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The Cryosphere Discussions

Interactive comment on "Influence of meltwater input on the skill of decadal forecast of sea ice in the Southern Ocean" *by* V. Zunz and H. Goosse

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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.

The referee's comments are in italic font and the author's response in upright font.

Response to Anonymous Referee #2's comments

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 will present the results of additional simulations that support the conclusion that an adequate initialisation can lead to a simulated increase in sea ice extent. We will also present more clearly the role played by the additional freshwater flux in our simulations.

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 will be presented in the revised version of the manuscript. We will also discuss the results of the hindcast simulations initialised in 1980 from a state extracted from this new simulation with data assimilation.

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 will insist on the fact that, in some case, the additional freshwater flux may lead to unrealistic solutions. We will include the results of the new simulation with data assimilation and a weakly varying additional freshwater flux. We will show that this weakly varying additional freshwater flux can also improve the efficiency of the data assimilation procedure without producing unrealistic solutions.

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 will be included in the revised version of the manuscript.

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 will be presented and discussed in the revised version of the manuscript. 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 will compare the absolute magnitude of the freshwater flux to the estimate of the freshwater input derived from the ice sheet mass imbalance.

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 will be shown in a Supplementary Material and we will summarise the conclusion drawn from this hindcast in the revised version of the manuscript. We will keep the results and the discussion related to the simulation DA_FWF 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.

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

Action: This will be specified in the revised version of the manuscript.

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

Action: “participates to" will be replaced by “contributes to".

p3580 line 18 would be better if it said "equivalent to a melting rate of 1.4 Gt per yearĖĘ2". 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} will be replaced by “equivalent to an acceleration of the melting of 1.4 Gt yr^{-2}".

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 will mention that different spatial structures of the freshwater input may lead to different results and we will briefly justify our choice for the spatial distribution of the freshwater flux in our simulations.

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 will add a column to Table 1 to indicate more clearly the number of members in each simulation.

References

Fetterer, F., K. Knowles, W. Meier, and M. Savoie (2002, updated daily), *Sea Ice Index, January 1980 to December 2009*, Boulder, Colorado USA: National Snow and Ice Data Center, doi: http://dx.doi.org/10.7265/N5QJ7F7W.

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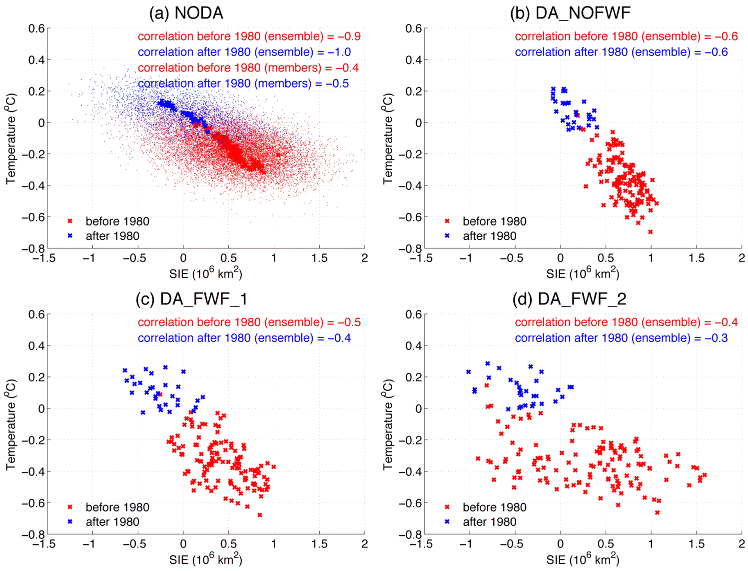

Fig. 1. Surface air temperature (averaged over the area south of 30°S) vs. sea ice extent on average over each year of the simulation. The years before 1980 are in red and the years after 1980 are in blue. The results are shown for a simulation without data assimilation (NODA), a simulation with data 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.

Fig. 1.

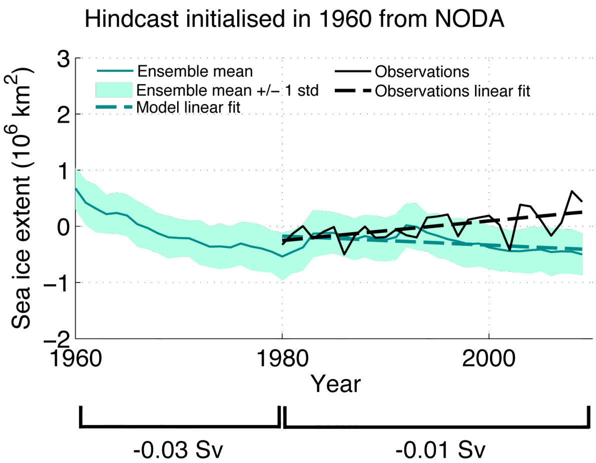

Fig. 2. Sea ice extent anomaly from a hindcast initialised in 1960 from the simulation NODA. An additional freshwater flux is applied (-0.03 Sv between January 1960 and December 1979, -0.01 between January 1980 and December 2009). Observations (Fetterer et al., 2002, updated daily) are shown as the black line.

Fig. 2.