SNOW ACCUMULATION ON A SMALL HIGH-ARCTIC GLACIER SVENBREEN: VARIABILITY AND TOPOGRAPHIC CONTROLS

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ABSTRACT. One of the main controls on the net mass change of land-terminating Arctic glaciers is the magnitude and distribution of snow accumulation. In Dickson Land, region of Svalbard with the greatest distance to the sea, the issue has not been receiving much scientific attention for decades. In this paper, new snow accumulation data are presented from Svenbreen in Dickson Land from end-of-winter surveys. The measured winter balance was 0.42 ± 0.15 m w.e. in 2010, 0.50 ± 0.10 m w.e. in 2011 and 0.62 ± 0.10 cm w.e. in 2012. Snow depth and water equivalent have been analysed in the background of altitude, slope and aspect extracted from the digital elevation model of the glacier. On steep northern slopes (>15°) accumulation was the highest, whereas it was decreased on southern slopes with moderate inclination (9–12°). Elevation, which on many glaciers proved to be highly correlated with snow depth, explained only 17–34% of snow depth variability due to complex interplay between local climate and geometry of a small valley.

Key words: glacier, snow accumulation, winter balance, topography, Dickson Land, Svalbard

Introduction

The Arctic has been experiencing evident climate warming in the last decades, causing negative volume changes of its ice masses (Serreze *et al.* 2009; IPCC 2013). In Svalbard the longest direct surface mass balance records from glaciers Austre Brøggerbreen and Midre Lovénbreen started in the 1960s and are shown to be stable over winter and summer time, with negative net balances (Hagen *et al.* 2003). Remote sensing and modelling techniques, as well as direct conventional studies, have helped us to better understand the general spatial pattern of the annual balance of Svalbard glaciers, all confirming the general loss in mass contributing to sea-level rise (e.g. Moholdt *et al.* 2010; Nuth *et al.* 2010; Lang *et al.* 2015). Although much attention has been paid to ablation processes in Svalbard, our knowledge of snow accumulation is patchy, both at local and regional scales.

On a local scale, winter snow cover on Svalbard glaciers is known to be greatly influenced by topography (Hodgkins *et al.* 2005; Grabiec *et al.* 2006). The most important variable determining snow distribution is altitude, a relationship often used as the sole control of winter balance distribution in surface mass balance models in Svalbard and other regions of the globe (e.g. Huss *et al.* 2008; Machguth *et al.* 2009; Rye *et al.* 2010). On a regional scale, the key factor is the distance to the sea and exposition to moisture inflow direction, resulting in increased winter balances along the coasts of Svalbard (typically 50–100 cm w. eq.) and lower accumulation rates in the interior of Spitsbergen (Winther *et al.* 1998; Grabiec 2005; Taurisano *et al.* 2007).

In the arid central part of the island, snow accumulation has been surveyed only on a few glaciers, including Longyearbreen, Bogerbreen and Bertilbreen (Troitskiy 1988), and on several other small ice masses with occasional data availability. The latter glacier Bertilbreen is located close to the abandoned Pyramiden town in Dickson Land and its lowest average winter balance from all Svalbard glaciers measured to date, 0.41 m *water equivalent* (*w.e.*) (Troitskiy 1988), coincides with the greatest distance from oceanic moisture sources (*c.* 100 km). However, it is not clear whether the figure is representative of the whole of Dickson Land or is influenced by local factors, such as valley aspect and glacier surface geometry.

This paper delivers new snow accumulation data from a poorly surveyed central Spitsbergen region of Dickson Land. The aim of this work is to investigate the magnitude and variability of winter balance on a small glacier Svenbreen at the end of the winter season in 2010, 2011 and 2012. As the first work from the interior of Spitsbergen, it characterizes the topographic controls of snow depth and it tests the widely used assumption of strictly elevation-dependant accumulation on a small high-Arctic glacier.

Study area and data

Svenbreen has been an object of detailed glaciological monitoring of Adam Mickiewicz University in Poznań, Poland since 2010. It is a small (4 km^2, 4 km long) land-terminating valley glacier spanning from 180 to *c*. 730 m a.s.l., with median elevation of *c*. 460 m a.s.l. (Fig. 1a). The surface of Svenbreen is generally even and moderately inclined (10° on average), although there are also steeper sections (Fig. 1c). The easterly flowing tongue is 2 km long and constitutes the ablation zone with asymmetric cross-profile, with the southern rim of the tongue being higher in elevation than the northern one. Close to the front, a small steep tributary cirque glacier, unofficially named Hannabreen, joins the tongue from the south. The highest zone of Svenbreen is composed primarily of a large shaded cirque with northern orientation (Fig. 1b). The other highly elevated areas are a minor patch of southern aspect, given the unofficial name Poznańskaret, and two small ice tongues flowing steeply towards the north from a mountain pass called Nataliaskaret.

The average annual precipitation and air temperature at the closest weather station Svalbard Lufthavn (50 km SSW) are 192 mm and –5.1°C respectively. The mean winter (October–April) precipitation is 115 mm and the temperature is –10.6°C, as measured by the Norwegian Meteorological Institute during 1981–2010. During the study period, both precipitation and temperature were higher than multiannual means: 157 mm, 144 mm, 150 mm and –7.4°C, –10.3°C and –5.5°C respectively for the winter seasons 2009/10, 2010/11 and 2011/12. The automatic weather station has been operating in the central zone of the glacier tongue (at 355 m a.s.l.) only since 2011. During the winter seasons 2011/12, 2012/13 and 2013/14, the average air temperature was about –10°C, the wind speed was low at *c*. 2.5 m s^{-1} and the prevailing wind direction was from the western sector (WSW, W and WNW, *c*. 50%; Fig. 1a). Due to progressive climate warming in Svalbard, Svenbreen has been showing long-term thinning at an average rate of 0.41 m a^{-1} (1960–2009), noticeably slower than all surrounding glaciers (Małecki 2013; Małecki *et al.* 2013; Ewertowski 2014). The glacier front has been retreating at a low stable rate of 4–5 m a^{-1} for the last few decades (Rachlewicz *et al.* 2007). Flow velocity is very low, *c*. 3 m a^{-1} at its maximum (Małecki 2014).

A preliminary study of snow distribution was performed on 30 Mar., 2010 when 43 snow thickness measurements (n) were done with an avalanche probe (12 probings km^{-2}). Full winter surveys on Svenbreen were carried out on 4 May, 2011, and 15 Apr., 2012, when spatial distribution of snow depth (s) was determined by 131 (35 km^{-2}) and 167 probings (45 km^{-2}). Ideally, snow depth probings should be coupled to the last summer surface investigations. However, since very little snow survived the summer seasons directly before the winter surveys, the effect of extra thickness introduced by the previous winter's snow was assumed to be negligible. In rare situations, in 2012 when snow depth exceeded the 250 cm length of the probe, the depth of 300 cm was recorded. Each snow depth probe was marked with a simple handheld GPS device, imported to ESRI ArcGIS software and plotted against a 2009 20 m *digital elevation model* (*DEM*) produced by Strzelecki (2012) from Norwegian Polar Institute aerial photographs with 0.5 m resolution. Topographic parameters, such as elevation (h), slope (α) and aspect (A), were then extracted from the DEM for each data point.

In order to convert s into w.e., snow density (ρ) studies in pits were performed in 2011 and 2012 at two sites: in the lower part of the glacier (at 277 and 358 m a.s.l. respectively for 2011 and 2012) and the upper part of the glacier (at 513 m). Each 10 cm column of a snow pit was collected into an aluminium tube, weighed and converted to density by a Winter Engineering gauge. Since variability of ρ within the collected samples was low (standard deviation of 70 kg m^{-3}), it was assumed reasonable to use the mean ρ for the entire glacier surface. In some analyses, a *snow depth deviation factor* (*SD*) was introduced, a measure of a shortage or surplus of snow accumulation for a given altitude. Average ρ multiplied by average s gave the glacier-wide winter balance for each season (B_w). The lower-case symbol b_w indicates point values of winter balance.

Local s and b_w values have been interpolated over the entire glacier area for each season from individual snow depth probings. Two interpolation schemes have been tested: kriging and minimum curvature spline technique. Due to the specific

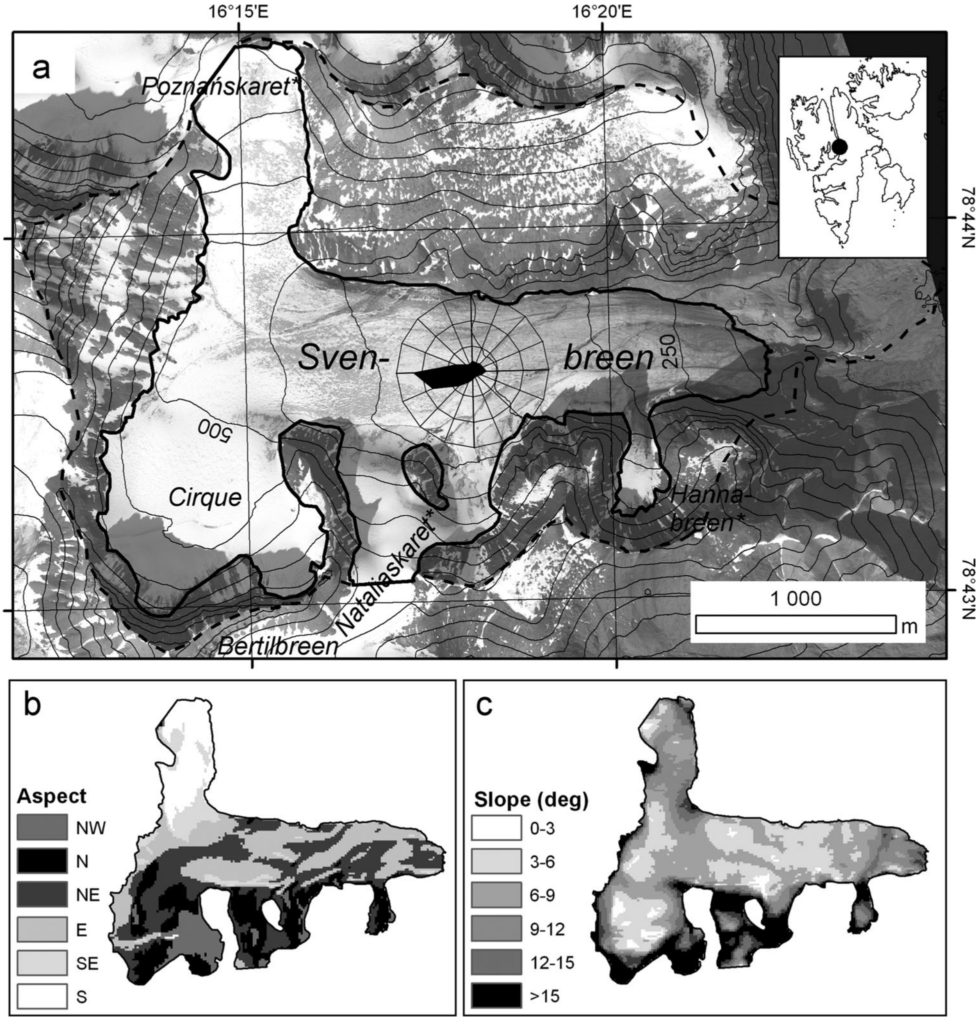

Fig. 1. (a) Aerial image of Svenbreen by Norsk Polarinstitutt with average winter wind rose at automatic weather station (the external circle is 30% frequency). Contour lines every 50 m, asterisks – unofficial names, bold line – boundary of the glacier, dashed line – boundary of Svenbreen basin, inset – location of the study area in Svalbard. (b) Distribution of aspect over the glacier (single pixels of other aspects than mentioned in the legend dismissed for clarity). (c) Distribution of slope over the glacier.

character of the kriging method and strong gradients of s on Svenbreen, this resulted in a certain mismatch between the interpolated and measured s values, represented by 11% standard deviation of the differences. In contrast, the spline method reproduced nearly identical values to those measured in the field. To further investigate uncertainties arising from interpolation, new test-rasters have been created for each season, having 10% of input points removed. A comparison made between the predicted and measured values at their locations revealed standard deviation of errors of 10% and 8% respectively for the kriging and spline techniques. The spline method was chosen for the final interpolation since it produced more realistic smooth rasters which better reflect the complex pattern of snow accumulation directly measured on Svenbreen. To estimate s in the unsurveyed areas of the glacier, an elevation–snow depth function relevant for each season was applied, also accounting for *SD* for a given slope aspect.

Snow accumulation measurements are associated with a number of inaccuracies. Here, a ±5% error is assumed for single snow depth probing due to surface roughness and non-vertical snowpack penetration by a probe. The position of each probing was marked by a GPS device with a typical horizontal error of ±5 m. For density measurements a conservative ±10% error is assumed, as, for example, soft snow is prone to escaping from the measuring tube or may be easily compressed. Under conditions found on Svenbreen, the inaccuracies described above correspond to an overall b_w error of ±0.03–0.08 m w.e., which is higher when *s* is greater. Further uncertainties arise from probing sample size, size of unsurveyed areas, interpolation quality and number of snowpits, which are used to obtain snow density data. Accounting for all the uncertainties above and the size of the standard deviation of *s* measurements, error bars for B_w estimates have been set at a higher level than for point values, with ±0.10 m w.e. for 2011 and 2012 and ±0.15 m w.e. for 2010, the year with less data availability.

Results

Spatial distribution of snow on Svenbreen in 2010, 2011 and 2012 was very complex, with the lowest snow depth *s* just at the front (0.70–0.80 m), the highest in the glacier cirque (up to >3 m) and multiple zones of increased accumulation all over the glacier (Fig. 2a–c). *s* also varied significantly between the study periods, being on average 1.29 m in 2010, 1.56 m in 2011 and 1.83 m in 2012. Mean snow density ρ in 2011 was 290 kg m^{-3} in the lower pit and 350 kg m^{-3} in the higher one; in 2012, it was 320 and 360 kg m^{-3} respectively (Table 1). Winter balance B_w was 0.50 m w.e. in 2011, 0.62 m w.e. in 2012 (Fig. 2d, e) and probably about 0.42 m w.e. in 2010, if average ρ was assumed.

Altitude *h* showed significant correlation with *s*, although at individual sites on the glacier it explained only 17–34% of the variation in *s* (Fig. 3a–c). However, if measured for 50 m elevation bands, the correlation rose drastically to 0.62–0.96 (Fig. 3d). The average accumulation–elevation gradient was variable between the seasons: 0.13 m (100 m)$^{-1}$ in 2010, 0.20 m (0.064 m w.e.) (100 m)$^{-1}$ in 2011 and 0.20 m (0.067 m w.e.) in 2012 (Table 1). The relationship between *s* and slope inclination α was relatively poor when analysed using all of the data points. However, when averaged within 3° inclination bins, a certain pattern became apparent: the lowest accumulation was noted on slopes with moderate α (9–12°) and the highest on flat areas and steeper slopes (Fig. 3e–g).

The slope aspect *A* on Svenbreen is strongly elevation dependent, since the low-elevated tongue is oriented towards E and NE, while higher zones show aspects of N, NW, S and SE (Fig. 1b). Therefore, to detect zones of abnormal accumulation the actually observed *s* values were compared with those calculated for a given point from accumulation–elevation gradients (Fig. 3a–c) and transformed to snow depth deviations *SD* (2010 data excluded due to low *n*). The analysis showed that S and SE slopes of Poznańskaret have reduced snow accumulation, with an average *SD* of –14%, while N and NW slopes of the cirque and Nataliaskaret receive an extra snow input, with mean *SD* of 8% (Figs 4 and 5). Spatial variability of *SD* was very high, but followed a similar pattern in 2011 and 2012, with positive values in the cirque, Nataliaskaret and central tongue.

Discussion

For decades, Bertilbreen has been the only glacier in Dickson Land with a direct mass balance record, now expanded with new B_w data from Svenbreen, neighbouring Bertilbreen from the north (Fig. 1a). B_w on the study glacier over the 2010–2012 period ranged from 0.42 to 0.62 m w.e., with average of 51 cm w.e., similar to mean B_w of other central Spitsbergen glaciers studied: Longyearbreen (0.48 m w.e.) and Bogerbreen (0.52 m w.e.).On the neighbouring Bertilbreen, B_w varied between 0.31 and 0.50 m w.e., with 0.41 m w.e. as a 1975–1985 mean (Troitskiy 1988). Accounting for the new data and earlier snow accumulation map of the Pyramiden area by Gokhman and Khodakov (1986), it seems very likely that B_w on Svenbreen is higher than in neighbouring valleys. Longer records are needed to verify this hypothesis, but the data show lower rates of Svenbreen thinning compared with mass loss rates of other Petuniabukta glaciers documented by Małecki (2013), Małecki *et al.* (2013), Ewertowski (2014) and Strzelecki *et al.* (2015).

The main difference between the two glaciers is orientation of their valleys: west–east for Svenbreen and north–south for Bertilbreen, strongly modifying local wind patterns and hence snow drift. Significant redistribution of snow starts at wind speeds of *c.* 4 m s^{-1} (Grześ and Sobota 2000; Winther *et al.* 2003), which on Svenbreen is only exceeded during 13% of wintertime. Despite a low average wind speed, large spatial variability of *s* on Svenbreen indicates the high importance of snow redistribution, confirming the particular

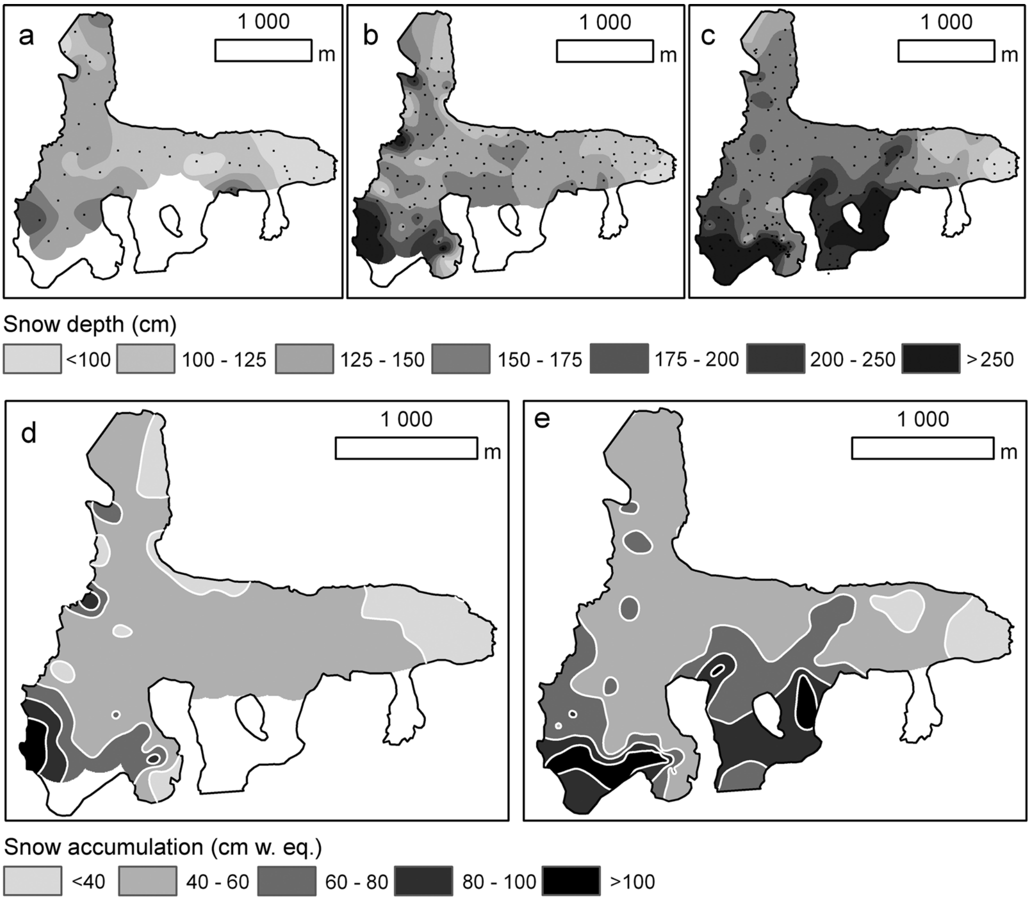

Fig. 2. Maps of snow depth on Svenbreen and locations of snow depth measurements (dots) in 2010 (a), 2011 (b), 2012 (c) and winter balance in 2011 (d) and 2012 (e). Unsurveyed zones are given in white.

predisposition of small and narrow valleys to snow drift occurrence (Pomeroy *et al.* 1993). Mild winds over the glacier result in low efficiency of snow wind-packing, which explains low snow density as for Svalbard [average of 320–340 kg m^{-3}, compare with ρ reported by Winther *et al.* (2003) and references therein].

Similar to other glaciers in Svalbard, h was an important topographic control of snow accumulation on Svenbreen. However, correlation of h with directly measured snow depths was surprisingly low and ranged from only 0.17 to 0.34. For other larger valley glaciers in Svalbard, higher r^2 values were calculated; for example, 0.38–0.60 for Finsterwalderbreen (Hodgkins *et al.* 2005) and 0.64–0.91 for three glaciers in southern Spitsbergen (Grabiec *et al.* 2006). The low predicting power of accumulation–elevation gradients on Svenbreen is a result of high spatial variability of snow distribution within individual elevation bands.

The average accumulation–elevation gradient in Svalbard has been estimated as *c.* 0.10 m w.e. $(100\ m)^{-1}$ (Winther *et al.* 1998). On coastal glaciers of W, S and E Spitsbergen, the observed gradients are typically on the order of 0.10–0.25 m w.e. $(100\ m)^{-1}$ (e.g. Migała *et al.* 1988; Winther *et al.* 1998; Grześ and Sobota 2000; Hodgkins *et al.* 2005; Grabiec *et al.* 2006; Sobota 2013). On glaciers of the interior, Winther *et al.* (1998) measured lower gradients of 0.091 and 0.011 m w.e. $(100\ m)^{-1}$. The gradients on Svenbreen were also low, with 0.064–0.067 m w.e. $(100\ m)^{-1}$, reflecting its inner-fjord location and arid climate in Dickson Land.

The other topographic variables, α and A, have also shown a significant relationship with s. Analysis of accumulation against α indicates

Table 1. Statistics of snow accumulation surveys on Svenbreen: n – number of snow depth measurements, s – snow depth, ρ – snow density, B_w – winter balance, r^2 – correlation coefficient.

	2010	2011	2012
Snow depth measurements			
n	43	131	167
s (min/mean/max)	0.78/1.29*/1.91 m	0.70/1.56*/3.20 m	0.80/1.83/>2.50 m
Standard deviation (% of mean)	0.26 m (22%)	0.40 m (27%)	0.53 m (28%)
Water equivalent			
ρ (lower/higher location)	no data	290/350 kg m^{-3}	320/360 kg m^{-3}
B_w	0.42 ± 0.15 m w.e.**	0.50 ± 0.10 m w.e.	0.62 ± 0.10 m w.e.
Accumulation–elevation gradient			
Mean s increase with elevation	0.13 m (100 m)$^{-1}$	0.20 m (0.064 m w.e.) (100 m)$^{-1}$	0.20 m (0.067 m w.e.) (100 m)$^{-1}$
r^2	0.34	0.31	0.17

*Mean snow depth in surveyed zones computed from interpolated raster; in unsurveyed zones, from average accumulation–elevation gradient and snow deviation relevant for given slope aspect.
**Assuming snow density of 330 kg m^{-3}.

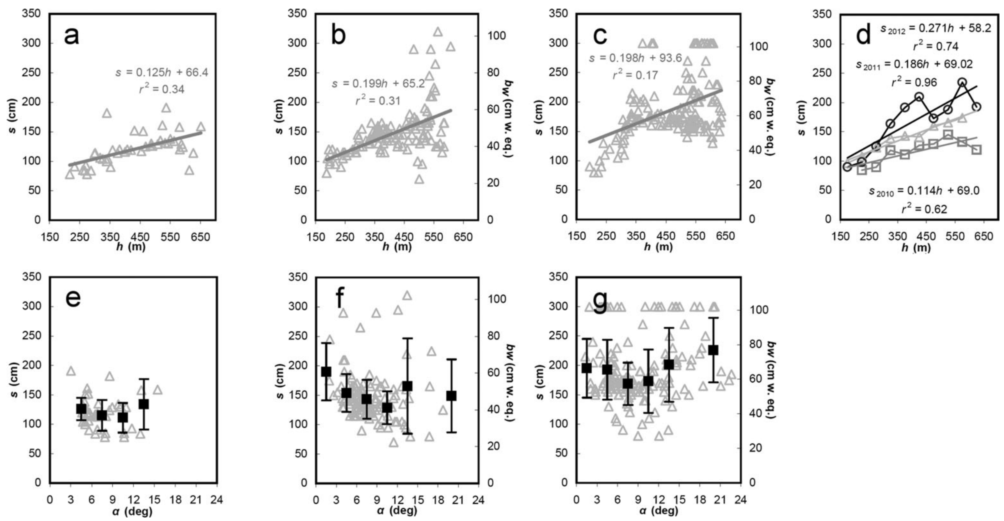

Fig. 3. Upper panel: snow depth (s) and point winter balance (b_w) against altitude (h) in 2010 (a), 2011 (b), 2012 (c) and mean s averaged for 50 elevation bands (d) for 2010 (dark grey squares), 2011 (light grey triangles) and 2012 (black circles). Lower panel: snow depth (s) against slope inclination (α) in 2010 (e), 2011 (f) and 2012 (g). Black squares – average s within 3° inclination bins with one standard deviation bars. Squares to the right on (f) and (g) represent bin >15°.

that moderately inclined surfaces (9–12°) were characterized by the lowest s, hence are likely prone to snow erosion. The highest s was observed on nearly flat areas, as well as on steep convex slopes where snow is deposited by snow drift and avalanches (Fig. 3e–g). Increased accumulation on N and NW slopes of the cirque and Nataliaskaret, as well as snow shortage on S and SW slopes of Poznańskaret (Figs 4 and 5), encourages one to speculate about the potential action of southern winds. These winds could deposit snow on the northern (lee) sides of the cirque and Nataliaskaret and erode windward Poznańskaret. However, such a pattern does not agree with the weather station records, which clearly show the domination of westerly winds on the tongue. A more detailed weather monitoring network is necessary to ascertain the wind control of snow accumulation in the highest zones of the glacier.

The above findings show that the reliability of the elevation-dependant accumulation assumption, widely used in distributed mass balance, energy balance and hydrological assessments, needs to be questioned for small Arctic glaciers of a few square

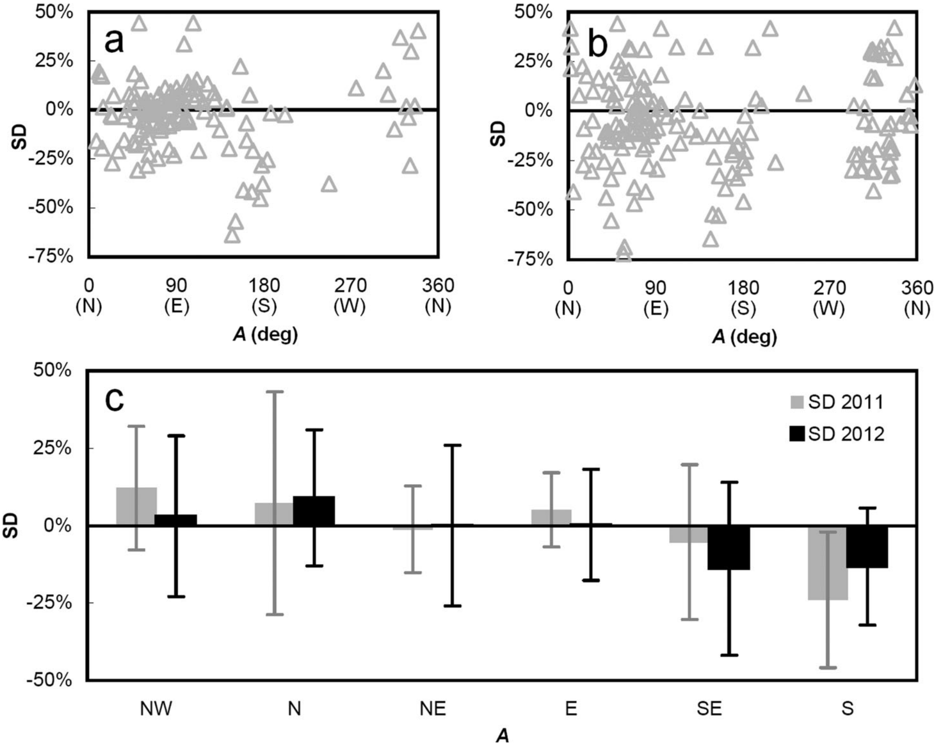

Fig. 4. Snow depth deviation (*SD*) at all snow depth probing locations against slope aspect (*A*) in 2011 (a), 2012 (b) and generalized *SD* for 2011 and 2012 with one standard deviation bars (c).

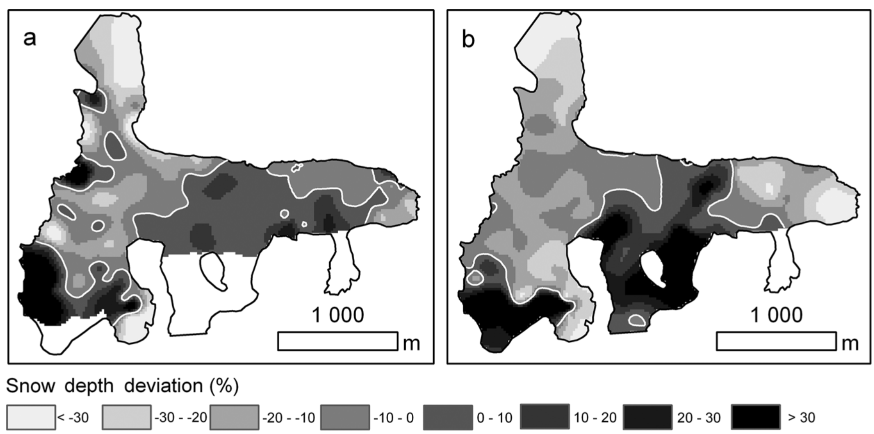

Fig. 5. Distribution of snow depth deviation in 2011 (a) and 2012 (b). White contours indicate zero, white areas – unsurveyed zones.

kilometres. The use of such a simple approach to estimate snow distribution on Svenbreen would not take into account the large variability within individual elevation bands and result in drastic underestimation of b_w on the northern slopes and its overestimation on exposed zones in the south. Accurate determination of b_w distribution is essential to recognize the spatial pattern of the annual glacier mass balance. As outlined by Hodgkins *et al.* (2005) and confirmed here, this may not be achieved by accumulation–elevation gradients on the smallest Arctic glaciers. However, the relationship between altitude and snow depth was found to be much stronger for elevation-averaged bins (Fig. 3d), implying the usefulness of glacier-wide modelling approaches, even for small Arctic valleys.

Conclusions

Snow accumulation on glaciers in arid Dickson Land, Spitsbergen interior has not been receiving scientific attention for almost 30 years. In this paper, new snow data from the small glacier Svenbreen have been presented, covering the three winter seasons of 2010, 2011 and 2012. The results suggest increased winter balance on Svenbreen compared with neighbouring glaciers: 0.42 ± 0.15 m w.e., 0.50 ± 0.10 m w.e. and 0.62 ± 0.10 m w.e. for 2010, 2011 and 2012, respectively. The average snow density was relatively low as for Svalbard: 320 kg m^{-3} in 2011 and 340 kg m^{-3} in 2012. This was likely related to low winter wind speeds over Svenbreen and resulting inefficient wind compaction. The spatial variability of snow distribution was very high as a result of the complex interplay of topographic variables and wind pattern, all acting in a small valley with a wide range of slope inclinations and aspects.

Among the terrain characteristics, altitude had the dominant effect on accumulation, but it failed to predict snow depth at a reasonable level, explaining only 17–34% of its variability. The influence of the complex topography of the Svenbreen valley blurs the orographic snow depth gradients due to local wind patterns and associated snow drift, resulting in redistribution of snow and formation of erosion zones (mainly southern slopes with *c*. 10° inclination) and deposition zones (steep surfaces with northern aspect). The Svenbreen case highlights the necessity of careful recognition of snow cover distribution on small (few kilometre square) high-Arctic ice masses before assessing distributed mass, energy and water balance models. However, use of the accumulation–elevation gradient remains a reliable tool to estimate winter balance, even for very small and topographically complex glaciers, although only on a glacier-wide scale.

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