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GEOSCIENCES

Glacier fluctuations and a proglacial evolution in King George Bay (King George Island), Antarctica, since 1980 decade

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Abstract: This study aims to investigate the glacier shrinkage and recent proglacial environment in King George Bay, Antarctica, since 1988 in response to climate change. Remote sensing data (SPOT, Sentinel, Landsat and Planet Scope images) were applied to glacial landforms and ice-marginal fluctuations mapping. Annual mean near-surface air temperature reanalysis solutions from ERA-Interim were analyzed. Moraines and glaciofluvial landforms were identified. The Ana Northern Glacier has the highest retreat value (3.64 km) (and area loss of 31%) in response to higher depth in frontal ice-margin and reveal ocean-glacier linkages. The Ana South Glacier changed from a tidewater glacier to land-terminating after 1995, and had an outline minimum elevation variation of 89 meters, a shrinkage of 0.63 km, and a new proglacial subaerial sector. The Ana South Glacier foreland had recessional moraines (probably formed between 1995 and 2022), lagoons, and lakes. There are many flutings in low-relief environments. The 1980-1989, 1990-1999, 2000-2009, 2010-2019 anomaly plots concerning to the 1980-2019 average for atmospheric temperature, are shown to be a driver of the local glacial trends.

Key words. Geographical Information System, polar regions, shrinkage environmental change, morainal landforms, climate change.

INTRODUCTION

Glacial mass balance is influenced by factors such as air temperature and precipitation, as well as solar radiation, humidity, and wind speed (Mackintosh et al. 2017). When snow or ice surface temperature is at or near their melting point, melting rates tend to increase with the warming of the overlying atmosphere and can lead to negative mass balance over time (Cuffey & Paterson 2010).

Glacial mass balance state variation at a given moment of analysis can result in changes such as retraction, stabilization, or the advance of the frontal margin (Copland 2011, Rinterknecht 2011). These events may be associated with climate change (Joughin et al. 2004). The landforms located in the ice-margin zone, such as latero-frontal moraines, exposed by glacial retreat, record the maximum extensions of glaciers in the past and show pinning points of the glacial front (Benn et al. 2003, Beedle et al. 2009).

Glaciers' marine terminus is influenced by interaction with the ocean (Murray et al. 2010, Porter et al. 2014, Cook et al. 2016, Rignot et al. 2019). Ice thickness at glacier margins also control their break-off rates (Benn et al. 2007). Glaciers with lower continentality and an annual average temperature at the Equilibrium-Line Altitude (ELA) above 0° have greater sensitivity in their mass balance than those are not in these conditions (Mackintosh et al. 2017).

Monitoring glaciers in the Antarctic Peninsula (AP) and its maritime region is relevant to understanding the various impacts of climate change on the site. Records of increasing maximum temperature rates between 2016 and 2020 at several regional stations were observed (Dalaiden et al. 2022). The atmospheric warming trend (0.26 °C/decade warming trend in the region) since the middle of the 20th century has been verified by the James Ross ice core and indicated that this recent warming in West Antarctic is not unusual in the context of the past 300 years (Mulvaney et al. 2012, Abram et al. 2013). The last period of glacier still-stand and small advance was linked to the Little Ice Age – LIA (1400-1700) in King George Island.

The interpretation of images from orbital remote sensors helps monitor glaciers and recently ice-free land areas. In response to atmospheric warming, it is essential to understand glacier retreat patterns. Several authors recorded glacial retreats in this sector of the AP and King George Island (KGI) in recent decades by remote sensing (Braun & Goßmann 2002, Rückamp et al. 2011, Rosa et al. 2015, 2020, Oliveira et al. 2019, Rignot et al. 2019, Perondi et al. 2019, 2020, Lorenz 2021).

Given this context of recent climate changes and their impacts on the polar regions, Braun & Goßmann (2002) point out that changes are expected in the glaciers of the region, with glaciers moving from maritime to terrestrial termination. There are also projections of a progressive increase in the number of days with temperatures ≥ 10 °C by Siegert et al. (2019) for the entire northern AP region for the next few decades. Ice-free land areas in Antarctica could expand by up to 25% by 2100 in response to climate changes and alterations in the continent's biodiversity (Lee et al. 2017).

This article aims to investigate the process of glacial retreating in King George Bay, KGI, Antarctica, between 1989 and 2022. The goals of this research were: a) glacier's termination characteristic changes, b) the glacier's ablation change response to lateral topographic pinning points and loss of floating area, c) the glacier's recent retreat and their evolution after the Little Ice Age, and d) the glacial evolution impact in proglacial landforms and lakes.

MATERIALS AND METHODS

Study area

King George Bay is located in the Eastern sector of the KGI, the largest of the South Shetland Islands (Figures 1 and 2). The Central, Kraków, and Oriental Icefields have tidewater and land-terminating glaciers. The tidewater glaciers are ice-calving (Silva et al. 2019). The longitudinal profile of the North Ana Glacier, a tidewater glacier located on Oriental Icefield, has the most significant topographic amplitude (703 m) and is fed by the highest elevation of the ice field, the Eastern Part.

Geologically, the islands are volcanics, with faults and sedimentary, metasedimentary, and volcanic rocks of the Late Jurassic and the Late Cretaceous to Miocene eras (Barton 1965, Maldonado et al. 1998).

The climate of the region is characterized by maritime subpolar with an air temperature above 0 ºC during some summer days (Setzer et al. 2004). The average annual air temperature is approximately -1.5°C, with the warmest average temperature in January (2.4°C) and the coldest in June (-5.6°C) (2012 observations) (Sobota et al. 2015). Precipitation in KGI is characterized by high annual variability with an estimated annual average of 701.3 mm during 1968–2011 (Kejna et al. 2013).

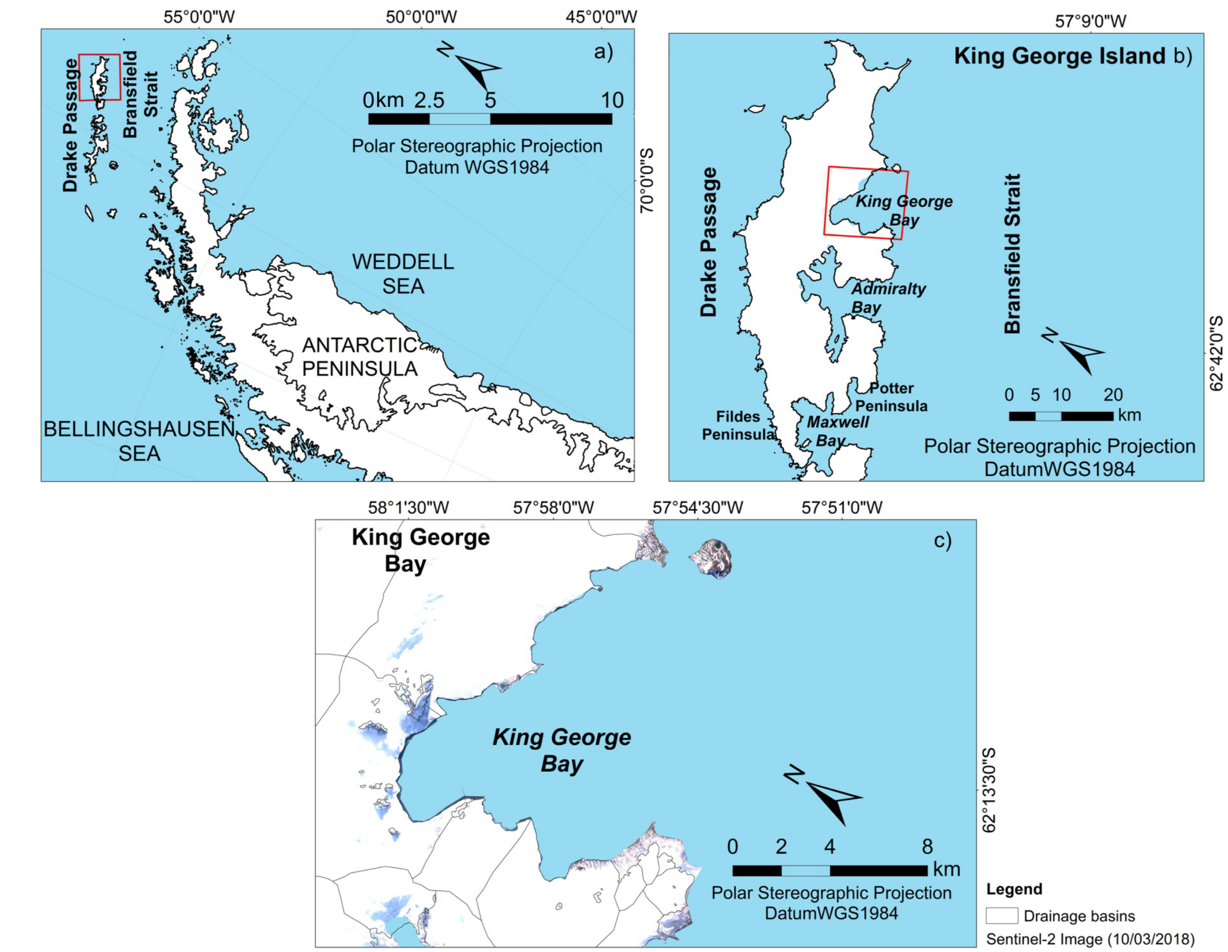

Figure 1. King George Bay is located in the south sector of King George Island. Quantarctica Database.

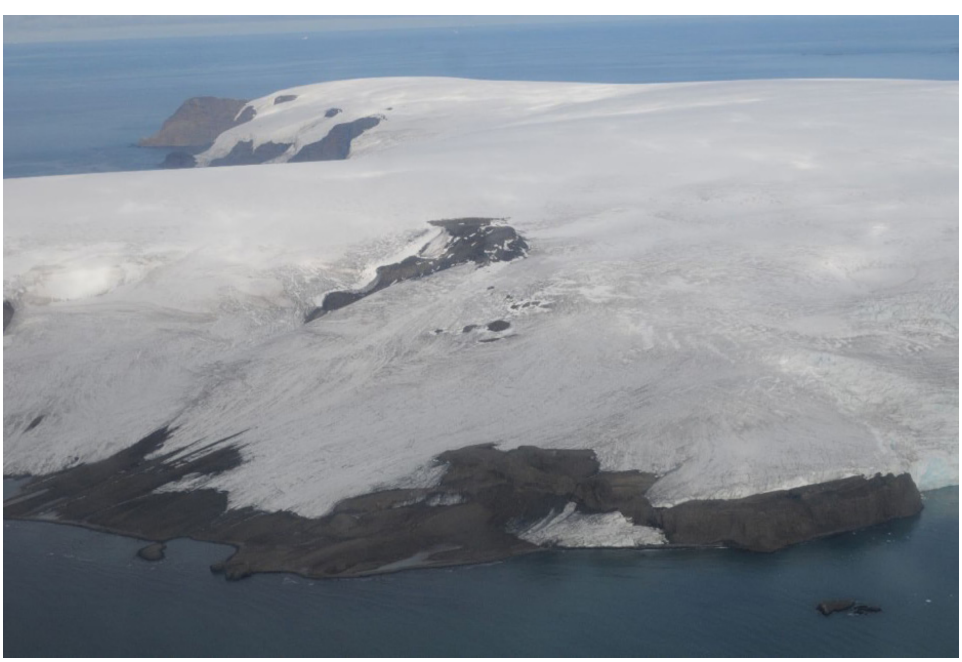

Figure 2. South Ana Glacier and their northern proglacial area, summer of 2019/2020.

Data and Methods

The data included satellite images, a digital elevation model (Table I), drainage dividers from Global Land Ice Measurements from Space, and coastline and bathymetry from Quantarctica (Gerrish et al. 2020).

The images of Planet Scope orbital sensors were obtained aboard CubeSat 3U nanosatellites and 3 m of spatial resolution. The generated data have processing level 3B and atmospheric correction by the radiative transfer model 6S. The 4, 5, and 3 bands of the Planet Scope images were also considered for this study.

Band 2 (blue ~490 nm), band 3 (green ~560 nm), band 4 (red ~665 nm), band 8 (NIR - Near Infrared ~842 nm), and band 11 (SWIR - Far Infrared Short Wave ~1610 nm) from the Sentinel-2B images were analyzed. Band 1 (blue 0.45 - 0.52 μm), band 2 (green 0.50 - 0.60 μm), band 3 (red 0.63 - 069 μm), band 4 (NIR - Near Infrared 0.76 - 0.90 μm) and band 5 (Infrared 1.55 - 1.75 μm) from the Landsat 4 TM sensor were used. Band compositions 321 and 432 were applied from SPOT imagery.

The images were co-registered with the Sentinel-2B images with an error of less than 1 pixel. The error in the co-registration of images of ±1 pixel is admissible, this value already being found by other authors (Nie et al. 2013, Li et al. 2020). In validating the mappings, the NDSI (Normalized Difference Snow Index) and the NDWI (Normalized Difference Water Index) indices were used (Hillebrand et al. 2018) after applying the atmospheric correction (Congedo 2016). Glacier length and area measurements were carried out for the years 1988/1989, 1995, 2000, 2005, 2016, 2019, 2020, and 2022 with the visual delimitation of satellite images. The uncertainty measurement of the glacier area and the linear uncertainty measurement of the glacier terminus were obtained according to Li et al. (2015). In the end, the shrinkage rate (in km/year) by period was obtained.

The ERA5 solutions on a 0.5 degree resolution grid are used in the present study to analyze

Table I. Satellite images and digital elevation model data.

Imagery/Sensor	Data	Bands	Spatial Resolution	Source
SPOT/MSM	02/1989	3,2,1	20m	Centro Polar e Climático
Landsat 4 TM	02/2020	3,2,1	30m	https://earthexplorer.usgs.gov/
SPOT/MSM	02/1995	3,2,1	20m	Centro Polar e Climático
ASTER	02/2005	3,2,1	20m	https://earthexplorer.usgs.gov/
SPOT/MSM	02/2000	3,2,1	20m	Centro Polar e Climático
Sentinel-2A	02/2016 and 11/2016		10m and 20m	https://earthexplorer.usgs.gov/
Sentinel-2B	03/2018	2,3,4,8/11	10m and 20m	https://scihub.copernicus.eu/dhus/#/home
Sentinel-2B	01/2020	2,3,4,8/11	10m and 20m	https://scihub.copernicus.eu/dhus/#/home
Sentinel-2B	01/2022	2,3,4,8/11	10m and 20m	https://scihub.copernicus.eu/dhus/#/home
Landsat 8 OLI	02/2020	7,5,3	30m	https://earthexplorer.usgs.gov/
Planet Scope Orthoscene	12/2019 and 02/2020	4 RGB+NIR	3m	https://www.planet.com/
Sentinel-1 IW HH	03/2020	C	5x20m	https://scihub.copernicus.eu/dhus/#/home
TanDEM-X	2016 (various dates)	X	12m	https://doi.pangaea.de/10.1594/PANGAEA.863567
Bathymetry	various dates	-	-	Quantarctica (Gerrish et al. 2020)

the trends and anomalies in atmospheric temperature (Hersbach et al, 2020). The 1980-1989, 1990-1999, 2000-2009, 2010-2019 anomaly plots were concerning the 1950-2019 average for atmospheric temperature.

The band composition 432, enhancement operations, and histogram manipulation was applied to Planet Scope images to glacial relief features visualization. The distinction between drumlins and flutings was carried out using the methodology of Kreczmer et al. (2021), which considers the morphological characteristics (length of the central axis and width of the relief feature) identified in high spatial resolution satellite images.

The last maximum ice margin extent in the LIA was interpreted based on Hall (2007). The hypsometry and bathymetry information was interpreted using the digital elevation and digital bathymetric model. Hall (2007) identified the most prominent morainic features formed during the LIA glacial margin stabilization. The topographic point in ice-free land area is identified to map lateral topographic pinning points in the bay.

RESULTS

Length glacier fluctuations

King George Bay showed one glacier characterized by land-terminating or terrestrially. In 1988, the glacier was marine terminating. Since 1995, the shrinkage was 0.74 km in the North Sector of ice flow and 0.44 km in South Sector. The retreat rate was 0.43 km/year and 0.25 km/year, respectively, between 1995 and 2022. During the 1988 - 1995 period, the retreat rate was 0.23 km/year and 0.28 km/year, respectively (equivalent to a shrinkage of 0.16 km and 0.20 km between 1988 and 1995) (Table II, and Figures 3 and 4).

Table II. Information about the glaciers.

Glacier	North Ana	Central Ana	South Ana Water-terminating ice flow and *land-ice flow
Mean Maximum Elevation (m)	703	354	431
Mean Minimum Elevation (m)	0	0	0-89
Mean Slope (%)	8	12	13
Total Area (2022) (km²)	33.17±0,03	10.10±0,01	20.40±0,02
Area (km²) LIG	54.91	12.59	25.79
Length (km) 1988	7.33	4.33	4.31-3.91*
Length (km) 1995	6.96	4.17	4.15-3.71*
Length (km) 2000	6.33	4.03	3.94-3.63*
Length (km) 2022	3.69	3.48	3.40-3.37*
Retreat (km) 1988-2022	3.65±0,15	0.85±0,05	0.9-0.36*±0,05
Retreat (km) 1988-1995	0.38±0,05	0.16±0,05	0.16-0.20*±0,05
Retreat (km) 1995-2000	0.63±0,03	0.14±0,03	0.20-0.08*±0,03
Retreat (km) 2000-2005	0.76±0,03	0.23±0,03	0.19-0.08*±0,03
Retreat (km) 2005-2016	1.48±0,01	0.18±0,01	0.18-0.15*±0,01
Retreat (km) 2016-2019	0.37±0,01	0.01±0,01	0.0-0.0*±0,01
Retreat (km) 2019-2022	0.21±0,01	0.06±0,01	0.08-0.07*±0,01
Outline Minimum Elevation Variation (m)	0	0	0-89*

The lengths of the ice-calving glaciers North Ana, Central Ana, and South Ana (only northward ice flow) were 7.3 km, 4.3 km, and 4.3 km in the 1988, respectively. The glacier lengths reduced to 3.7 km, 3.4 km, and 3.4 km in length in 2022, respectively, giving a glacial shrinkage of 3.64 km, 0.85 km, and 0.90 km, respectively (Figures 3, 4, and Table II).

The annual retreat rate of marine-terminating glaciers with iceberg calving along their ice fronts during the analyzed period was high. The temperature anomalies are observed in 1980, 1990, 2000, and 2010 decade's period considering the 1950-2019 period (Figure 4).

The melting of calving glaciers has been most significant since 1988, especially at the North Ana glacier front. The South Ana glacier had a higher variation during 1988-1995 (when it was characterized as a tidewater glacier). The retreat rate has decreased since the 2000 record due to its transition from being a water-terminating (tidewater) to the land-terminating glacier.

Area variation of the North Ana Glacier and Central Ana Glacier

The North Ana Glacier lost 31.02% (about 14.91 km²) of its area (total 54.91 km² in 1988) since 1988 (Figure 5) (glacier area loss of 21.74 km² between LIA and in the 2022). Currently, the glacier covers an area of 33.17 km². The North Ana Glacier lost 14.02% (approximately 6.74 km²) of its area between 1988 and 2005 and 17% (about 8.17 km²) between 2005 and 2022. This glacier had higher area loss in all periods and had a topographic influence in frontal stabilization positions (Figures 5 and 6).

The Central Ana Glacier lost 11.76% (approximately 1.34 km²) of its area (total 11.45 km² in 1988) since 1988. The frontal position of the glacier in 1988 or 1960/1970 decade is evidenced by a morainic bank. Currently, this glacier covers an area of 10.10 km². The North Ana and Central Ana glaciers lost 12% and 9% of the area between the LIA and the year 1988.

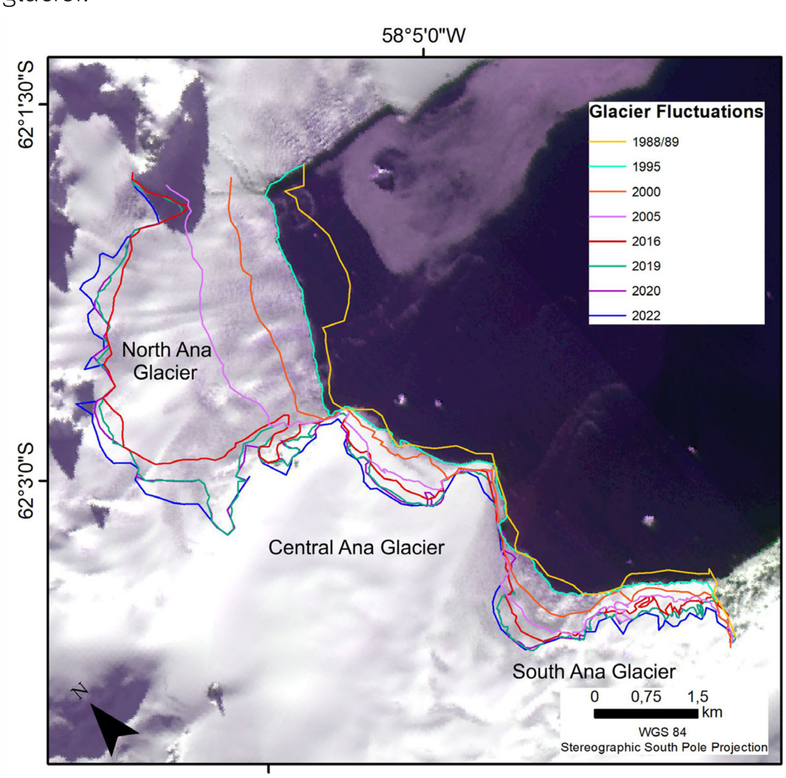

Figure 3. Glacier fluctuations since 1988. SPOT Imagery, 1995.

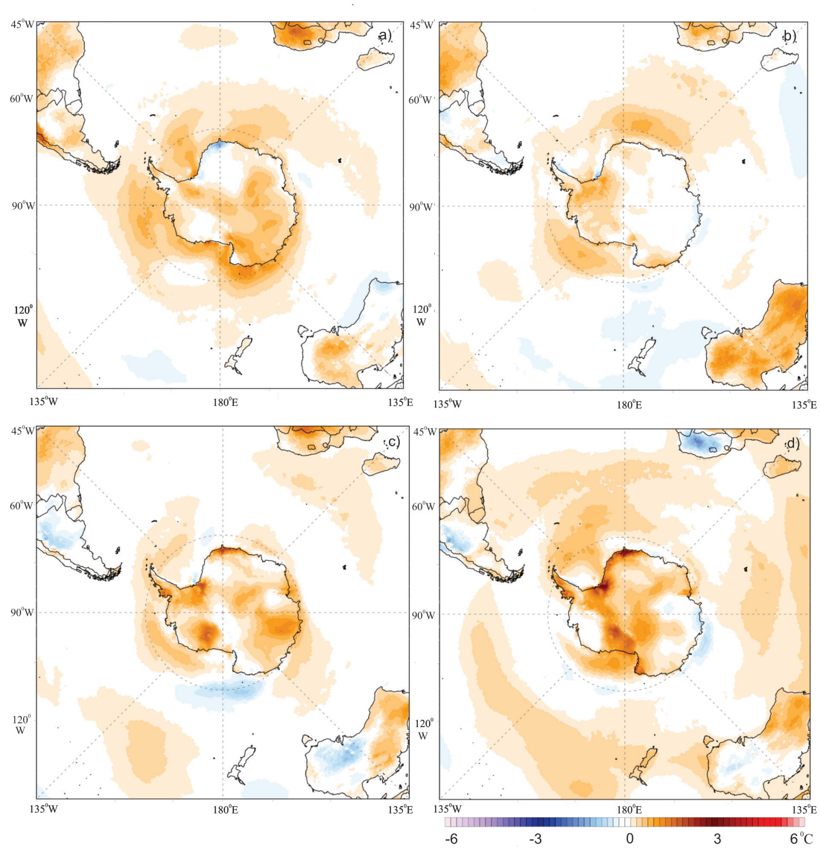

Figure 4. Air temperature (2m) anomaly by decade in 1980-2019 period. (a) Annual 1980-1990 (1950-2019), (b) Annual 1990-2000 (1950-2019), (c) Annual 2000-2010 (1950-2019), (d) Annual 2010-2019 (1950-2019). Database: ECMWF ERA5 (0.5 x 0.5 grid) and Climate Reanalyzer.org.

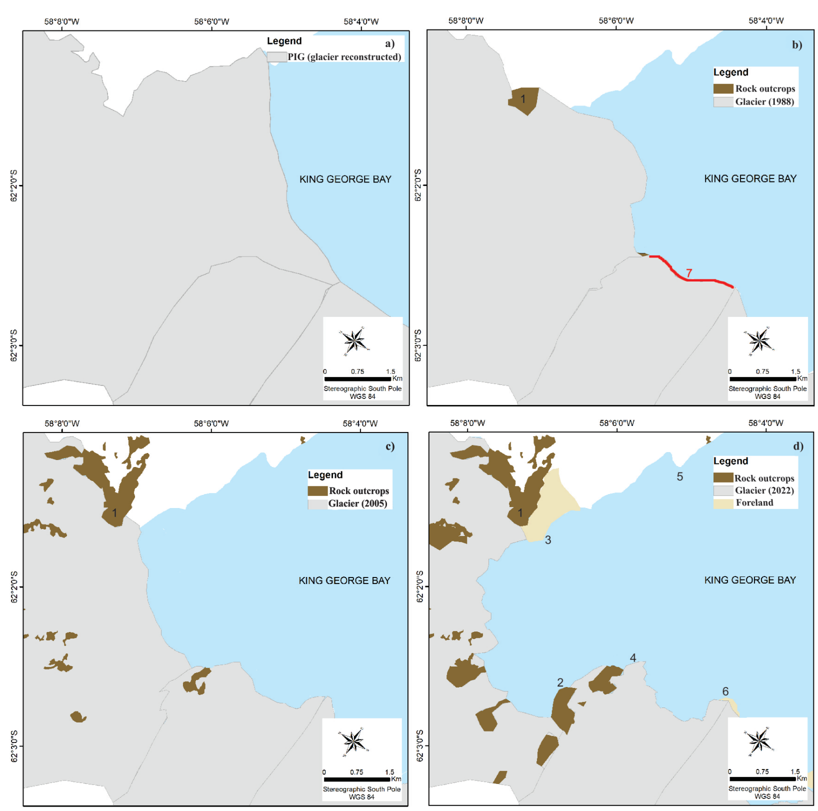

Figure 5. Evolutionary scenarios of glacier extension in the headwaters sector of the bay/fjord show the extension of North Ana and Central Ana glaciers (ice-calving) in: (a) Little Ice Age, (b) 1988, (c) 2005, and (d) 2022. The numbers showed positions of the topographic pinning points (1 - 6) and in subaerial sectors a morainic bank (7). The new nunataks (rock outcrops) could be observed between scenes.

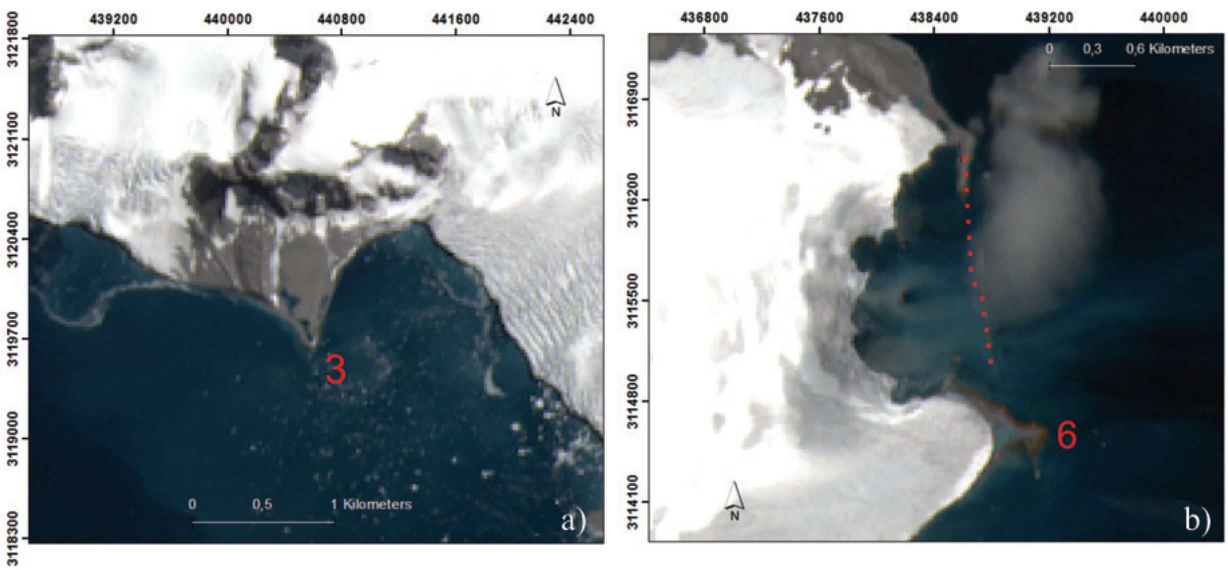

Figure 6. Topographic pinning points. (a) Topographic ridge number 3 in Figure 5 d. (b) Morainic bank (number 7 in figure 5b) exposed after the 1980sand topographic ridge number 6 in figure 5d.

Area variation of the South Ana Glacier

The South Ana Glacier lost 11.9% (2.74 km²) of the total area in 34 years (since 1988/89). The glacier changed from tidewater (marine) to the land-terminating since 1989-1995 (Figures 7 and 8). This glacier had a 10% area loss in LIA-1988.

A new land glacial system exhibits a proglacial area characterized by a flattening surface. In 2016, four coastal lakes connected to the glacier via meltwater channels. The glacial lake expansions (4 new lakes/lagoons) were identified in the proglacial area in response to glacial retreat since 2016.

More extensive moraines are identified in the distal sectors of the current margin and differ from recessional moraines in the proximal sector. On the greatest extent of the flat proglacial area, it is possible to observe linear parallel features arranged in the same direction as the glacier flow. The linear features are more than 5 m long and have a high degree of elongation (greater than 7 m) typical of flutings (Figure 9).

DISCUSSION

The proglacial environment

The progressive retreat of the glaciers increased ice-free land areas (1 km² since 1988 to South Ana Glacier). Special attention has recently been paid to the lagoon forming at the front of the retreating South Ana Glacier during the last 20 years.

When comparing the environmental fluctuations of this glacier with Windy Glacier, a tidewater glacier in KGI, we can verify similarities such as the appearance of a subaerial proglacial area in the same period. The new ice-free land areas exhibit final moraines, lagoons and lakes dammed by a moraine, as evidenced by the proglacial environment of the South Ana Glacier. In the proglacial environment of Windy Glacier, in Admiralty Bay, Kreczmer et al. (2021) identified recessional and push moraines and their landforms exposed beyond the 1979 glacial limit and probably formed between 1950 and 1977. The proglacial area of the South Ana Glacier has recessional moraines formed and exposed during the same period.

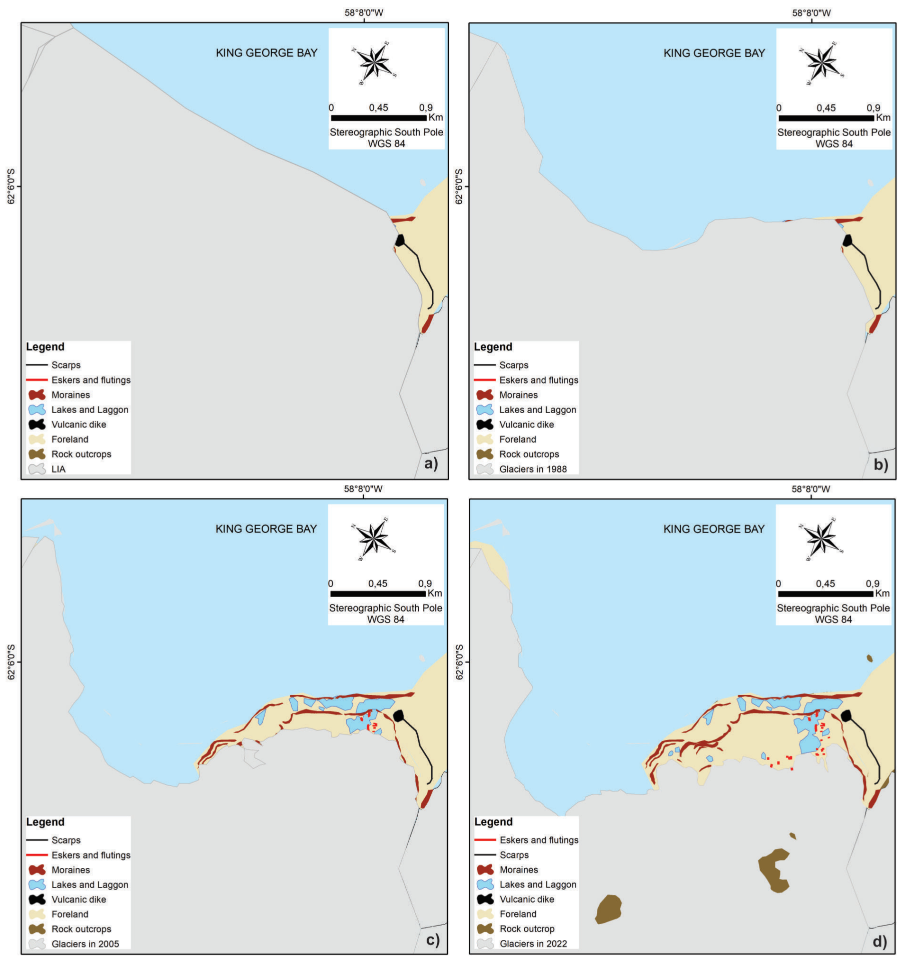

Figure 7. **Evolutionary scenarios of the western part of the bay/fjord for the South Ana glacier. (a) Ice-calving glaciers extent in the Little Ice Age; (b) Ice-calving glaciers extent for the 1988 year; (c) South Ana Glacier's behavior is impacted by the loss of marine influence. The central-northern sector of the Ana Glacier is marine-terminating.**

The elongated features parallel to the direction of glacial flow have been interpreted as eskers or flutings and make up the sectors proximal to the ice margin (Figure 6). Small drumlins have not been identified by Planet Scope imagery, but the presence of flutings evidences the humid thermo-basal regime and movement by basal sliding and internal ice deformation (Fountain 2011). The highest surface velocities are obtained at Ana Glacier by Osmanoğlu et al. (2013). Compared to the proglacial environment of Windy Glacier of Kreczmer et al. (2021), the flutings are only evidenced in the high spatial resolution image. For Windy Glacier also has uncertainties regarding these features (Kreczmer et al. 2021).

Results of the emergence and increase in proglacial lakes are by previous studies (Rosa et al. 2021, Oliveira 2020, Petsch et al. 2022). The study area is located on the south coast of KGI, and Oliveira (2020) points out that the most significant changes occurred in ice-free land areas facing the south coast of the Shetland Islands. According to Ding et al. (2021), changes in glacial environments can destabilise of this system and fast floods in summer due to the rupture of glacial lakes. The environmental changes in the study area are linked to glacial and hydrogeomorphic processes.

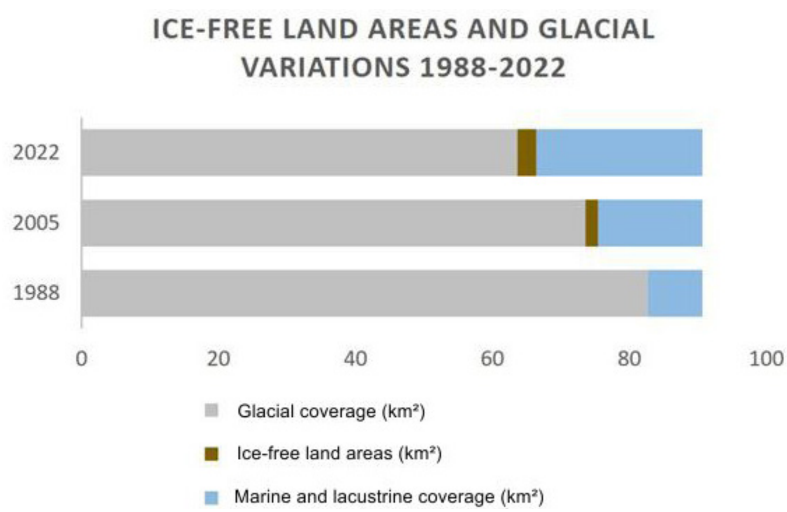

Figure 8. Variations in the glacial coverage (gray) and new ice-free land areas (proglacial - brown, and glacimarine - blue) for the 1988 - 2022 period in South Ana Glacier basins.

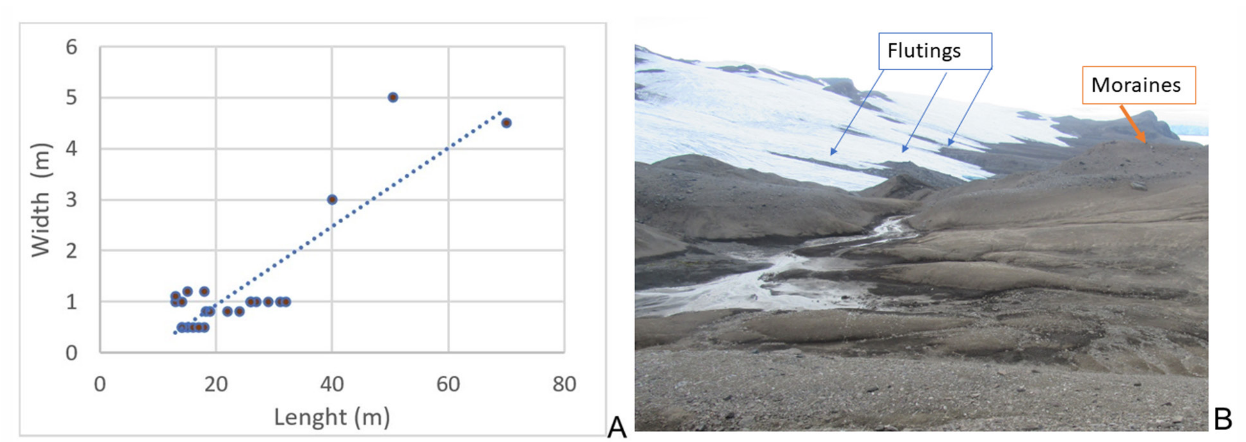

Figure 9. Glacial landforms characteristics. a) The graph illustrates the flutings landforms characteristics (differences in length and width in the b-axis) interpreted as flutings and eskers; b) Glaciofluvial landforms, as flutings and moraines (fieldwork data: 03.02.2022).

Frontal ablation pattern

Regarding the differences in area loss for the glaciers and their different types of termini, it is observed that the change in terminus configuration from marine to land- termination in recent decades (e.g. South Glacier) resulted in a decelerated area loss.

Considering the loss area and the total area of the glaciers, the marine-termination glaciers present the most significant shrinkage since 1988. North Ana Glacier belongs to the Eastern Icefield, which is evidenced by Lorenz (2021) as the one with the most significant loss of area on the island between 1988/89-2020. North Ana Glacier is located at the head of the fjord, on the Ezcurra Fault (EF), according to Birkenmajer (2003), and at greater depth in the marine sector next to the glacial margin.

The retreat of North Ana Glacier reflects a combination of factors. In general, the trend of increasing ocean temperatures influences these glaciers' mass loss (Rignot & Steffen 2008). The floating frontal ablation may respond to a decrease in sea-ice duration in the region. In general, the loss of ice can reduce resistance to ice flow from up glacier, leading to increased discharge and negative mass balance over the years (Bondzio et al. 2016). This ice-ocean linkage is also evidenced in glaciers in SW and SE Greenland. For example, the rapid retreat of Kangerdlugssuaq Glacier coincided with increased ocean heat available for melting at the ice front (Cowton et al. 2016). Winter sea-ice and annual sea-ice duration in the region are shortening (Smith et al. 2008, Plum et al. 2020, Hillebrand et al. 2021). Climate change in recent decades has triggered a reduction in sea ice (e.g. Smith et al. 2008, Plum et al. 2020, Hillebrand et al. 2021) and a negative mass balance in the KGI (Michalchuk et al. 2009).

Basal topographic pinning points control the ice calving rates. Some narrow sections of a fjord are identified and could be related to the terminus positions of North Ana Glacier in LIA, 1988, and 2005, and of Central Ana Glacier in LIA and 1988. The Central Ana Glacier front was located in a pinning point in the 1980s. Its terminus in a shallow marine context is evidenced by a morainic bank (Figure 6). The pinning points play an important role by influencing the mechanical stability of ice fronts and may allow glaciers to maintain a stable terminus position for years or decades (Benn et al. 2017). The detachment from these points may initiate a rapid retreat, as specially identified for North Ana Glacier since 1995.

The North Ana Glacier groundline is located in a deeper marine sector and has had the highest shrinkage since 1988 compared to others. Its frontal margin suffers greater basal and lateral friction, influencing its ice-calving rates. Deeper marine conditions influence the response of glaciers to marine dynamics, the glaciers should have a higher retreat rate than others with their terminus in shallow marine context (Braun & Goßmann 2002, Hill et al. 2018). Thus, the frontal ablation of this glacier could be an essential component of the mass balance of the Eastern Part of Warszawa Icefield in the KGI. Monitoring North Ana Glacier is relevant to ongoing changes in the KGI.

The new nunataks in recent satellite images indicate that the retreat is concomitant to the decrease in their ice thickness, as also identified by Pudełko et al. (2018) for glaciers flowing into Admiralty Bay. The thickness of ice fronts also influences the response of glaciers to marine dynamics (Osmanoğlu et al. 2013).

Bellingshausen Station also has the highest temperature in the four seasons, which can be attributed to its northerly location, lack of sea ice around the island, and its exposure to relatively warm northwesterly winds. The warming trend in the Bellingshausen Station was +0.17 ± 0.15 °C from 1969 – 2018 (Turner et al. 2019). One factor that influences high temperatures in the AP is the positive phase of the SAM (Southern Annular Mode) and its relation with Föhn winds that occur during intense westerly wind events (Marshall & Thompson 2016).

Comparing the last decades to the 1700 and 1988 period, it appears that the response of tidewater glaciers as a function of regional warming recorded since the last century and that these changes in glaciers were more significant than the retreat since the LIA. Temperature records from ice cores from Antarctica's Domo C and Domo Law suggest a cooling condition between 1200 and 1800 (Benoist et al. 1982) followed by gradual warming to the present time (Morgan 1985). The atmospheric warming trend observed since the middle of the 20th century is unprecedented when analyzing the last 2000 years. It has resulted in the most significant changes in the frontal position of glaciers.

CONCLUSION

Glacier mapping indicated the last position of the most significant fronts corresponding to LIA (1700 or 1800 until 1988). The area loss (mainly North Ana Glacier) is higher during the 1988-2022 period (31%) when compared to the LIA-1988 period (12%). The delimitation of the positioning of the glacier before 1988 considered the location of landforms as subaerial pinning points of the glacial margin and was considered satisfactory and relevant to scale the extent of the glacier in the past. The percentage loss of glacier area in King George Bay since the 1980s has been observed in response to atmospheric warming trends and temperature anomalies in the region. The Ana Northern Ana Glacier (a floating glacier and marine-terminating glacier) has the highest retreat value in response to higher depth in ice-margin.

The glaciers are retreating in this Antarctic Maritime region. The ice-free land areas and their lakes have been expanded in response to glacial-hydrogeomorphic processes and climate change. South Ana Glacier changed from a tidewater glacier to land-terminating in recent decades, and an outline minimum elevation variation of 89 meters.

In each phase of changes in the frontal position of the glacier that became terrestrial, records of the formation of different deposits and landforms have been identified. Comparing the stages of the glaciers and the formation of a proglacial environment adjacent to South Ana Glacier, it is verified that there was no evidence of Stage I advance moraines related to the moment of the LIA in the subaerial sectors, which must be in the form of morainic banks. Stage II of glacier evolution began in 1988/89 and features one of the glaciers with a subaerial proglacial environment. The geomorphology of the area is dominated by glacial depositional landforms, flutings, fresh and old moraine ridges, ice-dammed lakes, and marine landforms (recent beaches).

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