

**Antarctic Ice Sheet
fertilises the
Southern Ocean**

R. Death et al.

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Antarctic Ice Sheet fertilises the Southern Ocean

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Abstract

Southern Ocean (SO) marine primary productivity (PP) is strongly influenced by the availability of iron in surface waters, which is thought to exert a significant control upon atmospheric CO₂ concentrations on glacial/interglacial timescales. The zone bordering the Antarctic Ice Sheet exhibits high PP and seasonal plankton blooms in response to light and variations in iron availability. The sources of iron stimulating elevated SO PP are in debate. Established contributors include dust, coastal sediments/upwelling, icebergs and sea ice. Subglacial meltwater exported at the ice margin is a more recent suggestion, arising from intense iron cycling beneath the ice sheet. Icebergs and subglacial meltwater may supply a large amount of bioavailable iron to the SO, estimated in this study at 0.07–1.0 Tgyr⁻¹. Here we apply the MIT global ocean model (Follows et al., 2007) to determine the potential impact of this level of iron export from the ice sheet upon SO PP. The export of iron from the ice sheet raises modelled SO PP by up to 40 %, and provides one plausible explanation for very high seasonally observed PP in the near-coastal zone. The impact on SO PP is greatest in coastal regions, which are also areas of high observed marine PP. These results suggest that the export of Antarctic runoff and icebergs may have an important impact on SO PP and should be included in future biogeochemical modelling.

1 Introduction

Primary production in the Southern Ocean (SO) accounts for 5–10 % of total global oceanic primary production (Moore and Abbott, 2000; Arrigo et al., 2008) and has an important impact on climate via its regulatory effect upon atmospheric CO₂ concentrations (Sigman and Boyle, 2000). The SO is a High-Nutrient-Low-Chlorophyll (HNLC) region, where iron is the main limiting nutrient, preventing phytoplankton from using the available N and P (Martin, 1990). Hence, changes in the supply of iron are hypothesized to cause variations in SO PP, and hence CO₂ drawdown (Sarmiento and Orr,

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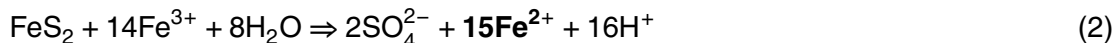
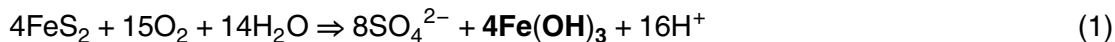
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1991). Well established iron sources include coastal sediments/upwelling (Tagliabue et al., 2009), sea ice (Edwards and Sedwick, 2001) and dust (Martin, 1990; Jickells et al., 2005), and more recently iceberg rafted debris (Raiswell et al., 2008; Raiswell and Canfield, 2012). Subglacial meltwater discharged from the ice sheet has received comparatively little attention to date (Statham et al., 2008; Wadham et al., 2013). The impacts both these glacial sources of iron upon SO PP have not yet been quantified and form the focus of this paper. The significance of glacial iron sources is heightened by predictions of rising meltwater and iceberg fluxes in future decades (Vaughan, 2006; Pritchard et al., 2012).

Debris entombed in icebergs and meltwater from beneath glaciers has been shown to be rich in bioavailable iron, arising from intense iron cycling in subglacial environments (Raiswell et al., 2008; Statham et al., 2008; Wadham et al., 2010; Bhatia et al., 2013). Sulphide oxidation produces Fe(III) (in the form of Fe(OH)₃) under oxic conditions and Fe(II) by microbial mediation under anoxic conditions (Eqs. 1 and 2 respectively) (Wadham et al., 2010). It is enhanced by the continual exposure of fresh and reactive sulphide minerals by glacial erosion.



Subglacial meltwaters are generated at the bed of the ice sheet by geothermal heating of basal ice layers (Pattyn, 2010). They are driven toward the margin via the dynamic filling and draining of subglacial lakes and/or via subglacial rivers (Fricker et al., 2007; Wingham et al., 2006), where they are exported via channels or as groundwater (Supplement 2). Solute fluxes associated with this water export are likely to be high and of a similar magnitude to those from some of the planet's largest rivers (Wadham et al., 2010). We would expect iron concentrations in subglacial meltwaters (SGM-Fe, i.e. aqueous + nanoparticulate + some colloidal Fe, < 0.4 µm) to be at the higher end of the reported range for glacial runoff (e.g. µM Fe, Supplement Table 1), consistent with the prevailing elevated rock:water ratios, prolonged water residence times and anoxic con-

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ditions. In support of this are high concentrations of sulphate ions in porewaters from the Kamb and Bindschadler Ice Streams (West Antarctica) and frozen lake ice from subglacial Lake Vostok (East Antarctica) (Skidmore et al., 2010; Christner et al., 2006). The highest dissolved iron concentrations in Antarctic coastal waters have also recently been measured in the Pine Island Polyna, thought to be associated with the release of iron rich meltwater from Pine Island Glacier (Gerringa et al., 2012). Glacial ice and sea ice are relatively dilute in comparison (nM Fe, Suppl. Table 1). We calculate that the potential iron export in subglacial meltwater is $\sim 0.009\text{--}0.09 \text{ Tg a}^{-1}$ (where SGM-Fe concentrations = 3 and 30 μM respectively). This spans a similar order of magnitude to Fe sources from icebergs and aeolian dust (Raiswell et al., 2008) (Table 1).

The potential impact of iron in iceberg rafted debris upon SO PP has received greater consideration in the literature (Raiswell et al., 2008; Lancelot et al., 2009). Sulphide oxidation in regelation waters, or the diffusion and subsequent oxidation of dissolved Fe(II) generated under anoxic conditions in subglacial sediment porewaters into oxic micro-environments at the ice–bed interface where rapid oxidation will occur, produces nanoparticulate iron oxyhydroxide (Raiswell et al., 2008). This nanoparticulate iron is bioavailable (Raiswell et al., 2008) and is exported in iceberg rafted debris to the SO. It has been shown by one modelling study to have an impact on SO chlorophyll *a* concentrations that substantially exceeds that of aeolian dust (Lancelot et al., 2009).

2 Methods

2.1 Numerical model

We evaluate the potential impact of iron fluxes via icebergs and subglacial meltwater on SO PP for the present day using the MIT global ocean model (Follows et al., 2007; Monteiro et al., 2010), and compare these impacts with those from aeolian dust iron inputs. The MIT global ocean biogeochemical/ecological model has a $1^\circ \times 1^\circ$ horizontal resolution and 23 vertical levels, and uses the ECCO-GODAE state estimates of ocean

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circulation (Wunsch and Heimbach, 2007). We initialized the model with nutrient fields of WOA01 (Conkright et al., 2002) and previous simulations (Monteiro et al., 2010). The model simulations are run for 10 yr, which is sufficient to attain surface iron steady state in the SO whilst maintaining other nutrient fields close to observations. The modeled ocean ecosystem represents a range of phytoplankton and two zooplankton types. The ecosystem structure of the modelled phytoplankton is self-assembled from an initialized random population which includes different types of diatoms, nitrogen fixers, other small cyanobacteria and large eukaryotes (Monteiro et al, 2010). In addition to phytoplankton activity and grazing, the model accounts explicitly for ocean dynamics of Dissolved Organic Matter (DOM) and Particulate Organic Matter (POM). The ocean biogeochemical cycles of phosphorus, nitrogen, silica and iron are represented in the model. Full description of the model iron cycle can be found in Sect. 3.1 of the Supplement.

2.2 Iron input fluxes to the model

We model five scenarios for iron inputs to the Southern Ocean (see Table 1), which are: (A) dust-only; (B) icebergs and dust; (C) subglacial meltwater and dust (where $[Fe] = 3 \mu M$); (D) subglacial meltwater and dust (where $[Fe] = 30 \mu M$) (Supplement Table 1) and (E) subglacial meltwater, icebergs and dust (where $[Fe] = 3 \mu M$). We assume that the Fe input via subglacial meltwater is Fe(II), as would be expected for the hypothesized anoxic conditions beneath the ice sheet. The following sections detail how iron fluxes from dust, subglacial meltwater and icebergs are calculated and input to the model as forcing fields for primary productivity of the Southern Ocean. Other glacially-sourced nutrient inputs (e.g. Si) are not included in these scenarios.

2.2.1 Dust fluxes

The standard run uses the MIT model, where the aeolian dust flux (Mahowald et al., 2005) is the only source of iron to the ocean. The solubility of dust iron is set in the MIT

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model at 2.0% (considered a higher estimate; Boyd et al., 2010) which is assumed to be bioavailable to phytoplankton.

2.2.2 Subglacial meltwater Fe fluxes

Meltwater beneath the ice sheet is generated using the GLIMMER model (Rutt et al., 2009), with the modifications described in Le Brocq et al. (2011). Meltwaters are supplied from the ice sheet to the coastal cells around the ice sheet perimeter using a flow routing scheme that apportions the flow downstream based on the surrounding local slope angle. The slopes are derived from the basal topography provided by the BEDMAP dataset (Lythe et al., 2001). The total subglacial meltwater output from the Antarctic Ice Sheet calculated using this method is 52.8 Gt a^{-1} , which is similar to a previous estimate of 65 Gt a^{-1} (Pattyn, 2010). The difference between these two estimates arises because the GLIMMER method applies a constant geothermal heat flux (GHF), in contrast to (Pattyn, 2010) who uses a spatially distributed field for GHF. The fluxes to the coastal cells are summed onto a latitude/longitude grid which is concordant with the MIT model grid. In the current configuration the meltwater is released to the surface ocean layer of the MIT model. We are aware that these waters are more likely to be released from the base of the ice sheet, which may be at some depth. However, since this water will be fresh compared to seawater it is likely to upwell close to the coast. Hence, assuming water input within the surface layer of the coastal grid cells of the MIT model is a reasonable approximation of the real world situation. We recognise that we have not allowed for loss of iron through scavenging during this upwelling, and hence, the iron delivered to the surface may be a maximum estimate in each scenario.

Iron fluxes in subglacial meltwater are calculated as the product of the water input (in m^3) within each coastal cell and a representative iron concentration value. We employ lower and upper boundary concentrations (in this case 3 or $30 \mu\text{M}$: see Supplement 1) based upon field observations of typical iron concentrations in subglacial meltwaters (see Supplement Table 1). These iron fluxes associated with subglacial meltwater are

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added to the aeolian dust iron input field deposition, and used in combination as iron input forcing to the model.

2.2.3 Iceberg Fe fluxes

The release of meltwater from icebergs accounts for 60–80% of the freshwater flux from Antarctica (Martin and Adcroft, 2010). The calving locations, number and size of icebergs are calculated from balance fluxes along the coastal margins. The iceberg flux is calculated at a $1^\circ \times 1^\circ$ resolution to match the resolution of the MIT model. A statistical distribution (Gladstone et al., 2001) is used to divide this iceberg mass flux leaving the coast into ten different size classes. This allows us to generate the number of icebergs within each size class for each coastal cell. We employ an iceberg model (Bigg et al., 1997) previously applied to the Southern Ocean (Gladstone et al., 2001) to model the iceberg flow paths. The modelled iceberg tracks compare well with observations, and are discussed in Supplement Sect. 3.1c (Supplement Fig. 1).

The bioavailable iron released from melting icebergs in the model is based upon a number of assumptions since there is little observational data of the sediment loading within icebergs from Antarctica. We assume that the sediment distribution within icebergs comprises a basal debris layer (the size of which has been reported between 1 to 10 m; Anderson et al., 1980; Syvitski et al., 1996), with the remainder of the iceberg containing a sediment concentration that reflects the aeolian dust flux to the Antarctic Ice Sheet. The dust flux is derived from observations of dust deposition over Antarctica (Mahowald et al., 2009) ($0.01 \text{ gm}^{-2} \text{ yr}^{-1}$). For this study we assume that the icebergs have a debris layer depth of 5 m, which is approximately the median of values reported in the literature (Anderson et al., 1980; Syvitski et al., 1996; Dowdeswell et al., 1995). The sediment density in the icebergs is estimated at 5%. Field observations from Antarctic icebergs (Anderson et al., 1980) suggest a debris content of between 4 to 8% by weight. For comparison, samples from twenty icebergs around Spitsbergen contained a range of sediment concentrations (0.02 to 28% by weight) within the basal debris layer (Dowdeswell and Dowdeswell, 1989). Photographic evidence sug-

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gests that icebergs also carry their sediment in englacial layers which is not accounted for in the current model configuration. Neglecting the englacial component of iceberg rafted debris will only serve to minimize the quantity and spatial distribution of iron delivery from icebergs to the SO, making model results conservative.

The form and reactivity of the iron within the glacial debris and the dust fraction is also considered in order to model the fate of the iron held within icebergs. For the ice containing only aeolian dust, we assume the same solubility (2%) as the direct dust flux to the ocean (see Sect. 2.2.1). The reactivity of the debris in the basal layer is calculated as follows. There are no direct measurements of the iron content of free-drifting icebergs, but estimates exist for sediment in grounded icebergs in Antarctica (Raiswell et al., 2008). Nanoparticles of iron oxyhydroxides are found within the iceberg hosted sediment in significant quantities, and the iron content in the reactive phases of ferrihydrite and nanogoetite is $0.10 \pm 0.11\%$. We assume that the proportion of this iron that is bioavailable is 10%, and hence, that 0.01% of the basal sediment is bioavailable iron (Statham et al., 2008). The bioavailable iron that is released by each iceberg into the MIT ocean grid cell is summed and overlaid onto the dust deposition field to produce an overall map of iron input to the Southern Ocean from icebergs and aerosol dust input.

3 Results and discussion

3.1 Modelled iron fluxes to the Southern Ocean

Iron fluxes in subglacial meltwaters are distributed along the Antarctic coast, in accordance with the pattern of subglacial water export (Fig. 1, Supplement 3). Iceberg-derived iron fluxes follow iceberg tracks (Fig. 1), which also correspond approximately to spatial patterns of subglacial meltwater release, since ice stream dynamics control the fluxes of both iron sources. Modelled surface ocean iron concentrations are enhanced in zones of high subglacial meltwater and iceberg iron input, most prominently

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around the coast (Fig. 1b and c, Supplement Fig. 2). Many of these zones of iron enhancement in the model correspond with areas of high measured iron concentrations, such as in the Ross Sea (Moore and Braucher, 2008) and Amundsen Sea sectors (Gerringa et al., 2012) (Fig. 1b and c, Supplement Fig. 2). Dust fluxes of iron (Fig. 1b) cannot explain some of the high measured iron concentrations in surface coastal ocean waters, pointing towards an additional iron source, such as that provided by the ice sheet.

3.2 Impact upon SO wide primary productivity

Iceberg, subglacial meltwater (B–D) and combined iceberg/meltwater (E) iron inputs have a pronounced (10–40 %) impact on total Southern Ocean PP (Fig. 2) above that generated by dust-only simulations (A). A fourfold difference between SO PP enhancement associated with subglacial meltwater with an [Fe] of 3 μM and 30 μM also indicates a sensitivity to meltwater Fe concentrations. The geographical distribution of ice sheet iron impacts on ocean wide SO PP reflect (a) the location of iron inputs from major ice streams or iceberg melting, (b) the redistribution of this iron via ocean circulation and (c) the geographical distribution of SO iron limitation. Many regions of elevated mean annual PP in both subglacial meltwater and iceberg iron input scenarios (Fig. 2) match to zones of high runoff or iceberg calving fluxes around the Antarctic margin (Fig. 1). These include large parts of East Antarctica, such as Prydz Bay, and the Ross, Weddell and Amundsen Seas, which are all areas of high observed summer PP (Demidov et al., 2007; Smith and Nelson, 1990; Smith et al., 1996; Gerringa et al., 2012). The similarities in the spatial distribution of annual PP enhancement in iceberg and subglacial meltwater flux simulations (Fig. 2) arises from the fact that the surface ocean currents that transport the icebergs also convey the subglacial meltwater away from the ice margin. Northward advection of ice sheet-derived iron by ocean currents is evident from the elevated PP values at lower latitudes relative to dust sources alone, with an effect that extends as far as 50° S in scenarios B–E (Fig. 2). For example, along the western margin of the Antarctic Peninsula (B–E) where runoff fluxes are low and

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the enhanced PP is stimulated by glacially-derived Fe advected north from the Ross Sea and Amundsen Sea. These results highlight the importance of ocean circulation in promoting iron fertilization from subglacial runoff and icebergs over a large proportion of the Southern Ocean.

3.3 Impact upon coastal primary productivity

In addition to ocean-wide effects on SO PP, glacial sources of iron also have the potential to drive strong enhancement of PP in the near coastal zone in spring/summer. Spring blooms, where primary productivity attains values of the order of $10^3 \text{ mg C m}^{-2} \text{ d}^{-1}$, are commonly observed at the ice edge in early summer (Arrigo et al., 2008) along the Antarctic Peninsula (Smith et al., 1998) in the Ross Sea (Smith et al., 1996), Weddell Sea (Smith and Nelson, 1990), Amundsen Sea (Gerringa et al., 2012) and Prdyz Bay (Westwood et al., 2010). This reflects the melting of sea ice during the austral spring, allowing sunlight to reach the nutrient rich surface ocean waters. Additionally, the input of fresh meltwater increases the upper ocean stratification which then leads to strong phytoplankton blooms. These blooms are commonly linked to Fe inputs from sea ice, upwelling and re-suspended coastal sediments, with recent work also considering icebergs (Lancelot et al., 2009). Only in the Amundsen Sea (Gerringa et al., 2012) and along the Antarctic Peninsula (Dierssen et al., 2002) has the possibility of a glacial meltwater influence been suggested. The dust-only simulation (A) does not capture these spring blooms to some degree (Fig. 3). However, simulations including icebergs and/or subglacial meltwaters (B–E) produce considerably higher spring PP (ca. $10^3 \text{ mg C m}^{-2} \text{ d}^{-1}$) which is closer to observed values around the Antarctic coast (Smith et al., 1996, 1998; Arrigo et al., 2008; Westwood et al., 2010). This suggests that the ice sheet-derived iron is important for the spring blooms observed in the coastal SO.

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4 Summary and conclusions

Model results presented here suggest that subglacial meltwaters may constitute a significant additional source of bioavailable iron to the SO, supplementing more well studied iceberg sources. The impact of the glacial iron flux may be large, extending across much of the SO due to the redistribution of the iron by ocean circulation. Increased surface melting has already been observed in some marginal areas of Antarctica, most notably the Antarctic Peninsula (Vaughan, 2006). Enhanced basal melting of ice shelves and ice-shelf shrinkage has also been reported across a number of Antarctic marginal sectors (Pritchard et al., 2012). Any significant change in iron fluxes associated with ice sheet mass balance change may influence the strength of the SO biological pump, and potentially influence atmospheric CO₂ drawdown via fertilization effects. Refinement of model predictions will be enhanced significantly by drilling campaigns to the ice sheet bed and sub-ice shelf waters, which will enable iron concentrations in subglacial meltwaters to be better constrained.

Supplementary material related to this article is available online at:
<http://www.biogeosciences-discuss.net/10/12551/2013/bgd-10-12551-2013-supplement.pdf>.

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Table 1. Iron fluxes Annual iron fluxes modelled in this paper for aeolian dust, icebergs and subglacial meltwater and in comparison to previously calculated values for these and other hypothesized iron sources to the Southern Ocean.

Fe Source	Flux (Tgyr^{-1})
Input to model	
Antarctic Subglacial Meltwater	0.009–0.90
Icebergs (aqueous and nanoparticulate)	0.065
Aeolian dust	0.075
Previously calculated fluxes	
Icebergs (aqueous) (Raiswell et al., 2008)	0.001–0.005
Icebergs (aqueous + nanoparticulate) (Raiswell et al., 2008)	0.06–0.120
Sea Ice (Edwards and Sedwick, 2001)	3×10^{-4}
Aeolian Dust (Raiswell et al., 2008)	0.01–0.130

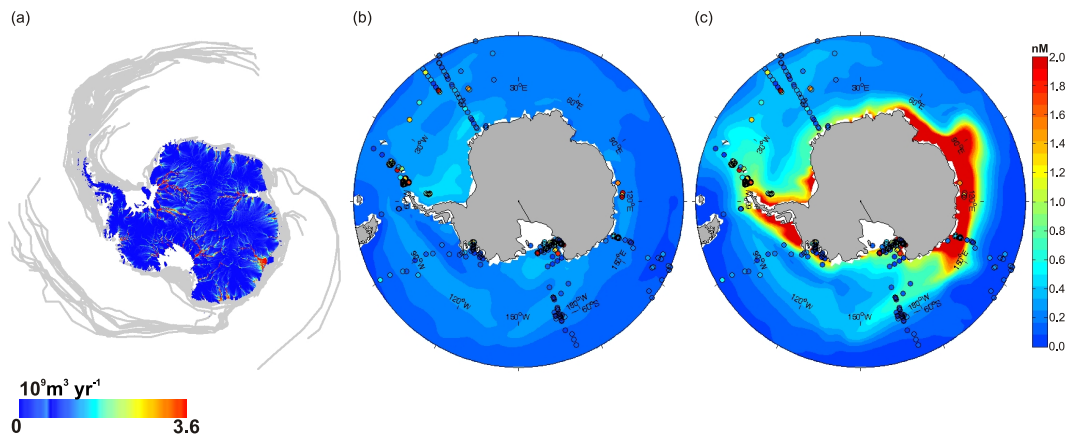


Fig. 1. (a) Distribution of ice-sheet derived iron fluxes showing modelled subglacial meltwater fluxes and iceberg tracks from the Antarctic Ice Sheet. Both of these ice-sheet derived mass flux distributions are controlled principally by the location of major ice stream complexes and ocean circulation. The geographical distribution of the impact of iron inputs upon modelled surface ocean iron concentrations is shown for (b) Scenario A (dust only) and (c) Scenario E (dust, subglacial meltwater and icebergs) and compared to Tagliabue et al. (2012) observational data (outlined by black circles).

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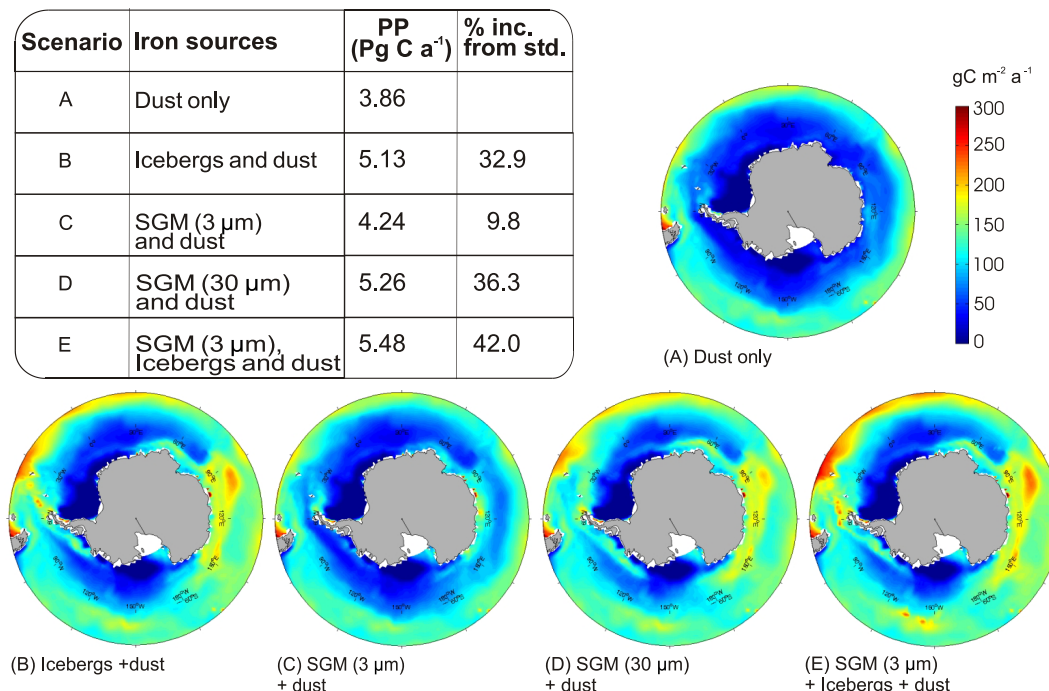


Fig. 2. Modelled sensitivity of annual primary productivity of the Southern Ocean to external iron inputs. Tabulated total PP generated by the different model scenarios and stereographic images of annual primary productivity for model scenarios, **(A)** aeolian dust, **(B)** icebergs, **(C)** subglacial meltwater, SMW, where $[Fe] = 3 \mu M$, **(D)** SMW, where $[Fe] = 30 \mu M$ and **(E)** aeolian dust + icebergs + SMW (where $[Fe] = 3 \mu M$).

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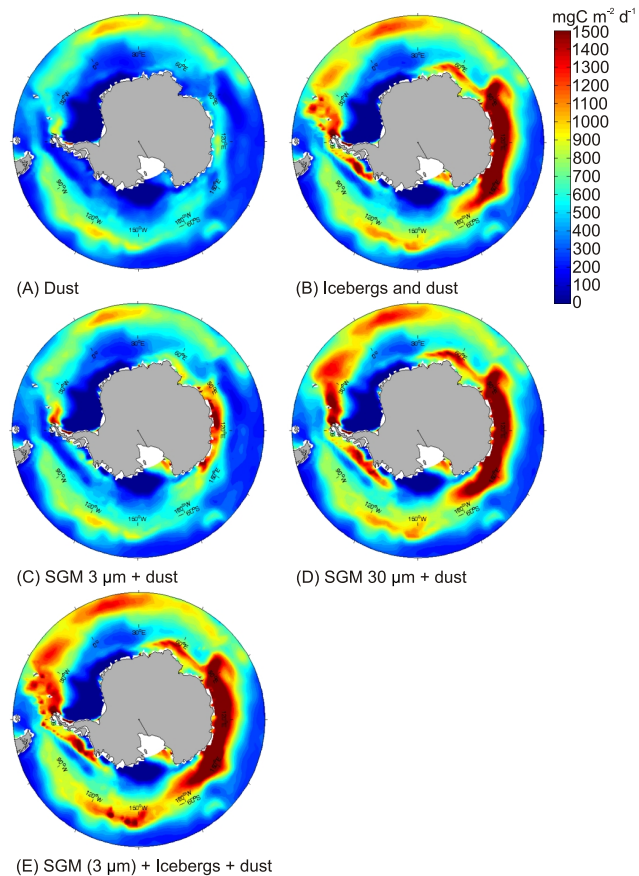


Fig. 3. Modelled mean seasonal primary productivity (January to March) of the Southern Ocean in response to dust and glacial iron inputs for model scenarios **(A)** aeolian dust, **(B)** icebergs, **(C)** SMW, where $[\text{Fe}] = 3 \mu\text{M}$, **(D)** SMW, where $[\text{Fe}] = 30 \mu\text{M}$ and **(E)** Aeolian dust + icebergs + SMW (where $[\text{Fe}] = 3 \mu\text{M}$).

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