Interactive comment on "Impact of millennial-scale oceanic variability on the Greenland ice Sheet evolution throughout the Last Glacial Period" by Ilaria Tabone et al. A. Svensson (Referee)

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The manuscript (MS) aims at estimating the Greenland contribution to sea level variability during the last glacial period in relation to D-O and Heinrich events. The authors apply an approach similar to that used in an already published paper concerned with glacial-interglacial cycles.

Overall, I think the exercise is very useful to give a first order estimate for the Greenland contribution to sea level variability during glacial times, and I think the approach of implementing ice-shelf ocean interaction is new and very relevant. I have one major point of concern, however, that I think needs consideration in order for the MS to make a good case.

It is very well established in the literature that during the last glacial period, the Heinrich events and the major ice rafting events in the North Atlantic are associated with the Greenland cold phases, the stadials. In contrast, during the mild Greenland periods, the interstadials, ice rafting and transport of continental material to the North Atlantic is much more limited. This is clearly illustrated in Figure 11 in the cited Hodell et al., QSR, 2010 paper, but also in many other studies where record resolution allows for a detailed comparison of marine records to the Greenland temperature record.

If I understand the model of the manuscript correctly, the ocean-terminating melt of GRiS is forced by the Greenland derived surface temperature, and the ocean temperature variability is assumed to be in phase with the (Greenland) atmosphere. Therefore, most of the marine-induced/basal melt from GRiS occurs during the interstadials. I see this as a highly unrealistic approach. Whereas the Greenland surface temperature is quite likely to give a good estimate for the Greenland surface melt during D-O events, I think this approach leads to a very unrealistic scenario for the basal melt that is mainly caused by interaction between the ice sheet and the subsurface ocean.

As seen in the MS figure 11, the modelled basal melt is completely out of phase with the melt events observed in the marine record. All the major modelled melt events occur during the Greenland interstadials, whereas all of the observed melt events occur during stadials. It is argued in the MS that the reason for this discrepancy could be that the source area for the marine IRD in this specific core could be different from Greenland. However, the timing of other IRD sources are also consistently occurring in the stadials. I think that the reason for this significant model-data disagreement is that the model approach of forcing the basal melt by Greenland surface temperatures is fundamentally wrong.

One could argue that is may not matter so much exactly when the ice sheet is losing or gaining mass as long as the inferred change in sea level variability is of the right order of magnitude. I this case, however, I think it is quite clear that the GRiS mass changes observed in the model are caused by an entirely wrong mechanism, and therefore are likely to be misleading and possibly of the wrong magnitude, also when it comes to sea level variability. Therefore, I think it is very important that a more realistic approach is applied for the basal melt/marine-terminating ice melt. It can possibly still be a simple approach, but it needs to include some estimated extent of sea ice in the North Atlantic, and some marine-based estimate of sub-surface ocean temperatures. The inclusion of sea ice is essential, because the sea ice partly seals off the ocean from direct heat exchange with the atmosphere, and thereby hampers the assumption of an in-phase temperature variability of ocean and atmospheric temperatures on the time scales relevant for D-O events.

Possibly, the authors can seek inspiration for a more realistic basal melt timing in those papers:

Dokken et al., Paleoceanography, 2013: Dansgaard-Oeschger cycles: Interactions between ocean and sea ice intrinsic to the Nordic seas.

Bassis et al., Nature, 2017: Heinrich events triggered by ocean forcing and modulated by isostatic adjustment.

We thank the reviewer for his constructive comments. Indeed, he raises a reasonable objection about the timing of the submarine melting peaks adopted in the manuscript, since most of the increased ice rafting events recorded into the North Atlantic during the last glacial period are indeed associated with Greenland stadials. This is supported by several sediment records coming from the Irminger Sea (Bond and Lotti, 1995; Van Kreveld et al., 2000; Rasmussen et al., 2016; Jonkers et al., 2010; Moros et al., 2002), the northern North Atlantic (Bond and Lotti, 1995; Barker et al., 2015; Hodell et al., 2010), the northwest flank of Iceland (Voelker and Haflidason, 2015) and the Nordic Seas (Rasmussen and Thomsen 2004). The Greenland ice sheet (GrIS) is proposed as one of the possible sources of the recorded ice rafted debris (IRDs) (Bond and

Lotti 1995; Moros et al. 2004; Prins et al., 2002), with a particular concentration of detritus coming from the East GrIS (Barker et al., 2015, Van Kreveld et al., 2000; Hodell et al., 2010; Andrews et al., 2017; Voelker and Haflidason, 2015; Rasmussen et al., 2016) and Northeast GrIS (Andrews et al., 2017), suggesting that the GrIS could have experienced intense ice mass variations throughout the Dansgaard-Oeschger (D-O) cycles.

The increase in iceberg discharge observed during cold stadials is attributed to warming of the subsurface, as many proxy records of the North Atlantic and Nordic Seas suggest (Ezat et al., 2014; Jonkers et al., 2010; Rasmussen and Thomsen 2004; Rasmussen et al., 2016; Sessford et al., 2018; Dokken et al., 2013). This decoupling between surface and subsurface during stadials is supported by modelling work as a result of reorganisations of North Atlantic Deep Water (NADW) formation (Vettoretti and Peltier, 2015; Brady and Otto-Bliesner, 2011; Mignot et al., 2007; Knutti et al., 2004; Marcott et al., 2011), and allows to explain the increase in ice rafting observed during stadials despite the low surface oceanic temperatures: warm subsurface waters would act as a trigger, or amplifier, of massive iceberg calving during the coldest stadials, such as the Heinrich events (Alvarez-Solas et al., 2011; Alvarez-Solas et al., 2013; Flückiger et al., 2006; Marcott et al., 2011; Bassis et al., 2017), and during the cold phases of D-Os (Shaffer et al., 2004; Petersen et al., 2013; Rasmussen et al., 2016; Boers et al., 2018).

The choice of a submarine melting signal in phase with atmospheric variations, i.e. surface warming during interstadials and surface cooling during stadials, was a simple approach based on the assumption that the Greenland continental shelf is relatively shallow. However, ice shelves are usually hundreds of meters thick and ocean-driven retreat processes are probably triggered by subsurface rather than surface waters. In the revised manuscript, the submarine melting rate evolution is now assumed to represent the conditions of oceanic waters at the subsurface, which are thought to be in antiphase with respect to the atmosphere (gradual stadial warming followed by interstadial cooling). For that, the interstadial-stadial oceanic temperature anomaly (ΔT^{mil}_{ocn}) is now chosen to be negative (stadial oceanic temperature is higher than that during the interstadial), such that $\beta * \Delta T^{mil}_{ocn}$ (and the submarine melting rate) mirrors the subsurface peaks of warming during stadials. The timing of the basal melting signal is therefore similar to that of Alvarez-Solas et al., 2010, Alvarez-Solas et al., 2013, Bassis et al., 2017 and Boers et al., 2018. By doing so, now we no longer simulate the ice discharges during Greenland Interstadials but, during stadials in a very consistent manner when compared with proxies (as pointed out by the referee; please see current Figure 8).

Many authors associate D-Os to changes in sea-ice cover over the Nordic Seas (Hoff et al., 2016; Dokken 2013; Li et al., 2010; Sime et al., 2019; Jensen et al., 2018). The absence of synchronicity between atmospheric and ocean warming due to the insulating effect of sea ice in the Nordic Seas during the stadials is now implicitly taken into account by our forcing by considering increased submarine melting during stadials. Perturbing the model with spatially variable subsurface oceanic temperatures, which may reflect variations in sea-ice cover, instead of a simple temperature time series, would likely affect the simulation of local ice mass variations throughout the last glacial cycle. Moreover, the few available model reconstructions of stadial-interstadial oceanic temperatures suggest that subsurface warming increases almost homogeneously across the ocean during the stadials, at least in the Nordic Seas (Fig S2 of Zhang et al., 2014, and Fig. 2 of Alvarez-Solas et al., 2018). This is also in agreement with large-scale subsurface warming suggested by Rasmussen and Thomsen, 2004 and Marcott et al. 2011. Thus, considering a spatial variation in oceanic temperatures (and sea ice) around the GrIS may not be fundamental for this study, which primarily aims to look at the response of the whole GrIS to D-Os, and the simplified approach of perturbing the ice-sheet model with a spatially constant oceanic forcing should be sufficient for our purposes.

All these points have been discussed in the new version of the manuscript.

Specifically, the following paragraph has been added in Section 2.3:

"*ΔT^{orb}_{ocn} and ΔT^{mil}_{ocn} are the glacial-interglacial and interstadial-stadial oceanic temperature anomalies (K), respectively. $(1 - \alpha(t)) * \Delta T^{orb}_{ocn}$ reflects the long timescales variations resulting from orbital changes. $\beta * \Delta T^{mil}_{ocn}$ expresses the millennial-scale temperature changes at the subsurface assumed to be in antiphase with respect to the Greenland atmospheric temperature inferred from Greenland ice cores (e.g. Johnsen et al., 2001; Kindler et al., 2014). Thus, we are assuming that subsurface water temperatures increase during stadials and decrease during interstadials. This is in agreement with the presence of warming subsurface waters during stadial periods as suggested by several records of the North Atlantic and Nordic Seas (Ezat et al., 2014; Jonkers et al., 2010; Rasmussen and Thomsen 2004; Rasmussen et al., 2016; Sessford et al., 2018; Dokken et al., 2013) and supported by modelling work (Vettoretti and Peltier, 2015; Brady and Otto-Bliesner, 2011; Mignot et al., 2007; Knutti et al., 2004; Marcott et al., 2011). The result is a submarine melting signal that peaks during D-O stadials. This is in line with the temporal evolution of oceanic forcings used to inspect the effect of subsurface warming during the coldest stadials, i.e. Heinrich events, by* *perturbing other ice-sheet models (Alvarez-Solas et al., 2010; Alvarez-Solas et al., 2013; Bassis et al., 2017), or, as done recently, to investigate the origin of D-O events through a conceptual model (Boers et al., 2018).*"

Also, the following paragraph has been added in the Discussion:

"*Many authors associate D-O events to changes in sea-ice cover over the Nordic Seas (Dokken et al., 2013; Hoff et al., 2016; Jensen et al., 2018; Li et al., 2010; Sime et al., 2019), however our ice-sheet model does not resolve sea-ice processes. Nevertheless, the absence of synchronicity between atmospheric and ocean warming due to the insulating effect of sea ice in the Nordic Seas during the stadials is implicitly taken into account by our forcing which associates peaks in submarine melting to stadials. We are aware that spatially-variable fields should be taken into account for an exhaustive investigation of the problem. Perturbing the model with spatially variable subsurface oceanic temperatures, which may reflect variations in sea-ice cover, instead of a simple temperature timeserie, would likely affect the simulation of local ice mass variations throughout the last glacial cycle. Both stadial-interstadial and glacial-interglacial temperature anomalies could be taken from existing transient model outputs, for instance. However, a complete map of the observed PD (present-day) basal melting rates for the whole Greenland domain does not exist yet, in contrast to Antarctica (Rignot et al., 2013), thus limiting the effectiveness of including additional complexity at this time. The fact that the few available model reconstructions of stadial-interstadial oceanic temperatures suggest that subsurface warming increases almost homogeneously across the ocean during the stadials, at least in the Nordic Seas (Zhang et al., 2014b; Alvarez-Solas et al., 2018), supports the choice of ignoring spatial oceanic variations as a first approach. This is also in agreement with large-scale subsurface warming suggested by Rasmussen and Thomsen (2004) and Marcott et al. (2011). Thus, considering a spatial variation in oceanic temperatures (and sea ice) around the GrIS may not be fundamental for this study, which primarily aims to look at the response of the whole GrIS to D-O events, and the simplified approach of perturbing the ice-sheet model with a spatially constant oceanic forcing should be sufficient for our purposes."*

Also, changing the oceanic forcing in the ice-sheet model has had implications in the analysis of the results and in the description of the experimental design. A new version of the manuscript tracking the changes will make the improvements to the manuscript clear.

REFERENCES:

Alvarez-Solas et al., 2010. Links between ocean temperature and iceberg discharge during Heinrich events. *Nature Geoscience*, 3, 2, 122.

Alvarez-Solas et al., 2011. Heinrich event 1: an example of dynamical ice-sheet reaction to oceanic changes. *Climate of the Past*, 7, 4, 1297-1306.

Alvarez-Solas et al., 2013. Iceberg discharges of the last glacial period driven by oceanic circulation changes. *PNAS*, 110, 41, 16350-16354.

Alvarez-Solas et al., 2018. Oceanic forcing of the Eurasian Ice Sheet on millennial time scales during the Last Glacial Period, *Clim. Past Discuss.*, https://doi.org/10.5194/cp-2018-89, in review.

Andrews et al., 2017. Denmark Strait during the late glacial maximum and marine isotope stage 3: Sediment sources and transport processes. *Marine Geology*, 390, 181-198.

Barker et al., 2015. Icebergs not the trigger for North Atlantic cold events. *Nature*, 520, 7547, 333.

Bassis et al., 2017. Heinrich events triggered by ocean forcing and modulated by isostatic adjustment. *Nature*, 542, 7641, 332.

Boers et al., 2018. Ocean circulation, ice shelf, and sea ice interactions explain Dansgaard-Oeschger cycles. *PNAS*, 115, 47, E11005-E11014.

Bond and Lotti, 1995. Iceberg discharges into the North Atlantic on millennial time scales during the last glaciation. *Science*, *267*(5200), 1005-1010.

Brady and Otto-Bliesner, 2011. The role of meltwater-induced subsurface ocean warming in regulating the Atlantic meridional overturning in glacial climate simulations. *Climate dynamics*, 37, 7-8, 1517-1532.

Dokken et al., 2013. Dansgaard-Oeschger cycles: Interactions between ocean and sea ice intrinsic to the Nordic seas. *Paleoceanography and Paleoclimatology*, 28, 3, 491-502.

Ezat et al., 2014. Persistent intermediate water warming during cold stadials in the southeastern Nordic seas during the past 65 ky. *Geology*, 42, 8, 663-666.

Flückiger et al., 2006. Oceanic processes as potential trigger and amplifying mechanisms for Heinrich events. *Paleoceanography*, 21, 2.

Hodell et al., 2010. Phase relationships of North Atlantic ice-rafted debris and surface-deep climate proxies during the last glacial period. *Quaternary Science Reviews*, 29, 27-28, 3875-3886.

Hoff et al., 2016. Sea ice and millennial-scale climate variability in the Nordic seas 90 kyr ago to present. *Nature communications*, 7, 12247.

Jensen et al., 2018. A spatiotemporal reconstruction of sea-surface temperatures in the North Atlantic during Dansgaard-Oeschger events 5-8, *Clim. Past*, 14, 901-922.

Jonkers et al., 2010. A reconstruction of sea surface warming in the northern North Atlantic during MIS 3 ice-rafting events. *Quaternary Science Reviews*, 29, 15-16, 1791-1800.

Knutti et al., 2004. Strong hemispheric coupling of glacial climate through freshwater discharge and ocean circulation. *Nature*, 430, 7002, 851.

van Kreveld et al., 2000. Potential links between surging ice sheets, circulation changes, and the Dansgaard-Oeschger cycles in the Irminger Sea, 60–18 kyr. *Paleoceanography and Paleoclimatology*, 15, 4, 425-442.

Li et al., 2010. Can North Atlantic sea ice anomalies account for Dansgaard–Oeschger climate signals?. *Journal of climate*, 23, 20, 5457-5475.

Marcott et al., 2011. Ice-shelf collapse from subsurface warming as a trigger for Heinrich events. *PNAS,* 108, 33, 13415-13419.

Mignot et al., 2007. Atlantic subsurface temperatures: Response to a shutdown of the overturning circulation and consequences for its recovery. *Journal of Climate*, 20, 19, 4884-4898.

Moros et al., 2002. Were glacial iceberg surges in the North Atlantic triggered by climatic warming?. *Marine Geology*, 192, 4, 393-417.

Moros et al., 2004. Sea surface temperatures and ice rafting in the Holocene North Atlantic: climate influences on northern Europe and Greenland. *Quaternary Science Reviews*, 23, 20-22, 2113-2126.

Petersen et al., 2013. A new mechanism for Dansgaard-Oeschger cycles. *Paleoceanography*, 28, 1, 24-30.

Prins et al., 2002. Ocean circulation and iceberg discharge in the glacial North Atlantic: Inferences from unmixing of sediment size distributions. *Geology*, 30, 6, 555-558.

Rasmussen et al., 2016. North Atlantic warming during Dansgaard-Oeschger events synchronous with Antarctic warming and out-of-phase with Greenland climate. *Scientific reports*, 6, 20535.

Rasmussen and Thomsen, 2004. The role of the North Atlantic Drift in the millennial timescale glacial climate fluctuations. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 210, 1, 101-116.

Sessford et al., 2018. High-Resolution Benthic Mg/Ca Temperature Record of the Intermediate Water in the Denmark Strait Across D-O Stadial-Interstadial Cycles. *Paleoceanography and Paleoclimatology*, 2018, 33, 11, 1169-1185.

Shaffer et al., 2004. Ocean subsurface warming as a mechanism for coupling Dansgaard-Oeschger climate cycles and ice-rafting events. *Geophysical Research Letters*, 31, 24.

Sime et al., 2019. Impact of abrupt sea ice loss on Greenland water isotopes during the last glacial period. *PNAS*, 201807261.

de Vernal et al., 2013. Sea ice in the paleoclimate system: the challenge of reconstructing sea ice from proxies - an introduction. *Quaternary Science Reviews*, *79*, 1-8.

Vettoretti and Peltier, 2015. Interhemispheric air temperature phase relationships in the nonlinear Dansgaard-Oeschger oscillation. *Geophysical Research Letters*, 42, 4, 1180-1189.

Voelker and Haflidason, 2015. Refining the Icelandic tephrachronology of the last glacial period–the deep-sea core PS2644 record from the southern Greenland Sea. *Global and Planetary Change*, 131, 35-62.

//Zhang et al., 2014. Instability of the Atlantic overturning circulation during Marine Isotope Stage 3. *Geophysical Research Letters*, 41, 12, 4285-4293.