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# Giant iceberg meltwater increases upper-ocean stratification and vertical mixing

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Ice-sheet mass loss is one of the clearest manifestations of climate change, with Antarctica discharging mass into the ocean via melting or through calving. The latter produces icebergs that can modify ocean water properties, often at great distances from source. This affects upper-ocean physics and primary productivity, with implications for atmospheric carbon drawdown. A detailed understanding of iceberg modification of ocean waters has hitherto been hindered by a lack of proximal measurements. Here unique measurements of a giant iceberg from an underwater glider enable quantification of meltwater effects on the physical and biological processes in the upper layers of the Southern Ocean, a region disproportionately important for global heat and carbon sequestration. Iceberg basal melting erodes seasonally produced winter water layer stratification, normally forming a strong potential energy barrier to vertical exchange of surface and deep waters, while freshwater run-off increases and shoals near-surface stratification. Nutrient-rich deeper waters, incorporating meltwater loaded with terrigenous material, are ventilated to below this stratification maxima, providing a potential mechanism for alleviating critical phytoplankton-limiting components. Regional historical hydrographic data demonstrate similar stratification changes during the passage of another large iceberg, suggesting that they may be an important pathway of aseasonal winter water modification.

The global ocean is warming at approximately triple the historical rate<sup>1</sup>, forcing increases in ice-shelf melting and iceberg calving<sup>2,3</sup>. Such calving accounts for approximately half the mass discharge (1,300 Gt yr<sup>-1</sup>) from Antarctic ice sheets, with 90% passing through the western Weddell Sea via 'iceberg alley'<sup>4</sup>. Implicated in climate fluctuations, including the modulation of glacial–interglacial cycles<sup>5</sup> and Heinrich events<sup>6</sup>, the hydrographic impact of icebergs is poorly understood and not represented explicitly in climate models, largely

due to the sparsity of field measurements of melt rates, spreading and entrainment of iceberg-derived freshwater.

Iceberg deterioration and dissolution can cause an appreciable freshwater flux into near-surface layers, strongly modifying upper-ocean stratification<sup>7</sup> and near-surface biological productivity<sup>8</sup>. Differential temperatures and velocities create a turbulent boundary layer for heat transfer<sup>9,10</sup>, causing side and basal melting, the instigator of substantial upwelling of water from below<sup>9,11</sup>. Horizontally,

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**Fig. 1** | **Experimental regime. a**, The trajectory of iceberg A-68A across the Scotia Sea from 21 January 2020 to 12 February 2021. The iceberg shapes are coloured according to date<sup>49</sup>. **b**, The trajectory of iceberg A-68A from 14 February to 22 March 2021 when the glider–iceberg separation was <75 km. The glider was trapped from 14 February to 4 March (transparent). Each coloured triangle (iceberg) and corresponding coloured square (glider) are temporally matched,

with the minimum separation distance between the glider and iceberg edge shown below. For both panels, the bathymetry (GEBCO Compilation Group, 2023) is shown with 1,000 m and 0 m isobaths illustrated as blue and black, respectively, and the ACC fronts are overlain using the SEANOE dataset<sup>50</sup>. SAF, subantarctic front; PF, polar front (PF); SACCF, Southern Antarctic circumpolar current front; SB, southern boundary.

meltwater plumes can extend tens of kilometres<sup>12,13</sup>, with many studies showing noteworthy water and biomass modification within 2 km of the iceberg<sup>14–18</sup>. Such plumes can supply terrigenous nutrients that can promote phytoplankton growth<sup>19–22</sup>. Upwelling can generate an episodic vertical nutrient transport<sup>11,16,23</sup>, producing a spatially heterogeneous environment with respect to ocean productivity, with algal stock increases often delayed by 6–10 days after iceberg passage, probably due to the interaction of physical and biological processes<sup>14–16,18</sup>.

In July 2017, A-68 calved from the Larsen-C ice shelf in the Weddell Sea<sup>24</sup>, the sixth largest iceberg on record at the time<sup>4</sup>, with an area of 5,800 km<sup>2</sup>. Subsequently, A-68 tracked northwards across the Scotia Sea (Fig. 1a), with the largest fragment (named A-68A) losing approximately one-third of its size as it approached South Georgia (SG). As A-68A recirculated to the southeast of SG, it fragmented further, probably triggered by ocean-current shear mechanisms<sup>25</sup>. Surface meteoric water concentrations exceeded 4% close to SG due to meltwater from A-68A<sup>26</sup>, with 152 ± 61 Gt of freshwater fluxed within 300 km

of SG between November and March 2021 (ref. 27), 27 times that of the annual freshwater outflow from  $SG^{28,29}$ .

In summer, this region of the Southern Ocean (SO) has a highly distinctive density structure with a surface mixed layer (ML) above a winter water (WW) temperature inversion (minima  $-125 \pm 25$  m) caused by the presence of a cold subsurface winter remnant. This acts as a potential energy (PE) barrier to the warm, nutrient-rich circumpolar deep water ((CDW) temperature maxima -500 m) below<sup>30,31</sup>. Overcoming this PE barrier can entrain heat, salt and nutrients into the ML, impacting primary productivity and air–sea gas exchange between the deep ocean, surface layers and the atmosphere. These physical changes have direct and indirect impacts on ecosystems and the cycling of nutrients and carbon.

Here, we report results from an innovative underwater glider deployment close to, and under, A-68A. When combined with shipboard and satellite measurements, the observations provide sufficient resolution to disentangle the effects of iceberg-derived meltwater



**Fig. 2** | **Hydrographic properties by distance from A-68A. a,b**, The glider realizations of conservative temperature (**a**) and absolute salinity (**b**) approaching A-68A from left to right, along with the GEM historical hydrography (black) with bootstrapped 95% confidence intervals (shaded grey) matched by dynamic height. Overlain are the individual glider profiles, coloured according to classification with blue (far), magenta (near) and red (adjacent)), with a running mean (dotted cyan) overlain. The mean glider–iceberg separation for each dynamic height group and classification is shown between **a** and **b**. The horizontal green line shows the mean iceberg draft. The data are staggered by

an incremental offset for illustration. **c**, Buoyancy frequency (*N*<sup>2</sup>) calculated from the running mean of each glider classification, with appreciable maximal stratification accentuated with horizontal lines (top and bottom are identical). **d**, The Ri estimated using ship-borne CTD and LADCP (the locations of which are illustrated in Fig. 1), with the vertical dashed green line showing the 0.25 threshold for criticality (top and bottom are identical). The grey shading in **c** and **d** is the quantified extent of upwelled basal meltwater (see Basal meltwater contribution).

from variability induced by the complex hydrographic, frontal and eddy structure of the region, allowing us to interpret and quantify iceberg-influenced ocean properties. Quantification of basal meltwater is compared with satellite-derived estimates, and shipboard data elucidate possible mechanisms of meltwater dispersion. Biogeochemical impacts in the wake of A-68A are examined and we conclude with assessment of historical hydrographic data to assess the regional impacts of meltwater from other giant iceberg transit events. We find consequential impacts from iceberg-induced mixing on stratification and the vertical supply of nutrients, with strong implications for globally important SO processes.

# Hydrographic impact of iceberg passage

To investigate the impact of A-68A meltwater on upper-ocean physics, productivity and biogeochemistry, the RRS James Cook conducted a series of conductivity-temperature-depth (CTD) and lowered acoustic Doppler current profiler (LADCP) profiles in close proximity to A-68A. On 14 February 2021 a Slocum glider was deployed, 23 km from A-68A. Equipped with sensors for physical (temperature, salinity and pressure) and bio-optical (chlorophyll-*a* and backscatter) measurements, this glider tracked within 75 km of A-68A for 49 days, collecting 265 vertical profiles up to 1 km in depth (Fig. 1).

This study focuses on the first 19 days of the deployment, where the glider approached A-68A from the 'upstream' side relative to the current. Two days after deployment, the glider became trapped under the thinner side of the iceberg relative to its calving edge at a depth of 163 m; this reduced to 112 m after 12 h, likely illustrating the uneven bottom of this giant iceberg. Using satellite altimetry<sup>27</sup>, the average of draft of A-68A on the 17 February was calculated to be 141 m. Combining these drafts, we obtain an estimated iceberg depth of 139 m.

Ocean conditions around SG are characterized by strong interannual variability and high biological productivity, with the surrounding ocean sitting more generally in the high nutrient low chlorophyll SO (regions of the SO where micronutrient iron has been shown to limit phytoplankton growth<sup>32</sup>). The Southern Antarctic Circumpolar Current Front (SACCF) and the Southern Boundary (SB) loop anticlockwise around the island from the south (Fig. 1), with numerous mesoscale meanders and eddies. Variability in transport and location of these fronts means isolating the effects of iceberg melt within this region can be challenging. The fronts and eddies obfuscate local hydrography, while iceberg fragments, growlers and brash ice follow current cores identified by sea surface height (SSH) contours, with fragments observed to rotate in eddies identified by circular SSH maxima (Fig. 1b).

To differentiate iceberg signals from background hydrography, a gravest empirical mode (GEM) parameterization<sup>33</sup> was calculated from historical data (Methods). The temperature and salinity profiles at all glider–iceberg separations are significantly different to that of the GEM (Fig. 2). The profiles are classified into three distinct regimes with average glider to iceberg separations of  $15.2 \pm 5.3$  km (far),  $2.6 \pm 0.22$  km (near) and  $0.28 \pm 0.21$  km (adjacent) (Fig. 2). The stratification ( $N^2$ ) mean for each classification is plotted in Fig. 2c.

A fresh cold water cap is evident in the adjacent and near profiles at -9 m and -16 m depth, respectively. This subducts the warmer saltier surface water, leading to a second peak in stratification at -44 m and ~63 m depth for adjacent and near profiles, respectively.

The far profiles, although offset from the GEM with warmer, saltier surface waters and cooler fresher water to -200 m, exhibit a similar-shaped profile with a single broad stratification peak at -73 m depth. In adjacent profiles, this WW layer is eroded, with stratification increasing above and below this well-mixed layer. Near profiles fall between these regimes. The eroded WW layer is also apparent in glider profiles when escaping the trapping event (not shown), but the highly recirculatory flow combined with the presence of numerous iceberg fragments means these profiles cannot be categorized by 'distance from iceberg' and are excluded from analysis.



**Fig. 3** | **Basal meltwater contributions.** A *T*-*S* diagram, with cast coloured by the distance from A-68A. The contours show the potential density at 0.5 kg m<sup>-3</sup> intervals. The red circled cast, at 2.4 km from A-68A, highlights a prominent meltwater intrusion with the associated Gade line (in green) overlain. Density classes indicating WW and CDW are labelled.

# **Basal meltwater contribution**

The WW erosion can be used to quantify the basal meltwater contribution of A-68A when considered in temperature–salinity (T–S) space (Fig. 3, with the inset highlighting the extreme sea surface salinities and temperatures on exiting the trapping event, the slope of which matches that of a freshwater run-off line). Water masses affected by meltwater are apparent in the form of intrusions, where the T–S profiles depart from the classic WW temperature minima. These intrusions are warmer and saltier along isopycnals, consistent with the upwelling of warm and saline water below the WW layer<sup>11,34</sup>.

With A-68A estimated to be moving at a velocity of 0.13 m s<sup>-1</sup> in a geostrophic flow of 0.26 m s<sup>-1</sup> (Methods), turbulent basal melting will occur, generating a small amount of fresh, cold water, which mixes with a much larger volume of ambient ocean water. This produces water with a characteristic slope in *T*–*S* space, known as the Gade line<sup>35</sup> (Methods). This water is positively buoyant compared with in situ properties and thus upwells, creating *T*–*S* intrusions. Water constrained by ridges/ keels under the iceberg may intermittently 'spill', entraining water as it rises to attain a new level of neutral buoyancy. Such complex interacting processes may result in multiple intrusions in a single profile or variability in their shape.

Here, we quantify the meltwater content within intrusions by determining the relative proportions of ambient and Gade line water masses along isopycnals, following ref. 11 (Methods). The mean depth of the ambient T-S source of the intruded waters was  $238 \pm 7.8$  m, with a maximum of 250 m to a minimum of 230 m as the glider moved within 2 km of A-68A, possibly impacted by internal waves induced by the wake of the iceberg. The mean volume of water upwelled was  $72.8 \pm 15.3$  m<sup>3</sup> m<sup>-2</sup>, with a mean meltwater content of  $0.52 \pm 0.1$  m<sup>3</sup> m<sup>-2</sup> over a mean vertical extent of  $106 \pm 7.8$  m from 197 m up to 91 m (Fig. 2c,d), influencing depths greater than the iceberg draft.

Intrusions cease at distances between 2.71 and 5.5 km from A-68A. Assuming the mean meltwater content is advected over an area of 3 km, integration yields an estimated basal meltwater contribution of  $1.9 \times 10^8$  m<sup>3</sup> (Methods). Taking the limits of iceberg and geostrophic flow speed, we obtain advection rates of  $6.9 \times 10^8$  m<sup>3</sup> day<sup>-1</sup>, and  $1.4 \times 10^9$  m<sup>3</sup> day<sup>-1</sup>, respectively. Quantifying the freeboard change over time<sup>27</sup> yielded  $1.7 \times 10^9$  m<sup>3</sup> day<sup>-1</sup> for basal melting, meaning satellite

estimates of melt rate are between 1.25 and 2.49 times our in situ estimates. The satellite and in situ estimates of basal melt are thus in broad agreement, especially considering the assumptions and inherent differences in measurement.

#### **Meltwater mixing**

To understand whether iceberg meltwater is vertically distributed within the water column via turbulent mixing, the Richardson number ((Ri) the ratio of potential to kinetic energy; Methods) is quantified using three ship-borne CTD and LADCP profiles, two at 4.5 km and one at 2 km from A-68A (Fig. 1). When the Ri falls below one-quarter (Fig. 2d, vertical green line), shear is considered sufficient to overcome the stability of stratification and turbulent mixing will likely occur. Buoyant meltwater creates an unstable water column and shear is likely to increase at the boundaries of stable stratification<sup>36</sup>. Ri is minimal when  $N^2$  is small, at the fringes of the stratification maxima in adjacent and near profiles. Active mixing is observed beneath the fresh cold water cap where warmer waters are subducted, and closest to the fully mixed temperature and salinity profiles. There is also active mixing near the base of the meltwater intrusions (grey shading), possibly signifying a boundary layer dragged by the iceberg. The locations of the peaks in Ri suggest that the change in stratification as the distance from the iceberg increases is due to turbulent mixing, likely generated by the upwelling plume, sidewall melt, surface water run-off and iceberg wake, with an influence extending below that of the iceberg draft.

#### **Biogeochemical impacts**

SG and its immediate surroundings are situated in a micronutrientlimited region of the Antarctic Circumpolar Current (ACC), with trace metal sources derived from the deep ocean, shelf sediments and glacial flour released from its melting glaciers<sup>37</sup>. Stratification changes induced by A-68A, the potential for micronutrient injection, loss by cell lysis, grazing, dilution or mixing with deeper marine waters or meltwater could have pronounced biogeochemical impacts that may affect the productivity of the region<sup>14</sup>.

Figure 4b shows low near-surface chlorophyll adjacent to A-68A whereas the backscatter is relatively high, likely illustrative of meltwater releasing particulates while simultaneously diluting in situ standing



**Fig. 4** | **Biogeochemical impacts. a**, A MODIS Aqua satellite image (see Acknowledgements) from 16 February 2021, overlain with A-68A outlines in February, before (blue) and during (coloured by date) the experimental campaign, with the day shown. The glider positions are coloured by date, except the red point (the last measurement before becoming trapped, 15 min before image acquisition). **b**, Glider-derived estimates of chlorophyll-*a* and backscatter plotted against glider–iceberg separation. **c**, Outlines of A-68A from

14 to 16 February are overlain on satellite altimetry SSH contours, indicating the geostrophic flow direction. From 8 to 12 February, the flow direction is consistent, all coloured blue. Subsequently, as the flow direction backs, the colours follow those of **a**. The overlain glider positions are coloured by integrated chlorophyll over the top 100 m, with quivers illustrating the full depth mean velocities (quiver key, top right in **c**).

stocks and/or increased turbidity causing lower light penetration and growth limitation.

At greater glider–iceberg separations, the near-surface increases in both chlorophyll and backscatter are apparent. Surface chlorophyll maxima at -16.7 km, when scaled with iceberg velocity, suggest a peak occurring -36 h after the passage of A-68A. Maximal biomass growth rates at these ocean temperatures are 0.5–1.5 doublings per day<sup>38</sup>. Using changes in integrated chlorophyll over the top 100 m (Fig. 4c) as a proxy for growth rate yields growth rates at or below these levels, indicating that the localized high biomass could be due to the passage of A-68A and is not suggestive of large advection.

Biological production can be enhanced in regions where marine and iceberg-derived nutrients are injected into nutrient-limited near-surface waters, with delays documented in the wake of iceberg passage<sup>14-16,18</sup>, potentially as a result of meltwater dilution and/or upper-ocean layer modifications. With strong near-surface stratification (Fig. 2) and freshwater surface run-off within 1 km of A-68A (Fig. 3), phytoplankton standing stocks could first be diluted by meltwater before stimulation of primary production and new growth occurs.

The SG region is known for high heterogeneity in the timing, location and magnitude of phytoplankton blooms<sup>39</sup>. Therefore, it is not possible to unambiguously attribute the patterns of chlorophyll discussed to the presence of the A-68A iceberg. Moreover, the relation to iceberg aspect is complex owing to the route of the iceberg before measurement and the fragments and brash ice present in the area (Fig. 4a). Nevertheless, the glider depth mean flow is consistent with that of the geostrophic flow direction deduced from the satellite SSH (Fig. 4c), with flow from a predominantly ice clear region to the west for at least 7 days before measurement. This strongly suggests that the biological response is related to the iceberg passage.

#### Significance

Figure 5a illustrates the climatological median of the cumulative buoyancy frequency across the WW layer for the South Atlantic region, obtained from historical hydrographic data from January to April (Methods). Historically, this region features relatively high WW stratification, thus recurrent iceberg-driven WW ventilation could be regionally important.

Large icebergs transited the region during these months in years 2004, 2015 and 2021. Climatologies that spatiotemporally match these iceberg and/or fragment locations are available for years 2015 and 2021 (see the spatial extents in Fig. 5a), and are shown in Fig. 5b–g, respectively, overlain on the historical climatologies for these extents. The mean separation of iceberg to climatological data profiles was



**Fig. 5** | **Historical WW climatology. a**, The climatological median of the WW cumulative buoyancy frequency for January–April 2005–2021 (2015 and 2021 omitted, see text), overlain on bathymetry (GEBCO Compilation Group, 2023). The pink and blue box extents (areal extents given in Methods) illustrate the spatial and temporal overlap between the iceberg and hydrographic profiles.

b-g, Conservative temperature (CT) (b and e), absolute salinity (SA) (c and f) and N<sup>2</sup> (d and g) coloured accordingly for each month's profiles (February 2021, b-d and April 2015, e-g), with the climatology overlain in grey. The shading illustrates the s.d.



**Fig. 6** | **Overview schematic.** A schematic illustrating the buoyancy field approaching A-68A. The colour contours are a manual linear colour scale application for each vertical stratification layer and the horizontal profile/ iceberg separation in T and S, which are overlain to produce the buoyancy

colouring. The T and S line profiles are drawn to scale with 1 °C and 0.5 g kg<sup>-1</sup> separation shown. The region of basal meltwater influence is represented with grey shading.

 $69.5 \pm 10.4$  km (minimum 58 km) and  $14.5 \pm 11.8$  km (minimum 1.9 km) for 2015 and 2021, respectively. Thus, 2015 separation is more reflective of the larger separations seen in Fig. 2 compared with that of 2021, and have been coloured accordingly.

Appreciable similarities in historical iceberg proximal data to the high-resolution glider data are observed. Stratification maxima is elevated and shallower than the climatological median when icebergs are present (Fig. 5d,g). As the iceberg/measurement separation increases, the maxima deepen and surface waters, initially cooler and fresher than the climatology, become fully mixed. Elevation in stratification due to iceberg passage is also observed below the WW core, possibly due to basal meltwater influence.

# Implications

Through an unprecedented set of high-resolution measurements, the impact of a giant iceberg on the upper water column stratification and biogeochemistry within the ACC has been documented. The results demonstrate the following:

- 1. Surface meltwater release induces a shallow peak in stratification, pushing warmer and saltier surface waters to greater depths.
- 2. The WW stratification is eroded, with turbulent mixing transporting a consequential amount of warm and salty CDW from below the iceberg draft. This CDW, containing remineralized and preformed marine nutrients, in addition to nutrient-rich terrigenous material from the iceberg, is upwelled into shallower waters under the shoaled stratification maximum.
- 3. Between 2.7 and 5.1 km from the iceberg, this cold and fresh surface run-off layer turbulently mixes and the WW profile below reforms, leaving a warmer, saltier surface layer and cooler fresher water below, with a shallower and stronger stratification peak compared with the climatological mean (Fig. 6).
- 4. Within 2 km of the iceberg, surface chlorophyll is diminished while backscatter remains high. As separation increases, algal standing stocks increase.

These results have widespread implications. First, the SO is a major sink for anthropogenic carbon, regulating climate change by slowing the increase of carbon dioxide in the atmosphere<sup>40</sup>. A key control on the subduction of carbon is the strength of stratification at the base of the ML, with recent research<sup>41</sup> suggesting that the global density contrast across this interface has increased in the past five decades. Iceberg melting and subsequent lateral mixing has been hypothesized to contribute to the WW structure<sup>42</sup>. This work provides observational evidence that giant icebergs increase stratification at the base of the ML in the SO.

Second, the stratification changes around the WW layer, and associated turbulent mixing, provide an important mechanism for modifying WW properties outside of winter. Iceberg modelling studies in Greenlandic fjords<sup>43–45</sup> support the view that meltwater release drives an overturning circulation, upwelling warmer waters. Here, we build upon this by observing directly the changes at intermediate depths in the SO. These changes will ultimately set the vertical stratification, temperature and salinity that persist in the WW layer into the following season.

Third, our results underline the complex impacts of iceberg melt on marine productivity. Key controls include, but are not limited to, micronutrient delivery from the iceberg and upwelled CDW, spatial dilution impacts and changes in stratification from meltwater; shoaling the ML and conceivably enabling storm/front or euphotic zone interactions. The nature of resource limitation is pivotal, with algal population structure influencing cell-size distribution, ecosystem functioning and carbon export, all affecting the marine biosphere<sup>21,46</sup>.

In the coming century, it is likely that the number of deep-drafted icebergs in the SO will increase, particularly in West Antarctica<sup>47,48</sup>. Since our fieldwork was conducted, the giant iceberg A-76A has transited the region<sup>49</sup>, and the similarly sized iceberg A-23 reached the northern end of the Weddell Sea, exiting into the Scotia Sea. Individual icebergs vary in draft, translation speed, distance and micronutrient loading. With considerable uncertainty remaining on future freshwater fluxes from icebergs, our study underlines the need to better observe and model the physical and biogeochemical processes. Only through understanding these processes will their impact on both physical and biological

carbon pumps be accurately quantified and future estimates of carbon fluxes be refined and represented effectively in both regional and global ocean models.

# **Online content**

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41561-025-01659-7.

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# Methods

#### Satellite-borne iceberg definitions

A-68A satellite images (NASA Worldview and Modified Copernicus Sentinel data 2021/Sentinel Hub) with a resolution of 250 m were manually delineated using OGIS software when cloud cover permitted. The centroid of the QGIS polygon shape files were obtained and utilized to estimate the speed and direction of the iceberg. The polygon edge points were then interrogated to obtain the glider separation from the closest point of the iceberg, with interpolation in time and space when no direct measurements were possible due to satellite overpass times or cloud cover.

#### **Glider observations**

The Teledyne Webb Research Slocum G2 glider (serial number 405) incorporated a pumped Sea-Bird SBE 41 CTD, alongside optical measurements of chlorophyll-a and backscatter. T and S were bin averaged onto 1 dbar levels, the turning points and trapping events of the glider identified and the vertical profiles were obtained. No despiking was undertaken in these quality control steps as it was found that despiking routines erroneously identified outliers that were in fact the iceberg signal, particularly when close to the iceberg edge.

To test for thermal lag effects, sequential upwards and downwards temperature profiles were compared using the SOCIB glider toolbox<sup>51</sup>. Owing to the CTD being pumped, thermal lag effects were very small and corrections were minimal. The corrected data were compared with high-quality CTDs obtained on RRS James Cook (JC211) at the start of the deployment. A small temperature (0.013 °C) and conductivity (0.0335 S m<sup>-1</sup>) offset was applied, with salinities recalculated. Finally geostrophic flow was estimated using the depth-averaged velocity estimation from each glider profile<sup>52</sup>.

#### Historical oceanographic context

The historical vertical temperature and salinity fields of the region were calculated by applying a GEM projection following ref. 33, utilising data from ship-borne CTDs at the locations shown in Fig. 1. Optimal interpolation of the CTD data<sup>53</sup> north of 58° S over the period 1995–2020 was used to produce vertical temperature and salinity fields at 5 dbar levels, as a function of integrated water column density (for example, dynamic height). The dynamic height was extracted relative to 990 dbar, with no seasonal correction for residuals to incorporate all surface variance. These time-invariant GEM fields produce T-S profiles for each dynamic height at each longitude. The 300 m reference level was extracted, then matched with glider positional referenced altimetry derived SSHs (EU Copernicus Marine Service information)54 for *T*–*S* comparisons. Ship-borne CTD data with no points between 21 m  $\ge$  x  $\le$  1,500 m depth range were excluded, leaving 113 casts for this analysis.

#### Ship-borne dataset

CTD casts were collected from RRS James Cook using a Sea-Bird Scientific SBE911plus system, with additional sensors for dissolved oxygen, chlorophyll fluorescence, photosynthetically active radiation and other parameters. In the vicinity of the iceberg, most casts were to 1,000 m, or to 10 m above the seabed if shallower. Water samples were collected to calibrate the conductivity and dissolved oxygen, and for additional biological and biogeochemical parameters. Salinities were analysed with a Guildline Autosal 8400B, calibrated against IAPSO standard seawater batch P164.

The CTD rosette was fitted with upwards- and downwards-looking Teledyne RDI Workhorse Monitor 300 kHz LADCPs. These were used to calculate current profiles for each cast using the inverse method<sup>55</sup>, using LDEO\_IX software version 13 available from ref. 56.

Three ship-borne CTD and LADCP profiles were used to calculate the Ri, the ratio of potential to kinetic energy, defined as

The basal meltwater concentration for each equivalent density level point is calculated, and the two of these are multiplied to produce a meltwater fraction at the T-S intrusion density level. The relative contributions are integrated over the vertical extent of the intrusion to obtain the amount of upwelled water content in the intrusion. The meltwater fraction at each T-S intrusion density level is integrated over the vertical extent of the intrusion to obtain the integrated meltwater content. Each cast contribution was then averaged to obtain the estimated mean volume of upwelled water and the mean meltwater content. All casts within 2.71 km of A-68A exhibited intrusions, with four casts on the approach to A-68A deep enough for this T-Sanalysis to be undertaken. Casts further than 5.5 km did not exhibit intrusions.

To quantify a melt rate from the iceberg, a number of assumptions are required. These included a uniform melt rate around the circumference of A-68A, that the iceberg is flat bottomed without pockets of meltwater stored in crevasses beneath and that all melting emanates from the base. The ice density at the base of the iceberg is taken as 915 kg m<sup>-3</sup> (ref. 58). Given the observation of intrusions up to 3 km from the edge of the berg, we assume this band is the 'influence area'; integrating this and the mean meltwater content in the profiles yields an estimated basal meltwater contribution of  $1.9 \times 10^8$  m<sup>3</sup>. Assuming only advection of the meltwater (and no diffusion), using limits of 0.13 m s<sup>-1</sup> from the iceberg speed and 0.26 m s<sup>-1</sup> from the glider depth mean flow speed, we obtain advection rates of  $6.9 \times 10^8 \text{ m}^3 \text{ day}^{-1}$  and  $1.4 \times 10^9 \text{ m}^3 \text{ day}^{-1}$ , respectively.

$$Ri = \frac{N^2}{\left(\frac{dU}{dz}\right)^2},$$
(1)

where  $N^2$  is the Brunt-Väisälä frequency, or buoyancy frequency, and  $(dU/dz)^2$  is the velocity shear. The locations of these casts are illustrated in Fig. 1 as red stars filled in blue, two at 4.5 km ship to iceberg separation and one at 2 km separation.

#### Quantification of basal meltwater

Turbulent entrainment of meltwater at the iceberg's base was calculated following ref. 11 by identifying warm, salty anomalies in T-S space compared with background levels, which are taken to be the profiles at greater glider-iceberg separation that exhibit a well-defined WW layer.

For each cast, a Gade line<sup>57</sup> is estimated, defined by

$$\left(\frac{\partial T}{\partial S}\right)_{\text{melt}} = \frac{\Delta T + LC_p^{-1}}{S},\tag{2}$$

where  $\Delta T$  (°C) is the elevation of ambient temperature above the freezing point of water at salinity S (psu), L = 334 kJ kg<sup>-1</sup> is the latent heat of fusion of water, and  $C_p = 4.2 \times 10^3$  J kg<sup>-1</sup> °C<sup>-1</sup> is the specific heat capacity of water.

The slope of this meltwater mixing line is the mean Gade estimations over the top 300 m. It is placed at a tangent to the maximum temperature in the T-S intrusion, representing the upper bound of Gade water contribution. This linear approximation is then projected back to find the source depth, which represents the minimum T-S required for the basal melting to produce the observed anomaly, located in the permanent thermocline where there is a minimum in absolute difference of Gade T-S to the ambient T-S. The upper and lower bounds of the intrusion's deviation from the background T-Sare noted for each cast, giving the upper and lower limits of the upwelled water. The relative contribution across density levels of ambient water and basal meltwater at each point along the intrusion in T-S space is calculated, that is, if a T-S point lies midway between the ambient water and the basal meltwater estimation, one deduces relative contribution of 50%.

As noted above, satellite altimetry estimates of melt rate are between 1.25 and 2.49 times our in situ estimates. For the altimetrybased meltwater estimate, the measurements were extrapolated into summer and include the meltwater release from all children icebergs that calved from A-68A after 28 November 2020. The glider estimate, in contrast, refers to meltwater only around the remaining biggest piece in February 2021. While altimetry detects thickness change and therefore meltwater when it is created, oceanographic methods detect meltwater when it is released and distributed into the water column. Moreover, for the glider, the antecedent differential meltwater due to wake influence, leading edge melt, stratification depth influence, meltwater 'shading' (where meltwater pools on the downstream side of an iceberg) and the glider being trapped and released from the shallower side of the once grounded glacier will affect the assumption of uniform melt rate around the circumference of A-68A.

#### **Biogeochemical estimations**

Manufacturer calibrations were used to derive bio-optical properties. The volume scattering function (in m<sup>-1</sup> sr<sup>-1</sup>) data were filtered according to ref. 59. Values of volume scattering function above 0.001 m<sup>-1</sup>sr<sup>-1</sup>, negative values and profiles of anomalously low-volume scattering function (maximum value of 0.0001 m<sup>-1</sup> sr<sup>-1</sup> or less) were removed from the dataset. The volume scattering function values were smoothed using a five-point median and seven-point mean filter. The optical particle backscattering (bbp) was calculated by correcting for scattering within a seawater medium (assuming an angle of 124° and for the wavelength of 650 nm) and integrating across all backwards angles using an assumed angular dependency for marine particles<sup>60,61</sup>. The chlorophyll data from each profile were despiked (to remove negative values and outliers above 10 mg m<sup>-3</sup>), before being dark-corrected by subtracting the median chlorophyll below 300 m from each value<sup>62</sup>. The chlorophyll data were corrected for quenching from all daylight profiles (local sunrise to sunset plus 2.5 h) based on published methods<sup>63</sup>. Briefly, quenching was assumed to occur above the depth of the maximum chlorophyll-a:bbp ratio within the ML, and was corrected for at each depth above that by multiplying the maximum chlorophyll-a:bbp with the corresponding bbp value, assuming that the algal population involved has a constant chlorophyll-a:bbp ratio.

#### WW median climatological estimations

Hydrographic profiles south of 40° S for the period 2004 to 2021 (ref. 64) were compiled from the combined datasets, Argo floats<sup>65</sup>, tagged marine seals<sup>66</sup>, ship-based CTD casts and glider profiles<sup>67</sup>.

We detected the presence of WW in each hydrographic profile following the definition in ref. 68, where a temperature inversion of less than 2 °C lies below the ML, and WW bounds are defined as the position of the maximum temperature gradients above and below the temperature minima. We computed the cumulative buoyancy frequency of WW as the sum of  $N^2 = -\frac{g}{\rho} \frac{\delta \rho}{\delta z}$  across the WW layer, which is proportional to the PE of the water column, and grid onto  $0.5^\circ \times 0.5^\circ$  median climatologies for the months of January, February, March and April. Subsequently, data from the years 2004, 2015 and 2021 were extracted from the dataset, since they sample years of known large iceberg proximity<sup>9,27,48,49,69,70</sup>.

The box extents of large icebergs and/or fragments in this region are defined as  $34-37^{\circ}$  W,  $55.5-57.5^{\circ}$  S for February 2021 ( $3^{\circ} \times 2^{\circ}$  coverage due to extreme fragmentation and distribution of A-68's constituents<sup>49</sup>) and  $34.5-35.5^{\circ}$  W,  $53-54^{\circ}$  S for April 2015 ( $1^{\circ} \times 1^{\circ}$  coverage coinciding with iceberg B-17a)<sup>69</sup>. No data coincided with the iceberg pathway in 2004. In these box extents, hydrographic profiles comprised 16 ship-based profiles during February 2021 and 2 Argo float profiles during April 2015. The climatological data for the same regions contained 70 profiles (constituting 27 Argo profiles, 16 ship-based CTDs and 27 Marine Mammals Exploring the Oceans Pole to Pole profiles) for 2021 and 7 Argo profiles for April 2015.

#### **Data Availability**

Satellite images are available from the NASA Worldview and Modified Copernicus Sentinel data 2021/Sentinel Hub via the NASA Worldview application at https://worldview.earthdata.nasa.gov/, part of the NASA Earth Observing System Data and Information System (EOSDIS). Glider data are available via the British Oceanographic Data Centre (BODC), National Oceanography Centre at https://platforms. bodc.ac.uk/deployment-catalogue/, with data provided under the UK Open Government Licence (OGL). The ship-borne dataset is available via the BODC at https://www.bodc.ac.uk/data/bodc database/ nodb/cruise/17790/, with the JC211 cruise inventory page available at https://www.bodc.ac.uk/resources/inventories/cruise inventory/ report/17790/. A-23 section data used for GEM are available via CLIVAR and the Carbon Hydrographic Data Office (CCHDO) at https://cchdo. ucsd.edu/search?q=A23. SSHs are available via EU Copernicus Marine Service information at https://doi.org/10.48670/moi-00149. Hydrographic profiles for WW estimations are from Argo floats<sup>65</sup>, tagged marine seals<sup>66</sup> and ship-based CTD casts and glider profiles<sup>67</sup>.

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# **Author contributions**

N.S.L.: conceptualization, data curation, formal analysis, investigation, methodology, software, validation, visualization and writing original draft preparation. J.A.B.: conceptualization, formal analysis, investigation, resources, supervision, validation and writing—review and editing. K.R.H.: formal analysis, investigation, validation and writing—review and editing. T.S.: data curation, investigation, methodology and software. A.B.-F.: formal analysis and validation. E.P.A.: investigation, data curation, formal analysis and investigation. M.P.M.: conceptualization, investigation, project administration, resources, supervision, validation and writing—review and editing. G.A.T.: conceptualization, investigation, funding acquisition, project administration, resources, supervision, validation and writing—review and editing.

# **Competing interests**

The authors declare no competing interests.

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