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Enhanced Southern Ocean marine productivity due to fertilization by giant icebergs

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Primary productivity is enhanced within a few kilometres of icebergs in the Weddell Sea[1,2] owing to the input of terrigeneous nutrients and trace elements during iceberg melting. However, the influence of giant icebergs, over 18 km in length, on marine primary production in the Southern Ocean is less well studied[1,3]. Here we present an analysis of 175 satellite images of open ocean colour before and after the passage of 17 giant icebergs between 2003 and 2013. We detect substantially enhanced chlorophyll levels, typically over a radius of at least 4–10 times the iceberg's length, that can persist for more than a month following passage of a giant iceberg. This area of influence is more than an order of magnitude larger than that found for sub-kilometre scale icebergs[2] or in ship-based surveys of giant icebergs[1]. Assuming that carbon export increases by a factor of 5–10 over the area of influence, we estimate that up to a fifth of the Southern Ocean's downward carbon flux originates with giant iceberg fertilization. We suggest that, if giant iceberg calving increases this century as expected[4], this negative feedback on the carbon cycle may become more important.

The Southern Ocean is a significant sink in the ocean component of the global carbon cycle, contributing ~10% of the ocean's total carbon sequestration through a mixture of chemical and biologically driven processes[5]. However, its contribution is at a lower level than that of the smaller South Pacific and Indian Oceans[5], owing to its low concentration of dissolved iron, an important trace nutrient for primary production[6]. Atmospheric dust is a major background source of iron to the region[7], but iron-rich sediment fluxes from islands[8], continental shelves[9], ice sheet meltwater[10] and melting icebergs[1] are known to be other, locally much more important, sources of iron. There are a few large-scale estimates of the contribution of icebergs to the Southern Ocean iron flux, derived from modelling studies of typical sub-kilometre sized icebergs[11,12] scaling up of observational studies[13,14] or remote sensing studies[2]. However, these assume iceberg inputs are well represented by those from the smaller, sub-kilometre, peak in the very bimodal size distribution[15]. In fact about half the total iceberg discharge volume is made up of giant icebergs[15]—those exceeding 18 km in horizontal dimension—and there have at present been only two observational studies of the phytoplankton blooms close to individual giant icebergs, both in conditions within or near sea-ice cover in the Weddell Sea[1,3]. Such areas may be subject to enhanced productivity due to the impact of sea-ice fertilization[16]. Although the calving of giant icebergs is very episodic[15], they derive from a range of geographical and geologic environments around Antarctica, and are thus likely to have different iron and nutrient characteristics. Several dozen such icebergs are present in the Southern Ocean at any one time[15], and they can survive for many years. Even when in areas of open water, giant icebergs can survive for longer than a year[17]. Here we examine the chlorophyll signature from a range of giant icebergs in the open Southern Ocean using remote sensing, to show that ocean fertilization from such icebergs is much larger than previously suspected.

Chlorophyll levels are well known to be raised near icebergs[1,2,18]. This derives from the meltwater plumes from icebergs containing significant concentrations of iron, but also a range of other nutrients[14]. As the Southern Ocean is a high-nutrient low-chlorophyll (HNLC) region[6], it is the bioavailable iron known to be in nanoparticle aggregates of ferrihydrite and goethite in iceberg sediments[13] that is the key nutrient within this meltwater. Dissolution of these particles leads to enriched concentrations of dissolved iron in the meltwater plume at levels 10–1,000 times those due to atmospheric dust[19]. Ship-based studies have demonstrated that, for an iceberg of maximum horizontal size L_i, chlorophyll levels are enhanced downstream over a distance of $\sim L_i$ (ref. 20). Similarly, it has been shown using SeaWiFS ocean colour that the probability of chlorophyll being enhanced six days after an iceberg with a L_i of ~1 km has passed over a location is a third higher than from chance alone[2]. However, the inherent practical limitations of these studies mean that an accurate picture of the chlorophyll enhancement in waters surrounding a giant iceberg is not known.

The potential for major enhanced production around giant icebergs is shown in Fig. 1, where chlorophyll levels in excess of ten times background extend in plumes at least 3–4 L_i both upstream and downstream of iceberg C16. Examining the chlorophyll signal of a range of giant icebergs calved from around Antarctica over a ten-year period (see Supplementary Methods and Supplementary Table 1), it is found that such an enhancement is ubiquitous and long lasting. A chlorophyll enhancement by a factor of ten is found at least a month following passage of a giant iceberg (Fig. 2a). This order of magnitude enhancement peaks 50–200 km from the giant iceberg, but some enhancement typically extends for over 500 km from the iceberg (Fig. 2b), and occasionally for over 1,000 km. Note that Fig. 2b also implies that measurements taken near a giant iceberg, as has normally been necessary in field campaigns, will significantly underestimate the fertilization peak. This lower production near the iceberg, and the unexpected enhancement of production ahead of the iceberg, are probably due to the buoyant plume associated with the basal melting of the iceberg. The buoyant meltwater plume takes a little time to rise to the surface ahead of the iceberg[20]. This displacement, coupled with the need for time for the enhanced production to develop and possible increased phytoplankton predation close to the iceberg[20], means that the fertilization near the iceberg is lower than further afield. It then spreads out near the surface, transporting dissolved material, allowing this fertilizing material to move ahead of the iceberg, driven by the surface ocean current. Figure 1 shows that this forward fertilization can be substantial.

There is no statistically significant difference between the magnitude of fertilization effects in spring and summer.

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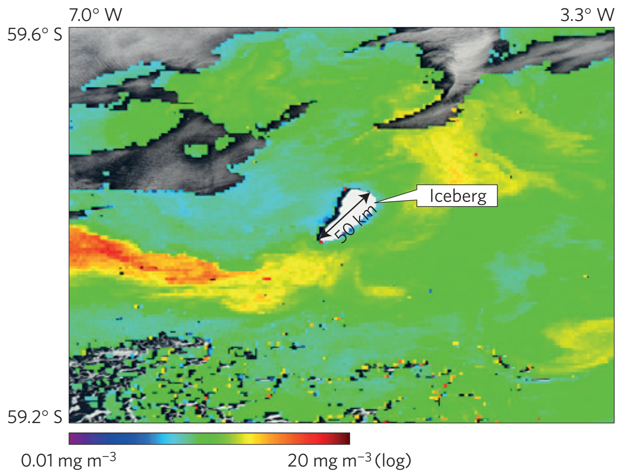

Figure 1 | Chlorophyll-*a* concentration on 12 January 2013, from the MODIS Aqua satellite. Giant iceberg C16 is visible in the centre of the picture, with enhanced levels spreading southwest and northeast from the iceberg. Greyscale areas show cloud cover.

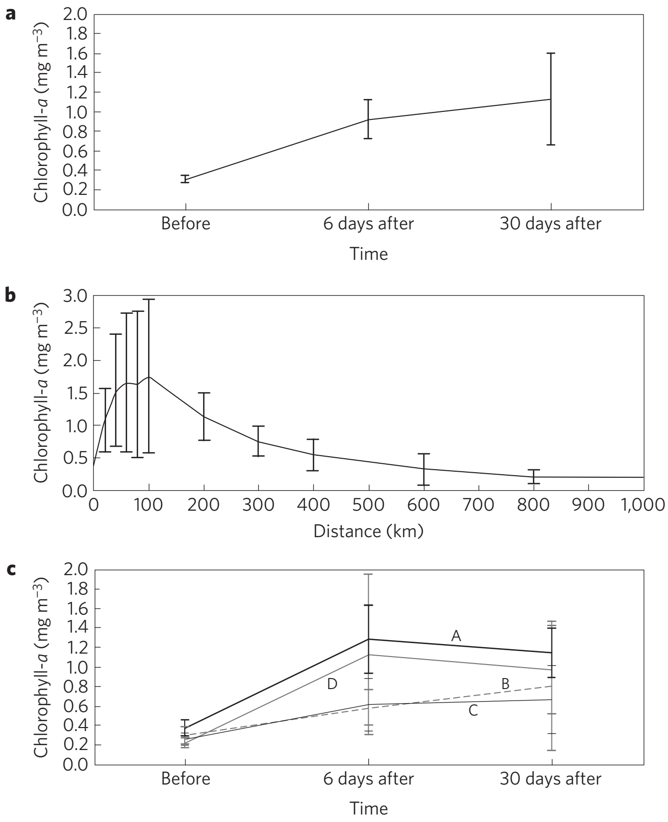

Figure 2 | Mean chlorophyll level associated with the passage of a giant iceberg. a, Mean chlorophyll level before and after passage. **b**, Mean chlorophyll level at a distance from such an iceberg. **c**, Sector dependence (for sectors A, B, C and D) of mean chlorophyll before and after passage. The levels are in mg m^{-3} and 95% confidence intervals are shown.

Similarly, there is no statistically significant difference between the origins of giant icebergs in their fertilization effect a month after passage (Fig. 2c). However, although there is a large degree of variability in the short-term fertilization effect of giant icebergs from sector D of the Antarctic (0°–90° E), giant bergs from sectors B and C (90°–180° W and 90°–180° E respectively) have only half the impact of those from sector A (0°–90° W). These differences correlate very well with the large-scale geology of Antarctica. Almost all of coastal East Antarctica (sectors C and D) is composed of Precambrian high-grade metamorphic rock from granitic facies[21], which will be less easily weathered than the low-grade Mesozoic metasedimentary and metavolcanic rocks of the Antarctica Peninsula (from which most of the sector A icebergs derive[15]). The exception to the East Antarctic geology is that the metamorphic grade of rock lowers polewards into the Amery Basin (~70° E; ref. 20), a major source of giant icebergs from sector D, consistent with a range of levels of ice-rafted debris embedded within sector D's icebergs. It is also worth noting that giant icebergs from sectors B and C often travel further before reaching the open sea[15], thus only then being able to be more easily examined by ocean colour instruments, meaning that their sediment load is likely to be depleted before they reach open water.

Noting these major increases in estimated productivity due to giant icebergs, it is pertinent to examine their implications for estimates of the contribution of icebergs in the Southern Ocean to global biogeochemical cycles. First, it is known that there is indeed an increase in the net flux of carbon to the sea floor near icebergs. A study of carbon export using Lagrangian sediment traps[18] showed a net carbon export past 600 m depth of 5.6 mg m^{-2} d^{-1} within 30 km of iceberg C18a, compared to a background of 2.5 mg m^{-2} d^{-1}. Given that the peak enhancement distance from our analysis (Fig. 2b) is at 100 km, but the traps used in the ship survey[18] were within 30 km of C18a, the estimate above of 5.6 mg m^{-2} d^{-1} is likely to be an underestimate of the peak flux. However, it gives us a starting point for a conservative global calculation of the iceberg contribution to the carbon cycle.

There have been two full biogeochemical model simulations of the impact of iceberg melting on production in the Southern Ocean[9,11]. Both suggest that coastal sediment fluxes are the major sources of iron fertilization in the Southern Ocean, leading to up to 75% of the total productivity. Both also have ~10% of the productivity deriving from icebergs. However, they were required to make assumptions about the mean bioavailable iron, including only dissolved iron and neglecting the nanoparticulate iron attached to sediments[13], with that iron being spread evenly according to model estimates of meltwater flux[15]. Given our study's implications of an area of influence for giant icebergs of more than an order of magnitude above that of 'typical' icebergs, and that approximately half of the iceberg discharge is as giant icebergs[15], with several dozen giant icebergs present in the Southern Ocean at any one time[4], these model calculations of iceberg productivity are likely to be a significant underestimate. This conclusion is supported by another modelling study which concentrated on glacial meltwater and higher iceberg fluxes, but did not include shelf sediment iron fluxes[12].

A rough estimate of this giant iceberg carbon export is 0.012–0.040 Gt yr^{-1} (see Supplementary Methods), approaching 10–20% of the estimated Southern Ocean total carbon export[5]. Our analysis therefore suggests that the total impact of icebergs on the carbon cycle in the Southern Ocean has been underestimated, and may constitute up to a fifth of the total carbon export of that ocean.

Although it is difficult to discern net trends over time in the very episodic calving of giant icebergs[15], satellite gravity measurements suggest that there has been a 5% increase in ice discharge from Antarctica over the past two decades[22]. Recently, concern over the stability of the West Antarctic Ice Sheet has arisen[4,23], with implications for more ice discharge in the future, and thus carbon drawdown through fertilization. Note that even an increase in regional sediment-rich ice sheet meltwater into coastal waters can lead to enhanced fertilization[10,12,24], although that associated with giant iceberg melting may be even greater (Fig. 3). The future may therefore see an increase in Southern Ocean carbon sequestration through this iceberg fertilization mechanism, acting as a secondary negative feedback on climate change.

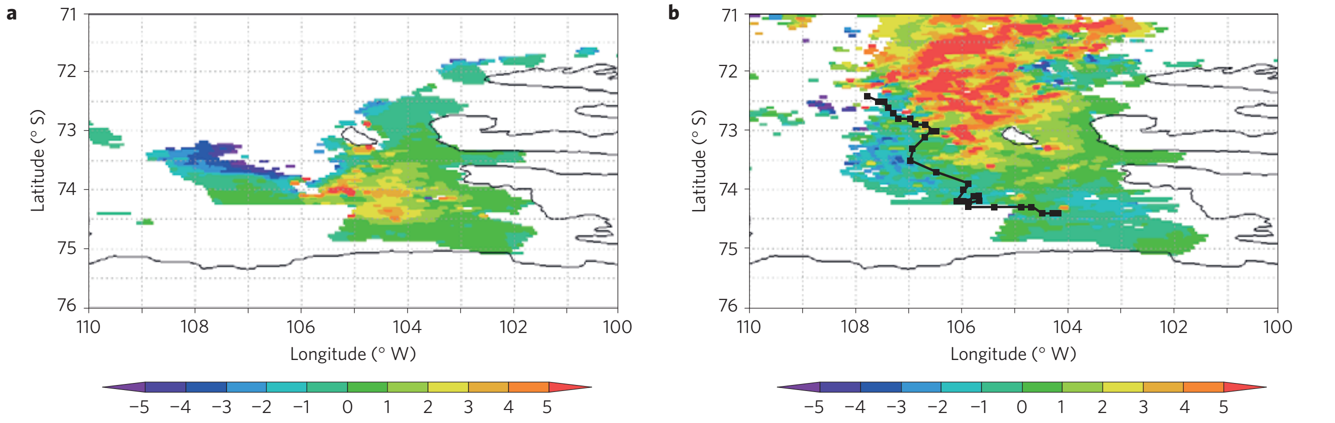

Figure 3 | Chlorophyll concentration anomaly in the Pine Island Bay region of West Antarctica related to the passage of giant iceberg, B31. a,**b**, Means for Jan.–Mar. of 2011 (**a**) and 2014 (**b**) from the MODIS Aqua satellite. The units are in mg m^{-3}, relative to the Jan.–Mar. mean over 2003–2015. Note the increased productivity offshore in 2014, downstream of B31 (ref. 25). The path of B31 over those three months is shown by the black line in **b**. White areas over the sea were covered by cloud for most of the respective three months.

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Author contributions

G.R.B. and L.P.A.M.D. conceived the project; L.P.A.M.D. carried out much of the analysis and assisted with writing; G.R.B. contributed to the analysis and was the principal writer of the final manuscript. D.J.W. carried out some of the tracking work shown in Fig. 3, and commented on the manuscript.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to G.R.B.

Competing financial interests

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Methods

The giant iceberg tracks used for the main analysis come from the Brigham Young University Center for Remote Sensing Iceberg Tracking database (www.scp.byu.edu/data/iceberg/database1.html) which uses satellite scatterometer backscatter to identify giant icebergs[26]. The resolution achievable by these satellite sensors is 4-5 km[26], but only those icebergs meeting the giant iceberg definition of having an L_i > 18 km enter the database from which we selected the icebergs to be analysed. All icebergs examined are therefore well resolved.

Once the positions of giant icebergs were obtained, the Level 1 and 2 MODIS ocean colour images were exported from oceancolor.gsfc.nasa.gov using SeaDAS software v7.0.2. Chlorophyll concentrations were analysed from eleven years (2003-2013) for 65 positions during a one-month period 20 days prior to a giant iceberg passage, 63 positions for the seven-day period post-passage, and 47 values for the seven-day period following the iceberg passage. These came from 17 giant iceberg tracks (see Supplementary Table S1). The number of positions for icebergs from the A-D sectors were 22, 16, 15 and 10 respectively. The positions were taken from sea-ice free areas, restricting the number of possible images analysed from sectors B-D, and were almost all from equatorward of 60°S. Only portions of tracks were chosen where it was clear that the icebergs were not grounded, as can be seen from the sequence of positions in Supplementary Table S1. Note also that the one iceberg, C19a, which was followed both before and after austral winter (2008) remained in

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open water throughout the entire time between its first and last used image[27].The mean chlorophyll concentration was obtained from a 15 km radius centred on the iceberg's geographical coordinates using the geometry mask tool from the SeaDAS software. The significant time difference between the before and after passage values was used because of the presence of major plumes both upstream and downstream from a giant iceberg's position (Figure 1).

A selection of 20 images (Supplementary Table S2) where a clear and delimited plume of increased chlorophyll could be visually associated with the iceberg was chosen to draw a chlorophyll concentration profile with respect to distance from the iceberg (Figure 2b). These images were selected according to the following four criteria.

1. Minimizing the degree of cloudiness around the iceberg and its surrounding sea water. From all NASA Ocean Colour images examined on a daily basis during the austral summer periods of 2003-2013, only a few dozen were sufficiently clear of clouds for it to be possible to identify the location of the iceberg and visualise the extent of its surrounding plume as a whole.

2. Clarity of the border of the plume. From the selection above, we chose the images with the clearest contrast between the iceberg's plume colour and the surrounding sea water. Highly dissipated or scattered plumes were rejected due to the uncertainty of the link to the iceberg.

3. Maximising the distance from shorelines and seasonal icepack. The images were all selected in the summer period and were far away from the seasonal icepack around the Antarctic continent. Images where the icebergs were close to South Georgia (a common route for giant icebergs coming out of the Weddell Gyre) were

not employed so as to avoid any interference from sedimentary iron released from the island's shelf.

4. Ensuring that icebergs were free-drifting. All the 20 images used were taken from part of the free drifting routes of the icebergs concerned. This was easily verified from the daily changing position of the icebergs during the previous and following days of the selected image.

From the images selected, a line was drawn from the iceberg edge toward the background value traversing the plume along its longest axis. Along this line, chlorophyll concentrations were obtained from 0, 3, 5, 10, 20, 40, 60, 80, 100, 200, 400, 600, 800, 1000 km distance from the iceberg and Figure 2b was generated from the mean value and standard deviation of observations from each distance.

There are clear limitations to the study. The number of images obtained were restricted due to the high degree of cloudiness of the Southern Ocean, and the limited number of sun-lit months further south. A number of the images are likely to be affected by other iron sources, such as coastal sediment fluxes from South Georgia[28, 29], although this was minimized as much as possible. Another limitation is that MODIS tends to overestimate chlorophyll concentrations that are low, minimizing the impact found. However, overall, MODIS's error accuracy for surface layer measurements in depths > 20 m is close to the instrument 35% target error[30]. A final limitation is that deep chlorophyll concentrations may occasionally be disturbed by passage of an iceberg, leading to an artificially enhanced chlorophyll level[2].

To estimate the additional carbon export through the increased area of influence of giant icebergs found in this study the following calculations were made. The observed 2.5 mg m^{-2} day^{-1} background export[18] was assumed to relate to the far-

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field chlorophyll concentration of Figure 2b. From Figure 2, this was assumed to be increased to 25 mg m^{-2} day^{-1} over an area of $\pi(4L_I)^2$, or 12.5 mg m^{-2} day^{-1} over an area of $\pi(10L_I)^2$ where a typical giant iceberg $L_I \sim 30$ km, and there are typical 30 such icebergs in the Southern Ocean[15, 26]. This gives a total giant iceberg export of 0.012-0.040 Gt yr^{-1}.

The images from Figure 3 were obtained from analyses and visualizations produced with the Giovanni online data system, developed and maintained by NASA GES DISC (gdata1.sci.gsfc.nasa.gov/daac-bin/G3/gui.cgi?instance_id=ocean_month). The track of iceberg B31 in Figure 3 comes from using a range of sources over January-March 2014: Terra and Aqua satellite MODIS reflectance, available from earthdata.nasa.gov/labs/worldview ; and SAR data from the TerraSAR-X and Radarsat2 satellites. Data on the track and evolving dimensions of B31 extending over a much longer period will be available towards the end of 2016 in the British Antarctic Survey's Polar Data Centre (https://www.bas.ac.uk/team/business-teams/information-services/polar-data-centre/).

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