrated to compute the cumulative mass flux. Due to data logger problems, there are gaps up to several days long in the time series of the different wind speed sensors. Therefore, all the CSAT and Young data was combined into a single wind speed time series with a temporal resolution of one minute. The averaged wind speed was calculated without adjusting for the height above ground of the sensors, which were at heights between about 1 m and 3.5 m.

Digital Surface Models (DSM) of the terrain around the two stations were acquired on several days with a Riegl VZ-6000 Terrestrial Laser Scanner (TLS). The scanner was positioned on a tripod on top of a container to increase the field of view and the incidence angle between the laser beam and the terrain.

About 450 SMP profiles were acquired. The same processing as in Sommer et al. (2017) was applied to them. In short, each profile is reduced to a characteristic number which is the 90% quantile of the force in the topmost centimeter of the snowpack. This variable, called the SMP hardness, is well suited to detect hardness changes at the surface. The location of SMP transects was marked with bamboo poles and the SMP positions in each transect was determined with a measuring tape. The bamboo poles are visible in the TLS scans, allowing for an accurate positioning of the SMP measurements with respect to the DSMs, which can therefore be used to calculate snow depth changes and Sx at the SMP positions. All SMP and TLS measurements were performed between the two blowing snow stations.

In Sommer et al. (2018), we showed that deposition of snow only led to hardening in wind-exposed areas. As explained in the introduction, the parameter Sx was used to describe wind-exposure and wind-sheltering. Based on the Kinect data, Sx could be calculated as a function of time. In Antarctica, the available DSMs can be used for a similar analysis. We cannot calculate a time evolution of Sx but the values calculated based on the scans should reflect the wind-exposure situation at the end of

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the deposition period. These values were then correlated to the SMP hardness change which reflects the hardness at the same point in time. The main wind direction was estimated to be 86° based on the dune's orientation. To determine Sx, a sector of 5° around the main wind direction up to a maximum search distance of 1 m was considered.

The data is publicly available on Envidat (Reference follows).

3 Results

Figure 1 gives an overview over the studied period. Figure 1A shows the wind speed, Fig. 1B the cumulative drifting snow mass flux and Fig. 1C the SMP hardness all as a function of time. Figure 1C also shows when TLS scans were acquired. The DSM of 18 December is used as a reference to calculate subsequent snow depth changes. The scan of 19 December has a lower resolution and was therefore not used. Between the reference scan and the begin of the snowfall period, the wind speed was high, reaching 8 ms^{-1} during three periods. The SPC data shows that there was drifting snow during those three periods. The wind speed decreased to below 6 ms^{-1} during the snowfall and consequently, almost no drifting snow was observed during and for several days after the snowfall period. Comparing the TLS scans from before and after the snowfall showed that there were about 10 cm of fresh snow in the area where SMP measurements were performed. SMPs were acquired on three days in the period after the snowfall without drifting and all of them have very soft snow at the surface. The SMPs acquired directly after the snowfall event on 22 December are called "Initial SMPs" and their average SMP hardness of 0.01 N is used as a reference to calculate SMP hardness changes. There was a small drifting snow event on 28 December. 105 out of the 128 SMPs acquired afterwards on 29 December have hardnesses below 1 N. However, 23 SMPs were harder than 4 N (squares in Fig. 1C). The DSM of the same day shows that all these SMPs were acquired in an area of deposition with respect to 18 December but it was noted at the time that there had been recent erosion in some areas. Most likely, snow was deposited there during the drifting snow events before the snowfall and the new snow that accumulated during the snowfall period, was eroded again during the drifting snow event on 28 December exposing the old surface. The hard snow surface is therefore part of a deposition of old snow. The main drifting snow event took place on 30-31 December. The wind speed was higher than 10 ms^{-1} and the cumulative mass flux increased by 28 kgm^{-2} which is 40 times higher than the increase during the small drifting snow event on 28 December. The TLS scans acquired afterwards show that barchan dunes formed everywhere in the study area (see Fig. 2). The wind speed decreased again to below 6 ms^{-1} after the event and there was almost no drifting snow anymore. The dunes remained correspondingly inert. SMPs were acquired on five days after the event. On 3, 6 and 7 January, the hardness of a selected dune was measured in a total of 10 transects. Seven more "Dune SMPs" (triangles in Fig. 1C) were acquired on 12 January. These seven measurements as well as seven SMPs from 7 January were repeat measurements that were acquired close to clearly identifiable measurement locations from previous days. It can be seen in Fig. 1C that there were areas with a soft surface before the snowfall as well as after the drifting snow event. This shows that drifting in itself is not a sufficient condition to form a wind crust.

Figure 2A shows an image of the surveyed barchan dune viewed from the scan position on the container. Figure 2B shows the snow depth change between 18 December and 6 January from the same perspective as Fig. 2A. The bamboo poles marking

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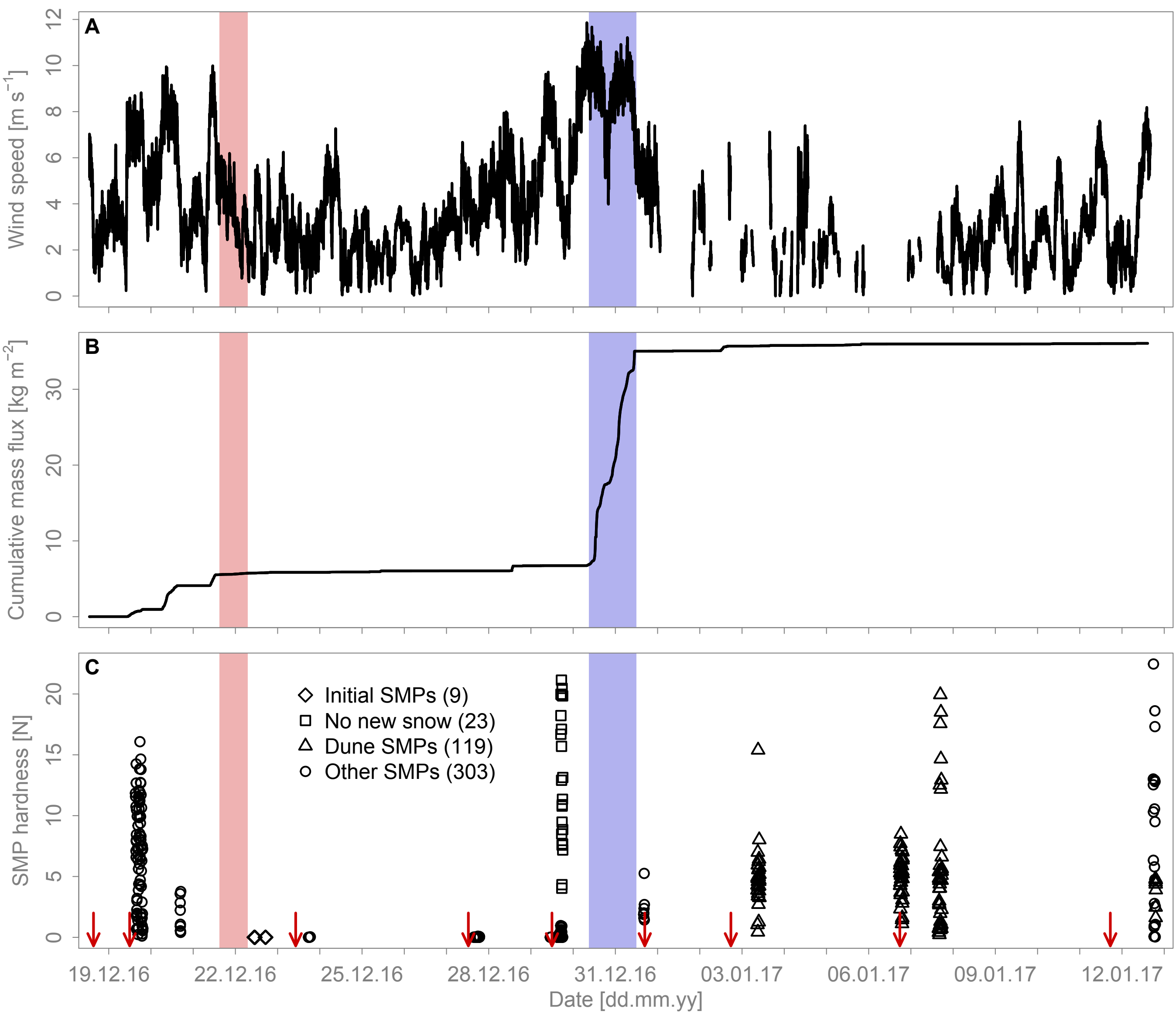

Figure 1. Overview of the observed snowfall and drifting snow event. (A) shows the wind speed, (B) the cumulative drifting snow mass flux and (C) the SMP hardness. The snowfall period (light red) and the main drifting snow period (light blue) are highlighted. The vertical red arrows in (C) show when TLS scans were acquired. The numbers in parentheses in the legend in (C) give the number of SMPs in the corresponding category. The "Initial SMPs" were acquired immediately after the snowfall period and are used as a reference to calculate hardness changes. The "No new snow" SMPs are measurements that were acquired in locations were all the new snow had been eroded. The "Dune SMPs" were acquired in ten transects of a selected barchan dune that formed during the drifting snow period.

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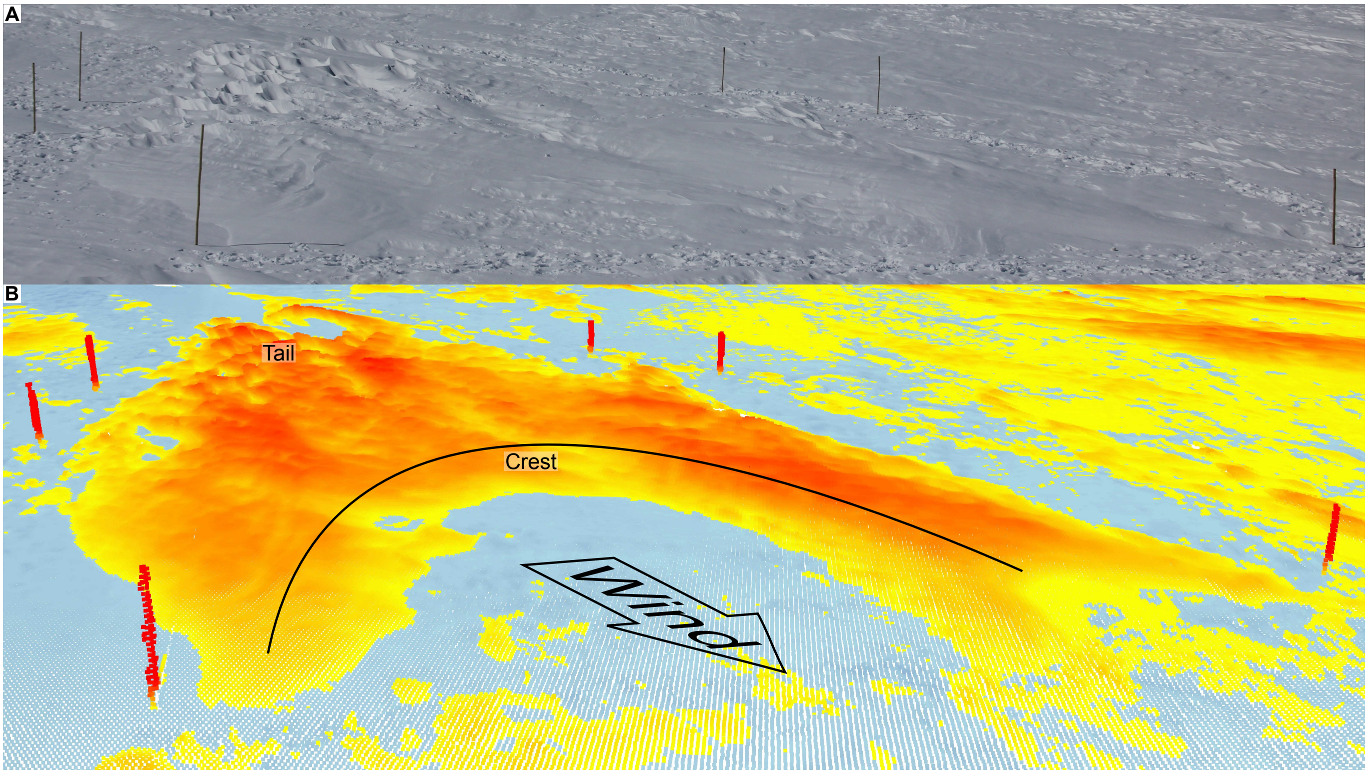

Figure 2. (A): View of the surveyed barchan dune from the scan position. The bamboo poles mark the position of the first three SMP transects measured on 3 January. Note the zastrugi at the tail of the dune. (B) shows the corresponding snow depth changes from the same direction but at a little steeper angle. The color code is the same as in Fig. 3. The arrow shows the direction in which the wind was blowing. The same nomenclature as in Filhol and Sturm (2015) is used here: The upwind end of the dune is called "tail" and the downstream end is called "crest".

the SMP transects are clearly visible in both parts of the figure. It can be seen in Fig. 2A that zastrugi formed in the tail area (upstream end, see Fig. 2B) of the dune. Zastrugi Filhol and Sturm (2015) are erosional surface features meaning that the dune has already been partly eroded again. The dune is about 25 m long, 11 m wide and 15-20 cm high. With these dimensions, the dune is rather large in the horizontal and average in the vertical compared to values reported in the literature Filhol and Sturm (2015). It is clear from Fig. 2A how shallow most barchan dunes are and that they may not even be detectable by eye without differential snow depth measurements.

Figure 3 shows a bird's eye view of the dune and the positions of the SMPs in all ten transects. The snow depth change shown here is the difference between the DSMs of 18 December and 11 January. The white areas are measurement shadows caused mainly by the zastrugi in the tail area of the dune (Fig. 2). To assess the hardening of the fresh snow, we only analyze SMPs with newly deposited snow at the surface (circles in Fig. 3). SMPs in areas where the old snow surface from before the snowfall is exposed were therefore removed. The difference between the DSMs of 31 and 29 December clearly show that the

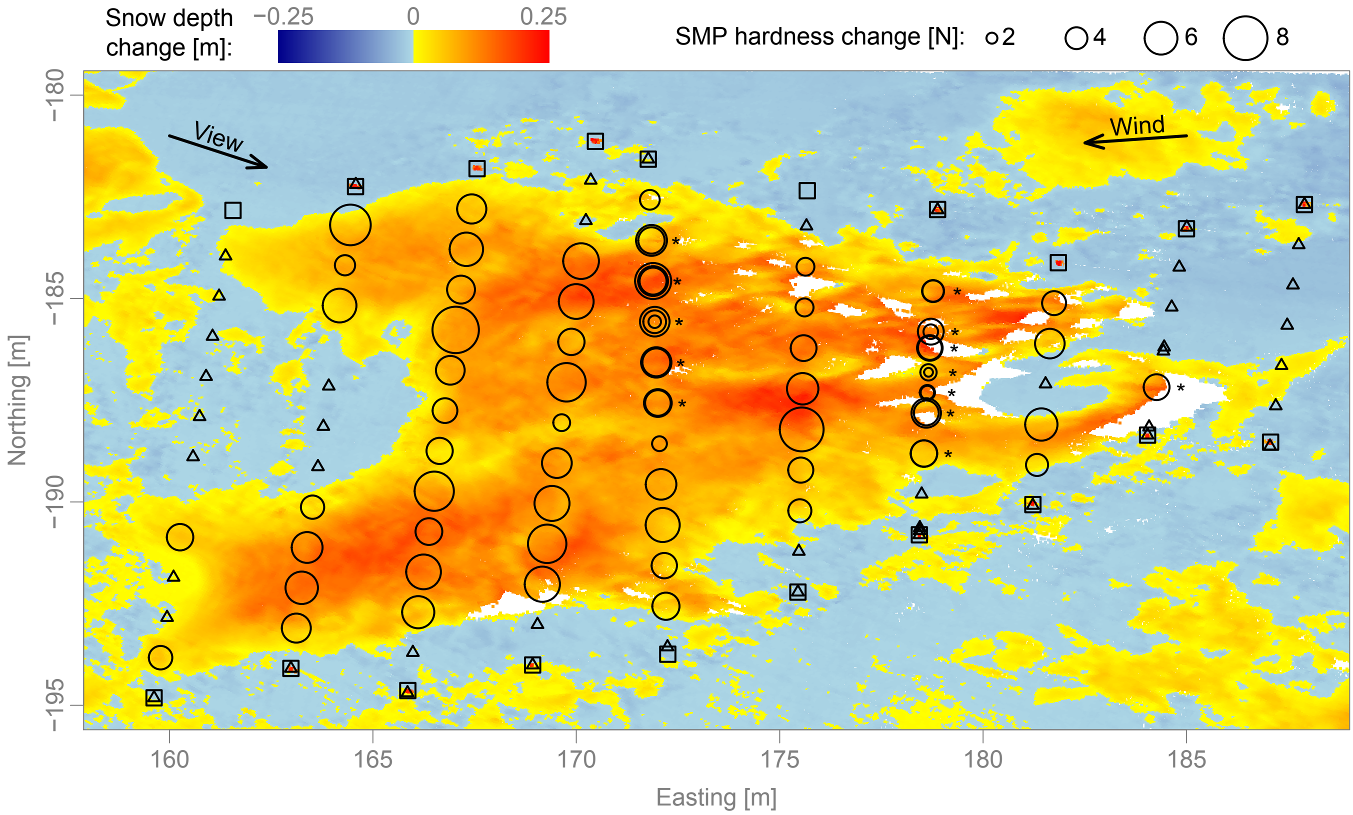

Figure 3. Top view of the dune. Squares (□) mark the positions of the bamboo poles. Triangles (△) show the positions of SMPs acquired in TLS measurement shadows or in areas where all the fresh snow had been eroded. Circles (○) show the positions of SMPs with freshly deposited snow at the surface. The diameter of the circles is proportional to the hardness increase. Asterisks (*) mark positions were repeat measurements were performed. The arrows show the predominating wind direction during the main drifting snow event and the approximate view direction in Fig. 2.

dune formed during this period. For other depositions of snow, it is not clear whether they accumulated during the drifting snow events before or after the snowfall event. The SMP measurements in these areas are therefore not analyzed here. As can be seen in Fig. 3, not all "Dune SMPs" are located on the dune itself, i.e. in areas with a positive snow depth change. A deposition of at least 1 cm is required in order not to consider old snow in the calculation of the SMP hardness. A threshold of 2 cm was used to allow for some uncertainty and all "Dune SMPs" with a snow depth change below 2 cm and SMPs in measurement shadows were discarded (triangles in Fig. 3). To calculate the snow depth changes, the DSM from 2 January was used for the SMPs from 3 January, the DSM from 6 January for the SMPs from 6-7 January and the DSM from 11 January for the SMPs from 12 January.

The size of the circles in Fig. 3 shows the SMP hardness change as a function of the position on the dune. The distribution seems to be mostly random but the snow tends to be slightly softer at the tail than at the crest. This can be seen more clearly

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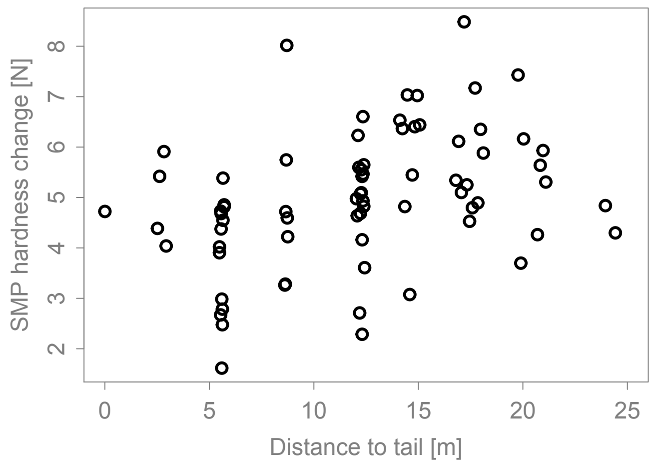

Figure 4. Scatterplot of SMP hardness change against the distance to the dune's tail. The correlation coefficient is 0.37. The correlation is significant with a p-value of 0.001.

in Fig. 4, which presents a scatterplot of SMP hardness change against the distance to the tail of the dune. The distance is measured in the main wind direction (86°) from the most upwind circle shown in Fig. 3. The correlation between the SMP hardness change and this distance is 0.37. As can be seen in Figs. 3 or 4 the trend is not very clear and the variability is high. Nevertheless, the correlation coefficient is significant with a p-value of 0.001. The repeat measurements are marked with asterisks (*) and show that the local variability can be high. These measurements were performed close to existing SMP holes and some of them have a remarkably different SMP hardness than their predecessors. For other repeat measurements, the SMP hardness change corresponded well. In these cases, the local variability was low. It must be kept in mind, that these SMPs were acquired on different days between 3-12 January. Even if the wind speed was below 6 ms^{-1} and the cumulative mass flux remained constant in this period, some of the variability may be due to temporal effects.

In Sommer et al. (2017), groups of SMPs acquired after wind periods with or without drifting snow were compared and it was shown that no crust formed without drifting. Here, the cumulative mass flux since the acquisition of the "Initial SMPs" is used as a measure of how much drifting occurred. There are three groups of SMPs. Those with basically no drifting (from 23 and 27 December), those acquired after the small drifting snow event (from 29 December) and those acquired after the main drifting snow event (from 3-12 January). The first group ("No drifting") is defined by a cumulative mass flux below 0.25 kgm^{-2}, the second group ("Small event") by a cumulative mass flux of 0.94 kgm^{-2} and the third group ("Main event") by a cumulative mass flux above 29.9 kgm^{-2}. The SMP hardness changes of these three groups are compared in Fig. 5 using boxplots. The boxes show the first and third quartiles and the length of the whiskers is 1.5 times the interquartile range at most. The SMPs with no new snow (squares in Fig. 1C) and SMPs in areas of erosion (triangles in Fig. 3) were removed such that only SMPs with freshly deposited snow at the surface remain. The plot shows the SMP hardness change relative to the mean SMP hardness of the 9 initial SMPs (Fig. 1C). The SMP hardness increased by up to 0.09 N in the "No drifting" group but

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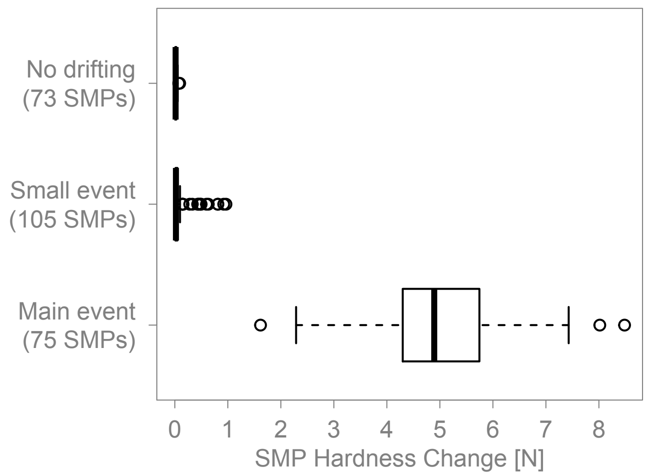

Figure 5. Boxplots comparing the SMP hardness change for three groups of SMPs. The "No drifting" SMPs were acquired on 23 and 27 December, the "Small event" SMPs were taken on 29 December after the small drifting snow event and the "Main event" SMPs were acquired on 3-12 January after then main drifting snow event. The boxes show the first and third quartiles and the length of the whiskers is 1.5 times the interquartile range at most.

the median SMP hardness change is only 0.01 N. The snow at the surface remained very soft. For the SMPs acquired after the small drifting snow event, the median SMP hardness change of 0.02 N is low as well. However, 17 SMPs in this group are classified as outliers and have hardness increases up to 0.96 N. A Kruskal-Wallis test comparing the "No drifting" and "Small event" groups confirms that they are different with a p-value of 0.007. The SMPs acquired after the main drifting snow event have SMP hardness increases between 1.62 N and 8.48 N with a median of 4.89 N. According to Kruskal-Wallis tests, the "Main event" group is different from the other two with p-values $\sim 10^{-16}$.

The scatterplot of Sx against the SMP hardness change is shown in Fig. 6. The correlation between the two variables is -0.26 and the coefficient of determination is therefore about 7%. The correlation coefficient is significant with a p-value of 0.03. The slope of the linear regression is -0.015 N^{-1}. The scatterplot contains 68 points. Five SMPs were removed because their search sectors contained less than four TLS points. The negative correlation shows that the hardening tends to be more efficient in more wind-exposed areas.

4 Discussion and conclusion

The observed event was a close approximation of our wind tunnel experiments. A homogeneous snowfall, a period with wind but without drifting snow and finally a strong drifting snow event. In Antarctica, a 10 cm snowfall without wind is rarely observed and we were fortunate to capture this event. The SMP and TLS data were analyzed similarly to the SMP and Kinect data acquired in recently published wind tunnel experiments. The comparison of the results provides a valuable validation of the wind tunnel experiments.

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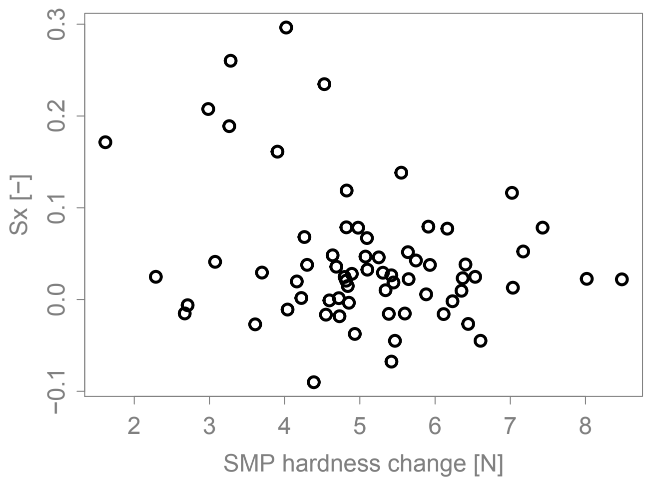

Figure 6. Scatterplot of Sx against the SMP hardness change. The correlation coefficient is -0.26. The correlation is significant with a p-value of 0.03

In the wind tunnel, we first compared SMPs that were acquired after wind periods with or without drifting snow. We found that drifting snow is a necessary but not sufficient condition for the formation of a wind crust. In Antarctica, we observed the same result (Fig. 5). For the SMPs with a cumulative mass flux close to zero the SMP hardness did not increase considerably. In the group of SMPs acquired after the small drifting snow event the hardness increased by up to 1 N. This is the range of hardness increases that was observed in the wind tunnel. The SMP hardness increases after the main drifting snow event are a lot higher than anything we have achieved in the wind tunnel. This is most likely due to higher wind speeds and more intense drifting in Antarctica. We do not have a logarithmic boundary layer in the wind tunnel and did not measure the mass flux. The conditions can therefore not be compared directly. However, the free stream wind speed in the wind tunnel was measured about 30 cm above the snow surface and rarely exceeded 6 ms^{-1}.

Kuznetsov (1960) measured the hardness of a mobile barchan dune and observed that the crest was softer than the tail (see also Filhol and Sturm (2015)). Our measurements, on the other hand, suggest that the tail area is slightly softer than the crest (Figs. 3 and 4). A clear difference between the two observations is that the dune we surveyed was already a few days old and not moving anymore. Furthermore, the tail area had also already been partly eroded again. The measurement conditions were therefore quite dissimilar and could explain the differing results.

With the parameter Sx we can explain only 7$\%$ of the variability of the SMP hardness change. This is in contrast to the wind tunnel experiments (Sommer et al., 2018) where Sx explained 40$\%$ of the variability. The correlation coefficient is negative in both cases but the slope of the linear relationship is also quite different. In the wind tunnel, the slope was -2.54 N^{-1} and in Antarctica it is -0.015 N^{-1}. The main difference is the range of Sx and SMP hardness values. The Sx range was higher in the wind tunnel where we performed experiments with artificial obstacles. This led to highly wind-sheltered areas with Sx > 1. In Antarctica, Sx did not exceed 0.3. The SMP hardness range, in contrast, is much higher in Antarctica, where it is about 2-8

N. In the wind tunnel, the highest SMP hardness considered in the Sx analysis was only 0.24 N. If only points from the wind tunnel experiments with Sx < 0.3 are considered, the resulting correlation coefficient of -0.43 is still higher than the -0.26 for the Antarctic event and the slope of the linear model decreases only to -0.996 N^{-1}. This could be due to the different range of SMP hardnesses and the various uncertainties in the Antarctic data. The position of the SMP measurements, the digital surface model and the wind direction are all less precisely known than in the wind tunnel. Furthermore, the available TLS scans do not allow to calculate a temporal evolution of Sx as the Kinect data do in the wind tunnel. Here, Sx can only be calculated after the deposition period. The lower correlation suggests that these values have less explaining power than Sx values calculated at the time of deposition.

Even though the results from Antarctica are less clear than those from the wind tunnel, the trends are the same. There was no hardening without drifting snow and the correlation between Sx and hardness is negative. This analysis documents for the first time quantitatively how fresh snow gets reorganized in a drifting snow event in Antarctica. The measured change in associated hardness is invaluable to improve existing models of snow deposition (Groot Zwaaftink et al., 2013).

Data availability. The data is publicly available on Envidat (Reference follows).

Author contributions. ML and NW designed the project and collected the data in Antarctica. CS and NW processed the data. CS analyzed the data and wrote the Manuscript. NW, ML and CF helped with the analysis and revised the manuscript.

Competing interests. The authors declare that there are no competing interests present.

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