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Short-term mass changes and retreat of the Ecology and Sphinx glacier system, King George Island, Antarctic Peninsula

IRENEUSZ SOBOTA[1], MAREK KEJNA[2] and ANDRZEJ ARAŹNY[2]

[1]*Nicolaus Copernicus Polar Station, Department of Hydrology and Water Management, Nicolaus Copernicus University, Lwowska 1, 87-100 Toruń, Poland*

[2]*Department of Meteorology and Climatology, Nicolaus Copernicus University, Lwowska 1, 87-100 Toruń, Poland*

irso@umk.pl

Abstract: This study investigated the mass balance, melting, near-surface ice thermal structure and meteorological conditions of the Ecology and Sphinx glacier system (ESGS), located on King George Island, Antarctic Peninsula. The study also analysed the role of climate change in glacial retreat of the ESGS in the long (1979–2012) and short term, with a particular focus on the impact on the 2012–13 mass balance of the ESGS. In 2012–13, the glaciers had a mean annual net mass balance of +17.8 cm w.e., but over the long term the glaciers have been receding in this region. The area loss of the ESGS between 1979 and 2012 amounted to 41%. This investigation of mass balance is especially important as it offers one of only a few records available on King George Island. The mean near-surface ice temperature (February to June 2012) for the Ecology and Sphinx glaciers was -0.3°C and -1.0°C at 10 m depth, respectively. From 1948–2012, the air temperature on King George Island increased by 1.2°C (0.19°C per decade).

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Key words: air temperature, Antarctic, climate change, glacier, glacier retreat, ice temperature, mass balance

Introduction

The Antarctic Peninsula responds very quickly to environmental changes. In recent decades, there have been substantial environmental changes in the area, both in the Southern Ocean (surface water temperature and sea ice changes; Andukhov *et al.* 2006) and on land (progressive deglaciation and ice-shelf disintegration; Kejna *et al.* 1998, Birkenmajer 2002, Rückamp *et al.* 2011). The mean rate of glacial retreat across the Antarctic Peninsula has been increasing since 1945. The standard deviations of retreat and advance rates over the entire domain are considerable (up to 150 m yr^{-1}), but due to the diverse behaviour of the individual glaciers this is to be expected (Cook *et al.* 2005). It is clear that the ice cap on King George Island has been reduced, which is closely linked to the widespread retreat of tidewater glaciers along the western coast of the Antarctic Peninsula (Kejna *et al.* 1998, Cook *et al.* 2005, Rückamp *et al.* 2010, 2011).

The ice cap that covers most of King George Island is particularly sensitive to climate change (Blindow *et al.* 2010). From 1948–2012, the air temperature on King George Island increased by 1.2°C (0.19°C per decade). The specific nature and climatic conditions on King George Island make it a very important contemporary climate change laboratory. It is an area where interactions between the cryosphere and natural environment, with all their effects, are particularly evident. Surface changes in the modern glacial areas are especially visible.

The Antarctic Peninsula is a heavily glaciated region, with *c.* 80% of its area classified as melt and percolation zones (Rau & Braun 2002). The equilibrium line altitudes (ELA) observed during the 1990s on King George Island revealed considerably higher values than those measured in the 1970s. This increase is consistent with higher mean air temperatures recorded during the 1990s (Braun & Gossmann 2002).

Changes in glacial mass balance in the Admiralty Bay region of King George Island have been recorded in recent years (Rückamp *et al.* 2011). For example, glaciers in the Martel Inlet lost *c.* 6.64 km^2 (13.2% of the total area), without any advances from 1979–2011. The tidewater glacier Dobrowolski (0.076 km^2 yr^{-1}) experienced the highest retreat rate, with 17.27% of its area lost during this period. The land terminus glaciers Wanda (31.27%), Dragon (53.84%) and Professor (39.71%) presented the highest area loss during the period (Rosa *et al.* 2013). From 1979–2007, the tongues of the individual glaciers in the Admiralty Bay region retreated by 200–900 m (Pudełko 2003).

The history of the cartographic representation of the Admiralty Bay region, with particular reference to the Ecology and Sphinx glacier system (ESGS) associated with the Arctowski Ice field, and the possibilities of using aerial photographs and thematic maps in relation to glacial fluctuations have been discussed by Kejna *et al.* (1998), Braun & Gossmann (2002), Simões *et al.* (2004), Pudełko (2007) and Rückamp *et al.* (2010, 2011).

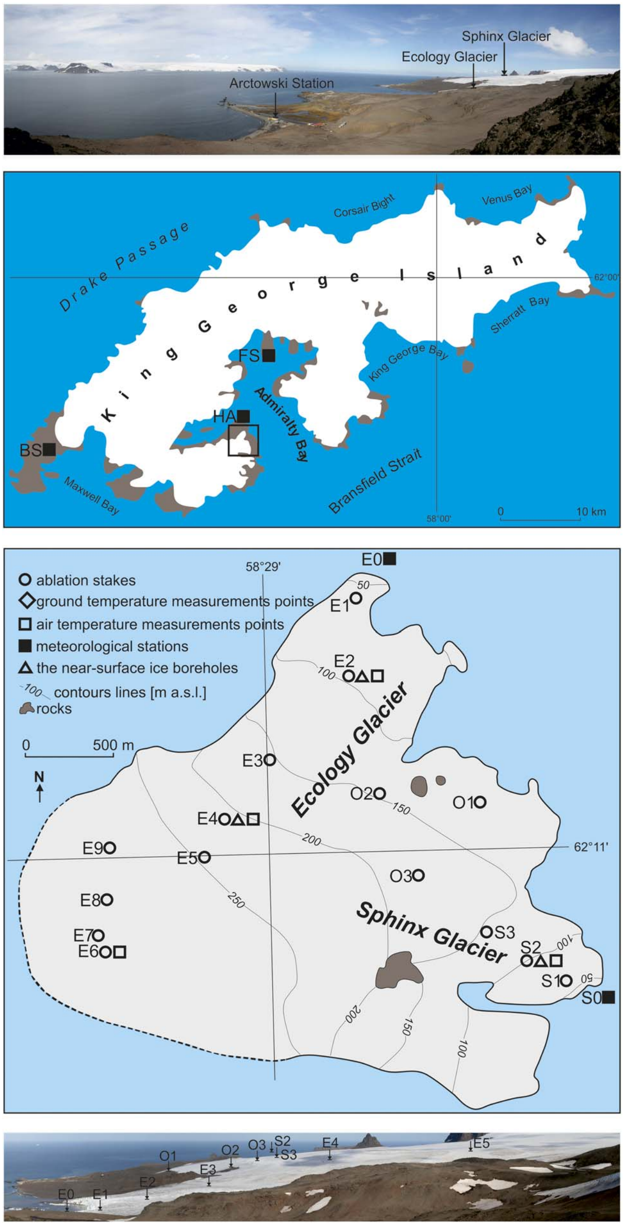

Fig. 1. Measurement sites on the Ecology and Sphinx glacier system (based on an orthophotomap by Pudełko (2007)) and weather stations on King George Island. BS = Bellingshausen Station, FS = Ferraz Station, HA = Arctowski Station (photo by I. Sobota). Explanations also in Table I.

From 1961–96, the maximum recession of the Ecology Glacier was *c.* 480 m in the land-terminating northern part, 380 m in the southern part and as much as 620 m in the central part where the glacier meets the sea. The average retreat rate of this glacier varied from 8.8 m yr^{-1} for 1961–78 to 30–40 m yr^{-1} for 1978–96, with a mean of 17.7 m yr^{-1} for 1961–96 (Kejna *et al.* 1998). This is mainly determined by of the retreat of the glacier's central front, which had a maximum recession of *c.* 270 m from 1956–1992 (Braun 2001).

Glaciological research on the ESGS has included studies on ablation, temporal changes, location of the glacier tongue, mass balance and meteorological conditions. Estimation of the mass balance of the ESGS was made with repeated point measurements at the glacier surface. This approach involved estimating the local mass balance using ablation poles and snow thickness measurements.

The primary aim of the present research was to assess the nature of the temporal variability and spatial structure of the mass balance of the ESGS, with a focus on changes in ice front position since 1979, as well as possible links between climate change and glacial retreat and changes in mass balance. The secondary aims of the study were to measure temporal variability in: i) the near-surface ice temperature in the ablation zones of the Ecology and Sphinx glaciers, ii) the ELA of Ecology Glacier, and iii) the vertical profiles. It is generally accepted that the thermal regime of a glacier directly controls glacier mass balance, hydrology and dynamics (Reijmer & Hock 2008, Sobota 2009, 2011, 2013). Unfortunately, direct measurements of thermal regimes are available for very few glaciers worldwide. The majority of the glaciers on the King George Island ice cap can be regarded as temperate (Macheret & Moskalevsky 1999, Blindow *et al.* 2010).

Study area

King George Island (Fig. 1) is located at the northern tip of the Antarctic Peninsula and is the largest of the South Shetland Islands. King George Island is characterized by some of the greatest temporal variations in climate conditions in the Southern Hemisphere (Kejna 2003, 2008, Vaughan *et al.* 2003, Steig *et al.* 2009, Araźny *et al.* 2013, Kejna *et al.* 2013). These variations result from the feedback between the sea surface temperature, sea ice and atmosphere. The island is predominately ice-covered (93%; Simões *et al.* 1999), consisting of several connected ice fields with pronounced outlet glaciers. The highest elevation reaches slightly more than 720 m to a dominant central dome. The average ice thickness in the Arctowski Ice field is 250 m and the maximum thickness is 420 m (Blindow *et al.* 2010). The snowline varies from 140–210 m a.s.l. (Birkenmajer 2002). The ice-free areas are either nunataks or coastal oases (Marsz 2000).

The study was conducted in the northern part of the Site of Special Scientific Interest (SSSI) No. 8 (Antarctic Specially Managed Area No. 128). The site was established in 1979, at the request of the Polish government, to protect the unique diversity of flora and fauna typical of the marine ecosystem (Rakusa-Suszczewski 2003). It has an area of *c.* 13 km^2 and includes the west coast of Admiralty Bay. Characterized by great geographical diversity, its area is cut by glaciers flowing from the Warszawa Ice field.

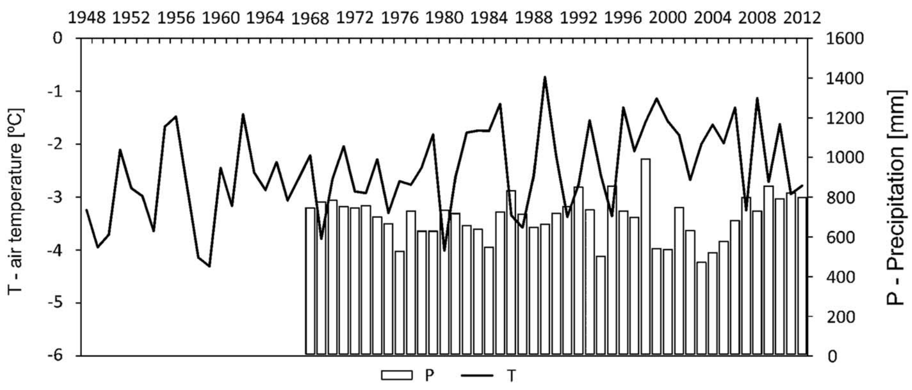

Fig. 2. Trend in air temperature (T) on King George Island, 1948–2012 (combined data from Admiralty Bay, Deception and Bellingshausen stations), and precipitation (P) at the Bellingshausen Station, 1968–2012. The method of combination of these series is described in Kejna *et al.* (2013).

These glaciers are the Ecology, Sphinx, Baranowski, Tower and Windy. Two major glacier types can be distinguished in this region: land-terminating and tidewater glaciers.

Ecology Glacier is a valley glacier with a tongue flowing from the Warszawa Ice field to Admiralty Bay. On the northern and southern sides, the glacier has created marginal zones with numerous lateral and frontal moraines. In the middle part, the glacier has the character of a glacial cliff, in front of which a marine bay has formed. Sphinx Glacier is located south of Ecology Glacier and its tongue terminates on land.

The Ecology and Sphinx glaciers were treated as a single glacial system (the ESGS) (Fig. 1). The analysis included the ablation zone, snow percolation zone, the ELA and the accumulation zone, which is part of the ice field. It is bordered by the Błaszczyk moraine to the south and by mountain ranges in the north. The ESGS covers an area of 4.96 km^2.

Table I. Sites and measurement ranges at Arctowski Station and on the Ecology and Sphinx glacier system.

Site		Latitude	Longitude	Elevation (m a.s.l.)	Measurement range
Arctowski Oasis					
Arctowski Station	HA	62°09'33.0"S	58°28'05.9"W	3	Vantage Pro + RHTemp101A HOBO
Ecology Glacier					
Forefield	E0	62°10'12.6"S	58°28'16.6"W	29	Vantage Pro + RHTemp101A
Ablation zone	E1	62°10'15.9"S	58°28'27.5"W	40	Ablation stake
	E2	62°10'15.5"S	58°28'27.9"W	101	RHTemp101A U30-NRC Ablation stake
	O1	62°10'52.8"S	58°27'42.6"W	103	Ablation stake
Equilibrium line	E3	62°10'43.8"S	58°28'58.0"W	145	Ablation stake
	E4	62°10'53.9"S	58°29'14.6"W	200	RHTemp101A U30-NRC Ablation stake
	O2	62°10'50.4"S	58°28'20.4"W	142	Ablation stake
	O3	62°11'03.5"S	58°28'04.1"W	170	Ablation stake
Accumulation zone	E5	62°11'00.0"S	58°29'24.3"W	243	Ablation stake
	E6	62°11'16.8"S	58°30'03.6"W	320	RHTemp101A Ablation stake
	E7	62°11'13.4"S	58°30'03.3"W	310	Ablation stake
	E8	62°11'07.6"S	58°30'01.2"W	295	Ablation stake
	E9	62°10'59.0"S	58°29'58.4"W	265	Ablation stake
Sphinx Glacier					
Forefield	S0	62°11'23.9"S	58°27'05.3"W	15	Vantage Pro + RHTemp101A
Ablation zone	S1	62°11'22.8"S	58°27'11.1"W	41	Ablation stake
	S2	62°11'19.5"S	58°27'25.2"W	90	RHTemp101A U30-NRC Ablation stake
Equilibrium line	S3	62°11'14.3"S	58°27'40.7"W	148	Ablation stake

Vantage Pro+: air pressure, wind direction and velocity, air temperature and humidity, precipitation, solar radiation and UV, RHTemp101A: air temperature and humidity, HOBO: ground temperature (HA), U30-NRC Station: near-surface ice temperature.

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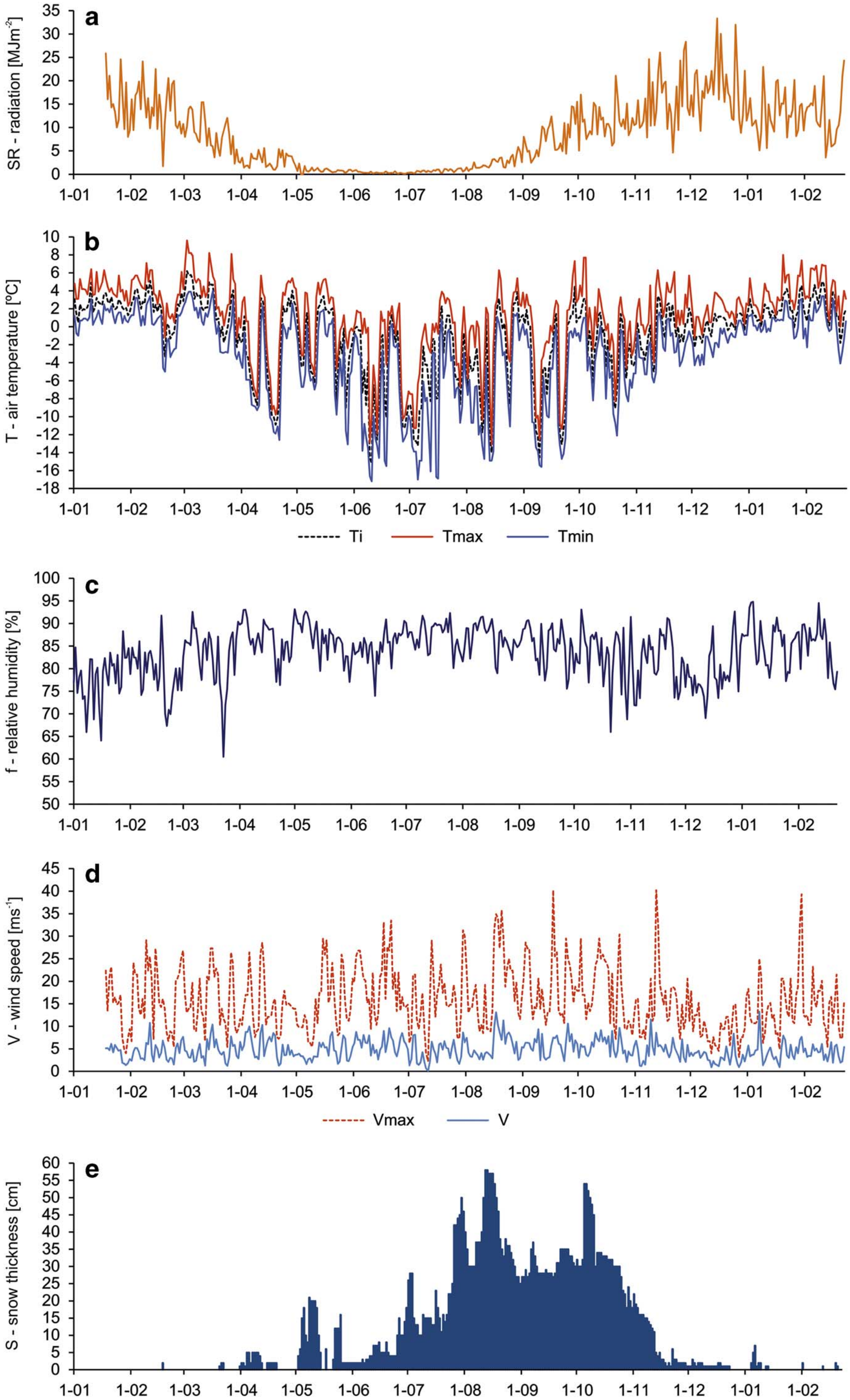

Fig. 3. Meteorological conditions at Arctowski Station from January 2012 to February 2013. **a.** Total global radiation (SR). **b.** Air temperature (T). **c.** Relative humidity (f). **d.** Wind speed (V). **e.** Maximum snow cover thickness (S_{max}).

Methods

Changes in air temperature in the King George Island area were analysed using combined data series from the following stations: Admiralty Bay (1948–60), Deception (1948–67), Bellingshausen (1968–2012) and Ferraz (1986–2010) (Fig. 2). The thermal relationship between these stations varies during the year. The method of combination of these series is described by Kejna *et al.* (2013).

Detailed topoclimatic studies were carried out in the region of the ESGS from January 2012 to February 2013. Selected meteorological parameters were measured by an automatic weather station and data loggers in several

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Table II. Monthly meteorological measurements at Arctowski Station (HA) from 1 January 2012 to 22 February 2013 (Araźny *et al.* 2013).

Month	SR (MJm^{-2})	T_i (°C)	T_{max} (°C)	T_{min} (°C)	F (%)	V* (ms^{-1})	S_{max} (cm)
Jan 2012	476.7**	2.4	6.4	-1.0	78.0	3.9**	
Feb 2012	415.2	2.0	7.1	-5.0	78.7	4.5	2
Mar 2012	257.7	2.1	9.6	-3.9	82.6	4.5	2
Apr 2012	89.0	-2.9	5.7	-12.6	86.4	5.5	5
May 2012	25.1	-1.6	5.3	-13.1	86.9	4.2	21
Jun 2012	10.4	-5.6	2.6	-17.2	84.8	6.1	18
Jul 2012	22.2	-4.9	3.9	-17.0	87.4	4.1	50
Aug 2012	75.3	-3.2	6.3	-14.9	86.7	5.7	58
Sep 2012	234.1	-4.1	7.3	-15.6	85.4	5.9	37
Oct 2012	343.5	-2.2	7.7	-12.1	82.5	5.6	54
Nov 2012	468.4	-0.3	6.3	-6.2	82.1	4.6	22
Dec 2012	567.8	0.2	3.8	-4.3	78.9	3.1	3
2012	2985.3***	-1.5	9.6	-17.2	83.4	4.8	58
Jan 2013	401.0	1.9	8.0	-1.3	85.9	4.5	7
Feb 2013****	278.4	2.3	6.9	-4.1	85.3	4.2	2

F = relative humidity, S_{max} = maximum depth of snow cover, SR = total global radiation, T_i = average air temperature, T_{max} = maximum air temperature, T_{min} = minimum air temperature, V = wind speed.
*At 2 m a.s.l., **19–31 January, ***19 January to 31 December, ****1–22 February.

parts of the region (Fig. 1, Table I). Three characteristic research facilities were selected: the non-glaciated Arctowski Oasis (the Arctowski Station, 3 m a.s.l.), Ecology Glacier (E2, E4) and its forefield (E0), and Sphinx Glacier (S2) and its forefield (S0). The main meteorological measurements were conducted at the meteorological site of the Arctowski Station (HA), located at 62°09'33.0"S, 58°28'05.9"W. Data were obtained with a Davis Vantage Pro+ automatic weather station and HOBO automatic loggers. Measurements were carried out from February 2012 to February 2013. Detailed information about the measurement points is shown in Table I, and their locations are indicated in Fig. 1.

Direct measurements of the mass balance of the ESGS were taken in 2012–13. Surface ablation was measured at 13 points on the glacier in January and February of each year (Fig. 1, Table I). Measurements of snow thickness were taken at many points during the study. The balance year adopted for this project ran from January 2012 to February 2013 (stratigraphic system), including the entire accumulation and ablation seasons. This remains the most precise and most frequently used glaciological method (Cogley *et al.* 2011).

To assess change in area of the ESGS, the cartographic method was used. The maps used (including Francelino *et al.* 2003, Pudełko 2007) were made between 1979 and 2007.

In 2012, GPS measurements were also taken. Clear delimitation of the range of the glaciers was provided by the optical differentiation of areas of uncovered glacier and areas covered with moraine which ended with a clear edge (Sobota 2013). Measurements were made using the World Geodetic System (WGS84) in accordance with UTM zone 21E. The percentage area changes are relative to 1979, which was used as the reference for all areas.

To study the near-surface ice thermal structure of the ESGS, thermistors were installed on the glacier during the summer in 2012 (Fig. 1). Temperature measurements were made from February to June 2012, to depths of 10 m. The thermistors (HOBO) automatically register the ice temperature at 1 hour intervals and store data in a data logger. The accuracy and resolution of the thermistors are ±0.2°C and 0.03°C, respectively, with a range of -40°C to +75°C. The locations of the measurement sites were chosen to enable investigation of the thermal structure of the near-surface layers of the ESGS.

Results

Meteorological conditions in 2012–13

An increase in air temperature, and in particular an increase in the number of days with positive air temperature, led to higher ablation rates. However, during the same period, the volume of precipitation did not increase (Fig. 2).

From 19 January to 31 December 2012, 2985.3 MJm^{-2} (8.60 MJm^{-2} day^{-1}) of solar radiation reached the surface at HA (Fig. 3a). The greatest monthly sums were recorded in December 2012, reaching 567.8 MJm^{-2} (18.3 MJm^{-2} day^{-1}), and the lowest in June, 10.4 MJm^{-2} (0.4 MJm^{-2} day^{-1}).

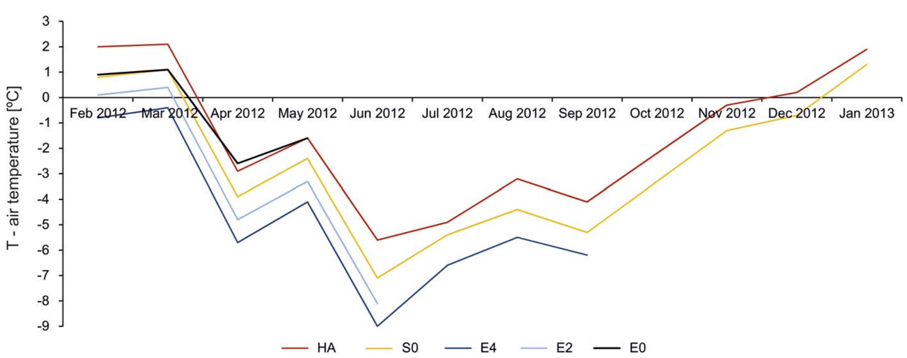

Fig. 4. Monthly air temperature at selected sites of the Arctowski Station and Ecology and Sphinx glacier system.

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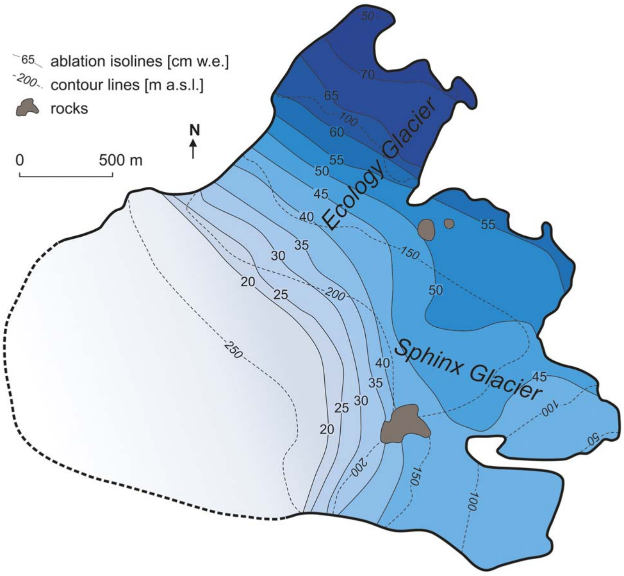

Fig. 5. Ablation map of the Ecology and Sphinx glacier system for February 2012.

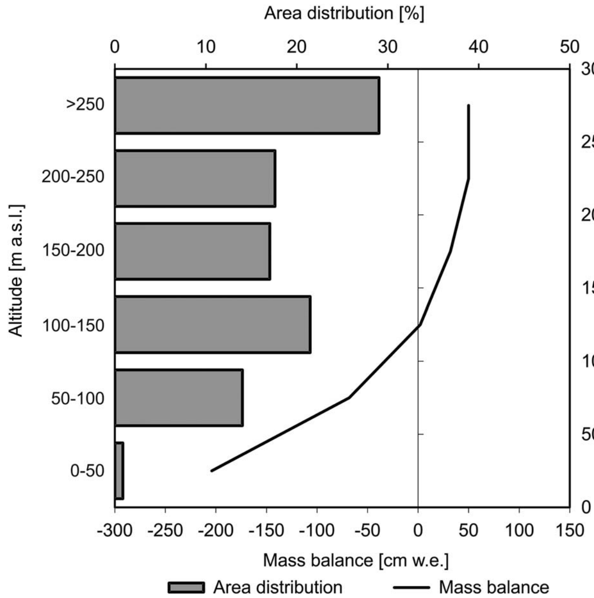

Fig. 7. Mass balance of the Ecology and Sphinx glacier system versus altitude (2012–13).

The greatest daily sums were recorded in November, December and January exceeding 25–30 MJm^{-2}, reaching, for example, 33.4 MJm^{-2} on 15 December 2012. In contrast, in June and July, values did not exceed 1 MJm^{-2} day^{-1}.

The South Shetland Islands are characterized by the mildest thermal conditions in the Antarctic. In 2012, the air temperature at Arctowski Station averaged -1.5°C, with the highest monthly mean occurring in January (2.4°C), and the lowest in June (-5.6°C; see Fig. 3b and Table II). In the summer, the weather was more stable, whereas in the winter dramatic rises and falls in temperature occurred, sometimes exceeding 10°C per day. In 2012, the highest air temperature was recorded on 2 March (9.6°C) and the lowest on 10 June (-17.2°C). Relative air humidity in the area of the Arctowski Station is high due to the prevalence of maritime air masses. In 2012, the mean relative humidity was 83% (Fig. 3c).

The highest average air temperatures were recorded on the sea terrace at Arctowski Station (HA). The Ecology and Sphinx glaciers are, on average, colder than at

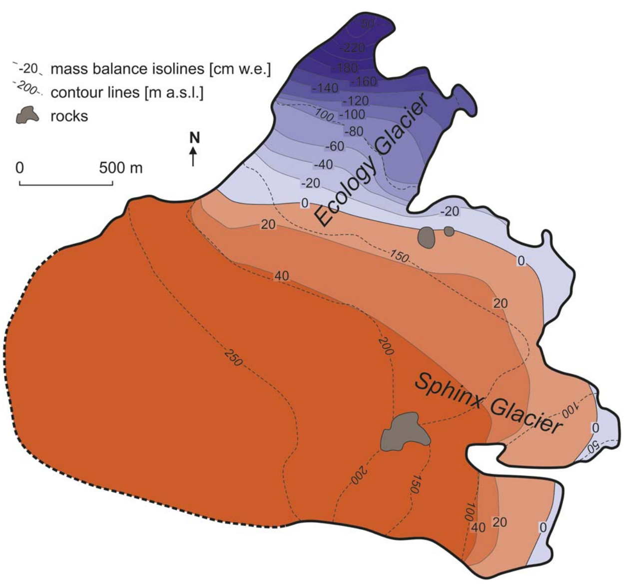

Fig. 6. Mass balance map of the Ecology and Sphinx glacier system in 2012–13.

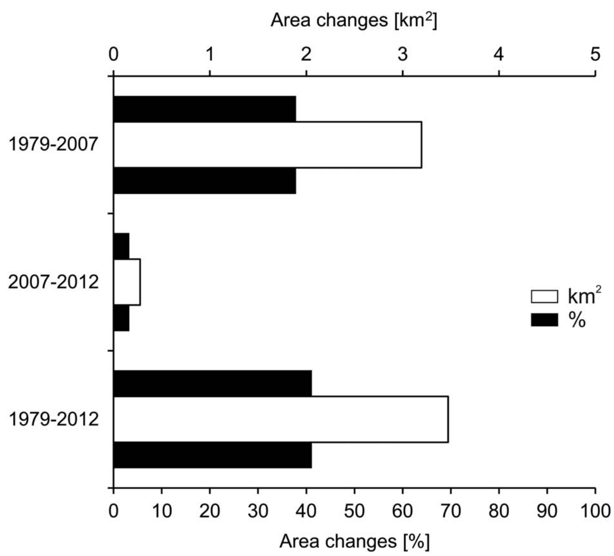

Fig. 8. Area changes of the Ecology and Sphinx glacier system from 1979–2012. Data for 1979 and 2007 are based on the western shore of Admiralty Bay orthophotomap (Pudełko 2007).

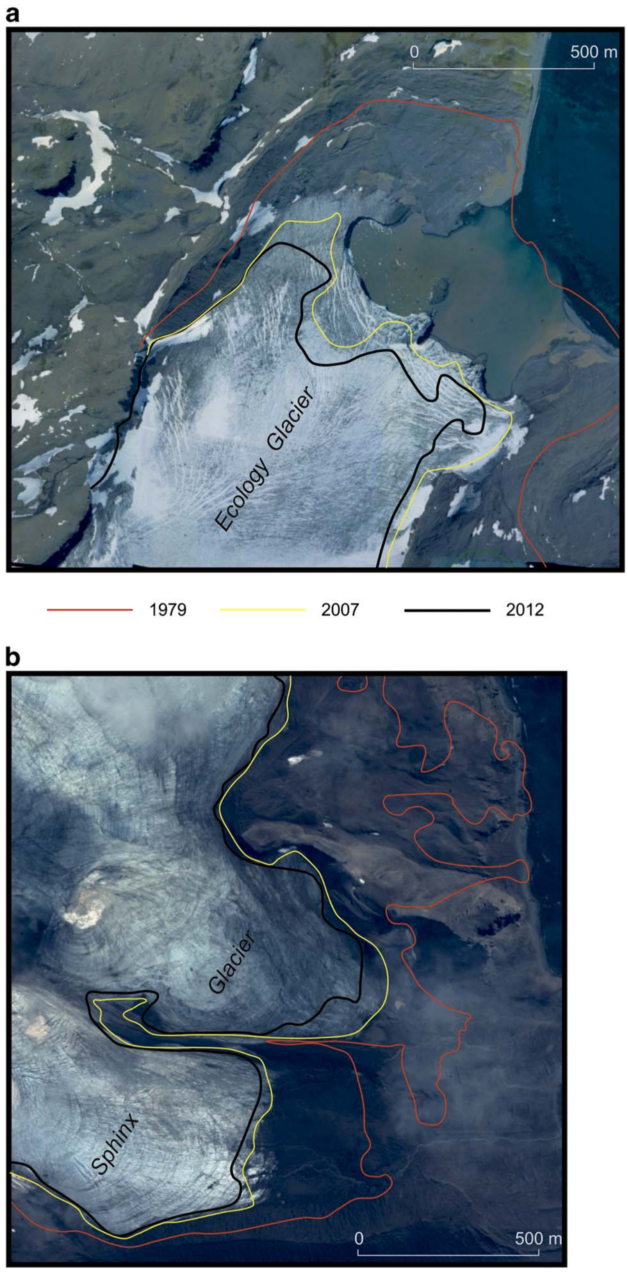

Fig. 9. Retreat of **a.** Ecology Glacier and **b.** Sphinx Glacier since 1979. The background image is based on non-conventional aerial photographs obtained during the 2002–03 summer (Francelino *et al.* 2003). Borders of glaciers in 1979 and 2007 are based on the western shore of Admiralty Bay orthophotomap (Pudełko 2007).

Arctowski Station. The air temperature in front of the glaciers was lower than at HA due to the recurrent flow of cool air formed over the glaciers and the influence of glacial ground. During the summer (for example, in February 2012) the difference in air temperature between HA and the glacier forefields (E0 and S0) was *c.* 1.1–1.2°C. The largest difference (2.8°C) occurred between HA and the upper glacial station E4 (the centre of the ESGS). The average air temperature gradient in February 2012 between E4 and HA was 1.4°C 100 m^{-1}.

The coldest month in the area was June. The temperatures recorded in this month reached -5.6°C in HA, -7.1°C at Sphinx Glacier (S0), and -8.1 to -9.0°C (E2 and E4, respectively) at Ecology Glacier (Fig. 4). The average vertical air temperature gradient in the middle of winter (June 2012) between the central part of Ecology Glacier (E4) and HA was 1.7°C 100 m^{-1}.

Mass balance and glacial retreat

The spatial pattern of the mass balance of the ESGS is influenced mainly by local weather conditions, morphology and, especially, snow conditions. In February 2012, ablation of Ecology Glacier reached > 70 cm w.e. (Fig. 5).

In 2013, the net mass balance in the ablation area of the glaciers was > -240 cm w.e. Some negative values were also obtained for the entire ablation zone of Ecology Glacier. The area of negative net balance in the ablation zone of Sphinx Glacier was smaller than for Ecology Glacier (Fig. 6). At altitudes above 100–150 m, melting is more intensive than at immediately lower elevations (Fig. 7).

Glaciers flowing from the ice cap are characterized by large differences in altitude between the melting ablation and accumulation zones. The average ELA on the ESGS for 2012–13 was 156 m a.s.l.

The mean net mass balance of the ESGS in 2012–13 was +17.8 cm w.e. The mass balance of glaciers for the area up to 50 m a.s.l. was -204 cm w.e. and up to 150 m a.s.l. was -30 cm w.e. The accumulation area ratio of the ESGS was 0.82.

Relative to its area in 1979, the ESGS had lost 41% by 2012. Between 2007 and 2012, the ESGS area decreased by 3% (Fig. 8). Between 2007 and 2012, Ecology Glacier retreated by 20–68 m in the central part of the ice cliff and 128 m in the northern part (Fig. 9). Sphinx Glacier retreated by 14–154 m in the northern part and 0–50 m in the southern part (Fig. 9). The average retreat rate of the ESGS between 2007 and 2012 was 16.6 m yr^{-1}.

Temperature of surface ice layers

The near-surface ice temperatures of Ecology Glacier changed markedly throughout the research period from February to June 2012. In early February, in the ablation zone, the ice temperature fell significantly with a minimum of -0.4°C recorded at the lowest thermistor at 10 m depth (Fig. 10). The mean amplitude of the monthly ice temperature was 0.1°C at 10 m depth (Figs 11 & 12).

At the ELA of Ecology Glacier (E4), the mean amplitude of monthly ice temperature was 0.06°C at 10 m depth (Fig. 12).

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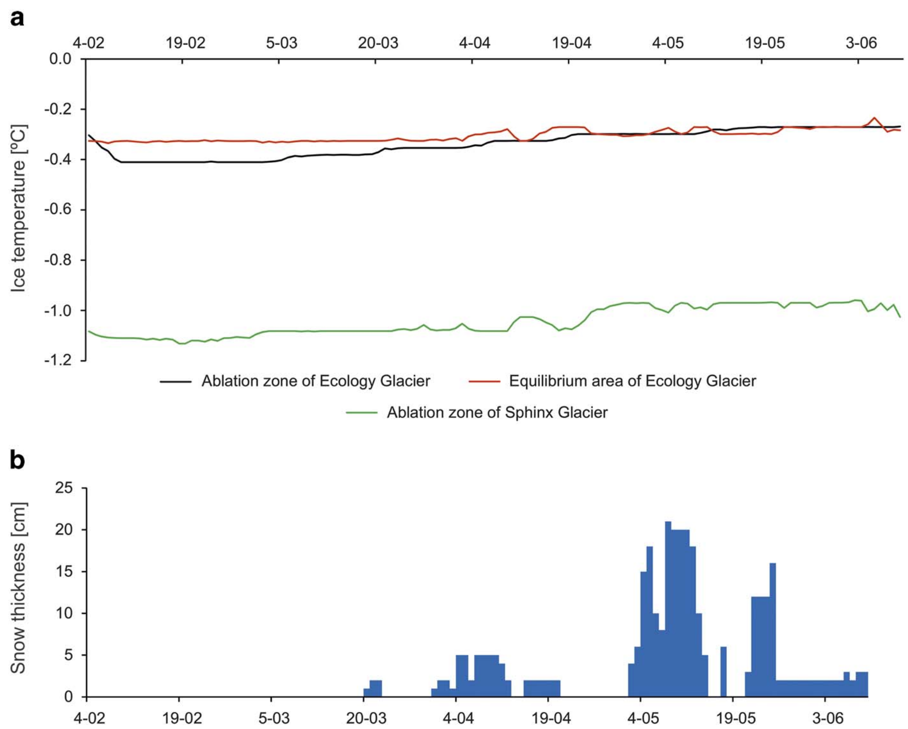

Fig. 10. Temporal variations in **a.** daily near-surface ice temperature at 10 m depth of the Ecology and Sphinx glacier system and **b.** snow thickness for February to June 2012.

The near-surface ice temperatures of Sphinx Glacier also changed throughout the research period (Fig. 11), with a mean amplitude of monthly ice temperature of 0.1°C at 10 m depth (Fig. 12).

Temperatures of Ecology Glacier at 10 m depth ranged from *c.* -0.3 to -0.4°C. In the ablation area of Ecology Glacier, the ice temperature was higher than in the same zone of Sphinx Glacier. Additionally, it is highly characteristic of the ELA of Ecology Glacier that, during the observed period, the monthly and daily ice temperature was aligned and clearly close to the melting point. In addition to meteorological conditions (air temperature), snow cover has an important influence on the temperature of the near-surface glacier ice, acting as an isolation layer between the atmosphere and the ice. Snow cover was observed at the measurement points throughout the majority of the study period (February–June 2012) (Fig. 10).

Table III. Mean meteorological measurements at Arctowski Station in 2012 and 1977–98*.

Period	January	February	March	April	May	June	July	August	September	October	November	December	Mean
Air pressure (sea level) (hPa)													
2012	985.3	985.5	990.8	996.7	993.6	979.4	989.7	989.8	994.9	982.5	986.5	993.5	989.0
1977–98	991.5	990.5	990.6	992.2	995.7	994.1	993.7	991.6	991.8	988.5	986.7	990.9	991.5
Wind velocity (ms^{-1})													
2012 (2 m)	3.9#	4.5	4.5	5.5	4.2	6.1	4.1	5.7	5.9	5.6	4.6	3.1	4.8
1977–98 (10 m)	5.7	6.2	6.9	6.8	6.5	6.6	6.7	6.7	7.4	7.3	6.7	5.5	6.6
Solar radiation (MJm^{-2})													
2012	476.7#	415.2	257.7	89.0	25.1	10.4	22.2	75.3	234.1	343.5	468.4	567.8	2985.3
1980**	488.1	303.0	263.3	106.5	33.3	15.8	35.7	115.3	290.8	554.6	582.8	740.4	3529.6
1995***	536.2	420.3	230.2	84.7	32.9	13.4	28.7	110.6	260.8	421.3	524.7	548.0	3211.8
1996****	499.1	415.6	240.5	95.6	27.9	10.9	20.6	75.6	177.2	374.7	472.8	566.9	2977.4
Air temperature (°C)													
2012	2.4	2.0	2.1	-2.9	-1.6	-5.6	-4.9	-3.2	-4.1	-2.2	-0.3	0.2	-1.5
1977–98	2.5	2.3	1.2	-1.1	-3.3	-5.0	-6.6	-5.6	-3.7	-2.0	-0.2	1.5	-1.6
Relative air humidity (%)													
2012	78.0	78.7	82.6	86.4	86.9	84.8	87.4	86.7	85.4	82.5	82.1	78.9	83.4
1977–98	82.9	82.8	82.3	83.1	82.8	82.6	83.0	81.9	82.4	81.8	82.6	83.3	82.3

*Marsz & Styszyńska 2000, **Marsz & Styszyńska 1994, ***Prošek *et al.* 1996, ****Kejna & Láska 1999.
#18–31 January.

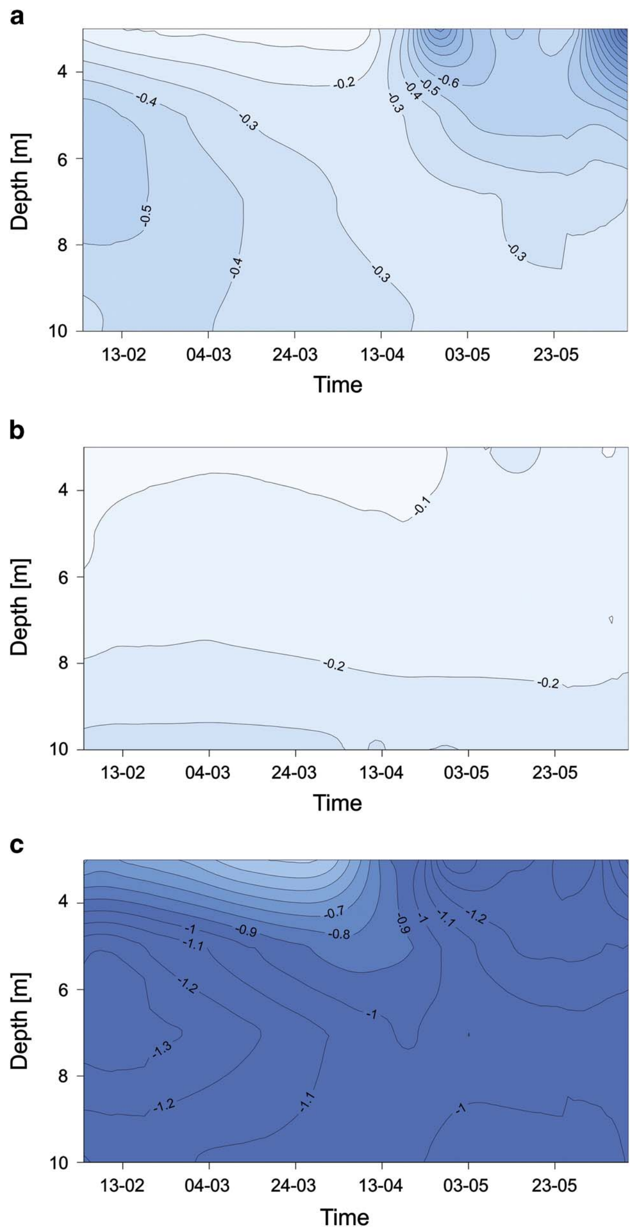

Fig. 11. Near-surface ice temperature (°C) of the Ecology and Sphinx glacier system for February to June 2012. **a.** Ablation zone of Ecology Glacier (E2). **b.** Equilibrium line of Ecology Glacier (E2). **c.** Ablation zone of Sphinx Glacier (S2).

Table IV. Area changes at Ecology Glacier, Sphinx Glacier and the Ecology and Sphinx glacier system.

Period	Area change (km^2)	Reference
Ecology Glacier		
1956–79	0.08	Braun 2001, Braun & Gossmann 2002
1978–88	0.19	Braun 2001, Braun & Gossmann 2002
1988–92	0.10	Braun 2001, Braun & Gossmann 2002
1956–92/95	0.37	Braun 2001, Braun & Gossmann 2002
1961–78	0.135	Kejna *et al.* 1998
1978–84	0.114	Kejna *et al.* 1998
1984–87	0.119	Kejna *et al.* 1998
1987–96	0.309	Kejna *et al.* 1998
1961–96	0.677	Kejna *et al.* 1998
2007–12	0.107/0.207*	Authors
Sphinx Glacier		
2007–12	0.069	Authors
Ecology and Sphinx glacier system		
1979–2007	3.195	Authors
2007–12	0.276	Authors
1997–2012	3.471	Authors

*Ecology Glacier tongue and southern part.

Discussion and conclusions

The climatic conditions of King George Island undergo considerable year-to-year variability. From 1948–2012, a statistically significant (at a level of 0.05) increase in mean annual air temperature occurred, reaching 1.2°C (0.19°C per decade. This warming affected all seasons except for spring. In winter, the warming rate was more than twice as rapid as in summer (Kejna *et al.* 2013). In recent years, however, this warming has ceased. In the twenty-first century there has also been a series of cool years (Table III).

The meteorological conditions in 2012 were not typical. Compared to the average values for recent years, 2012 was characterized by lower air pressure and lower incoming solar radiation. Large temperature anomalies in each month, especially summer 2012–13, which tended to be very cold with lengthy periods of snow cover.

The ESGS shows a spatial distribution of mass balance depending on the depth of the snow cover, which is variable over the glaciers. In the accumulation zones, the main factor influencing the depth of snow cover is precipitation, whereas redistribution by wind is important on the lower parts of the glacier. Positive mass balance was recorded at altitudes > 125 m a.s.l.

From 2012 to 2013, the mass balance of the ESGS was +17.8 cm w.e. This was primarily the result of weather conditions and snow cover thickness. In summer, with the exception of the front part of the Ecology Glacier, snow cover was observed over the entire area. Despite intensive melting, the snow cover was present until the end of the ablation season.

Between 1979 and 2012 the area loss for Ecology Glacier was 0.207 km^2 and for Sphinx Glacier was 0.233 km^2. In total, the ESGS lost 41% of its area. The average retreat rate of the ESGS throughout the entire analysed period of 2007–12 was 16.6 m yr^{-1}. For 1961–96, the area loss for Ecology Glacier was 0.677 km^2, producing a similar annual average loss rate (Table IV). An increase in air temperature in the South Shetland

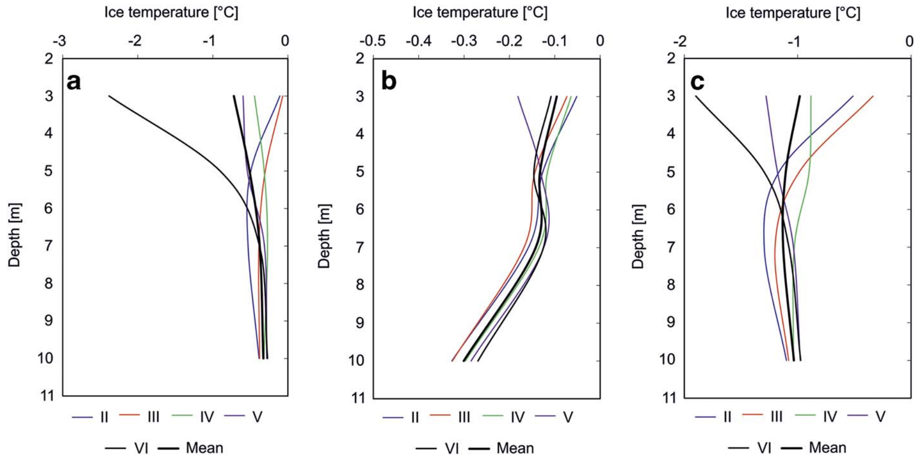

Fig. 12. Temperature profiles in selected parts of the Ecology and Sphinx glacier system for February to June 2012 (II–VI). **a.** Ablation zone of the Ecology Glacier (E2). **b.** Equilibrium line of Ecology Glacier (E4). **c.** Ablation zone of Sphinx Glacier (S2).

Islands region is considered to be responsible for the recession of Ecology Glacier in recent years.

From February to June 2012, the mean near-surface ice temperature at 10 m depth was higher than the annual mean air temperature by 3.1°C for Ecology Glacier and 1.5°C for Sphinx Glacier. The mean air temperature was -3.2°C and -1.6°C, respectively, whereas for the near-surface ice it was *c*. -0.1°C. At all measurement points to 10 m depth, the mean amplitude of monthly temperature was *c*. 0.1°C indicating that the near-surface ice temperature of the glaciers does not exceed 1°C. This is similar to the King George Island ice cap in a firn profile at *c*. 619 m a.s.l. in 1999–2000, which was also *c*. -0.3°C (Blindow *et al*. 2010).

Throughout most of the research period (February–June 2012), the mean monthly ice temperature at the ablation zone of Ecology and Sphinx glaciers tended to increase with depth. Only during the summer did temperature fall with depth. This is presumably related to the process of ice warming at the near-surface of the glacier.

The thermal structure of the near-surface layer of the ESGS indicates that, in the summer, the glacier's temperature is close to the melting point, and decreases with increasing depth below the surface. Throughout the rest of the year, the near-surface layer of the ice is also temperate. This confirms that most of the glaciers in the King George Island ice cap can be regarded as temperate.

The ESGS had a positive mass balance during 2012–13. Moreover, the tongue retreated and the glaciers showed a decrease in surface area in the long term. Hence, single-year measurements should be treated with some caution when extrapolating to longer time periods, to other or larger regions or when comparing different years. However, the direction of the mass changes can be determined only on the basis of detailed research in future years. Therefore, this investigation of the mass balance of the ESGS is especially important, as it offers one of only a few records available throughout King George Island, the Antarctic Peninsula and the Antarctic. Glaciological studies of the ESGS are an important component in the estimation of recent changes in the cryosphere of the King George Island region.

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Author contribution

I.S. described all glaciological problems and partly climate issues, and wrote the manuscript. M.K. and A.A. interpreted the meteorological data. I.S., M.K. and A.A. performed the field measurements. All authors contributed significantly to the interpretation of the data and revision of the manuscript.

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