Article:

Bigg, G.R. orcid.org/0000-0002-1910-0349 (2020) The impact of icebergs of sub-Antarctic origin on Southern Ocean ice-rafted debris distributions. Quaternary Science Reviews, 232. 106204. ISSN 0277-3791

https://doi.org/10.1016/j.quascirev.2020.106204

Opinion Paper

The impact of icebergs of sub-Antarctic origin on Southern Ocean ice-rafted debris distributions

Grant R. Bigg[a,*]

[a] Department of Geography, University of Sheffield, UK

* Corresponding author. Department of Geography, Winter Street, University of Sheffield, Sheffield S10 2TN, UK.

E-mail address: grant.bigg@sheffield.ac.uk (G. Bigg)

ABSTRACT

The presence of widespread terrigenous material of an ice-rafted origin in Quaternary sediments of the Southern Ocean has been recognized for almost 150 years. Normally this material has been ascribed to deposits from icebergs of continental Antarctic origin. However, during Quaternary glaciations there have been periods of extensive land ice across the sub-Antarctic, on both islands scattered around most of the circumpolar extent of the Southern Ocean, as well as in Patagonia, so providing alternative sources for debris-carrying icebergs. Here a relatively high resolution ocean and iceberg model is used to study the potential distribution of ice-rafted debris (IRD) from the range of past ice sources around the Southern Ocean. It is shown that IRD found in marine cores of the Southern Ocean is most likely to have derived from the Antarctic continent in some regions, particularly of the South Atlantic, but that for extensive regions of the Southern Ocean sub-Antarctic sources of IRD, rather than the continent itself, are more likely. This is particularly true equatorward of 55°S, away from the core continental iceberg outflow from the Weddell gyre. It is argued that the glaciated sub-Antarctic cannot be neglected in explaining past IRD records in the Southern Ocean. This has implications not just for reconstructing the history of glaciation in the sub-Antarctic, but also for understanding past variation in the upper ocean circulation within the Quaternary Southern Ocean.

Keywords

Quaternary

Paleoceanography

Southern Ocean

Modelling

Ice-rafted debris

Past glaciation

1. Introduction

The global oceanographic expedition of HMS Challenger (1872-1876) pioneered the study of marine ice-rafted debris (IRD). It provided the first extensive record of IRD in the sediments of the Southern Ocean (Thomson and Murray, 1896). It has therefore been known for a long time that IRD is present around the Southern Ocean, even reaching the southern sub-tropics. It is also known that an IRD record extends deep into marine sediments, reflecting the long-term glaciation history of Antarctica since at least the Late Pliocene (Ehrmann et al., 1991).

This extensive IRD record is normally considered to reflect variations in iceberg flux from Antarctica (e.g. Kanfoush et al., 2000; Nielsen et al., 2007). Even in today's interglacial conditions icebergs originating from Antarctica are found over extensive areas of the Southern Ocean, particularly in the outflow of the Weddell Gyre, where they occasionally reach 40^{o}S (Tournadre et al., 2016; Figure 1a). However, modern distributions also suggest icebergs rarely reach open water equatorward of ~ 55-60^{o}S over most of the Southern Ocean.

The circumpolar nature of the Southern Ocean, combined with the flow restriction through the Drake Passage, means the basic structure of a strong eastward-flowing Antarctic Circumpolar Current (ACC) is a constant during the Quaternary. During glacial periods it is likely that stronger, and northward-shifted, westerly winds (e.g. Kim et al., 2017) displaced northwards the sequence of oceanic fronts in the ACC (e.g. Manoj and Thamban, 2015). However, climate models of the last glacial do not even hindcast this with the same direction of change (e.g. Kim et al., 2017; Lowry et al., 2019). The contrast between glacial and interglacial patterns of Southern Ocean IRD should therefore be geographically modest.

However, the much more geographically extensive record of past iceberg presence, as interpreted through IRD levels in glacial sediments, combined with the increasing awareness of substantial, marine-terminating, past glaciations of the Southern Ocean's sub-Antarctic islands (Hodgson et al., 2014) and Patagonia (Rabassa et al., 2011), opens the question of whether down-core Southern Ocean IRD distribution conveys information about Southern Hemisphere glacial history beyond just Antarctica. Past research has largely ignored this possibility, even, for example, suggesting volcanic material in IRD was transported aerially to the Antarctic margin before being carried by icebergs or sea-ice into the South Atlantic, when a more straightforward interpretation would be iceberg transport from glaciated volcanic islands (Kanfoush et al., 2000; Nielsen et al., 2007). Here this open question is explored using a relatively high resolution intermediate complexity climate model containing a well tested iceberg model (e.g. Levine and Bigg, 2008; Wilton et al., 2015). The model simulations will show the necessity of including non-Antarctic iceberg sources in interpretation of Southern Ocean glacial IRD records.

2. Data & Methods

2.1 IRD IODP record

IRD has been recorded in lithological logs within the Quaternary sediments of the International Ocean Discovery Program (IODP) cores collected in the Southern Ocean since the late 1960s (Figure 1b). These show significant levels of Quaternary IRD further equatorward than those seen in today's interglacial (Figure 1a), although there is little, and in some ocean basins, no, IRD reaching beyond 40^{o}S even during glacial periods. Only in the Indian Ocean sector of the Southern Ocean is there a low background level of glacial period IRD further north.

2.2 Ocean and Iceberg Model

The FRUGAL (Fine ResolUtion Greenland And Labrador) intermediate complexity global climate model includes coupling between ocean, radiative-advective atmospheric, simple advective-thermodynamic sea-ice, and iceberg trajectory models (Levine and Bigg, 2008). The version of FRUGAL used here has a grid equivalent to approximately 2° longitude by 1.5° latitude in the Southern Hemisphere (see Wilton et al. (2015) for details of the ocean and sea-ice model configurations). The atmospheric part of FRUGAL is the same as that used for Levine and Bigg

(2008), with no feedback between the monthly-varying glacial wind stress and the sea surface temperature field. The iceberg module has both dynamic and thermodynamic components; in this study while there is dynamical melting of the moving icebergs there is no feedback of the meltwater into the ocean dynamics of FRUGAL as interest focuses on the trajectory envelope only.

In the basic model configuration seeded model icebergs are divided into ten different size classes (Levine and Bigg, 2008), based on observations of today's Arctic and Southern Ocean icebergs. However, here we also seed an additional giant iceberg class of 20x30 km icebergs from Antarctic ice shelves, as these will travel further before melting, particularly in glacial conditions. While ice fluxes from Antarctica will have varied significantly over past glacial periods (Kanfoush et al., 2000) the stability of sea level around the LGM compared to today, combined with glacial Antarctic climate simulations, suggests that the LGM Antarctic surface mass balance, and hence iceberg flux, was similar to that today (Berends et al., 2018). We therefore use similar continental Antarctic iceberg fluxes in our simulations as those used for today in Levine and Bigg (2008). While each model berg is assigned a scale factor appropriate to the mass flux from its specific seed site, as in Levine and Bigg (2008), here the emphasis is on the trajectory envelope as much as the simulated concentration distribution, as this cannot be known for previous glaciations.

An 1100 year spin-up simulation was run, using orbital parameter and atmospheric CO_2 levels from 21 kyr BP as well as the glacial topographic and atmospheric forcing used in Levine and Bigg (2008).

3. Modelling Results

Iceberg model simulations for the modern Southern Ocean (e.g. Levine and Bigg (2008); Marsh et al. (2015)) show similar distributions to modern day observations (Figure 1a). This is despite these simulations not including any explicit giant iceberg contribution.

During glacial periods icebergs entered the Southern Ocean from the Antarctic continental shelf edge, widely scattered maritime Antarctic and sub-Antarctic islands (Hodgson et al., 2014), and likely also from Patagonia (Rabassa et al., 2011). The icebergs of Antarctic origin were shed by a larger ice sheet, but in terms of likely release locations these would have only been displaced 2-3^{o} equatorward, except off the Ross and Weddell Sea ice shelves. In the experiments reported here the difference in iceberg density over the Southern Ocean is compared between an experiment seeded with glacial Antarctic icebergs, with assumed modern fluxes, and one with additional iceberg fluxes from other non-Antarctic glacial sources, all of which were assumed to contribute < 0.5 km^3yr^{-1}.

This difference is shown in Figures 1b-d, which clearly demonstrate the significantly wider geographical spread of iceberg trajectories, and hence IRD deposition, during glacial periods when non-continental Antarctic iceberg sources are considered. This difference, while visible in all areas of the Southern Ocean, is most obvious in the Southeast Atlantic and western/central Indian Ocean, due to the larger number of glaciated sources in the LGM Atlantic and SW Indian Ocean sectors.

4. Discussion and Conclusion

An important difference between present day iceberg densities in the Southern Ocean (Figure 1a) and those modelled in the LGM (Figures 1b-d) is the impact on iceberg trajectories of an LGM equatorward shift of Antarctic continental sources, combined with a similar shift of the ACC and sea surface temperature fronts. Many existing studies of IRD records in the Quaternary Southern Ocean are therefore likely to be sampling material of Antarctic continental origin. However, while there are a small number of LGM model icebergs that reach the southeast Atlantic and western

Indian Ocean, the model simulation with sub-Antarctic sources (Figures 1c, 1d) suggests it is much more likely that IRD in cores in this region does not originate from the Antarctic itself. This is also likely to be the case in cores off New Zealand and the Kerguelen Islands of the central Indian Ocean.

The comparisons in Figure 1d between model iceberg densities and a coarse measure of glacial IRD abundance show that the model is not perfect in reproducing the IODP distribution. The underlying last glacial climate model is of reasonable, but not eddy-resolving, resolution, and only a decade of simulation is sampled. The simulation is thus not fully representative of the variation in Quaternary glacial ocean and iceberg signals. However, the model experiments strongly suggest that a wider range of source regions than just Antarctica should be considered in IRD studies of the Atlantic/Indian sector of the Southern Ocean between ~ 15^{o}W and 60^{o}E, and up to 15^{o} downstream of previously glaciated sub-Antarctic islands or Patagonia.

What are the implications of this study for understanding the past Southern Ocean? No longer must the vast majority of past iceberg-debris be traced back to Antarctica itself. Many sub-Antarctic islands have volcanic origins (e.g. Nielsen et al., 2007), providing potentially easily sourced rocks for glacial entrainment. However, the South Georgia ice sheet (Graham et al., 2017), and Patagonia (Rabassa et al., 2011), have more sedimentary origins which need to be geochemically distinguished from rocks of Antarctic origin. Future work on IRD provenance in the Atlantic and Indian Oceans would then have a more representative set of potential source lithologies to aid current, and past glaciation, climate reconstruction.

Acknowledgements

I thank Ian Hall and Aidan Starr for our discussions on their work on the IRD of the Agulhas Plateau core U1475, which prompted me to embark on these experiments.

References

Berends, C.J., de Boer, B., van de Wal, R.S.W., 2018. Application of HADCM3@Bristolv1.0 simulations of paleoclimate as forcing for an ice-sheet model, ANICE2.1: set-up and benchmark experiments. Geosci. Model Dev. 11, 4657-4675.

Ehrmann, W.E., Grobe, H., Fütterer, D.K., 1991. Late Miocene to Holocene glacial history of East Antarctica revealed by sediments from sites 745 and 746. In: Proc. Ocean Drill. Prog. Ser. Res., ed. Barron, J., Larsen, B., Baldauf, J.G. et al., 119, 239-260.

Graham, A.G.C., Kuhn, G., Meisel, O., Hillenbrand, C.D., Hodgson, D.A., Ehrmann, W., Wacker, L., Wintersteller, P., Ferreira, C.D.S., Romer, M., White, D., Bohrmann, G., 2017. Major advance of South Georgia glaciers during the Antarctic Cold Reversal following extensive sub-Antarctic glaciation. Nature Comm. 8, 14798, doi:10.1038/ncomms14798.

Hodgson, D.A., Graham, A.C.C., Roberts, S.J., Bentley, M.J., Ó Cofaigh, C., Verleye E., Vyverma, W., Jmeli, V., Fvier V., Brustein, D., Verfaillie, D., Colhoun, E.A., Saunders, K.M., Selkirk, P.M., Mackintosh, A., Hedding, D.W., Nel, W., Hall, K., McGlone, M.S., Van der Putten, N.,Dickens, W.A., Smith, J.A, 2014. Terrestrial and submarine evidence for the extent and timing of the Last Glacial Maximum and the onset of deglaciation on the maritime-Antarctic and sub-Antarctic islands. Quat. Sci. Rev. 100, 137-158.

Kanfoush, S.L., Hodell, D.A., Charles, C.D., Guilderson, T.P., Mortyn, G., Ninnemann, U.S., 2000. Millennial-scale instability of the Antarctic Ice Sheet during the Last Glaciation. Science 288, 1815-1818.

Kim, S.-J., Jun, S.-Y., Kim, B.-M., 2017. Sensitivity of southern hemisphere westerly wind to boundary conditions for the last glacial maximum. Quat. Int. 459, 165-174.

Levine, R.C., Bigg, G.R., 2008. The sensitivity of the glacial ocean to Heinrich events from different sources, as modelled by a coupled atmosphere-iceberg-ocean model. Paleoceanogr. 23, PA4213, doi:10.1029/2008PA001613.

Lowry, D.P., Golledge, N.R., Menviel, L., Bertler, N.A.N., 2019. Deglacial evolution of regional Antarctic climate and Southern Ocean conditions in transient climate simulations. Clim. Past 15, 189-215.

Manoj, M.C., Thamban, M., 2015. Shifting frontal regimes and its influence on bioproductivity variations during the Late Quaternary in the Indian sector of Southern Ocean. Deep-Sea Res II 118, 261-274.

Marsh, R., Ivchenko, V.O., Skliris, N., Alderson, S., Bigg, G.R., Madec, G., Blaker, A.T., Aksenov, Y., Sinha, B., Coward, A.C., Le Sommer, J., Merino, N., Zalesny, V.B., 2015. NEMO-ICB (v1.0): interactive icebergs in the NEMO ocean model globally configured at coarse and eddy-permitting resolution, Geoscientific Mod. Dev. 8, 1547-1562.

Nielsen, S.H.H., Hodell, D.A., Kamenov, G., Guilderson, T., Perfit, M.R., 2007. Origin and significance of ice-rafted detritus in the Atlantic sector of the Southern Ocean. Geochem. Geophys. Geosystems 8, Q12005, doi:10.1029/2007GC001618.

Rabassa, J., Coronato, A., Martinez, O., 2011. Late Cenozoic glaciations in Patagonia and Tierra del Fuego: an updated review. Biol J Linnean Soc. 103, 316-335.

Thomson, C.W., Murray, J., 1891. Mineral substances of terrestrial and extra-terrestrial origin in deep-sea deposits. Deep-sea deposits (Chapter 5). Report of the Scientific results of the voyage of H.M.S. Challenger during the years 1873-76. HMSO, London, 291-336.

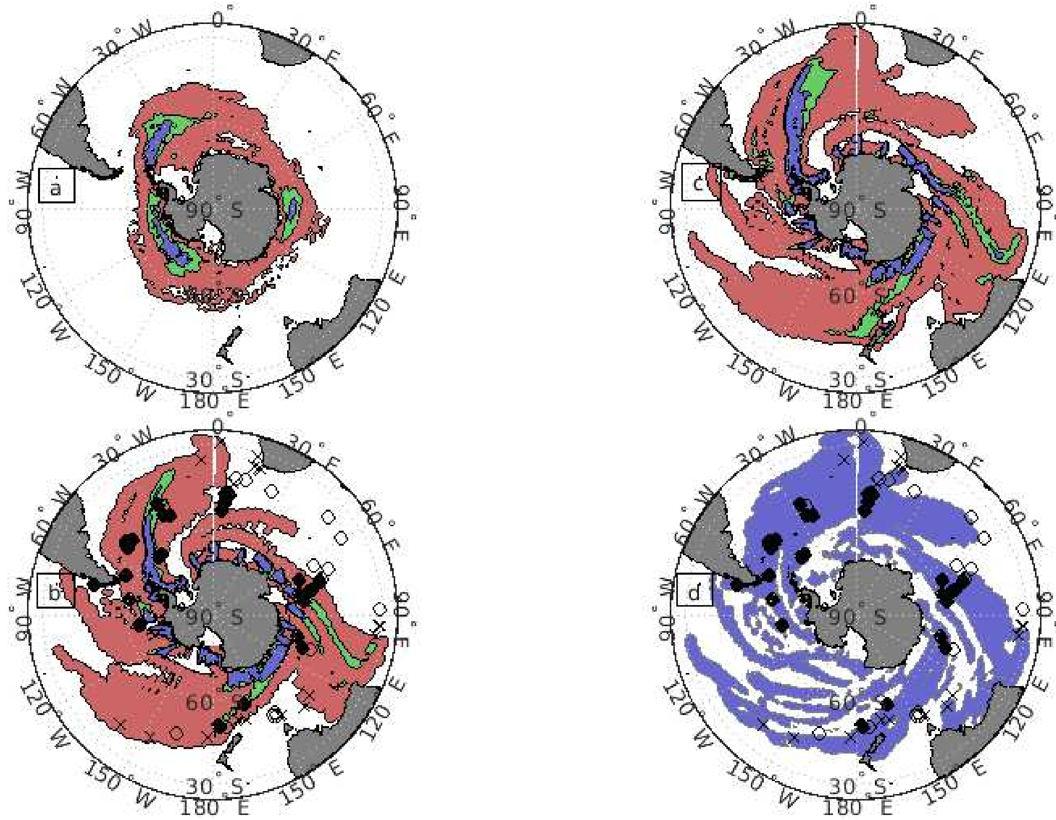
Tournadre, J., Bouhier, N., Girard-Ardhuin, F., Rémy, F., 2016. Antarctic icebergs distributions 1992-2014. J. Geophys. Res. Oceans 121, 327-349.

Wilton, D.J., Bigg, G.R., Hanna, E., 2015. Modelling twentieth century global ocean circulation and iceberg flux at 48°N: implications for west Greenland iceberg discharge. Prog. Oceanogr. 138, 194-210.

Figure Legend

Figure 1: a) Probability of iceberg presence in today's Southern Ocean, using data of Tournadre et al. (2016). Outer contour is mean probability of iceberg presence in any month over 1991-2019 of 0.0001; inner contours are 0.001 and 0.002. This panel is followed by maps showing mean model iceberg density over 10 years in b) LGM Antarctic-only and c) LGM complete Southern Ocean iceberg source simulations. Panel d) shows the region (in purple) where icebergs with a sub-Antarctic source occurred in the full simulation (Figure 1c). Outer contour in b) and c) is 0.2 iceberg/degree square/year, while inner contours are 200 and 400. Overlaid on panels b and d are IODP site measures of IRD presence. Solid circles show records of significant IRD through more than part of the Quaternary record. Open circles show some evidence of IRD, although of limited concentration or depth range. Crosses show locations where IRD is not mentioned in the Quaternary sections of lithologic logs. See Spreadsheet 1 in Supplementary Material for log summaries.

Figure 1



a
b
c
d
0°
30° E
60° E
90° E
120° E
150° E
180° E
30° W
60° W
90° W
120° W
150° W
90° S
60
30° S