Reply on RC1
Alizée Chemison et al.

The authors explored the impacts of ice sheet melting on global monsoon system in the 21st century under the RCP8.5 scenario. They conducted freshwater hosing experiment with IPSL-CM5A-LR in which freshwater is input in the North Atlantic and around Antarctic to mimic the freshwater discharge due to Greenland and Antarctic ice sheet melting. They found an AMOC slowdown and resultant southward shifts of the American and African monsoons. They also found that the North African monsoon generates a drier condition in boreal summer and the South African monsoon strengthens in austral summer, however, changes in the Asian and Australian monsoons are insignificant.

This study focuses on an interesting topic and potentially contributes to our understanding of the impacts of Greenland and Antarctic ice sheet melting on global monsoon system during the 21st century. Overall, the analysis is comprehensive and the results are convincing. Thereby, I would like to recommend publication pending on minor revisions.

Answer: We thank the reviewer for his/her constructive comments that helped improving the scientific quality of the manuscript.

Major comments

The authors may want to clarify how many ensemble members are used/produced for their historical, RCP8.5, WAIS3m, GrIS1m and GrIS3m simulations. I believe that there are multiple ensemble members for IPSL-CM5A-LR historical and RCP8.5 simulations available at the CMIP5 achieve. Also, are the results (e.g., Figures 2-9) based on the ensemble-mean of simulation?

Answer: All experiments are based on the first available ensemble member namely “r1i1p1”. Only one simulation was used for each ice melt experiment because of the magnitude of the added freshwater signal. To compare simulations, only a single ensemble member was used to avoid smoothing out internal variability of the model. In the following figure we compare global mean temperature and rainfall for all ensemble members available for the historical (Fig. 1A) and RCP8.5 (Fig. 1B) scenario carried out with the IPSL-CM5A-LR model. The spread between ensemble members is relatively moderate and the ice experiments (GrIS1m, GrIS3m and WAIS3m, with colder and drier
conditions, see Fig. 1B) clearly stand out from the internal model variability derived for all RCP8.5 simulations (Fig. 1B).

We have added the following figures (Fig. 1A and 1B here and Figure A1 and A2 in the paper) and a paragraph in "Appendix A: Ensemble experiments":

Lines: 507-513 "All experiments are based on the first ensemble member r1i1p1. Only one simulation was carried out for each ice melt experiment because of the magnitude of the added freshwater signal. To compare simulations, only a single ensemble member was used to avoid smoothing out internal variability of the model. In the following figures we compare global mean temperature and rainfall for all ensemble members available for the historical (Fig. A1) and RCP8.5 (Fig. A2) scenario carried out with the IPSL-CM5A-LR model. All historical and RCP8.5 scenario experiments simulate a warming-wetting trend. The spread between ensemble members is relatively moderate and the ice experiments (GrIS1m, GrIS3m and WAIS3m, with colder and drier conditions) clearly stand out from the internal model variability derived for all RCP8.5 simulations (Fig. A2)."

For more clarity we have added the following details in the method section:

Lines: 151-152 "All experiments were conducted using the IPSL-CM5A model at Low spatial Resolution (IPSL-CM5A-LR, 3.75 ◦in longitude and 1.875 ◦in latitude), using the r1i1p1 simulation as described by Dufresne et al. (2013)."

Lines: 186-188 "We compare a mid-century period (2041-2070) during freshwater release, with the historical period (1976-2005) for RCP8.5, GrIS and WAIS scenarios. For all experiment, only one simulation was used (see Appendix A for further details about model internal variability)."

Besides, how will the results be affected by model resolution considering the relative low ocean resolution of IPSL-CM5A-LR? In another word, for WAIS3m, if fresh water is released into the western Antarctic Ocean in a high-resolution model (e.g., 0.1-degree ocean), how will the results change?

Our simulations have been performed with the IPSL-CM5A-LR which ocean component is NEMO with a spatial resolution about 2° (with a meridional increased resolution of 0.5° near the equator) and with 31 vertical levels for the ocean (Dufresne et al., 2013). Indeed, such a low spatial resolution is not eddy resolving and we agree that increasing resolution by a factor of 10 should enhance the robustness of our results.

Given the review time frame, we could not repeat our simulations with an oceanic model at such high resolution. Consequently, we decided to discuss this issue using information from the available literature. Higher resolution ocean model (at 0.1°) can represent ocean eddies in contrast to our lower-resolution NEMO model (Kirtman et al. 2012). These eddies often occur in the Southern Ocean around Antarctica, and they are important sinks of energy between the ocean and the atmosphere, and this sink is more important the further east the wind is (Jullien et al., 2020). Thus, the representation of realistic surface winds in the atmospheric model is also an important issue. These eddies contribute to a global warming signal of about +0.2°C according to Kirtman et al. 2012. This eddy effect is significant but moderate compared to the temperature changes simulated in our ice-melt simulations (global cooling between GrIS3m and RCP8.5 of about 0.6°C on average, and may reach a maximum of 1.15°C over the period 2041-2070).

Merino et al. (2018) used an oceanic model with a spatial resolution of 0.25° that solves eddies. They show that freshwater inflow to Antarctica leads to increased sea ice formation except over the Amundsen Sea region. A higher spatial resolution of the ocean model would therefore allow for a better understanding of the mesoscale phenomena and
the increase in temperature associated with freshwater inflow. However, we believe that the trends in sea ice extent and the impact on the atmosphere would be similar at continental scale, with however a better representation of regional effects.

Jackson et al (2020) also show that finer spatial resolution can have an impact on the AMOC weakening. Both high and low-resolution models have significant biases (Chassignet et al., 2020, Jackson et al., 2020). Additional simulations on the impact of horizontal model resolution and bias improvement will be very valuable and useful for improving future climate projections.

Consequently, we have added the following paragraph in discussion:

Lines: 453-472 "The spatial resolution of the IPSL-CM5A-LR climate model is coarse. The slowing trend of the AMOC, the associated decrease in temperature and the southward shift of the rain belt in response to the addition of fresh water into the North Atlantic Ocean are robust results. These changes were found in other studies and they are related to large-scale parameters (Mulitza et al., 2008; Kageyama et al., 2013, Jackson et al., 2015, Liu et al., 2020). Concerning freshwater inputs in West Antarctica, a higher resolution ocean model (at 0.1° spatial resolution) could represent oceanic eddies that are not represented in our low-resolution simulations (Kirtman et al. 2012). These eddies occur in the Southern Ocean around Antarctica. These eddies are important sinks of energy between the ocean and the atmosphere, and this sink is more important the further east the wind is (Jullien et al., 2020). Thus, the representation of realistic surface winds in the atmospheric model is also an important issue. These eddies contribute to a global warming signal of about +0.2°C according to Kirtman et al. 2012. This eddy effect is significant but moderate compared to the temperature changes simulated in our ice-melt simulations (global cooling between GrIS3m and RCP8.5 of about 0.6°C on average, and may reach a maximum of 1.15°C over the period 2041-2070) also show that finer spatial resolution can have an impact on the AMOC weakening. Both high and low-resolution models have significant biases (Chassignet et al., 2020, Jackson et al., 2020). Additional simulations on the impact of horizontal model resolution and bias improvement will be very valuable and useful for improving future climate projections. The impact of the spatial resolution is more important at regional scale. Therefore, for the Asian and AUSMC regions it is difficult to simulate reliable trends. The presence of the Himalayas is poorly represented in our model simulations due to a too coarse resolution and very few island grid boxes are available in the AUSMC region to obtain reliable results. Our findings based on low spatial resolution model still simulate realistic monsoon dynamics and simulated future changes are in agreement with other published studies (Mulitza et al., 2008; Kageyama et al., 2013, Jackson et al., 2015, Liu et al., 2020)."

Section 3.2 and Figures 4-5: I am wondering whether the authors can also show the changes in Arctic and Antarctic sea ice, which might help understand the changes in surface temperature and perhaps others.

Answer: We have plotted the differences in sea ice fraction (%) between our different future scenarios (2041-2070) and the historical simulation (1976-2005) for boreal winter on Figure 1C and austral winter on Figure 1D. We have plotted the temporal evolution of sea ice fraction and temperature for our different simulations for the northern (Fig. 1E) and southern (Fig. 1F) hemispheres as well. To calculate indices, we have selected the sea ice area defined as follows: any grid point with a 30-year median (1976-2005) >= 15% sea ice. This analysis was done by seasons (MJJAS and NDJFM) and for each hemisphere. The largest ice melting is simulated for the RCP8.5 and WAIS simulations in the northern hemisphere during boreal winter (Fig. 1C.a-b and Figure 1E.a-c). The addition of freshwater in GrIS experiments tend to limit future ice-melting around Greenland (Fig. 1C.c-d and Fig. 1E.a-c). Most future experiments tend to simulate ice-melting over western Antarctica, while more ice is simulated over south-eastern Antarctica (Fig. 1D.a-c-
These findings are consistent with results from the IPCC AR6 report (Fox-Kemper, B., et al., 2021). Conversely, the WAIS experiments simulate more ice over the western part of Antarctica and a decreased sea ice extent over north-eastern Antarctica (Fig. 1D.b). The addition of freshwater in the northern Atlantic leads to colder temperatures (Fig. 1E.b-d), a decreased AMOC, and a more moderate sea-ice melting (Fig. 1E.a-c). A similar relationship is shown over the southern hemisphere for the WAIS3m experiment (Fig. 1F). There is no clear lag between simulated temperatures and sea-ice extent so we assume that this process is related to the coupling between the atmosphere, the ocean and the cryosphere.

We have added these figures and a paragraph in “Appendix B: Ocean and sea-ice dynamics”:

Lines: 521-536 “The differences in sea ice fraction (%) between our different future scenarios (2041-2070) and the historical simulation (1976-2005) for boreal winter is shown on Figure B3 and austral winter on Figure B4. The temporal evolution of sea ice fraction and temperature for our different simulations for the northern is presented on Figure B5 and for the southern on Figure B6. To calculate indices, the sea ice area was defined as follows: any grid point with a 30-year median (1976-2005) >= 15% sea ice. This analysis was done by seasons (MJJAS and NDJFM) and for each hemisphere. The largest ice melting is simulated for the RCP8.5 and WAIS simulations in the northern hemisphere during boreal winter (Fig. 3a-b and Figure 5a-c). The addition of freshwater in GrIS experiments tend to limit future ice-melting around Greenland (Fig. 3c-d and Fig. 5a-c). Most future experiments tend to simulate ice-melting over western Antarctica, while more ice is simulated over south-eastern Antarctica (Fig. 4a-c-d and Fig. 6a-c). These findings are consistent with results from the IPCC AR6 report (Fox-Kemper, B., et al., 2021). Conversely, the WAIS experiments simulate more ice over the western part of Antarctica and a decreased sea ice extent over north-eastern Antarctica (Fig. 1D.b). The addition of freshwater in the northern Atlantic leads to colder temperatures (Fig. 1E.b-d), a decreased AMOC, and a more moderate sea-ice melting (Fig. 1E.a-c). A similar relationship is shown over the southern hemisphere for the WAIS3m experiment (Fig. 1F). There is no clear lag between simulated temperatures and sea-ice extent so we assume that this process is related to the coupling between the atmosphere, the ocean and the cryosphere.”

I am wondering whether Greenland and Antarctic ice sheet melting will affect the seasonal delays of precipitation that is related to the monsoon system (e.g. Song et al. 2021).

Answer: Changes in seasonal rainfall has already been investigated on Fig. 7-8-9, (hovmöllers diagrams, note that we have now added moist static energy estimates to address another reviewer’s comment). For the North African monsoon, an increase in precipitation is simulated at the beginning and end of the wet season for the RCP8.5 and WAIS3m scenarios, while a drying signal is simulated during the wet season for the GrIS simulations. Over the coasts of guinea (5°N) the monsoon onset starts earlier, while over the Sahel (10°N) a rainfall decrease is simulated during the rainy season for the GrIS simulations. Song et al., 2021, highlighted a 4-5 days delay using gridded climate observation for the Sahel region they attribute to the impact of anthropogenic GHGs and sulphate aerosols. This finding is consistent with the study of Biasutti & Sobel (2009) that highlighted a simulated delay of the rainy season using standard climate change scenarios. For the South African region, the dry season is getting drier for all simulations, and an increase in precipitation during the wet season is simulated close to the equator. For the North American region, the seasonality varies in the southern part and changes depending on the scenario. In WAIS3m a slight increase in rainfall is simulated at the beginning of the rainy season, while for the other three scenarios there is a delay and an intensification during the wet season and more rainfall at the end of the season. The more water is added to the North Atlantic, the larger this anomaly becomes. Our study also
shows a latitudinal relationship with these seasonal delays, with drying being more pronounced in the northern part and increased precipitation in the southern part. For the South American region, the rain belt shifts southward. For the SAS region we can see an increase in the rainy season and a more pronounced dry season for all scenarios.

We added the following paragraph in the results section:

Lines: 358-360 "As a summary: Greenland ice melt has a strong impact on rainfall seasonality for the NAF and NAMS regions, thus over monsoon regions bordering the North Atlantic. The WAIS3m scenario mainly impacts the seasonality of the North American region and otherwise follows the trends simulated by the RCP8.5 scenario."

Following a suggestion by another reviewer, we have now added estimates of Moist Static Energy (MSE, sum of latent and sensible heat fluxes and geopotential) anomalies (ΔMSE). To derive MSE anomalies, we first calculate the MSE difference at 200 hPa and 850 hPa for each simulation, then we calculate differences between future scenarios and the historical experiment to obtain Δ MSE anomaly. Overall, an increase in precipitation is linked to a decrease in the Δ MSE anomaly, which leads to increased destabilisation between the surface and the top of the atmosphere at 200 hPa (Seth et al., 2013). Conversely, simulated decrease in precipitation is related to an increase in stability which is associated with an increase in the ΔMSE anomaly (Seth et al., 2013).

Lines: 360-367 “Changes in rainfall seasonality are linked to changes in the Δ MSE anomaly. When Δ MSE anomaly increases, atmospheric stability increases and precipitation decreases. Conversely, when the Δ MSE anomaly decreases, atmospheric destabilization and precipitation increase. This relationship between precipitation and MSE is shown for the American (Fig. 7), Southern African (Fig. 8 d-f-h-j), Southern Asian (at high latitudes, see Fig. 9) and South-east Asian monsoons (Fig. C1 c-e-g-i). In some regions, an increase in MSE occurs without an associated decrease in precipitation. This is related to the fact that MSE increases during the dry season, when precipitation is already close to zero, as is the case for Southern Africa (Fig. 8 d-f-h-j), for the North American monsoons at high latitudes (Fig. 7 c-e-g-i) and for the South American monsoon for the RCP8.5 and WAIS3m scenarios (Fig. 7 d-f).”

Minor comments

Lines 10-11: I suggested changing the sentence as “Changes in the North American monsoon occur later, while changes in the South American monsoon start earlier.”

Answer: Corrected

Lines: 12-13 “Changes in the North American monsoon occur later, while changes in the South American monsoon start earlier.”

Lines 38-39, Line 132, Line 195, Line 216 and many others: Please use “northern hemisphere”, “Northern Hemisphere”, “southern hemisphere” and “Southern Hemisphere” consistently through the text.

Answer: Corrected

Line 124: Temperature and precipitation changes outside the North Atlantic region could also be modulated by the Pacific meridional overturning circulation in paleo-climate (e.g. Liu and Hu 2015).

Answer: We have modified the text to highlight the impact of AMOC on the PMOC and added a reference to Liu and Hu, 2015.
A slowdown of the AMOC will also affect the Pacific meridional overturning circulation (PMOC) with potential changes in associated temperature and precipitation patterns at global scale (Liu and Hu, 2015).

References

- Liu, W. and Hu, A., 2015. The role of the PMOC in modulating the deglacial shift of the ITCZ. Climate Dynamics, 45, 3019-3034.

Please also note the supplement to this comment: https://egusphere.copernicus.org/preprints/egusphere-2022-197/egusphere-2022-197-AC1-supplement.pdf