Response to Anonymous Referee #2

In this paper, the authors aim to investigate the evolution of Greenland, Antarctica ice sheets and minor components of sea-level rise over a long period (10ky) using an integrative strategy. A model of intermediate complexity, LOVECLIMv1.3, is coupled with ice sheets models (Greenland and Antarctica) that enable them to test different pCO2 and methane scenarios for the period of 1000 to 10000 years.They investigate indeed the response of the Earth climate system to a large but short lasting perturbation. It is necessary to run long simulations that account for long time response of deep-ocean, ice sheets and CO2 evolution.The authors first describe the tool they used, the originality of which is to account for feedback between atmosphere/ocean and ice sheet, then they describe the scenarios they chose and they finally present their results in terms of different contributions.The paper is well written and the issues are interesting, nevertheless there is room for improvements on several points.

Author's response: Thank you very much for the positive evaluation and useful comments.

1. Discussion of the limitation of the study and its possible consequences: The scenarios are prescribed from an initial perturbation based on the four RCPs of IPCC scenarios and 2 supplementary scenarios. This paper represents an improvement compared to previous studies because feedbacks between climate and cryosphere are accounted for. The discussion on the CO2 evolution,which is driven by different anthropic pathways,is only discussed from a "mathematical" point of view. The authors should discuss the limitation of such an approach. Indeed there are also interactions between carbon cycle and ocean and interactions between vegetation and carbon cycle, which are not limited to permafrost and clathrate destabilizations, and which are not accounted for. For instance, a dynamical vegetation model could be useful to account for the effect of desertification (albedo and water cycle).

Author's response: The reviewer is right that we do not discuss all possible feedbacks when using the impulse response functions. There are certain aspects such as the influence of a vegetation model on albedo and water cycle that we neglected and we emphasised this in the scenario description. On the other hand, by using the impulse response functions based on a literature study, we take into account the existing model uncertainty about the magnitude of the ocean uptake of CO2 and the uptake of CO2 by vegetation, since the impulse response functions are based on carbon cycle models.

Another issue that is not discussed is the long-term climate evolution. Indeed all scenarios depict a complete melting of the GRIS. The simulated climates are similar to Pliocene climate and thus the impact of orbital forcing/orbital parameters may be drastically modified in comparison with Quaternary large glacial/interglacial oscillations.

Author's response: We discussed the long-term climate evolution in terms of global, Greenland and Antarctic mean temperature anomalies. The discussion of long-term climate evolution is now extended by showing plots of the spatial temperature anomaly above Greenland and Antarctica. Also, the influence on climate of the insolation changes is discussed in more detail and an additional figure showing the insolation changes at 70 ˚N and 70 ˚S for the period -130 kyr (onset of the Last Interglacial) to +50 kyr (next large boreal summer insolation minimum) is added, to put the insolation changes during the next 10,000 years into perspective (they are small on account of a low eccentricity).

2. Computation of grounding line evolution with coarse-grid modeling:The response of the grounding line is very important and should be discussed in more details because it is difficult to compute it using climate change simulation by a coarse-grid model. For instance, to test the capability of their model in order to compute correctly changes in grounding line, the authors could use the last deglaciation and they should validate their model over such a period.

Author's response: It is a valid remark from the reviewer to state that we use a rather coarse resolution Antarctic ice sheet model in our simulations. However, a similar model version with a resolution of 20 km has proven to be able to simulate the changes in the grounding line position for the Last Interglacial (Goelzer et al., 2016a) and the Last Glacial Maximum (Huybrechts, 2002). Also, we do a proper climatic spin-up over the period 1500-2000 AD, while the Antarctic ice sheet is spun up over the last four glacial cycles to carry the long-term ice sheet history. We believe that a full validation to simulate the last deglaciation is a study on itself and is far beyond the scope of this study. Moreover, the last deglaciation is not the best analogue for future ice sheet melting since it is a colder period with massive ice sheet melting from the Laurentide, Cordilleran and Fennoscandian ice sheets (ice sheets that are not included in our model set-up). A better analogy can be made with the Last Interglacial where the Greenland and Antarctic ice sheets were also reduced in size and where our model has proven to be valuable (Goelzer et al., 2016a, Goelzer et al., 2016b).

3. Parametrization and scenarios: Line 114-115: in addition to the fact that the authors wrote P11 in the text and P71 in the Table S3, this part of the paper is very unclear to me. The authors chose one set of parameters, and with this set, they provide 6 different simulations. All these scenarios do not need to be run again. But for the 2 extreme ones (RCP2.6 and feedback), we would like to have the result when using different parametrizations as far as LOVECLIMv1.3 needs parameterization to compensate the approximation made. Indeed we would like to know how much the results are dependent on the parametrization.

Author's response: We thank the reviewer to notice the mistake about the parameter naming. It should be P11 in Table S3 and it is now corrected. The different parameterizations mostly differ in the treatment of the long-wave radiation scheme (parameters amplw, explw, ampanir, ampanir2; see Supplementary Information). We did sensitivity tests with 2 other parameter sets: P32a (which is very similar to P32b) and P11 for the two extreme scenarios, as suggested by the reviewer. We now include a new paragraph in the result section that deals with the model uncertainty of the future sea-level change projections for scenario MMCP2.6 and MMCP-feedback.

Moreover, the scenario using methane from clathrate emission is important not only in terms of quantity of greenhouse gases emitted but these emissions could last several kyears, which is the duration of Paleocene-Eocene thermal maximum. The authors should explain the reason of their choice.

Author's response: The reason of our choice is now explained in more detail in the scenario description and the rate of methane release from clathrate emission during the next millennia is now compared to the order of magnitude of methane emissions during the PETM.

"*MMCP-feedback assumes a moderate methane release from methane hydrates of 600 GtC by adding constantly CO_2 after 2250 AD (from the peak concentration onwards) until the end of the simulations (equivalent to a release of 6.15 GtC per 100 year), in accordance with the experiments of Archer et al (2009a). It is thought that methane hydrate dissolution caused a strong increase in atmospheric CO_2 levels with a possible total release of > 5000 GtC during the Paleocene-Eocene Thermal Maximum (PETM; Dickens, 2011). This release would have been caused by an initial warming trigger and might have lasted for more than 100 kyr (Zeebe and Lourens, 2019). Therefore, our estimate of the strength of the methane emission feedback is in the same order of magnitude as the methane emission rate during the PETM (5 GtC per 100 year). Also, it is thought that it takes a long time (> 10,000 years) before a significant part of the sediment has warmed in reponse to the ocean bottom temperature increase (Zeebe, 2013b), supporting our conservative methane release in comparison to the size of the methane reservoir.*"

If the authors account for these main comments and more analytical comments below, I consider that this paper is a valuable contribution to an important issue and should be published in Earth System Dynamics.

More detailed comments:

-Title: the authors use the term "semi-equilibrated",which is never clearly defined. I would prefer "quasi-equilibrium" but anyway the author should give an objective criteria for this term.

Author's response: We chose to use the term 'semi-equilibrium' because sea-level has almost adapted to the forcing after 10,000 years. Semi means 'half' or 'partly', which is a good description in our opinion of the sea-level changes after 10,000 years. The term 'quasi-equilibrium' is stronger because it means that the changes are infinitesimal small. This is a state that we didn't achieve at the end of the simulations.

-Abstract:

what is a semi-equilibrium?

Author's response: With a semi-equilibrium we mean that sea-level rise has almost equilibrated. In our experiments, we consider that a semi-equilibrium is reached when sea-level changes drop below 5 cm per century.

“After 10,000 years, the sea-level change rate drops below 0.05 m per century and a semi-equilibrated state is reached”

Over 10ka it may be important to account for astronomical forcing, especially for precession cycle (the period of interest here 1-10 ky is half the duration of precessioncycle).

Author’s response: The astronomical forcing is included. We added this information to the abstract.

I don’t really understand the last sentence of the abstract: there is no geologic analogue for the next 10ky in Earth history -as far as I know.

Author’s response: We removed this last sentence from the abstract, since it is hard to explain the comparison with the geological archive in one sentence.

How is it possible to reach more than 5800 GtC?

Author’s response: RCP8.5 (and its extension to 2300 AD) is equivalent to a cumulative emission of ~5300 GtC (270 GtC before 2000 AD and 5018 GtC between 2000 and 2300 AD; see Meinshausen et al., 2011). The inclusion of the methane feedback release would add another 600 GtC during the next 10,000 years.

1. Introduction

The introduction is fine but 2 topics should be introduced or developed:

1. The last deglaciation,which lasts around 10000 y,is an interesting period to validate the model used here. The authors should discuss this point,which is completely absent in the introduction.

Author’s response: As stated before, we believe that a validation over the last deglaciation is a completely different scope, and moreover is not a particularly good analogue as it involved big ice sheets on the continents of the northern hemisphere which are no longer present. Therefore, we do not see the need to introduce this topic in the introduction and we would like to keep the focus on future sea-level rise and interactions with the Earth system.

2. The methane hypothesis should be clearly explained. There is a first short term feedback linked to the permafrost melting and a long term effect on clathrate destabilization. Concerning this second point, there are several unknowns: the quantity of methane, which is discussed by the authors but also the onset and the duration of these emissions,which they should discuss more.

Author’s response: We thank the reviewer for this good suggestion and added a discussion about the methane hypothesis in the introduction. We further extended the explanations in the scenario description section.

“Several feedbacks in the climate system reinforce an initial perturbation. The increase in polar temperatures releases methane from permafrost regions. This process is slow

and accelerates climate change on a centennial timescale (Schuur et al., 2015). It is believed that a warming ocean could potentially also release a massive amount of methane from methane clathrates, somehow similar to what has happened at the Paleocene-Eocene Thermal Maximum (PETM; Zachos and Zeebe, 2013). The PETM took place at about 56 Myr and was characterized by a rapid global temperature rise of more than 5 °C in addition to a strong background warming, probably caused by the massive release of methane from clathrate hydrates (Dickens, 2011). It is thought to be the best analogue for future climate warming in a strong greenhouse world (Zeebe and Zachos, 2013)."

2. Model description and initialization

The authors should clarify how they downscale the large grid of atmospheric and ocean models to high resolution ice sheet models (GRIS or AIS).

Author's response: We explain the use of anomaly forcing to force ice sheet models and the use of a PDD model to obtain melt rates on the high resolution grids of the ice sheet models. No other downscaling techniques are included.

Line 105: what are the range of corrected biases for present day climate?

Author's response: The mean error for the present day climate is 0.38 ˚C over Antarctica (range from -1.2 ˚C to + 0.9 ˚C) and 0.44˚C over Greenland (range of -1 ˚C to 1.5˚C). We added this information to the model description.

Line 106: is the PDD really appropriate for this study? Why did the authors use a method based on present day (cold context) rather than a method based on energy balance?

Author's response: The PDD model is a computationally efficient method to calculate the mass balance and allows to take into account the melt on the much finer ice sheet grid. Above all, the method takes into account the important feedback of height changes on mass balance. An energy balance model introduces more, in part poorly known, parameters and is therefore not necessarily superior.

Concerning the choice of parameters (Table S3) the authors should justify this choice and its possible consequences.

Author's response: We have justified our choice of the preferred parameter set P22 based on the sea-level change projections by 2300 AD and by the predicted polar temperatures by the end of the century. In parameter set P11, P32a and P32b, we had less confidence because of their worse performance during the coming decades to centuries in comparison with high resolution, coupled ice sheet-climate modelling studies.

Line 117: the tuning of parameterson the last 500y is not really appropriate to explore large changes of cryosphere. The last deglaciation is certainly a better but more complex target for the goal of this paper. Moreover, the authors selected a parameterization “because of its mid-range contribution to sea-level at 2100 AD and 2300 AD in comparison with recent studies”. Is it a correct criteria in science to be “mid-range”? I think the authors should favor more physically based parametrizations. We also would like them to use other parameterizations for the scenarios including feedbacks.

Author’s response: The different parameter sets were used to explore the climate and sea-level evolution over the next millennia. P22 is a parameter set that has been used in previous studies (Goosse et al., 2007; Loutre et al., 2011, Loutre et al., 2014, Goelzer et al., 2016a, Goelzer et al., 2016b) focusing on the last millennium or the Last Interglacial. The other parameter sets had a lower (P11) or higher (P32a and P32b) climate sensitivity and differed mostly in the longwave radiation scheme. As explained before, we had little trust in these parameter combinations on the longer term and therefore chose P22 as the preferred parameter set. Nevertheless, we added now sensitivity experiments for climatic model parameter set P11 and P32a using scenario MMCP2.6 and MMCP-feedback, as suggested by the reviewer, to explore the climate model uncertainty.

3. Scenario description

Line 150-153: scenario RCP8.5 leads to a maximum PCO2 of around 5000 ppm about 20 PAL. But is there enough fossil fuel to be burnt to achieve such a value?

Author’s response: The maximum pCO2 is around 2000 ppm and the total emissions are around 5000 GtC. The uncertainty in fossil fuel reserves is so large that we decided not to base our experiments on speculative estimates but chose to extend the IPCC RCP scenarios.

4. Climate response and global sea-level budget of individual terms

The last deglaciation is strongly nonlinear, with acceleration, as during meltwater pulse and reduced SLR during colder episodes.The ability of the model used here to reproduce the deglaciation should be discussed.

Author’s response: As discussed before, we believe that the last deglaciation is not the best analogue for future ice sheet melting. Meltwater pulses were related to fast reductions in the Laurentide or Eurasian ice sheets which are no longer there, or perhaps from fast ungrounding of the Antarctic ice sheet from its glacial maximum extent, different from the current geometry of the Antarctic ice sheet.

A plot showing both terms accumulation and ablation in the different scenarios could be interesting to be depict and discuss.

Author’s response: We show plots of accumulation and runoff (ablation and liquid precipitation), which is nearly the same.

For GRIS what is the ocean dynamics in North Atlantic? It seems that the AMOC recovers and is even stronger than for PD: does that mean that the GRIS could not be covered by perennial ice sheet for long periods?

Author's response: We extended the discussion about the AMOC and added references about its behaviour and the past (mid-Pliocene) and future. Our results are in line with the simulations of Jansen et al. (2018), who suggested that the AMOC strength increases in response to surface warming.

5. Long-term sea level rise in the light of the geological record

Line 312 and Fig 6
This is an interesting comparison. Nevertheless,there should be an hysteresis between the values of melting GRIS and AIS in the simulations described here and the pCO2 values corresponding to the onset of the same ice sheets during Cenozoic due to the changes of surface albedos.

Author's response: We thank the reviewer for this good remark. We improved the discussion by adding information on hysteresis and the difference between the onset of ice sheet growth versus ice sheet decay.

"The geological estimates of sea-level high stands includes data that are affected by the hysteresis effect between ice sheet growth and ice sheet decay, where an ice sheet can either exist or not exist at a certain CO_2 level depending on its history (Pollard and DeConto, 2005). Also the effect of a different paleotopography might have had an influence on the inception of ice on paleotimescales where the AIS could grow for lower CO_2 values during the Oligocene than at present (Paxman et al., 2019). Both arguments suggest that our curve (red line) is expected to be below the best estimate of the geological data (blue line), requiring higher CO_2 levels to melt the ice sheets on Earth in the future than during periods in geological history."

6. Discussion

Line 360:There are two sources of uncertainties that the authors should comment with more details:

1. The AMOC evolution because in PLIOMIP2, most of the models depicted a lower AMOC,which provided a context not favorable to the onset of GRIS

Author's response: We added information to the discussion about the AMOC response during the mid-Pliocene from PLIOMIP2 studies and about the simulated future evolution.

2. The authors should compare their highest scenarios to the resources available in terms of fossil fuel.The authors pointed out the possible mechanisms that speed up the AIS melting as Marine Ice Cliff Instability MICI. Moreover,the record of the previous deglaciation show much variability in SLR rise with acceleration and regression of the ice sheets. These simulations did not reproduce this variability in future scenarios maybe partly due to coarse resolutions.There are anyway hot debates on the prevision of SLR only concerning the end of this century and very few models are able to reproduce

using transient experiments the SLR during the last glacial/interglacial cycle.For all these reasons, the authors should be careful of uncertainties and limitations of their strategy even if it is a consistent approach for investigating long time scale.

Author's response: We have added the model uncertainty for the extreme forcing scenario. For scenario MMCP-feedback, melting of all land ice on Earth cannot be excluded, given the model uncertainty. In this scenario, there is a strong acceleration in sea-level rise after 7000 model years due to the strong albedo-temperature feedback that initiates once the ice sheet retreats on land, somehow similar to the strong increase in melt at the last deglaciation when the Laurentide ice sheet disappeared. We included an extra paragraph on these results.

Moreover, the evolution of the grounding line when using coarse grid model is difficult to capture and therefore, it is another limitation of the paper that the authors should comment.

Author's response: We believe that we gave a sufficient discussion of the model limitations and performance on L362-371 in the Discussion.

7. Conclusion

Their main results are summarized: A GRIS melting for all scenarios, this melting being irreversible in the time window of interest here whereas the AIS contributes to the SLR differently, depending on scenarios.These results are consistent with a GrIS becoming perennial only when CO2 is around 300-400 ppm whereas AIS needs a higher CO2 level to become perennial around 800 ppm.The authors should also discuss the consistency of their results when compared to the evolution of these ice sheets.

Author's response: It is not clear to us what the reviewer intends to say, nor how we should respond to it.

Comments on Figures

General comment for all the Fig. : In fact, while GMSL rises to high values (env. 30 m) many regions that are considered in the simulation as land points shift to ocean points. By the way, the ocean/continent distribution is changing with SLR. This is certainly a minor effect for the coarse grid model for several meters. But it may beimportant when SLR reaches 10 to 30 meters. This effect is not accounted for in the figure and I believe also that this distribution is kept fixed in all simulations. Thus, the authors should discuss this approximation.

Author's response: It is indeed true that we neglect the effect of GMSL changes on the plots of the GrIS and the AIS and we clearly mentioned this approximation in the given figures.

Fig 2: it could be interesting to show also the GRIS configuration for present day.Fig 3: interesting to have AIS for present day. Moreover,it could be interesting to add a snapshot at 3ky with WAIS and EAIS separately.

Author's response: We have added a figure with the configuration of the Greenland and Antarctic ice sheet simulated at the start of the simulations. We did not distinguish between the East Antarctic ice sheet and the West Antarctic ice sheet because this would require to define the ocean basins beforehand, which we did not do in this study.

Figure 7: the logic of the caption (a) (b) succession is not easy to follow at first sight.

Author's response: We adapted the figure caption to increase the logic.