Reply to Anonymous Referee #2, interactive discussion on

"*The impact of early Holocene Arctic Shelf flooding on climate in an atmosphere–ocean–sea–ice model* "

by M. Blaschek and H. Renssen

General comments

Thank you very much for your review and the useful criticism and suggestions for improving our manuscript. We agree with the reviewer that the atmospheric component of LOVECLIM is not the preferable choice for investigating atmospheric responses and dynamics, and this is also the reason why we have focused on the oceanic response rather than on the atmospheric dynamics. As noted by the referee, this is the first modelling study that specifically addresses the impact of deglacial shelf flooding on climate. It is clear that this study should be considered as a first step that should be followed by additional analyses with more complex models. Ultimately this topic should be studied using transient experiments performed with models including the coupled atmosphere-ocean-ice system.

The reviewer mentions that we have neglected the impact on climate of sea level changes outside the Arctic and that we have not compared our results with geological records. Our goal has been to specifically analyse the impact of Arctic Shelf flooding in a climate model. In our opinion the chosen experimental set up, with only changes in the Arctic, provides the best analyses to reach our research goal. If we would have had also included sea level changes in the rest of the world, it would have been very difficult to determine what the specific impact of the shelf flooding in the Arctic on climate is. Furthermore, we consider comparison with global geological records outside the scope of this study.

Individual Comments

Section 3.1.1 : Please also mention the sea ice export in the comparison of the model with observations. It is one of the key quantities analysed in the publication, and seems to be off substantially.

We agree that this is missing in the description of the "Modern climate" and we propose to add the follow sentence: "...agree well with observations (10.6 x10^{12} km^2 , c.f. Table 2). **Thus observed Fram Strait sea-ice export shows considerable lower (2.6 10^3 km^3, Spreen et al., 2009) volumes compared to 10.6 10^3 km^3 of annual cumulative sea-ice**

export in our model. Consequently, the export of sea ice through Fram Strait is likely to be too large in our model. ..."

Please compare the spatial distribution of the sea ice production with the present day values given in the introduction. The influence of the shelves on the sea ice production is of key importance in this publication so a comparison of the modelled present-day values with the presented observations would help putting the results into perspective.

We agree that sea-ice production is a key aspect of this paper and that it would be interesting to compare modelled sea-ice production to mentioned estimates from the introduction, but there are considerable differences like the areas considered or type of sea-ice production between studies. In combination with our relatively low resolution model it will be quite complicated to address all these issues at local scales for present-day. This is another reason why we focused on quantities like the Northern Hemisphere sea-ice extent or volume that rely on large-scale dynamics and assume that the underlying processes produce reasonable quantities of sea ice. Regarding the spatial distribution of this sea-ice production we show in Figure 8 where most sea-ice is produced at 9ka BP, this map is mostly true for our pre-industrial simulation (0kOG) as well. We propose to add the following sentence to clarify in section 3.1.1 right after previously added sentence: "...in our model. **The distribution of sea-ice production in the model is different from observations, because in our model the transpolar drift transports sea-ice from the western to the eastern side of the Arctic (Goosse et al., 2001; c.f. Fig.8, 9kOG, distribution is similar to present-day). This model bias results from the low resolution of the atmospheric component (Goosse et al., 2003; Goosse and Renssen, 2001), although Goosse et al. (2001) found that the atmospheric circulation in the Arctic and the position of Icelandic and Aleutian low is relatively close to observed ones under present-day conditions. The opposite wind direction is a result of an overestimation of the Aleutian low. Despite this deficiency** we conclude that our model is able to produce sea-ice quantities **at larger scale** in a reasonable range under pre-industrial conditions, suggesting that our model is suitable for a study of the impact of early Holocene shelf flooding on sea ice (c.f. Fig.2)."

Section 3.1.2: How much does which shelf contribute to the sea ice production in 9kOG? Do these contributions match with the changes in Arctic ocean sea ice production obtained in the experiments

with (individual) dry shelves?

The contribution of each shelf can be seen in Table 2, e.g. 9kOGBAR ($13.3x10^3$ km^3) vs. 9kOG ($13.8x10^3$ km^3) resulting in an impact of 500 km^3 by flooding the Barents Sea shelf. Combining 9kOGBAR, 9kOGCAN and 9kOGSIB gives 2800 km^3 compared to 2900 km^3 in 9kOGSHELF. So they match almost.

Section 3.2: p. 4202 lines 17ff. *The shift in convection results in cooler and fresher surface waters near the Denmark Strait (Fig. 5d-f) and along the EGC as far north as Fram Strait (Fig.5a-c), because of more sea-ice cover and increased sea-ice melting.* Please split this more clearly into effects in the north and in the south. From the current wording, it seems as if a southward shift in deep convection areas would lead to increased sea ice melting in the EGC near Fram Strait.

We rewrite: "The **southward** shift **of** convection results in cooler and fresher surface waters near the Denmark Strait (Fig. 5d-f) and along the **east coast of Greenland** as far north as Fram Strait (Fig.5a-c)**. The southward expansion of sea ice along the EGC increases** sea-ice cover and ~~**increased**~~ sea-ice melting **in the western Nordic Seas**. Although less sea ice is transported out of the Arctic ocean..."

Section 3.3.1: As stated above, I have limited trust in the capabilities of a 3-layer atmosphere model. Therefore a few words on how well the present-day simulations represent the features analysed at 9ka would be helpful for putting the results into perspective.

We propose to include a short introduction to the Arctic atmospheric circulation in our model as has been presented by Goosse et al. (2001) with an earlier version of our model. They analysed the atmospheric circulation and sea-ice transports under present-day conditions and compared to it to observations. We decided to add a more detailed description in combination with previous reply to your comment (#2) in section 3.1.1

Is there a substantial difference in cloud cover over the ocean areas in the Arctic and over the adjacent land? How do the prescribed clouds affect the modelled climate in the dry-shelf experiments? (might be part of the discussion)

ECBILT uses a climatological cloud cover that depends on the location and on the season, but is not changed once it is calculated. There are different long wave radiation profiles for land and sea that will account for climatological effects of clouds. The climatology used is ISCCP (Rossow et al., 1996). Therefore there are no substantial changes in cloud cover that

could affect the climate in the different experiments presented in this paper.

A mention of the differences (or similarities) between the experiments with and without ice sheet melt (presented in figure 7) would be interesting.

We propose to add the following sentence in section 3.3.1: "...in the eastern part (Fig. 7c). **Despite the substantial difference in mean climate between 9kOG and 9kOGGIS (-0.5 K globally cooler) the impact of the shelf flooding remains clearly present as an atmospheric pattern in Figure 7, indicating that the impact is robust.**"

Section 3.3.3: On page 4205 lines 9ff. you state However, it should be noted that our model has a low spatial resolution leading to a biased atmospheric circulation over the Arctic (Goosse et al., 2003; Goosse and Renssen, 2001). Please mention this in section 3.1.1 where you discuss the atmospheric changes and explain in which way you expect this bias to affect your results (the effect might also be part of the discussion, the problem should be mentioned in 3.3.1).

We mention this now in section 3.1.1 (see earlier comment #2) and we propose to add the following sentence to section 3.3.1: "...the impact is robust. The **previously mentioned bias in the Arctic atmospheric circulation in our model is affecting the transport of sea-ice in the Arctic due to changed winds, whereas one can argue that the meridional thermodynamic structure of the atmosphere is likely to be less affected by this bias, because the polar atmospheric circulation is mainly governed by its meridional component.**"

Section 4: In the comparison of modelled effects and proxies a few words on the effects of the general trends in background climate and deeper ocean bathymetry on the climatic features compared would be helpful.

We propose to add this sentence in section 4: "...a flooded shelf as in 9kOG / 9kOGGIS. **The early Holocene is a period that is still strongly influenced by deglaciation, with pronounced melting of the Laurentide and Greenland ice sheets, resulting in relatively cold conditions in large parts of Northern Hemisphere (Blaschek and Renssen, 2012; Renssen et al., 2009) and a rise in sea level across the globe. As these impacts begin to fade out, the orbitally induced changes in summer insolation become the main driver of Northern Hemisphere climate, leading first to a thermal maximum, followed by a**

long term cooling. Connected to our results a direct impact can be seen in the Nordic Seas sea-ice extent...”

On page 4207 lines 19ff. the modelled changes in sea-ice cover in the East Greenland Current are compared with proxy data from the northern Fram Strait. A comparison of data from the same location/region would probably be more enlightening.

We compare Fram Strait sea-ice cover to the “northern EGC”, which is reasonably close in our perspective.

On page 4207 lines 26ff. the almost complete summer-melt of the sea-ice cover in the 9kOG scenario is commented on. While this plausible because of the summer warming, it should be considered that the present-day simulations substantially underestimate the summer sea ice volume.

That is true and we will rewrite as the following: “...the Arctic ocean was not a reservoir for sea ice, which could then affect reconstructed sea-ice quantities. **Nevertheless one has to keep in mind that LOVECLIM underestimates present-day sea-ice volume and that early Holocene sea-ice loss is likely to be less severe.**”

Section 5: On page 4209 lines 1f it is stated that the decrease in Fram Strait Sea ice export (9kOG vs. 9kOGSIB) is not statistically significant. Is this referring to page 4202 lines 1f? Is this really not significant when comparing 100-year averages? If it is not significant, the abstract should be adopted to reflect this.

The reviewer is correct. The monthly values, as mentioned in section 3.2, are not significantly different, but the cumulative sums of the monthly exports are indeed significantly different with shelf flooding. We are sorry for the mistake and corrected the conclusions to state this. We rewrite: “In contrast to the hypothesis, sea-ice export through Fram Strait is reduced by 15 % (1138 km^3**, annual sum**) in a simulation with a flooded shelf (9kOG) compared to an experiment with a dry shelf (9kOGSIB). ~~However,~~ **This annual** decrease is ~~not~~ **statistically significant** and originates from changes in the Arctic sea-ice transport. ”

All minor and technical corrections have been changed accordingly to reviewers suggestions.

Figures will be updated to increase readability.

References:

Rossow, W. B., Walker, A. W., Beuschel, D. E., and Roiter, M. D.: International satellite cloud climatology project (ISCCP) documentation of new cloud datasets, WMO/TD-No 737, World Meteorological Organisation, 1996.