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Detailed quantification of glacier elevation and mass changes in South Georgia

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Abstract

Most glaciers in South America and on the Antarctic Peninsula are retreating and thinning. They are considered strong contributors to global sea level rise. However, there is a lack of glacier mass balance studies in other areas of the Southern Hemisphere, such as the surrounding Antarctic Islands. Here, we present a detailed quantification of the 21st century glacier elevation and mass changes for the entire South Georgia Island using bi-static synthetic aperture radar interferometry between 2000 and 2013. The results suggest a significant mass loss since the beginning of the present century. We calculate an average glacier mass balance of $-1.04 \pm 0.09$ m w.e.a$^{-1}$ and a mass loss rate of $2.28 \pm 0.19$ Gt a$^{-1}$ (2000–2013), contributing $0.006 \pm 0.001$ mm a$^{-1}$ to sea-level rise. Additionally, we calculate a subaqueous mass loss of $0.77 \pm 0.04$ Gt a$^{-1}$ (2003–2016), with an area change at the marine and lake-terminating glacier fronts of $-6.58 \pm 0.33$ km$^2$ a$^{-1}$, corresponding to $\sim$4% of the total glacier area. Overall, we observe negative mass balance rates in South Georgia, with the highest thinning and retreat rates at the large outlet glaciers located at the north-east coast. Although the spaceborne remote sensing dataset analysed in this research is a key contribution to better understanding of the glacier changes in South Georgia, more detailed field measurements, glacier dynamics studies or further long-term analysis with high-resolution regional climate models are required to precisely identify the forcing factors.

1. Introduction

Glaciers on Earth are important components of the climate system. Their changes are indicators of climate change and they contribute to global sea level rise (e.g. Forsberg et al 2017, Rignot et al 2019, Wouters et al 2019). However, in many areas of the Southern Hemisphere there is a lack of large-scale glacier change observations, especially in remote regions.

The largest ice-covered areas of the Southern Hemisphere are located in Antarctica, Patagonia, and across the surrounding islands of Antarctica. While there are several studies reporting glacier mass changes of the Antarctic ice sheet (e.g. Shepherd et al 2018, Rignot et al 2019), the Antarctic Peninsula (Rott et al 2014, Rott et al 2018) and Patagonia (e.g. Malz et al 2018, Braun et al 2019), less is known about the glaciers located on the sub-Antarctic islands and the potential impacts of atmospheric warming on their retreat during the 20th and 21st centuries.

South Georgia is the largest sub-Antarctic island ($\sim$3900 km$^2$) (figure 1). About 63% of the island’s surface is covered by glaciers. The island is dominated by its narrow southeast-northwest orientated mountain ranges with several peaks over 2000 m in elevation.
(e.g. Mount Paget, Mount Patterson), which form a physical orographic barrier. South Georgia has a maritime climate which is dominated by its proximity to the Antarctic Polar Front and the strong westerly winds (and associated moisture flux) that strike the island (Graham et al. 2017). On the north-east coast, the annual mean temperature and precipitation are 2.0 °C and 1590 mm, respectively (Bannister and King 2019), with strong winds (in excess of 30 ms\(^{-1}\)) reported at King Edward Point Research Station. Long-term observations show a trend of increasing temperatures at South Georgia (Thomas et al. 2018), akin to temperature increases at similar latitudes (Rasmussen et al. 2007 at Southern Patagonia Icefield; Berthier et al. 2009 at Kerguelen Island). Combined with the increase in regional temperatures, previous studies (Gordon et al. 2008, Cook et al. 2010) have also shown heterogeneous glacier retreat through the 20th century, with the greatest glacier retreat observed along the north-east coast of South Georgia, while glaciers on the south-west coast have retreated more slowly.

A previous estimate of glacier retreat on South Georgia was presented by Gordon et al. (2008) and later updated by Cook et al. (2010). Larger outlet glaciers showed relatively stable frontal positions during the last century, but with a greater rate of retreat after the 1980s (Gordon et al. 2008). The average glacier retreat rates increased from 8 m a\(^{-1}\) in the 1950s to 35 m a\(^{-1}\) at the beginning of the 21st century (Cook et al. 2010). These studies provide a view of the glacier retreat based on satellite images; however, a detailed quantification of the glacier elevation and mass change is still missing.

In this study, we present a detailed quantification and interpretation of glacier mass balances of the entire area of South Georgia between 2000–2013. We measure geodetic mass balances by differencing surface heights. The geodetic approach does not resolve seasonal variations but has been widely used to estimate long-term glacier mass balances, especially in remote regions (e.g. Malz et al. 2018, Braun et al. 2019) where meteorological and logistical conditions limit continuous glacier monitoring, such as at South Georgia. Therefore, we derive surface elevation change rates using interferometric synthetic aperture radar (InSAR) resulting in the calculation of island-wide glacier mass balances.

Additionally, we calculate the subaqueous mass loss using previous ice thickness estimations and the area changes at the glacier front section by comparing the glacier frontal lines derived from the Randolph Glacier Inventory (RGI V6) from 2003 to those derived from a Landsat image from 2016. Finally, we calculate the elevation changes using two repeat GNSS measurements in the Szielasko Glacier between 2012 and 2017, which we use for comparison.

2. Data and methods

2.1. TanDEM-X and SRTM

The surface elevation changes are computed from the difference between the digital elevation

![Figure 1.](image-url)
models (DEM) from Shuttle Radar Topography Mission (SRTM) and the TerraSAR-X add-on for Digital Elevation Measurement mission—TanDEM-X (TDX). The SRTM DEM is provided by the National Aeronautics and Space Administration (NASA) (Farr et al 2007) and TDX program is operated by the German Aerospace Center (DLR) and Airbus Defence and Space (Krieger et al 2007). To obtain the TDX DEM we use the SRTM DEM void-filled LP DAAC NASA Version 3 with 1 arcsec ground resolution (30 m). We process TDX DEM and calculate glacier elevation changes following the workflow by Braun et al (2019), which consists of: (1) Selection of the TDX scenes from the same season (Feb–Apr 2013) as the SRTM mission, in order to minimise the effects of radar penetration into snow and firm (table S1 is available online at stacks.iop.org/ERL/15/034036/mmedia). (2) The TDX scenes are processed using the differential SAR interferometry approach, whereas the SRTM DEM, vertically referenced to the Earth Gravitational Model (EMG96), is used as a reference (e.g. Seehaus et al 2015). (3) We filter the created interferograms and apply the minimum cost flow and branch cut algorithms during phase unwrapping (Costantini 1998, Goldstein and Werner 1998). For each TDX scene the better phase unwrapping product is selected manually and converted to differential heights. (4) Finally, the reference DEM heights are added and the resulting new TDX–X DEM is geocoded (figure S1).

Once the new TDX DEM is created, we vertically and horizontally co-register on stable ground with the SRTM DEM as a reference, using the universal co-registration approach (Nuth and Kääb 2011). Stable points are selected in areas outside glaciers (RGI V6) with less than 15° surface slope (using SRTM DEM, neglecting interpolated areas). Each TDX DEM is co-registered to the SRTM elevations using an iterative approach (Braun et al 2019). Finally, a large TDX DEM mosaic is created. The remaining elevation differences on ice-free areas after the post-processing are shown in figure S2.

In order to fill the gaps in our glacier elevation change measurements, which are due to voids in the SRTM DEM (~10% without coverage) and smaller regions affected by layover and shadow in the TDX scenes (~3% without coverage), we apply an elevation change versus altitude function by calculating the mean elevation change within 100 m height bins across the entire glacier area. To avoid artificial biases introduced by outliers we do not include steep slopes (>50°) (Neelmeijer et al 2017) and filter each elevation band by applying a quantile filter (1%–99%). The void-filled SRTM DEM is used as a height reference for the elevation bins. Details of the processing and calculation of TDX DEM are presented in Seehaus et al (2015), Braun et al (2019), and Farias-Barahona et al (2019).

Finally, we convert the elevation change measurements to mass budgets according to Cogley et al (2011). Our geodetic mass balance rates are based on two density scenarios. Scenario 1 assumes a density of 850 ± 60 kg m⁻³ (Huss 2013) and for scenario 2, a density of 900 ± 60 kg m⁻³ is used.

2.2. Uncertainties and error analysis for glacier mass balance

Details of the error analysis method employed in this study are presented in Braun et al (2019), which we briefly summarise here. For the uncertainty (dM) of our geodetic mass balances (M), we consider errors and uncertainties from the following contributions (equation (1)):

\[ dM = \left( \frac{M}{\Delta t} \right)^2 \left( \frac{\delta_{\text{h}}/\Delta t}{\Delta h/\Delta t} \right)^2 + \left( \frac{\delta_{\text{t}}}{A} \right)^2 + \left( \frac{\delta_{\rho}}{\rho} \right)^2 + \left( \frac{V_{\text{rem}}}{\rho} \right)^2 \]

\[ \delta_{\text{h}}/\Delta t \] corresponds to DEM differentiating (including spatial autocorrelation, hypsometric gap filling), \( \delta_{\text{t}} \) corresponds to errors in the glacier outlines, and \( \delta_{\rho} \) corresponds to uncertainties from volume to mass conversion with a mean density, radar signal surface penetration. To derive \( \delta_{\text{h}}/\Delta t \) we use equation (2) (Rolstad et al 2009):

\[ \delta_{\text{h}}/\Delta t = \frac{S_c}{5S_r} \sigma_{\text{h}}/\Delta t \text{AW} \]

To obtain \( \delta_{\text{h}}/\Delta t \) we aggregate all ice-free cells within 5° slope bins and apply a 2%–98% quantile filter in each slope bin to remove outliers. Eventually, we calculate the slope based area weighted standard deviations to obtain \( \sigma_{\text{h}}/\Delta t \text{AW} \). \( S_r \) corresponds to the glacier area and \( S_c \) is the spatial autocorrelation, which is displayed in equation (3).

\[ S_c = d_c^2 \ast \pi \]

(3) \( S_c \) is calculated using a semivariogram of the elevation change values on stable ground where we obtain a mean lag distance (\( d_c \)) of 340 m.

To obtain the error of the glacier outlines \( \delta_{\text{t}} \) for the glacier mass balance we use a scaling approach of the area-to-perimeter ratio (\( R_{\text{P/A}} \)) (Malz et al 2018, Braun et al 2019) which is based on a 3% error estimation from previous studies, and compare it to the area-to-perimeter ratio \( R_{\text{P/A2}} \) of Paul et al (2013), equation (4).

\[ \delta_{\text{t}} = \frac{R_{\text{P/A}}}{R_{\text{P/A2}}} \ast 0.03 \]

Studies in South Georgia are sparse and no SRTM X-band is available for comparison to SRTM C-band in order to estimate potential effects of X- and C-band radar penetration differences. The error signal penetration depends on the properties of the surface conditions. If the conditions of the glacier surface
contain water, the signal penetration can be neglected (e.g. Abdel Jaber et al. 2019). We follow a previous procedure to account for this uncertainty (e.g. Malz et al. 2018).

We calculate the potential volume bias due to surface penetration ($V_{pen}$) by integrating the altitude dependent penetration bias over the glacier area above the Equilibrium Line Altitude (ELA) (Braun et al. 2019). We assume a linear increase of signal penetration above the ELA, ranging from 0 m at the ELA to 5 m at the maximum elevations of South Georgia. Differences in surface penetration below the ELA are assumed to be negligible (Malz et al. 2018, Braun et al. 2019). From our rough inspection of the snowlines altitude (proxy of ELA) from optical imagery from February 2003, we observe a wide range from ~320 to ~600 m.a.s.l. Hence, for our error estimation we use an approximate ELA of 320 m a.s.l for South Georgia. We consider this the upper limit of the radar penetration error, since both acquisitions were during summer months with melt conditions most likely present as e.g. confirmed in Patagonia (Abdel Jaber et al. 2019).

2.3. Subaqueous mass loss estimation

The subaqueous melt and calving are important components in the total glacier mass balance, although the mass loss below sea level does not contribute to sea level change. In order to calculate a rough estimation of the subaqueous mass loss, we determine the area trend at the glacier front of marine and lake-terminating glaciers assuming a linear trend of the glacier front. The area changes of the glacier fronts are obtained from the Randolph Glacier Inventory (RGI V.6, 2003), which was created from Landsat image from the 7th of February 2003 and a Landsat image from the 19th of February 2016 (table S2). First, the 2016 Landsat was registered to the 2003 Landsat image and glacier area changes were manually digitised using standard procedures such as a band composition image (e.g. Paul et al. 2013) (figure S3).

The ice thickness values of South Georgia are derived from the ensemble-based ice thickness estimation of Farinotti et al. (2019), which is based on the RGI V6. Using our area changes at the front of the glaciers, the mean ice thickness on those area retreat (Farinotti et al. 2019) (figure S4), combined with the subaerial elevation changes, we obtain an average ice thickness of 130 ± 40 m. The ice loss below sea or lake level is converted to volume-to-mass assuming a density of 900 ± 60 kg m$^{-3}$ (scenario 2) (e.g. Braun et al. 2019).

2.4. GNSS measurements

Two repeat GNSS (Global Navigation Satellite System) track observations of about 2 km long, are used to obtain the elevation changes of Szielasko Glacier between 2012 and 2017. The two GNSS measurements were carried out by the University of Maine USA (Mayewski et al. 2016), and Universidad de Magallanes, Chile. Mayewski et al. (2016) processed the 2012 track using GrafNav software with a low accuracy of ±4 m since the GNSS equipment was obtained by a single frequency GNSS receiver with C/A code calculated with the Falkland Islands station (FALK, located 1470 km west). The surface topography of the Szielasko Glacier from 2017 was obtained in kinematic mode using a Topcon dual frequency GNSS receiver model Hiper SR. The GNSS data was also post-processed using GrafNav software, version 8.4 using the same Falkland Island GNSS station as a reference. Despite the distance, we obtained a reliable resolution of ambiguities at double-difference of the carrier-phase observations. To calculate elevation changes we compare both periods, point by point, using an intersect of 10 m (figure 5(a)).

3. Results

Figure 2(a) shows the derived elevation change for the entire South Georgia between 2000 and 2013 with a DEM difference coverage of 90% of the total glacier area. Figure 2(b) displays the remaining elevation change differences on all ice-free areas compared to surface slope. The respective glacier areas within each slope bin are indicated as bars. For the majority of the analyse area the remaining differences are close to 0.

A mean glacier elevation change rate of $-1.16 \pm 0.01$ m a$^{-1}$ is found for the observation period. The specific mass balance is $-1.04 \pm 0.09$ m.w.e a$^{-1}$, which corresponds to a mass change of $-2.28 \pm 0.19$ Gt a$^{-1}$ according to density scenario 2. This does not include subaqueous mass loss of tidewater glaciers or mass lost by calving. In table 1, we provide the two density scenarios for volume-to-mass conversion applied.

The distribution of surface elevation changes versus mean glacier aspect is shown in figure 3(a) for individual glaciers. Overall, most of the glaciers show negative elevation change. We observe the highest thinning rates for glaciers with an easterly aspect, particularly on large outlet glaciers (figure 3(a)).

We calculate the largest thinning rates for glaciers located in the north-east of South Georgia, with a mean elevation change of $-1.76 \pm 0.01$ m a$^{-1}$, whilst in the south-west, we obtain a mean elevation change of $-0.69 \pm 0.01$ m a$^{-1}$, with further details provided in the supplementary figure S5.

We estimate a mass loss of $0.77 \pm 0.04$ Gt a$^{-1}$ from the subaqueous melt and calved-off ice between 2003 and 2016 (table 1). The subaqueous mass loss is derived from an area loss of marine and lake-terminating glaciers at the glacier fronts of $6.58 \pm 0.33$ km$^2$ a$^{-1}$ between 2003 and 2016, corresponding to ~4% of the total glacier area. Figure 3(b) displays the distribution of
glacier types from RGI glacier inventory with the area change at the glacier front. Marine-terminating glaciers represent about 85% of the total glacier area, at the same time they also yield the highest area changes at the glacier front. Land-terminating glaciers present an area change at the glacier front of ∼1% of the total glacier area (figure 3(b)). Figure 3(c) shows the average hypsometric distribution of elevation change rates throughout South Georgia where negative surface elevation change rates occur over all elevation ranges.

In terms of individual glacier, the highest thinning rates are observed at Neumayer, Risting, Ross and Hindle, Twitcher and Herz glaciers (figure 4). The largest, Neumayer Glacier, shows an area loss of 1.43 ± 0.07 km² a⁻¹ (2003–2016) and strongly negative elevation change rates of −5.38 ± 0.01 m a⁻¹ and important contribution to subaqueous mass loss. Risting, Twitcher and Herz glaciers show elevation change rates of −4.23 ± 0.01, −2.76 ± 0.01 and −2.64 ± 0.01 m a⁻¹, respectively. In addition, Ross-Hindle Glacier is currently separated into two tributaries, which occurred presumably between 2008 and 2009. The results show a high thinning rate of −2.99 ± 0.01 m a⁻¹ with an area loss of 0.88 ± 0.04 km² a⁻¹ between 2003 and 2016. Located in the south-west coast, the front of Brøgger Glacier remains stable with a low surface elevation change of −0.15 ± 0.01 m a⁻¹. A detailed comparison is supplemented in figure S6.

From the four advancing glaciers reported in previous studies, Novosilski, Harker and one unnamed glacier are currently experiencing a phase of retreat, while Fortuna Glacier remained stable between 2003 and 2016 (figure S7). Novosilski Glacier shows an area change at glacier front of −0.41 km² a⁻¹ (−171 m a⁻¹ frontal change) with a mean elevation change of −0.83 m a⁻¹. Harker Glacier shows an area change of −0.07 km² a⁻¹ (−82 m a⁻¹ frontal change) and a mean elevation change of −1.01 m a⁻¹ (figures S3 and S7).

For the small Szielasko Glacier, we calculate an elevation change rate of −1.57 ± 0.01 m a⁻¹ derived from SRTM and TDX DEMs (2000–2013) (figure 5(b)), which is close to the calculated −1.51 ± 0.80 m a⁻¹ (figure 5(c)) elevation change with GNSS tracks between the later period 2012 and 2017.

Table 1. Island-wide mass balance rates from 2000 to 2013 as well as subaqueous mass loss estimation from 2003 to 2016.

| Density scenario 1 (850 ± 60 kg m⁻³) | Density scenario 2 (900 ± 60 kg m⁻³) |
|-------------------------------------|-------------------------------------|
| Mass balance rate (m.w.e a⁻¹)       | −0.98 ± 0.08                        | −1.04 ± 0.09                      |
| Mass change rate (Gt a⁻¹)           | −2.15 ± 0.18                        | −2.28 ± 0.19                      |
| Subaqueous mass loss (Gt a⁻¹)       | —                                   | −0.77 ± 0.04                      |
4. Discussion

Our results provide new evidence to confirm previous observations about the recession of the glaciers in South Georgia (Gordon et al. 2008, Cook et al. 2010).

Unfortunately, there are no similar studies regarding elevation changes and mass changes to make direct comparison with South Georgia. Hence, our comparison is limited to a more regional aspect (figure 1(a)). Overall, our results are in the line with recent studies in the Southern Hemisphere (table S3 and S4). In comparison with previous studies of the Antarctic and sub-Antarctic macro region which include South Georgia, our results present higher mass change rates for sub-
Antarctic Islands in comparison with Gardner et al (2013). We estimate that our results represent 15% of the mass change rates presented recently by Zemp et al (2019) for the Antarctic and sub-Antarctic region between 2006 and 2016. However, they also obtained a large uncertainty for this region. Two recent continent-wide glacier mass balance estimations for the entire South American continent observed low glacier mass balance rates in Tierra del Fuego region, which is similar latitude to South Georgia. This region includes the Cordillera Darwin icefield (>2500 km² of glacier area) which shows a region mean glacier mass balance of −0.27 ± 0.03 m w.e.a⁻¹ (Braun et al 2019) and −0.48 ± 0.27 m w.e.a⁻¹ (Dussaillant et al 2019) in a similar study period. All these values present less negative mass balance in comparison with our results. A different situation is observed in the Northern (NPI) and Southern Patagonia Icefield (SPI) where significant mass losses have been reported in the last years (table S4) (Willis et al 2012a, 2012b, Malz et al 2018, Dussaillant et al 2018, Abdel Jaber et al 2019, Braun et al 2019, Dussaillant et al 2019). These icefields have been highlighted as the largest contributor to sea level rise in the Southern Andes macro region (Wouters et al 2019, Zemp et al 2019). Our specific mass balance values present similar rates in comparison with NPI and SPI (Malz et al 2018, Abdel Jaber et al 2019, Braun et al 2019, Dussaillant et al 2019). However, some glaciers of NPI and SPI are almost balanced or slightly gaining elevation at higher altitudes (Malz et al 2018, Dussaillant et al 2018, Abdel Jaber et al 2019, Dussaillant et al 2019). Our results show negative glacier mass balance in the largest glaciers of the north-east or south-west coast of South Georgia. Positive or neutral (balanced) values can be found at the highest altitudes. The differences between

Figure 4. Surface elevation change map of the 5 glaciers with the highest thinning rates. In Neumayer Glacier (t) denotes the separate tributary. At the present Ross and Hindle glaciers both are separated. Surrounding glaciers are show in white transparency to enhance the changes of main glaciers and area loss in blue.
all those areas and South Georgia may be attributed to the precipitation amounts (Schaefer et al 2015, Lanhgammer et al 2018, Bravo et al 2019).

Further south on King George Island, the Ecology Glacier (2000–2016) and Bellingshausen Dome Glacier (1997/98–2010) show similar elevation changes in a comparable period with our results (Rückamp et al 2011, Pełlicki et al 2017). East of South Georgia, on the Kerguelen Islands (49°S, 69°E), Berthier et al (2009) presented similar thinning rates in a prior study from 1963 to 2000.

When we compare the contribution from different types of glaciers to the glacier mass balance, marine-terminating glacier present nearly all of the total glacier mass balance, followed by a small proportion of the land-terminating and lake-terminating glaciers, respectively.

The noticeable differences that we observe in surface elevation changes between glaciers along of the north-east and the south-west coasts agree with previous front change estimations (Cook et al 2010). Our

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Figure 5. (a) Distribution of GNSS measurements of 2012 and 2017 over Szielsko Glacier. GNSS intersect legend denotes the compared GNSS points. (b) Elevation change map of Szielsko Glacier between 2000 (SRTM) and 2013 (TanDEM-X). (c) Elevation change difference (m a⁻¹) between GNSS measurements from 2012 and 2017. The location of profile A-B is shown in panel (a).
area changes at the glacier front and the subaqueous mass loss also show differences between both coasts. Comparing the total contribution from subaqueous melt which is $-0.77 \pm 0.04$ Gt a$^{-1}$ for entire region, almost 70% of the subaqueous mass loss are from glaciers at the north-east coast. This value provides a partial picture due to the lack of ground-based data, therefore it is likely that this value is a lower bound.

In term of specific glaciers, the Neumayer Glacier, one of the largest glaciers on South Georgia, has undergone a retreat of 4.4 km between 1957 and 2008 (Cook et al. 2010), with a long period of recession between 1973 and 2003. The continuous retreat triggered the separation of the two southern tributaries (figure 4) (Gordon et al. 2008) and another tributary is likely to separate within the next few years. We also observe, in our study period, a front change of $-430$ m a$^{-1}$, showing similar rates to previous studies (Cook et al. 2010). These trends show that the Neumayer Glacier has been constantly retreating from the middle of the 20th century. For the Szielsko Glacier, the first observation of ice elevation changes in South Georgia was given by Mayewski et al (2016) based on SRTM DEM and GNSS measurements. They found an average thinning rate of $-1.6 \pm 0.7$ m a$^{-1}$ (2000–2012), which is very similar to our results from comparing SRTM with TDX DEMs. Furthermore, GNSS measurements acquired between 2012 and 2017 demonstrate consistency in the glacier elevation change rates obtained in our study, although SRTM-C and TDX DEMs (summer) and GNSS 2012–2017 (spring) were obtained in different seasons. Our results show important thinning rates for a small peripheral glacier as Szielsko Glacier.

South Georgia has one of the longest meteorological records of all the sub-Antarctic islands. Near-continuous meteorological measurements have been taken in the north-east coast from 1905 to 1982, with a large data gap until 2001, when an automatic weather station was installed by the British Antarctic Survey (BAS) (figure 1(b), King Edward Point station) (Thomas et al. 2018). The observed climate trends in the north-east of South Georgia show a significant warming trend of 0.13 $^\circ$C/decade between 1905 and 2016, accompanied by a strengthening in the westerly airflow (Thomas et al. 2018) which influences the frequency of föhn winds events (Bannister and King (2015), Thomas et al. 2018). Bannister and King (2015, 2019) suggested that local processes such as föhn winds (warm, dry, downslope wind descending on the lee side of a mountain range as a result of synoptic flow, cross-barrier flow) may be a driving force of the increased glacier surface melt in the north-east coast. These processes are known to occur and influence cryospheric changes across the Antarctic Peninsula (see e.g. Cape et al. 2015, Turton et al. 2018, Wiesenecker et al. 2018). Unlike the meteorological dataset in the north-east coast, for the south-west coast of South Georgia the meteorological variables remain uncertain, which limits our ability to link mass changes with specific atmospheric processes. Still, our results also show the highest thinning rates in glaciers located in the north-east as well as the subaqueous mass loss. Our knowledge about the glacier dynamics is limited, hence those patterns should be studied in detail in a long-term perspective in order to precisely identify the forcing factors.

5. Conclusions

In this study, we provide for the first time the island-wide glacier elevation and mass changes of South Georgia between 2000 and 2013. We also provide an estimation of the area change at glacier fronts and the subaqueous mass loss between 2003 and 2016. During the analysed period we observe a considerable mass loss and retreat rates in the glaciers of South Georgia, which is in accordance with estimates for similar latitudes. The computed mass loss for the entire South Georgia is estimated as $-2.28 \pm 0.19$ Gt a$^{-1}$ (2000–2013). These changes contribute $0.006 \pm 0.001$ mm a$^{-1}$ to sea level rise. Additionally, we calculate an extra $-0.77 \pm 0.04$ Gt a$^{-1}$ which corresponds to the subaqueous mass loss with an area change at the glacier front of $-6.58 \pm 0.33$ km$^2$ a$^{-1}$ of the marine and lake-terminating glaciers (2003–2016).

Overall, we observe along the north-east coast the highest negative glacier elevation changes. These differences between both coasts should be studied in more detail including glacier dynamics, field measurements or further long-term analysis with high-resolution climate models. We conclude that although glaciers in South Georgia show dramatic changes, our study provides a baseline for further comparison and calibration of model projection. With its unique location in the belt of strong westerly winds, South Georgia is one of the few regions in the world where assessment of the separate influences of local processes and climate drivers on the glacier mass balance can take place.

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**Author contribution**

D F-B designed the study, processed and calculated the InSAR, optical and GNSS dataset and wrote the manuscript. C S calculated the mass balance, uncertainty analysis, and contributed to the writing. Graphics were created by D F-B and C S D B, J V T, and T S assisted the climatological interpretation. T C S and P M contributed in the code development. G C and P A M helped with the interpretation of results and provided feedback throughout the work. M H B led the study. All authors discussed the results.

**Data availability**

Elevation change data are available via the World Data Center PANGAEA operated by AWI Bremerhaven under https://doi.org/10.1594/PANGAEA.909588.

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