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.

References

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