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Glacio-meteorology of Ebbabreen, Dickson Land, central Svalbard, during 2008–2010 melt seasons

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Abstract: Interior of Svalbard, High Arctic, is relatively arid and warm during the summer, but impact of this quasi-continental climate type on the glacio-meteorology, surface energy balance and melt processes has been seldom researched. This study brings new data from a weather station located on the largest glacier in Dickson Land, Ebbabreen, at 550 m a.s.l from July and August 2008–2010. The paper discusses air temperature and moisture, wind speed, incoming shortwave radiation and estimates of turbulent heat exchange of the melting surface in the background of atmospheric circulation over Svalbard. The results have shown that average insolation in the study area was low with *ca.* 135 W m^{-2}. Frequent occurrence of strongly negative temperature gradients resulted in mean July–August air temperature of 1.9°C at the measuring site. Relatively low air vapour pressure led to negative latent heat flux, particularly during advection of air masses from the northern and north-eastern sector. The local microclimate supports the sensible heat transfer, which reached its maximum during eastern circulation situations.

Key words: Arctic, Spitsbergen, glacier, meteorology, energy balance.

Introduction

Recent climatic change particularly influences the Arctic and its glaciers (IPCC 2013). In its Eurasian sector the largest portion of land ice masses is located in Svalbard, which is particularly sensitive to climate and ocean shifts (Hagen *et al.* 2003). Recent warming in Svalbard is best visible in air temperature of winter periods, but it is significant in case of summer seasons as well (Bednorz and Kolendowicz 2013; Nordli *et al.* 2014), being a clear manifestation of changing energy balance conditions. Increased energy availability is responsible for enhanced melting of local glaciers, leading to further changes of their extent and physical properties, dynamics and thermal structure (*e.g.* Dowdeswell *et al.* 1995; Nuth *et al.* 2007, 2010; James *et al.* 2012).

Glaciological research in Svalbard is well developed, although it is mainly focused along the western coasts of Spitsbergen (the largest island of the archipelago) and around Longyearbyen – the main settlement of Svalbard. For years, glaciers in inner-fjord parts of Spitsbergen remained relatively poorly investigated. They are partly isolated from maritime influence, hence experience quasi-continental climate features: very little precipitation (including solid) and relatively high summer temperature at the sea level (Hagen *et al.* 2003; Przybylak *et al.* 2014). These peculiar conditions are less favourable for their development than along the coasts, what is clearly manifested by little glacier cover of Spitsbergen interior, including Dickson Land, located the furthest from the open sea (*ca.* 100 km). Recent research has shown that local ice masses experience similar climatically-induced retreat and thinning rates as glaciers in more maritime locations (Rachlewicz *et al.* 2007; Małecki 2013a, b; Małecki *et al.* 2013; Ewertowski 2014).

Climate data from this arid region is sparse, with the exception of its central zone near Pyramiden town. Published records from this area were collected by Russian (*e.g.* Gokhman and Khodakov 1986), Polish (e.g. Kostrzewski *et al.* 1989; Rachlewicz 2003; Rachlewicz and Styszyńska 2007) and Czech researchers (Láska *et al.* 2012), all confirming higher summer air temperature and lower humidity than at the coasts of Spitsbergen. Until recently, influence of these climate features on the functioning of local glaciers was unknown. Małecki (2013a) published the first glacio-meteorological data for Dickson Land and concluded a clear impact of regional and local climate on the glacier surface energy balance structure. This study brings new weather data from Ebbabreen – the largest glacier in Dickson Land – for the period covering 3 melt seasons 2008–2010 and investigates turbulent heat exchange on its surface.

Study area

Ebbabreen is the largest glacier in Dickson Land (24 km^2, 7.5 km long), although genetically related to the Olav V Land icefields, as it is partially an outlet of Mittag-Lefflerbreen, and partially an independent valley glacier (Fig. 1). It flows to the western direction, but its large sectors also show northern and southern aspects. The glacier is relatively high elevated: the present-day front is situated at *ca.* 100 m a.s.l., median elevation is *ca.* 610 m, mouth sections of its glacial cirques are at 600–700 m, while its steep uppermost zones exceed 1000 m a.s.l. Theoretical steady-state equilibrium line altitude (ELA) of Ebbabreen is about 580 m (assuming accumulation area ratio of 0.6), but observations from the last decade suggest it is located higher, since most of glacier area is often snow-free at the end of summer season. The only published mass balance data from Ebbabreen (2001–2003) shows fast surface lowering at the front (*ca.* 2.5 m a^{-1}) and in its middle zones (*ca.* 1 m a^{-1} at 540 m, Rachlewicz 2009), indicating high energy available for melt. Since the termina-

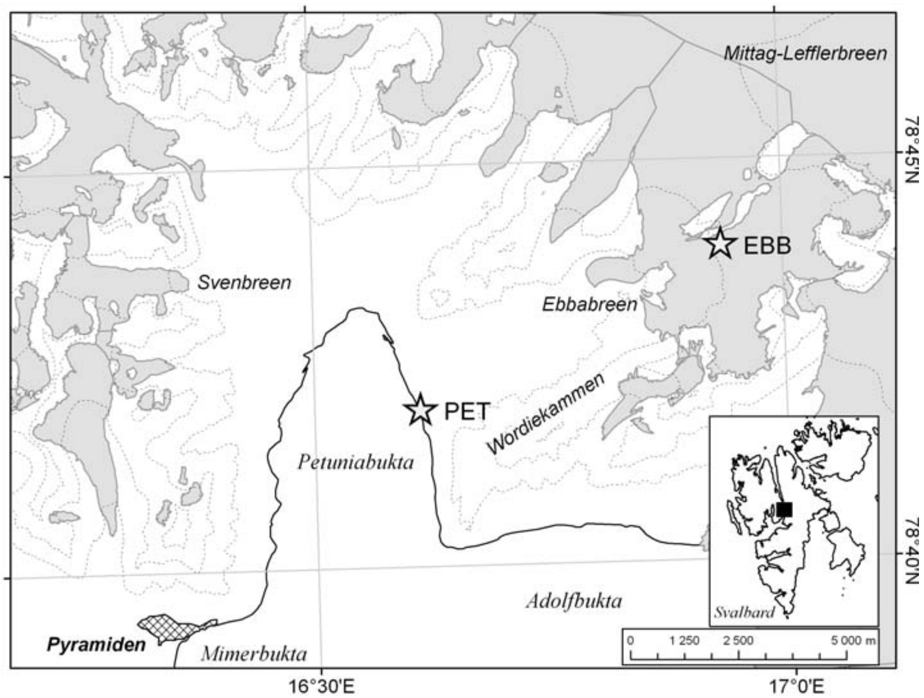

Fig. 1. Location of the study area and weather stations (asterisks) against modern glacier outlines (light grey). Bold line – coasts. Dashed lines – 250 m contours. Inset – location of the study area in Svalbard.

tion of the Little Ice Age (early 20th century) Ebbabreen has been retreating, leading to shortening of its length by 1 km until present (Rachlewicz *et al.* 2007).

Glacio-meteorological and surface energy balance records from Svalbard glaciers are seldom (*e.g.* Hodson *et al.* 2005; Migała *et al.* 2006; Krismer 2009; Schuler *et al.* 2014) and in case of central Spitsbergen are represented only by a yearly record from Svenbreen (Małecki 2013a). The net radiation measured on this glacier in July and August 2012 was very low (26 W m^{-2}), while turbulent heat fluxes were greatly influenced by local and regional climate peculiarities. Mean sensible heat flux contribution in the middle of Svenbreen was only 8 W m^{-2} due to very low wind speed in its valley, whereas negative contribution of latent heat flux (-2 W m^{-2}) was primarily caused by low air moisture. No meteorological data has been published for Ebbabreen yet, but its energy balance was supposed to be somewhat different from that observed on Svenbreen due to its different geographical setting.

Methods

The weather station on Ebbabreen (EBB) has been operating in its central part at 550 m a.s.l., close to the theoretical steady-state ELA of the glacier, 2 m above ice surface, during periods: 12/07–27/08/2008, 10/07–31/08/2009 (data hiatus in the period 17–22/08) and 16/07–21/08/2010. The device used was Vantage Pro, a portable weather station by Davis, measuring air temperature (T_a), relative humidity (*RH*) and wind speed (u) at 1 hour interval. *RH* was measured with respect to water, so it was corrected for ice with expression of Curry and Webster (1999) and then used to compute air vapour pressure e_a. Accuracy of measuring sensors given by the manufacturer is ± 0.5°C for T_a, ± 3% for *RH* lower than 90%, ± 4% for *RH* higher than 90% and ± 5% for u. However, in the field the errors are expected to be doubled, particularly during sunny weather, *e.g.* due to overheating of radiation shield.

Thermal gradient (ΔT_a) was computed using data from a similar weather station located at the shore of Petuniabukta (PET), 8.5 km WSW from EBB (Fig. 1). Other parameters measured at PET were incoming shortwave radiation *SWin* (with a simple silicon pyranometer) and cloud cover (inspected 4 times a day and given in octants). Daily weather conditions at EBB and PET have been analysed in the background of atmospheric circulation types classified by Niedźwiedź (2013). He distinguished 10 main circulation patterns over Svalbard: N+NE, E+SE, S+SW, W+NW (all in cyclonic *c* and anticyclonic *a* variants), C*a*+K*a* (central anticyclonic situation or wedge of high pressure), C*c*+B*c* (central cyclonic situation or through of low pressure) and an unclassified situation marked with *x* sign.

Sensible and latent heat fluxes at EBB (Q_H and Q_L respectively) were approximated at 1 hour time step using energy balance model by Brock and Arnold (2000). It uses the bulk aerodynamic approach and is based on the Monin--Obukhov similarity theory. It assumes i.e. logarithmic vertical profiles of u, T_a and e_a, proper stability corrections and constant surface roughness (here set as 5 mm, being moderate as suggested by the model authors). Conditions of low wind speed and strong stability are treated as unfavourable for turbulent heat transfer, hence Q_H and Q_L are zero when $u < 2$ m s^{-1} and $u/T_a < 0.3$ or when both $u < 1.5$ m s^{-1} and -1°C < T_a < 1°C. The model assumes surface temperature at 0°C, but due to the occurrence of cooler periods during the summer at EBB station such assumption is justified only for parts of the investigated periods. Therefore, results of turbulent heat fluxes modelling obtained for days with sub-zero T_a (common at the site) are not considered in this study, since surface temperature could have been well below the melting point at that time.

Results

The three analysed summer seasons differed in length and synoptic situation (Fig. 2). In 2008, relative importance of individual atmospheric circulation patterns was similar. The summer of 2009 was characterized by anticyclonic circulation, frequent passages of high pressure centres across Svalbard and air advection from E+SE. The measurement period of 2010 was dominated by cyclonic situations and

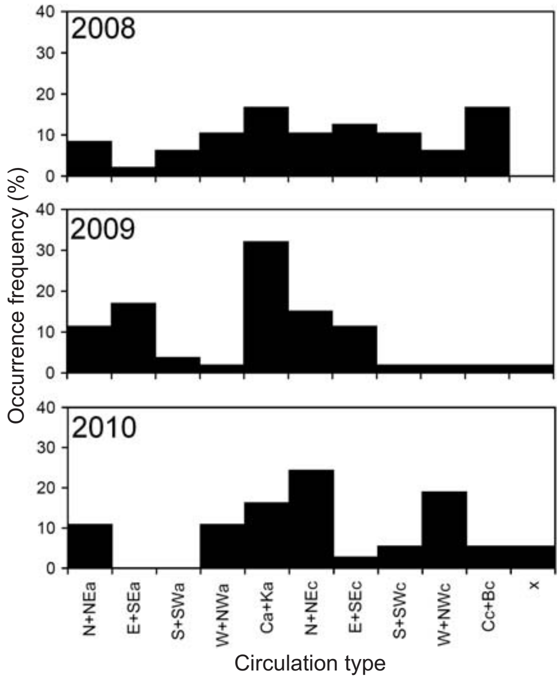

Fig. 2. Occurrence frequency of individual atmospheric circulation types during the investigated summer seasons on Ebbabreen.

frequent advection of air from N+NE and W+NW. Cloud cover was generally high, with 6.4 in 2008, 5.7 in 2009 and 6.6 in 2010, all given in octants. Overcast conditions resulted in generally low insolation of 136, 140 and 133 W m^{-2}, respectively for the investigated seasons. The mean amount of shortwave radiation delivered to the horizontal surface at PET was only 26–27% of the potential incoming shortwave radiation (*SWpot*) calculated for this latitude and clear horizon.

In 2008, mean daily T_a oscillated between -2.7°C and 5.7°C, with average of 1.9°C for 47 days covered with measurements. The season was characterised by the lowest average wind velocity (2.6 m s^{-1}). Temperature gradient ΔT_a was very variable during the season and ranged from -1.13°C/100 m to -0.09°C/100 m, with average being the least negative from all the investigated periods (-0.74°C/100 m). Air vapour pressure e_a has been exceeding 600 Pa only sporadically and was 562 Pa on average. Mean *RH* was 80.2% (Fig. 3).

Summer season of 2009 was the warmest from periods analysed in this paper (Fig. 4). The lowest daily T_a was -2.4°C, while the highest was 7.9°C. Mean air temperature was 2.7°C (from 47 days in total). Lapse rates were again highly variable (from -1.27°C/100 m to -0.27°C/100 m) and were on average slightly more negative than in the previous summer (-0.81°C/100 m). The season was also windy (mean u was 4.0 m s^{-1}, with maximum of 12.4 m s^{-1}) and relatively humid (e_a = 580 Pa), although mean *RH* was the lowest (77.7%).

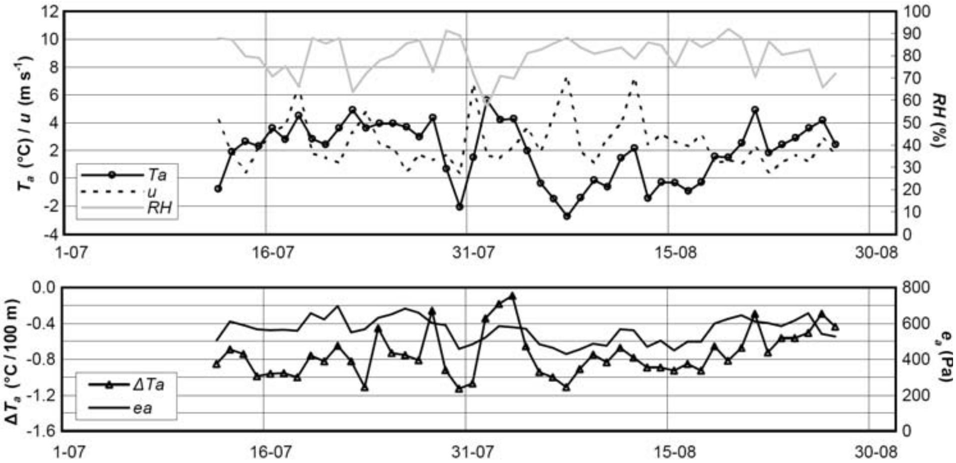

Fig. 3. Weather conditions on Ebbabreen during 2008 ablation season. Abbreviations: T_a – air temperature, u – wind speed, RH – relative humidity, ΔT_a – temperature gradient, e_a – air vapour pressure.

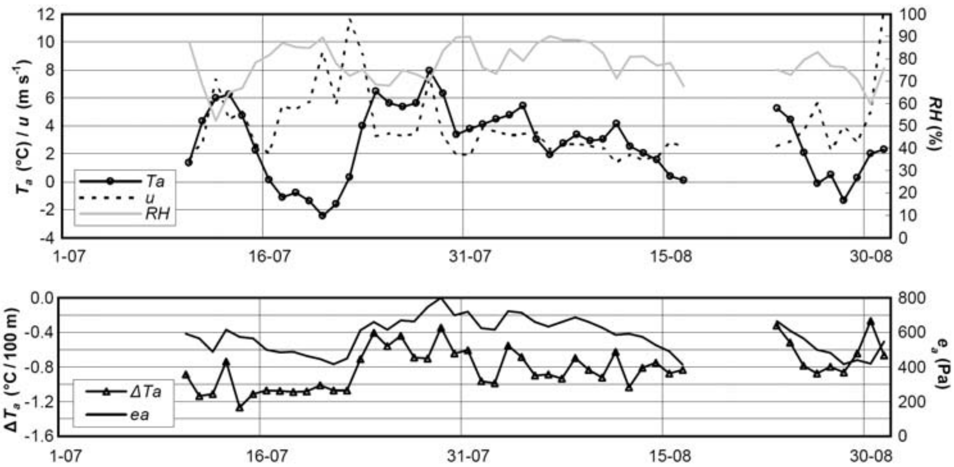

Fig. 4. Weather conditions on Ebbabreen during 2009 ablation season. Abbreviations: T_a – air temperature, u – wind speed, RH – relative humidity, ΔT_a – temperature gradient, e_a – air vapour pressure.

In the shortest studied period during the summer of 2010 (37 days), weather conditions were exceptionally stable (Fig. 5). For most of the time T_a oscillated around 2°C, until heavy snowfall events occurred in mid-August. The season was generally cold (mean T_a = 0.8˚C), with maximum air temperature of only 2.8°C and minimum of -3.8°C. RH showed low variability and was 86.2% on average. Mean wind speed was 3.0 m s^{-1} and air vapour pressure was low with 561 Pa. ΔT_a was poorly-variable and yielded -0.95°C 100 m^{-1} on average. In all the investigated seasons, thermal gradient showed relationship with air temperature and vapour pressure (Table 1). Highly negative ΔT_a rates have been occurring during

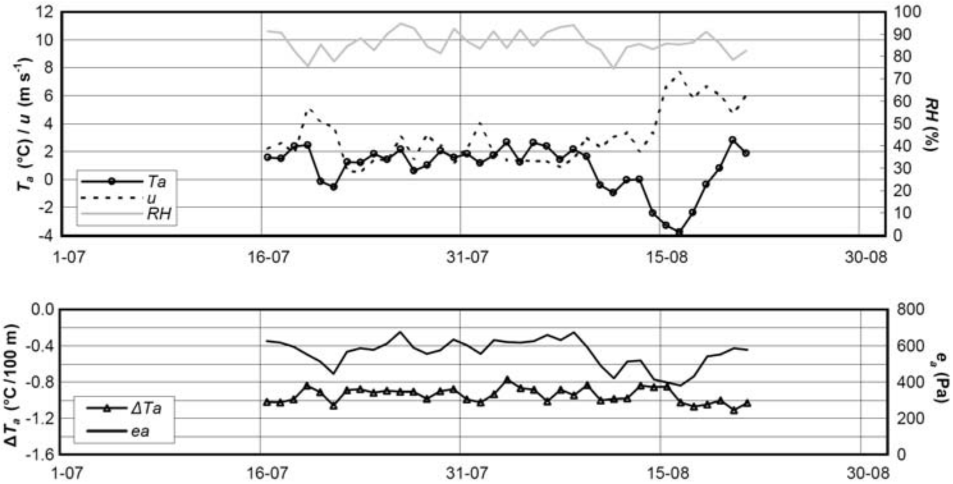

Fig. 5. Weather conditions on Ebbabreen during 2010 ablation season. Abbreviations: T_a – air temperature, u – wind speed, RH – relative humidity, ΔT_a – temperature gradient, e_a – air vapour pressure.

Table 1

Minimum, average and maximum daily values of the main meteorological elements on Ebbabreen in 2008, 2009 and 2010 ablation seasons.

		2008 (47 days)	2009 (47 days)	2010 (37 days)	Overall (131 days)
Cloud cover (octants)	min	0.5	1.3	3.3	0.5
	mean	6.4	5.7	6.6	6.2
	max	8.0	8.0	8.0	8.0
Incoming shortwave radiation* (W m^{-2})	min	38	24	59	24
	mean	136	140	133	136
	max	325	280	244	325
Air temperature (°C)	min	-2.7	-2.4	-3.8	-3.8
	mean	1.9	2.7	0.8	1.9
	max	5.9	7.9	2.8	7.9
Temperature gradient (°C/100 m)	min	-1.13	-1.27	-1.11	-1.27
	mean	-0.74	-0.81	-0.95	-0.82
	max	-0.09	-0.27	-0.77	-0.09
Relative humidity (%)	min	57.3	52.4	74.6	52.4
	mean	80.2	77.7	86.2	81.0
	max	92.0	90.1	94.8	94.8
Air vapour pressure (Pa)	min	429	414	380	414
	mean	562	580	561	568
	max	695	801	677	801
Wind speed (m s^{-1})	min	0.5	1.4	0.5	0.5
	mean	2.6	4.0	3.0	3.2
	max	7.3	12.4	7.6	12.4

* measured at the sea-level.

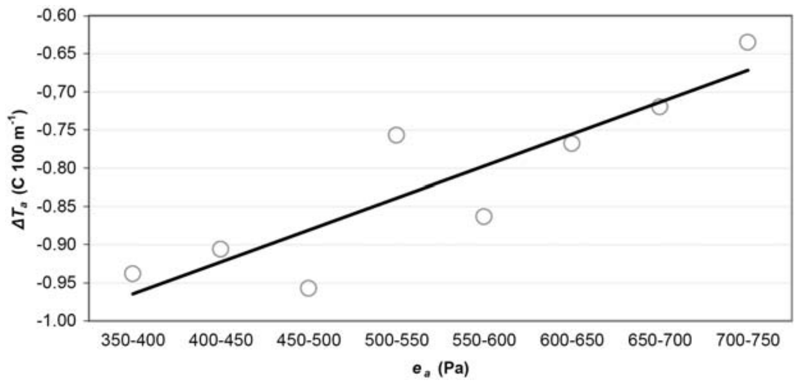

Fig. 6. Environmental lapse rates measured along transect Petuniabukta-Ebbabreen (ΔT_a) averaged for 50-Pa air vapour pressure bands measured at Ebbabreen (e_a).

low moisture content at low T_a. During warmer and humid days less negative gradients dominated (Fig. 6).

To estimate elements of surface energy balance during melting days, days with sub-zero T_a have been excluded. Cloudiness in 2008, 2009 and 2010 was generally high, so average incoming shortwave radiation measured at PET, *SWin*, was on the order of 135 W m^{-2} (Table 2, Fig. 7). Sensible heat flux, Q_H, is primarily dependant on wind speed and air temperature. Hence, average Q_H was modest in 2008 (16 W m^{-2}), high in 2009 (31 W m^{-2}) and low in 2010 (9 W m^{-2}). Maximum modelled

Table 2

Daily values of selected elements of surface energy balance on Ebbabreen during melt-days of 2008, 2009 and 2010 ablation seasons.

		Season (only days with positive air temperature)			
		2008 (34 days)	2009 (40 days)	2010 (28 days)	Overall (102 days)
Incoming shortwave radiation* (W m^{-2})	min	38	24	59	24
	mean	135	134	134	134
	max	325	280	244	325
Air temperature (°C)	mean	3.1	3.4	1.6	2.8
Relative humidity (%)	mean	78.6	76.7	87.0	80.1
Air vapour pressure (Pa)	mean	595	601	597	598
Wind speed (m s^{-1})	mean	2.4	3.5	2.4	2.8
Sensible heat flux (W m^{-2})	min	1	-9	-6	-9
	mean	16	31	9	20
	max	72	143	37	143
Latent heat flux (W m^{-2})	min	-36	-68	-17	-68
	mean	-4	-4	-3	-4
	max	4	40	7	40

* measured at the sea-level.

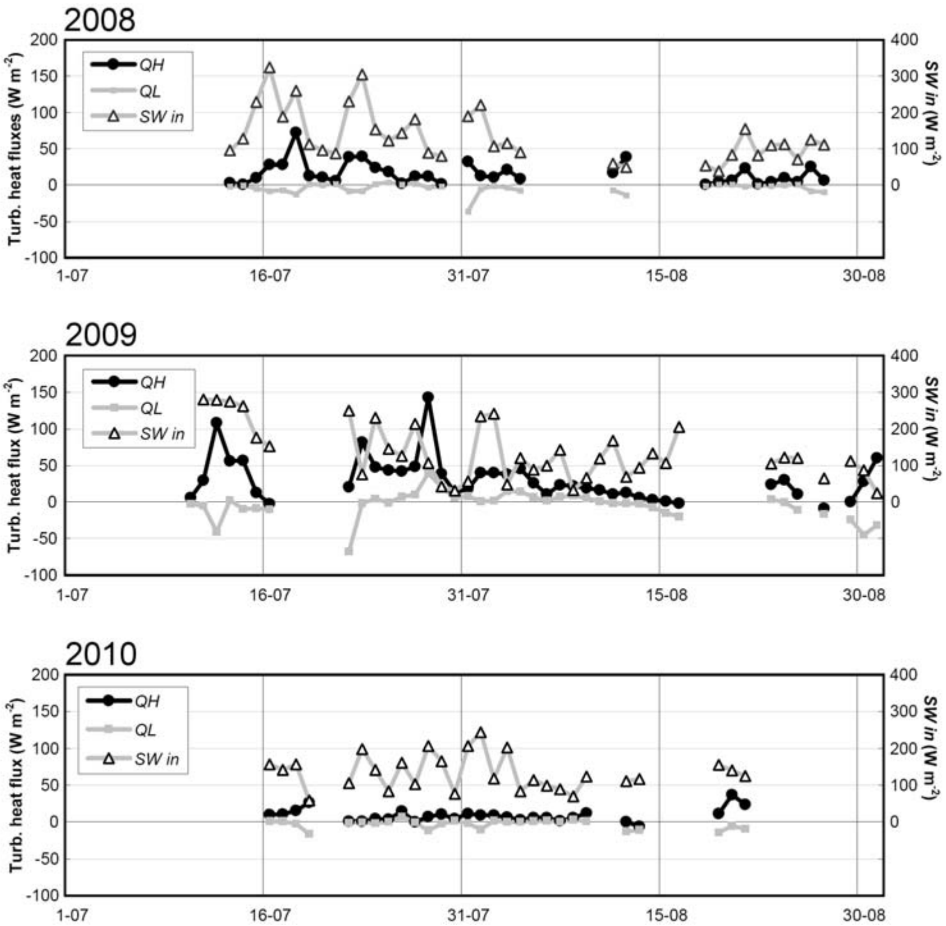

Fig. 7. Elements of surface energy balance of Ebbabreen during ablation seasons in 2008, 2009 and 2010. Gaps within the datasets indicate periods of subzero air temperature. Abbreviations: Q_H – sensible heat flux, Q_L – latent heat flux, *SW in* – incoming shortwave radiation. Note *SW in* was measured at the sea-level and that its vertical scale is different than that of turbulent fluxes.

daily Q_H was 143 W m^{-2} and coincided with the warmest day recorded at EBB (7.9°C) and a relatively strong wind event (at u = 7.4 m s^{-1}). Averaging daily means of Q_H from all summer seasons gives a mean value of 20 W m^{-2}.

Latent heat flux was of much lower overall importance and was generally negative, resulting in a slight decrease of energy available for melt due to evaporation and sublimation. Positive values of Q_L indicate condensation and have been occurring only exceptionally. The maximum Q_L (40 W m^{-2}) occurred on the same day as the maximum Q_H, during strong warm wind event and high as for EBB moisture content of the air (e_a = 748 Pa). The most negative flux of latent heat (-68 W m^{-2}) was noted when wind speed was very high (daily u = 11.6 m s^{-1}) and moisture content was among the lowest noted (e_a = 448 Pa). Such extreme situations were however rare and Q_L averaged for 102 summer days with positive air temperature was -4 W m^{-2}.

From the available dataset some general relations between weather at EBB and atmospheric circulation over north Atlantic could have been sketched (Fig. 8). Overcast conditions are typical for Svalbard area in the summer season, but advection of air masses from certain directions brings relatively sunny weather. During situations of N+NE (*a* and *c*), E+SE (*a* and *c*), W+NW*a* and C*a*+K*a* average cloudiness was about 6 octants, so 24–30% of potential shortwave radiation (*SWpot*) was delivered to the plain surface. During the other circulation types mean cloud cover was about 7 octants, resulting in slightly lower *SWin/SWpot* ratio of 17–25%.

Air temperature was relatively high during anticyclonic situations, particularly during E+SE*a*. High wind speed over Ebbabreen was observed during N+NE and E+SE circulation types. The lowest air moisture content e_a was noted during advection from N+NE. In effect, sensible heat flux Q_H was the highest during both types of E+SE circulation. Latent heat flux Q_L was generally close to zero during anticyclonic situations except for N+NE*a* and negative during cyclonic circulation, particularly N+NE*c* and E+SE*c*.

Discussion

Local glacio-meteorology against other sites in Svalbard. — Glacier surface properties and relatively high altitude have a clear impact on the weather at EBB. Since ice can not exceed 0°C and has high albedo, local microclimate is much cooler than over surrounding non glacier-covered terrain, as documented by Bednorz and Kolendowicz (2010) for Ebbabreen valley. Average air temperature at EBB during the warmest months of 2008, 2009 and 2010 was 1.9°C, although negative mean daily T_a has been occurring regularly during the measurement period (on 27% of days). For comparison, weather station operating at non-glacier covered Wordiekammen massif at similar elevation (500 m a.s.l.) (Fig. 1) shows daily T_a higher by about 1.5–2.0°C.

Correlation of yearly air temperature course between PET station and the closest synoptic station Svalbard Lufthavn (SVL, 60 km to the SSW) is very high, with reported r^2 values ranging from 0.96 to 0.98 (Rachlewicz and Styszyńska 2007; Láska *et al.* 2012). For the summer seasons the relationship is however slightly lower, *e.g.* with $r^2 = 0.79$ for the study period (Fig. 9a). Similar correlation analysis for PET and EBB, separated by distance of only 8.5 km, resulted in even lower r^2 (0.70) (Fig. 9b). When calculated for EBB and SVL the correlation coefficient was only 0.56 (Fig. 9c). It confirms that glacier surface characteristics strongly modify local microclimate, so to produce a reliable air temperature reconstruction for the glacier, based on archive SVL data, would require more sophisticated statistical analyses and longer EBB record.

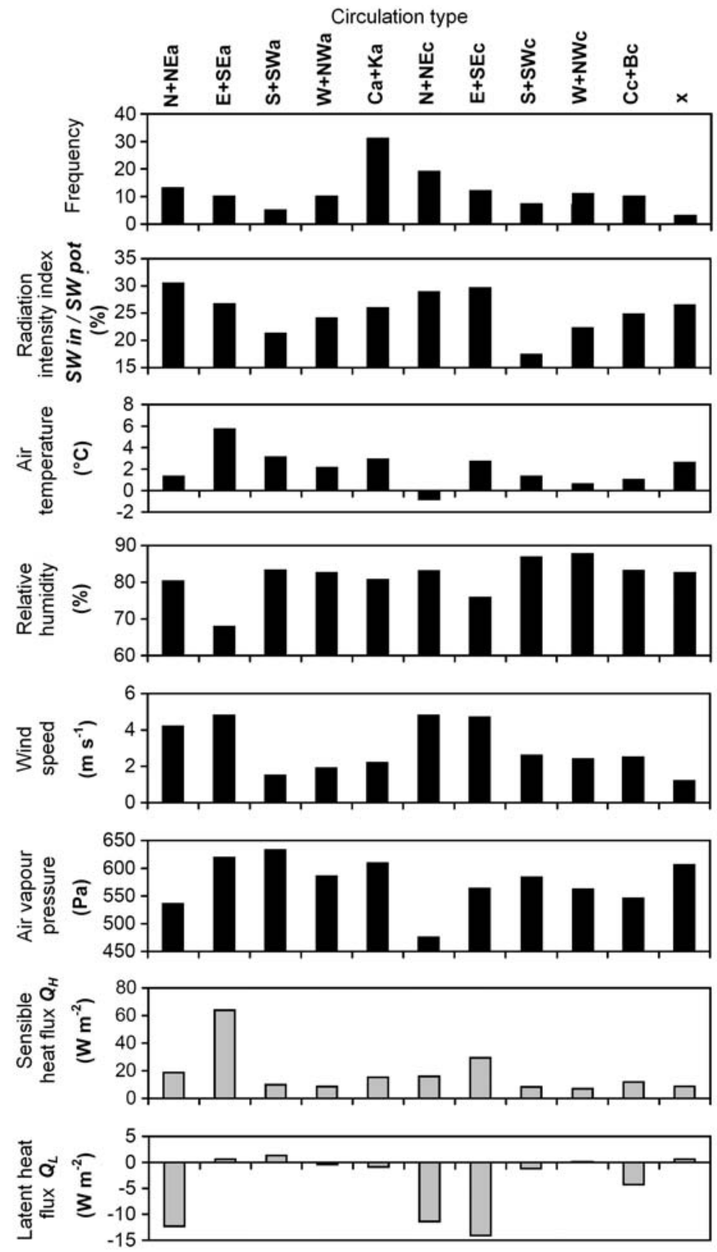

Fig. 8. Number of days with a given circulation type during the study period and average weather conditions on Ebbabreen against circulation types in July and August 2008–2010. Note: estimates of turbulent heat fluxes Q_H and Q_L were averaged only from days with positive air temperature; *SWin* was measured at the sea-level PET station; *SWpot* was calculated for clear sky and horizon.

Because temperature data published for other Svalbard glaciers origins from a wide range of altitudes, it is convenient to use averaged summer environmental

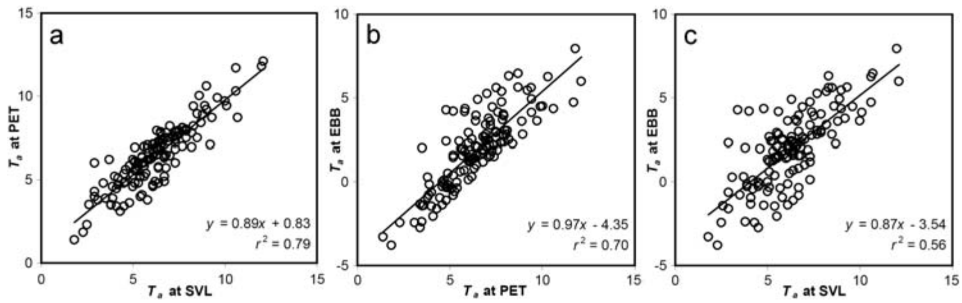

Fig. 9. Correlation of air temperature (T_a) measured at stations Petuniabukta (PET), Svalbard Lufthavn (SVL) and Ebbabreen (EBB). Data from SVL after Norwegian Meteorological Institute. All values in °C.

lapse rates, ΔT_a, for comparisons between air temperature at Ebbabreen and other ice masses. In this context, it must be pointed out, that mean gradient observed from the coast (PET) to EBB is relatively highly negative (-0.82°C/100 m), but it is strongly influenced by different land cover at the locations of weather stations. On more maritime glaciers in Svalbard, the values computed from near-coast and on-ice stations data are generally lower (*e.g.* Baranowski 1975; Piasecki and Gluza 1988; Kejna *et al.* 2010; Sikora *et al.* 2010, 2011). However, strongly negative values of ΔT_a (from -0.9 to -1.0°C per 100 m) were also inferred for single seasons for glaciers otherwise maritime (Piasecki and Gluza 1988; Krismer 2009). On Svenbreen, a small valley glacier 14 km west from EBB (Fig. 1), air temperature drops with elevation at a rate close to -1°C/100 m (Małecki 2013a). It may be therefore concluded that typical on-glacier air temperature gradient in Petuniabukta is more negative than in the coastal zones of Spitsbergen with *ca.* -0.8 to -1.0°C/100 m, a figure important for *e.g.* future melt modelling studies. It must be, however, made clear that air temperature change along a sloping glacier does not necessarily agree with the true vertical lapse rate.

Considerable distance from the open sea (*ca.* 100 km) reduces moisture transport to the study area. Relative humidity in July and August in the middle of Ebbabreen was on average 81.0%. It is a slightly lower value than noted on other Svalbard ice masses during summer months (*e.g.* Krismer 2009; Sikora *et al.* 2010, 2011; Østby 2010). At the sea-level PET station summer *RH* is also decreased (70–80%, Rachlewicz 2003; Láska *et al.* 2012), if to be compared with the western coast of Spitsbergen (80–90%, *e.g.* Piasecki and Gluza 1988; Kejna *et al.* 2010; Sikora *et al.* 2010; 2011). Averaged air vapour pressure at EBB in July and August was only 567 Pa. It is lower than most of values given or recalculated from the literature for similar season of the year for other glaciers in the archipelago (*e.g.* Kejna *et al.* 2010; Sikora *et al.* 2010, 2011). Limited air vapour pressure over Ebbabreen results not only from distance to the oceans but also from its high elevation and low air temperature. For comparison, mean air vapour pressure at 358 m a.s.l. on Svenbreen in July and August 2011–2014 ranged from 603 to 692 Pa (Małecki unpublished data). Assuming surface vapour pressure of melting snow and ice as 611 Pa, low e_a values at EBB clearly indicate domination of an upward humidity gradient, which results in evaporation/sublimation, rather than condensation/deposition.

Summer wind speed at EBB is on average 3.2 m s^{-1}, being significantly higher than noted on Svenbreen, well protected by high valley sides (Małecki 2013a). Several foehn-type wind events may be recognized in Figs 3–5, which are known to significantly boost melting. Average summer *u* reported for glaciers in other regions of the archipelago was *ca.* 2 m s^{-1} on Waldemarbreen (Kejna *et al.* 2010) and Midre Lovénbreen (Hodson *et al.* 2005), 2–4.5 m s^{-1} on Hansbreen (Migała *et al.* 2006; Sikora *et al.* 2010, 2011), *ca.* 3.5 m s^{-1} on Scottbreen (Bartoszewski *et al.* 2004) and on Kongsvegen (Krismer 2009) and *ca.* 4 m s^{-1} on Austfonna (Østby 2010).

Elements of energy balance of a melting surface. — All the meteorological elements described above have a direct impact on the heat exchange at EBB. Net radiation is the most important component of glacier surface energy balance and is composed of shortwave (*SW*) and longwave (*LW*) radiation, both incoming (*in*) and outgoing (*out*). Its only element measured in the study area over the study period was *SWin* at PET station. The average value of *SWin* for melt-days in July and August was 135 W m^{-2}, but pyranometer at PET was installed horizontally and was protected from direct sunlight at low sun angles, so the actual *SWin* at EBB is expected to be slightly different. The shortwave radiation balance (portion absorbed by the surface, *SWin - SWout*) is supposed to be the highest in 2009, since snow has melted out from EBB location yet in late-July, decreasing surface reflectance and increasing energy absorption. *LWin* is emitted mainly by the lower atmosphere and increases with its temperature and humidity, so it was most likely the highest again in 2009. On Svenbreen station at 358 m a.s.l., average *LWin* for July and August 2012–2014 was poorly variable from year to year and ranged from 278 to 287 W m^{-2} (Małecki, unpublished data), so *LWin* at EBB (550 m a.s.l.) could be expected to be lower than these values. *LWout* is a function of surface temperature, so it is fixed at 316 W m^{-2} for melting ice surface.

Before discussing the turbulent heat transfer, it must be underlined, that the values modelled for the purpose of this study are approximations suffering from great inaccuracies due to limitations of the available dataset. The estimated July–August sensible heat flux of 20 W m^{-2} observed on Ebbabreen was relatively high as for Svalbard (Table 3), as in the ablation zones of other glaciers it is typically lower than 15 W m^{-2} (Table 3). High value of Q_H on Ebbabreen results from considerable wind speed, but it is also strongly influenced by the quality of the sample and model used (*e.g.* days with T_a<0°C excluded). Q_L was negative for most of the time, favouring sublimation and limiting condensation. A similar situation is regular on Kongsvegen and was observed over Svenbreen in 2012, where

Table 3

Comparison of selected elements of surface energy balance of Ebbabreen with other glaciers of Svalbard. Abbreviations: T_a – air temperature, *RH* – relative humidity, *u* – wind speed, *SW in* – incoming shortwave radiation, Q_H – sensible heat flux, Q_L – latent heat flux.

Glacier	T_a	*RH*	*u*	*SW in*	Q_H	Q_L	Period	Reference
	(°C)	%	m s^{-1}	W m^{-2}	W m^{-2}	W m^{-2}		
Ebbabreen, 550 m*	2.8	80.1	2.8	135**	20	-4	Jul–Aug 2008–2010*	this work
Svenbreen, 358 m	2.1	84.5	1.9	131	8	-2	Jul–Aug 2012	Małecki 2013a
Midre Lovénbreen, 75 m*	4.1	92.3	2.2	129	15	8	Jul–Aug 1997–2003*	Hodson *et al.* 2005
Kongsvegen, 170 m	1.6	85.4	3.3	172	13	-1	Jul–Aug 2007	Krismer 2009
Kongsvegen, 550 m	0.7	86.3	3.5	189	7	-5	Jul–Aug 2000–2007	Krismer 2009

* only melt-days, ** measured at the sea-level.

the dominant humidity gradient between the surface and the air was also up-ward (Krismer 2009; Małecki 2013a). On glacier stations experiencing milder climate, latent heat flux is slightly positive during the summer, *i.e.* at low elevations of Midre Lovénbreen or Hansbreen (Hodson *et al.* 2005; Migała *et al.* 2006).

Impact of circulation patterns on weather and melting. — In the background of the relations from Figs 2 and 8, the synoptic situation explains well the weather conditions at EBB in different seasons. 2009 was the warmest because for 66% of the time the situation was anticyclonic, bringing generally warmer air and high turbulent heat transfer. 2010 season was the coolest, as for 65% of the measurement period cold air masses were advected from N+NE or W+NW. 2008 was moderate due to comparable frequency of individual circulation patterns.

Incoming longwave radiation was not measured at EBB, but it generally shows low interannual variability, also in Petuniabukta as measured on Svenbreen (Małecki, unpublished data). Since incoming shortwave radiation measured in the study area was also stable from year to year, the interannual variability of melt rates must have been largely driven by the magnitude of turbulent heat transfer. Accounting for the prevailing circulation types in each season, it may be expected that meltwater production was the highest in 2009 and the lowest in 2010. It is in agreement with hydrological observations by Szpikowski *et al.* (2014), who announced mean discharge in proglacial river of Ebbabreen at 5.0, 5.5 and 4.4 m^3 s^{-1}, respectively for July and August 2008, 2009 and 2010.

Conclusions

In this paper, the sparse glacio-meteorological record from Dickson Land has been expanded with measurements performed during 131 summer days (in July and August 2008–2010) on the largest glacier in the region Ebbabreen at 550 m a.s.l., close to its theoretical steady-state equilibrium line altitude. The study presents first data on some of the melt processes on the glacier and fundamental parameters important for future glaciological and climatological studies. The results have shown that air temperature gradient, relative humidity and air vapour pressure at the measuring site were relatively low when compared to more maritime glaciers of S and W Spitsbergen, reflecting arid conditions of Dickson Land. The main limitations of the available dataset are the quality and spectrum of the measurements provided by a low-cost portable weather station, short duration of measuring campaigns and uncertainties associated with turbulent heat flux modelling using a simple bulk aerodynamic approach, not validated by ablation surveys.

Cooling of the air with rising altitude is relatively fast on Ebbabreen, represented by strongly negative environmental lapse rates, with average gradient of -0.82°C/100 m measured between the glacier and the sea-level 8.5 km away. Average July–August air temperature at the measuring site was 1.9°C, while mean relative humidity was 81%. Low average air vapour pressure (568 Pa) favoured sublimation/evaporation from the glacier's surface, so on melting days latent heat flux was negative with -4 W m^{-2} on average. Mean sensible heat flux contribution to the energy balance of the melting surface is relatively high as for Svalbard and has been estimated as 20 W m^{-2}, supported by considerable wind speed (average of *ca.* 3 m s^{-1}). Shortwave radiation delivered to the glacier surface has not been measured directly, but at the sea-level the average July–August insolation was low with about 135 W m^{-2}, a value typical for this region of the Arctic.

Individual atmospheric circulation types bring distinctly different weather to Ebbabreen. N+NE situations result in relatively sunny, but cool and dry weather, favouring sublimation due to strong wind. Both E+SE types bring relatively sunny, warm and windy conditions with efficient sensible heat transfer to the surface, in case of E+SE*c* also with strong sublimation. The other circulation types (S+SW *a* and *c*, W+NW *a* and *c*, Ca+Ka and Cc+Bc) transport to the study area denser cloud cover and lower wind speed. Weather and circulation patterns over the glacier during individual seasons resulted in high melt intensity in 2009 and low melt rates in 2010, confirmed by the magnitude of proglacial river discharge reported by other authors. In this context, it seems clear that changes in circulation pattern over North Atlantic will be reflected by changing melt intensity of Ebbabreen.

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