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The Cryosphere Discussions

How does the ice sheet surface mass balance relate to snowfall? Insights from a ground-based precipitation radar in East Antarctica

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Abstract. Local surface mass balance (SMB) measurements are crucial for understanding changes in the total mass of the Antarctic Ice Sheet, including its contribution to sea level rise. Despite continuous attempts to decipher mechanisms controlling the local SMB, a clear understanding of the separate components is still lacking, while snowfall measurements are almost absent. In this study, the different terms are quantified at the Princess Elisabeth (PE) station in Dronning Maud Land, East Antarctica. Furthermore, the relation between snowfall and accumulation at the surface is investigated. To achieve this, a unique collocated set of remote sensing instrumentation (Micro Rain Radar, ceilometer, Automatic Weather Station, among others) was established operating for an unprecedented time period of 37 months. Snowfall originates mainly from moist and warm air advected from lower latitudes associated with cyclone activity. However, snowfall events are much more common than accumulation events. During 38 % of the snowfall cases observed, the freshly-fallen snow is ablated by the wind during the course of the event. Generally, snow storms of longer duration have a higher chance to attain for accumulation at the local scale, while shorter events usually attain for ablation (on average 17 and 12 hours respectively). As such, SMB records cannot be considered a good proxy for snowfall at the local scale. Accumulation and ablation also occur during non-snowfall conditions. A large part of the accumulation at the station takes place when preceding snowfall events were occurring in upstream coastal areas. This fresh snow is easily picked up and transported in shallow drifting snow layers to more inland locations, even when wind speed is relatively low (< 7 ms^{-1}). Ablation events are mainly related to katabatic winds originating from the Antarctic plateau and the mountain ranges in the south. These dry winds are able to remove snow and lead to a decrease in the local SMB. This work highlights that, even though observations are local, the SMB is strongly influenced by synoptic upstream conditions.

1 Introduction

The Antarctic Ice Sheet (AIS), being currently the largest ice body on earth, is an important regulator of the present and future global climate and water cycle (Vaughan et al., 2013; Previdi and Polvani, 2016). In order to asses its contribution to sea level rise, understanding the surface mass balance (SMB) of the AIS is of crucial importance. Coupled climate-surface models play

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an important role in understanding and quantifying the contribution of the AIS to sea level (rise) (Gregory and Huybrechts, 2006; Rignot et al., 2011; Ligtenberg et al., 2013; DeConto and Pollard, 2016). Yet, despite their importance, they simplify the different components of the SMB. It has been noted by several authors that in order to fully understand the impact of the AIS on future sea level rise, information on the individual components of the present-day AIS SMB, including direct snowfall measurements, is indispensable (van Lipzig et al., 2002; Rignot et al., 2011; Shepherd et al., 2012; Agosta et al., 2013; Lenaerts et al., 2016). A lack of observations of the present behaviour of these different components prevents the validation of climate models. As such, most studies rely on stake measurements registering only the total change in snow height (Vaughan et al., 1999; van Lipzig et al., 2004; Genthon et al., 2005; Magand et al., 2007; Eisen et al., 2008; Agosta et al., 2012). Gorodetskaya et al. (2015) were the first to quantify the different terms of the local SMB in a systematic way for the Princess Elisabeth (PE) station and to determine snowfall from radar measurements. In this study we focus on the relation / interactions between snowfall and accumulation in order to understand / assess the local SMB components in more detail.

The local SMB is influenced by several processes and can be written as the sum of snowfall (S), surface sublimation (SU_s), drifting snow sublimation (SU_{ds}), surface melt (ME) and wind-induced accumulation / ablation by drifting / blowing snow (ER_{ds}) (van den Broeke et al., 2004):

$$SMB = S + SU_s + SU_{ds} + ME + ER_{ds} \tag{1}$$

Although previous studies proposed a variety of techniques to calculate the local SMB, most are confined to measuring the sum of all components (net height change at the surface) using stake measurements and ice cores (Vaughan et al., 1999; Rotschky et al., 2007) or to one-dimensional snow models (Van Tricht et al., 2016). Generally, the separate measurement of any of the components of the local SMB is considered a difficult task (King and Turner, 1997; Vaughan et al., 1999; van Lipzig et al., 2002; van den Broeke et al., 2004).

Traditional snowfall measurements using rain gauges are inhibited by high wind speeds over the AIS and undercatchment, whereas ice cores and stake measurements are poor proxies for snowfall as they are affected by other components of the local SMB, such as e.g. blowing snow (see Eq. 1; Bromwich, 1988; van den Broeke et al., 2004). Again this indicates the importance of the separate measurement of the snowfall component and the existence of a non-linear relation between the local SMB and snowfall amounts. In recent years, remote sensing applications offer new possibilities regarding the determination of snowfall amounts on remote locations such as the AIS. A first estimate of snowfall rates over the AIS was derived from the Cloudsat satellite (Palerme et al., 2014). Its low overpass frequency, narrow swath width and ground clutter remains a limiting factor (Battaglia and Delanoë, 2013; Maahn et al., 2014; Casella et al., 2017). More locally, the operation of ground-based precipitation radars has proven to be an efficient way to detect snowfall over the AIS at several locations (Gorodetskaya et al., 2015; Souverijns et al., 2017; Grazioli et al., 2017a, b).

Wind-induced accumulation / ablation by drifting / blowing snow over the AIS has an important impact on the local SMB (Bromwich et al., 2004). The ER_{ds} component can however only be measured accurately using a network of snowdrift instrumentation (Leonard et al., 2011) and is difficult to take into account in Antarctic-wide SMB estimates (Genthon and Krinner, 2001; van den Broeke et al., 2004). Neglecting this term might however lead to significant errors (Lenaerts and van den

Broeke, 2012). ER_{ds} is therefore often considered as the leftover term in the local SMB over the AIS (Gorodetskaya et al., 2015). Recently, some new remote sensing techniques have been developed to detect ER_{ds} based on satellite-borne lidar and ground-based ceilometer measurements, adding to the understanding of the ER_{ds} component in the SMB (Palm et al., 2011; Gossart et al., 2017).

Both drifting snow sublimation and surface sublimation have been quantified for the PE station (Thiery et al., 2012). At the local scale, their significance can be fairly large (e.g. King et al., 2001; Bliss et al., 2011; Gorodetskaya et al., 2015; Grazioli et al., 2017b). However, this study mainly focuses on the relation between accumulation / ablation and snowfall. These terms, together with melt which is only relevant at coastal areas and ice shelves (Lenaerts et al., 2017), are therefore only quantified and not investigated in great depth.

The total SMB or snow height can be measured by an Automatic Weather Station (AWS), which is equipped with an acoustic height ranger (van den Broeke et al., 2004). The main advantage of the AWSs is the combination of snow height and meteorological observations.

Synoptic and meso-scale meteorology have a strong impact on the local SMB. For example, cyclone activity in the Antarctic circumpolar trough (50°-70° S) attributes for moist air penetrating into the atmosphere above the AIS. This leads to snowfall events and high wind speeds at both coastal and inland locations (King and Turner, 1997; Simmonds et al., 2003; Schlosser et al., 2010; Hirasawa et al., 2013; Gorodetskaya et al., 2013). In case large amounts of moisture are transported, these events are identified as atmospheric rivers (Gorodetskaya et al., 2014) having a profound impact on the local SMB. Nevertheless, the independent measurement of the snowfall component and the local SMB over the AIS are limited. Gorodetskaya et al. (2015) noted that snowfall events at the PE station do not necessarily contribute to accumulation or an increase in the height of the local SMB.

This study uses 37 months of independent snowfall and SMB measurements in order to asses the relation between snowfall and the local SMB. This analysis allows therefore to determine the quality of stake measurements as a proxy for snowfall at the local scale and to define the conditions when snowfall leads to accumulation or ablation. In addition, height changes in the local SMB take place without snowfall. A thorough analysis of meteorological conditions during these events adds to the understanding of the behaviour of the ER_{ds} component and their impact on the evolution of the local SMB over the AIS.

2 Material and methods

2.1 Site description and instrumentation

In order to gain insight in the relation between snowfall and the SMB, reliable, high-frequency and long-term in situ observations are indispensable. Long-term measurements of the individual components of the SMB over the AIS are scarce due to its harsh environment and difficult accessibility. To tackle this problem, a limited-maintenance and low-power meteorological observatory was established at the PE station in 2009 (Gorodetskaya et al., 2015). This station was built in the escarpment zone of the East Antarctic plateau (71°57’ S, 23°21’ E; 1392 m above sea level), 173 km from the coast, in Dronning Maud Land, north of the Sør Rondane mountain chain (Fig. 1; a detailed description of the site can be found in Pattyn et al. (2010)

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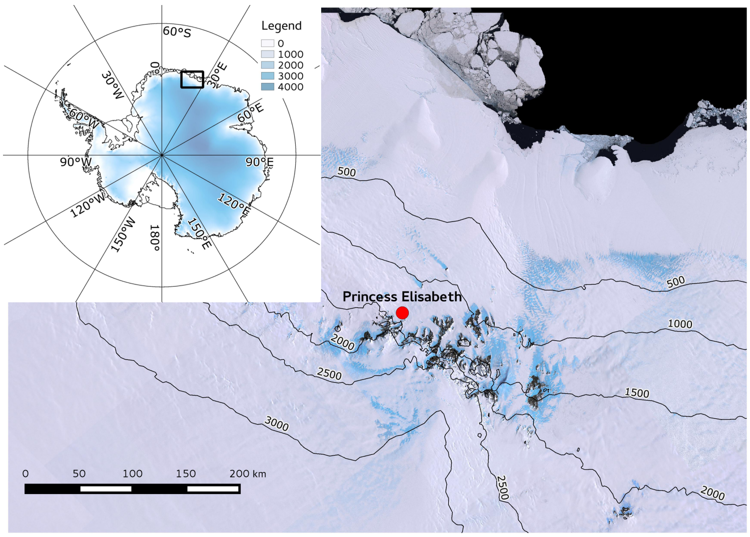

Figure 1. Location of the meteorological observatory at the Belgian Princess Elisabeth station. Source: Landsat Image Mosaic of Antarctica (LIMA) Project, http://lima.usgs.gov/.

and Gorodetskaya et al. (2013)). The main aim of this meteorological observatory is to collect a comprehensive database of meteorology, radiative fluxes, snow height changes, and cloud and precipitation properties (Gorodetskaya et al., 2015, http://www.aerocloud.be).

Snowfall measurements are recorded since 2010 by use of a vertically pointing Micro Rain Radar-2 (MRR) operating at a frequency of 24 GHz (Klugmann et al., 1996; Peters et al., 2002). The potential of millimetre radars to efficiently detect snowfall has been shown by Matrosov et al. (2008) and has been evaluated specifically for our type of radar by Kneifel et al. (2011). As the MRR was originally developed for rain observations, operational MRR procedures to derive standard radar variables like effective reflectivity factor (Ze) or mean Doppler velocity had to be modified for snowfall using the methodology of Maahn and Kollias (2012). In order to obtain reliable estimates of snowfall rates and their uncertainty, an optical disdrometer (Precipitation Imaging Package) was installed at the PE station (Newman et al., 2009). This instrument is based on a high speed camera and able to obtain detailed information about snowflake microphysics. Using this information, a relation between radar reflectivity measured by the MRR and snowfall rates was obtained including a constrain on its uncertainty (Souverijns et al., 2017).

The net local SMB is measured directly by an AWS. This instrument was installed in February 2009 and is located approximately 300 m east of the station (and the MRR). The AWS records meteorological variables, such as air temperature, pressure, wind speed and direction, relative humidity and radiative fluxes at 2 meters above the surface. Furthermore, it is equipped by an acoustic height sensor, which is able to measure snow height changes with an accuracy of 1 cm on an hourly time resolution. A running mean of 24 hours is applied including several corrections to remove erroneous data (Gorodetskaya et al., 2015). In January 2016, a new AWS was set up to replace the one installed in 2009, able to measure snow height changes more accu-

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rately. A detailed overview of the specifications of the old AWS can be found in Gorodetskaya et al. (2013) and of the new AWS in the Supplement (Table S1).

Ablation or accumulation attaining for changes in the SMB occur generally in blowing snow layers with a distinct vertical extent. Recently, an algorithm for the detection of blowing snow by the use of a ceilometer was developed. Ceilometers are ground based lidars originally developed to detect cloud base height (Gossart et al., 2017). This instrument is able to detect blowing snow particles in the backscatter signal and can be operated during all types of weather conditions (cloudy, snowfall conditions and at night). As such, it complements satellite retrievals of blowing snow from the CALIPSO satellite (Palm et al., 2011). The minimal height of the blowing snow layer to be detected by the ceilometer equals 30 m at the PE station.

Surface and snowdrift sublimation are quantified using the approach of Thiery et al. (2012) for which data is provided by the AWS.

The sampling period of our study is limited to time periods when both the AWS and MRR were operational between 2010-2016. These time frames are almost always restricted to austral summer months when the station is manned (Fig. S1 in the Supplement). Data acquisition during the austral winter season is often hampered by power failures at the PE station. The MRR was installed in the season 2009-2010 and a total record of seven austral summer seasons is available for analysis. For austral winter, only one season is available where both MRR and AWS were operating continuously i.e. 2012. Apart from this, in January 2015, a problem with the wind vane of the AWS was detected. This problem persisted until December 2015, leading to erroneous wind direction measurements. The year 2015 is therefore also discarded from our analysis. In the end, 37 months of collocated precipitation, total SMB and meteorological data are available, which is unprecedented for the Antarctic region.

2.2 Snowfall, accumulation and ablation events

The local SMB constitutes of the sum of different components (Eq. 1), which can be estimated from measurements using the ground-based instrumentation listed in Sect. 2.1, apart from the ER_{ds} term. Nevertheless, since the AWS measures the total SMB directly, ER_{ds} can be calculated as the residual term after inverting Eq. 1 (Gorodetskaya et al., 2015).

Snowfall is generally considered the main positive term of the local SMB (Davis et al., 2005). One would therefore expect that snowfall results in an increase in the height of the local SMB. However, this is not necessarily true over the AIS, where snowfall often coincides with strong winds. Consequently, snowfall events with strong redistribution can result in a net snow removal at the local scale. As stated in section 1, accumulation and ablation also occur during non-precipitating conditions. In order to define the conditions for these episodes and to assess a relation between snowfall and accumulation, different types of events were discriminated based on local SMB measurements from the AWS and snowfall records from the MRR:

- Accumulation during snowfall (SMB +, S +)
- Ablation during snowfall (SMB -, S +)
- Accumulation without snowfall (SMB +, S 0)
- Ablation without snowfall (SMB -, S 0)

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An event is confined to the period between the start of snowfall / accumulation / ablation and the moment no more snowfall / accumulation / ablation is observed. The time step and duration of an event have an hourly time resolution. Snowfall events are defined as exceeding the threshold of 1 mm w.e. during the continuous duration of snowfall measured by the MRR (this corresponds to 1 cm of snow when the density of fresh snow equals 100 kg m^{-3}). As the AWS measures snow height changes with a sensitivity of 1 cm, an increase in surface height larger than 1 cm over the duration of an event is considered to be an accumulation event, while an ablation event occurs when a decrease in surface height of more than 1 cm is recorded.

2.3 Local and large scale meteorology

In order to understand the mechanisms attaining for snowfall and wind-induced accumulation / ablation, the meteorological conditions of the four types of events defined in Sect. 2.2 are evaluated. For all members within these four types of events, average meteorological conditions are calculated. Wind speed and direction, humidity and radiative fluxes are obtained from the AWS. These measurements are processed following Gorodetskaya et al. (2013). Snowfall amounts are obtained from the MRR after applying the Ze-SR relation and methodology determined in Souverijns et al. (2017).

Further, the temporal extent of the cloud system is investigated using two different data products. Firstly, cloudy conditions are estimated based on longwave downward radiation measurements of the AWS. For this, the Clear Sky Index based on the methodology of Marty and Philipona (2000) and Dürr and Philipona (2004) is used, which calculates the ratio between the apparent and clear-sky longwave downward radiation. The apparent longwave downward radiation is calculated using observations of the AWS. For the clear-sky longwave downward radiation, local coefficients (see Eq. 3 and Sect. 3 in Marty and Philipona (2000)) are optimised for the PE station by comparing calculated clear sky and observed longwave downward radiation during visually detected cloud free conditions (based on camera images and ceilometer data). As a result, based on the ratio of apparent and clear-sky longwave downward radiation, one can discriminate between cloudy and clear-sky conditions. Secondly, the temporal extent of the cloud system at the PE station was estimated from ERA-Interim (Dee et al., 2011). ERA-Interim is generally considered the best reanalysis product over Antarctica (Bracegirdle and Marshall, 2012). Cloudy conditions over the station are defined as having a total cloud fraction of more than 95 % in the pixel over the PE station. Sensitivity studies have been executed on this threshold (varying between 80 and 100 %) and attain for only small relative differences not influencing the general conclusions significantly.

Apart from these local meteorological variables, an analysis of the large-scale circulation over Dronning Maud Land (including a large part of the Southern Ocean) was performed. A cluster analysis was applied to 500 hPa geopotential ERA-Interim reanalysis data covering the period of observations at the PE station (2010-2016). This gives an overview of the climatology and the typical circulation that is present over the region.

The SANDRA optimisation algorithm was selected to perform this cluster analysis, which is based on k-means clustering (Philipp et al., 2007). The ability of the SANDRA algorithm to classify circulation patterns for meteorological and climatological studies has been shown before for different parts of the world (Philipp et al., 2007; Huth et al., 2008; Beck and Philipp, 2010; Casado et al., 2010; Souverijns et al., 2016). Next to the choice of the classification algorithm, it is also necessary to define the total number of circulation patterns that covers the full climatology over Dronning Maud Land. For a range between

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2 and 27 total circulation patterns, the quality of the SANDRA algorithm is tested. Its ability to maximise the separability between the members of different circulation patterns, while minimising the variances within each circulation pattern, was investigated using the Fast Silhouette index (Rousseeuw, 1987). In this study, a total of nine circulation patterns was selected. The Fast Silhouette index shows a local optimum as increasing the total number of circulation patterns shows no significant improvement in the classification (Fig. S2). Based on this climatology, the dominant circulation present during the four types of events attaining for a change in the local SMB defined in Sect. 2.2 are determined.

Next to this cluster analysis, a backtrajectory analysis was performed for all individual events in order to get insights into the origin and history of the air masses. For this, the FLEXPART software, a Lagrangian transport and dispersion model which makes use of ERA-Interim data, is used at a spatial resolution of 0.75° x 0.75° (Stohl et al., 1995; Stohl and Seibert, 1998).

3 Results and discussion

3.1 Local surface mass balance

The four components of the local SMB, snowfall, surface sublimation, drifting snow sublimation and wind-induced accumulation / ablation, are converted to water equivalent values (Gorodetskaya et al., 2015). When snow height measurements are available the local SMB can be closed (treating ER_{ds} as a residual term; see Eq. 1). For the year 2012, both the AWS and MRR were operating year-round, allowing to visualise the evolution of the different components through time in a cumulative way (Fig. 2). Snowfall (S) is identified as a strictly positive term and the step-wise function indicates that the precipitation climate is characterised by several events per year. The local SMB is denoted by the green line and shows several peaks in both the upper and lower direction (indicating distinct accumulation and ablation events respectively). These events occur both with or without snowfall. This behaviour is also visible in the ER_{ds} term, allowing for easy identification of the individual accumulation and ablation events. Furthermore, it can also be noted that surface and drifting snow sublimation (SU_s and SU_{ds} respectively) are mainly negative. The rest of the study ignores these two components, as they are not our main focus.

For each of the four types of events defined in Sect. 2.2 one example is highlighted in Fig. 2. It can be seen that some snowfall events account for accumulation (SMB +, S +), but that this is not strictly the case. Wind can also remove mass from the site during a snowfall event, leading to a net removal of mass (SMB -, S +). Additionally, even during time periods without any snowfall, snow height varies continuously and several accumulation (SMB +, S 0) and ablation (SMB -, S 0) events can be identified without the presence of snowfall.

3.2 Large-scale meteorology

Using the SANDRA circulation pattern classification algorithm, it is possible to define the climatology of large-scale circulation over Dronning Maud Land and the nearby Southern Ocean (Fig. 3). Large-scale circulation over Dronning Maud Land is typically characterised by an anticyclone close to the pole and cyclones at latitudes between 50° S and 70° S, north or near the coast of the AIS. These low pressure systems form a ring around the Antarctic continent (Antarctic circumpolar trough),

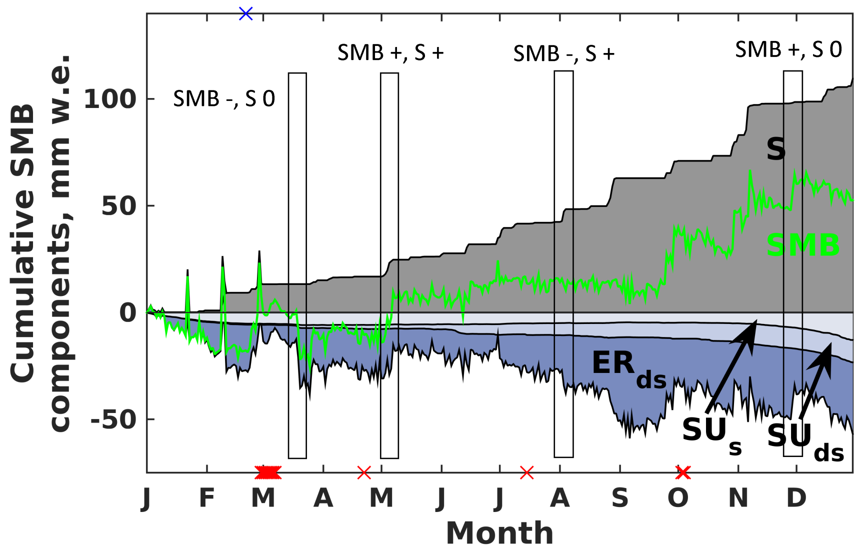

Figure 2. Cumulative daily surface mass balance components during 2012 at the Princess Elisabeth station: snowfall (S), surface sublimation (SU_s), drifting snow sublimation (SU_{ds}), wind-induced accumulation / ablation (ER_{ds}), and measured snow height changes since 1 January 2012 (SMB). SU_s and SU_{ds} are plotted as ablation terms. ER_{ds} is calculated and plotted as a residual term by inverting Eq. 1. Red crosses at the bottom indicate days of missing MRR data, while blue crosses at the top denote missing AWS data. Letters on x axis mark the first day of each month. Examples of the four types of events defined in Sect. 2.2 are indicated by black rectangles (adapted from Gorodetskaya et al. (2015)).

attaining for a high variability in meteorological regimes at the coastal areas of the AIS (King and Turner, 1997; van den Broeke and van Lipzig, 2003; König-Langlo and Loose, 2006; Hirasawa et al., 2013). The sequence of circulation patterns depicted in Fig. 3 is typical for the Antarctic region (Simmonds et al., 2003). Cyclones typically move from the west to the east, largely influencing the meteorological conditions at the surface. Apart from the circulation, also the average precipitation amounts associated to each circulation pattern are shown (Fig. 3). Precipitation estimates are obtained from ERA-Interim, currently considered the best Antarctic-wide precipitation product, however still strongly biased (Bromwich et al., 2011). A detailed description of each circulation pattern individually can be retrieved from the Supplement.

3.3 Snowfall

Snowfall is the main positive contributor to the local SMB. During the observational period 2010-2016, in total 50 independent snowfall episodes were detected attaining for at least 1 mm w.e. at the PE station. Snowfall events are characterised by high wind speeds originating mainly from the East North East (ENE; Table 1 & Fig. 4a). Only a limited number of snowfall events correspond to near-surface winds from other directions. This complies with literature, stating that moist air and precipitation is transported via cyclone activity in the Antarctic circumpolar trough towards the AIS (Sect. 1) and is also confirmed by our

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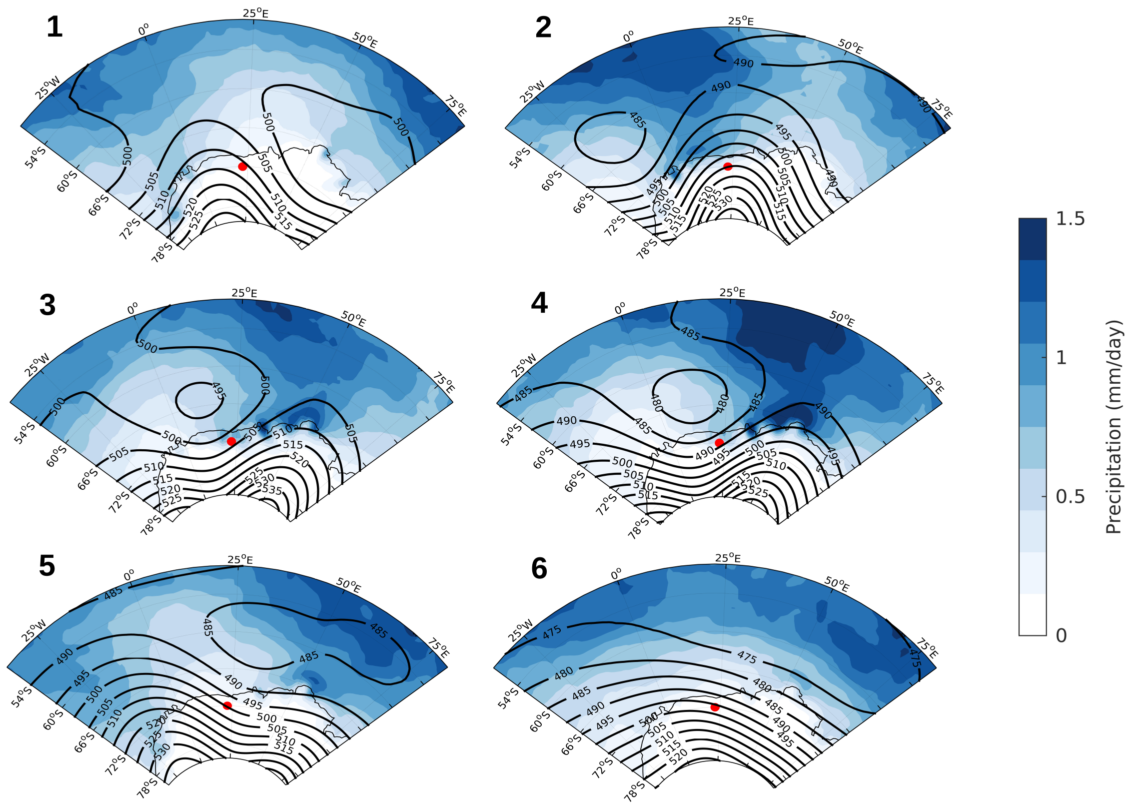
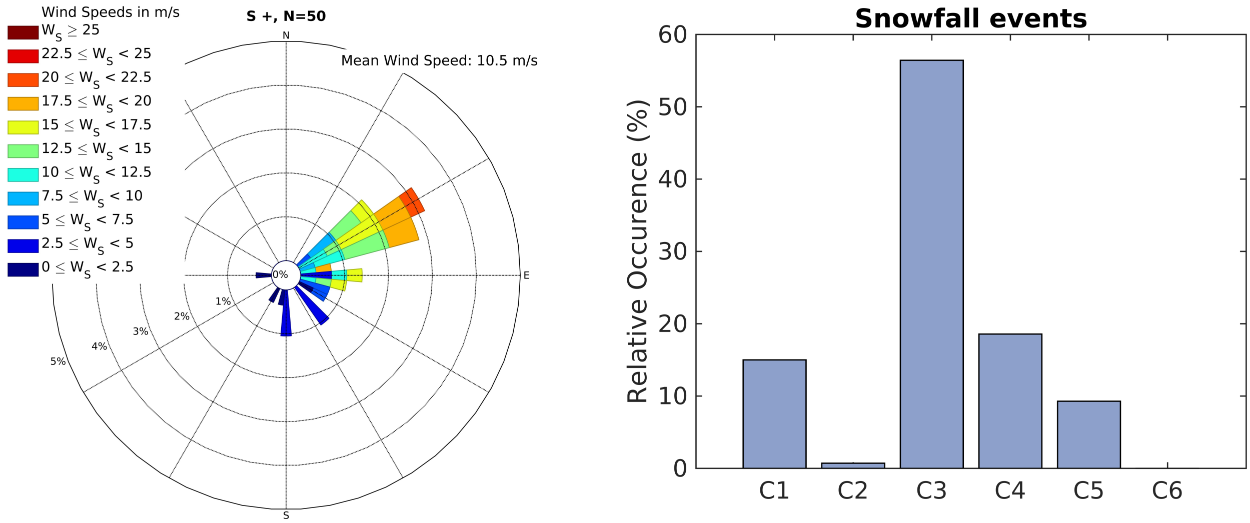


Figure 3. Weather atlas illustrating the circulation climatology over Dronning Maud Land. Thick lines denote the 500 hPa geopotential fields, while blue colours show average precipitation amounts linked to this circulation. The red dot indicates the location of the Princess Elisabeth station.

cluster analysis. A fraction of more than 70 % of all snowfall events coincide with cyclone activity (Fig. 4b). Winds originate from the north, but are slanted towards the east at the surface due to friction, the coriolis force and local topographic conditions at the PE station, as the station is surrounded by a mountain ridge in the south, behind which the Antarctic plateau is located (Fig. 1).

In order to validate the relation between large snowfall events and these meteorological conditions, interactions between the transport capacity of the cyclone, the origin of the air mass and the amount of snowfall that is recorded at the PE station are investigated. The transport capacity of the cyclone is parametrised by an index based on the pressure difference between the PE station and the location of the cyclone northwest of the station (0° E, 62° S, Fig. 3) as these cyclones attribute for the highest snowfall amounts at the PE station. Larger values for this index indicate higher pressure gradients and stronger wind speeds. The origin of the air masses (five days prior to the event) are deduced from backtrajectories arriving at the PE station



(a) (b)

Figure 4. (a) Wind rose showing the speed and direction of the snowfall events. N denotes the total number of snowfall events during the observation period. (b) Frequency of occurrence of the circulation patterns depicted in Fig. 3 for snowfall events

	SMB +, S +	SMB -, S +	SMB +, S 0	SMB -, S 0
Wind Speed (ms^{-1})	10.6	10.5	6.70	5.44
Wind Direction (° deviation from N)	87.7	83.8	108	146
Station Pressure (hPa)	830	830	828	829
Relative Humidity (%)	91.3	89.5	67.2	60.1
Snowfall summed over the event (mm w.e.)	5.25	3.56	-	-
Deviation from LW_{cs} (W m^{-2})	77.0	72.3	36.0	25.0
Deviation from SW_{cs} (W m^{-2})	109	83.2	71.1	34.0
Temporal extent of cloud system ERA-Int (hours)	46.8	32.4	31.8	27.0
Temporal extent of cloud system AWS (hours)	42.6	29.9	32.6	27.6
Total duration of the event (hours)	16.9	12.3	12.3	11.6
Number of events	31	19	72	87

Table 1. Average meteorological statistics for the four types of events stated in Sect. 2.2. Only events during coinciding measurements of the AWS and MRR are included. LW_{cs} denotes the longwave incoming radiation during clear-sky conditions, while SW_{cs} is the shortwave incoming radiation during clear-sky conditions.

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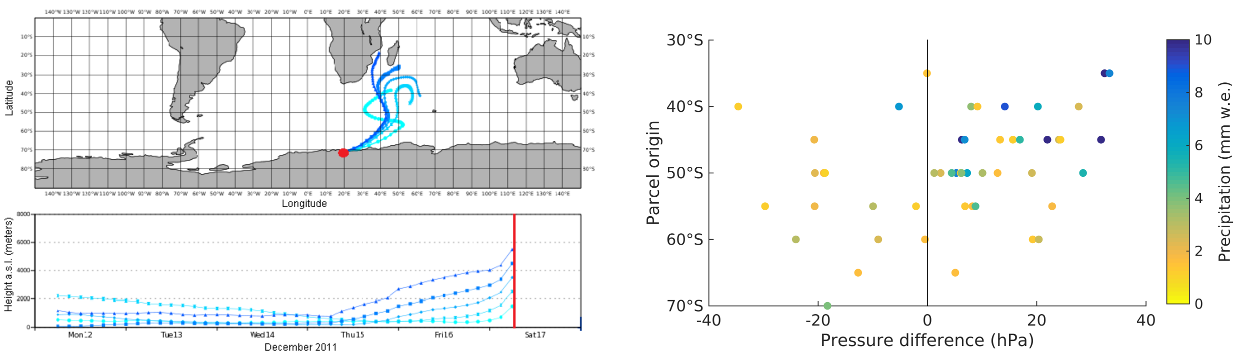

(a) (b)

Figure 5. (a) Backtrajectories for the snowfall event of the 17th of December 2011 at the Princess Elisabeth station. The red dot / line denote the location / time at the Princess Elisabeth station. (b) Relation between the transport capacity of the cyclone (based on the pressure difference between the Princess Elisabeth station and 0° E, 62° S), the origin of the air mass (based on the origin of the backtrajectories arriving at the PE station at altitudes below 3000 meters a.s.l. five days prior to the event) and the total amount of snowfall during the event. Positive values for the pressure difference denote the presence of a cyclone northwest of the PE station, while negative values indicate the absence of a cyclone.

at altitudes below 3000 meters a.s.l.. During snowfall events induced by cyclone activity, air masses typically originate from areas north of 50° N, take up moisture close to the oceanic surface and are generally lifted upwards when reaching the AIS continental margin (Fig. 5a). A significant relation between the transport capacity of the cyclone, the origin of the air mass and the amount of snowfall is observed (Fig. 5b). In case no cyclone is present (left side of the graph), snowfall amounts are generally low. This corresponds to events that are not related to winds originating from the ENE (Fig. 4a) and confirms that non-cyclone related snowfall amounts are low. In case a cyclone is present, a tendency for higher snowfall amounts during larger pressure gradients is present (significant at the 0.05 confidence level). Furthermore, during these conditions, air masses originate from more northern areas (Fig. 5b). As a conclusion, when the cyclone / trough is more developed and high pressure blocking is present NE of the PE station, moisture from more northern areas is able to be transported, leading to higher snowfall rates at the station. In case very high snowfall amounts are observed during this synoptic situation, moisture transport is likely related to atmospheric rivers (Gorodetskaya et al., 2014).

From the total number of snowfall events, 31 resulted in accumulation (62 %), while 19 led to ablation (38 %). Regarding the basic meteorological variables obtained by the AWS, no large differences between both types of events are observed. Only the duration of the event and the temporal extent of the cloud structure show a clear distinction regarding their mean values (Table 1). Accumulation events (SMB +, S +) have a longer duration compared to ablation events (SMB -, S +) significant at the 0.1 level (Fig. 6). Furthermore, the persistence of the cloud structure shows a notable difference for both methods described in Sect. 2.3 at the 0.05 level (Table 1 & Fig. 6). Accumulation events are characterised by a larger temporal extent of the cloud structure compared to ablation.

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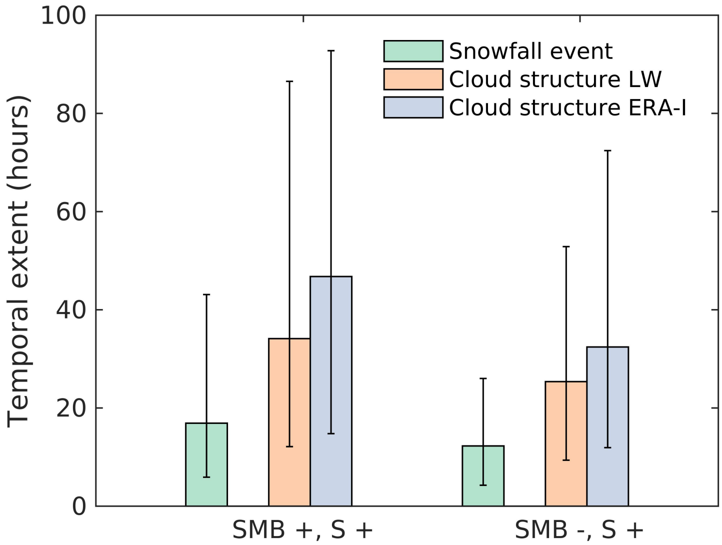

Figure 6. Duration (green) and the temporal extent of the cloud structure (red and blue) for snowfall events attaining for accumulation (SMB +, S +) and ablation (SMB -, S +) (hours). Columns denote the average value, while the error bars denote the 25th and 75th percentile based on all events.

Snowfall events are generally characterised by high wind speeds originating from oceanic areas (ENE at the PE station) redistributing snow continuously during the time of an event. In case a snow storm has a large temporal extent, fresh snow precipitates over areas with a large spatial coverage. Therefore, there is a higher chance that snow removed from the PE station is replaced by fresh snow from other areas located upstream. In case of a shorter event or cloud system, there is a lower probability that snow from other locations replaces snow that is blown away from the station. As such, the larger the cloud system or the duration of the event, the higher the chance that snowfall events attain for accumulation at a local scale, rather than ablation.

Redistribution of snow at the surface by high winds is usually denoted as blowing snow (drifting snow in case the height of the snow displacement layer is lower than 2 meters). By using information from the ceilometer at the PE station, it is possible to detect blowing snow layers with a vertical extent of 30 m (Gossart et al., 2017). The concurrence of blowing snow and snowfall events is analysed. For snowfall events attaining for accumulation, a blowing snow layer is detected in 95 % of the cases, while for snowfall events attributing for ablation, this concurrence equals 88 %. In total, all 50 snowfall events attained for 542 cm of height changes in the SMB (both accumulation and ablation; detected by the AWS). From this, the ceilometer was able to detect 486 cm (i.e. the sum of all height changes during events for which blowing snow was detected), showing the potential of the ceilometer to detect blowing snow during snowfall events.

During all snowfall events, a total amount of 230 mm w.e. (approximately 230 cm in case fresh snow density equals 100 kg m^{-3}) was registered by the MRR, which is lower than the height changes recorded by the AWS (542 cm). This indicates the

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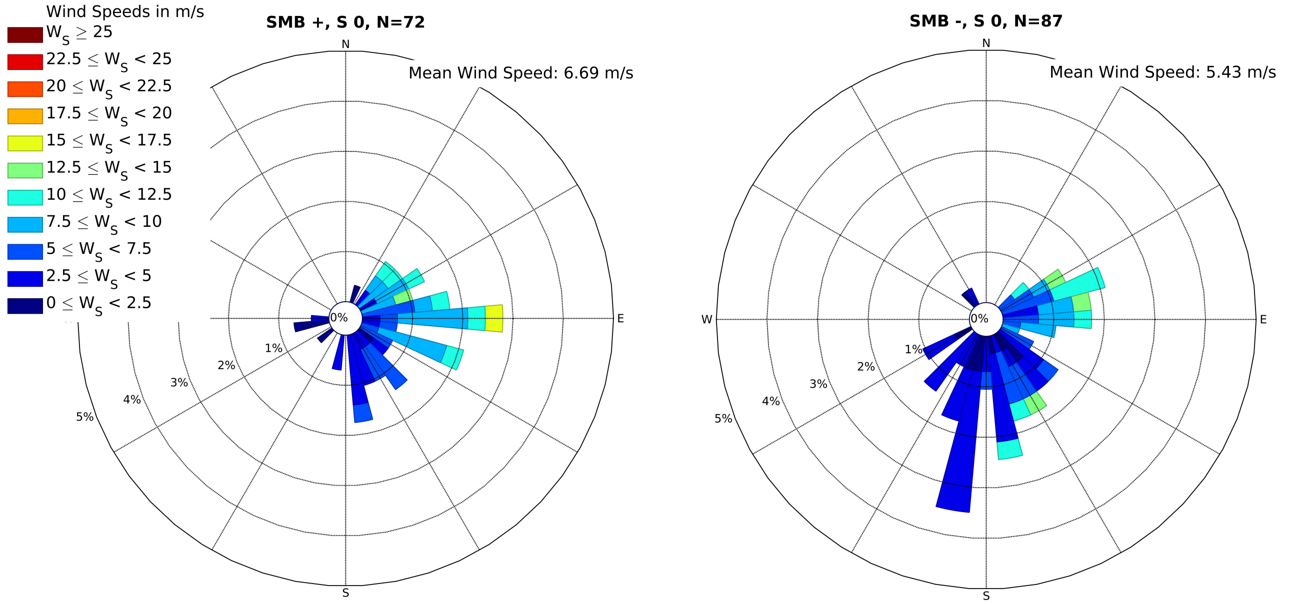

(a) Accumulation without snowfall.

(b) Ablation without snowfall.

Figure 7. Wind speed and direction for the two events attaining for wind-induced accumulation / ablation without snowfall. N denotes the total number of events during our observation period.

importance of the continuous movement of snow during snowfall events. Accumulation records are therefore not advised to be used as a proxy for snowfall over East Antarctica. A direct relation between snowfall and accumulation is however difficult to assess, apart that snowfall events of a longer duration have a higher chance to attain for accumulation.

3.4 Wind-induced accumulation / ablation

In the previous section, snowfall events proved to be able to attribute for both accumulation and ablation, depending on the duration of the event and temporal extent of the cloud structure. However, snow displacement events also occur without the presence of snowfall. The meteorological conditions during these non-precipitating events are clearly different from snowfall events (Table 1). More pronounced, clear differences in wind pattern are observed (compare Fig. 7 & 4a). Firstly, the mean wind speed is much lower for non-precipitating events compared to snowfall events, while secondly, two dominant wind directions are detected. Thirdly, in contrast with snowfall events, clear differences between the wind patterns of accumulation and ablation events are visible (Fig. 7). On the one hand there is a dominant easterly flow during accumulation events (SMB +, S 0), while southerly flow is more commonly related to ablation events (SMB -, S 0).

During accumulation events without snowfall (SMB +, S 0), one of the dominant wind directions is, just as during snowfall events, directed towards the ENE. However, wind speeds are much lower (Fig. 7a). Approximately 40 % of all accumulation events occur during a similar circulation than snowfall events (circulation pattern 3 & 4 in Fig. 8a). During accumulation events

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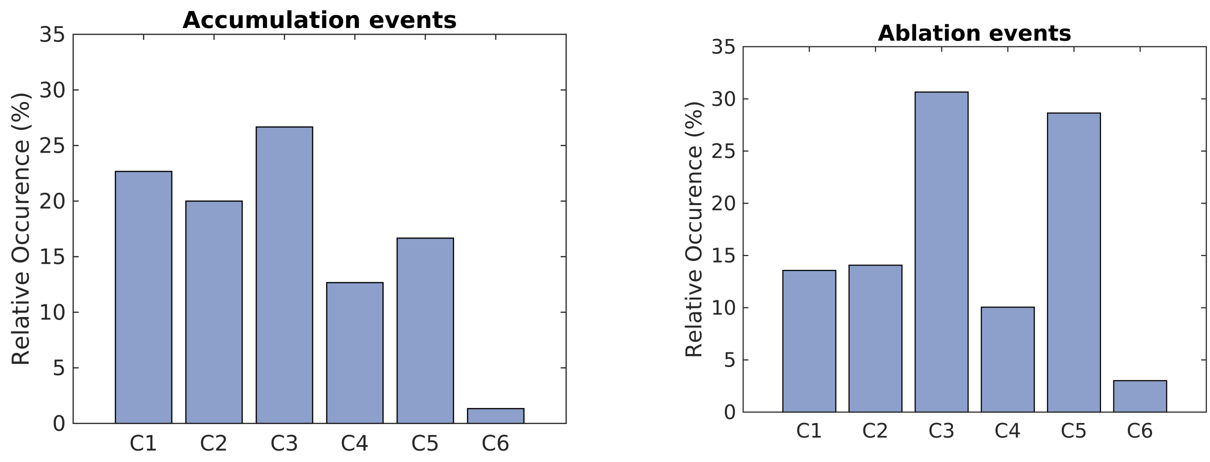

(a) Accumulation without snowfall.

(b) Ablation without snowfall.

Figure 8. Frequency of occurrence of the circulation patterns depicted in Fig. 3 for wind-induced accumulation / ablation without snowfall.

without snowfall, the amount of moisture that is transported from the ocean towards the AIS is generally lower than during snowfall events, limiting the regions that receive snowfall to coastal areas. In more than 50 % of the individual events (i.e. 38 out of 72 events), snowfall was found to be limited to the coastal areas, not reaching the PE station. This is also supported by the backtrajectory analysis, as the source area of the air masses is confined to the nearby ocean. During snowfall events, 86 % of all air masses originated north of 50° S within five days preceding the event (Fig. 5), while during accumulation events without snowfall, this is limited to 60 %. The freshly fallen snow at the coastal areas has a low density and is easily redistributed. As such, it can be transported by the wind, attaining for accumulation at more inland locations.

Apart from this, it was observed that 43 % of accumulation events occur within 24 hours after a snowfall event at the PE station (i.e. 31 out of 72 events). Highest snowfall amounts are expected to occur at the coast of the AIS, therefore these regions are the perfect source area of fresh snow. In case the wind pattern stays stable towards the ENE after the snowfall event, this fresh snow is transported towards inland locations, attaining for accumulation.

In case of ablation events (SMB -, S 0), the dominant wind direction originates from the south and is characterised by low wind speeds (Fig. 7b). It must be noted that a mountain ridge is located south of the station, beyond which the Antarctic plateau is situated (Fig. 1). The large-scale circulation analysis shows that there is a dominant occurrence of circulation pattern 5 (Fig. 8b), having only a limited influence of low-pressure systems. In order to understand these ablation events, their timing is investigated. A fraction of 46 % of the ablation events take place within 24 hours after a snowfall event. As stated in Sect. 3.3, snowfall events are mainly characterised by a ENE flow (Fig. 4a). After these snowfall episodes, the cyclone passes towards the east and winds tend to settle down (this evolution is depicted in Fig. 3). During calm conditions, a katabatic flow manifests originating from the mountain ridge and the Antarctic plateau (Parish and Cassano, 2003). These areas received generally less snowfall during the preceding snowfall event compared to the coastal areas. As such, these katabatic winds are generally dry and do not contain blowing snow particles. Arriving at lower altitudes, they are able to pick up the fresh snow attaining for ablation at the local scale.

Both accumulation and ablation events have a large overlap in their wind roses and take place during similar synoptic conditions (Fig. 7 & 8). For example, wind-induced ablation without snowfall is not only confined to katabatic winds, but can also occur during cyclonic influences (Fig. 8b). This indicates the importance of both synoptic as katabatic influences on the surface winds and in determining accumulation / ablation over Antarctica (Parish and Cassano, 2003).

An analysis of the wind roses indicates the occurrence of accumulation / ablation at very low wind speeds (Fig. 7). This points out that the time since the last snowfall event and the amount of low-density fresh snow that is available is of much higher importance than the wind speed in order to attain for blowing snow, confirming the results of Gallee et al. (2001); Mahesh et al. (2003); Scarchilli et al. (2010); Gossart et al. (2017).

Based on the ceilometer and its blowing snow detection algorithm, the concurrence of blowing snow and accumulation / ablation during non-snowfall conditions is analysed. For these accumulation and ablation events, blowing snow is detected by the ceilometer in only 27 % and 20 % of the cases respectively. A total of 1125 cm in SMB changes was measured by the AWS during the events. The ceilometer was only able to detect 274 cm, indicating that the blowing snow layer only has a limited vertical extent and that the transport of snow is restricted to shallow layers close to the ground during these type of events. Furthermore, it is noted that ablation and accumulation can significantly compensate each other (the total accumulation on a yearly basis is usually limited to approximately 100 mm w.e. at the PE station; but has a large interannual variability i.e. approximately 50 mm w.e. in 2012; see Fig. 2).

Almost half of the accumulation and ablation events without snowfall occurred shortly after a snowfall event. Furthermore, wind speeds were found to be lower during these events compared to snowfall episodes. In both the accumulation and ablation case, fresh snow is easily transported towards or away from the station. During these types of events, the vertical extent of the blowing snow layer does not generally reach 30 m and most of the transport of this freshly fallen snow including accumulation / ablation occurs in shallow layers at moderate wind speeds. As such, in order to get a good idea of accumulation and ablation during non-precipitating time periods and its influence on the local SMB, near-ground observations of drifting / blowing snow are indispensable (Takahashi, 1985; Bellot et al., 2011; Leonard and Maksym, 2011; Leonard et al., 2011).

4 Conclusions

The surface mass balance (SMB) of the Antarctic Ice Sheet (AIS) is a key component in understanding present and future changes in global climate and sea level. Previous research mainly focused on determining (changes in) the total SMB of the AIS. Local SMB measurements were limited to changes in the total height of the snowpack. These changes in snow height are often used as a proxy for snowfall amounts. However, in order to fully understand (changes in) the local SMB over the AIS, it is necessary to gain information about its individual components and the relation between the local SMB and snowfall. In this study, we quantified the different components of the local SMB at the Princess Elisabeth (PE) station and assessed their interactions and drivers, using a unique set of remote sensing instruments, which operated for a period of 37 months.

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Snowfall is the most important source term of the local SMB. Snowfall events were found to originate from oceanic air masses which are transported towards the AIS by cyclones in the Antarctic circumpolar trough. These air masses take up moisture from the ocean which mainly precipitate at the coastal areas of the AIS. Because of high wind speeds associated with these events, displacement of freshly fallen snow takes place in layers with a vertical extent of usually more than 30 m as detected by the ceilometer. During snowfall, both accumulation as ablation at the local scale was observed. Accumulation at the surface can therefore not be considered an accurate proxy for snowfall, as frequently more snow is transported by the wind than has precipitated locally. The distinction between accumulation and ablation events during snowfall was attributed to the duration of the event and the temporal cloud extent. Longer events attain for larger areas with fresh snow deposition. Therefore, there is a higher chance that snow that has been removed from a local site is replaced by snow that is available upstream.

Wind-driven accumulation and ablation also occur without snowfall. Accumulation events have a tendency to take place during similar types of circulation as snowfall events, however, they are characterised by lower wind speeds. During most of these accumulation events, snowfall takes place only at the coastal areas of the AIS. Winds easily pick up the freshly fallen snow and transport it towards inland locations, leading to accumulation at the local site. Ablation events originate more often from southerly flows and occur shortly after snowfall events at the station. These katabatic winds originate from the Antarctic plateau in the south, where less fresh snow is available. Katabatic flow originating from these areas is therefore dry, containing less snow particles, and removes the freshly fallen snow at the local site resulting in ablation. Both these accumulation and ablation events take place at low wind speeds in blowing / drifting snow layers of limited vertical extent, showing the importance of fresh snow availability in order to transport snow.

This study investigated the conditions influencing the observed occurrence of snowfall, accumulation and ablation events, their relation and influence on the local SMB over the AIS. Accumulation was found to be not an accurate proxy for snowfall over East Antarctica. Meteorological conditions during snowfall, accumulation and ablation, were indicated, including their impact on the local SMB, which was largely unknown up to now.

Observations for this study were limited to one location over the AIS. As such, results might depend on the local conditions. However, as the main conclusions are based on both an analysis of synoptic as local meteorology, deductions of our work are also deemed to be valid at other coastal areas over the AIS. In order to confirm this, future work should expand the measurements of the individual components of the local SMB to other sites over the AIS, in order to confirm the role of meteorological conditions at other areas including their effect on the local SMB.

Data availability. Data from the instrumentation at the Princess Elisabeth station can be obtained from the database on http://www.aerocloud.be

Competing interests. The authors declare that they have no conflict of interest.

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