Drifting snow statistics from multiple-year autonomous measurements in Adelie Land, eastern Antarctica

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Abstract. Drifting snow is a widespread feature over the Antarctic ice sheet whose climatological and hydrological significances at the continental scale have been consequently investigated through modelling and satellite approaches. While field measurements are needed to evaluate and interpret model and punctual satellite products, most drifting snow observation campaigns in Antarctica involved data collected at a single location

10 and over short time periods. With the aim of acquiring new data relevant to the observations and modelling of drifting snow in Antarctic conditions, two remote locations in coastal Adelie Land (East Antarctica) 100 km apart were instrumented in January 2010 with meteorological and second-generation IAV Engineering acoustic FlowCapt™ sensors. The data provided nearly continuously so far constitutes the longest dataset of autonomous near-surface (i.e., below 2 m) measurements of drifting snow currently available over the Antarctic continent.

15 This paper presents an assessment of drifting snow occurrences and snow mass transport from up to 9 years (2010-2018) of half-hourly observational records collected in one of the Antarctic regions most prone to snow transport by wind. The dataset is freely available to the scientific community and can be used to complement satellite products and evaluate snow-transport models close to the surface and at high temporal frequency.

1.   Introduction

20   Wind-driven transport of snow in Antarctica, organized in drifting (< 2 m above ground level) and blowing (> 2 m above ground level) snow, has important implications for the ice-sheet climate and surface mass balance. Erosive winds redistribute snow at the surface and can form areas of near-zero net accumulation (known as wind glaze areas) or even net ablation (known as blue ice areas) whose presence has a profound influence on the local surface energy balance (Bintanja, 1999; Scambos et al., 2012), possibly enhancing surface melt

25 (Lenaerts et al., 2017). In coastal (wind confluence) areas the horizontal divergence of snow through wind transport is responsible for an export of mass beyond the ice-sheet margins. Sublimation of snow particles during transport is a major component of the surface heat and moisture budgets in regions where most of the precipitated snow is relocated by wind.

Because of the widespread character of drifting and blowing snow over the vast and remote Antarctic

30 continent, estimates of their hydrological and climatological significances at the ice-sheet scale rely on parameterized methods (e.g., Gallée 1998; Déry and Yau 2002; Lenaerts and van den Broeke 2012; Palm et al., 2017; van Wessem et al., 2018; Agosta et al., 2019). A consensus emerging from these efforts that has persisted for more than two decades suggests that, although significant locally, mass loss through wind redistribution and export into the ocean is of minor importance while sublimation during transport remains the dominant sink of

35 mass when evaluated over the whole ice sheet. Conversely, contrasted results are to be found from one study to

another in the absolute values attributed to the relative contribution of these various mechanisms. Latest continent-wide estimations of wind-driven snow sublimation obtained from regional modelling (van Wessem et al., 2018) are lower by a factor of 4 than those computed from a combination of satellite products and meteorological reanalysis (Palm et al., 2017). Modelled snow mass fluxes presented in van Wessem et al. (2018)

40   exhibit a similar overall spatial pattern but are more than 3 times fewer than those reported in Agosta et al. (2019). Considering the diversity of interactions and the non-linearity of processes involved in the onset, development and magnitude of wind-driven snow occurrences (e.g., Déry et al., 1998; Bintanja 2000; Amory et al., 2016), the degree of plausibility of model-dependant features as well as the assumptions made in the formulations employed to produce them need to be carefully assessed with independent observations.

45   Advances in active lidar remote sensing of the atmosphere from space have provided recent insights into the spatial distribution and temporal variability of blowing snow over the last decade independently from modelling approaches. Although of unrivalled interest for studying blowing snow over large temporal, horizontal and vertical scales simultaneously, satellite lidar data provide snapshots of a particular set of blowing snow properties (frequency, layer depth, optical thickness) relatively to the satellite revisit time (Palm et al. 2011).

50   Moreover, satellite detection is restricted to clear-sky or optically thin cloud conditions and relatively deep (> 30 m) blowing snow layers, precluding its application for characterization of shallower (drifting and blowing snow) layers and for model evaluation in the vicinity of the surface. While this last limitation is also shared with ground-based remote sensing techniques (Mahesh et al., 2003; Gossart et al., 2017), measured vertical profiles of snow mass fluxes display however the strongest gradients in the lowest metres of the atmosphere (Budd, 1966;

55   Mann et al., 2000; Nishimura and Nemoto, 2005).

       Direct near-surface observations of wind-driven snow in Antarctica are sparse in time and space to the extent that long-term quality-controlled datasets that yet constitute essential development and evaluation bases for parametrization schemes barely exist. The absence of an official standard instrument has led to the use of a wide range of observation techniques from mechanical traps and nets to electronic (optical, piezoelectric,

60   acoustic) sensors (see Leonard et al. (2011) and Trouvilliez et al. (2014) for an extensive review) as well as visual observations carried out at some Antarctic manned stations (Mahesh et al., 2003; König-Langlo and Loose, 2007). However, like satellite products, visual observations are representative of instantaneous conditions only and are additionally dependent on personal appreciation of the observer who might change with time, leading to non-uniform and temporally discontinuous records.

65   In spite of their disparity, near-surface measurements have provided valuable and accurate information that cannot be sensed remotely nor determined visually. This includes, among others, particle size distributions and related dimensionless shape parameters, total particle numbers and snow mass fluxes at different heights. Although the data collected are also relative to the instrument used and can hardly compare to each other, they are eventually useful for modelling experiments. The dimensionless shape parameter and particle number are, for

70   instance, either predicted or prescribed quantities in snow-transport models that compute sublimation rates and snow mass fluxes assuming a gamma distribution of particles (e.g., Déry et al., 1998; Mann, 1998; Déry and Yau, 1999, 2001; Bintanja, 2000; Nemoto and Nishimura, 2004; Lenaerts et al., 2012). Additionally observed snow mass fluxes can be directly used to assess the ability of models to reproduce wind-driven snow conditions at a specific location in a qualitative (Lenaerts et al., 2012; Gallée et al., 2013) or a quantitative (Nishimura and

75   Nemoto 2005; Yang and Yau, 2008; Amory et al., 2015; van Wessem et al., 2018) perspective. However, even if

each dataset is individually valuable regarding the scarcity of observations, in most cases the data were collected at a single location and over a few months, precluding investigations into spatial and temporal (seasonal and interannual) variability.

80   In order to acquire new model-evaluation oriented observations, a field campaign specifically dedicated to drifting snow has been run in January 2010 in Adelie Land (Trouvilliez et al., 2014), a wind confluence area of East Antarctica. Two distinct locations, namely D17 and D47 (Fig. S1), were instrumented and equipped with second-generation IAV Engineering acoustic FlowCapt™ sensors[1] (hereafter referred to as 2G-FlowCapt™), which are particularly well-suited for long-term monitoring in remote environments and under harsh conditions (Trouvilliez et al., 2015). This study presents an assessment of drifting snow occurrences and snow mass

85   transport from analysis of multiple-year timeseries of meteorological data and snow mass fluxes collected in a katabatic wind region of the Antarctic ice sheet among the most prone to snow transport by wind.

2. Site characteristics and data

2.1. Instrumentation

The study area consists of a sloping snowfield with a break-in-slope at nearly 210 km inland at about

90   2,100 m a.s.l., downstream of which D47 and D17 are located (Fig. S1). The two measurement sites are 100 km apart, south-west of the permanent French station Dumont d'Urville (66°39'S, 140°00'W, 40 m a.s.l.). Because of their remote locations, access and maintenance activities are only possible in summer. At D17, a 7-m high mast is equipped with six levels of anemometers and thermo-hygrometers housed in naturally ventilated MET21 radiation shields (Fig. S2, left panel). The wind direction is sampled at the upper level of the meteorological

95   mast. At D47, wind speed and direction, temperature and relative humidity are measured at only one level (Fig. S2, right panel). The thermo-hygrometers are factory calibrated to report relative humidity with respect to liquid water. Goff and Gratch (1945) formulae are used to convert to relative humidity with respect to ice for air temperatures below 0 °C, using the sensor temperature reports in the conversion. Ultrasonic depth gauges are used to monitor surface height changes at both sites, from which the elevation of the sensors above the surface is

100   assessed throughout the year. At D17, this information is not available before December 2012 when the height ranger was deployed. The profile initially ranged from 0.8 m to 6.9 m in February 2010 and the instruments were raised back manually to original heights at the beginning of each summer field campaign. The remoteness and the frequently harsh weather conditions of D47 allowed for limited servicing time, so that summer visits were restricted to the maintenance of sensors without raising operations. As a result the measurement heights

105   decreased from initially 2.8 m for wind speed and 2.2 m for temperature and relative humidity to respectively 1.5 m and 0.9 m in late December 2012 when the equipment was entirely removed. The instrument types and specificities are summarised in Table S1. Data were sampled at 15-s intervals, and stored at a half-hourly time resolution on a Campbell CR3000 datalogger.

2.2. Meteorological settings

110   The surface climate in coastal Adelie Land is dominated by intense, frequent and persistent katabatic flows originating from the cold continental interior where strong temperature inversions develop. The local

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[1] http://www.flowcapt.com/.

topography controls the drainage of the sinking near-surface air as it converges and accelerates toward the steep coastal escarpment over a unobstructed snow-covered fetch of several hundreds of kilometres. Wind speed and temperature regimes at the two measurement locations follow an annual cycle typical of katabatic wind confluence areas (Fig. S3). Lower temperatures and higher wind speeds are observed in winter as a result of the strong radiative deficit of the surface and increased katabatic forcing. In summer, the absorption of shortwave radiation by the surface diminishes the katabatic forcing, air temperature increases and wind speed reduces. The higher incidence of drifting snow and inherent loading of air masses with moisture through sublimation combined to lower temperatures in winter account for an increase in near-surface relative humidity compared to summer values. Substantially lower temperatures and subsequent dampened seasonal variations in relative humidity are observed at D47 due to the higher elevation. Table 1 lists geographical settings and annual (2-m height) meteorological statistics for the two sites.

Even if D17 is located near the downstream end of the sloping ice terrain where stronger katabatic forcing can be expected, year-round higher wind speeds are consistently observed at D47 some 100 km inland, as already reported by Wendler et al. (1993). Although the question remains open for further study, an explanation for this feature may involve the deceleration and subsequent thickening of the atmospheric boundary layer flow beyond the ice-sheet margins where it is no longer sustained by the buoyancy (katabatic) force. The resulting accumulation of cold air downstream over the ocean leads to the establishment of an upslope pressure gradient force opposing the katabatic flow that is responsible for an additional slowing of the airstream when reaching the coastal area (Gallée and Pettré 1998), possibly accounting for the lower wind speeds at D17 compared to D47.

Both measurement sites show a very high constancy in wind direction (defined as the ratio of the resultant wind speed to the mean wind speed), reflecting the quasi-unidirectional nature of the flow in coastal Adelie Land (Table 1; Fig. S2). This evidences that topographic channelling strongly controls the surface wind regime, and indicates that cyclonic disturbances do not significantly alter the direction of the main flow.

2.3. Drifting snow data

At each station the meteorological records were complemented by drifting snow measurements made with 2G-FlowCapt™ sensors. The instrument consists of a 1 m long tube containing electroacoustic transducers that measure the acoustic vibration caused by the impacts of windborne snow particles on the tube. Using spectral analysis, the sensor accurately distinguishes the low-frequency noise generated by turbulence from the high-frequency drifting snow signal, which is proportional to the snow mass flux integrated over the length of the tube. This means that the measured acoustic vibration, and thus, the estimation of the snow mass flux depends on the shape, size, density and speed of each individual particle colliding with the tube (Cierco et al., 2007). As precipitating snow particles directly originating from clouds and drifting (saltating and/or suspended) snow particles relocated from the ground cannot be discriminated, measured snow mass fluxes account for all forms of wind-driven snow along the sampling height.

To remove electronic or turbulence noise and ensure that actual occurrences are detected, drifting snow has been considered to occur when the half-hourly mean of the snow mass flux exceeds a confidence criterion of 10^{-3} kg m^{-2} s^{-1} (Amory et al., 2017). In a comparison study between the 2G-FlowCapt™ and optical measurements made with the SPC-S7 in the French Alps, this criterion yielded an excellent agreement (98.6 %)

between the two types of sensors in terms of occurrence detection (Trouvilliez et al., 2015). The integrated snow mass fluxes provided by the 2G-FlowCapt™ were also shown to be underestimated compared to the optical measurements and should thus be considered as lower bound values.

In early January 2010 at D47, two 2G-FlowCapt™ were installed and superimposed vertically, with the
155   bottom of the lowest sensor located close to the surface (~0.1 m) in order to detect the onset of drifting snow occurrences. At D17 two sensors were deployed in February 2010 but only one was initially installed close to the surface while the other one was set up at the top of the measurement structure (4.5 to 5.5 m). The upper sensor was removed in January 2011 because of malfunction, and reinstalled after repair in late December 2012 similarly to the configuration adopted for D47.

160   Burial of the 2G-FlowCapt™ through accumulation of snow affects the estimation of the snow mass flux as it is vertically integrated over the uncovered part of the instrument. This is a matter of concern at both sites since precipitation along the Adelie coast occurs year round almost exclusively in the form of snowfall with a mean accumulation amounting to 362 mm water equivalent per year (Agosta et al., 2012). Like for the other meteorological instruments, the 2G-FlowCapt™ sensors at D17 were reset into their original position with the
165   lower sensor near the surface during each summer visits, except for austral summers 2015-2016 and 2016-2017 during which the pair of instruments was left unchanged. Consequently, substantial burial of the lower sensor took place along the 3-year period from early 2015 to late 2017 depending on snow accumulation and ablation. As no raising operations were undertaken at D47 the measurement structure progressively buried and the lower 2G-FlowCapt™ became entirely covered with snow during the course of the year 2012.

170   The 2G-FlowCapt™ can record continuous information as long as it remains partially emerged. This is an advantage over visual observations and satellite products provided at punctual intervals. Moreover, the ability of these sensors to detect events of small magnitude is particularly interesting, as remote sensing techniques can only retrieve information on blowing snow layers for which the snow particles are lifted at several tens of metres off the surface (Mahesh et al., 2003; Palm et al., 2011; Gossart et al., 2017).

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Station	D17	D47
Observation period	Feb. 2010 - Dec. 2018	Jan. 2010 - Dec. 2012
Location	66.7°S, 139.9°E	67.4°S, 138.7°E
Altitude (m)	450	1,560
Distance from coast (km)	10	110
Wind speed (m s^{-1})	9.8	11.9
Temperature (° C)	-15.5	-25.1
Relative humidity (%)	81.4	90.6
Wind direction (deg)	154	158
Directional constancy	0.92	0.95

Table 1. Geographical and climatological characteristics of the two measurement locations for the respective observation periods

3. Analysis of observations

3.1 Spatial and temporal variation in drifting snow occurrences

Monthly values of drifting snow frequency at D47 and D17 indicate that drifting snow is a regular feature of the coastal slopes of Adelie Land (Fig. 1; overall averages of 0.82 at D47 and 0.66 at D17). Frequency values have been computed for each month of the observation period as the ratio between the number of half-hourly observations with a snow mass flux higher than the confidence criterion of 10^{-3} kg m^{-2} s^{-1} and the total number of observations in that month. On each panel the shaded area corresponds to the frequency respectively computed using a relaxed and a stricter confidence criterion of 10^{-4} kg m^{-2} s^{-1} and 10^{-2} kg m^{-2} s^{-1} and is shown as a measure of uncertainty. While no particular inter-annual variability is depicted (Fig. S4), drifting snow frequency varies strongly within the year, with an amplitude that can differ from year to year. Both locations experience a higher incidence of drifting snow in winter (defined here as the 8-month period between 1 March and 1 November) than during the rest of the year, a pattern quite common over Antarctica (Mahesh et al., 2003; Scarchilli et al. 2010; Gossart et al., 2017; Palm et al., 2018). At the end of winter, a gradual decrease in drifting snow frequency is observed until a minimum is reached during summer, consistently with the annual course of wind speed (see Fig. S3, upper panel). This seasonal contrast is more pronounced at D17 than at D47 due to the stronger inhibition of erosion in summer resulting from lower wind speeds and higher air temperatures that promote the formation of cohesive bonds holding particles to the surface. Although the use of a lowered confidence criterion does not affect significantly the derived frequency, the stronger sensitivity to the increased confidence criterion evidences the important contribution of occurrences of relatively small magnitude (i.e., < 10^{-2} kg m^{-2} s^{-1}) to the overall frequency.
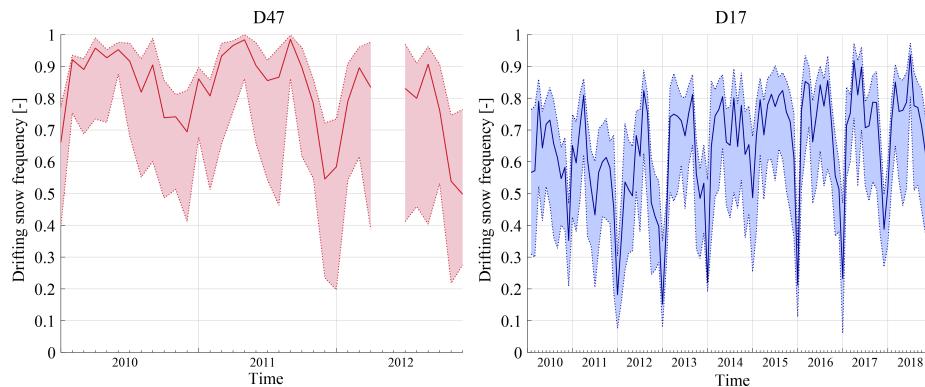
Figure 1. Seasonal variability of drifting snow frequency as recovered by the 2G-Flowcapt™ instruments. Note the absence of data at D47 during May and June due to instrument malfunction.

Higher monthly values of drifting snow frequency are also systematically observed 100 km inland at D47 than close to the coastline at D17. Analysis of drift conditions documented simultaneously at D17 and D47 for the 3-year period 2010-2012 evidences a significant spatial variability, with almost all drifting snow occurrences at D17 involving drifting snow at D47 while the opposite does not hold true (Table S2). Wind speeds at D47 for which drifting snow is observed at D47 only (28.2 % of occurrences) are generally lower (average of 11.3 m s^{-1}) compared to those for which the two locations experience drifting snow simultaneously

(average of 13.9 m s^{-1}). This means that the largest occurrences are seen at both sites, and the higher drifting

210   snow frequency at D47 is mainly due to additional occurrences of lesser magnitude for which the reduced wind

speed downstream at D17 is not high enough to trigger snow transport.

3.2 Frequency of occurrence

Wind speeds for which drifting snow is detected (averages of 13 m s^{-1} for D47 and 12.1 m s^{-1} for D17)

are generally higher than those occurring without drifting snow (averages of 6.8 m s^{-1} for D47 and 5.4 m s^{-1} for

215   D17), although a wide range of similar wind speeds coexists between both categories. Following the approach of

Baggaley and Hanesiak (2005) aiming at predicting the occurrence of snow transport from a set of common

meteorological parameters, a credibility index (CRED) was used in a simpler approach to provide an estimation

of the frequency of occurrence of drifting snow under specific wind conditions:

$$CRED = p/(p + n) \hspace{4cm} (1)$$

where p is the number of occurrences of drifting snow for a given wind speed range and n is the number of non-

220   occurrences within that range. CRED varies from 0 to 1 and reflects the probability of observing drifting snow

for a given range of wind speeds. Here a CRED of 0 means that no occurrence of drifting snow was observed for

the selected range of wind speeds, while a CRED of 1 indicates that all wind speeds in that range were associated

with drifting snow. CRED was calculated from the meteorological dataset within 1 m s^{-1} wide intervals of wind

speed. Occurrences observed below 2 m s^{-1} and above 22 m s^{-1} were not considered since their relative

225   proportion within each wind speed interval individually accounted for less than 1 % of the observations. As in

Fig. 1 the sensitivity of CREDs to the relaxed and stricter confidence criterion used for acknowledging the

occurrence of drifting snow is illustrated by the shaded areas.
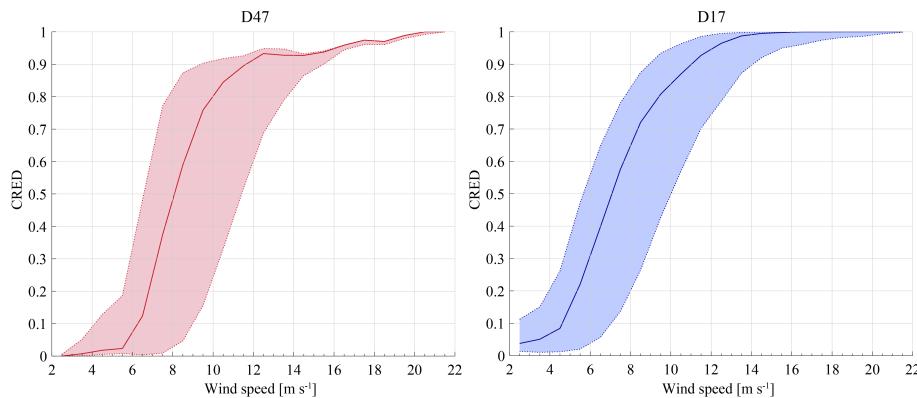
Figure 2. CRED distribution for drifting snow occurrences showing the increasing probability of observing

230   drifting snow with increasing wind speed.

The frequency of occurrence generally increases with wind speed (Fig. 2). As the 2G-Flowcapt™ does

not provide information on the source of windborne snow particles, CREDs in wind speed intervals lower than 5

m s^{-1} most likely correspond to rare occurrences detected during snowfall (without necessarily involving erosion

of snow) or shortly after the deposition of a loose snow layer easily erodible during light-wind conditions. Then,

235   for higher intervals, small differences in wind speed involve large variations in the CRED. At both sites, the

likelihood of observing significant drifting snow ($> 10^{-2}$ kg m^{-2} s^{-1}) becomes important (CRED > 0.5) when wind speeds rise above 10-11 m s^{-1}. Wind speeds above 15 m s^{-1} almost systematically produce drifting snow (CRED > 0.9) regardless of the confidence criterion, indicating that threshold (friction velocity) values for snow transport are most often exceeded in such wind conditions.

3.3 Duration of drifting snow events

Drifting snow ceases when the effective shear stress exerted on the snow surface by the overlying airstream, or the friction velocity, drops below the threshold value for erosion. This can either result from a weakening of the flow, an increase in aerodynamic roughness length, compaction of exposed surface snow particles or the exhaustion of erodible snow, the combination or the individual occurrence of which determining the duration and magnitude of drifting snow events. Following Vionnet et al. (2013), a drifting snow event has been defined as a period over which snow transport is observed for a minimum duration of 4 hours. An additional criterion requiring that a horizontal snow mass transport of at least 15 kg m^{-2} as recovered by the lower 2G-FlowCapt™ instrument is carried out along the event (corresponding to the snow mass transport resulting from a mean flux at the confidence threshold of 10^{-3} kg m^{-2} s^{-1} for a duration of 4 hours) was used.

By applying this selection protocol to the database, 1612 and 293 drifting snow events have been respectively identified at D17 and D47. Most events do not exceed 72 hours at D17 and can reach 10 days at most while a slight proportion (5.9 %) of events at D47 lasts more than 10 days with a maximum duration of 26 days (Fig. 3). In short, drifting snow events are on average twice as numerous but roughly two times shorter at D17 (yearly average number of 180 and median duration of 15 hours) than at D47 (yearly average number of 92 and median duration of 27.5 hours) where stronger winds can sustain longer events. Note that these statistics are not significantly altered if the length of the timeseries considered for D17 is reduced to that of D47.
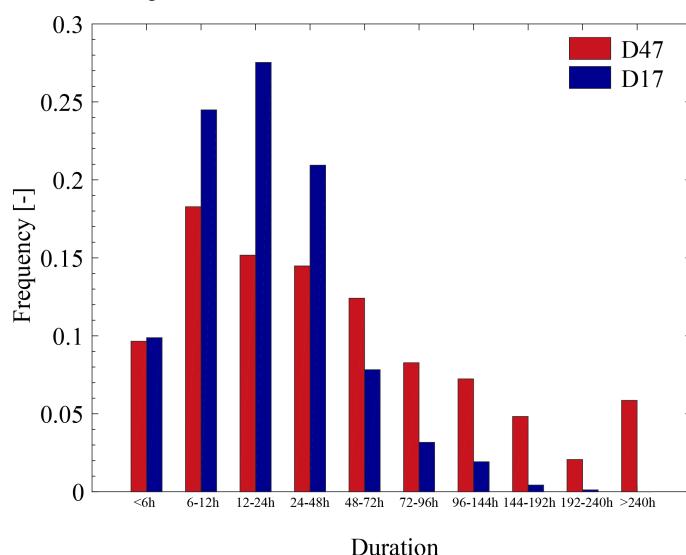
Fig. 3. Distribution of durations of drifting snow events at D47 (red) and D17 (blue) for the respective observation periods of 2010-2012 and 2010-2018. The minimum values of duration and snow mass transport for an event to be retained in the statistics are respectively set to 4 hours and 15 kg m^{-2}.

3.4 Horizontal snow mass transport in drift conditions

Due to snow accumulation and ablation, the sampling height of the lower 2G-FlowCapt™ sensor varied substantially and non-uniformly throughout the measurement period preventing direct comparisons of snow transport amounts over time. This is accounted for in a simple way by combining, when available, half-hourly snow mass fluxes from both sensors to derive a standardized estimate of the horizontal snow mass transport in drift conditions (i.e. between 0 and 2 m), Q_T, such that

$$Q_T = \Delta t \cdot \begin{cases} \sum \eta_1 + \eta_2 \,, & h_1 + h_2 \geq h_{ref} \\ \sum (\eta_1 + \eta_2) \dfrac{h_{ref}}{h_1 + h_2} \,, & h_1 + h_2 < h_{ref} \end{cases} \quad (2)$$

where Δt is the storage interval (1800 s), η_i (kg m^{-2} s^{-1}) is the observed snow mass flux integrated over the emerged height h_i (m) of the corresponding 2G-FlowCapt™ sensor and $h_{ref} = 2$ m. In other words, when $h_1 + h_2 < 2$ m, it is assumed that the measured snow mass flux is constant up to 2 m. To keep consistency with the threshold criterion for the detection of drifting snow occurrences (see Sect. 2.2), snow mass fluxes below 10^{-3} kg m^{-2} s^{-1} have been discarded from the calculations.
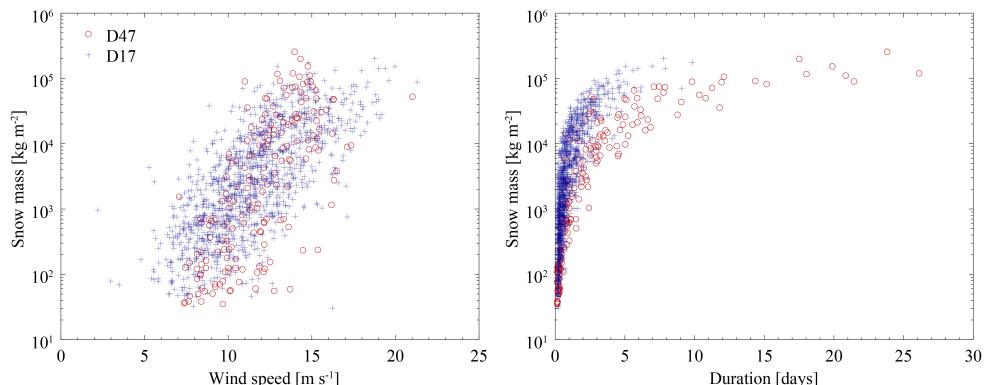
Figure 4. Logarithm of the snow mass transport in drift conditions (i.e. between 0 and 2 m) against mean wind speed (left panel) and duration (right panel) for each drifting snow event recorded at D47 (red circles) and D17 (blue crosses). Only periods for which two 2G-FlowCapt™ sensors were installed and/or not entirely covered with snow are considered.

Values of Q_T have been computed for each drifting snow event identified in the database and plotted as a function of the average wind speed and duration in Fig. 4. Periods during which only one 2G-FlowCapt™ was installed at D17 (i.e. 2010, 2011 and 2012) or the lower 2G-FlowCapt™ became completely buried at D47 (i.e. 2012) have been ignored because of the absence of information on drift conditions from 1 to 2 m and the inherent overestimation of snow transport produced by Eq. (2) in such cases. The linear relationship depicted in Fig. 4 (left panel) indicates that Q_T increases with wind speed in a power-law fashion, as already evidenced from similar data analyses performed at a higher time resolution (e.g., Mann et al., 2000; Nishimura and Nemoto, 2005; Amory et al., 2017). Note that the events with the highest average wind speed are not necessarily associated with the largest values of Q_T. This reflects the fact that other factors such as the availability and amount of erodible snow at the surface also influence drifting snow mass transport. More generally the dispersion can be explained by the diversity of factors governing the occurrence and magnitude of drifting snow

through variations in the difference between friction velocity and threshold friction velocity with time, as listed in the previous section.

290   Figure 4 (right panel) shows that Q_T increases roughly linearly with the event duration and hardly exceeds 10^5 kg m^{-2} even for the longest events, which thus seems to appear as an upper bound value for the mass transported in drift conditions during a single event. This is particularly well illustrated by D47 data. High values of Q_T for a wide range of durations involve large snow mass fluxes recorded at the two measurement levels, indicating the regular occurrence of well-developed, non-intermittent transport events in which particles are

295   simultaneously carried out through both the saltation and suspension mechanisms. This suggests that events of small magnitude for which transport in saltation dominates over transport in suspension must be comparatively short-lived.

On an annual basis, both kinds of events combine to produce yearly values of Q_T close to or above $2 \cdot 10^6$ kg m^{-2} at both locations (Table 2). Such high estimates suggest that redistribution of snow by wind together with

300   concurrent sublimation of snow particles during transport are important components of the surface mass balance in Adelie Land (Agosta et al., 2012; Amory and Kittel, 2019).

Year	Snow mass transport [kg m^{-2}]	
	D17	D47
2010	-	$1.93 \cdot 10^6$
2011	-	$1.74 \cdot 10^6$
2012	-	-
2013	$2.17 \cdot 10^6$	-
2014	$2.28 \cdot 10^6$	-
2015	$2.87 \cdot 10^6$	-
2016	$3.35 \cdot 10^6$	-
2017	$2.38 \cdot 10^6$	-
2018	$2.33 \cdot 10^6$	-

Table 2. Standardized estimates of annual horizontal snow mass transport within 2 m.

3.5 Contribution of major drifting snow events

305   The linear relationship between Q_T and event duration illustrated in Fig. 4 can be used to distinguish the contribution of the largest events to the drifting snow mass transport from that of the residual events. Major drifting snow events have been defined as the events whose duration is higher than the 75th percentile for each site. Figure 5 shows that such major events, preferably but not exclusively grouped in winter, account for a reduced proportion of the overall events (resp. 16 % and 18 % for D47 and D17) but mainly dictate the

310   variability of Q_T at the monthly scale, with the largest winter events capable of transporting alone up to 13 % of the annual quantity. The average monthly frequency resulting only from the occurrence of major events in each month is reported on the graph. As mentioned above, only the years for which the snow mass flux was measured continuously at two levels have been considered. Note that this requirement is met for distinct periods of time between both measurement locations which thus must not be compared directly.

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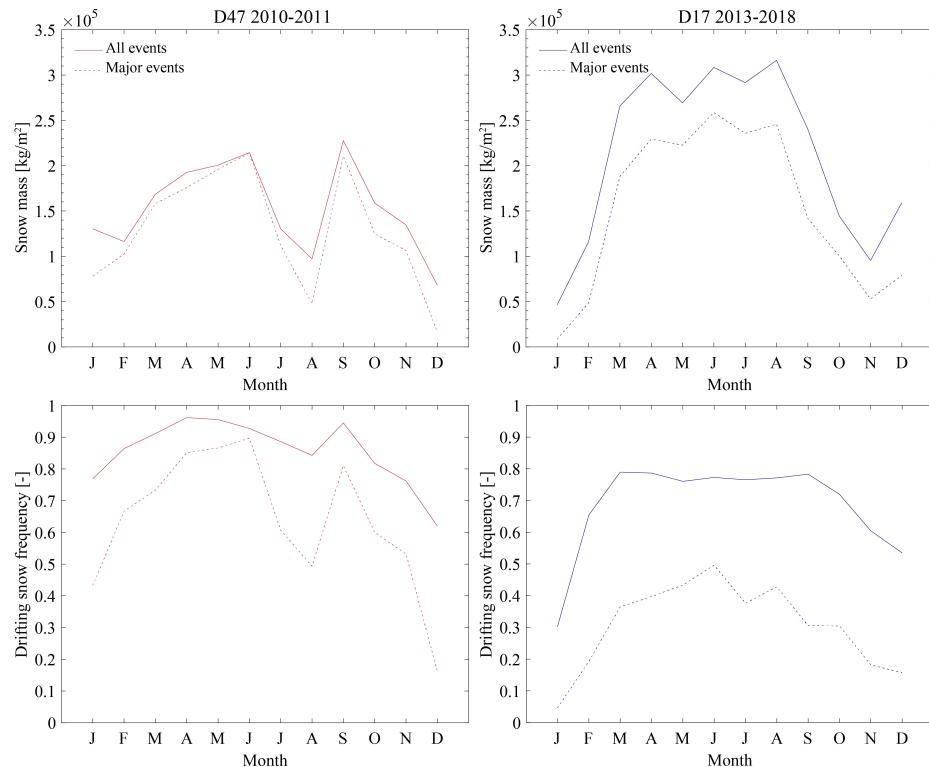
315   At D17 (Fig. 5, right panels), major events account for less than half of the observed frequency but contribute to a large part (> 70 %) of the mass transported in drifting snow. Larger monthly values of Q_T in winter result from an increased occurrence of major events combined with stronger snow mass fluxes (Amory et al., 2017), while drifting snow in summer mainly occurs in the form of residual events of lower magnitude.

     The data collected at D47 (Fig. 5, left panels) indicate that major events can contribute to an even larger
320 part (> 83 %) of the annual transport and bring a different general perspective by showing that drifting snow mass transport can be as important in summer than during some winter months, depending on the occurrence of major events. Despite a high and relatively uniform incidence of drifting snow in winter, the sharp decrease in Q_T from June to August at D47 is due to a reduced occurrence of major events during this period. This demonstrates that high monthly values of drifting snow frequency do not directly relate to the magnitude of
325 snow transport since they can mainly consist of multiple but relatively brief events involving low or moderate snow mass fluxes. This also suggests that, in a modelling perspective, representing these major events rather than the complete range of drifting snow occurrences would be sufficient to capture the bulk of the contribution of drifting snow processes to the local surface mass balance.

330 **Figure 5**. Intra-annual variability of snow mass transport (upper panels) and related drifting snow frequency (lower panels) at D47 (left panels) and D17 (right panels). The relative contribution of major drifting snow events (see text) is highlighted in dotted lines. Respective observation periods are indicated on the top of the upper panels. Summed mass transport and frequency values have been first determined for each month of the period considered, and averaged within each monthly bin to produce monthly average values. The variability
335 (standard deviation) in not shown due to the short length of the timeseries.

4. Concluding remarks

Meteorological data and snow mass fluxes automatically acquired at two locations 100 km apart in Adelie Land, D17 and D47, have been combined to illustrate the spatial and temporal variability in drifting snow frequency and mass transport in a small portion of the East Antarctic coast. While the equipment at D47 has been dismantled after a period of 3 years, station D17 is still operational and the data provided nearly continuously for the past 9 years constitutes the longest database of autonomous near-surface measurements of drifting snow currently available over the Antarctic continent. It should be noted that data collection continues at D17 and new measurements will be available in the future.

Statistical analysis of the current dataset indicates that the likelihood of drifting snow increases with wind speed. Drifting snow occurred 82 % and 66 % of the time on average at D47 and D17, with maximum and minimum frequency values respectively observed in winter and summer in line with the annual course of wind speed. The higher drifting snow frequency at the more inland location D47 is most likely the result of locally higher wind speeds. Such high incidences of drifting snow and annual mass transport values reaching or exceeding $2 \cdot 10^6$ kg m^{-2} at both sites suggest that drifting snow processes are important components of the local surface mass balance that would require a specific attention in a modelling context.

By imposing a minimum duration of 4 hours and a minimum mass transport of 15 kg m^{-2}, 293 and 1612 drifting snow events have been detected at D47 and D17 over the respective observation periods. Events at D17 typically last 15 hours (median value) and are roughly twice shorter than at D47 where longer events can be sustained by higher wind speeds. The observations also evidence that most of the mass transported annually in drifting snow is carried out through a few major events accounting for less than 20 % of the overall events and occurring preferably in winter, indicating that modelling the influence of drifting snow on the surface mass balance in this area might primarily rely on an accurate representation of these major events.

The instantaneous sampling of blowing snow properties through satellite techniques can be perceived as an undesirable limitation in regard of the mean duration of snow-transport events reported here. The presence of clouds impeding satellite retrieval is additionally responsible for the omission of overcast and/or snowfall conditions during which blowing snow is likely to occur preferentially because of the increased availability of loose snow. This can be particularly restrictive in coastal regions where the occurrence of blowing snow is often associated with synoptic-scale weather systems involving the presence of optically thick clouds (Gossart et al. 2017). The observations presented in this study, while providing spatially limited information, enable a continuous detection of snow-transport occurrences even in the presence of clouds and/or during snowfall. Although likely representative of local conditions, they constitute an original dataset dedicated to a poorly-documented, yet widespread feature of the Antarctic climate that can be used to complement satellite products and evaluate snow-transport models close to the surface and at high temporal frequency. Such exercises are needed to improve our understanding of the links between the occurrence and magnitude of drifting snow and ambient meteorological conditions, and ultimately better quantify the influence of drifting snow on the climate and surface mass balance of the Antarctic ice sheet.

Data availability. All data presented and described in this study are freely available by contacting the author.

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