Reply to Anonymous Referee #2:

We wish to thank the reviewer for his/her constructive comments on this manuscript. The comments are addressed below. Reviewer's comments are in italic.

Wang and co-authors present a modeling study examining the effects of sea ice on the marine iron cycle. In particular they focus on new parameterisations that examine the incorporation of iron into both Arctic and Antarctic sea-ice and its impact on biogeochemical cycling. Fluxes of iron associatd with the different components are quantified and the effects of interannual changes are discussed. The paper builds nicely on a recent Biogeosciences paper [Lancelot et al., 2009; Tagliabue and Arrigo, 2006] but with a deeper examination of how to model sea ice iron and providing a global context. The paper therefore fits well into the scope for Biogeosciences and subject to a thorough revision should be suitable for publication.

I have two main issues with the paper:

1- Organization: the paper structure is a bit confused and could merit from a clearer structure. Essentially the authors seek to do two things: i) look at the impact of different sea ice iron parameterizations (figs 1---5) and ii) associated effects of interannual changes (Figs 6,7). I would argue these are two separate goals. The first set of questions would be more easily isolated in a simpler set of simulations that are not subjected to interannual variability since the authors only show snapshots and they are (correctly for me) interested in looking at how different choices impact iron distributions. When run interannually, I was then always wondering whether the result was biased by a particular choice of year. Having then established the impact of different parameterization choices it is then sensible to move onto part 2 and examine interannual aspects. In this case, comparing their model to the result obtained without sea ice iron would be instructive I feel.

We modified the manuscript and added sentences for clarity. We added a table (Table 2) summarizing comparisons between observations of sea ice and seawater in the previous literatures and simulation results. We also rephrased many sentences and rearranged paragraphs to make the manuscript flow better.

2- Timescales: A discussion of timescales was for me not deep enough. One of the main aspects about sea ice is its seasonal variation and then subsequent to that its interannual changes. For example, does looking at the seasonal cycle more closely illuminate the importance of different processes? How does adding sea ice affect the modeled seasonal cycle in iron and biological productivity? Can satellite chlorophyll then help discern whether things are improved or not? Such questions would be equally true for the interannual timescales.

Sea ice shifts the timing and locations of iron supply to surface water. As discussed in the manuscript, iron fluxes to seawater during spring and summer increased with melting ice. Increased iron supply stimulates phytoplankton growth and leads to higher phytoplankton biomass. However, iron sequestration in sea ice has no significant effects on seasonality of biological productivity in our simulations, which is strongly influcenced by photosynthetically active radiation (PAR). PAR to the oceans is highly controlled by ice dynamics in the seasonal ice zone. There is no significant change in seasonality of sea ice in the simulated period. We have included a figure below showing the seasonal cycle of (a) ice volume and mixed layer depth, (b) iron supply to surface seawater, (c) diatom biomass, and (d) small phytoplankton biomass in regions south of 60°S in the CTRL simulation and the FULL simulation. We address the potential usefulness of the satellite data below.

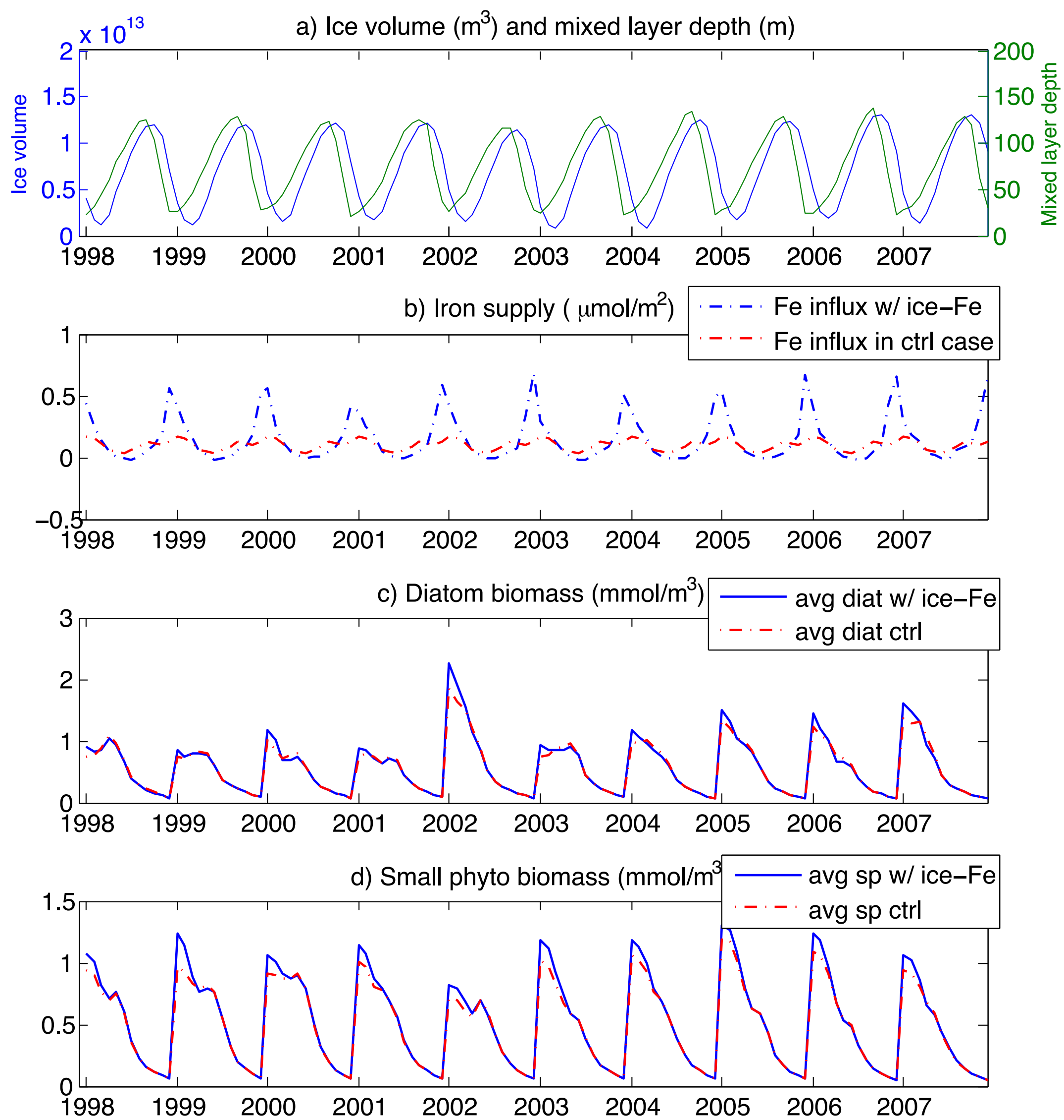

Fig. S1. Seasonal cycle of (a) ice volume and mixed layer depth, (b) iron supply to surface seawater, (c) diatom biomass, and (d) small phytoplankton biomass in regions south of 60°S in (red) the CTRL simulation and (blue) the FULL simulation.

Specific Comments:

P2386: Hydrothermal vents are also a potential supply of iron to the surface waters of the Southern Ocean since this is where deep waters are ventilated [Tagliabue et al., 2010]. Similarly, the authors mention atmospheric iron fluxes, but these are likely to be very low in the Southern Ocean are they not? (Particularly that part of the Southern Ocean that is sea ice covered). It is perhaps useful to note that sea ice fluxes of iron might be particularly important as an iron source once winter mixing has ceased [Tagliabue et al., 2014].

We have added hydrothermal flux of iron in the list of sources of iron to seawater. We agree with the reviewer that atmospheric iron fluxes are relatively low in the Southern Ocean. However, dust iron contributes to 28% of total iron released from melting sea ice. The timing and locations of atmospheric iron fluxes to the ocean are affected by sea ice. We therefore included dust iron as a source of iron to sea ice. We thank the reviewer for pointing us to this new paper. We have added several sentences as suggested.

P2389: I was unsure as to how the parameterization impacts the total iron budget. Some aspects seem to be sinks for seawater DFe and therefore don't change the total amount of iron in the system but redistribute it between the ocean and cryosphere. But the discussion of the additional take up of sedimentary iron seems to imply that overall more iron is added to the system? It would be nice if these aspects could be clarified and in particular how the different components affect the total iron budget.

Sediments in sea ice is considered as a new iron source to the ice-seawater system. We have added a paragraph summarizing simulated iron supply and compared with other estimates.

Overall, additional 8.3×10^8 g Fe/yr is added to the Southern Ocean (> 35 °S) by sediment-bearing ice. This is new iron to the ocean system. This iron supply is smaller than iceberg Fe ($1 – 3 \times 10^9$ g Fe/yr), sediment Fe ($257 – 635 \times 10^9$ g Fe/yr), hydrothermal Fe (20.8×10^9 g Fe/yr), and dust Fe ($4.5 – 30 \times 10^9$ g Fe/yr) (summarized by Tagliabue et al., 2010). Boyd et al. (2012) showed that iron flux from melting sea ice is one of the largest iron sources in some regions. It is likely the iron supply from sea ice is underestimated in this study, as our simulated concentrations are often lower than observed. In the Northern Hemisphere, sediment-bearing sea ice adds 3.9×10^9 g Fe annually to the oceans north of 45 °N, which is more than two times larger than the iron supply from dust (1.8×10^9 g Fe/yr).

P2391: the simulation plan was also not clear to me. Was the model spun up under interannually varying atmospheric forcings for 210 years until 2007 and then run on for a further 30 years? If so, what was the atmospheric forcing for this further 30 year period? Why not a repeated annual circulation?

Model year 210 corresponds to year 1977. The further 30-year simulations used observation-based forcing information from the period of 1978 to 2007. We used interannually varying atmospheric forcing in simulations to explore the impacts of changing sea ice on the iron cycle and marine ecosystems. In general, we have moved away from using climatological (or normal year) forcings for our ocean simuations. In part this is because the occasional deep mixing year can have important impacts on the biogeochemistry (i.e. ventilating oxygen, bringing more nutrients to the surface).

P2392: please scatter the observations over the model fields for the Antarctic

We have modified the figure as suggested. However, there are only a few Fe observations.

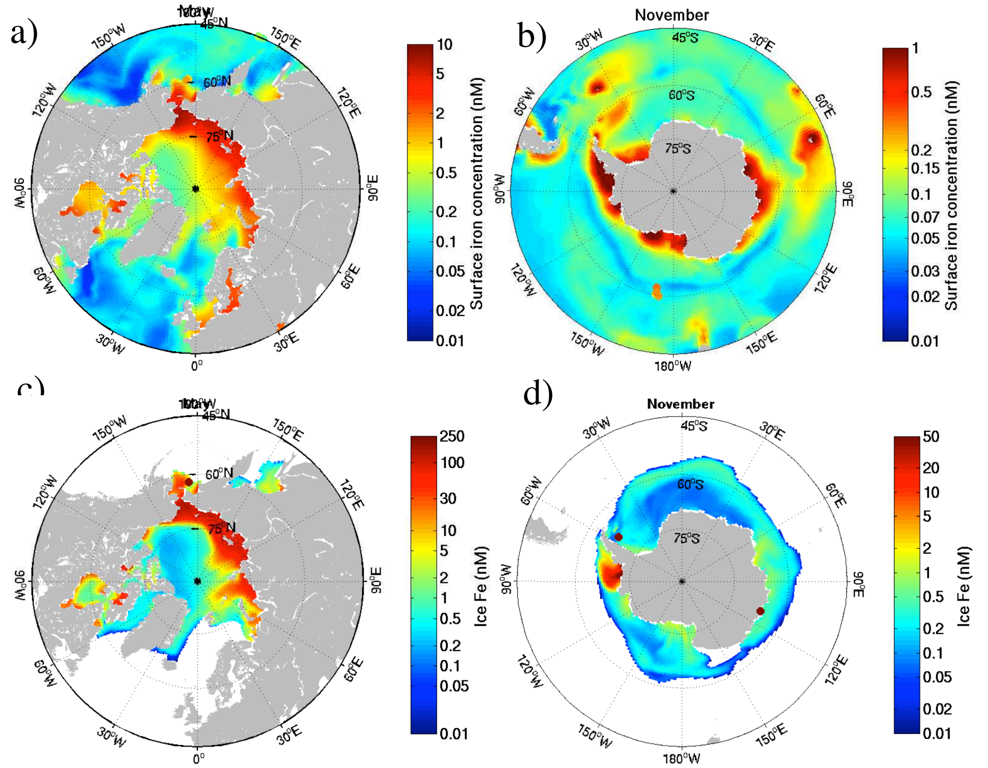

Fig. 1 Simulated iron concentrations in (a, b) seawater and (c, d) sea ice in (a, c) Arctic and (b, d) Antarctic. Results are iron concentrations in May in Arctic and November in Antarctic, when phytoplankton biomass starts increasing rapidly. The color scale is logarithmic. (c and d) show data where ice concentration is greater than 15% in simulation. Observations are scattered over the model fields.

P2394: What is the sensitivity to the fraction of DFe incorporated into sea ice during its formation?

Our simulations are not strongly sensitive to the fraction of DFe incorporated into sea ice. Differences in correlations between simulated iron content and observation were small for fractions in the range of 60%-100%.

P2394: please scatter the observations over the model fields for the Arctic

We have modified the figure as suggested. (See above)

P2394: I did not really understand the text talking about Klunder's observations in the Barents and Kara Seas.

Klunder et al. (2012) suggested the depletion of iron in the Barents Sea and Kara Sea is caused by biological uptake. Simulated iron concentrations are higher than observations in this region, which is likely due to underestimation of phytoplankton biomass and therefore weak biological uptake of iron. We have modified the manuscript to clarify this point.

P2394: If you want to say that the model agrees that well with the data it is necessary to actually show some data-- -model comparison!

We have added a table (Table 2) summarizing comparisons between observations of sea ice and seawater in the previous literatures and simulation results.

P2395: 'impacts of sea ice on iron concentrations' – this part needs an understanding of whether the total amount of iron in the system has changed or not!

An additional 8.3×10^8 g Fe/yr is added to the Southern Ocean (> 35 °S) by sediment-bearing ice, which is smaller than other iron sources (dust, hydrothermal, sediments) summarized by Tagliabue et al. (2010). In the Northern Hemisphere, 3.9×10^9 g Fe/yr is added to the ice-seawater system north of 45 °N. To the best of our knowledge, there is no previous estimate of iron fluxes between sea ice and seawater for the Arctic Ocean. But our simulated iron concentrations in the Arctic agree reasonably well with observations.

P2396: I thought the Gerringa study referred more to glacial sources?

We agree with the reviewer. The reference is removed.

P2397: The species composition paragraph is very speculative, either solidify things or remove it.

We have removed our speculation that changes in the phytoplankton composition may contribute to ecosystem shift at high latitudes. We showed only simulated changes caused by iron sequestration in sea ice in the revised manuscript. We have also added more details about differences of phytoplankton biomass between the FULL simulation and the CTRL simulation.

P2399: Would be useful to compare the fluxes to those compiled elsewhere [Boyd et al., 2012; Tagliabue et al., 2010].

We have added comparisons with Boyd et al. (2012) and Tagliabue et al. (2010).

“Simulated iron supply from sea ice in the Ross Sea is 4.9 μmol Fe/m^2/month during the growth season and totals 14.7 μmol Fe/m^2 ‘new’ iron annually, which is one order of magnitude smaller than previous estimates compiled by Boyd et al. (2012).”

“Overall, an additional 8.3×10^8 g Fe/yr is added to the Southern Ocean (> 35 °S) by sediment-bearing ice. This iron supply is smaller than iceberg Fe ($1 – 3 \times 10^9$ g Fe/yr), sediment Fe ($257 – 635 \times 10^9$ g Fe/yr), hydrothermal Fe (20.8×10^9 g Fe/yr), and dust Fe ($4.5 – 30 \times 10^9$ g Fe/yr) (summarized by Tagliabue et al., 2010). “

P2400: Some comparison to sea ice data would be helpful here, and interannual trends in productivity should be compared to those measured from satellite.

Unfortunately, the CESM does not simulate the year to year variations in sea ice cover well enough for this to be a useful comparison. The simulated seasonal cycle of climatological ice extent captures the general pattern of observations (Fig. S2). Correlations between simulated ice extent and area and observations from 1998 to 2007 are 0.14 and 0.23 respectively. Due to relatively weak impact of sea ice iron on biological productivity in our simulations and the low fidelity in simulated sea ice interannual variations, we do not expect significant benefit for more detailed comparison of interannual variations in ice and productivity. The goal of section 3.4 in the present study is more to show the potential impact of changes in sea ice extent on the iron cycle and marine ecosystems. Though model cannot fully reconstruct observed sea ice and productivity patterns, our results demonstrate the importance of ice in the iron cycle and sensitivity of marine ecosystems to changes in ice dynamics.

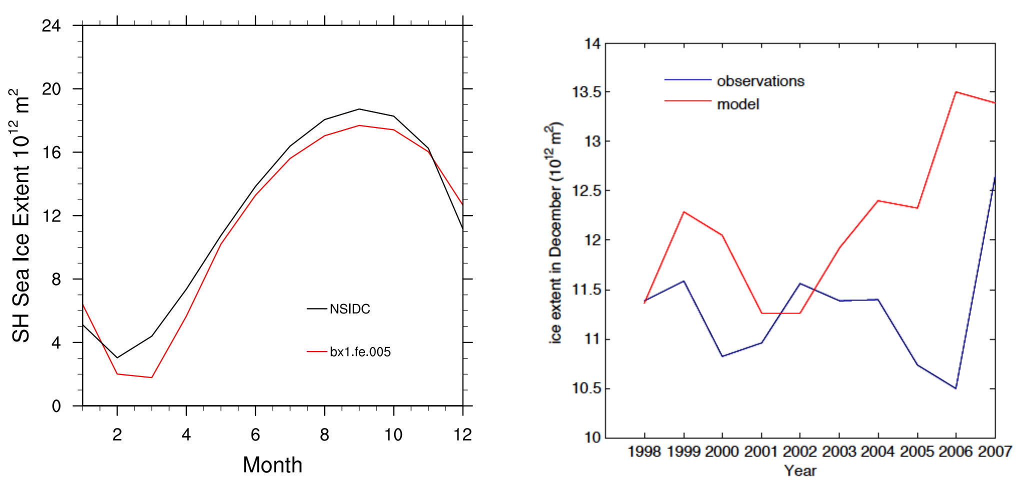

Fig. S2. (left) Seasonal cycle of Southern Hemisphere ice extent (red) compared to observations (black). (right) Comparison between observed (black) and simulated (red) December ice extent from 1998 to 2007.

P2400: It would be useful to isolate the order of the different processes in driving the modeled interannual trends in productivity? For example, how much is simply due to the interannual changes in sea ice and the associated freshwater flux and how much is due to the iron aspects?

We agree with the reviewer that it is useful to understand driving mechanisms for interannual variations in productivity. From 1998 to 2007, simulated phytoplankton carbon biomass in surface water south of 60 °S is in the range of 0.08 to 6.36 $mmol/m^3$. Interannual anomalies of biomass (10 year mean seasonal cycle removed) are in the range of -0.82 to 0.67 $mmol/m^3$. Changes of phytoplankton biomass due to iron flux from sea ice are in the range of -0.01 to 0.52 $mmol/m^3$, less than 22% of total biomass. All simulations conducted in this study are forced using repeated atmospheric reanalysis forcing. Thus, physical fields (including ice) in all simulations are the same. Differences between the FULL simulation and the CTRL simulation are only due to iron sequestration in sea ice. However, we cannot further quantify the order of different mechanisms due to the nonlinear interactions of different processes.

P2402: An interesting angle to the discussion is how, in reality, iron may be retained in bioavailable forms when supplied by sea ice because of the specific environment it is introduced to. In other words, the low temperature – high light meltwater environment has been suggested to enhance photochemistry and retard oxidative losses of iron [Tagliabue and Arrigo, 2006].

We have added several sentences to discuss this issue. Please see manuscript line 588-594.

“Another caveat in the present work is that iron speciation and related chemical reactions in both seawater and sea ice are not considered. Tagliabue and Arrigo (2006) showed that the cold and well-illuminated environment created by melting sea ice enhanced photochemical activity, which effectively leads to Fe recycling and retention. The impacts of iron released from melting sea ice on marine ecosystems may then be enhanced under such conditions. Chemical reactions should be considered in addition to physical processes in future studies.”