Reply to Anonymous Referee #1:

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.

General comments: The paper discusses a key component of the high latitude HNLC: iron inputs to and from sea ice. This area of research is especially pivotal in a climate change perspective because the magnitude of this mode of Fe delivery to surface waters is forecasted to change. The approach is novel and this work definitely brings new information to this field of research. Although the results of the model fit reasonably well with some observations in the Arctic, there are still some large differences between the model output and the field observations in the Southern Ocean and Greenland Current and Farm Strait. These differences are likely due to the fact that what is missing in the model is the actual mechanism of Fe entrapment in sea ice (to be modelled in the next paper maybe?). Here the authors consider that Fe is passively incorporated in sea ice, just as a percentage of what Fe observed in seawater. This is only part of the story, and not representative of what actually happens in the environment. Iron could be incorporated in sea ice with detrital and living organic matter, under the particulate form and then degraded into dissolved Fe via heterotrophic processes. The other incorporation mechanism is via active biological uptake of dFe by sea ice algae. In both cases, Fe incorporation into sea ice is mediated by biology, in the particulate form, which is ignored in this study because these mechanisms are currently not quantified. The authors do mention this in the discussion/summary section, but I think this could be further highlighted in the text, by stating that this model clearly shows that there are additional modes of incorporation of Fe in sea ice (=biological processes) than just passive incorporation (=physical processes). The model also makes the assumption that Fe is transferred from seawater into sea ice, and therefore Fe becomes depleted in seawater, which again is not the case in the environment. The sea ice environment is not a box. Lateral and vertical transport mechanisms (dust, glacial inputs, continental margins of deep sea sediments) bring new Fe to seawater all year round, therefore constantly feeding seawater (and therefore sea ice) with new (and recycled) Fe during autumn/winter.

We agree with the reviewer that there are other mechanisms for transferring iron from seawater to sea ice, including entrapment of particulate iron during ice formation and continuous biological uptake. We have modified the manuscript and further highlighted the missing mechanisms in this study (ms line 279-280, 285-291). In this study, we did not assume that iron is depleted in seawater during ice formation. In fact, we only allow a fraction of iron to be incorporated in sea ice during ice formation to avoid depletion of iron in surface water. The supplies of bioavailable iron from dust, sediments, recycling, and lateral and vertical transport to surface seawater are included in the CESM1.0-BEC. These sources of iron feed surface seawater (and therefore sea ice). Simulated surface iron concentrations are lower in the modified model than dFe in the standard CESM, which did not consider ice sequestration in sea ice.

Overall, the manuscript does not flow very well. The paper collects a suite of results and ideas, jumping from Arctic to Antarctic, without a clear train of thoughts. Maybe a table summarizing the ranges observed in seawater and sea ice in the literature versus the ranges obtained from the model output would help. I also find that the English could be greatly improved. The paper needs to be reorganized with an eye to clarity.

We have modified the manuscript. Sentences are added to clarify the goal of each section (ms line 101-107, 246-251). We also rephrased sentences and rearranged paragraphs to make the manuscript flow better. We have also added a table (Table 2) to summarize comparisons between observations and model output. We revised the language in the manuscript.

Table 2 Comparison between simulated iron concentrations and observed data (nM) [a]

	Location	Model	Data	Data reference
Surface Southern Ocean		0.15	0.14 - 0.43 [b]	Moore and Braucher, 2008; Tagliabue et al., 2012 [b]
Antarctic sea ice	Bellingshausen Sea	0.25-23.08	1.1 - 30.2	Lannuzel et al., 2010
	East Antarctic	0.25-0.34	2.64-112	Lannuzel et al., 2007
		0.29-0.41	0.23-14.4	van der Merwe et al., 2009 and 2011b
		- [c]	2.11-81.0	van der Merwe et al., 2011a
	Ross Sea	- [c]	1.1 - 6.0	Grotti et al., 2005
	Weddell Sea	0.08-0.17	0.7-36.8	Lannuzel et al., 2008
Surface Arctic Ocean	Barent Sea	0.14-0.77	0.6-0.8	Klunder et al., 2012
	Bering Sea	0.05-4.31	0.9 – 16.5	Nishimura et al., 2012
	Bering Sea	0.28-0.73	0.8 – 3.14	Aguilar-Islas et al., 2008

	Central Arctic	0.26-1.30	0.5 – 2.6	Klunder et al., 2012
	Canada Basin, Chukchi Sea	0.25-4.10	0.5 – 3.18	Nakayama et al., 2011
	Chukchi Sea	0.37-4.80	2.1-16.3	Nishimura et al., 2012
	Fram Strait	0.16	5.7-23.1	Tovar-Sanchez et al., 2010
	Laptev Sea	0.07-3.77	0.3 – 10.5	Klunder et al., 2012
Arctic sea ice	Bering Sea	9.5-61	2.92 - 376	Aguilar-Islas et al., 2008
	Fram Strait	0.01-0.51	219.9 – 3599.4	Tovar-Sanchez et al., 2010

[a] model data shows simulated iron concentrations from the locations of measurements, except the surface dFe concentrations in the Southern Ocean, which show mean concentrations.

[b] Moore and Braucher (2008) and Tagliabue et al.(2012) have thoroughly compiled observations of iron in the Southern Ocean waters. Detailed comparison between simulated and observed iron concentration in the Southern Ocean seawater can be found in Moore and Braucher (2008).

[c] The location is not simulated in the 1° CESM due to the coarse resolution.

Specific comments

1. p2385 line 14- remove Taylor et al., 2013- it is a model result, no a field observation.

The reference is removed.

2. P2385 line 21-“changes in sea ice what?” volume, extent?

We have modified the text to “changes in sea ice volume and/or extent”.

3. P2385 line 26 “phytoplankton competition” over what?

We have changed the sentence to “The demand for iron and uptake efficiency varies among phytoplankton groups, so that concentrations in seawater also influence the competition between different groups.”.

4. P2386 line 8-9 “in polar regions, atmospheric deposition is obstructed by ice cover *during the cold season, when dust accumulates in the sea ice". Please rephrase this. Do you mean that direct deposition of dust into seawater is obstructed by the presence of sea ice?*

We have rephrased the sentence to "In polar regions, dust deposition into seawater is obstructed by the presence of sea ice during winter. Dust deposited on the ice surface accumulates within the ice".

5. P2386 I think that lines 17 to 23 should be moved earlier in the text, before explaining the different sources of Fe to sea ice.

We have moved the sentences and added some words to arrange the paragraph better.

6. P2386 replace "about" by "on" in lines 24 and 28.

Modified as suggested.

7. P2387. Please rephrase "data atmosphere and land components that prescribe observationally-based forcing in-formation"

We have rephrased the sentence to "In this study, we use both active ocean and sea ice components. Atmosphere and land components are set up as data models, which prescribe observation-based forcing information to ocean and ice."

8. P2388 line 5. Note that iron is not a passive tracer in the environment. It is highly reactive.

We agree with the reviewer. In this study, we only considered physical processes, through which sea ice affects the iron cycle. Iron speciation, chemical reactions and biological processes in sea ice are not considered. We have clarified this in the manuscript.

9. P2388 line 6. Please list the Fe sources you consider. Also rephrase to "iron incorporated in sea ice"

We have rephrased the sentence to "Iron accumulating in sea ice comes from different sources and can be transported by ice motion. Sources of iron to sea ice considered in this study include dust, seawater, and sediment. Detailed description is in section 2.3."

10. P2389 line 8. Replace "observed" by "measured".

Modified as suggested.

11. P2389 line 11: what do you mean by "transport and removal in sea ice"? do you mean "loss from melting sea ice into seawater"? I would rephrase this to "the mechanisms for iron sequestration in sea ice and the effects of its release in the marginal ice zone are currently not well constrained"

Modified as suggested.

12. P2389 line 15: how is Fe "frozen" in sea ice? Do you mean "incorporated into sea ice". And what do you mean by "proportional"?

We have replace "frozen" by " incorporated". Incorporation of sedimentary iron into sea ice is assumed to be proportional to iron concentrations in seawater with a spatially varying coefficient as described in the equation $Fe_{sed\text{-}ice} = percSed^{*} * dFe_{water}$. $percSed^{*}$ is a spatially-varying constant, which is determined by the fraction of sediment area in the model grid cell and a constant fsed. fsed is optimized using a series of simulations. Mechanisms governing these processes are highly unknown. This assumption is our best guess for simulating the process. We have also revised this paragraph for clarity.

13. P2389 line 23- what is the "percSed" term? Is the % of dFe in seawater originating form sedimentary inputs? And how is fsed decided? It sounds just like a random number applied to get the model to match the observations, which means that the model is not validated, which defeats the purpose of the study. What dfe conc in seawater was used?

The percSed term represents the fraction of sediment area in grid cells, which were calculated using the high-resolution ocean bathymetry from the ETOPO2 version 2.0. fsed is a constant coefficient, which is optimized using a series of sensitivity simulations with different fsed values in a wide range. The value was chosen for higher correlations between simulated iron concentrations and observational data in both sea ice and seawater. We acknowledge this caveat regarding model validation. However, observational data are too scarce to fully constrain the parameterization. dFe_{water} is the simulated iron concentration in surface seawater.

14. P2389 line25: "match the observations in sea ice"?

We have modified this sentence to "better correlations between simulated iron concentrations and observational data in sea ice and seawater"

15. P2390 line 3. Rephrase to "removed from seawater during sea ice formation was proportional to the concentration of dissolved Fe in seawater". This sounds just like what you said in the 1st assumption. Ie. Where is the dFe in this sw originating from? How is that % decided? How do you know that 60% is a moderate removal fraction? What physical mechanism is used to remove that Fe? It all depends on the effectiveness of the brine convection processes.

We have rephrased the sentence as suggested. Surface layer simulated dissolved iron concentrations are used in the calculations. The fraction is optimized using a series of simulations and determined based on correlations between model output and observations. We agree with the reviewer that the removal process depends on the effectiveness of the brine convention process. However, physical mechanisms governing transfer of biogeochemical tracers between seawater and sea ice are not included in the CESM1.0. As a first attempt to simulate the role of sea ice in the iron cycle, assumptions were thus made to represent the removal process. We also addressed this issue in the discussion section.

16. P2390 line 11: dust, snow and sea ice are 3 different things. You have dust in snow, you have snow on top of sea ice, you can have dust in seawater which is then is entrained in sea ice when it forms, and you can even have dust deposited on top of sea ice. Which one are you referring to? Are you referring to snow deposition on top of sea ice, which is the released in seawater during the melting season?

In this study, we consider sea ice and overlying snow as a barrier and a temporary reservoir for dust deposition. CICE4 simulates both snow and sea ice. Dust, falling on the top of sea ice covered grids, is stored in ice or overlying snow. We have clarified this in the revised manuscript.

17. P2393 line 1- rather than iron inputs. I think what is missing is the actual mechanisms of Fe entrapment in sea ice. Here you consider Fe is passively incorporated in sea ice, just as % of what is in seawater. This is not representative of what actually happens. Fe could be incorporated in sea ice with detrital and living organic matter, under the particulate form and then degraded into dissolved Fe via heterotrophic processes. The other mechanism is via active biological uptake. In both cases, Fe incorporation into sea ice is mediated by biology, which is ignored in this study because it is currently difficult to quantify. The authors do have to mention this as a potential missing reservoir of dFe in their model.

We agree with the reviewer and have modified the manuscript to point out these potential missing mechanisms for incorporation of iron into sea ice.

Revised ms line 279-280: The low bias in our results is likely due to underestimation of iron inputs or the omission of other mechanisms.

Revised ms line 285-292: It is also possible that certain mechanisms for incorporation of iron into sea ice are missing from our simulations. Iron can be incorporated into sea ice with detrital and living organisms during ice formation and then degraded into dissolved Fe via heterotrophic processes (Lannuzel et al., 2010). Iron may also be continuously transferred from seawater into sea ice due to active biological uptake by ice algae (Lannuzel et al., 2010). These mechanisms are ignored in our study, but could be included in future work. This may cause some biases in our simulations.

18. P2393 line 25: what do you mean by "moved iron from seawater to sea ice to ensure this value"?

"When sea ice forms, DFe is pumped from the ocean model upper layer to the sea ice in order to ensure a maximum concentration of 16.5 μ mol DFe m^{-3} in the forming ice layer. The latter value is determined based on iron records in winter Antarctic pack ice (Lannuzel et al., 2007). If the DFe simulated in the ocean upper layer is not sufficient for sustaining the ocean-ice transfer required to reach this concentration, the model assumes that all the DFe of this oceanic layer is transferred to the sea ice."- cited from Lancelot et al., 2009

We have also replace "moved" by "transferred".

19. P2394 line 16: what do you mean by "simulated biomass in this region is biased low". Add reference.

We have added a reference. The sentence is modified to "simulated phytoplankton biomass in CESM1.0 is biased low in this region (Moore et al., 2013)."

20. P2394: line 29. 3 orders of magnitude higher is a lot. I do not think that the fact that it is multiyear ice alone could explain these large differences. Where the ice is collected is most likely not where it originally formed. That ice might have formed in shallow waters and exported out to open waters, therefore explaining the high Fe. + biological pathways can also help to entrain and retain that Fe in sea ice.

We have modified the manuscript and pointed out the possible explanation for discrepancies between model output and observations, which was suggested by the reviewer.

Revised ms line 339-340: It is also possible that the ice samples collected in the previous study formed in shallow iron-rich waters and were transported out to the open sea.

21. P2395: line 2-3. What do you mean by "Multiyear ice may accumulate more iron through interactions between brine channels and sea ice biota, processes not included in the model"? what processes are you referring to? Heterotrophic activity? Retention of EPS-bound organisms and Fe onto the walls of the brine channels?

Continuous biological uptake of iron by ice algae pumps iron directly from seawater to ice (Lannuzel et al., 2010). Ice algae incorporate iron into the particulate form and lower dissolved iron concentrations in brine channels. Brine drainage initiates convection at the seawater/ice interface, which allows transfer of iron from iron-rich seawater into ice (Vancoppenolle et al., 2010). We have also modified the manuscript to clarify this point.

Vancoppenolle, M., H. Goosse, A. de Montety, T. Fichefet, B. Tremblay, and J. - L. Tison, Modeling brine and nutrient dynamics in Antarctic sea ice: The case of dissolved silica, J. Geophys. Res., 115, C02005, doi:10.1029/2009JC005369, 2010

22. P2395."which reduces iron concentrations in the seawater" the authors should indicate that in reality there should be a constant input of dFe in seawater from new sources. The system is not closed. How come figure 2 shows negative Fe fluxes in the central arctic and Weddell Sea in may and november respectively?

We agree with the reviewer. We have modified the sentence and pointed out that iron is incorporated into sea ice during ice formation, which leads to a negative iron flux (from seawater to ice). Negative Fe fluxes in the central Arctic and Weddell Sea in May and November, respectively, suggests iron is primarily incorporated into sea ice from seawater, because the rate of ice formation is larger than the rate of ice melting in these regions during these months.

23. P2396. Line 6 How do these fluxes compare with estimates from the literature?

We have added more comparisons between our results and previous estimates for the Southern Ocean in the revised manuscript. To the best of our knowledge, there is no previous estimate of iron fluxes between sea ice and seawater for the Arctic Ocean.

24. P2396 line 16-17. This sentence makes it sound like light is responsible for the release of Fe in seawater. Please rephrase to " Iron is enriched in sea ice in winter and released into seawater in spring and summer, at a time ideal for phytoplankton growth because the light availability and stratification of the water column are optimum" or something similar.

Modified as suggested.

25. P2396 line 19. How was POC flux evaluated? Discuss the potential contribution of seeding of sea ice algae on carbon export.

Simulated POC flux is compared with sediment trap data. CESM-BEC does a reasonably good job in capturing observed POC flux. Detailed comparison can be found in Lima et al. (2014). We agree that it is necessary to study the contribution of seeding of sea ice algae on carbon export. However, sea ice algae are not considered in this study. The contribution of ice algae to carbon export is beyond the scope of this paper.

Lima, I. D., Lam, P. J., and Doney, S. C.: Dynamics of particulate organic carbon flux in a global ocean model, Biogeosciences, 11, 1177-1198, doi:10.5194/bg-11-1177-2014, 2014.

26. P2396 line 21. add reference to "In the Arctic region, primary production is mainly limited by light and macronutrient concentrations, except for some areas in the Bering Sea and the Sea of Okhotsk" .

A reference is added.

27. P2397 line 21 "Iron from ice may also affect denitrification at high latitudes (Arrigo et al., 2008)" is a bit random. Please explain further why it matters.

We agree with the reviewer. This sentence is removed in the revised manuscript.

28. P2397 line 26. I have a problem with the "iron originally from seawater is temporarily removed and released in spring and summer". There should be a constant flux of new dFe to seawater from vertical and lateral transports.

We agree with the reviewer that there should be a continuous flux of iron between ice and seawater. However, potential missing mechanisms for incorporation of iron into sea ice are missing in this study. See response above. In section 3.3, we discussed three sources of iron supply to sea ice included in the present study. Considering seawater and sea ice as a system, iron from dust deposition and sediments is new to the system. Iron supply from seawater to ice redistributes iron between ocean and ice, but caused no changes to total iron budget.

29. P2397-2398. Please rephrase this sentence.

This sentence is rephrased in revised manuscript.

"Our focus will be on the impacts of iron supply from sea ice to water on phytoplankton production. Model output for summer is analyzed in this section and contributions of different sources of iron incorporated in sea ice are calculated."

30. P2398 line7. Use "the highest" or "higher"

This is corrected.

31. P2398- line 7-8. Please clarify here how it is accumulated here. Is dust deposited onto sea ice or in seawater and then entrained in sea ice during formation? Note that dust or snow deposited on top of the ice in winter usually cannot percolate through the ice cover because the ice is not yet permeable (low brine volume fractions).

The sentence is rephrased to "Dust from Asia depositing onto the top of the pack is stored in ice over the winter and released to surface waters along with melting ice in spring".

32. P2398 line 12-13: please rephrase.

Sentences are rephrased to "Spatial variation of the flux is relatively low. The total amount of dust iron in sea ice meltwater is less than 1% of global dust deposited on the oceans. However, dust iron from Southern Ocean sea ice dominates the supply of iron from sea ice to phytoplankton growth in marginal ice zone."

33. P2398 line 23. Replace "compared to" with "lower than".

This is corrected.

34. P2398 lines 25-28. Please rephrase with an eye to clarity.

Sentences are rephrased to "The supply from seawater is higher when ice forms in iron-rich coastal waters. The distribution of fluxes of iron originally from seawater and incorporated into the pack mainly tracks the supply of seawater iron to ice, except in the Ross and Weddell Seas where iron-rich sea ice has drifted away from continental areas".

35. P2399 line 3- sediments are most likely not "frozen" in the ice, but instead sit in the brine pockets. Please use the term "sediment-laden ice" or "sediment-bearing ice".

We agree with the reviewer and the sentence is revised as suggested.

36. P2399 line 5. Add "corresponding to" in front of "a flux of 2.2…"

Modified as suggested.

37. P2399 line 10: "sensitivity" of what? Please add ecosystem, or phytoplankton species composition.

Modified as suggested.

38. P2399 line 11. Add a reference.

References are added.

39. P2399 line 12. Add "extent" or "volume" after "declining sea ice"- same for line16. Specify what sea ice change you are referring to.

Modified as suggested.

40. P2399- please rephrase lines 18 to 21.

These sentences are rephrased to "We compare differences between the FULL simulation and the CTRL simulation from year to year, focusing on the role of iron released by sea ice. The simulated physical environment is the same in these two simulations. Differences in the biomass of diatoms and small phytoplankton from 1998 to 2007 are shown for the month of December in Fig. 6. These discrepancies are caused by iron-ice interactions. However, variations from year to year are a result of combined effects of the physical environment of surface water and iron fluxes from ice."

41. P2399 line 24- How do we know that the ice volume in the AP is lower in 2002 than in 2004? Please add Figure 7.

Time series of the Weddell Sea region is added in the revised manuscript.

42. Please mention that interannual variability in phytoplankton production can be linked to how much algae and Fe can remain in surface waters at the end of the summer bloom (depending on export or grazing) and be trapped again in sea ice when it forms in autumn.

We have added this point in the revised manuscript (see ms line 536-540).

"Note that the amount of iron released from melting ice is affected by iron concentrations in seawater during the previous autumn, which depends on biological uptake in the growing season. Thus, phytoplankton production from year to year can also be linked through iron sequestration in sea ice."

43. P2403 line 4. "and other trace metals" which other trace elements and why (ref)? are they also preferentially incorporated in sea ice? Could sea ice melting also fertilise HNLC waters with these essential elements?

Tovar-Sanchez et al. (2010) and Lannuzel et al. (2011) found concentrations of iron and some other bioactive metals (Zn, Cu, Ni, Mn, Co, Cd) in sea ice are one to two orders of magnitude higher than seawater. We would like to point out the potential importance of sea ice in fluxes of these metals. To the best of our knowledge, there is no evidence showing fertilization effects of these bioactive metals, other than iron. We have also modified the manuscript to include references.

44. Font on figure 6 needs to be bigger.

We have modified the figure and increased font sizes.