

## ***Interactive comment on “Comparing ice discharge through West Antarctic Gateways: Weddell vs. Amundsen Sea warming” by M. A. Martin et al.***

**M. A. Martin et al.**

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1 General statement

The manuscript “Comparing ice discharge through West Antarctic Gateways: Weddell vs. Amundsen Sea warming” by M. Martin and others studies the impact of ocean warming on future evolution of the Weddell and Amundsen sea sectors for the next five centuries. The authors find that the Weddell Sea sector is much more vulnerable to ocean warming than the Amundsen Sea sector due the topography of these areas, and that even small changes in ocean conditions would rapidly and drastically impact the Weddell Sea sector.

C1496

Author Answer: We would like to thank this reviewer for his/her time and effort to evaluate our manuscript.

This manuscript presents an important and timely study as ocean has been triggering the changes happening in the Amundsen Sea sector today, however model studies remain inconsistent as pointed out in the introduction. The experiments performed here are appropriate and the paper is generally well written, however some details about the modeling and the experiments performed are missing or unclear. The ocean melting applied, for example, is never shown while this is the main link between the ocean and the ice stream:

Author Answer: We have now included a figure showing the ocean melting induced by the temperature forcing applied.

the discussion focuses on the topographic differences between these two sectors but does not analyze the impact of changes in ocean circulation.

Author Answer: We do indeed not focus on potential changes in ocean circulation. This would be a very interesting project, but at the same time require some very sophisticated ocean modelling, which is beyond the scope of our work currently. We have rather opted to test the impact of uniform and stepwise temperature increase, aiming at avoiding the impression of realistic experiments. This approach has the advantage that it allows for direct comparison of the ice response to temperature increase in two very different basins.

Another major point that strikes me is that the authors report that the ocean is warming more rapidly in the Weddell Sea sector, that this area is more susceptible to changes in ocean circulation and that such changes would happen over a shorter time scale; however remote sensing observations show rapid changes in the Amundsen Sea sector and a relative stability of the Weddell Sea sector. I think that this difference of behavior between modeling results and observations should be addressed in the paper. I therefore think that this manuscript would be greatly improved with some clarifications in the

C1497

experiments performed and some additional discussions.

Author Answer: This appears to be a misunderstanding. There are projections of Weddell sea warming during the 21st century (Hellmer et al, 2012) which are strong in comparison to observed Amundsen warming. We have clarified this in the abstract.

## 2 Specific comments

As mentioned above, I think that there is a contradiction between the observations and the modeling results described in this paper. The abstract for example mentions “much stronger warm-water intrusion into ice-shelf cavities in the Weddell Sea compared to the observed Amundsen warming” and “ocean warming in the Weddell Sea leads to more immediate ice discharge [in the Weddell Sea] with a higher sensitivity to small warming levels than the same warming in the Amundsen Sea”. However all observations (gravity, InSAR velocities, altimetry) suggest large changes in the Amundsen Sea sector today, while they show limited changes in the Weddell Sea. How do the authors explain this discrepancy?

Author Answer: We assume that there is a misunderstanding. It was not our intention to suggest that there are such changes in the Weddell Sea, but wanted to highlight that there might be in the future. We hope that we have successfully eliminated the confusing formulation in abstract.

One possible reason that is not discussed in the paper is the impact of the model initial conditions. All simulations are run starting from a steady- state while the Amundsen Sea sector is far from being in equilibrium. How does this impact the simulations? Could it explain this discrepancy of behavior? Does it mean that the ocean is not responsible for the observed changes?

Author Answer: The fact that all experiments are started from a steady state does surely influence the results. But since we are not aiming at performing experiments that represent the current state of the basin, but rather try to enhance comparability of

C1498

the ice response of the two very different basins to “the same” forcing (by “the same” we mean ocean temperature, and not melt rate), this choice is part of our strategy. Would we start from more realistic initial state, there would be another type of conclusion possible, namely about the future behavior of the two basins. But there would be a large amount of uncertainty added, and we would run the risk of comparing apples with oranges. This is discussed in Sect.2.3 in the main text: “. . .As we are using steady states of the ice sheet as starting points for our simulations, there would be no qualified exactness added when being more selective in the model versions. In order to constrain the initial state better, a historically validated (Hillenbrand et al., 2013) dynamical spin-up of an ensemble of model versions would be necessary, in order to exclude those that are over- or underresponsive to external perturbations (Aschwarden et al., 2013). This, however, is beyond the scope of this paper.”

p.1707 l.3: Loss of buttressing is caused by both grounding line retreat and ice shelf thinning (at least for confined ice shelves). This second aspect is not discussed in the manuscript.

Author Answer: This is now part of the main text, Sect 2.1: “PISM captures lateral resistance as well stress transmission across the grounding line by using the hybrid shallow approximation (Bueler and Brown, 2009; Winkelmann et al., 2011). The model hence simulates the loss of buttressing caused by ice-shelf thinning (Gagliardini and Durand, 2010) and the possible resulting grounding-line retreat”

p.1708 l.15 and Appendix A3: the initialization procedure and the experiments are clearly detailed in the manuscript, however the number of experiments done, the parameters used and the resolution used for the experiments is not very clear. How many sets of sensitivity experiments are done (by set I mean looking at the impact of ocean for a given initial state)? This is not clearly specified in the manuscript and results from Fig. 7 and 8 are not really discussed. I think this part should be moved from the appendix to the main manuscript, as the uncertainty associated to the results is a critical part.

C1499

Author Answer: According to both reviewers suggestion we have moved the respective part to the main text and clarified it.

Fig. 8 suggests that the response of the Weddell Sea to a 2K ocean warming is not significantly affected by the initial conditions while the initial state is critical in the case of the Amundsen Sea, with a contribution to sea level rise varying between 0.2 to more than 3.0 m (figure is truncated) after 500 years. To go back to a previous comment, is that linked to the Amundsen Sea being further from a steady-state equilibrium today? And how does this impact the conclusions of the paper?

Author Answer: It is not only the initial state, but also the parameters during the run, which are not changed when starting the experiment after the spinup. Although this does not relate to the actual Amundsen basin being in whatever state (see our comments on our concept above), the question of how this impacts the conclusions of the paper is valid. Fig. 8 (now Fig. 6) shows, however, that the shape of the curve is the same for all parameter sets, and always different to the shape from the Weddell Sea Sector experiments. The conclusions of our paper concern this qualitative difference, and not the quantitative results. We have now more clearly mentioned that the quantitative results for the Amundsen Sector are indeed more sensitive to the parameter choice.

p.1709 l.12: How does the ocean temperature impact the sub-ice shelf melting rate? Melting rates are never shown in the paper while this is the main link between the ocean and the ice streams. I suggest adding a figure with initial sub-ice shelf melting rates and impact of ocean warming on melting rates for both Amundsen and Weddell Sea sectors. This could also explain the difference of response between these two sectors so it should be added in the discussion.

Author Answer: We have added the respective figures and discussed this issue now.

p.1714 l.2: Why use ALBMAP and not Bedmap2 (Fretwell et al., 2013)? There are some substantial differences in the Amundsen Sea and Weddell Sea sectors, so how

C1500

do they affect the results presented here?

Author Answer: The manuscript has developed over a quite long duration of time along with the preparation of the PISM-Antarctica contribution to the SeaRISE effort. By the time Bedmap 2 became available, re-running the simulations with the updated topography would have been too expensive, computationally. But, more importantly, we estimate that the changes do not affect our results in a way to change the main conclusions: Figure 13b in Fretwell et al. 2013 summarizes the differences in bed elevation between ALBMAP and Bedmap2. In the areas that are relevant for our experiments, there are much less pronounced changes than in many other Antarctic areas. An exception might be Recovery Glacier (see section 7.1 in Fretwell et al.), where a deep trough and an overdeepening have been discovered. Recovery Glacier is not showing pronounced retreat in our simulations, so our ice loss estimation for the Weddell Sea Sector might be underestimated indeed, which could strengthen our results. Figs. 2a and b in Ross et al, 2012, where the regions relevant to our paper are analyzed in great detail and where the relevant data is part of Bedmap2, support our ALBMAP-based assertion of the characteristic differences in H/H<sub>f</sub> (see our Fig. 1). These characteristics are the ones that are our conclusions are based on.

3 Technical comments

p.1706 l.9: “Amundsen warming” → “Amundsen Sea warming” p.1706 l.12: “more immediate ice discharge” → “more immediate increase in ice discharge”

Author Answer: Done

p.1706 l.16-17: Precise what sector you are discussing here.

Author Answer: Done

p.1708 l.1: “deepness” → “elevation”?

Author Answer: This has been changed.

C1501

p.1708 l.7: “ice needs to get into motion first”: I am not sure what the authors mean here as the Amundsen Sea sector ice streams are already the fastest moving glaciers in Antarctica, with a velocity well above 3000 m/yr for Pine Island and Thwaites glaciers.

Author Answer: We have rephrased this in the manuscript. We meant that the ice needs to get much thinner, by flowing away.

p.1708 l.15: why do the authors use a 24 km grid while we know that results at this resolution remain inaccurate and grounding is poorly resolved, especially as they also perform simulations at much higher resolution? Fig. 7 is also very noisy at 24 km resolution.

Author Answer: This is of course true. The 24 km runs were solely performed in order to provide a broader range of resolutions.

p.1713 l.7: “compare Favier” → “compare to Favier”

Author Answer: Done

p.1713 l.7: for a 50 km wide ice stream, a resolution of 24 km is not going to resolve anything.

Author Answer: This is of course true. We were referring to the finer resolutions, and have rephrased this in the manuscript.

p.1714 l.4: “this measure”: what measure?

Author Answer: We meant “of  $H/H_f$ ”. Replaced in the manuscript.

p.1714 l.12: “The melt rates therefore roughly adapt to changing ice-shelf depth”: How does it adapt? This part should actually be more detailed and moved to the main body of the text as it is a key part of the model and the sensitivity experiments.

Author Answer: Done.

p.1714 l.27, p.1715 l.2, l.4, l.6: Equations should be added to describe these parame-

C1502

ters. I appreciate that this paper is concise and does not repeat once again the SIA or SSA equations, however the friction laws or other specific parameters should be clearly stated, the PISM manual being very likely to change in the future.

Author Answer: We have inserted the crucial equations and given a more detailed explanation. We have also referenced the according literature as well as the PISM-PIK description papers for more specific details.

p.1715 l.12: There seems to be more than 24 acceptable initial configurations from Fig. 9, so which ones are kept? The range of parameters studies should also be mentioned in the text.

Author Answer: In Fig. 9 (now Fig. 5) all tested parameter combinations are shown, and the coloring indicated the ones that are acceptable, as described in the figure caption. We have clarified this now in both text and figure caption.

p.1715 l.23: How are the models rescaled from 15 to 12 km? Is it just interpolation?

Author Answer: It is interpolation of the modeled fields (ice topography, temperature and so on) and then a shorter equilibrium run. In the manuscript we now write: “In order to rescale the horizontal resolution to 12km, two thousand years of simulation time with steady input are added for the 24 steady states selected so far, which excludes two further ensemble members. Our final 12km-ensemble therefore consists of 22 initial states.”

p.1721: black lines on fig. a and b are difficult to see.

Author Answer: We apologize for that. However, we have tested several choices and still think that this is the best option.

p.1728: Results for the Weddell Sea sector look similar at 5 km and 12 km suggesting that the results are not very dependent on the grid resolution unlike results for the Amundsen Sea sector. For the latter case, results at 2.5, 5 and 12 km are quite different, with a contribution to sea level rise after 500 years varying from 0.5 to 1.2 m in the

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case of a 2 K increase in the ocean temperature.

Author Answer: This is true. In our response to reviewer 2 we have discussed this issue more clearly and also changed the manuscript accordingly. The bottom line is that we cannot provide quantitatively accurate results, but that we are confident that the differences in the shape of the curve between the two basins, which are the same over a broad range of resolutions, provides a strong indication that our results (namely the qualitative differences) are robust, even if grid resolution was further refined.

p.1730: It is not clear what simulations are kept. The text mentions 22 and 24 simulations kept at 12 km and 5 km but more seem acceptable from this figure. Also the initial condition picked for the Weddell Sea sector (Fpw= 0.91 and ESSA= 0.5 does not seem an acceptable initial guess as described in the figure caption.

Author Answer: We have aimed at clarifying the figure description, which is now partly in the main text of the manuscript. The letter W indicated choices for 5km resolution, while the coloring is 15 km resolutions.

p.1731 l.4: The PISM manual is not a proper citation: 1) it has not been peer-reviewed, 2) it is constantly changing and 3) the authors of ice flow models should be credited.

Author Answer: We have changed that in the revised manuscript. p.1731 l.24: “proper grounding-line positions”: How is that evaluated? Visually or is there a quantitative criterion?

Author Answer: It is an “by eye evaluation”, excluding only such states that are unacceptable on first sight. This non-quantitative approach is possible, because there is a clear distinction between parameters combinations yielding entirely grounded ice-shelves or disappeared WAIS sectors and, on the other hand, roughly acceptable states.

p.1732: These velocities are quite lower than observed today, how does this impact the results?

C1504

Author Answer: The ice velocity is part of the parameter variation. We have shown the representative member, for which 5km runs were performed.

#### 4 References

Fretwell, P., et al., Bedmap2: Improved ice bed, surface and thickness datasets for Antarctica, *Cryosphere*, 7(1), 375–393, 2013.

Author Answer: Hellmer, H. H., Kauker, F., Timmermann, R., Determann, J. and Rae, J.: Twenty-first-century warming of a large Antarctic ice-shelf cavity by a redirected coastal current, *Nature*, 485(7397), 225–228, doi:10.1038/nature11064, 2012.

Ross, N., Bingham, R. G., Corr, H. F. J., Ferraccioli, F., Jordan, T. A., Le Brocq, A., Rippin, D. M., Young, D., Blankenship, D. D. and Siegert, M. J.: Steep reverse bed slope at the grounding line of the Weddell Sea sector in West Antarctica, *Nat. Geosci.*, 5(6), 393–396, doi:10.1038/ngeo1468, 2012.

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