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Interactive comment on "The impact of melt water discharge from the Greenland ice sheet on the Atlantic nutrient supply to the Northwest European Shelf" *by* Moritz Mathis and Uwe Mikolajewicz

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Authors responses to

Anonymous Referee 2

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Mathis and Mikolajewicz investigate the sensitivity of freshwater discharge from the Greenland Ice Sheet on conditions at the Northwest European Shelf in future model scenarios. They find that increased meltwater discharge results in larger variability at the shelf-break. Subpycnocline nutrient concentration increase and results in increased nutrient fluxes and variability at the shelf break. They find that a regime shift occurs 1-2 decades earlier depending on the discharge rate.

I find the sensitivity experiments very interesting and the results can contribute to our understanding of the impact of climate change in the northern North Atlantic. However, some aspects of the design of the experiments need to be clarified, including the sources of freshwater discharge, and also I find that some of the interpretations of the results needs to be clarified or modified, as I describe below. Finally, I have some minor comments. When these issues have been clarified I can recommend publication in Ocean Science.

Comments

It is not clear where the increased freshwater discharge (FWD) in the experiments takes place. A reference is made to an unpublished manuscript (Martin et al., 2019) and it is described as following the observational climatology. However, relatively few studies have been made on this issue so more information about the locations of the increased discharge and the actual present day values are needed to fully understand the implications of the sensitivity study. It would be interesting to know how the discharge field scales in comparison with observations, for example related to the studies of Bamber et al., (2017) and Mouginot et al. (2019).

R: We added a figure showing the spatial distribution of freshwater discharge along the coast of Greenland (Fig. 2). Furthermore, we added more information about the used climatology and compare it with other observational data.

L133: "The spatial distribution of the runoff (Fig. 2) follows the climatology by Bamber et al. (2012), based on satellite observations and regional climate modeling. The seasonal cycle (Fig. A1) has been derived by Martin et al. (2019). The annual mean GIS freshwater flux according to this study corresponds to 0.05 Sv and is comparable to the estimate of about 0.04 Sv since the year 2010 by Yang et al. (2016) and Bamber et al. (2018). In our simulations, the prescribed freshwater fluxes enter the surface layer of the ocean model, thus ignoring that many marine-terminating outlet glaciers have a grounding line depth several hundred meters below sea level (An et al., 2017; Morlighem et al., 2017)."

l. 150: The sensivitity study is designed as a linear increase of FWD where the final 0.1 Sv is obtained from an ice sheet model. It is not clear whether this simple linear transient increase is just a simple (ad hoc) model for the changing rate or if it is based on numerical experiments?

R: We added more information about this approach.

L160: "The assumption of a linear increase is an idealized approach to deal with the uncertainty in the construction of a hydrological sensitivity parameter, often defined as a constant freshwater discharge per degree atmospheric warming (e.g. Zickfeld et al., 2008; Kuhlbrodt et al., 2009), and has likewise been applied e.g. in Jungclaus et al. (2006)."

l. 161: As far as I know, a value of 1Sv is far above any present estimate of future runoff from GIS (20 times the present day value). Has it any relations to estimates of future runoff rates?

R: Indeed, this high melting rate goes beyond any estimates for the 21st century. Experiment E100 was designed only to better understand the processes that limit the freshwater impact on the regime shift timing. We extended the explanation of this experiment in section 2.2.

L175: "This high discharge rate is purely motivated by process understanding and exceeds any present estimate of GIS runoff during the 21st century. In fact, given a present-day GIS volume of about 2.9 x 10^{15} m3, it would lead to a complete disintegration of the ice sheet in the first half of the 22nd century, depending on the surface mass balance."

l. 295: Time series in Fig. A5 should illustrate the earlier onset of the shallow MLregime for increasing GIS melting rates. I can not see this. There is hardly any difference, as far as I can see, between the HIST and HIST/0.1Sv. Even the 0.25Sv (only a single realization) is quite similar to the HIST. So either this conclusion is reached based on the 0.25 and 1.0 Sv single-realization experiments or it has to be described more clearly where the difference occur. If the conclusion is based on the two large discharge rate experiments it should be pointed out that these experiments (bothsingle realizations) imply discharge rates between 5-20 times present day values, and also application of these high rates should be justified further, cf. my comment above.

R: We agree with the reviewer that an impact of 10-20 years was somewhat overestimated. We removed this estimate from the conclusions, and in the results (section 3.3) we focus more on the generally weak impact on the regime shift timing. In addition to Fig. A6 (former A5) we refer to the PO4 time series shown in Fig. 12 and 16 to support the interpretation for experiment E010 showing an earlier onset by about 10 years.

L369: "Nevertheless, the changes in the regime shift timing are surprisingly weak, given the melting rates vary considerably between the experiments. For a melting rate of 0.1 Sv (E010) the impact is only about 10 years (see also PO4 time series shown in Fig. 12 and 16)."

l. 328-334: The decrease in inflow to the North Sea is in qualitative accordance with the study of Holt et al. (2018). This is a very interesting results. However, it is not clear whether the mechanism for the reduced inflow is the same in the two models. Did the authors calculate the change in stratification and the deformations radius and relate it to the curvature of their coarser bathymetry? If not, I would suggest to include it or, otherwise, it should be clarified that this was not analysed.

R: We don′t think a comparison with the curvature of our model topography is meaningful here. Holt et al. have shown that the geostrophic component of the Norwegian Trech inflow scales well with the deformation radius, supporting the general explanation that a relaxation of topographic steering leads to a reduction of the inflow. Accordingly, we added simulated changes in the stratification and deformation radius near the entrance of the Norwegian inflow as well as the correlation between the deformation radius and the strength of the inflow. Furthermore, we found an intensification of the Nordic Seas circulation, in particular the southeastward flowing branch of the East Iceland Current, in line with Holt et al. and added a figure showing this (Fig. A8). We thus confirm the increasing influence of fresh Arctic water masses on the Norwegian Trench circulation but also point out the different timing in our simulations as well as the missing reversal of the inflow to a persistent outflow.

L401-422: "The inflow along the western side of the Norwegian Trench is mainly governed by topographic steering as the slope current follows the sharp topographic turn to the right at about 62°N. Our simulations indicate a substantial weakening of this inflow (Fig.14c) and are in line with the findings by Holt et al. (2018). The proposed driving mechanism is an increase in the deformation radius due to the strengthening of the stratification. In addition to the general weakening of the slope current, a smaller fraction of the slope current is then able to follow the topographic turn. In our simulations, the permanent stratification around the entrance of the Norwegian Trench strengthens by about 5 gm-4 in experiment E0 and 7 gm-4 in E010 (Fig.A2), and the baroclinic deformation radius increases by about 4-5 km in E0 (similar to 3-4 km in Holt et al., 2018), and 7 km in E010. The maximum deformation radii at the end of the simulations are about 10 and 12 km, respectively. During the shallow-ML regime (2101-2150), the correlation between the Norwegian Trench inflow and the deformation radius is about -0.35 (detrended time series) for both experiments. After around 2120, the remaining inflow to the Norwegian Trench does not penetrate further south than about 60°N, implying a reduction down to 0 in Fig.14c.

In Holt et al. (2018), the changes in the stratification and deformation radius are amplified by a strengthening of the circulation in the Nordic Seas, in particular the East

Iceland Current, leading to a southward intrusion of cold and fresh Arctic water masses into the northern inflow region of the North Sea. Similar in our simulations, the Nordic Seas circulation strengthens and a larger fraction of the East Iceland Current passes the Faroe Islands southeastward, joining the slope current to the north of the Shetland Islands (Fig.A8). Northeast of the Faroes, the East Iceland Current intensifies by about 30% (in E0 and E010). We thus confirm the enhanced influence of Arctic water masses on the Norwegian Trench inflow projected by Holt et al. (2018). A sudden shutdown due to positive feedback with the accumulation of coastal North Sea water of low salinity, however, does not occur in our simulations. The changes in the circulation are rather smooth over several decades (see Fig.14c for the Norwegian Trench inflow, not shown for the East Iceland Current) and simulated to happen later than in Holt et al. (2018) by about 30 years. Moreover, a reversal of the Norwegian Trench inflow to a persistent outflow, as also projected by Tinker et al. (2016), is not indicated but may happen post 2150."

l. 333: It is stated that the results are similar to Holt et al. (2018). This may by so in a qualitative sense but it is not clear whether the mechanisms are the same, cf. my comment above. Also there is only a qualitative similarity in the sense that the inflow decrease.

R: Our additional analysis mentioned in the response to the previous comment has shown that the mechanisms are indeed qualitatively the same. Due to the quantitative differences, however, we interpreted our results as "in qualitative agreement".

L444: "The maintained connection to nutrient-rich Atlantic subpycnocline water masses gains particular importance as the southward turn of the slope current into the Norwegian Trench is found to weaken substantially during the first half of the 22nd century, thus closing the only direct inflow of deeper Atlantic water to the NWES (in qualitative agreement with Holt et al., 2018)."

Minor comments:

l. 135: The reason that CMIP5 could not be used because of they were made on another super-computer and hence inconsistent is not clear. What was the relevant problem with the super-computer?

R: The high sensitivity of complex earth system models to differences in the representation and accuracy of high precision float numbers on the hosting super computer ultimately leads to independent trajectories already after short simulation times (butterfly effect). We added a sentence to make this more clear.

L143: "The original CMIP5 simulations could not be used here because they were run on a former high-performance computer (HPC) and hence are inconsistent with our GIS discharge experiments. A bitwise reproduction of a simulation is not possible on different HPCs, leading to independent trajectories even when started from identical initial conditions."

l. 186: change -> changed

R: "change" is not used as a verb here but as the term "change signal", commonly inferred from the concept of climate change signal.

L256: "The contrasting impact on the nutrient distribution seen in the meltwater discharge experiments (E010 and E025) indicates that also here the change signal in the NE Atlantic is not coherently transferred to the shelf but there are other mechanisms involved influencing the on-shelf nutrient transport."

l. 232: ..the meridional "density gradient" -> density difference (the units are not gradients).

R: Changed (L305).

Table 2: the meridional "density gradient" -> density difference (the units are not gradients).

R: Changed (Table 2).

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Table 2: ".. at 500-1000m ..." Is it averaged between 500-1000m?

R: Changed to "averaged over 500-1000 m depth" (Table 2).

l. 273: explain "..MLD in the NE Atlantic is lower ...". Do you mean more shallow?

R: Changed to "more shallow" (L346).

l. 277-280: This sentence need to be clarified. It seems to imply a relation between SLP and MLD standard deviations (?) and this need to explained.

R: The impact of SLP anomalies over the NE Atlantic on the MLD was a main finding in M19 and is summarized here in L334-344. We added a referring sentence to the caption of Table 3.

"The relation between SLP and MLD anomalies is explained in section 3.2"

l. 315: detailled -> detailed

R: Changed (L387).

l. 366-370: The argument that meltwater or iceberg-transported substances can make a significant difference to subpycnocline nutrient-concentrations in the northern North Atlantic is not supported by the studies referred. This needs to be clarified or modified.

R: The cited studies suggest that glacial runoff from the GIS serves as a significant source of bioavailable nutrients to the surrounding coastal ocean, which is likely to increase as GIS melting escalates under climate warming. Parts of the nutrients released to the upper ocean are consumed by phytoplankton and transferred to deeper levels by export production. We added a sentence for clarification.

L456: "Moreover, the subpycnocline nutrient enrichment may be underestimated because our model system does not account for the effect of biologically relevant substances transported into the ocean by meltwater and iceberg calving due to microbial activity and hydrolysis reactions at the interface between land ice and the bedrock (such as dissolved iron, silicate and nitrogen; Bhatia et al., 2013; Duprat et al., 2016; Wadham et al., 2016; Hatton et al., 2019). Part of this additional nutrient input to the upper ocean would be consumed by primary producers and exported to deeper levels."

l. 384: The contribution to the "nutrient flux" is described. However, there are no calculations of the fluxes. (Do you mean a contribution to PP?)

R: We added calculated nutrient fluxes to section 3.1 and refer to them respectively.

L295: "Net on-shelf PO_4 fluxes decrease from 839 mol s-1 (1971-2000) to 311 mol s-1 (2101-2150) in E0, 265 mol s-1 in E010, and 211 mol s-1 in E025. This increasing reduction among the experiments, however, is dominated by the decreasing volume transports (-0.25 Sv in E0, -0.30 in E010, -0.32 in E025) and does not reflect the changes in the nutrient concentrations."

L475: "The contribution to the mean nutrient flux (section 3.1) though is only about 3% for E010."

Table 4: the definition of the area ("the northern North Sea") is not specified.

R: We introduced a new figure (Fig. 4) showing the bathymetry of the study area, the transect across the Celtic shelf break and the specification of the northern North Sea. We refer to this figure in the relevant figures and tables, as e.g. in Table A1 (former Table 4).

Fig. A5: in a) and b) only the blue color is described.

R: Changed (now Fig. A6).

References

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