Response to Reviewer #2's comment on "The sensitivity of the Greenland ice sheet to glacial-interglacial oceanic forcing" by Tabone et al.

The study titled "The sensitivity of the Greenland ice sheet to glacial-interglacial oceanic forcing" aims the evaluate the impact of oceanic forcing over the last two glacial cycles. Tabone et al. apply a linear oceanic forcing parameterization to assess the relative impact of oceanic forcing relative to atmospheric forcing when simulating the Greenland ice sheet. An index scheme is applied to temporally evolve the atmospheric and oceanic forcing. The index is derived from a multi-proxy temperature reconstruction which spans the last two glacial cycles. Assuming a single climate forcing scenario, a sensitivity analysis is conducted on an idealized ocean forcing parameterization. The study targets pertinent scientific questions with respect to Greenland ice sheet evolution which are within the scope of CP. The study is the first to evaluate the impact of millennial-scale oceanic forcing across Greenland. However, given a number of issues listed below with the experimental design, the results and claims of the study are not substantiated and require additional developments and experiments. The title reflects the content of the paper and the abstract summarizes the analysis conducted. The paper is nicely structured; however, some parts are poorly written with superfluous statements and the results section reads like a string of figure captions. There is an insufficiently description of the model set-up and little discussion is placed on pertinent model weaknesses which directly impact their results (see Main Remarks). For these reasons, I suggest that the study is resubmitted upon addressing the outstanding issues discussed below. A pdf has been attached with minor technical comments of the manuscript.

Most corrections suggested by the reviewer have been taken into account in the new version of the paper. The description of the model setup has been improved and the experimental design has been modified by forcing the model with a relative sea-level change reconstruction taken from Grant et al., 2014 (as mentioned in the response to Reviewer #1).

However, given the aim of this study, we believe that some of the reviewer's concerns are somewhat overstated. Here, we want to address the impact of the ocean on the Greenland Ice Sheet (GrIS) evolution through a sensitivity test, thus we are not looking for perfect realism, but rather to understand some of the most critical processes which could have influenced its past behavior. It is true that some simplifications made in the experiments and some model limitations will influence the results to a small degree, as already reported in the Discussion section. However, the general behavior of the system and our conclusions are definitely not affected by these limitations. On the contrary, the simplicity of our experiments serve to make the conclusions more straightforward. Also, it is important to note that we are not interested in millennial-scale phenomena as the reviewer wrote, but here we focus only on orbital time-scale variability. Perhaps, this led to a misunderstanding in following the general purpose of the study.

More precise answers are followed point by point in Main Remarks below, while the suggested corrections annotated in the manuscript by the reviewer have been considered in the new version of the paper.

Main Remarks:

1. Sea-level change

The simulations do not prescribe a eustatic sea-level history (e.g. benthic stack from Lisiecki and Raymo, 2005) which results in sea-level variations on the order of ∼120 meters over a glacial cycle. This could explain the model's inability to expand beyond the present-day coast line. A lowered sea level exposes parts of the continental shelf which can allow for the ice sheet to expand outward and show much greater sensitivity to atmospheric forcing than presented in this work. Furthermore, the glacial isostatic adjustment component applied is based on an elastic lithosphere relaxed asthenosphere model which uses a single decay time and only considers local ice load changes. It has been shown that the North American ice sheets such as the Laurentide and Innuitian ice sheet impose a non-negligible glacial isostatic response across Greenland through the formation and collapse of a peripheral forebulge. These processes which are left out in this work were first incorporated in Greenland ice sheet studies in Simpson et al. (2009) and this further contributes to sea-level variability.

As stated in the response to Reviewer #1, we initially chose to maintain sea level constant to keep the experimental design as simple as possible. However, we agree that considering a variable sea level in our experiments would have been more realistic. The effect of a changing sea level on the advance and retreat of the grounding line shouldn't be neglected considering the purposes of our work. Thus we have repeated all our simulations by forcing the model with the paleo sea-level reconstruction by Grant et al. (2014). The results show that forcing the model with a changing sea level signal actually makes the GrIS even more sensitive to the ocean, as easily expected, and thus further corroborate our conclusions. The old results have now been substituted by these new ones and the whole text of the paper reflects these changes.

It is also true that the evolution of the Innuitian and Laurentide Ice Sheet affects the GrIS local response to the growth/reduction of the ice load at glacial-interglacial time scales, contributing to the sea-level variability. However, for simplicity, only the GrIS local isostatic response has been considered here, which has a far greater impact, while these non-local processes have been omitted. This caveat has been discussed in Section 4:

"As described in Section 2.1, our ice-sheet-shelf model is provided with an internal GIA scheme which accounts for bedrock deformation due to changes in the GrIS ice load. However, since the GrIS rests on the peripheral forebulge of the North American Ice Sheets (NAIS), such as the Laurentide Ice Sheet, variations in the NAIS ice load induce consequent vertical motions of the lithosphere beneath the GrIS (Lecavalier et al., 2014). The resulting GrIS isostatic adjustment is, therefore, the combination of these local and non-local responses which make the GIA treatment rather complex. In principle, these non-local effects should be taken into account as they contribute to the sea-level variability, becoming especially relevant at the beginning of deglaciations when the ice mass loss is significantly induced by sea-level rise (Lecavalier et al., 2017). However, for the sake of simplicity, the GrIS isostatic adjustment is assumed here to be only due to local ice mass variations, as other works have done in the past (Greve et al. 2009; Helsen et al., 2013; Huybrechts, 2002; Langebroek et al., 2016; Stone et al., 2013)."

2. LGM geometry

A number of previous modelling studies have shown the ability of the Greenland ice sheet to expand onto the continental shelf (Huybrechts et al., 2002; Simpson et al., 2009; Lecavalier et al., 2014). These previous studies lacked an explicit ocean forcing scheme based on past ocean temperatures and demonstrate a much greater sensitivity to atmospheric climate forcing. This highlights a key weakness in the current work since their simulations do not exhibit nowhere near this range of sensitivity (Bref=0,k=0), which directly impacts the main results of this work.

This is visually illustrated in Figure 11 of Tabone et al. which shows the deglacial evolution from their work compared to previous studies. Even in the case with no present-day oceanic forcing Bref=0, with the sensitivity parameter k=0, the ice sheet remain near its present-day geometry even during the glacial periods. This demonstrates that their model is unable to grow the ice sheet without the oceanic forcing scheme used as an unphysical method of ice accretion at the margin to advance the grounding line (upward to 20 m/a of accretion).

Here we must disagree with the reviewer concerning what he states is a "key weakness" of our work. This can be justified in several ways:

First, there is no strong reason to assume that a much larger expansion should be possible in the total absence of oceanic forcing. It is important to bear in mind that all the studies cited by the reviewer (Huybrechts 2002, Simpson et al. 2009, Lecavalier et al. 2014) are based on the same ice-sheet model, albeit with different versions. Although these studies did not include an explicit oceanic forcing, they did include a variable sea level and the removal of ice beyond the coastline, which implicitly involves an oceanic forcing. In the case of our model, the new simulations forced with a variable sea level show a greater expansion of the grounding line during the LGM (these new results are shown in the new version of the manuscript). For B_{melt}=0 (B_{ref}=0, κ=0) the maximum ice volume reached is about 2 m SLE above present day, which is closer to the result achieved by Huybrechts (2002) for the LGM. Under this condition, the GrIS extension is now far from the PD above-sea-level borders and the grounding line is found close to the continental shelf break. Thus, according to this, the interpretation of our results is compatible with what we learned from the previous ones.

Second, Fig. 11 only shows the decrease in ice volume during the last deglaciation, not the evolution of the ice-sheet extent. It is true that the simulation for B_{melt}=0 (B_{ref}=0 and κ=0), at the upper limit of the gray shadow, shows that the maximum volume reached at the LGM is lower than that from previous works. However, the GrIS extension at the LGM for the same simulation was not shown in the manuscript until now (Fig. 12b of the new version of the manuscript). Note that the grounding-line location shown in Fig. 12 (of the first version of the manuscript) refers to the case for B_{melt}=1 m/yr (B_{ref}=1 and κ=0). Thus, the statement that the ice sheet remained near its present-day geometry even during the glacial periods is not supported by our results. It is also true that without melting/freezing at the grounding line the GrIS cannot expand as expected, as we wrote in the manuscript. However, even without reaching the continental shelf borders at the LGM, the simulation with constant sea level forcing under no melting/freezing conditions shows that the GrIS is able to extend past the present-day (PD) coastline (not shown in the old version of the manuscript).

Finally, an important factor that can partly determine the capability of the grounding line to expand more or less during the glacial period is model dynamics, including its associated parameterisations and parameter values. An example is the sliding law chosen and the value assigned to the sliding coefficient (Bradley et al., 2017): sensitivity experiments that we have performed with our model show that larger drag under fast-moving areas can help driving the grounding line to advance beyond the continental borders (not shown). However, here we are not interested in analyzing the sensitivity of the GrIS with respect to such parameterisations or parameters, but only to those related to the submarine melting rate. Such assessment should be in the scope of future work.

3. Oceanic forcing scheme

The basal melt scheme is a linear scheme which is attempting to capture a non-linear process, that of grounding line melt and migration, buoyancy transport and mixing, sub-ice-shelf melt and accretion. This idealized parameterization consists of two parameters, one tuned to achieve present day geometries (spatially constant) and the other is a sensitivity parameter which scales the LGM-present ocean temperature anomaly (spatially constant). This temperature anomaly is scaled by a climatic index, specifically a multi-proxy atmospheric temperature reconstruction. Firstly, the index scheme that scales the ocean temperature anomaly should not be derived from atmospheric temperatures, a proxy of past ocean temperatures is more appropriate (e.g. benthic record).

We agree with the reviewer that an oceanic-index derived from past ocean temperatures could be more appropriate. To analyze how this could affect the results, we compared our multi-proxy atmospheric index with an oceanic index calculated from benthic-retrieved ocean temperatures (Waelbroeck et al. 2002) (Fig. R1, at the end of this document). Although they clearly agree in the last deglaciation, the signals show appreciable differences in glacial times and at the Eemian peak. For this reason we initially followed the reviewer's suggestion and re-did all simulations with this benthic-retrieved oceanic temperature signal. However, the results of the new simulations show very little differences from the original ones. Therefore, since our goal is to address the ice-ocean influence problem through maintaining the experimental design as simple as possible, we decided to keep the same index for both atmosphere and ocean as in the first version of the work. Nevertheless, we have included a statement in the manuscript to indicate that we tackled this issue and that results did not change significantly:

"We have also tested whether forcing the ocean with a specific index retrieved from past ocean temperatures could change our results. To this end, we ran additional simulations by applying the multi-proxy index, for the atmosphere, and another index for the ocean calculated from benthic-retrieved ocean temperatures (Waelbroeck et al. 2002). However, the results of the new simulations show very little differences from the ones reported here (not shown). Thus, although the usage of an oceanic-index could be more appropriate, such a distinction in forcing does not affect the main results of this work."

As previously mentioned, the sensitivity parameter k, is used as an accretion scaling parameter at the grounding line in the current framework. The sensitivity experiment tests the model's ability to respond to basal accumulation during glacial periods since the ice sheet cannot expand to the continental shelf without significant grounding line accretion (several meters of ice-equivalent sea-level). A plot illustrating the volume difference for a given Bref model run and sensitivity parameter (e.g. vol(Bref=0,k=20)-vol(Bref=0,k=0)) would clearly show the volumetric impact of the oceanic melt and accretion implementation. This would emphasize the unreasonable accretion of several meters of ice-equivalent sea-level during the glaciation for grounding line advance.

Here we must disagree with the reviewer, since our parameterisation does not need a massive grounding line accretion to expand the GrIS to the continental shelf. The model was actually able to simulate a GrIS glacial expansion to the continental shelf break already for κ=5 m a^{-1} K (which now is true for κ=1 m a^{-1} K in the new simulations with variable sea level forcing). For that oceanic sensitivity, the ice volume at the LGM is comparable to that of Simpson et al. (2009), although the model reproduces volumes close to that of Huybrechts 2002 already for κ=1-2 m a^{-1} K (Fig. 11). As shown in the manuscript, for κ > 5 m a^{-1} K the glacial expansion saturates at the continental shelf (Fig 8b), and from that threshold the volume changes are mostly due to surface accumulation (Fig. 5a and Fig. 8a). Therefore, in one hand, referring to κ=20 m a^{-1} K to support this objection is misleading, since it represents an extreme case between the analyzed range of κ. And, on the other hand (as explained by the saturation effect for κ > 5 m a^{-1} K) our oceanic scheme does not imply any "unreasonable accretion of several meters of ice-equivalent sea-level", but is rather negligible compared to surface accumulation and not a necessary condition for the grounding line advance.

Secondly, the LGM-present ocean temperature anomaly is chosen to be a spatially constant value of -3K. This assumes no spatial gradients in ocean temperature change over time which is quite simplistic when there are snapshot and transient LGM ocean temperature anomaly model results available (e.g. TraCE experiments from Liu et al., 2009).
Finally, the present-day melt rate Bref used to achieve present day grounding line extent is constant across the ice sheet, although at present the melt rates at the grounding line varies across the ice sheet since this depends on the temperature of the water column that is advected to the ice-ocean interface, among other processes. Ultimately, using a spatially constant reference melt rate and LGM anomaly is overly idealized since it does not factor for any of the spatially variability at present and through time. It would be more appropriate to implement spatially variable present and past ocean temperatures within a physically based temperature-dependent basal melt scheme.

We address the two issues above together, since they are related. Considering a spatial oceanic temperature for the LGM and a constant present-day melt rate B_{ref} around Greenland is a choice we made to directly observe the dependence of the basal melt rate equation on κ, as all other parameters of the basal melting parameterisation are kept constant. It is true that choosing this option we are overlooking some processes at the ice-ocean interface and at the water column which might be more relevant in a more realistic temperature-dependent parameterisation of the basal melt. Both spatially inhomogeneous LGM temperature anomalies and the present-day basal melt rate around Greenland, which, as the Reviewer says, can be retrieved from available model outputs, should be in the scope of future work. However, we already performed some experiments by using spatially variable temperatures at the LGM taken from Climber-3alpha model outputs for the Greenland area (Montoya and Levermann, 2008). Despite some local differences in the distribution of ice, the main results did not change, since for the oceanic sensitivities tested, the GrIS was still found to be able to reach the continental shelf break. Since the results are qualitatively the same as those reported in the manuscript, we decided not to put these results in our work. We justify the choices made by adding the following in the Discussion (section 4):

"Our melting parameterisation is highly conditioned by the B_{ref} value assumed to represent the present-day submarine melting rate around the GrIS (Fig. 8). Using a single value for this term is a coarse approximation of the reality, but, since maps of the present-day sub-shelf melt along the coasts do not exist yet for Greenland, the retrieval of a 2D field would be complex and highly uncertain. Nevertheless, the choice of B_{ref} affects the sensitivity test as it consequently determines the lower κ needed to make the GrIS respond to the ocean."

4. Model limitations
The model uses a horizontal resolution of 20 km by 20 km which inadequately resolves high frequency topographical features such as fjords. In this current state, this study evaluates the sensitivity of the glacial Greenland ice sheet to oceanic forcing since there lacks a subgrid fjord representation which corrects for the unresolved ice-ocean interface once the ice sheet predominantly reaches the present-day coastline during an interglacial climate. Therefore, it is not appropriate to discuss or emphasise Holocene and Last Interglaciation model results since the results depend primarily on the single atmospheric forcing applied in this study, as illustrated by the model result convergence during interglacial periods in Figure 5.

It is important to remark that our work is a sensitivity study whose main goal is to assess the impact of the oceanic changes in the past evolution of the GrIS at a continental scale. For instance, the inability of our model to capture the dynamics of the fjords might be more relevant if we were interested in local changes of ice at small spatial scales. In our case, the mentioned limitations of our model only lead to second-order effects, which do not compromise the conclusions of our work. The Eemian and Holocene are key periods in the evolution of the GrIS of the last two glacial cycles, and worth discussion. However we agree that we did not fully treat this caveat. Thus, we have modified the Discussion as:

"The coarse model resolution prevents the model from resolving fine-scale physical processes at the marine-terminating outlet glaciers that end in narrow fjords, although they are considered as the primary sources of ice discharge today due to oceanic changes. Such an inability of our model may be more relevant when modelling the GrIS retreat during LIG and Holocene. The lack of a subgrid fjord treatment does not allow proper treatment of the ice front processes which become relevant when the retreat has reached the continental area above the sea level. Especially when, as in our case, the submarine melt goes abruptly to a high value at the grounding line, the implementation of a sub-grid scale parameterisation would allow the small processes at the fjords to be accurately resolved (Calov et al., 2015; Favier et al., 2016; Gladstone et al., 2017). However these limitations lead to only second-order effects given the scope of our work."

This study is interested in ice sheet mass balance, somehow the study does not include a description of the calving scheme. This is a key process in ice sheet mass balance and it warrants a mention.

We agree. The calving scheme has been added in the Model description section (Section 2.1):

"The calving scheme used is based on a two-condition thickness criterion (Peyaud et al., 2007; Colleoni et al., 2014). First, an ice-shelf front must have a thickness lower than 200 m to potentially contribute to ice discharge. This threshold is in agreement with the thickness of many observed shelves at their ice-ocean interface. Then, only if the ice coming from each upstream point is not sufficient to maintain the ice-front thickness higher than that threshold, the grid point at the front calves."

The paper aims to explore the relative impact of atmospheric and oceanic forcing on ice sheet evolution. The study claims that oceanic forcing is the dominant driver of Greenland ice sheet evolution. However, the claim lacks robustness since parametric uncertainties in the atmospheric forcing have not been equally explored for a true relative comparison. Additionally, a broad exploration of the boundary conditions should be considered using a variety of ocean temperatures and atmospheric precipitation and temperatures at the Last Glacial Maximum since this would yield a much broader range of viable climate forcing scenarios.

It is true that we did not explore the sensitivity of the GrIS to other atmospheric forcings. This is a choice made to focus our work on the effects that the ocean has on the advance/retreat of the GrIS throughout the cycles. However, we agree with the reviewer that claiming that the ocean forcing is the dominant driver of the GrIS evolution is too strong for the type of study pursued. Therefore, to make this point clearer in the manuscript we added this sentence in the Discussion section:

"The GrIS evolution during the last two glacial cycles has been assessed from an oceanic point of view, while the influence of different atmospheric forcings has not been investigated. This component may be especially important for the results shown for the LIG and for the Holocene, in which the minimum extension of the GrIS is mostly induced by surface ablation.”

Also we have partly changed our conclusions replacing the sentence “the ocean is the dominant driver of the GrIS glacial advance” with “the ocean is a primary driver of the GrIS glacial advance”.

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Figures

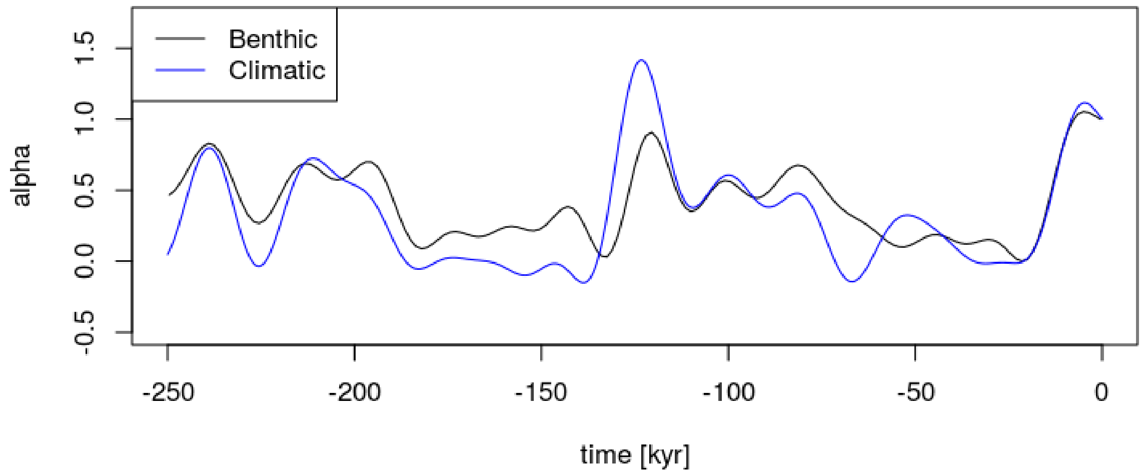

Fig. R1. Multi-proxy index used for the atmospheric forcing (blue curve) compared to an index retrieved from benthic $\delta^{18}O$ records in the North Atlantic (black curve). Both signals are filtered through a windowed low-pass frequency filter (f_c = 1/16 ka^{-1}) in order to remove the spectral components associated with millennial time scales and below.