Dear Editor,

We have uploaded the revised version of the manuscript tc-2014-80 (*Influence of meltwater input on the skill of decadal forecast of sea ice in the Southern Ocean*). We have included the changes proposed in our responses to the Referees comments, listed below.

The Referees comments are in italic font and the author's response in upright font. In the revised version of the manuscript, changes are highlighted in red (text added), blue (text moved) and strikethrough (text removed).

In the initial version of the manuscript, the ocean heat and salt contents were not computed correctly. This has been corrected in the revised version of the manuscript, leading to very small changes in the curves displayed in Fig. 4 as well as in the values of the correlations given in Table 2. However, these corrections do not impact any of the conclusions drawn in the present work.

We hope that this revised version of the manuscript adequately takes into account the Reviewers suggestions.

Best regards,

Violette Zunz

Response to Anonymous Referee #1's comments

The authors thank Anonymous Referee #1 for the careful reading and for the constructive and encouraging comments on the manuscript. We will take his/her remarks into account in the revised version of the manuscript as detailed below.

The authors assess the impact of an unspecified additional freshwater flux on the trend in simulated Southern Ocean sea ice extent and concentration using an 'ensemble' simulation with data assimilation for the period 1850–2009 as well as different hind- casts all initialized with assimilated data of 1980 and extending to 2009. For simulations with data assimilation and an additional freshwater flux the trend in sea ice extent and concentration from 1980 to 2009 improves the reconstruction. The hindcast simulations also have to be forced by an additional freshwater flux to avoid a model drift. Since the resulting trends in sea ice extent and concentration are in satisfying agreement with satellite observations, the authors are optimistic to have found an experimental design for sea ice predictions in the Southern Ocean. They also claim that the positive sea ice trend over the last 30 years is mainly determined by the ocean state in the late 1970's and does not need an increased meltwater flux from the Antarctic Ice Sheet as previously stated by others.

General comments:

*The paper represents an interesting study especially with regard to recent claims relating the observed positive sea ice trend, although this has been questioned lately (**?**), to an increase in ice shelf basal melting. With this new view on the satellite measurements the authors might have to discuss their results from a slightly different perspective, i.e., the NODA and NOFWF simulations (Fig. 2) might be closer to reality than originally thought. However, their analysis provides additional evidence for the previous misinterpretation of the impact of ice shelf basal melting on the Southern Ocean sea ice extent.*

Therefore, I urge the authors to consider this new finding thoroughly when analyzing the model results, but if done, I recommend publication in TC after consideration of the comments/corrections listed below.

Response: The recent work of **?** indeed raises the issue whether the Antarctic sea ice extent has increased at a statistically significant rate during the last 30 years or not. The sea ice extent derived from the version 1 of the Bootstrap algorithm displays a trend of 6.3×10^6 km^2 yr^{-1} between 1979 and 2004 while the version 2 of the Bootstrap algorithm provides a trend of 14.8×10^6 km^2 yr^{-1} over the same period. Although it has not been demonstrated which version is closer to reality yet, we agree that it is important to discuss the results of our simulations with regard to the datasets derived from both versions of the Bootstrap algorithm in order to determine the influence of the related uncertainties on our conclusions. In the initial version of the manuscript, the observations of the sea ice extent correspond to the sea ice index (**?**) which is derived from sea ice concentration estimates from the NASA Team algorithm (`http://nsidc.org/data/docs/noaa/g02135_seaice_index/`). The trend in sea ice extent computed from the sea ice index is very close to the one computed from the version 2 of the Bootstrap algorithm. Our simulations NODA and DA_NOFWF provide trends in sea ice extent that are closer to the trend derived from version 1 than version 2 of the Bootstrap algorithm. Nevertheless, both simulations have more negative trends than the ones derived from observations. Among these two simulations, DA_NOFWF provides a trend in sea ice extent that is the closest to version 1 of the Bootstrap algorithm. Therefore, our conclusion that the data assimilation procedure used here improves the simulated trend in sea ice extent remains valid. Besides, the conclusion that including an additional freshwater flux in our simulation with data assimilation improves the agreement with data depends on the reconstruction selected and is thus not robust.

Action:

- In the revised version of the manuscript, we have replaced the sea ice extent data from the sea ice index by the sea ice extent estimates based on the version 2 of the Bootstrap algorithm in order to be consistent with the observation dataset used for the sea ice concentration (p. 8, l. 253-257).

- In Sect. 1 Introduction, we draw attention to the the different results of the two versions of the Bootstrap algorithm (p. 2, l. 30-36).

- In Sect. 2 Methodology, we specify that our results are, unless specified, compared to the observations of the sea ice concentration and extent derived from the version 2 of the Bootstrap algorithm (p. 8, l. 254), as done in many studies.

- In Sect. 3 Results, our results are now discussed with regard to the trends estimate derived from the two versions of the Bootstrap algorithm (p. 10, l. 334-337 and p. 18 l. 624-627).

- In Sect. 4 Summary and conclusions, we summarise the impact of the uncertainty of the observed trend on our conclusions (p. 19, l. 641-643).

Specific comments:

1. *The authors consider an unspecified additional freshwater flux which can but does not need to be related to ice shelf basal melting. Therefore, I recommend to modify the title to 'Influence of freshwater input....'*

   Response: We totally agree with this suggestion.

   Action: The title will be changed to "Influence of freshwater input on the skill of decadal forecast of sea ice in the Southern Ocean".

2. *The authors distribute the additional freshwater within the sector 0°to 170°W. Although I understand the rational behind, I question its applicability. The Filchner-Ronne and Ross ice shelves can be considered as 'low-melters', so why including the Weddell Sea and part of the Ross Sea? On the other hand, the coasts of East Antarctica are receiving most of today's precipitation, which will end up in marginal seas not included, and will be transported westward with the Antarctic Slope Current. The authors should show the difference with regard to sea ice extent for a circumpolar vs. sectoral distribution of the freshwater.*

   Response: Distributing the additional freshwater flux within different sectors indeed impacts the results of a simulation. Nevertheless, we want to keep the spatial distribution of the additional freshwater flux as simple as possible to limit the parameters associated with the additional freshwater flux. We have chosen a simple spatial distribution that seems reasonable compared to the observations. Investigating in detail the influence of the spatial distribution of the freshwater flux would certainly provide insightful results and this issue should be tackled in future studies.

   Action:

   - In the revised version of the manuscript, we point out that the choice of the sector over which the additional freshwater flux is distributed may impact the results of a simulation, in particular the spatial structure of the trend in sea ice concentration (p. 7, l. 234-238).
   - We also discuss the effects of different magnitudes and frequencies of variations of the freshwater flux in additional simulations, as suggested by Referee #2.

3. *Several figures, in particular Figs. 2, 4, 5, and 7, are too small to read labels, annotations, etc.*

   Action: These figures have been enlarged in the revised version of the manuscript and we will pay particular attention to the size of these figures in the final printed version in order to ensure their readability.

Technical corrections:

P 3571/L10: ...flux from the estimate of the . . ...
P3572/L06: . . ..,south of 70°S (area....
P3572/L18: ...inherit the value...
P3573/L16: ...consist of weighted averages.
P3574/L24: ...(Fig. 2a and 3b),...
P3575/L16: ...(green solid lines in Fig. 4a and b).
P3575/L20: ...(Fig. 4c).
P3576/L09: ...increase in the eastern Weddell Sea,..

P3577/L13: ...Bellingshausen and....
P3581/L27: If the decrease in the western part of the Southern Ocean is considered to be too large, it should also be mentioned that the increases in the Weddell and Ross seas are too low.

Action: The technical corrections listed above have been included in the revised version of the manuscript.

Response to Anonymous Referee #2's comments

The authors thank Anonymous Referee #2 for the constructive comments and for the relevant suggestions that will certainly help us to clarify the revised version of the manuscript. We will take his/her remarks into account in the revised version of the manuscript as detailed below.

It seems to me the major finding in this study is that imposing a large negative freshwater flux for a decade before 1980 and then reducing the flux by 1/3 or so after 1980 causes sea ice to expand. There was no need to ramp up the freshwater flux after 1980, instead the abrupt jump at 1980 caused the expansion. The paper is technically very complex, with data assimilation and variable freshwater hosing, yet the result is very basic. Previous studies have shown that suddenly turning on freshwater in ∼1980 is effective at causing the sea ice to expand. The main new innovation shown here is that the same result can be gained by tinkering with the freshwater prior to 1980, so that there is a relative increase in the freshwater flux in 1980. It is pretty clear that the minor ramping after 1980 has little effect as in Swart and Fyfe (2013). However, I disagree with the conclusion in this study that "Bintanja et al (2013) is not confirmed in the present study". In my mind, this study has a strong response for exactly the same reason as Bintanja et al. Both have an abrupt increase in freshwater flux at the start of the period of validation (e.g., 1980 in this study) that is imposed thereafter for 30 yrs. The main difference is that in this study the initial state is forced to be a high mixing state by adding a negative freshwater flux prior to 1980 and the freshwater flux is positive after 1980 in only a relative sense.

Response: Turning on abruptly the freshwater flux can indeed cause an expansion of the sea ice cover, as demonstrated for instance by Bintanja et al. (2013). Nevertheless, our results show that an expansion of the sea ice cover can also be provided by a hindcast simulation adequately initialised, i.e., from an initial state that favours the growth of sea ice. In the simulation DA_FWF, the additional freshwater flux averaged over the period 1950-1979 (1980-2009) equals −0.02 Sv (−0.03 Sv). There is thus no increase in the mean additional freshwater flux between the 30-year periods before and after 1980 in this simulation. We have performed additional simulations whose results allow concluding that, in our case, it is not necessary to increase the freshwater flux after 1980 compared to the period before 1980 to induce an increase in the ice extent. Furthermore, our experiments show that the sea ice changes are not simply due to the variations of freshwater flux but that the initialisation through data assimilation is indeed required to reproduce the observed trends (see below for details, in particular the suggested additional experiment). In our simulations with data assimilation, the additional freshwater flux acts as a perturbation and improves the efficiency of the particle filtering. Indeed, thanks to the additional freshwater flux, the ensemble gets wider and more likely contains a solution that is close to the observations. While our results confirm that the sea ice cover is sensitive to changes in the freshwater input, they do not allow concluding that the recent increase in sea ice extent is due to an increase in the freshwater input in the Southern Ocean.

Action:

- In the revised version of the manuscript, we present the results of additional simulations that support the conclusion that an adequate initialisation can lead to a simulated increase in sea ice extent (Sect. 3.3 pp. 15-18).
- We also present more clearly the role played by the additional freshwater flux in our

simulations (Sect. 3.2, pp. 13-15).

The data assimilation without freshwater gives results that are not too surprising. The ensemble can be sampled (or selected) and nudged in a way to give good agreement with observations. The much lower coupling between ocean surface and layer below in Fig 4 indicates that climate relationships change with data assimilation. In this case the two ocean layers are weakly coupled compared to without data assimilation. However, the run with data assimilation without freshwater is unable produce adequate initial conditions for the hindcast runs because it does not have the outlandish variability prior to 1980 that is key to the cases that do have expanding sea ice. Because I view the high variability as a problem, I am left to assume that the model is flawed (also not too surprising considering that CMIP5 GCMs have similar problems) either because it is lacking some key physics or forcing.

Response: The simulation DA_NOFWF provides reconstructions of the trends in sea ice extent and concentration that are in better agreement with the observations than the simulation NODA. However, among the simulations presented in the initial version of the manuscript, the best reconstruction of the trends in sea ice is provided by the simulation DA_FWF. The additional freshwater flux applied in this latter simulation increases the spread of the ensemble and improves the efficiency of the particle filtering, as mentioned above. Nevertheless, we agree on the fact that this strongly varying additional freshwater flux leads to a high variability in the sea ice extent that seems unrealistic. We have performed a simulation with data assimilation and a weakly varying additional freshwater flux. The results of this new simulation display a reasonable variability. Furthermore, hindcasts initialised in 1980 from a state extracted from the reconstruction provided by this simulation display increasing trend in sea ice extent. This indicates that our results are robust and that a very large variability is not necessary to obtain adequate initial conditions.

Action:

- The results of the simulation with data assimilation and a weakly varying additional freshwater flux (DA_FWF_1) are presented in the revised version of the manuscript (pp. 11-12, l. 357-387). The simulation called DA_FWF in the initial version of the manuscript has been renamed DA_FWF_2 in the revised version.
- We also discuss the results of the hindcast simulations initialised in 1980 from a state extracted from this new simulation with data assimilation (HINDCAST_2.1, HINDCAST_2.2 and HINDCAST_2.3, p. 16, l. 545-567). The hindcast simulations named HINDCAST_2, HINDCAST_3 and HINDCAST_4 in the initial version of the manuscript have been renamed HINDCAST_3.1, HINDCAST_3.2 and HINDCAST_3.3 respectively.

With large stochastic freshwater input added along with data assimilation, the variability becomes sufficient to send the model into a (unphysical?) state with very high ocean mixing just prior to 1980. The variability of ice and ocean skyrockets prior to 1980, when observations are too sparse to control it. If the observations were more complete, would this have been possible? The authors should address this question. It appears to me that the massive random freshwater input is selected in the resampling process because observations are insufficient to rule out these cases. I am not at all convinced it is a realistic initial state.

Response: If the observations were more complete, the data assimilation would have resulted in stronger constraints on the system. In this case, the variability of the sea ice extent and ocean variables in the simulation DA_FWF would likely be weaker. We agree on the fact that the strong variability in the simulation DA_FWF may pull the solutions towards unrealistic states. To test the potential influence of this large variability, as mentioned above, we have performed a new simulation with data assimilation and a weakly varying additional freshwater flux. The results of this new simulation display a variability that is much weaker than in DA_FWF. Furthermore, the state extracted from this simulation in 1980 leads to an increase in sea ice extent when integrated forward in time in a hindcast simulation. Without sufficient observations, we cannot prove that the state obtained in 1980 is realistic but at least a state leading to an increase in ice extent can be obtained thanks to (objective) data assimilation using different hypotheses for the freshwater flux and the variability of the system before 1980.

Action:

- In the revised version of the manuscript, we insist on the fact that, in some case, the additional freshwater flux may lead to unrealistic solutions (p. 12, l. 403-405 and l. 414-416).
- We have included the results of the new simulation with data assimilation and a weakly varying additional freshwater flux (DA_FWF_1, pp. 11-12, l. 357-387). We show that this weakly varying additional freshwater flux can also improve the efficiency of the data assimilation procedure without producing unrealistic solutions (Sect. 3.2 pp. 13-15).

The authors should show the relationship between mean surface air temperature (Fig 5) and sea ice extent (Fig 2) by plotting these variables on each axis of a scatter plot. I expect it would show that their relationship changes fundamentally after about 1980 in the run with data assimilation and freshwater forcing. A conservative view would be that non stationary behaviour is a flaw in the model results without observations to prove it happened or a good physical explanation.

Response: In all our experiments, both before 1980 and after 1980, there is a negative correlation between the surface air temperature and sea ice extent. Adding freshwater fluxes reduces the correlation between the ensemble means of the latter variables because the freshwater flux adds some additional noise (Fig. 1). Note that care should be taken when comparing the ensemble means of simulations with and without data assimilation as the former represents the modelled forced response of the system while the latter is designed to also reproduce the observed internal variability. Nevertheless, the additional freshwater flux does not fundamentally modify the relationship between the surface air temperature and the ice extent. Indeed, the correlation between the ensemble mean of the surface air temperature and the sea ice extent in the simulations with data assimilation and additional freshwater flux (Fig. 1c,d) is close to the correlation between the surface temperature and the sea ice extent for the individual members in the simulation NODA (Fig. 1a). Furthermore, there is no clear changes in the relationship in 1980 in any of our experiment. We thus have no reason to consider that there is a flaw in the model results.

Action: A brief caution note on this subject has been included in the revised version of the manuscript (p. 14, l. 460-466).

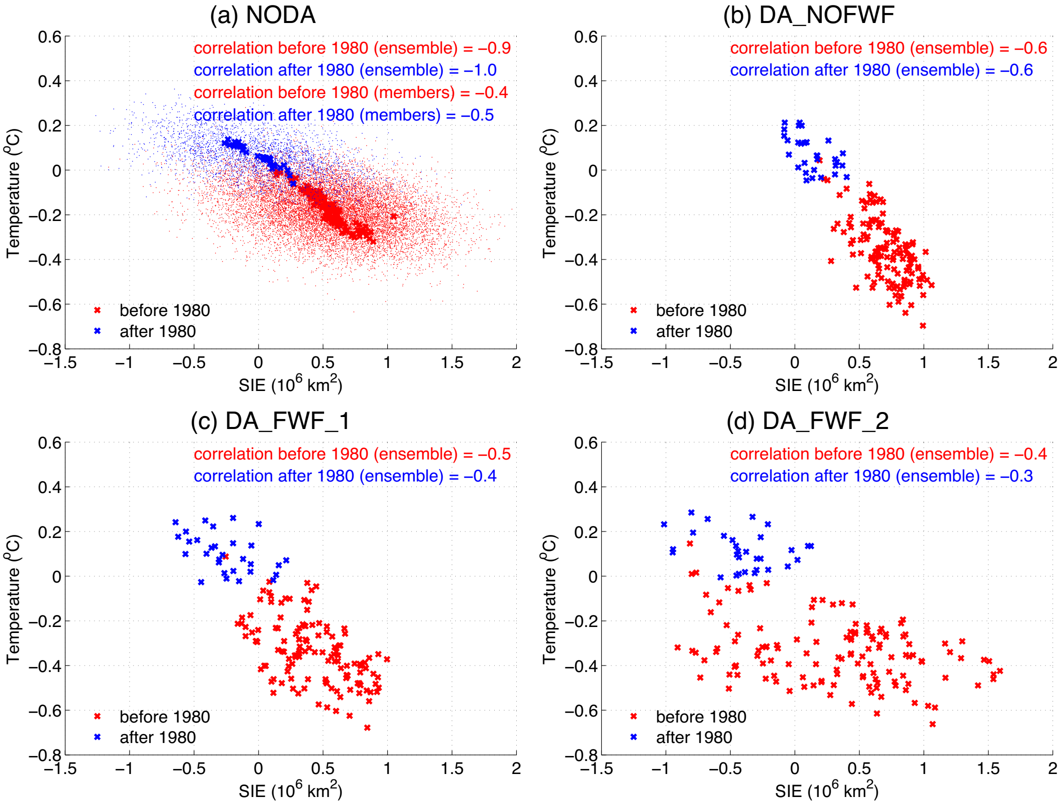

Figure 1: Surface air temperature (averaged over the area south of 30˚S) vs. sea ice extent on average over each year of the simulation. The years before 1980 are in red and the years after 1980 are in blue. The results are shown for a simulation without data assimilation (NODA), a simulation with data assimilation (DA_NOFWF), a simulation with data assimilation and a weakly varying additional freshwater flux (DA_FWF_1), not present in the initial version of the manuscript) and a simulation with data assimilation and a strongly varying additional freshwater flux (DA_FWF_2, i.e., the simulation DA_FWF in the initial version of the manuscript). The crosses correspond to the values of the ensemble mean and the dots are for the values of the individual members, shown only for the simulation NODA for simplicity.

One conclusion of this study is that the initial condition must adequately represent the observed state to perform skillful predictions. Maybe this is true, but how can we be convinced this was achieved in this study? In other words, how can we be sure that unrealistic initial conditions cannot achieve skillful predictions by accident? The authors point out that the data assimilation can account for model biases, which I think means that the initial conditions might be necessarily unrealistic.

Response: It is of course difficult to prove that our predictions are not skillful by accident but, as mentioned above, we have performed new hindcasts started from a simulation with data assimilation and a weakly varying freshwater flux which also have some skill in predicting the sea ice extent. Nevertheless, as stated in the initial version of the manuscript, additional experiments are required to further test the skill of predictions in the Southern Ocean.

Action: The results of new hindcast simulations are presented and discussed in the revised version of the manuscript (HINDCAST_2.1, HINDCAST_2.2 and HINDCAST_2.3, p. 16, l. 545-567). This should reinforce our conclusion that an adequate initial state can improve the skill of a prediction for the 30-yr trends in sea ice concentration and extent.

The authors only put the magnitude of the freshwater into observational perspective when they discuss the ramp rate after 1980. But they then show the ramping is irrelevant. They should also mention their typical freshwater input of 0.01 Sv equals about 300 Gt/yr, which is similar to the freshwater that was imposed in a steady or ramped fashion by Swart and Fyfe (2013) and Bintanja et al (2013). It is also a lot higher than the Grace imbalance.

Response: The additional random freshwater flux in the simulation DA_FWF follows an autoregressive process with a standard deviation of 0.01 Sv which indeed corresponds to a larger flux than the one derived from the estimates of the Antarctic ice sheet mass imbalance.

Action: In the revised version of the manuscript, we compare the absolute magnitude of the freshwater flux to the estimate of the freshwater input derived from the ice sheet mass imbalance (p. 15, l. 498-505).

The DA_FWF does not seem necessary in this study. It adds considerable complication, and slows the reader from getting at the essence of the results. I recommend the authors do another hindcast experiment where they branch from the DA_NOFWF run in about year 1960 and add a negative freshwater flux until 1980 and then reduce it substantially and abruptly for the remainder of the run. I expect the results would be just as skillful and much easier to understand. The authors than would have to decide if the DA_FWF run is useful in spite of the objections raised here. I can appreciate that DA_FWF arrives at an initial state using and objective method, while my suggested hind cast could seem arbitrary. The issue is whether the objective method has enough observations to be satisfactory.

Response: We have performed the suggested hindcast. This hindcast starts in January 1960 from initial conditions extracted from the simulation NODA. Between January 1960 and December 1979, a constant additional freshwater flux of -0.03 Sv is applied. This freshwater flux is abruptly increased in January 1980 to a value of -0.01 Sv and then remains constant until the end of the simulation (December 2009). The sea ice extent increases rapidly after the abrupt change in the additional freshwater flux in 1980 but decreases again after a few years (Fig. 2). The trend in sea ice extent over the period 1980-2009 equals $-8.1 \times 10^3 km^2 yr^{-1}$. The results of this hindcast confirms that an abrupt increase in the additional freshwater flux is not responsible for the increase in sea ice extent between 1980 and 2009 in the hindcast simulations initialised from the simulation DA_FWF. These additional results support our conclusion that adequately initialised hindcast simulations can provide trends in sea ice extent and concentration that are close to the observations. Changes in freshwater fluxes likely play a role in the observed state in the Southern Ocean but this role is more complex than juste a change in the mean input.

Action: The results of the suggested hindcast are shown in a Supplementary Material and we summarise the conclusion drawn from this hindcast in the revised version of the manuscript (p. 18, l. 630-639). We keep the results and the discussion related to the simulation DA_FWF, renamed DA_FWF_2 in the revised version of the manuscript.

Minor points

p3566 line 21-22 I do not understand the claim that significant predictability for the trend spans several decades, unless you are referring to a perfect model.

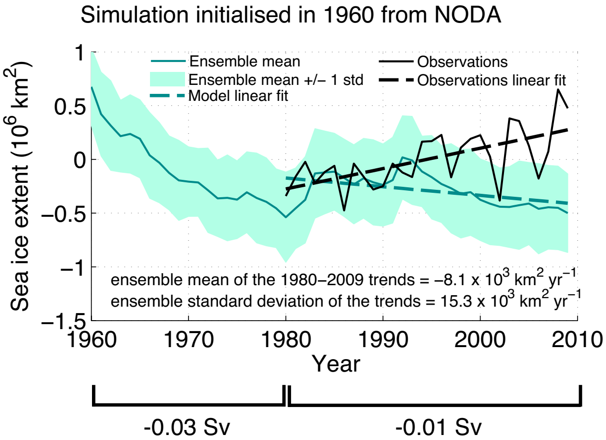

Figure 2: Sea ice extent anomaly from a simulation initialised in 1960 from the simulation NODA. An additional freshwater flux is applied (-0.03 Sv between January 1960 and December 1979, -0.01 between January 1980 and December 2009). Observations (**?**) are shown as the black line.

Response: This conclusion has indeed be drawn in a perfect model framework.

Action: This is specified in the revised version of the manuscript (p. 3, l. 82).

p3580 line 4 I think "participates to" should be "contributes to"

Action: "participates to" has been replaced by "contributes to" (p. 14, l. 474).

p3580 line 18 would be better if it said "equivalent to a melting rate of 1.4 Gt per year^2". I had to get out my ruler to verify this is what was meant.

Action: "equivalent to a change in melting rate of 42 Gt yr^{-1} has been replaced by "equivalent to an acceleration of the melting of 1.4 Gt yr^{-2}" (p. 14, l. 489).

Fig 1, the spatial distribution is unfortunate for skipping the outlet of meltwater from the Ross Shelf in McMurdo Sound. Though it is probably not critical.

Response: A different spatial distribution may indeed be more adequate to represent the meltwater input from the Antarctic ice shelves. Nevertheless, in order to limit the constraints on the freshwater distribution, we prefer to keep the spatial structure of the freshwater input as simple as possible.

Action: In the revised version of the manuscript, we mention that different spatial structures of the freshwater input may lead to different results and we briefly justify our choice for the spatial distribution of the freshwater flux in our simulations (p. 7, l. 234-238).

Table 1 would help if it had number of ensemble members indicated, especially for the hindcast runs. I didn't realize there were ensembles until I saw the shading in Fig 7.

Response: In the initial version of the manuscript, the number of members is indicated in the caption of Table 1.

Action: In the revised version of the manuscript, we have added a column to Table 1 to indicate more clearly the number of members in each simulation.