Response to reviewer #1

The authors present a model study investigating how Fe input into the Southern Ocean from icebergs and the Antarctic Ice Sheet affects the distribution of Fe and primary production in the marine environment. Recognizing the uncertainty in the magnitude and nature of these Fe sources, and thus several difficulties in meaningfully parametrizing them to date, the authors opt to model several scenarios with important differences in Fe solubility and the distribution of melt-derived Fe in the water column. The results, with respect to primary production and C export, fall within the (very broad) range of other model studies suggesting a modest impact of this Fe on Southern Ocean productivity. A key strength of this specific study is that it makes considerable effort to highlight the many uncertainties surrounding this Fe source. Numerous other recent works have proposed much stronger effects but neglected to consider some, or all, of the uncertainties highlighted herein. Whilst there are a few areas in the text where I think some improvements can be made, I generally therefore consider this to be a valuable addition to the field, suitable for publication in BGS and, in my opinion, one of the most comprehensive manuscripts on the subject of modelling these Fe fluxes to date.

My expertise is in biogeochemistry, I defer to a more qualified reviewer for issues concerning details of the model used. Before returning the text to the journal, it would benefit slightly from a read through from an English editor.

We thank reviewer #1 for his detailed review and general support for our manuscript.
We present our response in bold and preceded by '>' in case of formatting errors.

General comment; have the authors considered the meltwater 'pump' effect outlined in some recent work (see comment on page 4, (Cape et al., 2019; St-Laurent et al., 2017, 2019)? I wasn't clear if this effect would be captured in the model or not.

In our model configuration, the cavities below the ice shelves are not opened. To mimic the overturning circulation driven by these unresolved ice shelves, we used the parametrisation of Mathiot et al. (2017) which prescribes a meltwater flux of ice shelf uniformly distributed over the depth and width of the unresolved cavity opening, from the mean ice front draft down to the seabed, or the grounding line depth if it is shallower. Mathiot et al. (2017) showed that this parametrisation of the ice shelf melting drives a buoyant overturning circulation along the coast, i.e. the meltwater pump, similar to that simulated by cavities when they are explicitly resolved.

General comment: How is C export scaled to primary production in the model, does the model successfully replicate the observed relationship between the two? Looking at some other models and calculations in the literature, it appears to me that a key reason why very broad ranges are often quoted for C export from specific Fe fertilization scenarios is simply because of the way Fe or productivity/chlorophyll a is scaled to C export. The 'high' C export estimate of (Duprat et al., 2016) is scaled linearly with chlorophyll/productivity –which is not consistent with observational Southern Ocean data. It is not clear to me if this is also a problem with the (Laufkötter et al., 2018) model which matches the Duprat calculation surprisingly well producing a fertilizing effect significantly above that found herein. (Observations with multiple methods show that C export efficiency declines sharply with increasing productivity in the Southern Ocean, although the precise reason(s) for this seem to be unclear (Maiti et al., 2013; Le Moigne et al., 2016).

We completely agree with this comment. But in the actual context of non-consensus about the export ratio in the Southern Ocean, it is very difficult to estimate whether our model replicate "realistically" the observed relationship between C export and primary productivity due to the poor data spatial and temporal coverage. In our model, the relationship between PP and C export does not show a linear pattern as illustrated in Figure 1. Nevertheless, there is a clear trend that shows higher export with higher primary productivity which is highly variable at the local and temporal scale. We don't know if in the COBALT model used by (Laufkötter et al., 2018), the relationship is different which could explain the differences. In fact, a detailed and thorough comparison with that study is really challenging because we lack many information that would be necessary. These differences are really intriguing and would probably deserve a careful analysis involving a collaboration between the two groups.

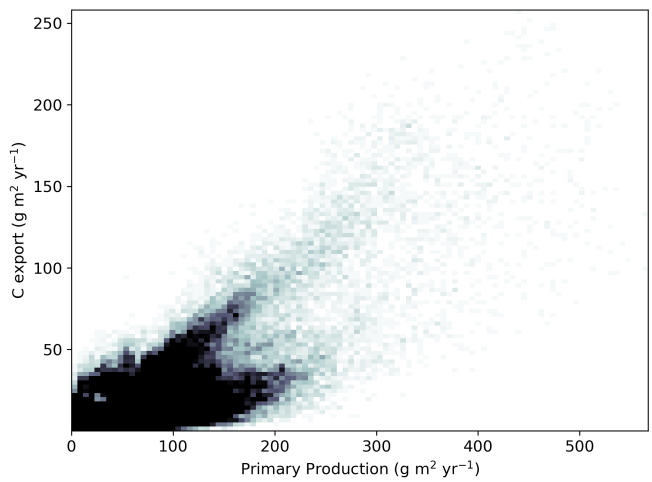

Fig 1. Density relationship between primary production and C export at 150 m depth over the Southern Ocean, south of 50°S, in the SOLUB5 experiment.

Specific comments by Page/line Title: Antarctic Ice Sheet

> Acknowledged and addressed

1/12 ‘seasonal variations’ in the timing of melting? If I understand correctly, this sentence would read better ‘Seasonal variations make almost negligible differences...’

To clarify a possible misunderstanding, we modified the sentence as follows :
“seasonal variations of the iceberg Fe fluxes have regional impacts which are small for annual-mean primary productivity and C export at the scale of the SO”

2/3 Raiswell 2016 does not contain extensive atmospheric dust work, I am sure there are better values/references for dust deposition

Other references cited for dust deposition.

2/14 ‘the mean flux’. You mean the total flux?

We mean the total mean flux. Modified.

2/16 ‘the few modelling studies conducted to date’`

> Acknowledged and addressed

2/27 ‘fueling surface waters’. You mean ‘fueling’ productivity or just delivering Fe?

We mean “delivering Fe”. We modified the sentence to clarify this point as follows:
“The melting of icebergs and ice shelves releases Fe to seawater as particulate, dissolved, and potentially dissolvable forms fueling the water column in Fe”

2/28 Not sure this is accurate, it has been speculated that glacially derived Fe was fueling primary production in the Southern Ocean for some time e.g. (Hart, 1934), it just has proved very difficult to quantify.

We thank reviewer #1 to introduce this reference.
Text modified in accordance.

2/32 See also (Wu and Hou, 2017) - a particularly interesting read as it, when compared to (Duprat et al., 2016) demonstrates that there are significant differences in observational data constraining the effect of icebergs, not just in the models.

OK.

2/34 ‘the Prydz bay’. Delete the

> Acknowledged and addressed

3/12 : : :will increase the supply of Fe: : : Assuming that the Fe input scales linearly with ice-melt, which may be a little speculative

We agree with this comment.
Sentence changed as follows:
“The projected decline of the AIS will potentially increase the release of Fe from icebergs and ice shelves in the SO with possible significant impacts on marine productivity and biogeochemical cycles, depending on how Fe inputs relate to productivity and carbon export.”

3/18 ‘along the water column’ means horizontal, you mean ‘through’

> Acknowledged and addressed

4/10 Here something concerning the ‘meltwater pump’ may be relevant. High Fe concentrations adjacent to Ice sheets (in the ocean) would generally be attributed to direct input from melt/sediment release etc, but release of meltwater can also ‘pump’ ambient to the surface and thus bring Fe from shelf sediments and the sub-surface Fe reservoir into surface waters. These effects are difficult to tease-apart from field data. But some model calculations suggest that the magnitudes of Fe from ‘pumping’ and from direct input (melt/freshwater/freshwater derived particles) are comparable – all be it with large uncertainties. See (Cape et al., 2019; St-Laurent et al., 2017, 2019) for overviews of this effect and what we do/don’t know about it.

Please, see our answer to general concerns.
Text modified to detail that the parametrisation of the ice shelf melting from Mathiot el at. (2017) simulates the buoyant overturning circulation along the coast and the associated meltwater pump.

4/23 It is not clear to me what the % here refer to, I guess the % weight of sediment which is ferrihydrite, but please clarify (also specifically what is the mean – a global mean??)

wt.% added after data
Here we mean the mean content of the estimated range from Raiswell et al. (2016)
Modified in the text.

4/24 This is a muddled concept in the field in general. All labile Fe could be potentially ‘biologically available' if processed/delivered in the right way, I would stick specifically with the 'soluble' fraction rather than trying to define a 'biologically available' fraction as this is an arbitrary exercise. The concept of 'utilization' (Boyd et al., 2012) is perhaps more useful as 'bioavailability' is a qualitative term.

We agree with Reviewer #1 that the concept of bioavailability is rather vague. Bioavailability depends on numerous factors such as the nature of the iron particles, the interactions with the ligands, the environmental conditions, … As a consequence, the fraction of iron that can be ultimately available to phytoplankton (and bacteria) is highly variable and very difficult to infer. Boyd et al. (2012) have studied the Fe utilization by phytoplankton based on observed Fe/Chl ratios. They compared this utilization to the magnitude of different sources (dust, sediment resuspension/mobilization, meltwater, …) to evaluate if these sources are related to a higher Fe utilization. The concept of utilization is thus very useful to qualitatively investigate the potential fertilization effect of different iron sources. However, this remains qualitative and based on many assumptions, among which the values of the Fe/Chl ratios are among the highest. Furthermore, the comparison to supply mechanisms still requires the definition of a bioavailable iron fraction to evaluate the magnitude of the sources. Finally, in a prognostic model, utilization is prognostically predicted based in part on the amount of iron that is available which turns back to the definition of bioavailable iron.

4/30 Seems like an odd thing to say. 'no data allow the constraining of: : :' or 'allow us to'

Sentence reworded as follows:
"no observational data are available that allow the ice shelf Fe fluxes to be constrained, as the Antarctic estimates from..."

5/30 The 'buoyancy effect' is widely attributed with bringing iceberg-derived components (e.g. particles/Fe) to the surface, but as far as I'm aware there isn't much clear evidence of it actually doing this, or even much data to show how ice melt behaves in the real world. An alternative argument is that something akin to convective cells develop up the sides of the iceberg, and that these reach neutral buoyancy before they reach the surface i.e. most melt doesn't 'rise' to the surface. In any case, there is certainly very limited data to show how ice melt behaves around icebergs (Helly et al., 2011; Stephenson et al., 2011).

OK. We thank the reviewer for drawing our attention to these papers.

6/30 How do these concentrations compare to 'real' Fe concentrations in these areas?

Due to the poor availability of data in the Atlantic plume northeast of the Antarctic Peninsula, it is difficult to compare to real concentrations. However, these concentrations are probably at the upper limit of Fe concentrations in the open ocean but potentially realistic in coastal regions (de Jong et al.,

2012).

7/9&10 This line ‘Furthermore, in winter,: : :’ does not make sense

Sentence modified as follows:
“Furthermore, in winter, deep mixing entrained to the surface Fe that was released in summer below the euphotic zone and that escaped consumption by phytoplankton due to the lack of light.”

7/6 These concentrations are not feasible, how is scavenging constrained? Such a high dissolved Fe concentration (27 nM) would, practically immediately, precipitate.

In coastal regions, Fe concentrations can be very high as shown in the article of de Jong et al. (2012) with measured surface Fe concentrations up to 50 nmol L^{-1}.

3.1.4 Whilst the effect is poorly defined, the meltwater ‘pump’ should be at least mentioned here.(St-Laurent et al., 2017, 2019)

Text modified to mention the meltwater pump.

10/33 The mains

> Acknowledged and addressed

11/11 the Bouvet Island. Delete ‘the’

> Acknowledged and addressed

11/20 Nevertheless, though small

> Acknowledged and addressed

11/25 CHL at the blooming season, you mean ‘throughout’ or ‘during the season’ (general comment CHL is, at a glance, similar to CTL, maybe use ‘Chl a’ or similar)

We mean during the season. Modified.
We choose SChl for surface chlorophyll concentrations instead of CHL

12/30 equal to

> Acknowledged and addressed

12/33 'are almost unchanged.' Compared to?

Compared to the CTL experiment.
Added in the sentence.

13/27 'leads to a significant increase in'

> Acknowledged and addressed

13/32 Indeed. The first thing I did after reading this study was to refer to (Laufkötter et al., 2018). I was very surprised to find that both studies use very similar parameterizations for the total Fe input. As a biogeochemist, my simplistic conclusion is therefore that these results (collectively) are not reproducible between models, as completely opposite conclusions are reached using practically the same Fe input. More surprising is that the results of the studies don't even overlap- given that both studies use very broad ranges in Fe input which were designed to span all environmentally relevant scenarios. This is problematic, because it makes the studies (again, collectively-this is not a specific critique of this study) impossible to interpret from a biogeochemical perspective. So the critical question is why is there such a large difference? The authors herein do a generally good job of discussing the differences between existing iceberg models, but perhaps this information (presently in the text) could be thinned a little and compiled in the form of a table which would at least eliminate some causes of differences between independent models. As a biogeochemist it is difficult to comment further other than to raise a flag that model results should be treated with extreme caution until some consensus can be found between different model studies.

Please see also our answer to the general concerns.
We totally agree with your last comment and we will modified the conclusion section in accordance to this point.

14/2 Yes, but be careful here concerning 'regionally sig. C export'. Compare (Wu and Hou, 2017) and (Schwarz and Schodlok, 2009) with (Duprat et al., 2016), the later study claims a much larger effect, but only in the C export calculated, I suspect this is largely because of how the observed data (chlorophyll) is scaled to C export and thus reflects different assumptions in the calculation rather than actual differences in the raw data.

14/29 Does (De Jong et al., 2015) not conclude that much of the Fe is sub-surface?

Yes, this is their main conclusion regarding the iceberg Fe delivery.

15/19 'runoff' [as a macronutrient source] this is a bit of a misleading statement, even in the North Atlantic, where macronutrient concentrations are much lower in the mixed layer, runoff dilutes the concentration of N and P macronutrients (Meire et al., 2016), so a missing macronutrient-runoff source couldn't plausibly explain the problem herein. Similarly ice contains very low macronutrient concentrations.

Supply mechanism removed.

15/22 This seems more plausible, see for example (Cape et al., 2019), although even these 'upwelled' nutrient fluxes would be modest and I doubt sufficient to explain the model problem-plus they would come with Fe. In these references here, I think the authors mean (Hopwood et al., 2018) rather than the Hopwood paper listed. Alternatively, how scavenging is accounted for in the model (a difficult thing to do) presumably could cause this effect, if Fe is removed a little too slowly, it will 'over-fertilize' in the model world and thus, all other things being equal, drawdown macronutrients much faster than would be the case otherwise. As noted, I am not a model expert, but I would guess that macronutrient distributions in the model match real data better than Fe distributions and thus would speculate that problems are more likely to arise from how Fe is parametrized than with macronutrient sources/sinks.

Reviewer #1 is correct in the fact that macronutrient distributions are better simulated by models, including ours, than Fe distribution. This is illustrated in the reference paper of PISCES (Aumont, et al., 2015). Models tend to have difficulties at properly simulating the iron distribution in the ocean ((Tagliabue et al., 2016) even if PISCES tends to perform quite well in comparison with other models that participated to the FeMIP exercise. The drawdown of nutrients close to the coast is explained by an intense primary productivity that drives an intense export of carbon and nutrients. Due to the lack of data, primary productivity is difficult to evaluate as well as chlorophyll values. We have to rely on satellite-retrieved values which may be biased in that specific region and in areas closed to the coast. This comparison indicates that we don't hugely overestimates chlorophyll levels even if they tend to be too high on average. Thus, a too intense fertilization by iron may be part of the explanation, either because scavenging is too low and/or iron input from sediments and ice shelves is too large. Another probable reason is that export is too large and efficient in the model in that region. However, due to the lack of data, this proves to be impossible to investigate properly.

You are right, we mean (Hopwood et al., 2018).
Reference modified.

16/2 See also (Boyd et al., 2012) – specifically the 'utilization' of Fe shifts significantly along 'Iceberg Alley'

Effectively, their results suggest that the rates of iron utilization appear to be considerably less than that potentially supplied from iceberg melting along their drift. They also revealed the impossibility to evaluate to which extent because of the contributions from other sources of Fe (sediment and dust) in this region. Moreover, the Fe utilization was computed from the net primary production derived from satellite products which might be potentially severely biased. Indeed, in the Southern Ocean, satellite products were pointed out to particularly underestimate chl a concentrations (Johnson et al., 2013), and inferred net primary production are associated with very large uncertainties (Saba et al., 2011).

The shift in the "utilization" of Fe from iceberg of Boyd et al. (2012) has been added in this section.

16/7 Perhaps, but then this becomes a question of organic ligands and to what extent these are able to transfer Fe into the dissolved phase. I'm not aware of any work around icebergs looking at ligand-iceberg interactions, but this has been investigated with respect to glacially derived particles, for general discussion of how ligands may limit the transfer of Fe between labile particulate and dissolved phases see (Hopwood et al., 2016; Lippiatt et al., 2010; Thuroczy et al., 2012)

Ligands clearly control the amount of iron that can remain in the soluble fraction when particles released by icebergs and ice shelves dissolve in sea water. The studies mentioned by Reviewer #1 show that meltwater contains quite significant amounts of ligands that increase the amount of iron that can dissolve or remain dissolved. As a consequence, the apparent solubilization of glacial particles is controlled partly by these ligands. In our model, we don't include a potential source of ligands from meltwater because as said by Reviewer #1, we do not have any data to constrain that input. Thus, the ligands concentration in the vicinity of the icebergs is supposed to be identical to that of the open ocean. If meltwater is an important source of ligands, this would mean that our model is underestimating the supply of soluble iron from icebergs (and ice shelves).

16/13 I think these fluxes have been defined, Raiswell (et al.,) has conducted very extensive work on the different fractions of Fe present in glacially derived particles (Raiswell et al., 1994, 2010; Raiswell and Canfield, 2012) and what this means for lability. It was this early work, to my understanding, which lead to the more recent focus on the labile ferrihydrite fraction – because this is, to a first order approximation, the labile sedimentary Fe fraction which may plausibly affect primary production.

OK. We thank the reviewer for drawing our attention to these papers.

17/10: : : onwards. Given that models cannot agree on how important Fe-fertilization is in the present, how can you robustly conclude that the Fe source will increase in the future? I'm not sure the authors present anything that supports this statement and think the conclusion would be stronger without it. It is (unless you can produce literature to support this) presently an unsupported argument that increasing discharge will increase Fe fertilization.

You are right, however a mechanistic increase in the AIS supply will at least increase surface Fe concentrations in the model. We might better say that as no agreement are found between models in their biogeochemical response to the AIS Fe supply, it is for now impossible to evaluate the impacts of climate change on this external source of Fe and their consequences on marine biogeochemistry in the Southern Ocean. This also points to the necessity to understand the mechanisms that explain the very large differences that are simulated by the models.

Figure 1: Just to clarify, on (b) the 'day-1' means as if the flux was uniform across the year (i.e. an annual value divided by 365)? This seems a little strange way of displaying the data as presumably the actual melt rate during summer is much larger than this and for much of the year it is 0.

We modified Figure 1 to express the AIS Fe fluxes in kg m^{-2} yr^{-1}.

Figure 3: What does the white area correspond to? Maybe define, I guess something like no meaningful change?

Caption modified as suggested.

Figure 5: I assume the colour bar should be the same as 4?

It is the same colour bar as in Figure 4. Added to Figure 5.

Figure 8. The caption for this figure seems to be completely incorrect.

Here, the right caption is: "Surface chlorophyll concentrations in summer (December, January, and February) from (a) satellite observations (MODIS-Aqua, Johnson et al., (2013)), (b) the CTL experiment, and (c) the SOLUB5 experiment in the Southern Ocean, south of 50° S.

References

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Hopwood, M. J., Carroll, D., Browning, T. J., Meire, L., Mortensen, J., Krisch, S., & Achterberg, E. P. (2018). Non-linear response of summertime marine productivity to increased meltwater discharge around Greenland. *Nature Communications*, *9*(1). https://doi.org/10.1038/s41467-018-05488-8

Johnson, R., Strutton, P. G., Wright, S. W., McMinn, A., & Meiners, K. M. (2013). Three improved satellite chlorophyll algorithms for the Southern Ocean. *Journal of Geophysical Research: Oceans*, *118*(7), 3694–3703. https://doi.org/10.1002/jgrc.20270

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Response to Reviewer Robert Raiswell

Person Review by Raiswell. This is an excellent contribution and is entirely suitable for Biogeosciences. The authors have used a biogeochemical model to examine the delivery of Fe from the Antarctic Ice shelf. I agree with their statement that iceberg and ice shelf delivery have largely been ignored in other biogeochemical modelling studies and this is a welcome attempt to address this issue. The model produces some important new insights which will need validating in further studies, when appropriate data are available. I also agree with the authors that; 1) There is considerable uncertainty in the magnitude of all the different fluxes (and this applies just as much to atmospheric dust, as to the newer, less well-studied fluxes such as icebergs), 2) There are also difficulties in using the data to examine the down-stream impacts on productivity and export. The value of this paper is in recognising these issues and making sensible attempts to address them. I would hope that this study is used by the community to focus on the main areas of uncertainty, and stimulate further observational studies. Especially as a particular difficulty the authors faced is that there are few relevant iceberg data sets and, in fact, there are more observational data from the Greenland ice-hosted sources than from the AIS. I commend the authors on reviewing the literature so thoroughly.

I emphasize that I lack the expertise to comment on the models in detail but other comments below are keyed to page and line numbers.

We thank Robert Raiswell for his review and general support for our manuscript. We present our response in bold and preceded by '>' in case of formatting errors.

Page 2, line 3. The Raiswell reference is not the best as there are numerous studies of dust deposition to the SO. However the Raiswell data (I hope!) is more useful than many others because the extraction used relates to mineralogy, and specifically to ferrihydrite which is potentially the most bioavailable mineral form. You could move the Tagliabue ref to after 'SO' and before the colon, and then maybe cite a Boyd reference, perhaps the Mar Chem 2010 paper. The Raiswell reference would be better in the iceberg citations.

> Acknowledged and addressed

Page 2, line 25. Delete 'through finely ground rocks'. The rock source is larger than the dissolved sources but the latter is not negligible and may be the most bioavailable.

> Acknowledged and addressed

Page 2, line 27. Add 'fueling productivity in surface waters'.

We mean "delivering Fe".
We modified the sentence to clarify this point as follows:
"The melting of icebergs and ice shelves releases Fe to seawater as particulate, dissolved, and potentially dissolvable forms fueling the water column in Fe"

Page 3, line 3. Unfortunately the 50 samples are largely from Greenlandic icebergs and not Antarctica. Clarify this.

Clarified in the article

Page 3, line 14. The impacts on productivity are the point at which my biological expertise starts to fail. The impact critically depends on how Fe affects on productivity and thus carbon export. The authors obviously need to explore this issue but an expression of caution would be wise. Maybe add 'cycles, depending on how Fe inputs relate to productivity and carbon export'.

Expression of caution added in the article

Page 3, line 18. I welcome the attempt to consider vertical distributions of iceberg Fe and their influence on the surrounding seawater. No doubt the distributions will turn out to be very variable, not least because the vertical iceberg Fe contents will alter as icebergs overturns.

Page 4, line 25. 10% is OK but probably conservative. I would think that most ferrihydrite would be bioavailable, especially as ferrihydrite carries a significant fraction of ferrous iron. There is a brief discussion of this in my recent Frontiers paper, v. 6. No 222, doi: 10.3389/feart.2018.00222. You might be interested to look at this and at the EPSL 493, 92-101 paper by Hawkings. The Frontiers paper also raises the issue that ice is not inert and is able to catalyse the reduction of ferrihydrite. Also the freezing of sea ice produces pockets of Fe-enriched, chloride complexed brines that would be released early in melting. I am not suggesting that you need to cite these papers, I am only making the point, as you realise, that there are many areas of uncertainty which could profoundly alter the bioavailability percentage. It might be worth stating that you have not considered ice-water-mineral reactions.

We thank the reviewer for drawing our attention to these two papers.
Text modified

Page 4, line 23. Add wt.% after data.

> Acknowledged and addressed

Page 4, line 30. Reword as ‘no observational data are available that allow the shelf Fe fluxes from Antarctica to be constrained, as..’ There is a very crude estimate of 5.3 Gmoles/yr in Raiswell et al (2016)

Here we mean “Antarctic ice shelf Fe fluxes” and not “Antarctic shelf Fe fluxes”.
Sentence reworded.

Page 5, line 5. It would be good to have a table showing the fluxes and solubilities assumed for dust, sediments and sea ice in the CTL model.

Fe fluxes from other sources simulated in the CTL experiment added in table 1.

Page 6, line 30. This states that the 1.5 and 6.3 nmol/L values are over and above the CTL data. Can the authors clarify what is being derived here? I think the models produce ‘dissolved Fe’ (see the discussion in the Raiswell Frontiers paper). In any event the data would have to be compared with seawater measurements on water filtered through 0.45 micron, which is ‘dissolved Fe’. These model values would be at the upper limit of actual seawater ‘dissolved Fe’ concentrations outside of coastal regions.

The model values are concentrations in dissolved Fe.
Due to the poor availability of data in the Atlantic plume northeast of the Antarctic Peninsula, it is difficult to compare to real concentrations. However, it is true that these concentrations are probably at the upper limit of Fe concentrations in the open ocean but still potentially realistic in coastal regions (de Jong et al., 2012).

Page 7, line 9. Sentence unclear.

Sentence modified as follows:
“Furthermore, in winter, deep mixing entrained to the surface Fe that was released in summer below the euphotic zone and that escaped consumption by phytoplankton due to the lack of light.”

Page 7 line 30. The caption to fig. 5 needs to clarify which are the positive and negative areas.

Caption modified in order to clarify this point.

Page 8 line 17. The potential of this deep reservoir is one of the important insights that your study produces.

Page 10, line 10 on. This seems reasonable. The whole point about icebergs is that they can transport, which is not true for ice shelf sources. But it is good to see this confirmed.

Page 10, line 24. My figure 8 shows the difference in surface Fe concentrations, not chlorophyll. Has a diagram been incorrectly inserted?

The right caption for Figure 8 is:
"Surface chlorophyll concentrations in summer (December, January, and February) from (a) satellite observations (MODIS-Aqua, Johnson et al., (2013)), (b) the CTL experiment, and (c) the SOLUB5 experiment in the Southern Ocean, south of 50° S.

Page 11, line 11. Delete 'the' before Bouvet island.

> Acknowledged and addressed

Page 13, line 30 on. I agree that this difference is hard to understand but you make a crucial point; that modelling the ice-hosted sources is at present difficult; although the attempt is certainly valuable (see above).

Page 15, line 25 on. Yes, delivery will vary as iceberg melting occurs.

Page 16, line 5. I would prefer to be cautious here and describe the most labile source as' potentially bioavailable'. But I agree that there will be a range of Fe mineral reactivities each with different rates of reaction or dissolution or grazing interactions, and thus different bioavailabilities.

OK replaced in the text.

Page 17, line 2. This is another useful finding, although again not unexpected that iceberg effects are spatially variable.

References

de Jong, J., Schoemann, V., Lannuzel, D., Croot, P., de Baar, H., & Tison, J.-L. (2012). Natural iron fertilization of the Atlantic sector of the Southern Ocean by continental shelf sources of the Antarctic Peninsula. *Journal of Geophysical Research: Biogeosciences*, *117*(G1), n/a-n/a. https://doi.org/10.1029/2011JG001679

Johnson, R., Strutton, P. G., Wright, S. W., McMinn, A., & Meiners, K. M. (2013). Three improved satellite chlorophyll algorithms for the Southern Ocean. *Journal of Geophysical Research: Oceans*, *118*(7), 3694–3703. https://doi.org/10.1002/jgrc.20270

Response to reviewer #3

This paper presents a study evaluating the impact of Fe supply from Antarctic ice shelves and icebergs on productivity/chlorophyll in the Southern Ocean. It presents a thorough examination of the uncertainties associated with the fertilisation capacity of this input and highlights remaining differences between the observations and model results even when these Fe sources are included. The authors highlight particular areas where existing models can be improved, or futher in-situ observations are required. With some improvements, I believe this paper is a valuable addition to the field.

I am reviewing this paper with shallow knowledge of the biogeochemistry and will be focusing on iceberg and ice shelf melt.

We thank reviewer #3 for his detailed review and general support for our manuscript.
We present our response in bold and preceded by '>' in case of formatting errors.

Larger corrections
It was not clear whether the Fe supply is injected at a particular layer, and no further dynamics apply, or whether once the Fe is added, those waters are able to mix (as is likely to happen associated with the buoyancy injection from meltwater)? This applies throughout the paper, but in particular on page 13 (line 30-35) where you discuss the possible cause of differences between your primary production are that found in Laufkötter et al (2018). Some further discussion of this, and the general background associated with the meltwater pump would be valuable. Recent papers have shown the effect of this in Antarctic waters (St-Laurent et al., 2017, 2019: Cape et al., 2019) and in your discussion you only refer to this process associated with Greenland glaciers (pg 15, line 21). Similar to the meltwater pump model for ice shelves, are similar processes considered for iceberg melt? For iceberg melt occurring at depth, mixing with surrounding waters may result in upwelling of nutrient-rich waters, rather than the iceberg Fe-source remaining trapped below the ML.

In our model configuration, the cavities below the ice shelves are not opened. To mimic the overturning circulation driven by these unresolved ice shelves, we used the parametrisation of Mathiot et al. (2017) which prescribes a meltwater flux of ice shelf uniformly distributed over the depth and width of the unresolved cavity opening, from the mean ice front draft down to the seabed, or the grounding line depth if it is shallower. Mathiot et al. (2017) showed that this parametrisation of the ice shelf melting drives a buoyant overturning circulation along the coast, i.e. the meltwater pump, similar to that simulated by cavities when they are explicitly resolved.

For icebergs, it is true that a similar mechanism may occur (Helly et al., 2011; Stephenson et al., 2011) but the scale of that process is small (Biddle et al., 2015). This subgrid-scale mechanism is not

represented in the iceberg and ocean models used to produce the iceberg meltwater climatology (Marsh et al., 2015; Merino et al., 2016) and not relevant with our model setup of 1° resolution. However, investigating different distribution of iceberg Fe fluxes allowed us to explore the potential impact of that mechanism on ocean biogeochemistry. The surface distribution of iceberg Fe fluxes can be seen as a highly effective meltwater pump, the homogeneous distribution throughout the water column as a moderate meltwater pump and a distribution at depth as an inefficient meltwater pump.

Regarding the study of Laufkötter et al. (2018), their method, results, and model outputs do not allow to disentangle physical or biogeochemical reasons for differences with our model. Many reasons might explain the very different sensitivity of C export to AIS Fe fluxes: different distribution of freshwater fluxes, different modelled physical properties, different nutrient distribution, a different relationship between primary productivity and C export (see also our answer to reviewer #1). In fact, a detailed and thorough comparison with that study is really challenging because we lack many information that would be necessary. These differences are really intriguing and would probably deserve a careful analysis involving a collaboration between the two groups.

Smaller corrections

Abstract: Line 12-13: The comment that seasonal variations have regional impacts that are then "almost negligible" is slightly confusing. May be better to re-word this sentence?

Sentence reworded as follows: "The Fe supply is effective all year round and seasonal variations of the iceberg Fe fluxes have regional impacts which are small for annual-mean primary productivity and C export at the scale of the SO"

Pg2: Some other references to consider in this section are Cape et al (2019) (ice shelf meltwater pump), Biddle et al (2015), in-situ observations of productivity from iceberg melt

References added in this section of the article.

Line 17: I'm not sure you've defined AIS yet. Be very clear about the differences between AIS (I assume Antarctic Ice Sheet?), ice shelves and icebergs.

The acronym AIS used for the Antarctic Ice Sheet is defined in the abstract.

Line 27: "fueling" in what way? Is the Fe used, or is it just supplied?

Here we mean "supplied".
Sentence modified.

Line 34: remove "the" before "Prydz Bay"

> Acknowledged and addressed

Pg 3, line 18: I would read "along the water column" as along the iceberg tracks (spatial/ horizontal). Is this what you mean, or do you mean the vertical distribution?

We mean vertical distribution, i.e. through the water column.
> Acknowledged and addressed

Pg 4, line 10: For those unfamiliar with the model, a brief description here of how the freshwater fluxes are added would be helpful. Are the ice cavities simulated? Or is it a vertical wall in the model that freshwater/Fe is added through? In the latter case, what does "between the base and the grounding line of the ice shelves" then refer to – freshwater fluxes are equally added between the depth of the ice shelf (say 400 m) and the seabed? In this situation, many recent papers have shown that the strongest outflow is at the base of the ice shelf and diminishes with depth, in addition to buoyant upwelling to the surface (Naveira Garabato et al., 2017; Nakayama et al., 2014). Again, this is relevant to the meltwater pump.

Please, see our answer to general concerns.
Text modified to detail that the parametrisation of the ice shelf melting from Mathiot el at. (2017) simulates the buoyant overturning circulation along the coast and the associated meltwater pump.

Pg 6, line 24: "as well as in the Ross Sea until the Amundsen Sea" – I'm not sure what you mean by this? The Indian and Pacific sectors include these coasts? (See comment in figures about specifying what region you are referring to).

You are totally right, Indian and Pacific sectors include these coasts.
We removed this part from the sentence.
The Southern Ocean sectors are added in Figure 1.

Pg7, line 9-10: I am not sure what you mean by "Furthermore, in winter: : :".

Sentence modified as follows:
"Furthermore, in winter, deep mixing entrained to the surface Fe that was released in summer below the euphotic zone and that escaped consumption by phytoplankton due to the lack of light."

Pg 10, Lines 14-18: I think the meltwater pump should be included here – the ice shelf Fe is not just injected deeper than the mixed layer.

You are right. We modified the text in accordance.

Line 33: “The mains” ! “The main”

> Acknowledged and addressed

Pg 11, Line 11: remove “the” in front of Bouvet.

> Acknowledged and addressed

Line 15: remove “by” in front of “1.3: : :”

Replaced by « up to »

Pg 13, Line 30-35: This deserves more discussion about why there are differences between the models with similar Fe fluxes. Are there physical differences in the models in how they treat mixing of meltwater/depth of meltwater input?

Please see our answer to the general concerns.

Pg 15, Line 20-23: This seems quite likely (e.g. Cape et al, 2019) – see earlier general comment. Line 34: “we did not explore”

Figures – I would like the labels on the maps for longitudes to be slightly larger, and to be consistent with the direction/order of labelling panels. You also refer to the different sectors a lot (e.g. Indian-Pacific sector) – is it possible to mark the boundaries of these sectors, perhaps just on the first figure?

OK figures modified.
Indian, Atlantic, and Pacific sectors added in Figure 1.

Figure 5 – what is the colorbar for this figure?

The colour bar is identical to figure 4 and added in figure 5.

Figure 8 has an incorrect caption (it is identical to Figure 7).

Corrected to the right caption:

"Surface chlorophyll concentrations in summer (December, January, and February) from (a) satellite observations (MODIS-Aqua, Johnson et al. (2013)), (b) the CTL experiment, and (c) the SOLUB5 experiment in the Southern Ocean, south of 50° S.

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Sensitivity of ocean biogeochemistry to the iron supply from the Antarctic ~~ice sheet~~ Ice Sheet explored with a biogeochemical model

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Abstract. Iron (Fe) delivery by the Antarctic Ice Sheet (AIS) through ice shelf and iceberg melting enhances primary productivity in the largely iron-limited Southern Ocean (SO). To explore this fertilization capacity, we ~~implemented~~ implement a simple representation of the AIS iron source in the global ocean biogeochemical model NEMO-PISCES. We ~~evaluated~~ evaluate the response of Fe, surface chlorophyll, primary production and carbon export to the magnitude and hypothesized vertical distributions of the AIS Fe fluxes. Surface Fe and chlorophyll concentrations are increased up to ~~25~~ 24 % and 12 %, respectively, over the whole SO. The AIS Fe delivery is found to have a relatively modest impact on SO primary production and C export which are increased by 0.063 ± 0.036 PgC yr^{-1} and 0.028 ± 0.016 PgC yr^{-1}, respectively. However, in highly fertilized areas, primary production and C export can be increased by up to 30 % and 42 %, respectively. Icebergs are predicted to have a much larger impact on Fe, surface chlorophyll and primary productivity than ice shelves in the SO. The response of surface Fe and chlorophyll is maximum in the Atlantic sector, northeast of the tip of the Antarctic Peninsula, and along the East Antarctic coast. The iceberg Fe delivery below the mixed layer may, depending on its assumed vertical distribution, fuel a non-negligible subsurface reservoir of Fe. The AIS Fe supply is effective all year round~~and seasonal variations in iceberg melting~~. The seasonal variations of the iceberg Fe fluxes have regional impacts which are ~~almost negligible~~ small for annual-mean primary productivity and C export at the scale of the SO.

1 Introduction

Iron (Fe) is a vital micronutrient for phytoplankton photosynthesis and marine life. While being the fourth most abundant element in the continental crust (Wedepohl, 1995), Fe is present at extremely low concentrations in most of the oceans. In the ~~SO~~Southern Ocean (SO), the largest High Nutrient Low Chlorophyll (HNLC) region, this trace metal exerts with light a strong limitation on primary productivity (Martin et al., 1990; Smetacek, 2001; Coale et al., 2004; Boyd et al., 2007). Iron supply therefore modulates the intensity of the biological carbon pump in the SO (Bowie et al., 2001; Blain et al., 2007; Boyd et al., 2007) and possibly plays a key role on glacial-interglacial carbon-cycle regulation of climate (Martin, 1990).

Several sources contribute to the Fe pool in the SO: atmospheric dust deposition ~~(Tagliabue et al., 2009; Raiswell et al., 2016)~~ (Wagener et al., 2008; Tagliabue et al., 2009; Boyd et al., 2010a, 2012; Hooper et al., 2019; Ito et al., 2019), sediment resuspension and dissolution (Dulaiova et al., 2009; Tagliabue et al., 2009; de Jong et al., 2013; Borrione et al., 2014), hydrothermal activity (Tagliabue et al., 2010), iceberg calving and melting ~~(Smith et al., 2007; Lin et al., 2011; Duprat et al., 2016)~~(Smith et al., 2007; Lin e
, ice shelves ~~(Gerringa et al., 2012; Herraiz-Borreguero et al., 2016)~~(Gerringa et al., 2012; Herraiz-Borreguero et al., 2016; St-Laurent et a
, and sea ice (Lannuzel et al., 2007, 2010, 2016; Lancelot et al., 2009). Modeling studies have highlighted the different levels of significance of these Fe sources to sustain primary productivity in the SO (Lancelot et al., 2009; Tagliabue et al., 2009, 2014a; Borrione et al., 2014; Death et al., 2014; Wadley et al., 2014; Wang et al., 2014; Laufkötter et al., 2018). Nevertheless, large uncertainties remain in their fertilization capacity due to an important lack of data, hampering their integration in biogeochemical and climate models (Tagliabue et al., 2016).

Among the Fe sources in the SO, icebergs and ice shelves have been largely overlooked in ocean biogeochemical models. For instance, none of the models participating to the FeMIP exercise includes these glacial iron sources (Tagliabue et al., 2016) while observations estimate the total mean flux of potentially bioavailable Fe from SO icebergs to span 1 to 3 orders of magnitude higher than from dust deposition (Shaw et al., 2011; Raiswell et al., 2016) ranging from 3.2 to 25 Gmoles yr^{-1} for icebergs and from 0.0 to 0.02 Gmoles yr^{-1} for atmospheric dust (Raiswell et al., 2016). The few modeling studies conducted to date scaled the contribution of the AIS ~~iron~~ Fe source in the same order of magnitude as atmospheric dust (Lancelot et al., 2009; Death et al., 2014) or one order of magnitude higher (Wadley et al., 2014; Laufkötter et al., 2018) but with a larger uncertainty in the biological response to its fertilization effect. Thus, the iceberg Fe source is estimated to increase the SO primary production by 6 ~~%~~ to 10 % in Wadley et al. (2014) while Death et al. (2014) evaluated the iceberg and subglacial contribution to primary production to be up to 40 %. Recently, Laufkötter et al. (2018) estimated, in a preindustrial context, the AIS ~~iron~~ Fe source to sustain 30 % of the marine particle export production in the SO consequently reducing by 30 % the carbon outgassing in this region.

Icebergs and ice shelves contain higher Fe concentrations than seawater (de Baar et al., 1995; Lin et al., 2011; Shaw et al., 2011; Herraiz-Borreguero et al., 2016), mainly as lithogenic material from glacial sediments (Raiswell et al., 2006; Shaw et al., 2011; Hopwood et al., 2017). The melting of icebergs and ice shelves releases Fe to seawater as particulate, dissolved, and potentially dissolvable forms (Raiswell et al., 2008, 2016; Hawkings et al., 2014; Herraiz-Borreguero et al., 2016; Hodson et al., 2017), fueling ~~surface waters and~~ the water column ~~(Lin et al., 2011; De Jong et al., 2015)~~in Fe (Lin et al., 2011; De Jong et al., 2015). In the 1930s, Hart (1934) speculated that a link may exist between the phytoplankton populations observed in the Weddell Sea and potential Fe from the large number of debris-rich icebergs. ~~Fe in glacial sediments was long considered to be unavailable to phytoplankton .~~ Raiswell et al. (2006) showed that glacial sedimentary Fe contains nanoparticulate Fe of which a small fraction can be biogeochemically reactive and potentially bioavailable to phytoplankton. The iron fertilization capacity of icebergs has been evidenced from ~~*in situ* observations (Smith et al., 2007; Lin et al., 2011)~~ in situ observations

(Smith et al., 2007; Lin et al., 2011; Biddle et al., 2015) and hotspots of primary productivity have been observed by satellites in the wake of drifting icebergs ~~(Schwarz and Schodlok, 2009; Duprat et al., 2016)~~(Schwarz and Schodlok, 2009; Duprat et al., 2016; Wu a . In coastal regions, the under ice shelf delivery of bioavailable Fe can ~~also~~ be significant to sustain primary productivity as ~~estimated~~ highlighted in the Amundsen Sea ~~(Gerringa et al., 2012) and in the~~ (Gerringa et al., 2012; St-Laurent et al., 2017, 2019) and in Prydz Bay (Herraiz-Borreguero et al., 2016). The meltwater pump is also estimated as a significant Fe supply mechanism in polynyas (St-Laurent et al., 2017, 2019) and in coastal regions (Cape et al., 2019). However, the mean supply of the bioavailable Fe fraction from icebergs and ice shelves is difficult to quantify because of the heterogeneous nature of the Fe distribution in these sources (Raiswell et al., 2016; Hopwood et al., 2017). Until recent years, very few data were available. Estimates of iceberg Fe fluxes were based on only 6 samples (Raiswell et al., 2008) and, to our knowledge, no representative data are available for ice shelves. New observations, largely from Greenland icebergs, increased the set of iceberg data to about 50 glacial samples (Raiswell et al., 2016), offering the opportunity to better constrain the Fe supply from ~~the AIS~~ ice sheet to seawater and its effect on primary productivity in biogeochemical models.

Quantifying the ~~contribution of the AIS to the Fe~~ AIS contribution to the iron pool in the SO is of great interest for marine biogeochemistry as this source may be influenced by global warming. Indeed, the SO is a large sink of anthropogenic carbon (Sabine et al., 2004; Khatiwala et al., 2013) whose physical environment is evaluated to be severely affected by climate change (Rintoul et al., 2018). The AIS has already lost a significant amount of its mass over the period 1992-2017. The total loss of ice mass is of 2,720 ± 1,390 billion tons, and is particularly strong in West Antarctica and in the Antarctic Peninsula region, where annual melting rates have increased by factors of 3 and 5, respectively (The IMBIE team, 2018). In a business as usual scenario, the glacial coverage in Antarctica is estimated to be massively altered with a possible 23 % reduction of the ice shelf volume by 2070 (DeConto and Pollard, 2016; Rintoul et al., 2018). The projected ~~decline of the AIS will~~ AIS decline could increase the release of Fe from ~~icebergs and ice shelves in the SO with possible significant impacts on~~ ice shelves and icebergs, with possible impacts on SO marine productivity and biogeochemical cycles, yet this would depend on how Fe inputs relate to productivity and carbon export.

In this study, we ~~evaluate~~ assess the AIS impacts on Fe concentrations and marine primary productivity in the SO and investigate their sensitivity to the main characteristics of the iron delivery from icebergs and ice shelves. Firstly, we focus on the magnitude of the AIS Fe supply. For this purpose, different soluble fractions of sedimentary Fe ~~were~~ are assumed in the ocean biogeochemical model NEMO-PISCES, associated with recent iceberg and ice shelf freshwater flux estimates. Secondly, because the distribution of released Fe from icebergs ~~along~~ through the water column is largely undocumented, we ~~investigated~~ explore several possible vertical distributions of iceberg Fe delivery to seawater to encompass this large uncertainty. ~~The~~ Thirdly, the effects of the seasonal variations in the iceberg Fe supply are evaluated against an annual mean climatology of the iceberg Fe fluxes. ~~We also evaluated~~ Finally, we assess the relative contributions of ice shelves and icebergs to the SO Fe pool.

2 Method

2.1 NEMO-PISCES model description

We ~~used~~ use the hydrodynamical and biogeochemical model NEMO-PISCES version 3.6 (Madec, 2008). This modeling platform is based on the ocean dynamical core OPA (Madec, 2008), the marine biogeochemistry model PISCES-v2 (Aumont et al., 2015), and the Louvain-La-Neuve sea ice model LIM3 version 3.6 (Rousset et al., 2015). We ~~used~~ use a global configuration of NEMO-PISCES at 1° horizontal resolution ~~of~~ on an isotropic mercator grid with a local meridional refinement up to 1/3° at the equator. The vertical grid follows a partial step z-coordinate scheme and has 75 levels with 25 levels in the upper 100 m. Lateral mixing is computed along isoneutral surfaces (Madec, 2008). Mesoscale eddy-induced turbulence follows the Gent and Mc Williams (1990) parameterization and vertical mixing is parameterized using the turbulent kinetic energy scheme (Blanke and Delecluse, 1993) as modified by Madec (2008). The biogeochemical model PISCES simulates two phytoplankton functional types (diatoms and nanophytoplankton), two zooplankton size classes (microzooplankton and mesozooplankton), the biogeochemical cycles of five limiting nutrients (NO_3, PO_4, NH_4, $Si(OH)_4$, and Fe), dissolved oxygen, dissolved inorganic carbon, total alkalinity, dissolved organic matter, small and large organic particles. Different external sources of Fe are included: atmospheric dust deposition, sediment mobilization, rivers, and sea ice. The implementation of these ~~iron~~ Fe sources in NEMO-PISCES is fully described in Aumont et al. (2015).

2.2 Modeling the Antarctic Ice Sheet Fe supply

To represent the AIS Fe supply to seawater in our model, we ~~used~~ use recent freshwater flux climatologies of ice shelves and icebergs based on Depoorter et al. (2013). The modeled annual mean freshwater flux from the AIS is estimated ~~to~~ as ∼2790 Gt yr^{-1} partitioned into a liquid and a solid phase of about the same magnitude with an annual release of ∼1439 Gt yr^{-1} from ice shelves and of ∼1351 Gt yr^{-1} from icebergs. The climatology of the coastal runoff estimate of Antarctic ice shelves is assumed to be a steady freshwater flux ~~throughout~~ through the year. ~~The ice shelf freshwater flux is homogeneously distributed along the water column between the base and the grounding line of ice shelves using the prescribed meltwater flux parameterization of Mathiot et al. (2017). This parameterization has been developed to represent the unresolved overturning circulation in cavities beneath ice shelves where melting mainly occurs (Depoorter et al., 2013; Herraiz-Borreguero et al., 2016; Mathiot et al., 2017)~~ ~~.~~ For icebergs, we ~~used~~ use a model-based seasonal climatology of iceberg melting over the SO (Fig. 1) from Merino et al. (2016). The monthly climatology distribution of freshwater flux from icebergs ~~has been~~ was estimated using an improved version of the Lagrangian iceberg model NEMO-ICB (Marsh et al., 2015) coupled to a 1/4° global configuration of NEMO (Merino et al., 2016). The ocean model was forced by a climatological repeated-year atmospheric forcing based on ERA-interim and by recent estimates of Antarctic freshwater (Depoorter et al., 2013).

In our model configuration, the cavities below the ice shelves are not opened. We use the parameterization of Mathiot et al. (2017) to mimic the overturning circulation driven by the unresolved ice shelves. The meltwater flux of ice shelves is uniformly distributed over the depth and width of the unresolved cavities, from the mean ice front base down to the seabed, or the grounding line depth if shallower. This parameterization of the ice shelf melting drives a buoyant overturning circulation along the coast similar to that simulated by cavities when they are explicitly resolved. The so-called meltwater pump driven by this mechanism is pointed out to play an important role in the supply and delivery of Fe to polynyas (St-Laurent et al., 2017, 2019) and coastal regions (Cape et al., 2019). For icebergs, a similar mechanism may occur (Helly et al., 2011; Stephenson et al., 2011) but the scale of that process is small (Biddle et al., 2015). This subgrid-scale mechanism is not represented in the coupled iceberg-ocean model used to produce the iceberg meltwater climatology (Marsh et al., 2015; Merino et al., 2016) and not relevant with our model setup of 1° resolution.

The iceberg-hosted sediment content ~~is~~ while poorly constrained by observations ~~and~~ is estimated to range from 0.4 to 1.2 g L^{-1} (Anderson et al., 1980; Shaw et al., 2011). To simulate the Fe fluxes delivered by melting icebergs and ice shelves in the SO, we ~~associated to~~ associate with the freshwater flux climatologies a sediment content of 0.5 g L^{-1} as used in Raiswell et al. (2006) and Death et al. (2014) assuming, as a crude assumption, that sediment content in icebergs and ice shelves ~~are~~ is roughly equivalent. The ~~mean content of labile~~ content of ferrihydrite, the most soluble Fe in iceberg-hosted sediments, ~~mainly in the form of ferrihydrite~~and thus potentially bioavailable, has been recently estimated to range from 0.03 ~~%~~ to 0.194 wt. % with a mean ~~value~~ content of 0.076 wt. % (Raiswell et al., 2016). Shaw et al. (2011) estimated a range of ~~labile Fe~~ ferrihydrite of 0.04 to 0.4 wt. % for free-drifting icebergs in the Weddell Sea. In our study, we set the mean sediment content in ferrihydrite to be 0.1 %. ~~The~~ A conservative value of the fraction of ferrihydrite that can be biologically available as Fe nanoparticles (i.e. the soluble fraction of ferrihydrite) is ~~assumed to be of~~ around 10 % (Raiswell et al., 2008; Death et al., 2014). However, the ice-water-mineral reactions may profoundly alter the bioavailability percentage of Fe in glacial sediments (Hawkings et al., 2018; Raiswell et al., 2010, 2018). In order to account for the uncertainty of the bioavailable fraction of glacial Fe ~~(Boyd et al., 2012), we used~~ (Boyd et al., 2012; Raiswell et al., 2010, 2018), we use a solubility within a range of 1 ~~%~~ to 10 % which corresponds to a total annual Fe flux of 0.25 to 2.5 Gmoles yr^{-1} (Table 1). ~~This range~~ The range of the modeled iceberg Fe fluxes is relatively similar to other modeling studies (Death et al., 2014; Laufkötter et al., 2018) ~~.~~ ~~The modeled iceberg Fe fluxes are in~~ and lies within the lower range of previously published estimates based on observations (Raiswell et al., 2008, 2016; Shaw et al., 2011). To our knowledge, no ~~data allow to constrain the ice shelves Fe fluxes as the Antarctic estimates from Hawkings et al. (2014) are~~ observational data are available that allow ice shelf Fe fluxes from the AIS to be constrained. However, the modeled ice shelf Fe fluxes are in the lower range of estimates by Hawkings et al. (2014) for the AIS, while extrapolated from Greenland ~~ice sheet~~ Ice Sheet data.

2.3 Experimental design

We ~~designed~~ design 9 model experiments with different Fe solubilities for both ice shelves and icebergs, and different vertical distributions of delivered Fe from icebergs (Table 2). For consistency with the climatological forcing of the Antarctic freshwater release, all these experiments are run in a climatological setup using the CORE-I normal year atmospheric forcing (Griffies et al., 2009) and are initialized from a 120 ~~years~~ year long spin up simulation. They all include external sources of Fe from dust, sediments, sea ice, and rivers even though the latter does not contribute to the ~~Fe~~ iron pool in the SO. Each experiment is run for 20 years to achieve a sufficient equilibrium state for the Fe cycle in the framework of our sensitivity study.

The control experiment (CTL) is used as a reference run in the rest of the study and does not take into account any ~~iron~~ Fe source from the AIS. Figure 2 shows the annual mean distribution of surface Fe concentrations over the SO simulated by the CTL experiment. This distribution is contrasted with regions showing high surface Fe concentrations in coastal regions around the Antarctic continent and in the surrounding waters of SO islands such as South Georgia, the Crozet archipelago, the Kerguelen Plateau, and with large areas in the open ocean displaying very low values. The modeled surface distribution of Fe concentrations reflects the main contribution of sediments among the different external iron sources ~~actually~~ currently implemented in the standard version of the PISCES model (Aumont et al., 2015). The Fe distribution of the NEMO-PISCES model has been validated at the global scale in Tagliabue et al. (2016) and over the SO in Person et al. (2018) showing reasonable performance compared to available data (Tagliabue et al., 2012).

Three different solubilities of Fe from icebergs and ice shelves are tested in the SOLUB1, SOLUB5, and SOLUB10 experiments, imposing 1 %, 5 %, and 10 %, respectively. The corresponding annual Fe fluxes amount to 0.25, 1.25, and 2.5 Gmoles yr^{-1}, respectively, with similar contributions from both glacial sources (Table 1). The ISF, ICB-SURF, ICB-ML, ICB-KEEL, and ICB-ANNUAL experiments have an iceberg and ice shelf Fe solubility of 5 % as in the SOLUB5 experiment. The ISF experiment only includes the Fe source from ice shelves in order to assess its contribution ~~against~~ relative to icebergs.

Different vertical distributions of the iceberg Fe fluxes ~~have been~~ are explored. In the SOLUB1, SOLUB5, SOLUB10 and ICB-ANNUAL experiments, Fe is homogeneously released from icebergs over the top 120 m of the water column. This value corresponds to the average depth of the submerged part of the five ~~class sizes~~ size classes of icebergs modeled by the NEMO-ICB model (Marsh et al., 2015) and computed by applying the formulation of Rackow et al. (2017) to the average thickness of the modeled icebergs. In the ICB-SURF experiment, the whole iceberg Fe supply is released at the surface, i.e. in the first vertical level of our model which is 1 m thick. In the ICB-KEEL experiment, this flux is released at ∼120 m, i.e. at the mean depth of the keel of modeled icebergs. The ICB-KEEL experiment is set up to evaluate the contribution of a theoretical distribution of iceberg Fe fluxes delivered only at the base of icebergs. The ICB-KEEL experiment can be seen as the mirror experiment of the ICB-SURF experiment keeping in mind that this distribution is most probably unrealistic ~~,~~ as the potential buoyancy effect ~~tending~~ tends to upwell the iceberg meltwater to the surface ~~(Smith et al., 2007).~~ (Smith et al., 2007; Helly et al., 2011; Stephenson et al., 2011). The different vertical distributions of iceberg Fe fluxes prescribed in our experiments offer an indirect means to explore the potential impact of that mechanism on ocean biogeochemistry. In order to evaluate the role played by the iceberg Fe fluxes distributed below the mixed layer (ML), that is, the fraction not directly available for surface primary productivity, we ~~designed~~ design the ICB-ML experiment where this fraction is removed. Thus, the iceberg Fe fluxes in the ICB-ML experiment are distributed ~~along~~ throughout the water column, i.e. until a depth of 120 m, as in the SOLUB5 experiment, but the iceberg Fe flux values below the MLD are set to zero unlike in the SOLUB5 experiment. Finally, in the ICB-ANNUAL experiment, an annual mean climatology of the iceberg Fe fluxes is used instead of the monthly climatology to ~~evaluate~~ assess the impact of the seasonal variability in the supply of Fe from icebergs in the SO.

3 Results

3.1 Contribution of the Antarctic Ice Sheet to the spatial distribution of Fe

3.1.1 Sensitivity to the magnitude of the Antarctic Ice Sheet Fe supply

The uncertainty in the magnitude of the AIS Fe source is estimated to span, at least, 1 order of magnitude (Table 1). We ~~evaluated~~ assess the impact of this range on the spatial distribution of Fe in the SO by imposing three different soluble fractions of Fe: 1 %, 5 %, and 10 % (Table 2). The Fe supply from the AIS increases the Fe concentrations in the first 120 m in the SOLUB1, SOLUB5, and SOLUB10 experiments compared to the CTL experiment, respectively, the surface anomaly increasing with the Fe solubility (Fig. 3).

~~Globally, higher~~ Higher surface Fe concentrations are simulated in coastal regions all around the Antarctic continent. The most noticeable Fe anomaly is a marked plume northeast of the Antarctic Peninsula that expands until 50° S in the Atlantic sector and reaches the western sector of the Indian Ocean (Fig. 3c-3f). The spatial extent of the Fe anomalies becomes larger as the Fe solubility increases, particularly in the Atlantic sector and in the Ross Sea which appear to be the offshore areas that are the most greatly influenced by the AIS Fe source. The SOLUB1 experiment simulates a moderate impact with ~~an~~ annual mean surface Fe concentrations ~~higher~~ increased by $\sim$~~0.015~~ 0.026 nmol L^{-1} over the SO, south of 50° S, relative to the CTL experiment, i.e. 3 % more. The supply in the Atlantic plume increases the surface Fe concentrations by up to 0.16 nmol L^{-1} in summer (Fig. 3a). The highest Fe values are found in winter along the coasts of the Ross Sea and of the Amundsen Sea with surface Fe anomalies that reach 1 nmol L^{-1} (Fig. 3b). In the SOLUB5 experiment, the contribution of the AIS Fe source is more significant with ~~a~~ mean surface Fe ~~concentration that is~~ concentrations that are $\sim$~~0.07~~ 0.12 nmol L^{-1} higher, i.e. 13 % more than in the CTL experiment (Fig. 3c and 3d). The Atlantic plume is clearly marked and extends further eastward until 10° E with surface Fe concentrations in summer up to $\sim$0.8 nmol L^{-1} higher (Fig. 3c). Along the Antarctic ~~coasts~~coast, the AIS supply in winter increases the surface Fe anomalies by up to 3.8 nmol L^{-1} particularly in the Indian and Pacific sectors ~~as well as in the Ross Sea until the Amundsen Sea~~ (Fig. 3d). Two additional plumes emerge: a large one north of the Ross Sea and a smaller one in the vicinity of South Georgia (Fig. 3c and 3d). The SOLUB10 experiment strengthens the seasonal and spatial patterns of the surface Fe anomalies simulated in SOLUB5 with extensive Fe anomalies in the Atlantic plume, in the Ross Sea, in the Weddell Sea, and all along the Antarctic ~~coasts~~ coast (Fig. 3e and 3f). Over the SO, south of 50° S, the annual mean Fe concentrations are $\sim$~~0.13~~ 0.21 nmol L^{-1} higher than in the CTL experiment, an increase of 24 %. The surface Fe concentrations in the Atlantic plume and along the Antarctic ~~coasts~~ coast are up to $\sim$~~1.5~~ 1.4 nmol L^{-1} and $\sim$6.3 nmol L^{-1} higher, respectively. ~~With a~~ These Fe concentrations are difficult to compare to observations in these areas due to the scarcity of data. However, they are probably at the upper limit of Fe concentrations in the open ocean but still potentially realistic in coastal regions (de Jong et al., 2012) . With an Fe solubility of 10 %, the SOLUB10 experiment predicts an important contribution of the AIS source to the SO Fe pool (Fig. 3e), which is even larger near the coasts in winter (Fig. 3f).

The AIS significantly alters the surface Fe concentrations both in summer and winter (Fig. 3). The spatial patterns between these two seasons exhibit noticeable differences. In summer, surface Fe anomalies are marked and intense whereas, in winter, they extend over larger areas and are more diffuse (Fig. 3c-3f) showing lower maximum values but having higher mean levels. These seasonal differences reflect two different dynamics in the supply of Fe from the AIS and its subsequent loss from the surface. In summer, the release of Fe associated ~~to~~ with more intense iceberg freshwater fluxes drives surface Fe concentrations to high values. Environmental conditions are favorable for phytoplankton growth and the intense biological activity efficiently consumes the supplied Fe preventing it to be transported over large distances, especially in iron limited areas. In winter, biological activity is much weaker due to strong light limitation and the delivered Fe from the AIS can be advected further away. Furthermore, in winter, deep ~~mixed layer entrained~~ mixing entrains to the surface Fe ~~released~~ that was released in summer below the euphotic zone ~~that thus escapes summer~~ and that escaped consumption by phytoplankton due to the lack of light. This unconsumed fraction is also advected over significant distances by the intense ocean circulation in the SO. This explains the much sharper gradients simulated in summer, particularly noticeable in the SOLUB5 and SOLUB10 experiments.

3.1.2 Sensitivity to vertical distributions of the iceberg Fe supply

It is well established that ice shelf meltwater is injected at depth into the ocean (Depoorter et al., 2013; Mathiot et al., 2017)~~,~~ ~~the basal melting being~~ . The basal melting is driven by the properties of water masses that enter the ocean cavities underneath ice shelves (Jacobs et al., 1992) contributing directly and indirectly to the supply of Fe to the upper layer of the water column (St-Laurent et al., 2017, 2019). While the iceberg Fe supply has been evidenced by ~~*in situ*~~ in situ observations (Lin et al., 2011; Shaw et al., 2011; De Jong et al., 2015), almost nothing is known to our knowledge of where the Fe delivery occurs along the immersed part of icebergs and where this input is ~~mainly~~ predominately available to phytoplankton. Nonetheless, FitzMaurice et al. (2017) recently pointed out that the nonlinear response of iceberg melting leads to meltwater injected near the surface or mixed at depth depending on whether the flow velocity is weak or strong, respectively. Here we ~~evaluate~~ assess the impacts of four different theoretical vertical distributions of iceberg Fe fluxes on surface Fe concentrations over the SO as well as on vertical profiles of Fe in the upper 300 m of a large area highly fertilized by the AIS northeast of the Antarctic Peninsula (36° W-56° W, 58° S-63° S). For this purpose, we compare the ICB-SURF, ICB-ML, and ICB-KEEL experiments against the SOLUB5 experiment (Fig. 4).

The surface distribution of the iceberg Fe fluxes in the ICB-SURF experiment results in a large excess of surface Fe concentrations in summer ~~, all over the SO,~~ compared to the volume distribution applied in the SOLUB5 experiment (Fig. 4a). This excess is regionally important with surface Fe concentrations ~~reaching values higher by~~ up to 1.5 nmol L^{-1} higher in the large plume of the Atlantic sector and up to 27 nmol L^{-1} ~~.~~ higher in coastal areas than in the SOLUB5 experiment. Such maximum coastal concentrations of surface Fe are rarely observed except in a nearshore area north of the Antarctic Peninsula (de Jong et al., 2012). In the ICB-SURF experiment, the iceberg Fe supply in the mixed layer is maximum and is not sensitive to the depth of the mixed layer. By contrast, when the Fe flux is distributed over the upper 120 m (SOLUB5), the shallow pycnocline in summer severely limits the iceberg Fe supply in the mixed layer, with most of this supply being injected below the MLD. The differences between both experiments in winter are significantly less marked with large patterns of positive and negative differences in surface Fe concentrations highlighting the role played by the interactions between the seasonal variations of the MLD and the injection of Fe at depth (Fig. 4b). When the MLD is deeper than 120 m, the ICB-SURF experiment simulates slightly lower Fe concentrations, up to ∼0.04 nmol L^{-1} lower than in SOLUB5 in the Atlantic sector south of 60° S and ~~, globally, all~~ regionally around the Antarctic ~~coasts~~coast. The boundary zone between positive and negative values in the Atlantic sector is driven by the interplay between a MLD shallower than 120 m (Fig. 5) and the oceanic circulation resulting in Fe concentrations up to 1.5 nmol L^{-1} higher in the ICB-SURF experiment than in SOLUB5 ~~. Finally, higher~~ along the eastern coasts of the Antarctic Peninsula. Higher Fe concentrations are also simulated in ICB-SURF in localized areas in the Ross, Amundsen, and Bellingshausen Seas, and near the coasts of the Indian sector between 70° E and 85° E but without clear correlation with the MLD.

The vertical profiles of Fe in the highly fertilized area of the Atlantic plume northeast of the Antarctic Peninsula (36° W-56° W, 58° S-63° S) illustrate the different dynamic in the seasonal supply of Fe to the upper ocean in both experiments (Fig. 6). In summer, these vertical profiles are very different (Fig. 6a). In the mixed layer, Fe concentrations are higher in ICB-SURF than in SOLUB5 by a factor of 2.2. Below the MLD, the ICB-SURF experiment simulates Fe concentrations that decrease strongly until 70 m. In the SOLUB5 experiment, Fe concentrations increase significantly from below 30 m until 120 m and from there, decrease until 150 m~~depth~~. Below 150 m~~depth~~, both experiments converge to the same vertical profile of Fe. In winter, the vertical profiles are qualitatively similar in the upper 300 m (Fig. 6b). Yet, the ICB-SURF experiment displays a smaller vertical gradient in the upper 150 m than in SOLUB5. The scarcity of the data makes it challenging to discriminate whether the ICB-SURF experiment or the SOLUB5 experiment simulates a realistic vertical distribution of Fe.

The ICB-ML experiment ~~allows to quantify~~ permits assessment of the influence of the iceberg Fe supplied below the MLD, i.e. the importance of the non-directly available fraction of the iceberg Fe source, on the spatial distribution of Fe over the SO. Surface Fe concentrations in the ICB-ML experiment are lower than in the SOLUB5 experiment in both seasons and over the whole SO (Fig. 4c and 4d). Surface Fe values in summer and winter are up to ∼0.55 nmol L^{-1} and ∼0.4 nmol L^{-1} lower, respectively, than in the SOLUB5 experiment. This comparison suggests that the Fe fraction delivered by icebergs below the MLD is not completely scavenged and constitutes ~~a~~ an Fe pool that can supply surface waters in Fe as soon as the mixed layer deepens.

The seasonal evolution of the vertical Fe profiles supports the important role of the subsurface additional pool of Fe due to iceberg melting (Fig. 6). In summer, the SOLUB5 experiment has ~~a Fe concentration~~ Fe concentrations in the mixed layer ∼0.1 nmol L^{-1} higher than in the ICB-ML experiment (Fig. 6a). Below the MLD, Fe concentrations in SOLUB5 display a local maximum between 30 m and 150 m ~~. In contrast,~~ that the ICB-ML experiment does not simulate~~this local maximum in summer~~. In winter, Fe profiles in SOLUB5 and ICB-ML are qualitatively ~~almost~~ similar except that ~~iron~~ Fe levels in ICB-ML are about 0.06 nmol L^{-1} higher (Fig. 6b). This comparison illustrates that the Fe released by icebergs in summer below the MLD may represent a significant subsurface reservoir that can ~~feed in Fe~~ supply Fe to the surface layer by intraseasonal events such as storms (Swart et al., 2015; Nicholson et al., 2016), by strong meso- and sub-mesoscale activities (Swart et al., 2015; Rosso et al., 2016) as well as by deep mixing in winter (Tagliabue et al., 2014b).

The iceberg Fe supply at depth in the ICB-KEEL experiment shows a significant decrease in surface Fe concentrations compared to the SOLUB5 experiment in both seasons (Fig. 4e and 4f). In summer, surface Fe concentrations are up to ∼2.8 nmol L^{-1} lower than in the SOLUB5 experiment in the Atlantic plume and all around the Antarctic ~~coasts~~ coast (Fig. 4e).

In winter, the difference is weaker than in summer with surface Fe concentrations up to ∼0.8 nmol L^{-1} lower than in the SOLUB5 experiment (Fig. 4f). Moreover, the spatial differences between both experiments in the open ocean in winter are less widespread than in the ICB-ML experiment (Fig. 4d) where the iceberg fertilization effect is less effective ~~,~~ south of the Atlantic plume and, more generally, south of 60° S offshore of the Antarctic ~~coasts~~coast. While low, the supply of Fe from icebergs at depth can have a large area of influence on surface Fe concentrations in winter.

The vertical profile of Fe in the Atlantic plume presents a marked peak at a depth of 120 m~~depth~~, which corresponds to the depth at which Fe is ~~bieng released from icebergs~~ released from iceberg melting. At ~~that depth, iron~~ this depth, Fe concentrations reach 1.2 nmol L^{-1} in summer, which is 0.5 nmol L^{-1} higher than in the SOLUB5 experiment (Fig. 6a). In the upper layer, Fe concentrations are lower by ∼0.2 nmol L^{-1} than in the ~~the~~ SOLUB5 experiment and almost equal to the CTL experiment. The vertical gradient is the strongest of all the experiments. In winter, surface Fe concentrations in the mixed layer are ∼0.09 nmol L^{-1} lower than in the SOLUB5 experiment and slightly higher than in the CTL experiment (Fig. 6b). The vertical gradient between the surface and 120 m ~~depth~~ remains stronger than in any other experiments but the difference is weaker. Below 120 m and down to about 200 m, differences with the other experiments are significantly smaller than in summer. These results show that a predominant supply of Fe at the base of icebergs will generate an important subsurface reservoir of ~~iron~~ Fe that can be entrained to the surface by the deepening of the MLD. The role of the subsurface reservoir of Fe is pointed out to be critical to sustain the iron supply to surface waters (Tagliabue et al., 2014b).

3.1.3 Sensitivity to the seasonal variations of the iceberg Fe supply

The variations of the AIS Fe fluxes due to the seasonal variability of iceberg calving and melting ~~of icebergs~~ (Fig. 1a) impact the seasonal cycle of Fe over the SO. To assess to what extent these variations are significant for the ~~Fe pool in the SO~~SO Fe pool, we compare the ICB-ANNUAL experiment to the SOLUB5 experiment. ~~Globally, over~~ Over the whole SO, the surface Fe concentrations in the ICB-ANNUAL experiment and the SOLUB5 experiment are increased by 9 % and 13 % in summer and by 15 % and 13 % in winter, respectively, relative to the CTL experiment. Imposing an annual mean iceberg supply of Fe also leads to differences in the spatial distribution of Fe (Fig. 4g and 4f). In ICB-ANNUAL, surface Fe concentrations in summer are lower in the Atlantic sector and ~~all~~ around the Antarctic ~~coasts~~ coast than in the SOLUB5 experiment with values up to ∼1.9 nmol L^{-1} lower (Fig. 4g). On the other hand, some other areas such as downstream of South Georgia, in the Weddell Sea, and in the Ross Sea are predicted to have higher Fe concentrations. In the Weddell Sea, along the east coasts of the Antarctic Peninsula, the Fe values in the ICB-ANNUAL experiment are up to 0.2 nmol L^{-1} higher than in the SOLUB5 experiment. In winter, an opposite spatial pattern is simulated (Fig. 4h). Surface Fe concentrations in the Atlantic plume and along the east coasts are up to ∼0.75 nmol L^{-1} higher in the ICB-ANNUAL experiment whereas ~~offshore of 80° E,~~ downstream of South Georgia, in the Weddell Sea, ~~and~~ in the Ross Sea, and offshore of 80° E these concentrations are up to ∼0.45 nmol L^{-1} lower. When looking at the vertical Fe distribution in the Atlantic plume, vertical profiles in summer have almost the same shape in both experiments (Fig. 6a). However, Fe concentrations in ICB-ANNUAL are lower by ∼0.1 nmol L^{-1} in the upper 120 m than in SOLUB5. In winter, the vertical profile of Fe in ICB-ANNUAL is noticeably different with Fe concentrations higher by ∼0.18 nmol L^{-1} in the upper 50 m and with values that increase and then decrease by ∼0.1 nmol L^{-1} between 50 m and 150 m whereas Fe concentrations in the SOLUB5 experiment increase gradually in this depth range (Fig. 6b). Thus, when the seasonal variations of iceberg Fe are not considered, the seasonal amplitude of the Fe cycle over the SO is increased with ~~higher concentrations~~ Fe concentrations higher in winter and lower ~~concentrations~~ in summer (Fig. S2a) leading to significant regional differences in the surface distribution of Fe.

3.1.4 Evaluation of the ice shelf contribution

~~Fe supply from the AIS~~ The AIS Fe supply occurs through two main processes: (1) the basal melting of ice shelves which is coastal, and (2) the calving and melting of icebergs which is more widespread over the SO. Both freshwater sources are estimated to be of the same order of magnitude (Depoorter et al., 2013). ~~However, the~~ In addition, the ice shelf melting contributes indirectly to the supply of Fe to the upper layer of the water columnn through the meltwater pump driven by the buoyancy overturning circulation near the ice shelf fronts (St-Laurent et al., 2017, 2019). The relative contribution of each source of Fe to the SO ~~Fe~~ iron pool is not known, mainly due to the lack of data for ice shelves. Here we ~~compared~~ compare the ISF experiment, which only accounts for the ice shelf Fe source, against the SOLUB5 experiment which encompasses both sources of Fe from the AIS. The surface Fe anomalies in the ISF experiment ~~remarkably differ~~ differ remarkably from the SOLUB5 experiment (Fig. 7). The ice shelf contribution is trapped near the Antarctic ~~coasts~~ coast extending further offshore in winter (Fig. 7c and 7d) whereas the spatial contribution of icebergs ~~extends~~ spreads more widely the influence of the AIS Fe source ~~significantly more widely~~ over the SO until 50°S (Fig. 7a and 7b).

The surface Fe concentrations in the ISF experiment are increased by 1 % and 3 % compared to the CTL experiment in summer and winter, respectively. The contribution of ice shelves to the ~~Fe pool over the SO~~ SO Fe pool is one order of magnitude lower than in the SOLUB5 experiment which simulates surface Fe concentrations that are increased by 13 % in both seasons. The comparison between both Fe sources ~~suggests two features of the AIS iron source: the high~~ highlights the higher fertilization capacity of icebergs due to a delivery at ~~a longer time scale and the strong limitation that exerts the injection of ice shelf Fe at depth in subsurface waters deeper than the~~ larger spatial scales. It also suggests that the direct and indirect supplies of Fe to surface waters from ice shelf melting are significantly limited by the stratification of the mixed layer. Moreover, the ice shelf ~~Fe~~ supply occurs in coastal regions ~~that are~~ already highly fertilized by sediments ~~leading to~~ and where elevated Fe concentrations ~~and experiencing already an~~ experience intense scavenging. ~~Therefore, the additional Fe released~~ The additional Fe from ice shelves is therefore rapidly scavenged and lost from surface waters.

3.2 Fertilization effect of the Antarctic Ice Sheet on surface chlorophyll

The SO is the largest HNLC region where Fe is the main limiting micronutrient for primary productivity. We ~~showed~~ show that the Fe supply by ice shelf and iceberg melting can fertilize the surface waters all year round (Fig. 3). This additional input of Fe can be used at the blooming season by phytoplankton from November to February. Here ~~,~~ we qualitatively evaluate the ~~fertilizing~~ fertilization effect of the AIS on surface chlorophyll concentrations (~~CHL~~SChl) in summer (December, January, and February). First of all, we briefly ~~compared the CHL~~ compare the SChl climatology from satellite observations of the MODIS-Aqua ocean color product estimated by Johnson et al. (2013) to the CTL experiment (Fig. 8a and 8b). At the scale of the SO, two main qualitative characteristics can be observed. The CTL experiment represents with a rather good approximation the ~~CHL~~ SChl distribution in summer around the Antarctic continent, from the Antarctic ~~coasts~~ coast until 65° S. But, in the open ocean, north of 65° S, quite large differences between observations and the standard version of the model are seen especially in the Atlantic sector and in the Pacific sector, north of the Ross Sea where large spatial patterns of SChl are not simulated.

To assess the fertilization effect of the AIS on ~~CHL, we computed the CHL~~ SChl, we compute the SChl difference between the eight experiments and the CTL experiment (Fig. 9). ~~Globally, the~~ The AIS impact on ~~CHL~~ SChl is mostly apparent in the ~~large plume of the~~ Atlantic sector northeast of the Antarctic Peninsula, along the Antarctic ~~coasts~~ coast in the Indian and Pacific sectors, and, more moderately, ~~in the Pacific sector,~~ north of the Ross Sea. The fertilization effect increases with the Fe solubility with ~~CHL~~ SChl higher by 2 %, 7 %, and 12 % in the SOLUB1, SOLUB5, and SOLUB10 experiments, respectively (Fig. 9a-9c). The main features driven by the intensity of the ~~iceberg~~ AIS Fe source are the extension of an Atlantic plume until the Indian sector as well as the increased ~~CHL~~ SChl along the coasts from 80° E until the Ross Sea. In the SOLUB1 experiment, the impact on ~~CHL~~ SChl is particularly low, restricted to the Atlantic sector and in ~~a coastal area~~ coastal areas around 135° E (Fig. 9a). The Atlantic plume has the smallest extent from the Antarctic Peninsula until the South Orkney Islands where ~~CHL~~ SChl values are up to ∼0.4 mg m^{-3} higher than in the CTL experiment. The Fe solubility of 5 % implemented in the SOLUB5 experiment increases significantly the impact of the AIS on SChl (Fig. 9b). The Atlantic plume extends eastward, far from the Antarctic Peninsula and the South Orkney Islands. The blooms along the Antarctic ~~coasts~~ coast in the eastern sector and in the Ross Sea get more intense and two modest plumes emerge north of the Ross Sea and around 90° E. The maximum contribution to ~~CHL~~ SChl between the Antarctic Peninsula and the South Orkney Islands is ∼1 mg m^{-3} higher than in the CTL experiment, and 2.2 mg m^{-3} higher in the coastal area around 135° E. The SOLUB10 experiment ~~exacerbated~~ emphasizes the spatial patterns described in the SOLUB5 experiment with ~~CHL~~ SChl higher by ∼1.2 mg m^{-3} in the Atlantic sector until Bouvet Island and up to ∼2.4 mg m^{-3} higher along the coasts in the eastern sector of the SO (Fig. 9c). The plume that extends northward ~~until 60° S~~ from the Ross Sea until 60° S has more elevated ~~CHL~~ SChl levels, about ∼0.3 mg m^{-3} higher than in the CTL experiment.

In the ICB-SURF experiment, the ~~largest contribution to CHL is simulated with surface chlorophyll concentrations increased by~~ simulated contribution to SChl is the largest with an increase of 12 % over the whole SO. The maximum SChl are ~~by~~ up to ∼1.3 mg m^{-3} higher in the Atlantic plume ~~,~~ and up to ∼2.5 mg m^{-3} higher in the Ross Sea and along the east coasts of Antarctica relative to the CTL experiment (Fig. 9d). Despite a slightly higher intensity of the bloom, the spatial patterns in the ICB-SURF experiment are very similar to the SOLUB10 experiment (Fig. 9c and 9d). On the contrary, in the ICB-KEEL experiment, the iceberg contribution to ~~CHL~~ surface chlorophyll is the lowest, ~~surface chlorophyll concentrations~~ SChl being on average only 2 % higher relative to CTL. The Atlantic plume is absent as well as the elevated concentrations along the Antarctic ~~coasts~~ coast and in the Ross Sea (Fig. 9f). ~~Nonetheless, even~~ Nevertheless, though small, a ~~significant~~ fertilizing effect is simulated with ~~CHL~~ SChl values that are locally higher by 0.25 mg m^{-3} than in the CTL experiment. The ICB-ML experiment produces ~~CHL~~ SChl anomalies that lie between the SOLUB1 and the SOLUB5 experiments with maximum ~~CHL~~ SChl up to ∼0.9 and ∼1.6 mg m^{-3} higher than in the CTL experiment in the Atlantic plume and in local areas along the east coasts of Antarctica, respectively (Fig. 9e). The influenced area is clearly smaller than in the SOLUB5 experiment demonstrating that the non-directly available fraction of Fe delivered by melting icebergs may have a non-negligible impact on ~~CHL~~ SChl during the blooming season. The ICB-ANNUAL experiment simulates ~~CHL~~ SChl levels that are on average higher by 6 % over the SO compared to the CTL experiment with anomalies higher by ∼0.7 mg m^{-3} in the Atlantic plume and up to ∼1.2 mg m^{-3} along the Antarctic ~~coasts~~ coast (Fig. 9g). Although maximum ~~CHL~~ SChl values in the Atlantic plume are ∼0.3 mg m^{-3} lower, the simulated spatial extent of the ~~CHL~~ SChl anomalies in the Atlantic sector is wider than in the SOLUB5 experiment, the other impacted areas being almost identical in the ICB-ANNUAL and the SOLUB5 experiments. In the ISF experiment, the increase of ~~CHL~~ SChl is very small as a consequence of the weak impact of ice shelf melting on Fe (Fig. 9h, see subsection 3.1.4).

3.3 Model evaluation

The purpose of this sensitivity study is not to specifically improve the skill of the biogeochemical model at representing the Fe and ~~CHL~~ SChl distributions in the SO but to investigate the uncertainties associated to the external source of Fe from the AIS. However, in order to ~~evaluate~~ assess that large biases ~~were~~ are not introduced by the implementation of the new iron source in the biogeochemical model, we ~~have performed~~ perform a statistical model-data comparison for Fe and ~~CHL~~ SChl over the SO, south of 50° S. For Fe, we ~~compared~~ compare the model experiments to a global database constructed by Tagliabue et al. (2012). For surface chlorophyll concentrations, we ~~used~~ use a monthly climatology of a satellite-based (MODIS-Aqua) estimates from Johnson et al. (2013). The statistical comparison shows that performance scores for annual Fe concentrations integrated over the upper 200 m and surface chlorophyll in summer are almost similar in all experiments (Tables S1 and S2). The biases are relatively small ranging to -0.07 to 0.02 nmol L^{-1} for Fe and -0.13 to -0.07 mg m^{-3} for ~~CHL~~SChl. The main difference is the increase of the mean Fe and surface chlorophyll concentrations showing a better agreement with observations such as in the SOLUB5 experiment for Fe (Table S1) and in the SOLUB10 and ICB-SURF experiments for SChl (Table S2). This statistical analysis reveals no degradation of the performance ~~skills~~ skill of the standard version of the biogeochemical model when the ~~external source of Fe from the AIS~~ AIS Fe source is added but also no improvements in the spatial distributions of Fe and chlorophyll concentrations. Thus, the absence of ~~glacial~~ the AIS Fe fluxes is not a major cause that explains the biased representation of Fe and ~~CHL~~ SChl in the NEMO-PISCES model.

3.4 Contribution of the Antarctic Ice Sheet to primary production and carbon export

The Fe supply from the AIS stimulates, at the blooming season, the phytoplankton activity which can be quantified in terms of primary production and carbon (C) export. The increase ~~of~~ in the annual primary production of phytoplankton (diatoms and nanophytoplankton) integrated over depth is ~~, globally,~~ relatively low in the Fe solubility experiments compared to the total primary production of 2.39 PgC yr^{-1} computed over the SO, south of 50° S, in the CTL experiment (Table 3). The increase in primary production ranges from 0.01 PgC yr^{-1} in the SOLUB1 experiment to 0.12 PgC yr^{-1} in the SOLUB10 experiment, i.e. a difference of one order of magnitude between the least and the most impacted cases. In the SOLUB10 experiment, primary production is 5 % higher than in the CTL experiment, a difference that drops to less than 1 % in the SOLUB1 experiment. This slightly enhanced primary productivity increases C export by 1 % in the SOLUB1 experiment and by more than 8 % in the SOLUB10 experiment. With ~~a Fe solubility fraction~~ an Fe solubility of 5 %, primary production simulated in the SOLUB5 experiment is ∼3 % higher and C export around 5 % higher than in the CTL experiment. Thus, the ~~iron source~~ supply of Fe from the AIS results in a ~~significant but very~~ non-negligible but modest increase in C export at the scale of the SO and subsequent sequestration of carbon in the interior of the ocean.

For the other sensitivity experiments, the predicted impacts on primary production and C export all fall in between those simulated by the SOLUB1 and SOLUB10 experiments. Releasing Fe at the surface as tested in the ICB-SURF experiment produces changes that are only slightly lower than in the SOLUB10 experiment. This suggests that the efficiency of the AIS Fe source is higher when located at the surface. The comparison of the SOLUB5 experiment with the ICB-ML experiment reveals that the non-directly available fraction of Fe released from icebergs may increase by ∼40 % the impact of the source on primary production and C export. The ICB-ANNUAL experiment shows a primary production and a C export almost ~~equals~~ equal to the SOLUB5 experiment suggesting no effect of the seasonal variability of iceberg Fe ~~supplies~~ supply on annual primary productivity and C export at the scale of the SO. Finally, when only the ice shelf Fe source is considered in the ISF experiment, primary production and C export are almost unchanged compared to the CTL experiment.

4 Discussion

4.1 Sensitivity of Fe and chlorophyll to the iron source from the Antarctic Ice Sheet

Our sensitivity study aims at delineating the biogeochemical impacts of the uncertainties surrounding the fertilization capacity of the AIS. Different aspects of the AIS Fe fluxes ~~have been~~ are explored: the intensity of the source, the impact of the iceberg Fe distribution ~~along~~ in the water column, and the contribution of the seasonal variations of the iceberg meltwater.

The Fe supply from the AIS is highly sensitive to the hypothesized solubility of ferrihydrite revealing strong impacts on the spatial distribution of Fe. The main supply of Fe occurs in the Atlantic sector downstream of the Antarctic Peninsula, along the Antarctic ~~coasts~~coast, and, more moderately, in the Ross Sea. The iceberg contribution to surface Fe is large and can extend until 50° S as shown by the large plume expanding from the Antarctic Peninsula until the Indian sector (Fig. 3). The spatial distribution of the surface Fe anomalies in our model setup is in line with Laufkötter et al. (2018) but differs substantially from Death et al. (2014). In Death et al. (2014), the main fertilized area is simulated along the eastern sector of the Antarctic ~~coasts~~ coast showing a larger offshore extent, the Atlantic plume is clearly much less marked and extended, and the AIS influence in the region of the Ross Sea is weaker. These differences may be linked to the implementation in Death et al. (2014) of basal iceberg sediment loading which induces high Fe concentrations in the basal layer and very low concentrations above this basal layer whereas an homogeneous distribution is considered in our study. Their vertically-varying distribution of Fe in icebergs may simulate a stronger fertilization effect in the calving regions driven by an important basal melting. Further offshore, once the basal Fe rich part of icebergs has melted, the release of Fe is strongly decreased due to the lower Fe concentrations in the upper part of icebergs, resulting in a weaker fertilization effect in remote areas of the open ocean such as in the Atlantic sector.

The AIS fertilization impact on surface chlorophyll depends on the intensity of the AIS Fe source as well as on the choice of its vertical distribution (Fig. 9). The efficiency of the fertilization is regionally important with increased ~~CHL~~ SChl along the east coasts of Antarctica and in the core of the Atlantic plume off the tip of the Antarctic Peninsula. However, at the scale of the SO, south of 50° S, the AIS impact on primary production is quite modest reaching a maximum increase of 5 % in our set of experiments relative to the control run (Table 3). Our results are similar (lower by 3 %) to Wadley et al. (2014) but contrast sharply with the 30 % increase in primary production estimated in Death et al. (2014). The AIS contribution in Death et al. (2014) is evaluated against atmospheric dust, sediments being not taken into account. The lack of the sedimentary Fe source, estimated to be the largest in the SO (Lancelot et al., 2009; Tagliabue et al., 2009, 2014a; Borrione et al., 2014; Wadley et al., 2014), leads to ~~increase significantly~~ a significant increase in the fertilization effect of icebergs and ice shelves, particularly in coastal regions where sediment supplies have a large influence. Our study suggests that the AIS fertilization effect is weaker than suggested by Death et al. (2014), especially in coastal areas, as a consequence of the large input of Fe from sediment remobilization.

The enhanced primary production increases the C export by 8.4 % in our most impacted case (Table 3), a result significantly lower than the increase in particle export of 30 % in Laufkötter et al. (2018). The reasons for such a difference are difficult to disentangle as the modeled Fe fluxes from the AIS, atmospheric dust, and sediments are ~~in~~ the same order of magnitude between both studies ~~. A potential difference in both~~ (Table 1). Potential differences in the two modeling setups may arise from a different treatment of sediment mobilization, in particular in the description of the horizontal and vertical distribution of sediments ~~. However, while~~ or from a different relationship between primary production and C export. Indeed, observations suggest that the C export efficiency declines significantly with inreasing primary productivity in the SO, although the causes remain unclear (Maiti et al., 2013; Le Moigne et al., 2016). In our model, this relationship, highly variable at local and temporal scales, is not linear in the SO but has a clear trend where a higher primary productivity is associated with a higher C export (not shown). In the model used in Laufkötter et al. (2018), a different relationship could explain the differences in the C export. While low at the scale of the SO in our model, the fertilization effect of the AIS on primary productivity and C export can be regionally significant as ~~pointed out by observations~~ estimated from data (Smith et al., 2007; Duprat et al., 2016; Herraiz-Borreguero et al., 2016; Wu and Hou, 2017). For instance, in the highly fertilized area of the Atlantic plume, northeast of the Antarctic Peninsula (36° W-56° W, 58° S-63° S), primary production and C export are increased by ∼30 % and by ∼42 %, respectively, in the SOLUB10 experiment compared to the CTL experiment (Table 3), i.e. 5 to 6 times higher than at the scale of the whole SO.

Climatically our study points out that the fertilization effect of the AIS on C export is moderate on time scales of 50 to 100 years. However, when integrated over time scales of thousands years, the role played by the AIS on ~~the~~ carbon sequestration might be ~~important and be evaluated as~~ a key component ~~such as~~ alongside atmospheric dust iron for glacial-interglacial regulation of the carbon cycle (Martin, 1990). In a climate change perspective, our results suggest that any change in the supply of Fe from ~~an~~ increased melting of icebergs and ice shelves should result in a quite moderate impact on ocean biogeochemistry and export production at the scale of the whole SO. Indeed, doubling the AIS Fe fluxes in the SOLUB10 experiment increases by only ∼3.6 % the C export compared to the SOLUB5 experiment (Table 3). Nevertheless, at a more local scale, the fertilization effect of the AIS induced by global warming could be drastically strengthened with potentially important consequences for phytoplankton physiology, nutrient availability and marine ecosystems (Boyd et al., 2010b, 2015; Hopwood et al., 2017; Boyd, 2019).

The choice of the iceberg Fe source distribution leads to significant differences in the magnitude of the fertilization effect of the AIS. In the case of a surface distribution, the effect is maximum. All the Fe delivered by the iceberg meltwater flux to the mixed layer is available to sustain primary productivity in spring and summer and strongly affects the vertical profiles of Fe particularly in highly fertilized areas (Fig. 6). This theoretical distribution may lead to an overestimated supply of Fe in summer when the mixed layer is highly stratified, particularly in the case of large icebergs, partially ignoring the specific role of the Fe delivered below the MLD. Antarctic icebergs have different shapes (Romanov et al., 2012) and ~~class-size~~ size class categories (Silva et al., 2006; Tournadre et al., 2015, 2016) both evolving during their life cycle (Bouhier et al., 2018). Moreover, the sediment distribution within icebergs is highly heterogeneous (Raiswell et al., 2016; Hopwood et al., 2017). All these features combined with distinct regimes of iceberg melting (FitzMaurice et al., 2017) fully constrain the delivery of Fe ~~along~~ through the water column and below the mixed layer. Thus, the inherently heterogeneous nature of icebergs and its temporal evolution is extremely difficult to consider and to implement in a model. The choice of a surface distribution might be inappropriate to represent the iceberg supply in the ocean but without any degree of certainty. In fact, measured vertical profiles of Fe concentrations around icebergs in the Bellingshausen Sea in summer (De Jong et al., 2015) and in the Weddell Sea in autumn (Lin et al., 2011) suggest that both ICB-SURF and SOLUB5 experiments simulate vertical distribution of Fe that could be observed in the wake of melting icebergs. At least, based on future observations, the representation of the iceberg Fe source could be better constrained and parameterized in models.

While the iceberg freshwater fluxes vary monthly (Fig. 1a), the AIS contribution to the SO Fe pool is almost equally effective in summer and winter, mainly driven by the balance between high AIS Fe fluxes and phytoplankton consumption in summer, and low AIS Fe fluxes and light limitation in winter. However, the seasonal variations of the iceberg Fe fluxes contribute to significant differences in the spatial distribution of Fe (Fig. 4g and 4h) which have small impacts on annual primary production and C export when integrated over the SO (Table 3). The spatial differences in surface chlorophyll are ~~globally~~ relatively modest in summer between the SOLUB5 and the ~~ANNUAL~~ ICB-ANNUAL experiments. Nevertheless, the larger amplitude of the Fe cycle over the SO in the ~~ANNUAL~~ ICB-ANNUAL experiment (Fig. S2a) modulates the seasonality of surface chlorophyll during the growing season: the bloom initialization occurs earlier, the bloom apex in December is higher and the bloom decay is faster from January to April (Fig. S2b). Thus, the monthly variations of the iceberg Fe supply alters the seasonal cycle of chlorophyll in the SO.

4.2 Model caveats and uncertainties

A surprising result that may be linked to a potential model deficiency is the absence of iron fertilization effect in the very close vicinity of the Antarctic ~~coasts~~coast. This can be observed in the difference of ~~CHL~~ SChl between the SOLUB5 experiment and the CTL experiment (Fig. 9b). In fact, none of the iceberg fertilization experiments shows an increase in chlorophyll near the Antarctic shores (Fig. 9). This unexpected result is due to a strong and systematic nutrient limitation in summer simulated by the biogeochemical model (Fig. S1). The seasonal cycles of nutrients at a station near the shore of the Amundsen Sea (106° W, 75° S) in the CTL and SOLUB5 experiments display a marked limitation in NO_3, PO_4, and Si in January and February (Fig. S1a-S1c) whereas Fe is non limiting (Fig. S1d). The nutrient limitation strongly affects ~~CHL~~ SChl in both experiments, the seasonal cycles being almost similar (Fig. S1e). The nutrient limitation may occur locally along the Antarctic ~~coasts~~coast, however high levels of primary productivity in spring and summer are observed in large regions such as in the numerous coastal polynyas present in the SO (Arrigo and van Dijken, 2003; Arrigo et al., 2015). ~~Thus, this~~ This possible biased behavior of our model may result from missing, misrepresented processes or sources that may supply macro-nutrients in the mixed layer such as the oceanic circulation in ice shelf cavities (Jacobs et al., 2011; Herraiz-Borreguero et al., 2015; White et al., 2019) ~~, the glacial meltwater runoff (Beaton et al., 2017; Hawkings et al., 2015, 2017; Hodson et al., 2017)~~ or the melting of ice shelf and ice sheet (Pritchard et al., 2012; Arrigo et al., 2015, 2017; Hawkings et al., 2015; Wadham et al., 2016; St-Laurent et al., 2017). Another process that can be advocated is the entrainment of nutrient-rich waters by subglacial discharge plumes induced by basal melting of grounded glaciers, a physical mixing process observed in west Antarctic Peninsula (Cape et al., 2019) and for Greenland glaciers ~~which highlights the role of subglacial discharge plumes on upwelling of macro-nutrients such as NO3 in the euphotic zone~~ (Meire et al., 2017; Hopwood et al., 2018; Kanna et al., 2018).

We ~~highlighted~~ highlight that the distribution of the iceberg Fe fluxes below the MLD may represent a non-negligible fraction of bioavailable Fe for primary productivity. Indeed, the iceberg Fe delivery at depth in the SOLUB5 and ICB-KEEL experiments ~~feed~~ feeds a subsurface reservoir of Fe that can supply surface waters by the deepening of the MLD through subseasonal storms (Swart et al., 2015; Nicholson et al., 2016) or deep mixing (Tagliabue et al., 2014b). We suggest that this distribution of the iceberg Fe source has to be considered if implemented in biogeochemical models. However, in our sensitivity study, we only ~~applied~~ apply one average depth of the submerged part of icebergs whereas several ~~class sizes~~ size classes coexist in the SO where large tabular to small icebergs are observed covering a size range of 0.1-10000km^2 (Tournadre et al., 2015, 2016; Silva et al., 2006). The size evolution of icebergs along their life cycle is poorly documented, but fragmentation is a significant mechanism ~~process~~ in the reduction of their size which increases the iceberg melt (Bouhier et al., 2018). This process impacts the ~~time variations of the~~ temporal delivery of bioavailable Fe ~~at depth that we did not exploredhere~~that we have not explored. Moreover, the distribution of the iceberg Fe fluxes ~~along~~ in the water column, i.e. around and below icebergs, is probably not homogeneous as reported in De Jong et al. (2015) and Lin et al. (2011) giving an additional uncertainty not ~~explored in this study.~~ investigated here. Another uncertainty relates to the rates of utilization of Fe released from melting icebergs along their drift that is estimated to be far less than that potentially supplied (Boyd et al., 2012). The assessment of this utilization is unfortunately impossible because of the contributions from other sources of Fe (sediments and dust). Furthermore, the Fe utilization is computed from satellite-derived net primary production that is associated with large uncertainties (Saba et al., 2011) and significant underestimates of surface chlorophyll in the SO (Johnson et al., 2013).

A large uncertainty in the fertilization capacity of Fe delivered by icebergs and ice shelves comes from the intrinsic nature of this sedimentary source. Indeed, a very large fraction of Fe found in icebergs has a lithogenic origin (Raiswell et al., 2006; Shaw et al., 2011). The supply of lithogenic Fe can be separated into three categories: the ~~labile Fedirectly~~ most soluble Fe, and thus potentially bioavailable, the semi-labile particulate Fe that will not dissolve rapidly once released to seawater, and the refractory insoluble fraction. We focused our study on the first fraction. However, the semi-labile fraction may have a significant contribution in fertilizing the surface waters of the SO. If lithogenic Fe with a low dissolution rate is not scavenged or experiences low sinking speeds (nanoparticles), this fraction can be maintained in the upper layer and ~~be~~ become bioavailable on long time scales. This residence time may strongly affect the dissolved iron distribution from icebergs over the SO. As particulate lithogenic Fe is a significant pool of Fe in icebergs (Raiswell et al., 2006; Raiswell, 2011; Shaw et al., 2011), the contribution of the non-directly bioavailable fraction to surface dissolved iron can be higher than actually observed. However, nothing is known about the fraction of lithogenic Fe bioavailable at long time scales as well as ~~on~~ its quantity.

5 Conclusions

We ~~implemented~~ implement in the biogeochemical model NEMO-PISCES (Aumont et al., 2015) the external source of iron from the Antarctic Ice Sheet based on recent estimates of Antarctic meltwater fluxes from icebergs and ice shelves (Depoorter et al., 2013; Merino et al., 2016). The modeled Fe fluxes from the AIS are in the range of previous modeling studies (Death et al., 2014; Laufkötter et al., 2018) and in the lower range of recent estimates from data (Raiswell et al., 2016). ~~We investigated~~ The potential indirect supply of Fe by the ice shelf melt-driven circulation, i.e. the meltwater pump (St-Laurent et al., 2017, 2019), is also represented by using the parameterization of Mathiot et al. (2017). We investigate the impacts of different sources of uncertainties related to the AIS iron source on Fe and surface chlorophyll distributions: the solubility of Fe, the vertical distribution of the iceberg source and its seasonal variability. Large differences in the ~~AIS iron fertilization~~ fertilization effect of the AIS are ultimately attributable to varying Fe solubility (1-10 %), currently poorly constrained by observations (Boyd et al., 2012; Raiswell et al., 2010, 2018). The ~~supply of Fe from the AIS~~ AIS Fe supply is significant in the Atlantic sector northeast of the Antarctic Peninsula and along the Antarctic ~~coasts~~coast, particularly in the eastern sector, with large implications for the magnitude of phytoplankton blooms. The surface Fe and chlorophyll concentrations are increased by 3 to ~~25~~ 24 % and by 2 to 12 %, respectively, at the scale of the SO. The contribution of Fe released from ice shelves is restricted to coastal areas with ~~very small impacts~~ limited impact on chlorophyll and primary productivity whereas modeled Fe fluxes from ice shelves and icebergs are almost similar. Our results also underline the role played by the vertical distribution of the iceberg Fe source due to the potentially non-negligible contribution of Fe delivered below the MLD. This non-directly available supply can not be considered as a lost fraction for primary production but as a subsurface reservoir. The variability of the AIS contribution to the SO Fe pool is strongly linked to the interplay between the seasonal variations of meltwater released from icebergs and the physical and biological processes that characterize the ~~dynamic~~ dynamics of the SO: light limitation, MLD variations, iron limitation, and Fe consumption by phytoplankton.

At the scale of the SO, the ~~AIS fertilizing effect~~ fertilization effect of the AIS on primary production, mainly driven by icebergs, is relatively weak but with a non-negligible contribution to C export~~: primary production~~. In the most contributive case, primary production (integrated over depth) and C export (at 150 m) are increased by 5 % and 8.4 %, respectively, ~~in the most contributive case~~ compared to our control experiment. However, in highly fertilized regions in the Atlantic sector and along the Antarctic ~~coasts~~coast, the AIS impact is ~~significant~~more important, primary production and C export being increased by up to 30 % and 42 %, respectively. ~~Our results over the SO are~~ The magnitude of the C export simulated here is noticeably lower than the AIS Fe contribution to the marine particle export recently estimated to 30 % over the SO in Laufkötter et al. (2018). This ~~significant difference reveals~~ large difference emphasizes the necessity to continue exploring the large uncertainties that encompass the AIS Fe source and to understand the mechanisms that explain the very different sensitivity of C export to the AIS Fe fluxes simulated by models. Our results also point out the need to pursue in situ observations ~~, particularly~~ to better constrain the distribution of Fe ~~in~~ and meltwater throughout the water column in the close vicinity of icebergs, ~~as well as modeling studies to reduce the large uncertainties that encompass the AIS source of Fe. Indeed, representing~~ their sediment content and the range of bioavailability of Fe from the AIS. Representing the biogeochemical features of the SO in ocean models is particularly challenging~~, however~~ . However, we argue that the ~~integration of the AIS iron source~~ implementation of the external source of Fe from the AIS may help to fill the gap of misrepresented ~~characteristics in the SO and to represent~~ regional characteristics and to better represent the complexity of SO iron cycle (Boyd and Ellwood, 2010; Tagliabue et al., 2017). Given that the ~~complex cycle of Fe in the SO (Boyd and Ellwood, 2010). Moreover, since the~~ Antarctic continental ice sheet has experienced a significant reduction of its mass (The IMBIE team, 2018) that may continue and amplify in the near future ~~due to climate change~~ (Rintoul et al., 2018), it could be particularly relevant to integrate the AIS Fe source in ~~biogeochemical and~~ climate models in order to assess its role ~~to~~ for marine ecosystems and ~~take into account~~ its potential negative feedbacks on climate change (Barnes et al., 2018). However, ~~according to the modest impacts we find in our study we can speculate a relatively moderate increase of primary production and C export to climate change until the end of the present century~~ as there is currently limited agreement between models on the sensitivity of ocean biogeochemistry to the AIS Fe supply, the evaluation of climate change impacts on this external source of Fe and the consequences for marine biogeochemistry in the SO would be highly speculative.

Code and data availability. The version code of the NEMO model, including PISCES-v2, used for this study is freely available at https://www.nemo-ocean.eu/. To access the NEMO svn repository, users should register on the NEMO website at https://forge.ipsl.jussieu.fr/nemo/register. Model data are available at https://doi.org/10.5281/zenodo.2633097

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- Conceptualization: RP and OA
- Formal analysis: RP
- Funding acquisition: OA and LB
- Investigation: all
- Methodology: RP, OA, and GM
- Validation: RP and OA
- Visualization: RP
- Writing original first draft: RP
- Writing, review: all

Competing interests. The authors declare that they have no conflict of interest.

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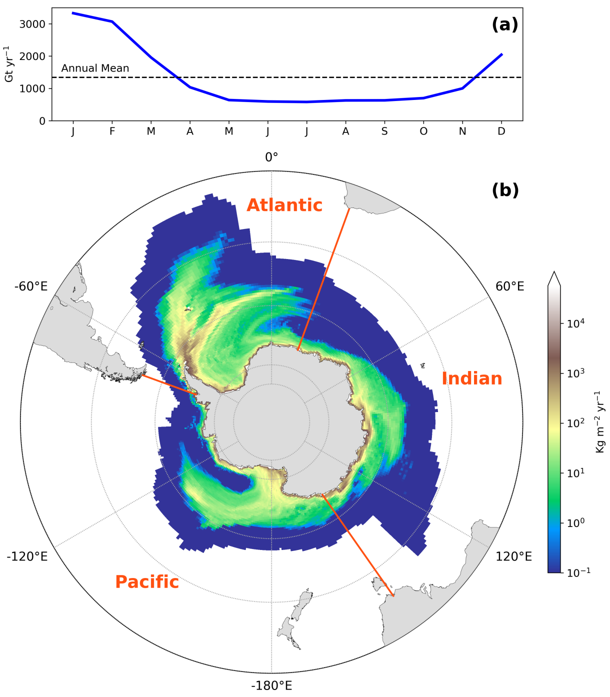

Figure 1. (a) Seasonal cycle of iceberg freshwater fluxes over the Southern Ocean from the climatology of Merino et al. (2016). (b) Annual mean freshwater fluxes from icebergs (Merino et al., 2016) and ice shelves (Depoorter et al., 2013) over the Southern Ocean, south of 30° S, used to represent the Fe supply from the Antarctic ~~ice sheet~~ Ice Sheet in our study. In orange are displayed the Atlantic (70° W-20° E), Indian (20° E-145° E), and Pacific (145° E-70° W) sectors of the Southern Ocean. Note the logarithmic scale.

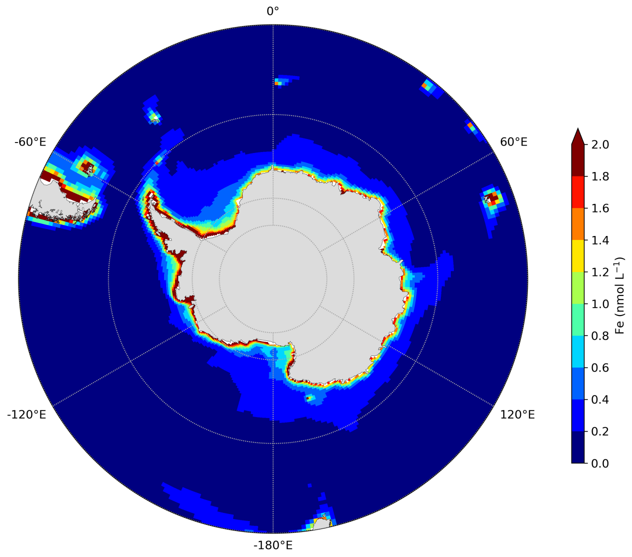

Figure 2. Annual mean of surface Fe concentrations in the Southern Ocean, south of 45° S, in the CTL experiment.

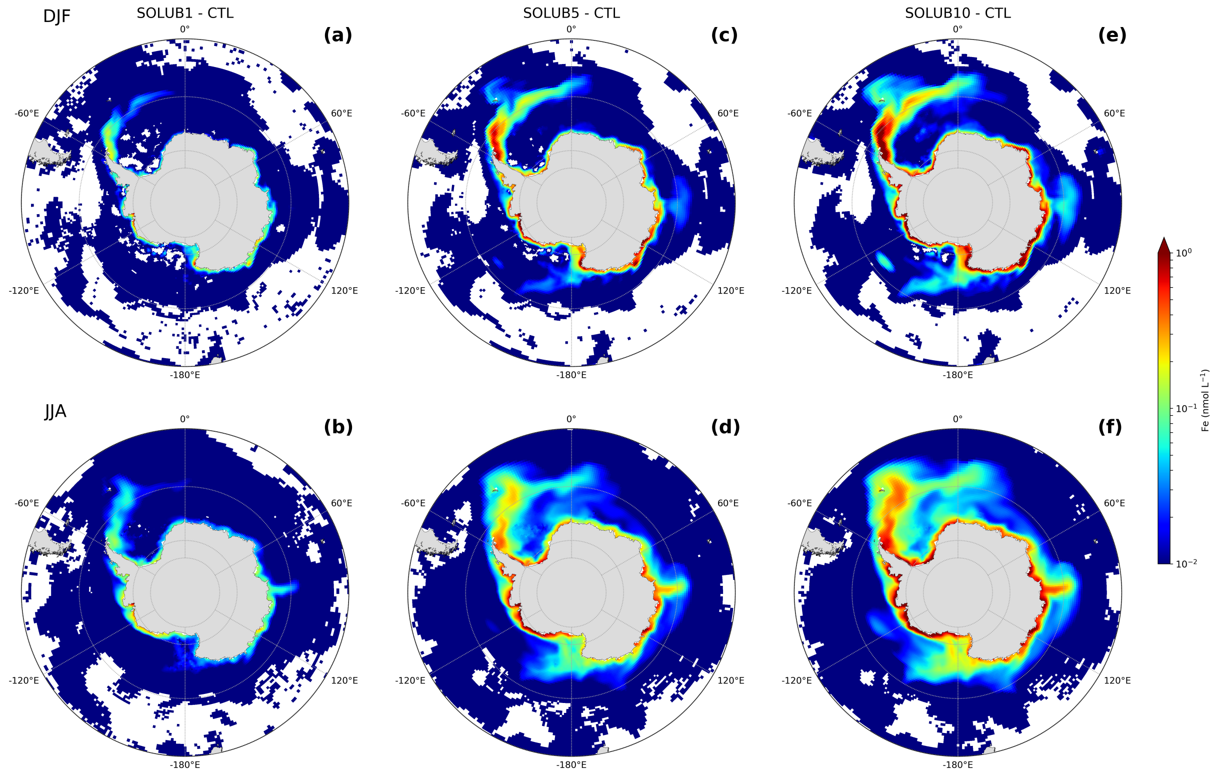

Figure 3. Difference in surface Fe concentrations between the (a and b) SOLUB1, (c and d) SOLUB5, (e and f) SOLUB10 experiments and the CTL experiment (experiments minus CTL) in (a, c, and e, upper row) summer (December, January, and February) and (b, d, and f, lower row) winter (June, July, and August) in the Southern Ocean, south of 45° S. White areas are regions with non-significant changes. Note the logarithmic scale.

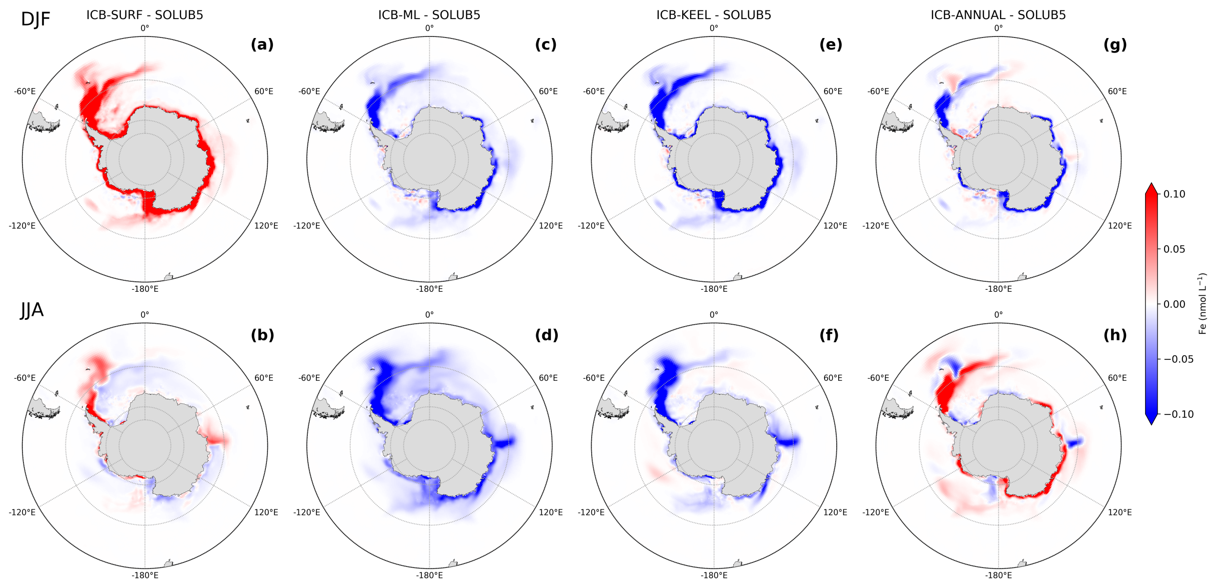

Figure 4. Difference in surface Fe concentrations between the (a and b) ICB-SURF, (c and d) ICB-ML, (e and f) ICB-KEEL, (g and h) ICB-ANNUAL experiments and the SOLUB5 experiment (experiments minus SOLUB5) in (a, c, e, and g, upper row) summer (December, January, and February) and (b, d, f, and h, lower row) winter (June, July, and August) in the Southern Ocean, south of 45° S. Positive values in red are regions with surface Fe concentrations higher than in the SOLUB5 experiment and negative values in blue are regions with surface Fe concentrations lower than in the SOLUB5 experiment.

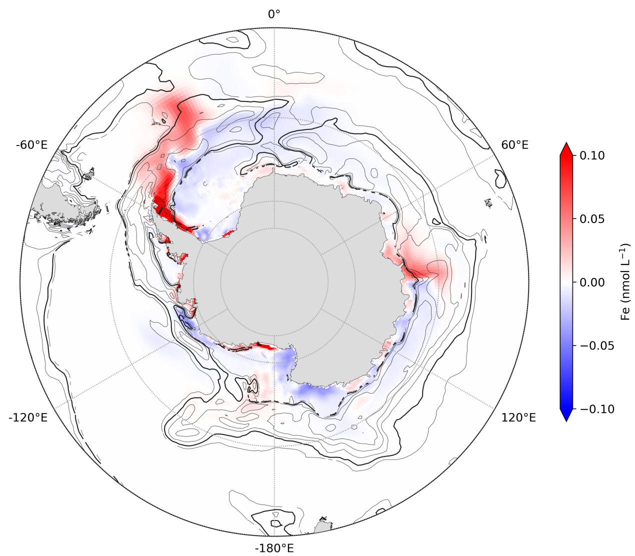

Figure 5. Difference in surface Fe concentrations between the ICB-SURF and the SOLUB5 experiments in winter (June, July, and August) in the Southern Ocean, south of 45° S. The black isoline represents the mixed layer depth at 120 m and the grey isolines represent mixed layer depth shallower than 120 m.

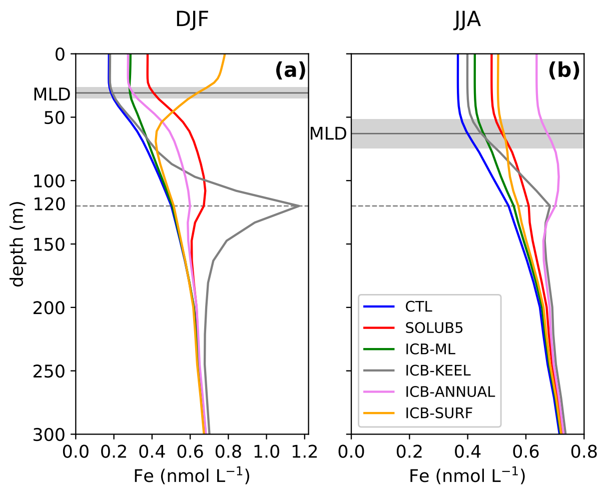

Figure 6. Vertical profiles of Fe concentrations until 300 m northeast of the Antarctic Peninsula (36° W-56° W, 58° S-63° S) in the CTL (blue), SOLUB5 (red), ICB-ML (green), ICB-KEEL (grey), ICB-ANNUAL (pink), and ICB-SURF (orange) experiments in (a) summer (December, January, and February) and in (b) winter (June, July, and August). Solid light grey line is the mixed layer depth (MLD) in (a) summer and (b) winter averaged over the region, in grey shading is the standard deviation of the MLD over the region in (a) summer and (b) winter, and the dashed gray line is the 120 m ~~depth~~isobath.

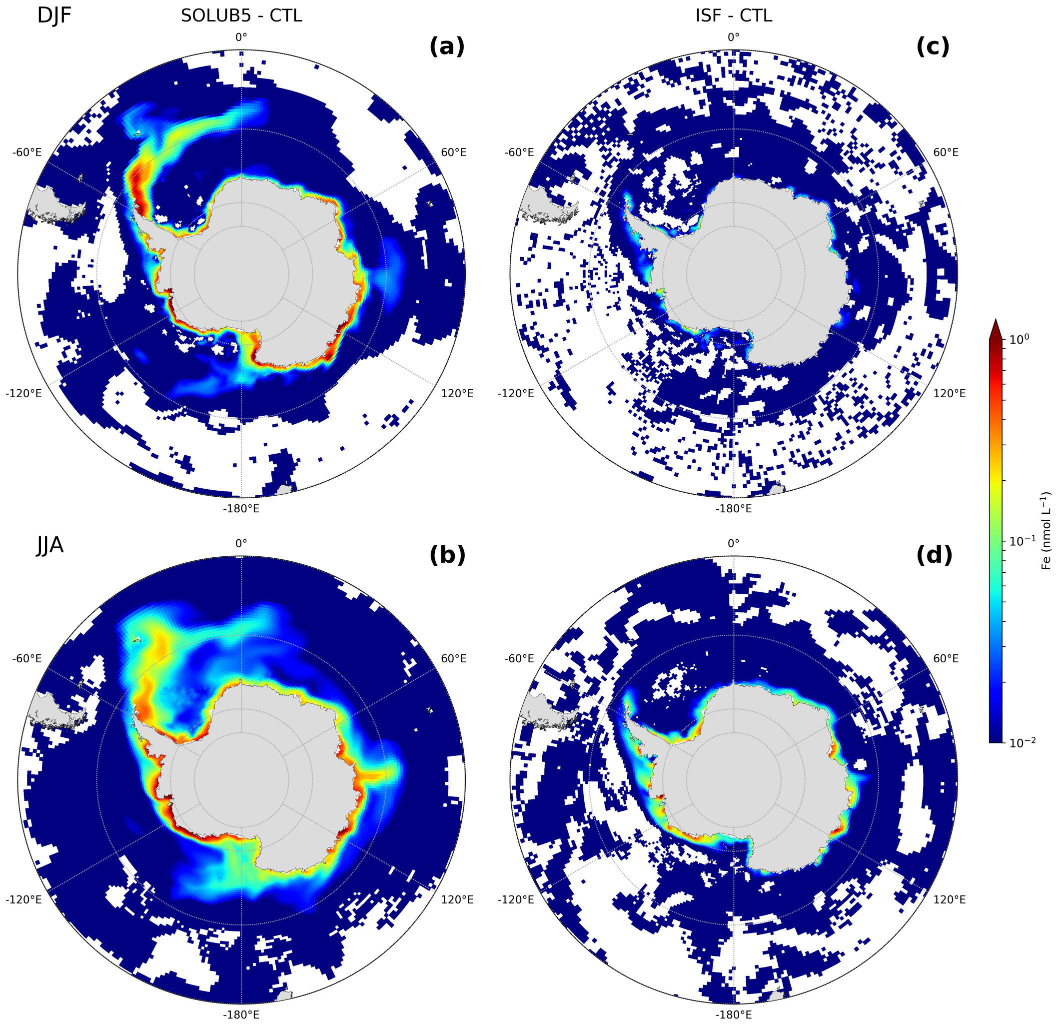

Figure 7. Difference in surface Fe concentrations between the (a and b) SOLUB5, (c and d) ISF experiments and the CTL experiment (experiments minus CTL) in (a and c, upper row) summer (December, January, and February) and (b and d, lower row) winter (June, July, and August) in the Southern Ocean, south of 45° S. White areas are regions with non-significant changes. Note the logarithmic scale.

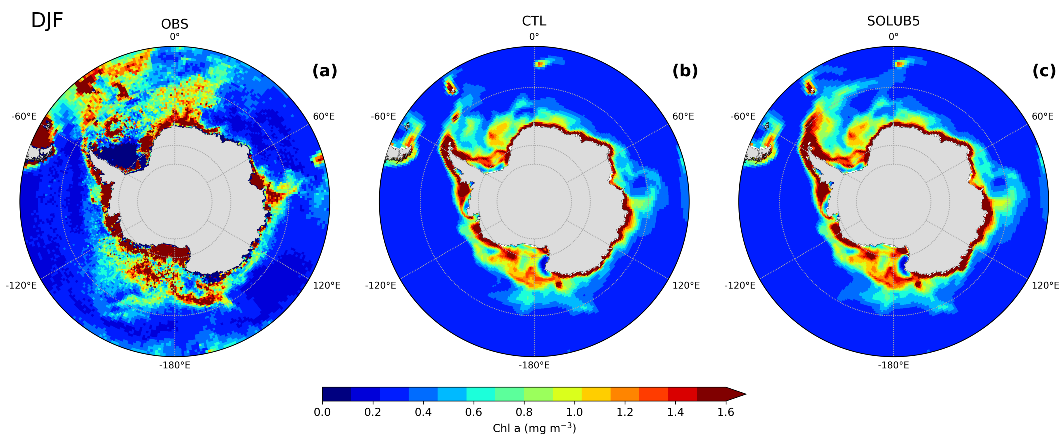

Figure 8. ~~Difference in surface Fe~~ Surface chlorophyll concentrations ~~between the (a and b) SOLUB5, (c and d) ISF experiments and the CTL experiment (experiments minus CTL)~~ in ~~(a, and c, upper row)~~ summer (December, January, and February) ~~and~~ from (~~b, and d, lower row~~a) ~~winter~~ satellite observations (~~June~~MODIS-Aqua, ~~July~~Johnson et al. (2013)), (b) the CTL experiment, and ~~August~~(c) the SOLUB5 experiment in the Southern Ocean, south of ~~45~~50° S.~~Note the logarithmic scale.~~

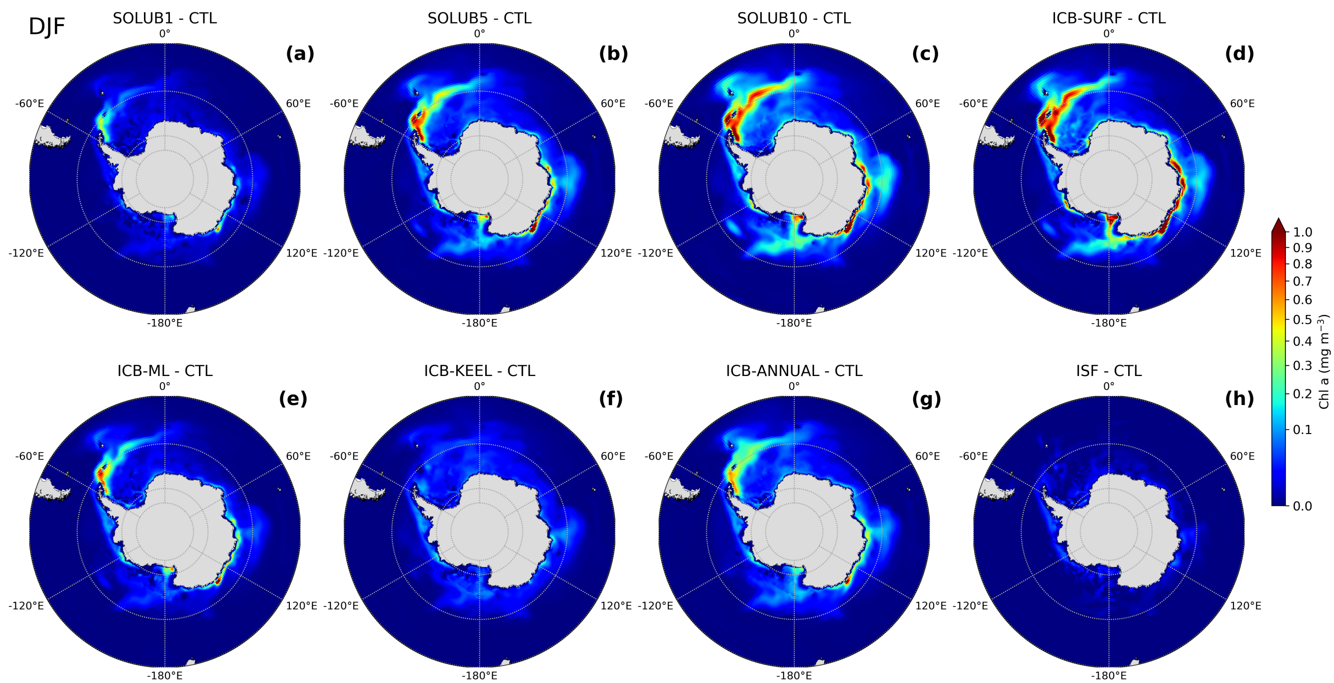

Figure 9. Difference in surface chlorophyll concentrations in summer (December, January, and February) between the (a) SOLUB1, (b) SOLUB5, (c) SOLUB10, (d) ICB-SURF, (e) ICB-ML, (f) ICB-KEEL, (g) ICB-ANNUAL, (h) ISF experiments and the CTL experiment (experiments minus CTL) in the Southern Ocean, south of 45° S.

Table 1. Annual estimates of Fe fluxes from observational and modeling studies in the SO. The iceberg ~~bioavailable~~ Fe flux from Raiswell et al. (2016) is calculated applying a Fe solubility of 10 % to their estimates of potentially bioavailable Fe fluxes.

References	Fe Flux (Gmoles yr^{-1})				
	Dust deposition	Sediments	Iceberg	Ice shelf	Iceberg + Ice shelf
Raiswell et al. (2008)	-	-	1.07 – 2.15	-	-
Raiswell et al. (2016)	-	-	0.32 – 2.5	-	-
Shaw et al. (2011)	-	-	0.72 – 7.2	-	-
Hawkings et al. (2014)	-	~~1.1~~ -	-	1 – 3	-
Wadley et al. (2014), south of 58° S	0.04	12.5	1.54	-	-
Death et al. (2014)	1.3	-	1.16	0.16 – 1.6	1.32 – 1.76
Laufkötter et al. (2018), south of 50° S	0.28	3.8 – 5.2	0.05 – 2.54	0.06 – 0.6	0.11 – 3.14
Our study, south of 50° S	0.36	9.6	0.12 – 1.2	0.13 – 1.3	0.25 – 2.5

Table 2. Description of model experiments. The ice shelf Fe ~~release distribution~~ supply is ~~applied between~~ uniformly distributed over the ~~base~~ depth and width of the unresolved cavities, from the mean ice front base down to the seabed, or the grounding line ~~of ice shelves~~ depth if shallower, following the parameterization of Mathiot et al. (2017). The climatology of ice shelf Fe fluxes is annual.

References	Iceberg source	Ice shelf source	Fe solubility (%)	Iceberg Fe release distribution	Climatology of Iceberg Fe Fluxes
CTL	no	no	0	n.a.	monthly
ISF	no	yes	5	n.a.	n.a.
SOLUB1	yes	yes	1	0 - 120 m	monthly
SOLUB5	yes	yes	5	0 - 120 m	monthly
SOLUB10	yes	yes	10	0 - 120 m	monthly
ICB-SURF	yes	yes	5	surface	monthly
ICB-ML	yes	yes	5 in ML - 0 below ML	0 - 120 m	monthly
ICB-KEEL	yes	yes	5	at ∼120 m	monthly
ICB-ANNUAL	yes	yes	5	0 - 120 m	annual

Table 3. Annual primary production integrated over depth (PP) and C export at 150 m depth in the CTL experiment and in the AIS Fe source experiments over the Southern Ocean, south of 50° S. In brackets are the increase in PP and C export relative to the CTL experiment in the highly fertilized plume of the Atlantic sector, northeast of the Antarctic Peninsula (36° W-56° W, 58° S-63° S).

References	PP ($PgC\ yr^{-1}$)	% increase PPL from CTL	C export 150 m ($PgC\ yr^{-1}$)	% increase C export from CTL
CTL	2.39		0.63	
ISF	2.39	0.1	0.63	0.3
SOLUB1	2.40	0.7 (7)	0.64	1.1 (8)
SOLUB5	2.46	2.9 (24)	0.66	4.8 (30)
SOLUB10	2.51	5.0 (32)	0.68	8.4 (42)
ICB-SURF	2.49	4.3 (35)	0.68	7.5 (45)
ICB-ML	2.43	1.6 (15)	0.65	2.6 (20)
ICB-KEEL	2.42	1.2 (2)	0.64	2.1 (3)
ICB-ANNUAL	2.45	2.8 (21)	0.66	4.7 (28)