Review of Tigchelaar et al. :

„Nonlinear response of the Antarctic ice sheet to Quaternary sea level and climate forcing“

Tigchelaar et al. discuss the transient evolution of the Antarctic Ice Sheet in response to late Quaternary climatological and sea level boundary conditions by means of 3D ice sheet modelling. They force their ice sheet model with the output of an Earth System Model of intermediate complexity covering the last 408 kyr employing a continuous sea level forcing. Their discussion of the individual impact of a single forcing component versus the integrated effect of combined forcings on ice volume and geometry changes is intriguing and worth publishing. The topics covered in their manuscript fit into the scope of The Cryosphere and the manuscript is generally well written. In principal I would suggest publication of their manuscript if some key issues regarding the discussion of their results and methodology are addressed.

In the following I will lay out my main general remarks which should be addressed before publication followed by some minor corrections of typos and wording.

1. Methods and ocean forcing.

While the method section is clearly written, I think that a more transparent discussion of the strengths and weaknesses of the forcing approach would improve the manuscript and help the reader to put the results into perspective with the literature in the field. The fact that a transient model run spanning several hundred thousand years is used to force the ice sheet model is very impressive, but it should be clearly stated that this is at the expense of resolution which is very coarse. It is for example well known that global ocean models have a hard time resolving circumantarctic circulation which mostly leads to inaccurate representations of warming during interglacials and therefore a muted response of the Antarctic Ice Sheet (e.g. Sutter et al., 2016). I would imagine that the representation of variability of circumantarctic ocean temperatures is even worse in EMICs. I guess this is one of the reasons why ice sheet volume remains relatively high for most interglacials in the manuscript presented here, as well as in Tigchelaar et al. (2018). Throughout the manuscript (Methods, Results, Discussion), it should be re-iterated that with the ocean forcing used in this manuscript, the impact of ocean temperatures on transient interglacial ice sheet dynamics in the late Quaternary cannot be accurately assessed. Upon reading the manuscript, I had the impression that the results shown here imply that ocean temperature forcing in Interglacials or deglaciation phases is not important for ice sheet retreat which would contradict the current literature on how the Antarctic Ice Sheet responds to warmer worlds or in glacial terminations. I am sure that this is not the intended take away message but the chance of misinterpretation for someone not familiar with the field is high.

2. Ice sheet model

The description of the ice sheet model is rather compact, which is probably due to the fact, that it has been discussed at length in the cited literature. However, a quick reference as how ice shelf mass balance is treated would be helpful (calving, basal melt parameterization). Providing an assessment of how well the basal ice shelf melt pattern matches the present day observed melt rate (e.g. Depoorter et al., 2013, Rignot et al., 2013) would be helpful as well. How is the model tuned, and how does it perform against present day and paleo benchmarks? Also it would be worth mentioning how the resolution (40 km) used here could affect the results compared to higher resolution studies.

3. Representation of ocean temperatures

The authors mention in section 2.2.2, that LOVECLIM Southern Ocean temperatures are generally too coold. As you use an anomaly forcing to prevent bias propagation it would be interesting how big the glacial and interglacial temperature anomalies (e.g. at 400 m depth) close the the ice shelves are.

4. Presentation of Results

The presentation and discussion of the results is currently written in a very affirmative manner which sometimes ignores the biases introduced by the experimental setup. For example 3.4.4 suggests that temporal ocean temperature changes are not relevant for ice volume changes. While this is true for the setup used here, it is not the case in multiple publications on the matter (e.g. Golledge et al., 2015, 2017, 2019, DeConto & Pollard 2016, Sutter et al. 2016,2019, Albrecht et al., 2019 TCD). The authors state that they will discuss the validity of the results in the Discussion (p.11 L 10-11), but I have the impression that a serious debate about the shortcomings of the approach and therefore the scope of the results is lacking.

Specific comments:

Title: as the authors focus on the AIS evolution during the last 408 ka I would rename the title to

“Nonlinear response of the Antarctic ice sheet to **late-**Quaternary sea level and climate forcing”

and use late-Quaternary instead of Quaternary throughout the manuscript (already done in the header of section 3.1).

Check Antarctic Ice Sheet (AIS) throughout the manuscript. Usually it is written in capital initial letters. Furthermore, while you introduce the abbreviation on page 1 L 17 you mostly don’t use it later on.

P2 L10: The importance for what?

P2 L18-19: I think this is mostly true for glacials but less so for interglacials. While e.g. Konrad et al. (2014) show that a sea level drop due to changes in the gravitational pull during ice loss in interglacials can stabilize the grounding line the overall rise in sea level during interglacials doesn’t play a large role in grounding line retreat as it is mostly limited to just a few meters.

P2 L22: maybe rephrase to : “particularly leading to a growth of the East Antarctic Ice Sheet (EAIS)”

P3 L11-14: inconsistent use of Section versus Sect.

P4 L1: maybe rephrase to "Each land grid cell …"

P4 L19: rephrase to "While the cimate model run closely follows …, here the longwave radiative effect of CO2 was amplified …"

P4 L34: is the duration of the experiments the reason for the 40km resolution? Then rephrase: Due to limited computational resources and long timescale of the simulations we had to use a relatively coarse resolution of 40 km.

P5 L1: rephrase to "Present day climate forcing is obtained from the […] interpolated to the ice model grid."

Do you use the ALBMAP v1 bedrock topography or BEDMAP2 for the initial ice sheet configuration?

P5 L12-30: I would expect the description of the parameterization of the basal shelf melt calculation and calving to be in the ice sheet model section and not in the climate forcing section.

P6 L6-8: Here I do not understand whether the climate forcing "jumps" every thousand years to a new set of climate anomalies (i.e. the ISM is forced with the same climate anomalies for 1000 years) or whether the transition is smooth. Please clarify.

P6 L 8-10: maybe rephrase to:

The atmospheric temperature T_a is modified by a lapse rate correction of γ=0.008°Cm^{-1} to account for surface elevation differences between the reference ice sheet geometry (z^{obs}; Le Brocq et al., 2010) and both the simulated elevation at time t (z(t)), as well as for differences with respect to the LOVECLIM orography (z^{LC}).

P7 L1-2: As you force the ISM with ocean temperature anomalies I guess the glacial-interglacial variability is more relevant for the ice sheet's evolution than the present day bias. Please add a sentence which quantifies the ocean warming e.g. in MIS5e and MIS11 and the cooling e.g. during the LGM relative to the PI control climate state (LOVECLIM 1000 year average?).

P7 L 11-12: remove sentence "The bottom half of Fig. 2 …"

P7 L26: it would help the reader if CO_2 is plotted in Fig. 3j as well to make the pacing more evident.

P7 L31: Maybe I overlooked this but how do you create the ice core composite? If I understand it correctly you use Dome Fuji, EDC, Vostok, TALDICE and EDML. Only Dome Fuji, EDC, Vostok cover the whole 408 ka.

P8 L8: Again, you use only one coastal ice core (TALDICE) and 4 interior ice cores. For the latter, the lapse rate correction would be stronger in glacials (e.g. Pollard et al. 2009 and Sutter et al. 2019 TCD Fig. 10). But the biggest discrepancies shown in 3l and 3j occur in Interglacials with too cold ocean and surface temperatures.

P8 L17-18: I could imagine that the underestimation of ocean temperature variability in interglacials is the main reason why the ocean forcing is the weakest driver of interglacial ice volume changes in your simulations. This has important implications for your conclusions as this is a methodological bias and not necessarily reflects the actual response of the AIS e.g. in MIS5e and MIS11.

P8, L23-26: Actually MIS7 shows the lowest surface temperature warming in Antarctic ice cores, how come that for this period the AIS volume is higher than in the other interglacials in your simulations?

P9, L12: rephrase to: Figure 5 shows where the individual forcing components have the largest effect on the Antarctic Ice Sheet.

P9, L14-15: what is the reason for this thickening? Reduced surface melt? Retreat caused by hydrofracturing?

P9, L16: again I expect this to be caused by the forcing setup and that it is not representative during Interglacials.

P9, L20: maybe rephrase to: Combined forcing leads to a more pronounced grounding line advance during glacials than in simulations with single forcing.

P9, L27: rephrase to: Figure 7 depicts the response of grounded ice volume to the respective forcing in the different sensitivity runs.

P9, L27: rephrase to: It is important to note that the impact of the sea level forcing in isolation leads to the conversion of grounded into floating ice (during Terminations???).

P9, L30: Do surface melt rates really increase in glacials?? The maximum elevation change of ice shelves during glacials would be ca. 120 m.

P10, L5: quantify “fairly consistently”.

P10, L6: Wording. (Now, …)

P10, section 3.4.3. This section needs to be expanded, discussing the reasons why the ocean forcing plays a negligible role in the simulations (see main remarks).

P10, L23: rephrase to: Our sensitivity runs show that the **simulated** response of the AIS to **late** Quaternary external drivers […]

Section 3.4.4. and the Discussion requires a more detailed disentanglement of what the authors deem to be realistic responses of the AIS to late Quaternary climate and boundary conditions and what they think is due to methodological biases.

P11, L30: I do not understand this sentence. Increased ice loss due to sea level rise induced warming? This needs to more explicit, warming due to sea level driven ice sheet retreat and therefore surface lowering?

P12, L7-8: What is meant by "manually offset"?

P12, L10: rephrase, e.g. : In particular, as the ice sheet grows ice sheet areas with higher precipitation expand leading to a positive feedback while at the same time, the ice margin advances into warmer ocean waters which leads to a negative feedback.

P12, L15-18: This is the only place in the manuscript which states that LOVECLIM ocean temperature variability is too low and that this could be causal to the muted response during interglacials. Unfortunately, this sentence is right away relativized in the next sentence, citing **one** publication, while a wealth of publications identified ocean warming to be the main driver of ice loss in late Quaternary interglacials (e.g. Golledge et al., 2015,2017,2019, DeConto & Pollard 2016, Sutter et al., 2016).

P12, L28-29: replace sentence "Previous modeling studies have failed to elucidate how these different external drivers interact in driving large glacial ice sheet growth and interglacial sea level highstands." E.g. With "In contrast to previous studies, here we focus on the interaction of different external forcings driving Antarctic Ice Sheet changes". There are previous studies who discuss individual forcing components (e.g. Pollard et al. 2009, deBoer et al. 2013), just not as comprehensive as done here.

P12, L 33-35: I am not fully convinced that this is the case, or at least that this study shows that, as the effect of ocean temperature changes in interglacial ice sheet retreat are not adequately captured in the simulations presented here.

Figures 1,4,5,6,8 : move labels a),b),c) out of the figures panels

References:

(Pollard 2009, de Boer, van de Wal et al. 2013, Depoorter, Bamber et al. 2013, Rignot, Jacobs et al. 2013, Konrad, Thoma et al. 2014, Golledge, Kowalewski et al. 2015, DeConto and Pollard 2016, Sutter, Gierz et al. 2016, Golledge, Levy et al. 2017, Tigchelaar, Timmermann et al. 2018, Golledge, Keller et al. 2019)

de Boer, B., R. S. W. van de Wal, L. J. Lourens, R. Bintanja and T. J. Reerink (2013). "A continuous simulation of global ice volume over the past 1 million years with 3-D ice-sheet models." Climate Dynamics **41**(5-6): 1365-1384.

DeConto, R. M. and D. Pollard (2016). "Contribution of Antarctica to past and future sea-level rise." Nature **531**(7596): 591-597.

Depoorter, M. A., J. L. Bamber, J. A. Griggs, J. T. M. Lenaerts, S. R. M. Ligtenberg, M. R. van den Broeke and G. Moholdt (2013). "Calving fluxes and basal melt rates of Antarctic ice shelves." Nature **502**(7469): 89-93.

Golledge, N. R., E. D. Keller, N. Gomez, K. A. Naughten, J. Bernales, L. D. Trusel and T. L. Edwards (2019). "Global environmental consequences of twenty-first-century ice-sheet melt." Nature **566**(7742): 65-+.

Golledge, N. R., D. E. Kowalewski, T. R. Naish, R. H. Levy, C. J. Fogwill and E. G. W. Gasson (2015). "The multi-millennial Antarctic commitment to future sea-level rise." Nature **526**(7573): 421-+.
Golledge, N. R., R. H. Levy, R. M. McKay and T. R. Naish (2017). "East Antarctic ice sheet most vulnerable to Weddell Sea warming." Geophysical Research Letters **44**(5): 2343-2351.
Konrad, H., M. Thoma, I. Sasgen, V. Klemann, K. Grosfeld, D. Barbi and Z. Martinec (2014). "The Deformational Response of a Viscoelastic Solid Earth Model Coupled to a Thermomechanical Ice Sheet Model." Surveys in Geophysics **35**(6): 1441-1458.
Pollard, D. D., R. M. (2009). "Modelling West Antarctic ice sheet growth and collapse through the past five million years." Nature **458**: 329-333.
Rignot, E., S. Jacobs, J. Mouginot and B. Scheuchl (2013). "Ice-Shelf Melting Around Antarctica." Science **341**(6143): 266-270.
Sutter, J., P. Gierz, K. Grosfeld, M. Thoma and G. Lohmann (2016). "Ocean temperature thresholds for Last Interglacial West Antarctic Ice Sheet collapse." Geophysical Research Letters **43**(6): 2675-2682.
Tigchelaar, M., A. Timmermann, D. Pollard, T. Friedrich and M. Heinemann (2018). "Local insolation changes enhance Antarctic interglacials: Insights from an 800,000-year ice sheet simulation with transient climate forcing." Earth and Planetary Science Letters **495**: 69-78.