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# Surface melting and chemical analysis of a firn core from South Georgia: Implications for future drilling sites and paleoenvironmental records

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## Abstract

In 2015, a continuous 15.4 m snow/firn core was recovered from central South Georgia Island at ∼850 m a.s.l. All firn core samples were analyzed for major (Al, Ca, Mg, Na, K, Ti and Fe) and trace element concentrations (Sr, Cd, Cs, Ba, La, Ce, Pr, Pb, Bi, U, As, Li, S, V, Cr, Mn, Co, Cu and Zn) and stable water isotopes. The chemical and isotopic signal is well preserved in the top 6.2 m of the core. Below this depth, down to the bottom of the core, signal dampening is observed in the majority of the elemental species making it difficult to distinguish a seasonal signal. Thirteen elements (As, Bi, Ca, Cd, Cu, K, Li, Mg, Na, Pb, S, Sr and Zn) have crustal enrichment factor values higher than 10 suggesting sources in addition to those found naturally in the crust. While this study shows that 850 m a.s.l. is not high enough to preserve a record including recent years, higher-elevation (>1250 m a.s.l.) glaciers may be likely candidates for ice core drilling to recover better-preserved, continuous, recent to past glaciochemical records.

## 1. Introduction

The study of past climate based on ice cores has been largely developed from the polar regions and more recently in high-elevation mountain areas at low(er) latitudes. However, a gap still remains in the sub-Antarctic zone, where a few islands, some supporting glaciers and ice caps, punctuate an otherwise uninterrupted expanse of open ocean. Ice cores from these locations provide a unique opportunity to capture atmospheric chemistry and atmospheric circulation of the Southern Ocean (King and others, 2019; Thomas and others, 2021). A previous reconnaissance study conducted on South Georgia focused only on a subset of major and trace elements (Mayewski and others, 2016).

The longest and most complete meteorological records for the Southern Atlantic region are from Grytviken meteorological station, South Georgia Island (54°16'53" S, 36°30'29" W, 1 m a.s.l.), and Orcadas meteorological station, Laurie Island (60°44'17" S, 44°44'16" W, 8 m a.s.l.). These meteorological records, which began in 1905 and 1903, respectively, extend up to the present, making them the longest available records in the region. The associated temperature measurements show a warming trend, with an average rate of 0.13°C decade$^{-1}$ at Grytviken and 0.2°C decade$^{-1}$ at Orcadas (Turner and others, 2005; Thomas and others, 2018). A similar warming trend is reported for King George Island, South Shetland Islands on the west side of the Antarctic Peninsula (Angiel and others, 2010). Moreover, an increase in annual mean wind speed, precipitation and cloudiness has been observed in the South Western Atlantic region (Jones and others, 2016). For example, at Grytviken an increase in precipitation (45 mm decade$^{-1}$) is noted for the period 1907–2016, and mean annual precipitation of 1590 mm is found over the climatological period 1951–80 with the highest precipitation totals in March–May (MAM) and June–August (JJA) (1905–2016) (Van Den Broeke, 2000; Yan and others, 2005; Thomas and others, 2018; Bannister and King, 2020). Sub-Antarctic atmospheric circulation, on inter-annual to decadal timescales, is dominated by the interaction of the Southern Annular Mode, the Antarctic Circumpolar Wave and the El Niño-Southern Oscillation (Thompson and Solomon, 2002; Mayewski and others, 2016).

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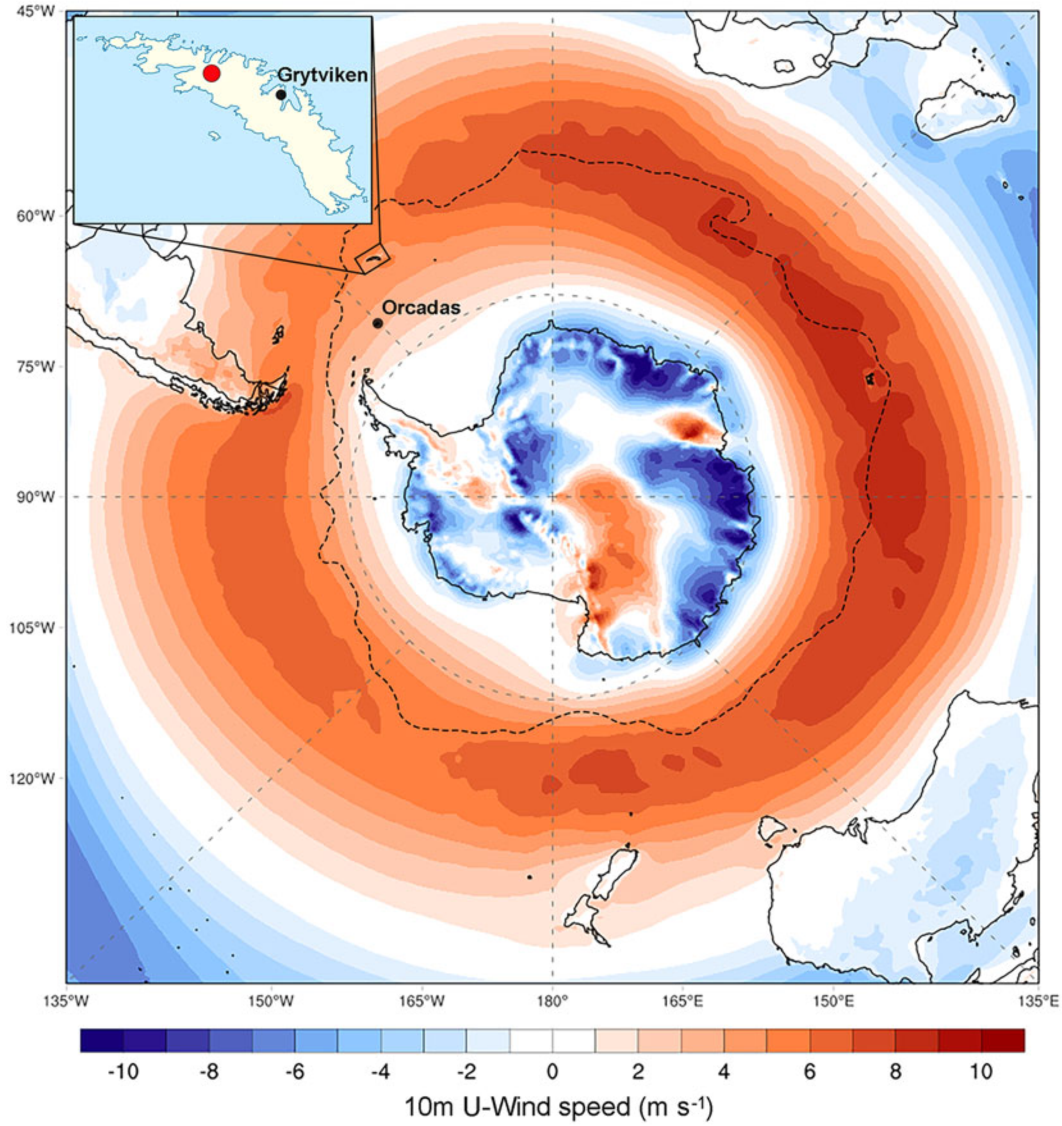


**Figure 1.** Map showing average (1950–2022) 10 m U-Wind speed in m $s^{-1}$, with the Antarctic Polar Front indicated by a black dashed line (Moser and others, 2021). An inset location map for South Georgia firn core site (red dot). Map created using ClimateReanalyzer.org (CCI, 2023) using source data from ERA5 (see Section 2.3).
South Georgia base map: https://en.m.wikipedia.org/wiki/File:South_Georgia_location_map.svg

South Georgia is the largest of the sub-Antarctic islands. Due to its location, south of the marine polar front and within the westerly atmospheric flow in the mid-latitude Southern Hemisphere, where the core of the Southern Hemisphere westerly winds in the South West Atlantic sector is generally situated between 50° S and 54° S (Monteath and others, 2022), the island is an important and potentially rare site for obtaining past climate records (Fig. 1). Unfortunately, South Georgia glaciers are retreating in response to modern warming (Graham and others, 2017), making ice core retrieval at this site a critical priority. Data indicate that the speed at which these glaciers are retreating has surged from an average of 8 m $a^{-1}$ in the 1950s to 35 m $a^{-1}$ in the last decades. This trend is especially prominent on the northeast coast, where current rates of glacier retreat average 60 m $a^{-1}$ (Cook and others, 2010). The calculated total mass loss for South Georgia stands at approximately $-2.28 \pm 0.19$ Gt $a^{-1}$ for the years 2000–13 (Farías-Barahona and others, 2020).

## 2. Methods

### 2.1. Site description and firn core characteristics

In October 2015, a continuous 15.4 m snow/firn core (SG-15), consisting of 29 sections, was recovered by our team from a site in central South Georgia. The core was drilled using a 2-inch diameter Stampfli Electromechanical Ice Core Drill. Based on real-time field observations of glacier morphology, surface slope in particular, we determined that the ideal location for the drill site was on the divide between the Briggs and Esmark Glaciers at ~850 m a.s.l. (54°11’23” S, 37°5’43” W). The core was recovered with minimal breakage and contained some easily identifiable melt layers (Fig. 2) mostly below 7 m in depth. In the field, we placed the core on a precleaned high-density polyethylene tray and utilized shading alongside LED lighting on-site to enhance the visibility of the melt layers, which were then visually identified and measured using a ruler. Layers thinner than 1 cm were challenging to identify, thus setting 1 cm as the established minimum threshold for the reliable identification

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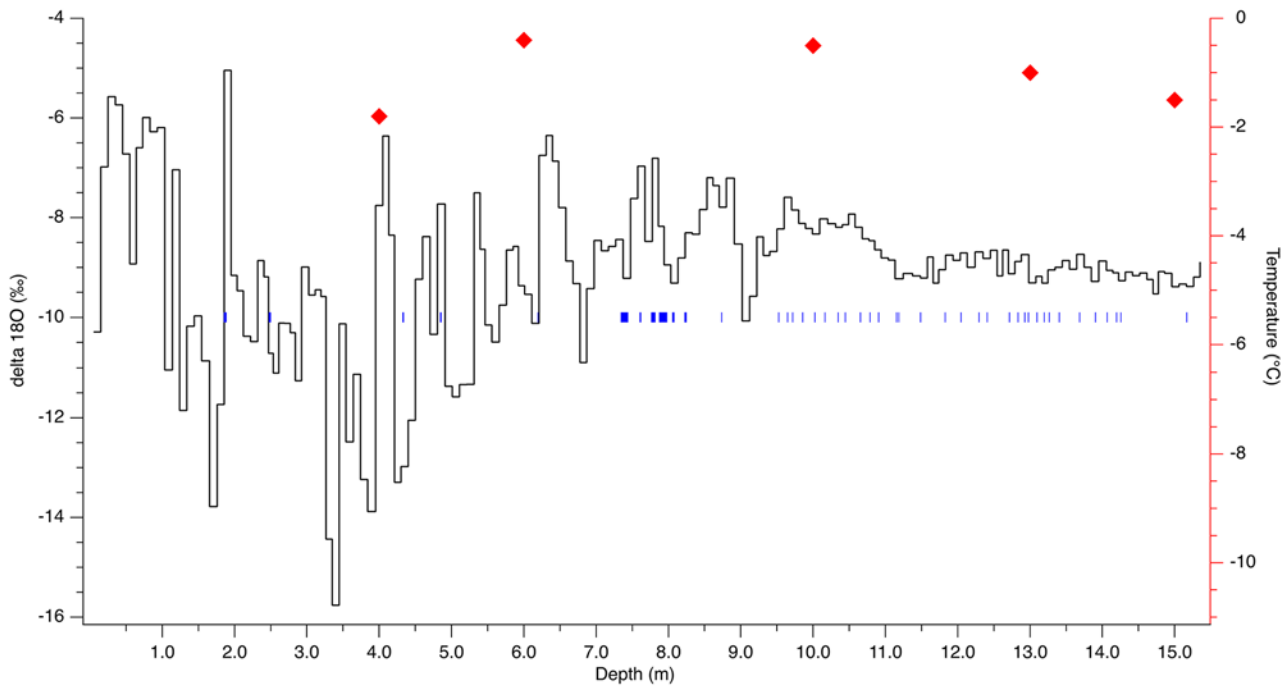


**Figure 2.** $\delta^{18}O$ (‰) record with melt layers indicated in blue and measured borehole temperatures indicated by red diamonds.

of melt layers. We also measured borehole temperatures using temperature data loggers (Omega OM-EL-USB-2-LCD-PLUS, ±0.3°C Accuracy) attached to the string at the following depths: 4 m, 6 m, 10 m, 13 m and 15 m.

### *2.2. Core processing and analysis techniques*

The firn core was processed at the drill site because logistics for this reconnaissance effort did not allow for ice to be returned to the lab in a frozen state. To prevent contamination from the drilling process, the core was cut into ∼10 cm sections, and then each section was scraped to remove the outer ∼5 mm layer, using a plastic ice core lathe and a clean ceramic knife. Subsequently, each scraped section was split lengthways into two parts. One part was used for elemental analysis and the other for stable isotope measurements. Each dedicated elemental sample was placed into a pre-cleaned (using 10% trace metal grade $HNO_3$) 120 ml polypropylene Sarstedt container. Also, each stable isotope sample was transferred to a pre-cleaned (using Deionized Water) 120 mL polypropylene Sarstedt container. Our field sampling protocol follows the procedures described by Hooper and others (2019) and laboratory measurements follow the procedure presented by Osterberg and others (2006).

In November 2015, the 162 SG-15 firn core samples were transported, while maintained in a frozen state, to the Climate Change Institute laboratory at the University of Maine, USA. All sample containers remained in cold (4°C) storage pending analysis. Before analysis, each sample was weighed and acidified to 1% solution with Optima double-distilled $HNO_3$ under a class-100 HEPA clean hood and allowed to digest for 60 days. All acidified samples were analyzed for major and trace element concentrations (Sr, Cd, Cs, Ba, La, Ce, Pr, Pb, Bi, U, As, Li, Al, S, Ca, Ti, V, Cr, Mn, Fe, Co, Na, Mg, Cu, Zn and K) using a Thermo Electron Element 2 ICP-SFMS.

SG-15 stable water isotope samples were analyzed for δD and $\delta^{18}O$ (Reissig, 1983) using a Picarro Laser Cavity Ringdown Spectrometer (Model L2130-i) with a high throughput vaporizer (Model A0212). Samples are reported as ‰ with respect to the international water isotope standard VSMOW (Vienna Standard Mean Ocean Water) (Introne, 2021).

### *2.3. Historical climate analysis*

The ECMWF Reanalysis version 5 (ERA5) (Hersbach and others, 2018) was utilized to examine monthly and annual mean 2-m air temperature, precipitation and zero degree level (physical height above sea level of the melting/freezing point in the atmosphere) at the study site. ERA5 has a horizontal gridcell resolution of 0.25° × 0.25°, which is ∼27 km × 27 km at the latitude of the drill site (Fig. S1).

## 3. Results

### *3.1. Stable isotopes and borehole temperatures*

Both isotope records ($\delta^{18}O$ and δD) look almost identical. The signal of $\delta^{18}O$ from the top ∼6 m of SG-15 appears to be well-preserved with considerable variability. The values range from −5‰ to −15.8‰ (Table S1). Below this depth, down to the bottom of the core, the $\delta^{18}O$ values display less variability than the upper part (Fig. 2), ranging between −6.8‰ and −10.1‰ and the signal is dampened due to melting.

The thickest melt layers are located between the depths at which the highest borehole temperatures were recorded, with measured air temperatures of −0.4°C at 6 m depth and −0.5°C at 10 m depth. The majority of ice layers are below 7.3 m. Notably, the thickest layers, ranging from 3 to 12 cm, were found at depths between 7.3 and 8.3 m. Below 9.3 m depth, there are multiple ice layers, each ranging from 1 to 2 cm in thickness. Borehole temperatures range from −1.8°C at 4 m depth to −1.5°C at the bottom with a peak of −0.4°C at 6 m depth (Fig. 2).

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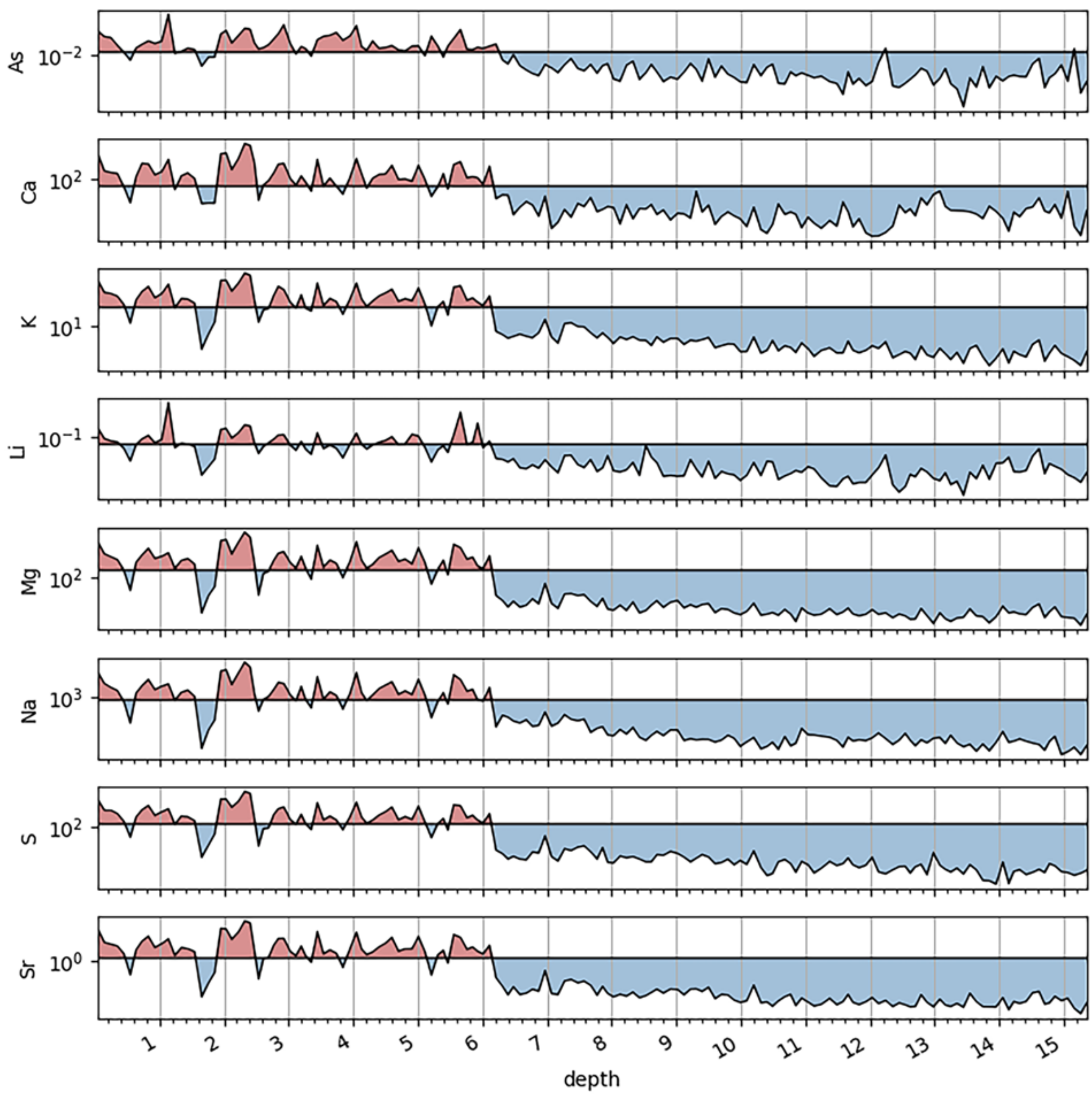


**Figure 3.** Concentration values by depth for selected SG-15 elements. Red color indicates values greater than the mean and blue below the mean value for each element.

### *3.2. Elemental chemistry*

Eight (As, Ca, K, Li, Mg, Na, S and Sr) of the twenty-six chemical elements we analyzed display a dampened signal (Fig. 3), similar to the isotopes, below ∼6 m depth (Fig. 2). These elements are likely deposited in a more soluble form than the rest of the analyzed elements. The remaining 18 elements (Cd, Cs, Ba, La, Ce, Pr, Pb, Bi, U, Al, Ti, V, Cr, Mn, Fe, Co, Cu and Zn) either exhibit negligible or minimal dampening effects. This suggests different post-depositional processes may be at play for these particular elements than those displaying dampened signals. Moreover, elements with consistently well-preserved signal across the depth profile lack discernible seasonal variations.

To assess natural versus anthropogenic source for the core chemistry, we conducted crustal enrichment factor (EFc) calculations using mean upper crustal elemental abundance values (Wedepohl, 1995), where $EFc(x) = ([x/r]\ \text{sample}/[x/r]\ \text{upper crust})$ and $r$ is one of the conservative crustal elements: Ce, La, Pr or Ti. We first calculated the EFc for each element four times using the four conservative elements. We then calculated a final EFc value, $x$, for each element, using the mean result from the four conservative elements (Potocki and others, 2016, 2022). EFc values higher than 10 are considered to be highly enriched relative to natural crustal levels (Planchon and others, 2002). Thirteen elements (As, Bi, Ca, Cd, Cu, K, Li, Mg, Na, Pb, S, Sr and Zn) have EFc values higher than 10 and in some cases higher than 100 (Fig. 4). Highly enriched elements may still indicate a crustal material source (Duce and others, 1975), but EFc values greater than an order of magnitude above crustal inputs likely indicate the influence of other emission sources (Vallelonga and others, 2004).

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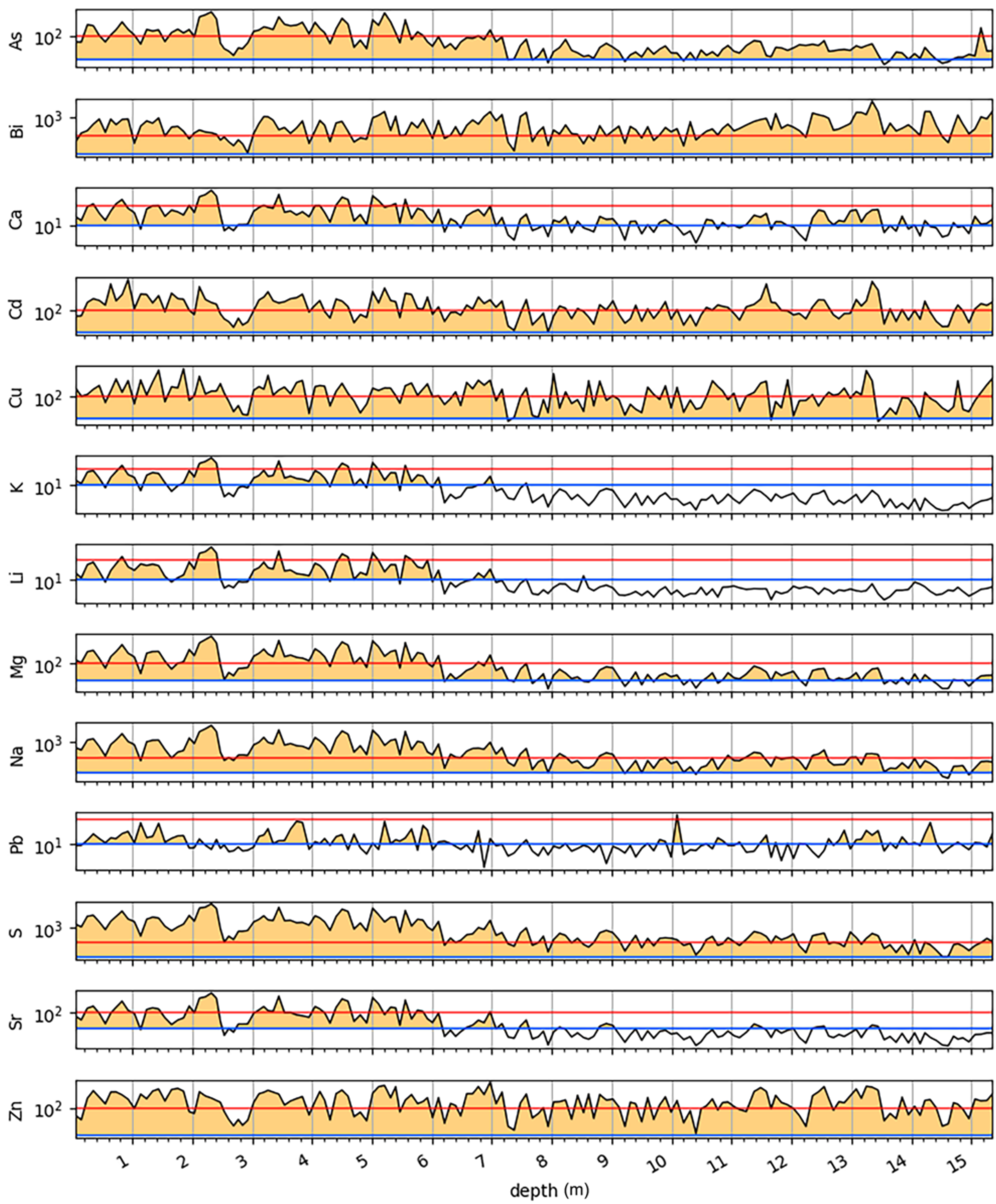


**Figure 4.** Crustal enrichment factor (EFc) values by depth for selected SG-15 elements (As, Bi, Ca, Cd, Cu, K, Li, Mg, Na, Pb, S, Sr and Zn). The blue line indicates values greater than 10 and the red line is a value of 100.

### *3.3. EOF analysis*

To further distinguish between potential sources of chemical elements deposited at the SG-15 drill site, we employed empirical orthogonal function (EOF) analysis (Matlab R2013b) (Peixoto and Oort, 1992; Mayewski and others, 1994; Meeker and others, 1995). We ran the EOF using all 26 chemical elements and two stable water isotopes. The first seven EOFs are the most significant, as indicated by the total variance explained (TVE, Table 1). EOF 1 (48.6% TVE) includes most of species and we interpret it as a dust signal, represented by common crustal elements. EOF 2 includes marine

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**Table 1.** EOF table of major and trace elements, $\delta^{18}O$ and $\delta D$ as measured in the SG-15 firn core samples. The numbers in each row represent the percent variance for each associated EOF

| | EOF 1 | EOF 2 | EOF 3 | EOF 4 | EOF 5 | EOF 6 | EOF 7 |
|---|---|---|---|---|---|---|---|
| TVE (%) | 48.59 | 20.98 | 9.16 | 6.94 | 5.05 | 3.14 | 2.27 |
| Sr | 24.56 | 74.35 | −0.62 | 0.01 | −0.04 | −0.03 | 0.00 |
| Cd | 75.43 | −10.94 | −7.15 | −1.43 | −1.23 | −0.03 | 0.47 |
| Cs | 10.25 | −0.23 | 6.26 | 0.00 | 2.34 | 78.82 | 1.97 |
| Ba | 84.74 | −5.98 | −0.35 | −0.48 | −0.50 | −0.04 | 0.04 |
| La | 36.94 | −2.23 | 47.63 | 0.67 | −11.51 | −0.48 | 0.12 |
| Ce | 32.01 | −1.72 | 52.88 | 0.94 | −11.07 | −0.54 | 0.06 |
| Pr | 39.74 | −2.41 | 50.38 | 1.59 | −4.80 | −0.09 | 0.00 |
| Pb | 77.33 | −13.73 | −4.30 | −1.62 | −0.55 | 0.00 | 0.03 |
| Bi | 53.18 | −15.09 | −7.70 | −1.99 | −1.55 | −0.10 | 0.14 |
| U | 59.73 | 20.30 | 10.10 | 0.79 | −4.40 | −0.01 | 0.02 |
| As | 70.63 | 14.48 | −0.30 | −0.93 | −0.04 | 0.05 | 0.09 |
| Li | 87.81 | −0.89 | −5.20 | −1.41 | −1.19 | −0.04 | 0.14 |
| Al | 76.63 | −13.70 | −5.17 | −0.88 | −0.54 | −0.01 | 0.07 |
| S | 23.24 | 75.23 | −1.03 | 0.02 | −0.05 | −0.02 | 0.00 |
| Ca | 30.61 | 66.26 | −0.57 | 0.00 | 0.00 | 0.61 | 0.11 |
| Ti | 52.54 | −0.34 | 3.78 | 6.84 | 22.59 | −0.18 | −7.78 |
| V | 76.65 | −1.67 | 0.78 | 2.23 | 10.91 | −0.05 | −4.54 |
| Cr | 76.32 | −12.41 | −6.50 | −1.90 | −1.02 | −0.02 | 0.08 |
| Mn | 12.89 | −0.58 | 4.55 | 2.95 | 31.08 | −5.43 | 42.38 |
| Fe | 66.15 | −2.22 | 2.75 | 4.06 | 17.28 | −0.19 | −4.02 |
| Co | 60.96 | −6.97 | 0.37 | 0.58 | 9.32 | −0.03 | −1.07 |
| Na | 22.70 | 75.50 | −0.80 | 0.03 | 0.00 | −0.04 | 0.00 |
| Mg | 22.70 | 75.26 | −1.07 | 0.00 | −0.02 | −0.04 | 0.00 |
| Cu | 77.50 | −11.32 | −5.31 | −1.18 | −0.22 | 0.39 | 0.03 |
| Zn | 77.78 | −12.18 | −5.83 | −1.56 | −0.67 | 0.12 | 0.14 |
| K | 30.88 | 67.68 | −0.90 | 0.01 | −0.05 | −0.01 | 0.00 |
| $\delta^{18}O$ | 0.15 | −2.68 | −13.25 | 78.57 | −4.10 | 0.24 | 0.09 |
| $\delta D$ | 0.51 | −1.19 | −11.06 | 81.65 | −4.21 | 0.22 | 0.26 |

sources and accounts for 21% TVE. It is composed primarily of marine elements such as Na, Sr, Mg, Ca, K and S, demonstrating the significant marine influence impacting South Georgia. EOF 3 (9.2% TVE) comprises rare earth elements such as La, Ce and Pr. This EOF is interpreted as dry deposition from a distinct dust source given that it is inversely associated with stable isotopes. At the same time, EOF 4 (6.9% TVE) is dominated almost exclusively by stable water isotopes. We interpret EOF 4 as an indicator of the variation in the temperature of the captured precipitation (Legrand and Mayewski, 1997). EOF 5 (5.1% TVE) is dominated by Mn and Ti, which are inversely associated with the rare earth dust elements from EOF 3. This likely represents yet another distinct dust source. EOF 6 (3.1% TVE) contains Cs exclusively (78.8%), suggesting that Cs reaches South Georgia Island from a singular point source. There are major Cs deposits in Namibia and Zambia, where intermittent mining is known to take place (Butterman and others, 2004). Although the South Georgia record is too short to be certain, previous studies show a high correlation between Cs concentrations in the Antarctic Peninsula and zonal winds in the Southern Africa region (Fig. S2) (Potocki and others, 2016). EOF 7 (2.3% TVE) is dominated by Mn alone (42.4%), suggesting yet another distinct source for this element.

We also ran EOFs for the upper (0–6.2 m depth) versus the lower (6.2–15.4 m depth) part of the SG-15 firn core to assess the effect of the well-preserved upper section of the firn core versus the dampened lower section (Tables S2 and S3). The results demonstrate that EOF 1 and EOF 2 are represented by the same chemical elements as previously calculated. Therefore, we interpret EOF 1 and EOF 2 to represent atmospheric dust and sea spray signals, respectively.

## 4. Discussion

In our research, we found that As, Ca, K, Li, Mg, Na, S and Sr show weaker signals below a depth of ∼6 m. This can likely be attributed to their greater susceptibility to alterations caused by meltwater percolation within the firn (Clifford and others, 2023). On the other hand, a separate group of 18 elements, including Cd, Cs, Ba, La, Ce, Pr, Pb, Bi, U, Al, Ti, V, Cr, Mn, Fe, Co, Cu and Zn, appear to be less affected by such post-depositional processes, possibly due to their lower solubility. While prior research indicates that some of these less soluble elements can serve as stable indicators for environmental reconstructions (Avak and others, 2019; Clifford and others, 2023), unfortunately, none of the elements we analyzed display a signal that we can confidently interpret as seasonal. The observed dampening in the chemical record is likely a consequence of summer surface melting and water percolation down the profile (Brimblecombe and others, 1985; Eichler and others, 2001). Meltwater is known to alter the stratigraphic integrity of firn layers, redistributing soluble ions and trace elements and thereby complicating their interpretation for paleoclimatic reconstruction (Gascon and others, 2013; Thompson and others, 2013).

Comparative analysis with other high-altitude sites in different mountain ranges, such as the European Alps (Avak and others, 2018, 2019) or Andes (Clifford and others, 2023), has suggested that the state of preservation of trace elements can be variable and site-specific. For example, Ce, Eu, La, Mo, Nd, Pb, Pr, Sb, Sc, Sm, U and W were found to be well-preserved under wetter conditions in the European Alps (Avak and others, 2018). In our dataset, the relatively stable profile of some of these elements supports their potential utility as robust indicators for climate reconstruction, particularly under varying environmental conditions and depositional regimes. Our data indicate that elements with minimal dampening effects such as Cd, Cs, Ba, La, Ce, Pr, Pb, Bi, U, Al, Ti, V, Cr, Mn, Fe, Co, Cu and Zn are more reliable for constructing robust paleoenvironmental records, provided that the site-specific conditions are carefully accounted for.

Isotopic analysis of δD and δ18O from the SG-15 core demonstrates a relationship that follows the global meteoric water line (GMWL) with a slope of 7.75 (Fig. S3), although slightly below the expected slope of 8 (Craig, 1961). Such a deviation from the GMWL is consistent with some effects of post-depositional processes, such as meltwater percolation, which is a common feature in temperate and sub-Antarctic ice cores (Masson-Delmotte and others, 2008). The evidence of melt layers in the SG-15 core, particularly below 6 m, suggests that these layers were influenced by percolating meltwater, redistributing isotopic signals altering the stratigraphy at these depths (Dansgaard, 1964). Variability in deuterium excess (d-excess) further supports this interpretation (Fig. S4), as d-excess is a sensitive indicator of changes in moisture source conditions and post-depositional processes. D-excess values in the SG-15 core display variation, particularly below 6 m, where the isotopic and chemical signals are dampened. This pattern is consistent with the kinetic fractionation effects observed in regions subject to significant melt and refreezing (Ciais and Jouzel, 1994; Masson-Delmotte and others, 2008). These findings suggest that while the upper part of the core preserves seasonal isotopic information with minimal alteration, the deeper sections have been more strongly affected by melt processes, leading to a some redistribution of isotopic and chemical signals.

Given that the presence of a seasonal signal in the analyzed elements is uncertain, it remains unclear whether the dampened signal below ∼6 m depth pertains to the previous warm season

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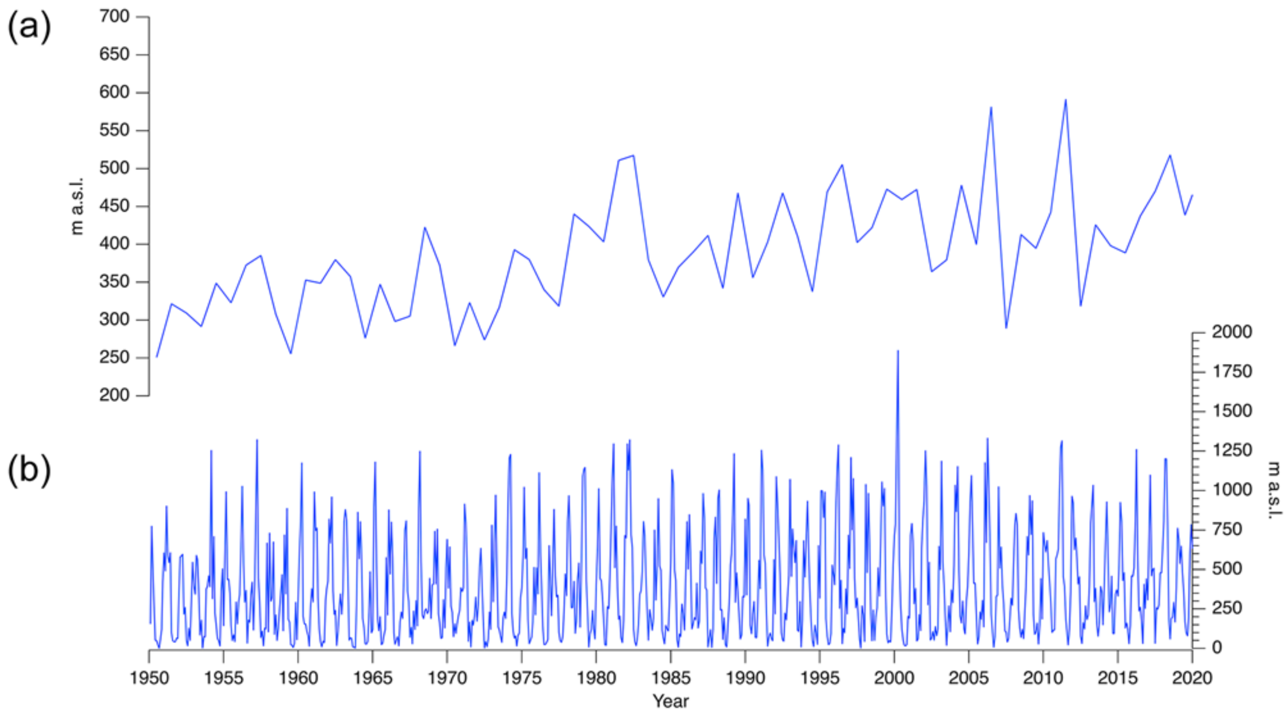


**Figure 5.** Annual average freezing height (m a.s.l.) (a) and monthly average freezing height (m a.s.l.) (b) for site SG-15 from ERA5.

of 2014/15 (December–January–February [DJF]) or encompasses a multi-year record. It is also uncertain whether the upper 6 m of the core solely captures the coldest segment of the year, lasting ∼6–7 months. Considering the depth of 15.4 m in the SG-15 firn core, it is highly unlikely that this represents merely 1 year of accumulation. Such a scenario would imply an exceptionally high rate of snow accumulation, not consistent with existing mean annual precipitation figures—1590 mm at Grytviken (Thomas and others, 2018), 2000 mm (mean annual total precipitation from 1940 to 2023) according to the ERA 5 for the drill site (Fig. S5) and even 2500 mm at the Detroit Plateau on the Antarctic Peninsula (Potocki and others, 2016). Due to these complexities and the lack of discernible annual seasonality in our elemental analyses, we are unable to establish an age scale for this ice core.

If we hope to recover high-quality ice core climate records that are not affected by summer surface melt, we must consider whether the annual freezing heights on South Georgia have ever been low enough to support good quality ice core sites.

ERA5 2-m mean air temperature for DJF 2014/15 at the drill site was 1.5°C, which was 0.5°C colder than the 1991–2020 average for the same period. The coldest part of the year, JJA in 2015 exhibited an average temperature of –1.9°C, which was 0.8°C warmer than the JJA average for the period 1991–2020.

The ERA5 zero degree level (physical elevation of melt/freeze point) variable was used to estimate monthly and annual average freezing heights at the SG-15 drill site from 1950 to 2020 (Fig. 5). These freezing heights will elucidate the temporal prevalence of conditions conducive to snowpack preservation. From 1950 to 1970, the freezing height was at about 400 m a.s.l. and approximately at 600 m a.s.l. from 2000 to 2020. During this most recent period, the highest annual average freezing height occurred in 2021 at 650 m a.s.l. (Fig. 5a). However, from the monthly time series, it is apparent that austral summer freeze heights can reach 1250 m a.s.l. or above (Fig. 5b). The maximum freezing height at the SG-15 drill site in the 72 year ERA5 record is 1889 m a.s.l., attained in March 2000.

Based upon the SG-15 firn core data, we know that any other potential ice core sites on South Georgia Island located at 850 m a.s.l. or below are subject to significant surface melting and associated chemical record loss (Fig. 6a). Due to poor weather conditions and time constraints, our original goal to recover an ice core at ∼1000 m a.s.l. on either Esmark Glacier or Kohl Plateau still needs to be achieved. Final field operations were instead restricted to ice coring at the divide between the Briggs and Esmark glaciers (850 m a.s.l.). The ERA5 monthly freezing height estimates in Figure 6 indicate that a site located above 1250 m a.s.l. may offer more suitable conditions for recovery of ice favorable for paleoenvironmental reconstructions. Thus, viable drilling sites areas may be limited to the highest areas of the Lancing Glacier, Christophersen Glacier and the Mount Paget (2934 m a.s.l.) area, Novosilski Glacier and Herz Glacier between Mount Patterson (2195 m a.s.l.) and Mount Carse (2331 m a.s.l.) (Fig. 6b).

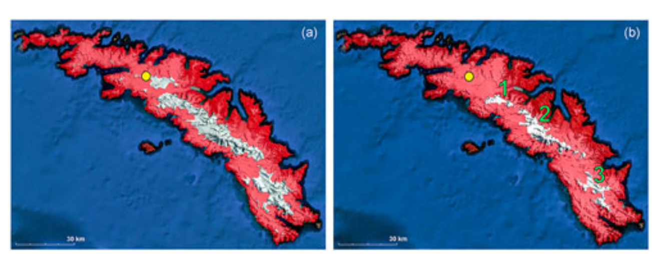


**Figure 6.** (a) South Georgia with elevations below 850 m a.s.l. shaded in red and (b) below 1250 m a.s.l. shaded in red. 1—Lancing Glacier, 2—Christophersen Glacier and Mount Paget, 3—Novosilski Glacier and Herz Glacier. The yellow dot indicates the SG-15 drill site. Aerial image and elevation data from Google Earth Pro—Image 2023 British Antarctic Survey.

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GPR field readings conducted during our field season indicate an ice depth greater than 400 m at the SG-15 drill site, confirming the ice thickness calculations (250–500 m) of Cooper and others (2012) and demonstrating potential for a relatively long environmental record. Based upon the findings of Mayewsk and others (2016), deeper sections of South Georgia ice still contain well-preserved environmental records, as demonstrated by their identification of 'annual layers' using ultra-high resolution (120 micron) laser ablation inductively coupled plasma mass spectrometer iron and calcium measurements in basal ice from the Fortuna and Nordenskjöld Glacier termini radiocarbon dated at between ∼8600 and ∼11 000 years old.

## 5. Conclusions

Paleoenvironmental records from South Georgia Island are needed to provide a baseline for recent and future climate changes in the sub-Antarctic and the Southern Ocean. Mayewski and others (2016) suggested that sites in the Kohl Plateau region ∼1000 m a.s.l. and small ice caps above 2000 m a.s.l. could contain well-preserved recent climate records. However, this study demonstrates that significant melting occurs at least up to 850 m a.s.l. during austral summer, this elevation is therefore unsuitable for ice core paleoenvironmental record preservation. The isotopic analysis of $\delta$18O and $\delta$D indicates a relationship that follows Craig's meteoric water line, with a slight deviation (slope = 7.75), suggesting meltwater percolation in the firn. This is supported by variability in d-excess, particularly below 6 m, where chemical and isotopic signals are increasingly affected by post-depositional processes. Due to the lack of identifiable trends or seasonal markers, whether the core represents a time frame of less than 1 year characterized by frequent storm events or spans multiple years remains inconclusive. However, the likelihood that a 15.4-m core length could represent just a single full year is low, particularly given that such high annual accumulation rates are not observed on South Georgia.

Higher-elevation (>1250 m a.s.l.) ice core sites located on glacier plateaus are still likely candidates for well-preserved, continuous modern to past environmental records. Since the recovery of an ice core of ∼400 m as determined for the SG-15 site requires significant effort and equipment (drilling fluid, a larger camp, more personnel and all of the associated logistical challenges), future drilling attempts will likely require helicopter support that is at present not permitted or available on South Georgia. Further research on more accessible ice from glacier margins that can be radiocarbon dated offers at least the potential for snapshots of past sub-Antarctic and Southern Ocean climates. Our findings also shed light on the role of meltwater percolation in the firn column. Meltwater is known to alter the stratigraphic integrity of firn layers, redistributing soluble ions and trace elements and thereby complicating their interpretation for paleoclimatic reconstruction (Gascon and others, 2013). The mechanisms governing this redistribution are complex and not fully understood, emphasizing the need for further study on the impact of meltwater on different elements and their post-depositional behavior.

**Supplementary material.** The supplementary material for this article can be found at found at https://doi.org/10.1017/jog.2024.110.

**Data availability statement.** The data for this article can be found at Climate Change Institute, University of Maine (https://icecoredata.org/Antarctica.html#SouthGeorgia).

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**Competing interests.** The author(s) declare none.

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