Antarctic Science 32(5), 398–407 (2020) © Antarctic Science Ltd 2020 doi:10.1017/S0954102020000279

Contrasting responses of land-terminating glaciers to recent climate variations in King George Island, Antarctica

KÁTIA KELLEM DA ROSA [1,2,3], CLEIVA PERONDI [1,2], BIJEESH KOZHIKKODAN VEETTIL [4,5], JEFFREY D. AUGER [1] and JEFFERSON CARDIA SIMÕES [1]

[1] *Centro Polar e Climático, Instituto de Geociências, Universidade Federal do Rio Grande do Sul (UFRGS), Porto Alegre/RS, Brazil*
[2] *Programa de Pós-graduação em Geografia, Instituto de Geociências, Universidade Federal do Rio Grande do Sul (UFRGS), Porto Alegre/RS, Brazil*
[3] *Programa de Pós-graduação em Sensoriamento Remoto, Universidade Federal do Rio Grande do Sul (UFRGS), Porto Alegre/RS, Brazil*
[4] *Department for Management of Science and Technology Development, Ton Duc Thang University, Ho Chi Minh City, Vietnam*
[5] *Faculty of Environment and Labour Safety, Ton Duc Thang University, Ho Chi Minh City, Vietnam*
bijeesh.veettil@tdtu.edu.vn

Abstract: In this study, we aim to analyse the glacier dynamics of land-terminating glaciers in King George Island (Antarctica) between 1956 and 2018. Glacial fluctuations are estimated using space-borne remote sensing data (SPOT, Landsat, PlanetScope, Sentinel-1, Sentinel-2, WorldView-2 and TanDEM-X). The eastern sector of Warszawa Icefield witnessed continuous glacier retreat during 1979–2018 (surface loss of 30%). The decreases in the ice-covered areas of the Tower, Windy, Ecology, Baranowski and Sphinx glaciers were 70%, 31%, 25%, 25% and 21%, respectively, with their accumulation area ratios (AARs) exhibiting negative mass balances. The winter air temperature was cooler during the 1970s with warming trends in the 1980s and early 2000s followed by a cooling trend until the present day. However, the annual time series has shown high interannual variability in air temperature during these periods. We show that the AAR, dimensions, length, frontal elevation, maximum elevation, slope and changes in the terminus position influence the glacier response to climate change at various timescales. Furthermore, three geomorphic activity intensity zones and a complete paraglacial sequence are identified while contrasting the proglacial systems. Overall, subglacial deposits predominate and indicate that meltwater flows on the bed, producing wet-based thermal regimes.

Received 20 April 2018, accepted 13 March 2020

Key words: Admiralty Bay, climate change, multi-temporal analysis, proglacial systems

Introduction

Glacier retreat is dynamic and can be influenced by several factors, such as topography and atmospheric temperature variability (Nesje & Dahl 2000, Cuffey & Paterson 2010). Tidewater and land-terminating glaciers in the Antarctic region are important targets for monitoring dynamic glacial responses and sensitivity to changes in climate (Liang *et al.* 2018). Geomorphological changes in glaciers can be considered indicators of environmental fluctuations (Benn & Evans 2010, Knight & Harrison 2012).

During the second half of the twentieth century, a trend of increase in air temperature was reported in the vicinity of King George Island (KGI), Antarctica (e.g. Ferron *et al.* 2004, Kejna *et al.* 2013). In a recent study, Comin & Justino (2017) additionally showed an increase of 0.8–1.0°C in air temperature during 1955–2010 using data from two meteorological stations (Bellingshausen and Jubany). The average surface air temperature of KGI increased by 1°C from the 1950s to the 2000s (Kejna *et al.* 2013). Kejna *et al.* (2013) and Sobota *et al.* (2015) argued that the warming atmospheric trend directly interferes with the mass balance of glaciers in KGI.

Turner *et al.* (2016) showed evidence of a warming trend (+0.32°C) between 1979 and 1997. For the 2001–2010 period, Carrasco (2013) identified a decrease in air temperature in the western stations of the Antarctic Peninsula and a slight cooling trend in KGI. These environmental changes are linked to the regional warming trend, which has been observed for several decades, and variations in sea-ice and sea surface temperatures (Li *et al.* 2014).

The glaciers throughout the KGI have been retreating in recent decades (Kejna *et al.* 2013, Simões *et al.* 2015, Sobota *et al.* 2015, Petlicki *et al.* 2017, Pudełko *et al.* 2018, Perondi *et al.* 2019). Pudełko *et al.* (2018) observed fluctuations in the glacier outlines of five glaciers in KGI, namely the Ecology, Sphinx, Baranowski, Tower and Windy glaciers, for the 1979–2018 period, and they suggested that the glacier retreat rates were the lowest between 2001 and 2007. Pudełko *et al.* (2018) affirmed that water-terminating glaciers (Windy, Baranowski and Ecology) with lagoon ice-contact systems and land-terminating glaciers (Tower and Sphinx) have distinct behaviours in the same period of analysis, with the latter exhibiting retreat.

In this paper, we analyse the surface area fluctuations of five glaciers (i.e. Ecology, Sphinx, Baranowski, Tower and Windy) and their proglacial systems located on the west coast of Admiralty Bay, KGI (Antarctica) from 1979 to 2018. In the case of the Ecology Glacier, the glacier surface data (starting in 1956) are analysed. The winter air temperature observations (1956–2018) and tendencies of glacier retreat under various decadal-scale atmospheric temperature trends are analysed for the glaciers of various dimensions and topographies. Furthermore, the retreat patterns of the proglacial systems under various environmental conditions, such as land- and marine-terminating glaciers, are analysed.

Study area

The study area (Fig. 1) is located in the western sector of Admiralty Bay, KGI, which is a part of the Antarctic Specially Managed Area. The study area is composed of five glaciers, namely Ecology, Sphinx, Baranowski, Tower and Windy glaciers, and their proglacial systems.

Precipitation in KGI is characterized by high annual variability, with an estimated average of 701.3 mm during the 1968–2011 period (Kejna *et al.* 2013). The average annual air temperature is approximately -1.5°C, with the average warmest month being January (2.4°C) and the coldest being June (-5.6°C) (2012 observations) (Sobota *et al.* 2015). According to Kejna *et al.* (2013), the prevailing wind near Ecology Glacier is katabatic, originating from the Warszawa Icefield, which is domed

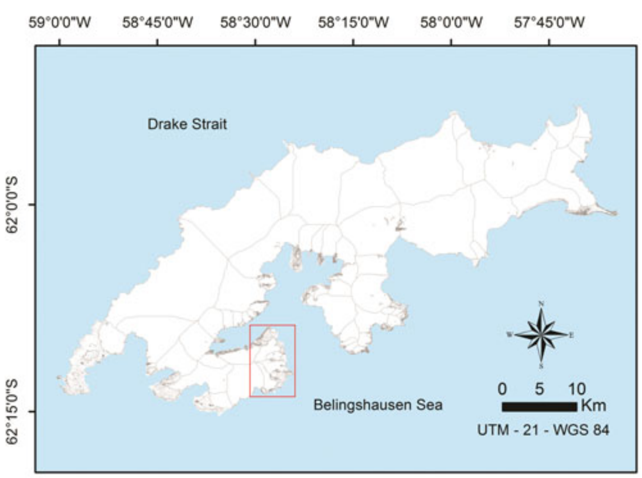

Fig. 1. Geographical location of Ecology, Sphinx, Baranowski, Tower and Windy glaciers and their ice-free areas in the eastern sector of Warszawa Icefield, King George Island.

with an asymmetric shape and ice flow directions towards the west and east (Rachlewicz 1999).

Sziło & Bialik (2018) and Perondi *et al.* (2019) discuss the various landforms in the recent proglacial landscape (i.e. striated pavement, eskers, terminal, lateral, latero-frontal, ice-cored and fluted moraines, kames, outwash plains, kettle and moraine-damage lakes, talus slopes, debris flow gullies, meltwater channels and glaciolacustrine and lacustrine landforms). The frontal area of Baranowski Glacier displays rapid geomorphological changes owing to the high variation in sediment particles (Sziło & Bialik 2018).

Data and methods

For mass balance analysis, the accumulation area ratio (AAR), which is the ratio of the accumulation area at the end of the melt season to the total glacier area (0–1% or 0–100%), was estimated using the methods of Meier & Post (1962) and Kulkarni (1992). The accumulation area is identified based on snowline altitude estimations using the Sentinel-1B data. The synthetic aperture radar (SAR) C-band data of Sentinel-1B were acquired in March 2017 (after geometric and radiometric corrections) and have a spatial resolution of 5×20 m (https://sentinel.esa.int/documents/247904/349449/S1_SP-1322_1.pdf). Various radar surface zones on the glaciers are identified, based on Rau *et al.* (2004), to estimate the snowline altitudes and AARs. The snowline identification is based on the backscattering characteristics of the Sentinel-1B data (C-band, double polarization, Extra Wide Swath model, Level 1 Product, Ground-Range GRD and Standard - S). The images were processed (radiometric calibration, clipping and application of the 5×5 median filter in the NEXT ESA SAR Toolbox) and backscatter limits were obtained (-8 dB threshold is appropriate to delimit the upper boundary line of the frozen percolation radar zone).

The variations in glacier area were identified and vectorized using images from Landsat ETM+ (acquired in January 2007), Sentinel-2 (acquired in March 2018), PlanetScope (acquired in February 2018) (Table I) and WorldView-2 (acquired in March 2014). This was possible owing to the reflectance difference between snow and ice-free areas, as well as those among snow (albedo: 0.8–0.9), exposed ice (albedo: 0.3–0.4) and ice-free land areas (Marshall 2012). The WorldView-2 and Sentinel-2 data were acquired at the end of the ablation season for cloud-free images as well as for better visibility of the glacier termini. Orthorectified WorldView-2 images have a spatial resolution of 0.5×2.0 m in their panchromatic and multispectral channels (eight bands). The Sentinel-2 Multispectral Instrument (MSI) data consist of 13 spectral bands, 4 of which have a spatial resolution of 10 m in the wavelength range 490–842 nm (https://sentinel.esa.int/web/sentinel/missions/sentinel-2). The Sentinel-2

https://doi.org/10.1017/S0954102020000279 Published online by Cambridge University Press

Table I. Specifications of the optical satellite data used in this study.

Sensor	Product level	Image ID	Acquisition date	Spatial resolution	Bands	Source
WorldView-2 PAN MS	Ortho-3A	103001002C993800	6 March 2014	0.46 m	Panchromatic: 450–800 nm Coastal: 400–450 nm Red: 630–690 nm Blue: 450–510 nm Red edge: 705–745 nm Green: 510–580 nm NIR 1: 770–895 nm Yellow: 585–625 nm NIR 2: 860–1040 nm	CPC Project
Sentinel-2	Multispectral	S1A_IW_SLC_1SSH	11 Feb 2018	10 m, 20 m, 60 m	B1 (443 nm)	USGS/NASA
MSI	Image-1C	_20180613T080102_ 2_022335_026AF4_EBF4			B2 (490 nm) B4 (665 nm) B5 (705 nm) B6 (740 nm) B7 (783 nm) B8 (842 nm) B8a (865 nm) B9 (940 nm) B10 (1375 nm) B11 (1610 nm) B12 (2190 nm)	
PlanetScope constellation (four-band frame imager with a split-frame NIR filter)	Ortho scene-3B	20180310_124407_1029_3B	5 Feb 2018	3 m	Blue: 455–515 nm Green: 500–590 nm Red: 590–670 nm NIR: 780–860 nm	Planet Labs, Inc.
Landsat ETM+	1GS	LE72171032007014EDC00	14 Jan 2007	30 m	Blue: 450–520 nm Green: 520–600 nm Red: 630–690 nm NIR: 770–900 nm Shortwave infrared 1: 1550–1750 nm Thermal: 10,400–12,500 nm Shortwave infrared 2: 2090–2350 nm Panchromatic: 520–900 nm	USGS/NASA

NIR = near-infrared.

images used in this study were obtained from the United States Geological Survey (USGS; https://earthexplorer.usgs.gov) at no cost. Frontal variation data, obtained using SPOT (1988–95 and 2000) imagery, were additionally considered in this study. The glacier area loss data for the 1956–79 period were available for Ecology Glacier (obtained using aerial photographs) at the Polar and Climatic Centre of the Federal University of Rio Grande do Sul, Brazil. The details of the optical satellite data used for this research are summarized in Table I. While an uncertainty of ± 1 pixel is assumed for glaciers with surface areas > 0.1 km^2 (Frey *et al.* 2012), the maximum uncertainty is < 5% for all the datasets, which is within the tolerable range.

The TanDEM-X digital elevation model (DEM) data were used to analyse slopes and elevation changes (maximum and minimum elevation values for each glacier) (Perondi *et al.* 2019). The DEM used here has a spatial resolution of 12 m and a vertical accuracy of 3.5 m (https://doi.org/10.1594/PANGAEA.863567).

The annual mean surface air temperature data for the study region were scarce and discontinuous and hence were obtained from multiple stations. The Brazilian Comandante Ferraz Antarctic Station (-62.08°S, -58.39°W; 5 m a.s.l.), installed by the Brazilian National Institute for Space Research (INPE), provided data for the 1986–2013 period. The Russian Bellingshausen Station (-62.19°S, -58.94°W; 1 m a.s.l.), located in Fildes Peninsula (30 km from the Brazilian station) in the western part of KGI, provided data for the 1968–76 and 2014–2018 periods. The Polish Henryk Arctowski Station (-62.09°S, -58.28°W; 2 m a.s.l.), located in Admiralty Bay, KGI, provided data for the 1977–85 period. The Argentine Deception Station (-62.59°S,

-60.34°W; 7 m a.s.l.), located on Deception Island, South Shetlands (138 km from the Brazilian station), provided data for the 1956–68 period. The method of combining these time series is described in |Ferron *et al.* (2004) (positive correlation; $r > 0.9$). In order to analyse the relationship between air temperature and variations in the glacier surface area, the coefficient of determination (r^2) is estimated.

In addition to station observations, the ERA Interim reanalysis data, which are currently being replaced by ERA5 (https://cds.climate.copernicus.eu/cdsapp#!/home), are used in the present study. These data are available at no cost (e.g. https://climatereanalyzer.org) and provide high-quality solutions on a global scale (Auger *et al.* 2018) (i.e. ERA Interim solutions are closer to the observations).

The proglacial systems are classified into various zones according to glacial landform and geomorphic intensity (glacial and paraglacial sediment supply, deposition and reworking). The geomorphic analysis is based on previous geomorphological mapping (Sziło & Bialik 2018, Perondi *et al.* 2019) and field observations (January 2011).

Results

Trends in atmospheric temperature and glacier fluctuations

A strong positive correlation between the annual temperature observations from this study and the annual temperature solution from the ERA Interim data is observed over KGI ($r > 0.90$, $P > 0.05$), demonstrating that the latter can be used as a good estimate for air temperature in this region (Fig. 2). The atmospheric observations during the 1956–2018 period reveal an increase in the winter average annual temperature (Fig. 3). The eastern sector of Warszawa Icefield shows a loss of 5.1 km^2 (30%) in surface area for the 1979–2018 period. The area loss has an r^2 value of 0.6 with the trends observed in the winter air temperature.

The surface area loss of Ecology Glacier during 1956–2018 was 1.79 km^2 (25% of 7.11 km^2 in 1956). During 1979–2018, the individual glacier area losses presented by the Sphinx, Baranowski, Tower and Windy glaciers were 0.36 km^2 (21% of 1.70 km^2 in 1979), 0.76 km^2 (25% of 3.09 km^2 in 1979), 1.28 km^2 (70% of 1.82 km^2 in 1979) and 1.10 km^2 (31% of 3.51 km^2 in 1979), respectively (Fig. 4 & Table II). (The maximum errors were < 5% for all the data sets.)

For the 5 year period from 1995 to 2000, a fast retreat was observed (0.3 km^2 year^{-1}, overall 1.5 km^2, which is 8% of 17.2 km^2 in 1979) for all of the glaciers studied, particularly for the Ecology, Baranowski and Tower glaciers (Fig. 5 & Table II).

However, during the subsequent 18 years (2000–18), the glaciers (with the exception of Windy Glacier) displayed a lower surface area loss rate (4×10^{-2} km^2 year^{-1}), indicating a lower rate of retreat since the 2000 measurement (Fig. 5).

In 1979, the areas of the Ecology, Sphinx, Baranowski, Tower and Windy glaciers were 7.10, 1.70, 3.09, 1.82 and 3.51 km^2, respectively. In 2018, the individual surface areas of these five glaciers were estimated to be 5.31, 1.34, 2.34, 0.53 and 2.40 km^2, respectively.

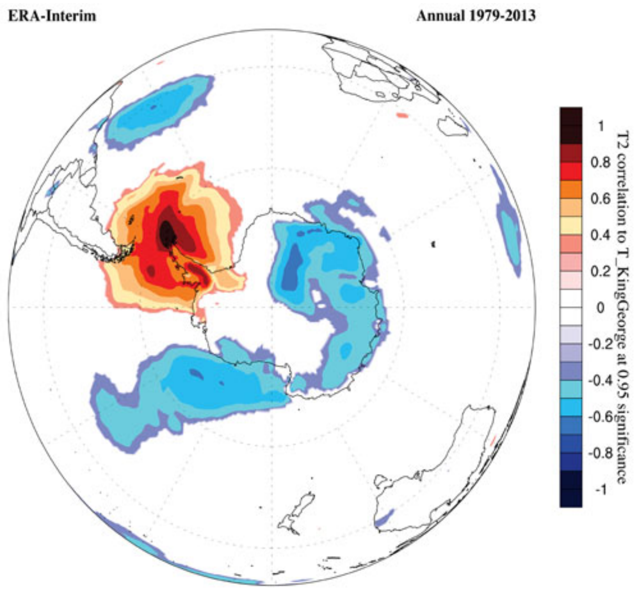

Fig. 2. Correlation between annual temperature observations and ERA Interim data for 2 m temperature.

Proglacial environment and its recent changes

On Warszawa Icefield, the increase in ice-free areas is estimated to be ~5.1 km^2 between 1979 and 2018. The foreland shows three zonations (high, moderate and low geomorphic intensity zones) (Figs 6 & 7). The high geomorphic intensity zone is characterized by recent changes in glacier margins and an elevation class of 50–100 m, and this represents the 2000–18 period. Ice-marginal lakes, meltwater channels, recessional moraines, eskers and flutings are susceptible to intense paraglacial processes. Active slumping occurs on parts of the upper ice-distal faces in association with the steep slopes of the moraines. The moderate geomorphic intensity zone has been a land-free area since the 1970s and is characterized by an elevation class of 0–50 m and discontinuous esker and moraine ridges owing to a gully system. The low geomorphic intensity zone is characterized by old glacial landforms (ice-free land before the 1970s) and an elevation class of 0–25 m, and it exhibits the complete paraglacial sequence. Here, the lakes have lost connection with the glacier margins and there is an absence of eskers and flutings in the smooth

https://doi.org/10.1017/S0954102020000279 Published online by Cambridge University Press

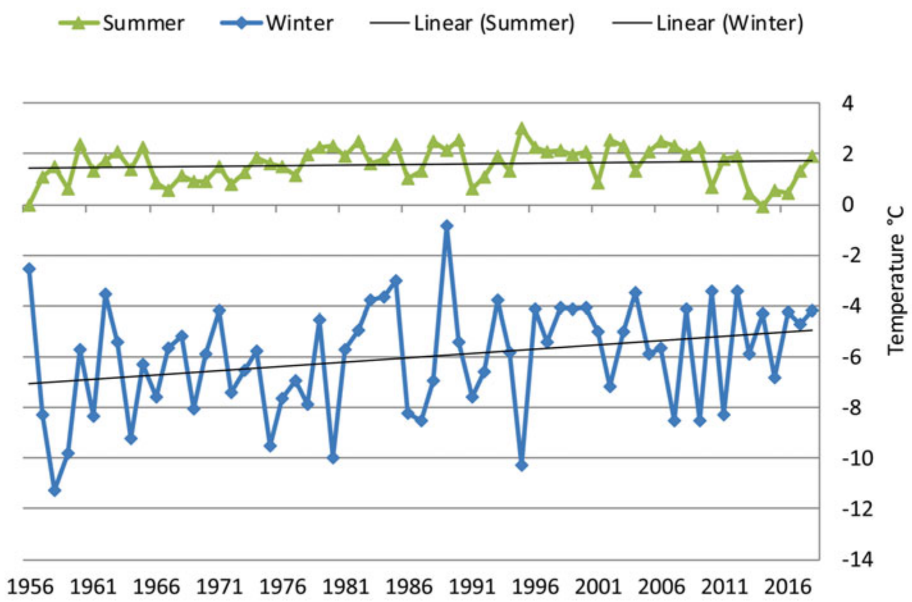

Fig. 3. Historical station data of average annual atmospheric temperature for the winter (June–August) and the summer (January–March) in King George Island from 1956 to 2018.

terrain. The paraglacial sediments are stored in the outwash plain.

Windy Glacier shows a predominantly high geomorphic intensity zonation. The proglacial environments of the Baranowski, Tower, Sphinx and Ecology glaciers display three zones of (high, moderate and low) geomorphic activity.

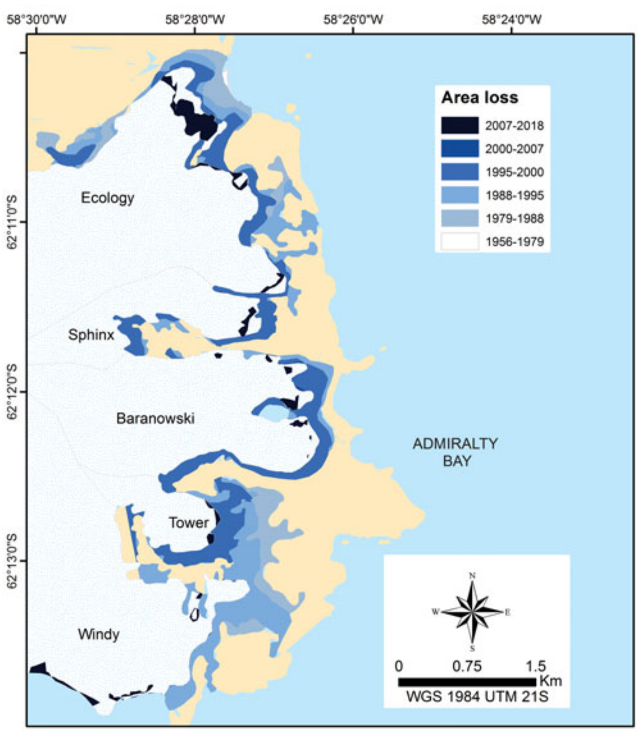

Fig. 4. Glacial fluctuations (by period) in eastern sector of Warszawa Icefield, Admiralty Bay.

Ecology Glacier has developed new ice-contact lakes at the terminus with meltwater channels supplying the lagoon–Admiralty Bay connection. The analysis of satellite images indicates that, since 1988, a large portion of its frontal sector has terminated on land, with the lagoon becoming partially connected to the central part of the glacier owing to local tidal variations. The landscape displays striated pavements, roche moutonnées, eskers and latero-frontal moraine ridges. Flutings and recessional moraines are observed only in the low geomorphic intensity zone of Sphinx Glacier. The proglacial environment of Tower Glacier displays relatively smaller ice-marginal recessional moraines and a paraglacial sequence at a distance from the glacier margin.

Discussion

The glacial AARs indicate negative mass balances (data acquired in 2018) for the Windy, Sphinx, Baranowski and Ecology glaciers, with AAR values of 0.07, 0.18, 0.35 and 0.45, respectively.

A 10 year running mean of air temperature shows generally colder winters during the 1970s and warmer winters in the 1980s and early 2000s, followed by a cooling trend. However, the annual time series shows high interannual variability in air temperature during these periods. During the 1990s, a retreating trend is observed for all five glaciers.

The differences among the coefficients of determination (0.4–0.7) suggest heterogeneous responses of the glaciers. The glacier retreat patterns for the 1979–2018 period show that the Tower and Windy glaciers present the highest variations in total area (in terms of percentage of surface area loss) compared to the Ecology, Baranowski

Table II. Surface areas, accumulation area ratios (AARs) and geomorphometric values of glaciers in the eastern sector of Warszawa Icefield, Admiralty Bay.

Glacier	Tower	Windy	Baranowski	Ecology	Sphinx
Maximum elevation (m)	320	435	454	323	445
Minimum elevation (m)	188	21	0 (northern sector); 31 (southern sector)	0	50
Mean slope (%)	13	12	16	13	17
Length (m)	1700	3000	3600	4100	3050
AAR (km^2)	0	0.07	0.35	0.43	0.18
Total area (km^2), 1979	1.82	3.51	3.09	7.10	1.7
Total area (km^2), 1988	1.60	3.38	3.09	6.70	1.7
Total area (km^2), 1995	0.96	2.69	2.99	6.17	1.67
Total area (km^2), 2000	0.69	2.66	2.54	5.57	1.39
Total area (km^2), 2007	0.55	2.52	2.37	5.42	1.34
Total area (km^2), 2018	0.53	2.40	2.34	5.31	1.34
Area loss (%), 1979–2018	70.6	31.4	24.6	25.2	21.2
Area loss (km^2), 1979–2018	1.28	1.10	0.76	1.78	0.36
Area loss (km^2), 1956–1979	-	-	-	0.01	-
Area loss (km^2), 1979–1988	0.22	0.13	0	0.39	0
Area loss (km^2), 1988–1995	0.64	0.69	0.11	0.53	0.03
Area loss (km^2), 1995–2000	0.37	0.03	0.45	0.60	0.28
Area loss (km^2), 2000–2007	0.04	0.14	0.17	0.14	0.05
Area loss (km^2), 2007–2018	0.01	0.11	0.03	0.12	0.001
Outline/minimum elevation variation (m)	1	21	4	0	1

and Sphinx glaciers, which have lower area losses (Table II).

The Tower and Sphinx glaciers show the lowest areal loss for the 2000–18 period compared with the other three glaciers. This suggests that, on a decadal timescale, glaciers with smaller lengths and areas at the lowest elevation band have been reflecting a cooling trend in the annual air temperature in recent years. Both glaciers have lower areas compared with the other glaciers considered in this study. Sphinx Glacier has lower frontal elevation and higher AAR, length and maximum elevation values than Tower Glacier, but has higher slope values (Table II).

Ecology Glacier presents a high areal loss without variation in frontal elevation and a recent deceleration in retreat (2000–2018) (Table II). The observed variations in area and elevation reveal the influence of the low maximum elevation, AAR value and anchor points on the ice flow. This observation is in good agreement with the results presented by Petlicki *et al.* (2017) and Pudełko *et al.* (2018).

Sphinx Glacier shows the lowest change in surface area, which reveals the influences of hypsometric weight, length and AAR on glacier retreat (Table II). Baranowski Glacier displays higher frontal elevation variation (2000–18) than the other glaciers (with the exception of Windy

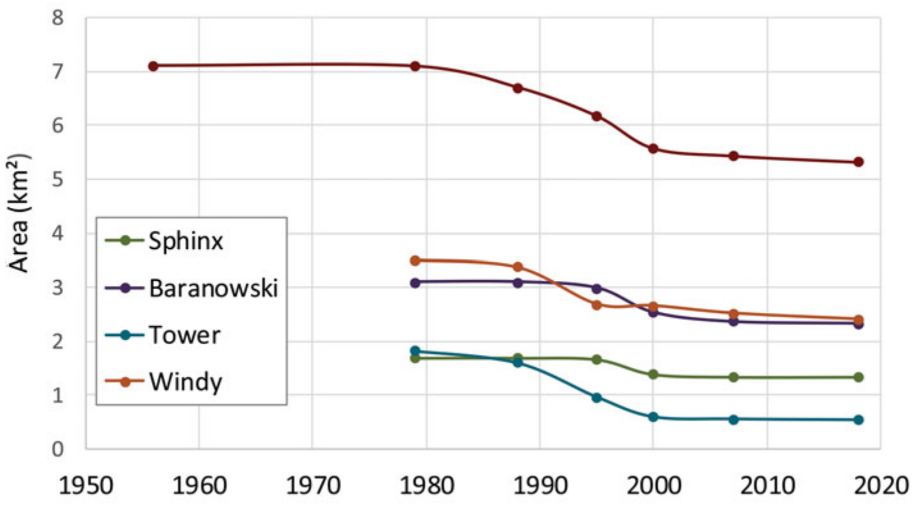

Fig. 5. Variations in individual glacier areas (1956–2018).

https://doi.org/10.1017/S0954102020000279 Published online by Cambridge University Press

Fig. 6. a. Ice-free land area on the western coast of Admiralty Bay, **b.** recessional moraines and **c.** spatial distribution of recessional moraines in proglacial environments in the western sector of Admiralty Bay (photographs were taken during fieldwork in the summer of 2011). LIA = Little Ice Age.

Glacier) and can be influenced by high slope values at the snout.

Some adjacent glaciers with similar maximum elevation, such as Baranowski, Sphinx and Windy, show significant heterogeneous areal loss, possibly owing to differences in AAR, length and topographical or glacio-geomorphological characteristics. Windy Glacier exhibits the highest variation in frontal elevation and higher shrinkage compared with the other glaciers considered in this study. This glacier presents an important change in its environmental conditions, where its classification has changed from a marine-terminating to a land-terminating glacier (non-tidewater). Glasser *et al.* (2011) noted that the dynamics of land-terminating glaciers are related primarily to climatic conditions. Windy Glacier was marine-terminating until approximately the mid-1990s. Pudełko *et al.* (2018) confirmed that Windy Glacier lost its connection with the lagoon between 2011 and 2018. From this environmental change, it is possible to understand the deceleration in glacier retreat during the 1995–2018 period compared with those in previous years (1988–95).

Windy Glacier's behaviour is impacted by the loss of marine influence and it has anchor points on the ice flow, as Rau *et al.* (2004) comment. There are differences in terms of frontal retreat rates between terrestrial and marine glaciers, wherein the frontal retreat rates of

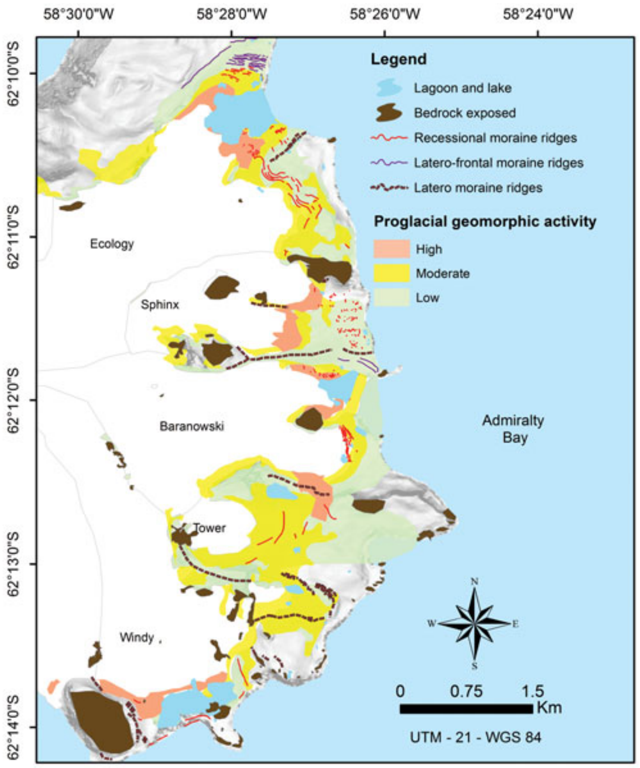

Fig. 7. Landform spatial distribution in foreland with three zones of (high, moderate and low) geomorphic activity.

glaciers are higher for tidewater-terminating glaciers than for land-terminating ones (Sole *et al.* 2008). Tidewater glaciers present complex dynamics as their mass balance and dynamic behaviour are affected by various elements, such as climate, ocean conditions, form, total precipitation and surface melting (Cook *et al.* 2012). Furthermore, the frontal ablation of tidewater glaciers is influenced by wave dynamics and sea surface temperatures (Luckman *et al.* 2015).

The retreat patterns of land-terminating glaciers (non-marine) in this region are influenced by proglacial as well as subglacial conditions. Eskers, flutings, striated pavements and roche moutonnées indicate a wet-based thermal regime for glaciers and can be influenced by glacial movement owing to bedrock sliding. Tower Glacier does not exhibit eskers and flutings owing to its lower glacier dynamics (decreased ice-flow velocity and glacial sediment transport). The absence of glaciofluvial landforms shows low sediment transport by subglacial meltwater channels owing to stagnated ice flow.

Pudełko *et al.* (2018) reported that the glacier retreat pattern of land-terminating glaciers in this region is influenced by proglacial ice-contact anchor points on the frontal ice flow and the presence of glacier–lagoon connections. The Ecology and Baranowski glaciers present glacier–lagoon connections different from other land-terminating glaciers. Petlicki *et al.* (2017) argue that Ecology Glacier had some areas in which the frontal position was stable compared with those of the other glaciers during the 2012–16 period.

Compared with the Collins and Polar Club glaciers (KGI), the five glaciers studied here (Ecology, Sphinx, Baranowski, Tower and Windy) present moderate to high shrinkage rates (0.05, 0.01, 0.01, 0.03 and 0.03 km^2 $year^{-1}$, respectively) and greater percentages of surface area loss since 1979 (70% for Tower Glacier). The retreat rates observed for these five glaciers encompass more area (in terms of percentage) than those of the Collins, Polar Club, Dragon, Professor and Wanda glaciers (which are also located on KGI) in recent decades.

Pudełko *et al.* (2018) observed variations in the frontal retreat of glaciers, showing that 6.1 km^2 of ice-free areas were formed. However, our results show a surface area loss that is 16% lower (5.1 km^2) than the estimates of Pudełko *et al.* (2018) owing to differences in spatial analyses in estimating the total area of Windy Glacier, excluding the Dera Ice Fall sector.

The foreland spatial zonation (high, moderate and low geomorphic intensities) suggests proglacial lake changes in years to decades. The paraglacial sequence is recorded in glacier forelands as an increase in slope stability, decrease in lateral erosion, enhancement in sediment deposition and vegetation establishment with exposition age. The temporal paraglacial adjustment has been suggested by Heckmann & Morche (2019).

Generally, the glacier shrinkage observed in the eastern sector of Warszawa Icefield is related to regional climate variability. Braun & Goßmann (2002) argue that the significant decline in land-terminating glaciers shows the changing parameters controlling glacier mass balance, particularly atmospheric temperature.

Conclusions

A high retreating trend was observed for the Ecology, Sphinx, Baranowski, Tower and Windy glaciers in the 1990s. The winter air temperature was cooler during the 1970s, with warming trends in the 1980s and early 2000s, followed by cooling to date.

It is observed that glaciers in the same icefield (Warszawa Icefield) exhibit various retreat rates and thus contradictory glacier responses to climate change under the influence of various environmental factors. The glaciers show a deceleration in retreat during the 2000–18 period compared to the 1979–2000 period, demonstrating that glaciers with smaller areas can reflect, on a decadal timescale, a cooling trend, as is seen in the annual air temperature recorded in recent years. It is worth noting that a number of other factors (e.g. oceanic, atmospheric,

https://doi.org/10.1017/S0954102020000279 Published online by Cambridge University Press

topographic and inherent glacier systems) influence the temperature trend and fluctuations in glaciers at decadal timescales in addition to topography and atmospheric temperature.

Windy Glacier presented an important change: its terminus position changed from tidewater to land conditions during the 2000–18 period, thus modifying its surrounding conditions, and it has displayed a deceleration in retreat in recent years.

Briefly, the understanding of the dynamic behaviours of land-terminating glaciers in this sub-polar region is relevant to the detection of regional environmental changes through investigations into the geomorphological evolution of ice-free areas.

Acknowledgements

We acknowledge Dr Mathias Braun for the TanDEM-X data and Planet Team, Planet Application Program Interface and the Brazilian National Council for Scientific and Technological Development (CNPq).

Author contributions

All authors analysed the data and wrote the paper.

Financial support

This work is a contribution of the *Antarctic Science* reviewers, Brazilian Antarctic Program (PROANTAR), and is supported by research grants from the Foundation for Research Support of the State of Rio Grande do Sul (FAPERGS). Cleiva Perondi is thankful to the Brazilian Coordination for the Improvement of Higher Education Personnel (CAPES) for a scholarship.

References

Auger, J.D., Birkel, S.D., Maasch, K.A., Mayewski, P.A. & Schuenemann, K.C. 2018. An ensemble mean and evaluation of third generation global climate reanalysis models. *Atmosphere*, **9**, 10.3390/atmos9060236.

Benn, D.I. & Evans, D.J.A. 2010. *Glaciers and glaciation*, 2nd ed. London: Hodder Arnold Publication, 816 pp.

Braun, M. & Goßmann, H. 2002. Glacial changes in the area of Admiralty Bay and Potter Cove, King George Island, Antarctica. *In* Beyer, M., Boelter M., *eds. Geoecology of terrestrial Antarctic oases.* Berlin: Springer, 75–89.

Carrasco, J.F. 2013. Decadal changes in the near-surface air temperature in the western side of the Antarctic Peninsula. *Scientific Research*, **3**, 10.4236/acs.2013.33029.

Comin, A.N. & Justino, F. 2017. Investigação Climatológica na Península Antártica e no Arquipélago das Shetland do Sul. *Anuário do Instituto de Geociências*, **40**, 74–81.

Cook, A.J., Murray, T., Luckman, A., Vaughan, D.G. & Barrand, N.E. 2012. A new 100-m digital elevation model of the Antarctic Peninsula derived from ASTER Global DEM: methods and accuracy assessment. *Earth System Science Data*, **4**, 10.5060/D47P8W9D.

Cuffey, K.M. & Paterson, W.S.B. 2010. *The physics of glaciers*, 4th ed. Oxford: Elsevier Science, 380 pp.

Ferron, F.A., Simões, J.C., Aquino, F.E. & Setzer, A.W. 2004. Air temperature time series for King George Island, Antarctica. *Pesquisa Antártica Brasileira*, **4**, 155–169.

Frey, H., Paul, F. & Strozzi, T. 2012. Compilation of a glacier inventory for the western Himalayas from satellite data: methods, challenges, and results. *Remote Sensing of Environment*, **124**, 10.1016/j.rse.2012.06.020

Glasser, N.F., Scambos, T.A., Bohlander, J., Truffer, M., Pettit, E. & Davies, B.J. 2011. From ice-shelf tributary to tidewater glacier: continued rapid recession, acceleration and thinning of Röhss Glacier following the 1995 collapse of the Prince Gustav Ice Shelf, Antarctic Peninsula. *Journal of Glaciology*, **57**, 10.3189/002214311796905578.

Heckmann, T. & Morche, D. 2019. *Geomorphology of proglacial systems: landform and sediment dynamics in recently deglaciated alpine landscapes.* Basel: Springer, 361 pp.

Kejna, M., Arazny, A. & Sobota, I. 2013. Climatic change on King George Island in the years 1948–2011. *Polish Polar Research*, **34**, 10.2478/popore-2013-0004.

Knight, J. & Harrison, S. 2012. Evaluating the impacts of global warming on geomorphological systems. *AMBIO*, **41**, 10.1007%2Fs13280-011-0178-9.

Kulkarni, A.V. 1992. Mass balance of Himalayan glaciers using AAR and ELA methods. *Journal of Glaciology*, **38**, 10.3189/S0022143000009631.

Li, X., Holland, D.M., Gerber, E.P. & Yoo, C. 2014. Impacts of the north and tropical Atlantic Ocean on the Antarctic Peninsula and sea ice. *Nature*, **505**, 10.1038/nature12945.

Liang, Q., Peng, S., Niu, B., Zhou, C. & Wang, Z. 2018. Mapping glacier-related research in polar regions: a bibliometric analysis of research output from 1987 to 2016. *Polar Research*, **37**, 10.1080/17518369.2018.1468196.

Luckman, A., Benn, D.I., Cottier, F., Bevan, S., Nilsen, F. & Inall, M. 2015. Calving rates at tidewater glaciers vary strongly with ocean temperature. *Nature Communications*, **6**, 10.1038/ncomms9566.

Marshall, S.J. 2012. *The cryosphere. Princeton primers in climate.* Princeton, NJ: Princeton University Press, 288 pp.

Meier, M.F. & Post, A.S. 1962. Recent variations in mass net budgets of glaciers in western North America. *International Association if Scientific Hydrology Publication*, **58**, 63–77.

Nesje, A. & Dahl, S.O. 2000. *Glaciers and environmental change*, 1st ed. London: Taylor & Francis, 216 pp.

Perondi, C., Rosa, K.K. & Viera, R. 2019. Caracterização geomorfológica das áreas livres de gelo na margem leste do campo de gelo Warszawa, Ilha Rei George, Antártica Marítima. *Revista Brasileira de Geomorfologia*, **20**, 10.20502/rbg.v20i2.1433.

Petlicki, M., Szillo, J., Macdonell, S., Vivero, S. & Bilaik, R.J. 2017. Recent deceleration of the ice elevation change of Ecology Glacier (King George Island, Antarctica). *Remote Sensing*, **9**, 10.3390/rs9060520.

Pudełko, R., Angiel, P., Potocki, M., Jędrejek, A. & Kozak, M. 2018. Fluctuation of glacial retreat rates in the eastern part of Warszawa Icefield, King George Island, Antarctica, 1979–2018. *Remote Sensing*, **10**, 10.3390/rs10060892,

Rachlewicz, G. 1999. Glacial relief and deposits of the western coast of Admiralty Bay, King George Island, South Shetland Islands. *Polish Polar Research*, **20**, 89–130.

Rau, F., Mauz, F., De Angelis, H., Jana, R., Arigony-Neto, J., Skvarca, P., *et al.* 2004. Variations of glacier frontal positions on northern Antarctic Peninsula. *Annals of Glaciology*, **39**, 10.3189/172756404781814212.

Simões, C.L., Rosa, K.K., Czapela, F.F., Vieira, R. & Simões, J.C. 2015. Collins Glacier retreat process and regional climatic variations, King George Island, Antarctica. *Geographical Review*, **105**, 10.1111/j.1931-0846.2015.12091.x.

Sobota, I., Kejna, M. & Arzany, A. 2015. Short-term mass changes and retreat of the ecology and Sphinx Glacier System, King George Island, Antarctic Peninsula. *Antarctic Science*, **27**, 10.1017/S0954102015000188.

Sole, A., Payne, T., Bamber, J., Nienow, P. & Krabil, W. 2008. Testing hypotheses of the cause of peripheral thinning of the Greenland Ice Sheet: is land-terminating ice thinning at anomalously high rates? *The Cryosphere*, **2**, 10.5194/tc-2-205-2008.

Sziło, J. & Bialik, R.J. 2018. Recession and ice surface elevation changes of Baranowski Glacier and its impact on proglacial relief (King George Island, West Antarctica). *Geosciences*, **8**, 10.3390/geosciences8100355.

Turner, J., Lu, H., White, I., King, J.C., Philips, T., Scott Hosking, J., *et al*. 2016. Absence of 21st century warming on Antarctic Peninsula consistent with natural variability. *Nature*, **535**, 10.1038/nature18645.