Reviewer 1

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":

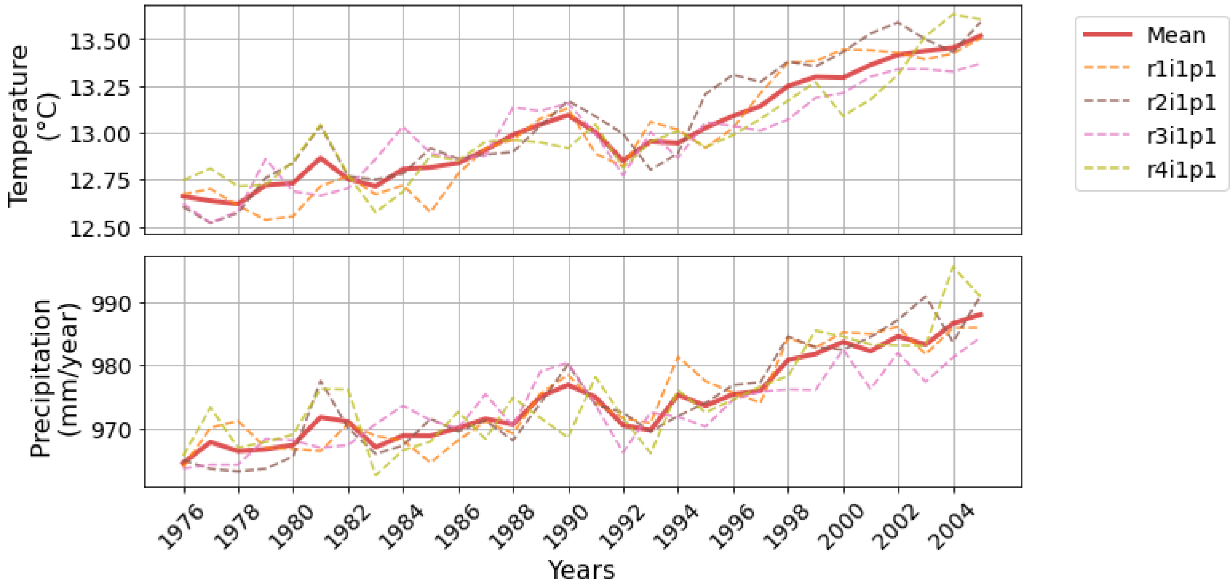

Figure 1A: Temporal evolution of a) temperature and b) precipitation over the historical period for the different ensemble members. The solid orange line depicts the simulation used in the study. The thick red line shows the ensemble mean of all simulations from r1i1p1 to r4i1p1.

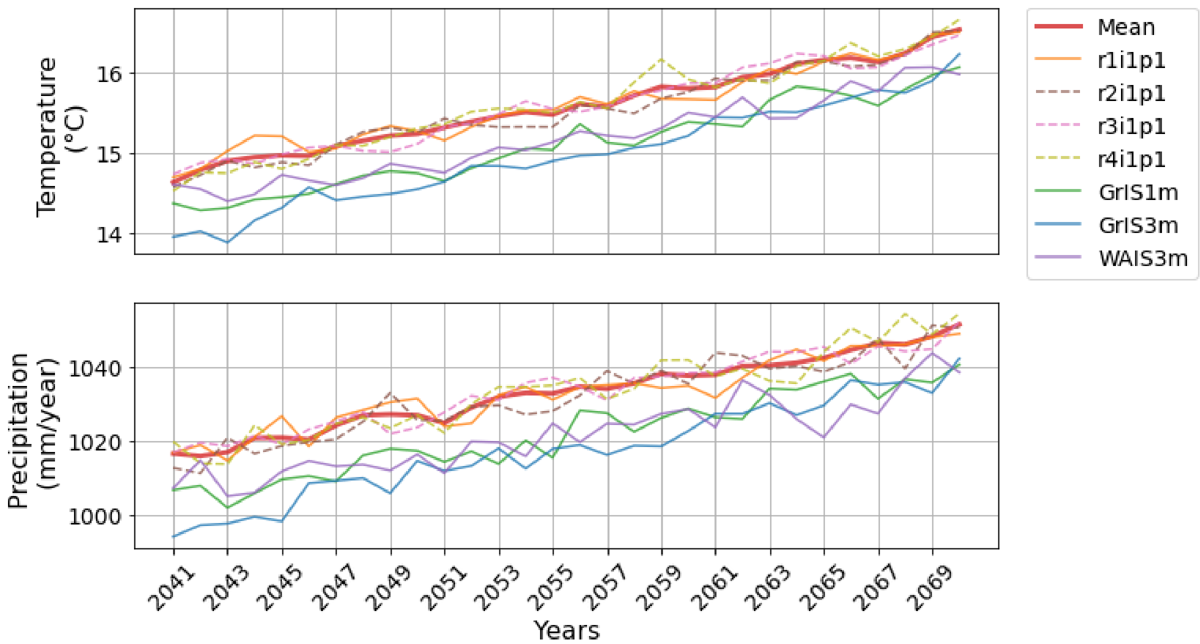

Figure 1B: Temporal evolution of a) temperature and b) precipitation over the future period for the different RCP8.5 runs (r1i1p1, r2i1p1, r3i1p1, r4i1p1) and for the different ice melt simulations (GrIS1m, GrIS3m, WAIS3m). The solid orange line depicts the simulation used in the study. The thick red line shows the ensemble mean of all RCP8.5 simulations from r1i1p1 to r4i1p1.

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.

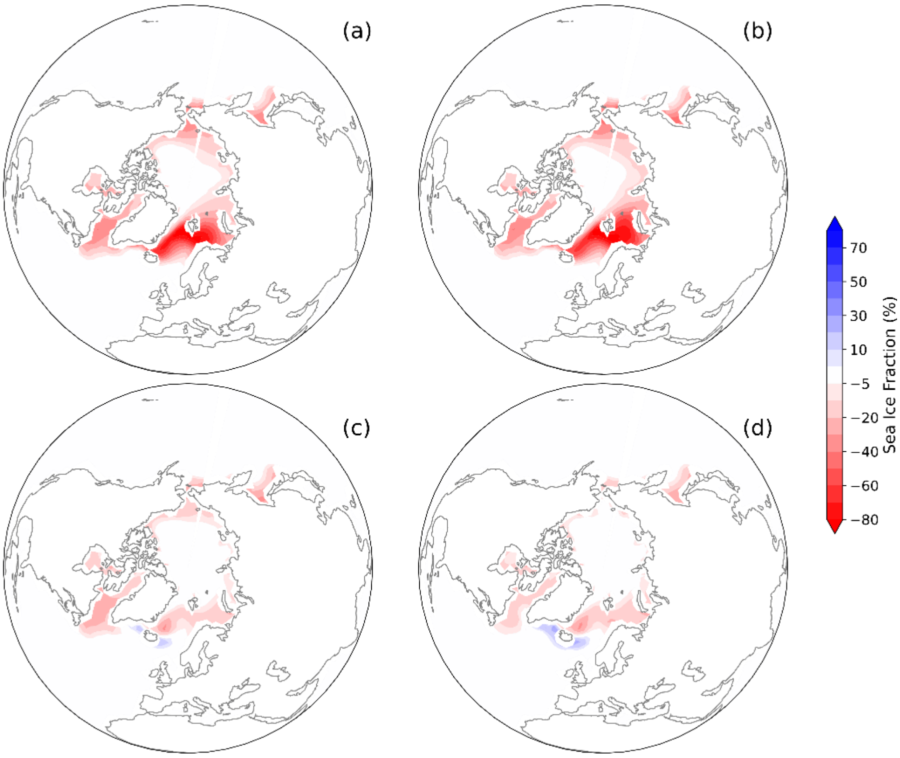

Figure 1C: Sea ice fraction difference (%) between future scenario (2041-2070) a) RCP8.5 b) WAIS3m c) GrIS1m d) GrIS3m and historical simulation (1976-2005) for the Northern Hemisphere in NDJFM.

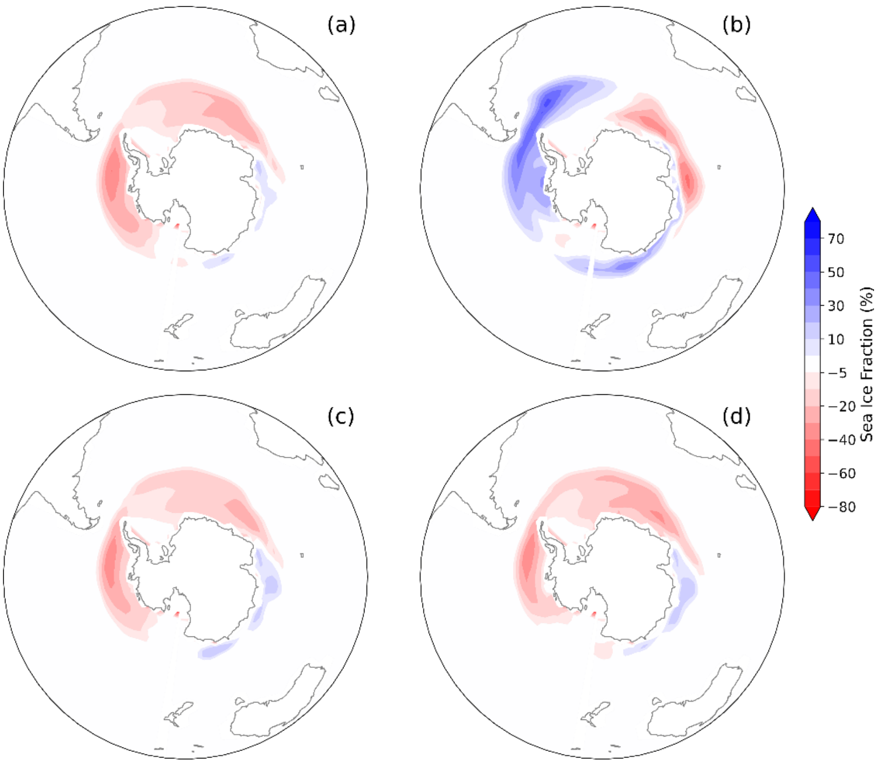

Figure 1D: Sea ice fraction difference (%) between future scenario (2041-2070) a) RCP8.5 b) WAIS3m c) GrIS1m d) GrIS3m and historical simulation (1976-2005) for the Southern Hemisphere in MJJAS.

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-d and Fig. 1F.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. 4b). The addition of freshwater in the northern Atlantic leads to colder temperatures (Fig. 5b-d), a decreased AMOC, and a more moderate sea-ice melting (Fig. 5a-c). A similar relationship is shown over the southern hemisphere for the WAIS3m experiment (Fig. 6). 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."

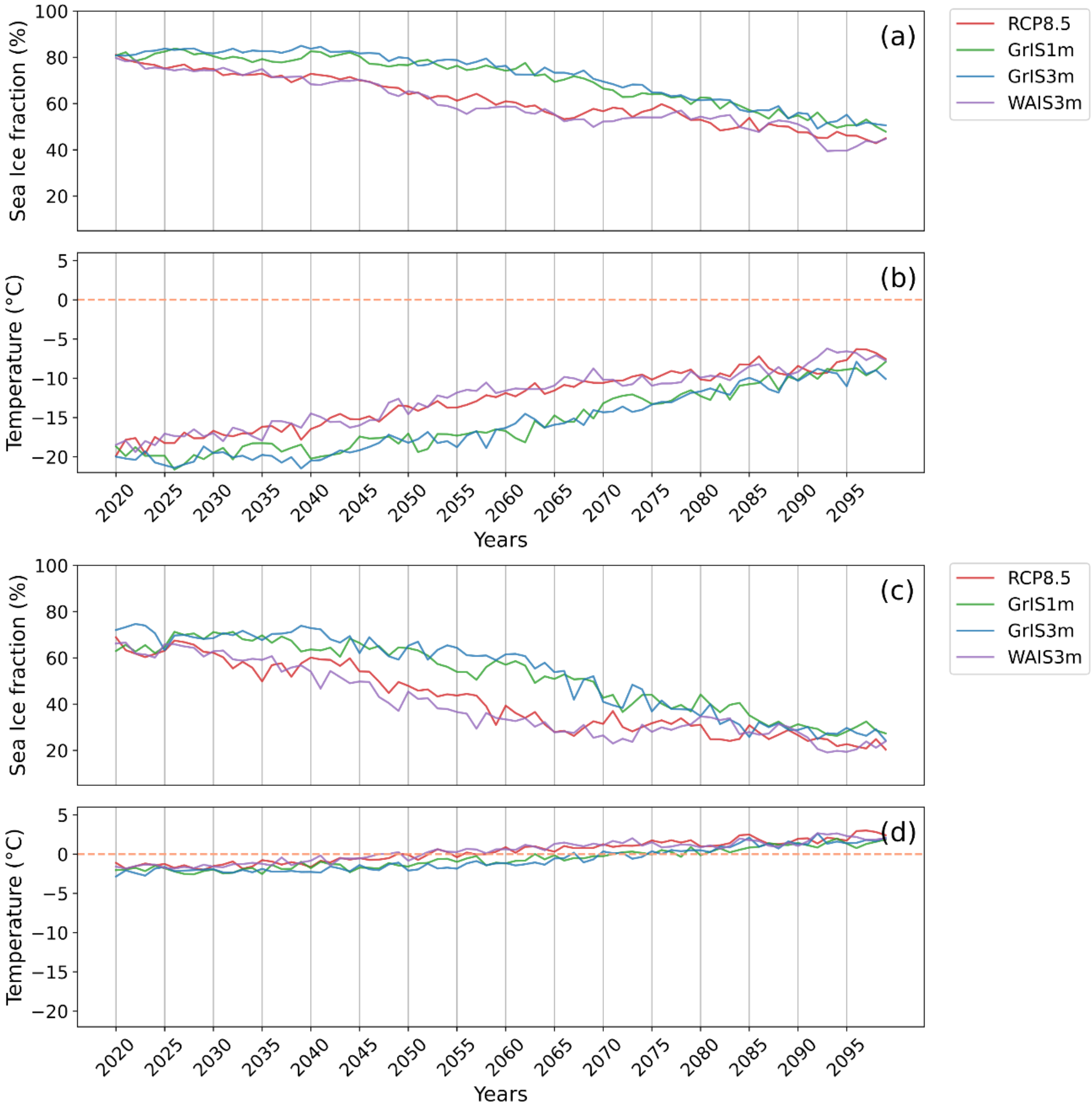

Figure 1E: Temporal evolution of a-c) sea ice fraction (%) and b-d) temperature (°C) in the Northern Hemisphere for a-b) NDJFM and c-d) MJJAS. The orange dotted line represents the 0°C isotherm.

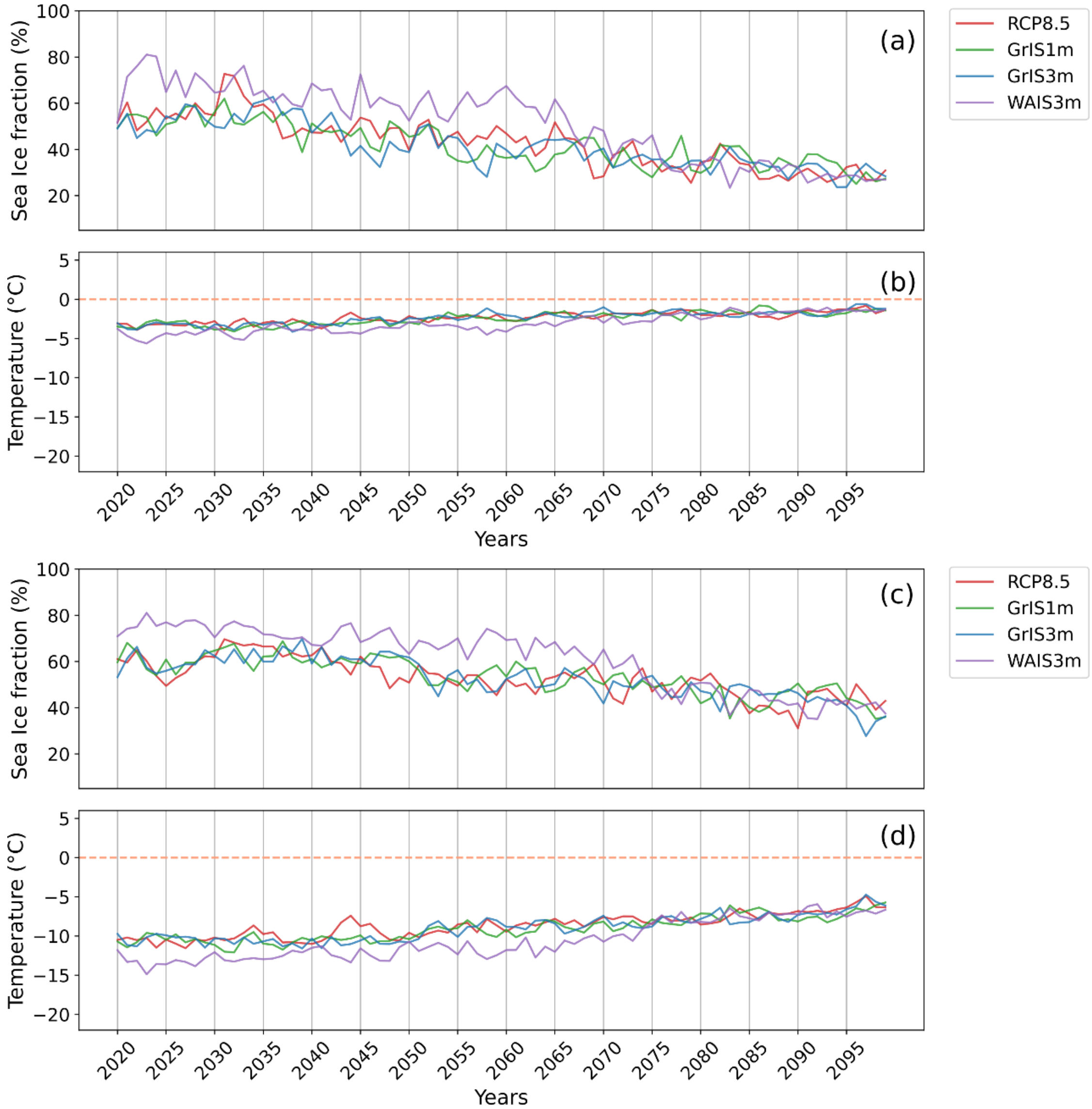

Figure 1F: Temporal evolution of a-c) sea ice fraction (%) and b-d) temperature (°C) in the Southern Hemisphere for a-b) NDJFM and c-d) MJJAS. The orange dotted line represents the 0°C isotherm.

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.

Lines: 115-117: "A slowdown of the AMOC will have 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

- *Biasutti, Michela, and Adam H. Sobel. "Delayed Sahel rainfall and global seasonal cycle in a warmer climate." Geophysical Research Letters 36.23 (2009).*
- *Chassignet, Eric P., et al. "Impact of horizontal resolution on global ocean–sea ice model simulations based on the experimental protocols of the Ocean Model Intercomparison Project phase 2 (OMIP-2)." Geoscientific Model Development 13.9 (2020): 4595-4637.*
- *Dufresne, J-L., et al. "Climate change projections using the IPSL-CM5 Earth System Model: from CMIP3 to CMIP5." Climate dynamics 40.9 (2013): 2123-2165.*
- *Fox-Kemper et al., Ocean, Cryosphere and Sea Level Change. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press. In Press. (2021)*
- *Jackson, Laura C., et al. "Impact of ocean resolution and mean state on the rate of AMOC weakening." Climate Dynamics 55.7 (2020): 1711-1732.*
- *Jullien, Swen, et al. "Impact of ocean–atmosphere current feedback on ocean mesoscale activity: Regional variations and sensitivity to model resolution." Journal of Climate 33.7 (2020): 2585-2602.*
- *Kirtman, Ben P., et al. "Impact of ocean model resolution on CCSM climate simulations." Climate dynamics 39.6 (2012): 1303-1328*
- *Liu, W. and Hu, A., 2015. The role of the PMOC in modulating the deglacial shift of the ITCZ. Climate Dynamics, 45, 3019-3034.*
- *Merino, Nacho, et al. "Impact of increasing Antarctic glacial freshwater release on regional sea-ice cover in the Southern Ocean." Ocean Modelling 121 (2018): 76-89.*

- *Song, F., Leung, L.R., Lu, J., Dong, L., Zhou, W., Harrop, B. and Qian, Y., 2021. Emergence of seasonal delay of tropical rainfall during 1979–2019. Nature Climate Change, 11, 605-612.*

Reviewer 2

Chemison et al. investigate the impact of ice sheet melting in Greenland and Antarctic on global monsoon using IPSL-CM5A-LR with freshwater hosing experiments. They find that freshwater input to sea from Greenland and Antarctic has different impacts. The former may slowdown the Atlantic meridional overturning circulation, and result in a southward shift of rain belt and thus monsoon in American and Africa. However, the impact of freshwater input from Antarctic is moderate due to circumpolar current dilution. They also study the changes in some monsoon index to depict the details of monsoon changes.

I find this study is interesting because the climatic and hydrological impacts of ice melting and freshwater input are unclear and have large uncertain. This study may improve our understanding of future monsoon change and the underlying mechanisms.

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

However, in some sections, such as the introduction and results, the authors present quite a large amount of details of all monsoon regions one by one which is hard to follow. The coherence should be improved. In addition, the methodology and novelty need to be clearly presented or highlighted before publication.

Answer: We tried to simplify the introduction and avoid repetitions. We also underlined the novelty of this manuscript.

Major comments:

Freshwater input is added continuously between 2020 and 2070. What is the rate of release each year? Is it constant during the 50-yr period? More details on the process of release will aid the reader to fully understand the setup of the water hosing experiments and your analysis. I think something like Figure 3 is a good example.

Answer: The annual rate of freshwater release is constant during the 50-yr period (2020-2070). The flow rate is 0.68 Sv for the GrIS3m and WAIS3m scenarios and 0.22 Sv for the GrIS1m scenario. 1 Sv corresponds to $10^6\ m^3.s^{-1}$. The annual volume of freshwater release is 21 444, 480 $km^3.year^{-1}$ for GrIS3m and WAIS3m and 6 937,920 $km^3.year^{-1}$ for GrIS1m (see details below).

$0,68.10^6 * 3600 * 24 * 365 = 21\ 444\ 480.\ 10^6\ m^3.year^{-1}$ and so 21 444,480 $km^3.year^{-1}$

$0,22.10^6 * 3600 * 24 * 365 = 6\ 937\ 920.\ 10^6\ m^3.year^{-1}$ and so 6 937,920 $km^3.year^{-1}$

We added the following sentence [lines 173-174]: "The annual rate of freshwater release (0.68 Sv or 0.22 Sv depending on the simulation) is constant over 2020-2070."

Lines 112-115, and Lines 381-387: It seems that some previous studies have done similar work to yours. What's the difference and did you gain some new findings in this work? Your novelty and key results should be highlighted.

Answer: The main novelty of our study relies on a detailed analysis of monsoons response to rapid ice-sheet melting at the ocean-atmosphere-cryosphere interface. Former work from our team focused on the African monsoon (Defrance et al., 2017) and the Köppen classification at global and regional scale, while omitting a detailed analysis of all monsoon systems and mechanisms at play (changes in large scale dynamics and relationship between rainfall and moist static energy).

To underline the innovative aspect of our study we have added the following paragraphs:

In introduction:

Lines: 133-138 "Previous studies have shown that freshwater release from melting ice sheets can have a major impact on climate (Defrance et al., 2017, Defrance et al.2020). However, the response of global and regional monsoons to such rapid ice melting has not been investigated in great details. The main objective of this study is to determine the impact of melting ice sheets on global monsoon but also on each regional monsoon using detailed analysis of mechanisms at play. In this study we highlight potential changes in rainfall seasonality and intensity using Hovmöller diagrams. We also investigate mechanisms at play at the ocean-atmosphere-cryosphere interface and assess the relationship between rainfall changes and moist static energy using the IPSL-CM5A-LR model."

Line 380: The choice of scenarios and climate models has a strong impact on the robustness of the results. What is the impact of the two factors on your results?

Answer: This sentence in the text was not very clear. We discuss the differences between our scenarios extensively in the text, but we only used one climate model (a multi-model risk assessment would require more funding and partners involved). This statement is based on a study by Stouffer et al, 2006, which is a multi-model analysis of the impact of different freshwater release simulations. We have added details to this paragraph to improve clarity:

Lines: 420-433 "The choice of scenarios and climate models has a strong impact on the robustness of the results as demonstrated by Stouffer et al. (2006). Stouffer et al. (2006) conducted a multi-model analysis in pre-industrial climatic conditions using freshwater inputs of 0.1 Sv and 1 Sv (to compare to 0.22 Sv and 0.68 Sv in our simulations). All climate models simulate a temperature decrease over the Northern Atlantic and Greenland, consistently with our findings, but the responses between climate models vary significantly over other regions of the Northern Hemisphere. A southward shift of the ITCZ is also simulated by other climate models and this change was robust with the addition of +1 Sv. Pressure gradients change, resulting in a north-south pressure force that pushes the rain belt southward, this phenomenon is also confirmed by the proxy studies carried out by Mulitza et al. (2008); Marzin et al. (2013b) and Liu et al. (2020). The addition of fresh water into a hemisphere leads to cooling of that hemisphere and a southward shift of the ITCZ is simulated in response to fresh water inputs in the North Atlantic, regardless of the selected climate model. Regarding the choice of scenario, the northern or southern location of freshwater input plays a crucial role in the see-saw effect. The amount of added water also impacts the intensity of changes. For example, the spatial and temporal trends between the

GrIS1m and GrIS3m scenarios are similar, but much more pronounced with the latter for which a larger amount of freshwater is released. For the WAIS3m scenario, the freshwater disturbance tends to be diluted by circumpolar currents in our simulations."

The authors study the monsoon changes at both global and regional scales. However, global monsoon includes land and sea areas while regional monsoon is only limited to land area. This should be clearly noted in the methodology, subtitle or caption. Please add "land monsoon" or something similar to avoid misunderstanding.

Answer: This is an important point indeed. For the sake of clarity, we have modified the methodology section as follows:

Lines: 206-209 "Monsoon areas consist of any land grid point corresponding, in at least one of the simulations, to the aforementioned criterion (Lee and Wang, 2014). Thus, the selected monsoon areas include monsoon regions for historical and scenario simulations (RCP8.5, GrIS1m, GrIS3m, WAIS3m). All land grid points per monsoon region were retained to derive spatial averages, except for the AUSMC box for which one outlier (southernmost point) was removed. Only Land data was considered."

Lines: 229-232 "Six indices, defined by the Expert Team on Climate Change Detection and Indices (ETCCDI), were used to determine changes in daily rainfall extremes and statistics per land monsoon region (Sillmann et al., 2013): the average precipitation (Pav), the number of rainy days (R1mm), simple precipitation daily intensity index (SDII), seasonal maximum 5 days precipitation total (RX5day), seasonal maximum consecutive dry days (CDD) and seasonal maximum consecutive wet days (CWD)."

Accordingly, we also updated the following captions:

"Table 2. Definition and description of land monsoon indices, during monsoon period, used in this study."

"Figure 10. Comparison of the interannual variability of each land monsoon index for the period 2041-2070 with the average of the historical period (1976-2005) for a) NAMS, b) SAMS, c) NAF, d) SAF, e) SAS and for each simulation. RCP8.5 is shown in red, GrIS1m in green, GrIS3m in blue and WAIS3m in purple."

Minor comments:

Line 16: tropical regions with perennial rain regime are not belong to monsoon regions.

Answer: Corrected

Lines: 17-19 "Monsoons influence tropical regions without perennial rain regime, providing the vast majority of rainfall in one season (Wang and Ding, 2006). Consequently, monsoons have a significant impact on two thirds of the world's population (Wang and Ding, 2006; Moon and Ha, 2020)."

Line 19: add some early seminal refs on land-sea temperature contrast in addition to Zhou and Zou, 2010, such as Li et at al., 1996.

Answer: We have added the reference to Li et al., 1996, as well as two references (Sutton et al., 2007 & Fasullo, 2012) about changes in ocean-land temperature contrasts in the context of climate change.

Lines: 20-24 "Monsoons are related to atmospheric moisture content, land–sea temperature contrast (Li and Yanai, 1996; Sutton et al., 2007; Zhou and Zou, 2010; Fasullo, 2012), thermodynamic and dynamic features (Kitoh et al., 2013; Endo and Kitoh, 2014), land cover and use (Timbal and Arblaster, 2006), atmospheric aerosol loadings (Lau et al., 2008) and vegetation physiological effect of rising atmospheric CO2 (Cui et al., 2020)."

Lines 19-20: monsoon is also impacted by other possible drivers such as thermodynamic and dynamic (Kitoh et al. 2013; Endo et al., 2014), vegetation physiological effect of rising atmospheric CO2 (Cui et al. 2020).

Answer: Agreed, see former paragraph.

Line 21: the order of first and last names of the authors is not correct. Please check.

Answer: Thank you we have carefully checked but we have not found the error. Only the last names are listed in the core text and we did not find an error in the bibliography at the end of the paper.

Line 31: important?

Answer: Yes, we think this is an important precision. This is a well-known bias in the literature and for ethical purposes it is an important uncertainty to mention. Moreover, it justifies our choice to study a long time period (30 years) in the medium term (2040-2070).

Lines 33-34: total precipitation is projected to decreases in the North American monsoon regions by CMIP5/6, e.g. Wang et al., 2021.

Answer: We have added the reference to Wang et al., 2021 to mention differences across GCMs.

Lines: 58-59 "For the NAMS, a decrease in precipitation is simulated over the 21st century, although significant differences are shown across GCMs (Wang et al., 2021)."

Lines 43-66: the authors only list previous studies by monsoon regions and some of them are common knowledge. Shortening these sections may improve the coherence and legibility.

Answer: We did our best to reduce this section, but another reviewer asked to include more references so we have tried to simplify this paragraph while adding extra references. We hope that this part now reads better but it is still detailed.

Figure 4f ,h: the precipitation shows contrasting change in north and south Equator at very short distance in tropical America and Atlantic. What's the reason for this strange phenomenon?

Answer: The release of fresh water into the North Atlantic modifies the wind and pressure patterns (Figure 4f-h). An increase in pressure is shown where a significant decrease in rainfall is also shown in Northern Hemisphere particularly visible between 60°West and 120°West and between 0 and 30°North. In the southern hemisphere, in the Atlantic near the equator, decrease in atmospheric pressure is associated with a rainfall increase. This is a dynamical shift, pressure changes push the rain band southward. In addition, changes in Moist Static Energy (MSE) are consistent with simulated rainfall changes in the Tropics (the MSE analysis was required by another reviewer).

Line 278: how did you infer double ITCZ from Figure 6?

Answer: The double ITCZ is shown on Figure 6 with the presence of two distinct rain bands over the Pacific Ocean, which is a standard bias in coupled GCMs. We have added this precision:

Lines: 307-308 "All model experiments tend to simulate a double Intertropical Convergence Zone (ITCZ), highlighted by the presence of two distinct rain bands over the Pacific Ocean, a classical drawback in state-of-the-art GCMs (Fig. 6)"

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Reviewer 3

The manuscript “Impact of an acceleration of ice sheet melting on monsoon systems” uses the AOGCM IPSL-CM5A to investigate the impact of fresh water input from ice sheet melting over Greenland or the Antarctic on top of RCP8.5 scenario, with a particular focus on the response of global major monsoon systems. It is found that the Antarctic fresh water input has moderate global impact due to dilution by the circumpolar current. However, Greenland ice sheet melting fresh water input is able to significantly slow down the AMOC and shift ITCZ southward due to energy constraint (Schneider et al. 2014). As a result, some regional monsoons closely linked to ITCZ shift are greatly impacted, which include later (earlier) onset of North (South) American monsoon and drying (wetting) North (South) African monsoon. However, the response of the Asian and Australian monsoons, which are weakly linked to ITCZ shift, is not clear.

Monsoon variability and response to external forcings are very important topics in climate science given its impact on a large number of population and yet it is a great challenge due to the complexity of the system that involves interaction of various components. Overall, this is an interesting study and highlights one important driver (fresh water input from ice sheet melting) in the future warming climate that is often neglected in model simulations and projections. I recommend publication after concerns from the reviewer being addressed.

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

Major comments:

1. The spatial resolution of the atmospheric component (3.75 deg longitude x 1.875 deg in latitude) is relatively low and might not be able to capture some key effect of high orography, which is crucial for some monsoons (e.g the Asian monsoon in Boos and Kuang 2010 and the North American monsoon in Boos and Pascale 2021). The authors need to discuss if the major results are sensitive to the spatial resolution.

Answer: The low spatial resolution of IPSL-CM5A-LR is indeed a caveat. 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). 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. 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, which has a strong impact on the Asian monsoon (Boos and Kuang, 2010), 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)."

2. The study focuses on multiple regional monsoons in response to ice sheet melting fresh water input but lacks some process-based analysis to answer the question of why the response is way it is. Examples of such analyses include moisture static energy (MSE) budget analysis as in Seth et al. 2013, Hill et al. 2017 and Jacobson et al. 2020, which may provide deep insight into the response of monsoons. I recommend the authors conduct similar analysis, or add some discussion on the limitation of the scope of current manuscript if the authors would like to leave such analysis in future study.

Answer: This is a good point. Following your comment, we carried out a moisture static energy (MSE) analysis similar to the one presented by Seth et al. 2013 (in figure 4). Our analysis is based on the MSE difference between 200 and 850 hPa (proxy of atmospheric stability/instability). Then, we show future differences of this MSE vertical gradient on Figures 7-8-9 and Figure B1 in Supplementary materials. Theoretically, when the MSE anomaly increases, the stability between the surface and the upper atmospheric layers increases, which leads to a decrease in simulated precipitation. Conversely, a decrease in the MSE anomaly causes a reduction in vertical stability and thus an increase in precipitation (Seth et al., 2013).

We have added the following paragraph in Methodology:

Lines 206-227: "Monsoon areas consist of any land grid point corresponding, in at least one of the simulations, to the aforementioned criterion (Lee and Wang, 2014). Thus, the selected monsoon areas include monsoon regions for historical and scenario simulations (RCP8.5, GrIS1m, GrIS3m, WAIS3m). All land grid points per monsoon region were retained to derive spatial averages, except for the AUSMC box for which one outlier (southernmost point) was removed. Only Land data was considered. To better understand simulated precipitations changes, we calculated Moist Static Energy (MSE) in $J.kg^{-1}$ as follows:

$$MSE = cpT + gZ + Lq$$

Cp ($J.kg^{-1}.K^{-1}$) is the the specific heat at constant pressure, T (K) is the layer temperature, g ($m.s^{-2}$)is the gravity constant, Z (m) is the geopotential height, L ($m^2.s^{-2}$)is the latent heat of evaporation and q ($kg.kg^{-1}$) is the specific humidity.

Hovmöller diagrams were derived for each land monsoon region. Rainfall was averaged longitudinally. They represent the average monthly precipitation over our 30-year study period. Then, the difference between the future period (2041-2070) and the historical period (1976-2005) was calculated. The statistical significance of this difference was evaluated using the Wilcoxon-Mann-Whitney test for p-values greater than 0.05 (Seneviratne et al., 2013). For each land monsoon area, Δ MSE, the difference between the MSE at 200 hPa and 850 hPa, was calculated following Seth et al., 2013.

$$\Delta MSE = MSE200 - MSE850$$

Then, the Δ MSE difference between the future and historical period is calculated for each future simulation and for each region (Δ MSE anomaly hereafter). Δ MSE anomaly was averaged longitudinally and monthly and overlaid on the Hovmöller precipitation diagrams.

Hovmöller diagrams are shown for NAMS, SAMS, NAF, SAF and SAS. Diagrams for AUSMC and EAS are presented in Appendix C. It is noteworthy that changes for AUSMC and EAS are mostly non-significant and too few land pixels were available for the AUSMC region."

Supplementary information was added in results:

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 decrease. 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)."

A more detailed regional analysis of future changes in MSE at 850 hPa and 200 hPa is provided below for the NAMS region:

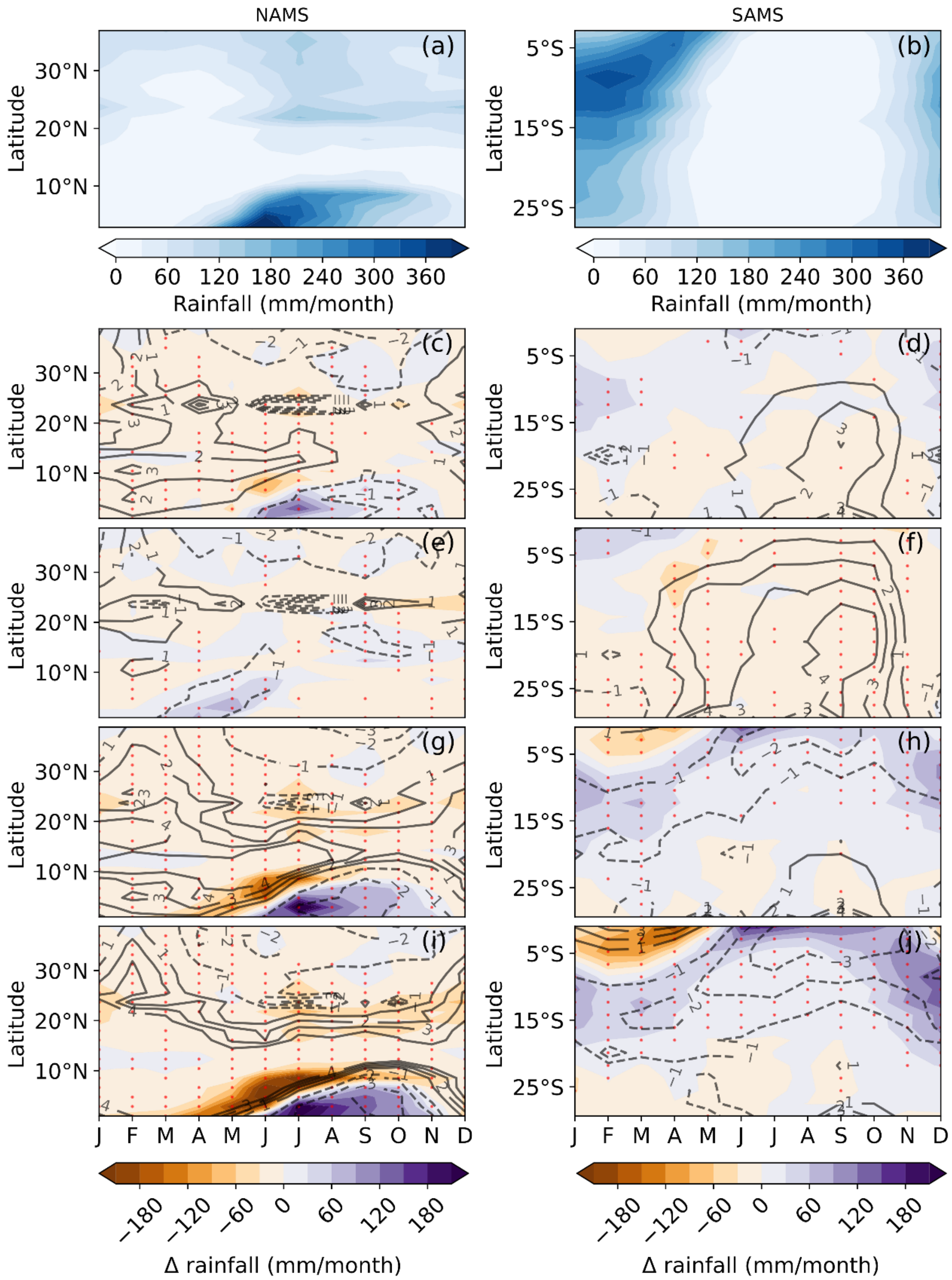

Figure 3A: Hovmöller Diagram for the American continent domains. The left column corresponds to the NAMS domain (a,c,e,g,i) and the right column to the SAMS domain (b,d,f,h,j). a.b) correspond to the precipitation values in mm month−1 over the historical period (1976-2005). All other diagrams correspond to the precipitation difference (colors) and the MSE difference (black contours, dashed lines for negative values) between the future scenario (2041-2070) with c,d) RCP8.5, e,f) WAIS3m, g,h) GrIS1m and i,j) GrIS3m and the historical period (1976-2005), in mm month−1. Significant differences at the 95 % confidence *interval are depicted by red dots according to the Wilcoxon-Mann-Whitney test (see Sect. 2.3).*

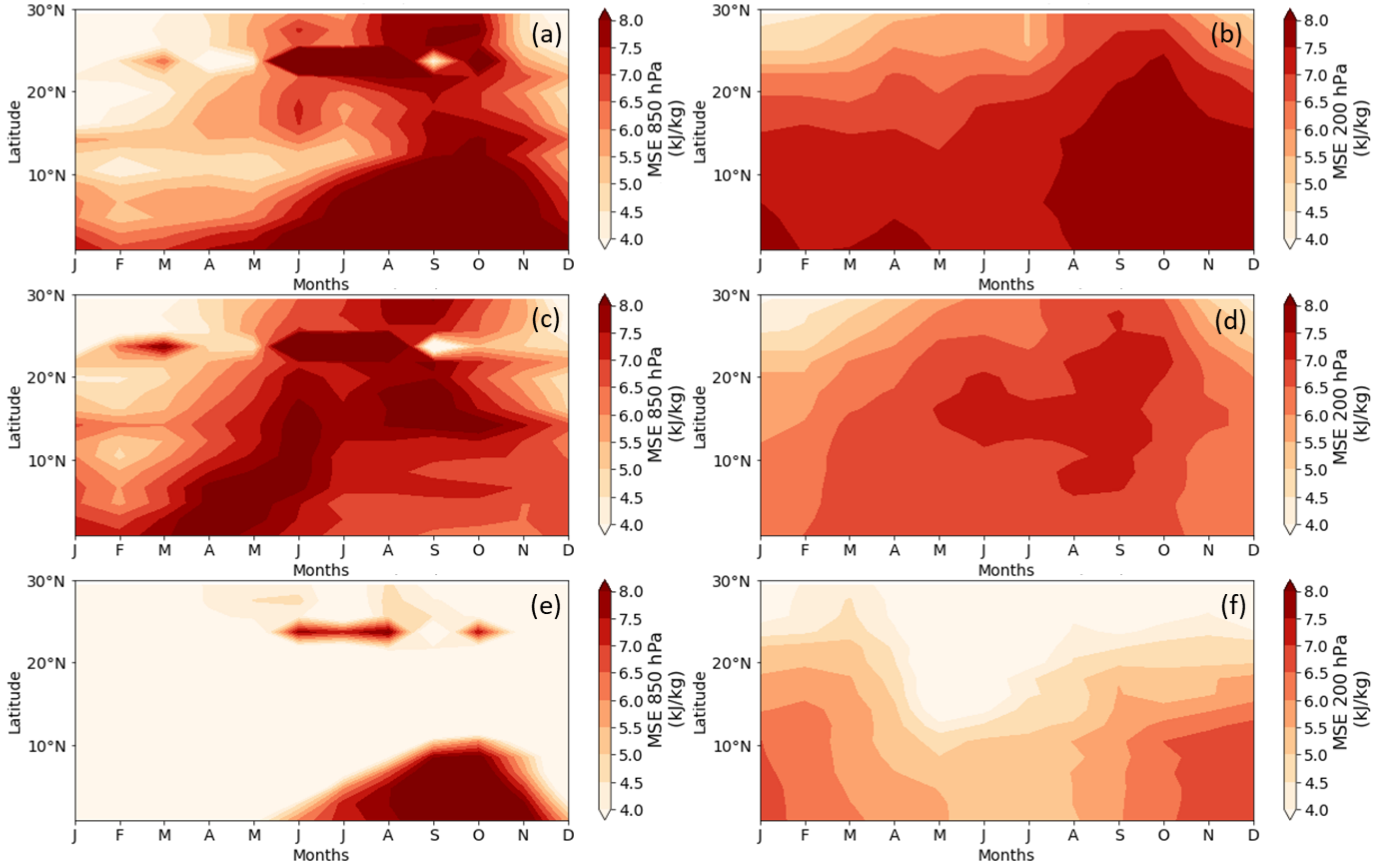

Figure 3B: Hovmöller Diagrams of the MSE difference at a-c-e) 850 hPa and b-d-f) 200 hPa, between future scenario and historical simulation for the NAMS domain for a-b) the RCP8.5 scenario, c-d) WAIS3m scenario and e-f) GrIS3m.

For the NAMS region, a delay in the rainy season is simulated in spring with the standard scenario RCP8.5 (Fig 3A.c) and is associated with an increase in MSE. Then, during the wet season, larger rainfall is simulated further south during the rainy season and is associated with a decrease in MSE.

If we focus on MSE changes at different altitudes:

- RCP85 (Figure 3B.a-b): At low level (850 hPa) there is an increase in MSE from June to December. At the top of the troposphere (200 hPa), there is a major increase in MSE from August to December. The difference between 200 and 850 hPa is therefore negative in June and July with an associated increase in precipitation at low latitudes. The MSE increase is almost zero at 850 hPa from January to May, which leads to an increase in Δ MSE anomaly associated with a drying that is not apparent because it occurs during the dry season. However, such changes in MSE may lead to a slight rainfall delay during the wet season at low latitudes.

- WAIS3m (Figure 3B.c-d): At 850 hPa, MSE mainly increases in March, April and May. At high latitudes this increase mostly occurs during the wet season. Decrease in Δ MSE is associated with a slight increase in precipitation and an earlier start of the wet season.

- GrIS3m (Figure 3B.e-f): At 850 hPa, the MSE increase is located between the equator and 10°N from June to December. At high altitude the MSE increase is mostly located between the equator and 20°N and during the dry season. At high altitude the decrease in MSE does not impact precipitation because the changes at both low and high levels are almost zero. At about 20°N the increase in MSE (linked to the simulated increase at 200 hPa, thus linked to the increase in temperature) leads to a slight drying. Largest changes are simulated between the equator and 10°N. From March to May (and from May to August at higher latitudes) the increase in MSE leads to a decrease in precipitation and thus to a delay in the wet season. On the other hand, from June onwards, there is a very strong increase in surface MSE (latent heat flux, hence moisture input) which leads to a negative MSE anomaly associated with a strong increase in precipitation during the wet season which extends until November.

Specific comments:

Page 1, lines 16-17: add some references to this statement.

Answer: We added references to Wang and Ding, 2006 & Moon and Ha, 2020:

Lines: 17-19 "Monsoons influence tropical regions without perennial rain regime, providing the vast majority of rainfall in one season (Wang and Ding, 2006). Consequently, monsoons have a significant impact on two thirds of the world's population (Wang and Ding, 2006; Moon and Ha, 2020)."

Page 3, lines 69-71: add some references to the statements. Also notice that the confidence on the future projection of East African rainfall can be greatly reduced given the bias of simulation in the current climate (see Yang et al. 2015).

Answer: Following comments from other reviewers we have shortened this paragraph that describe the evolution of regional rainfall. Following your advice, we have added references Ongoma et al., (2018), Yang et al., (2015), Biasutti et al., (2009), Biasutti, (2013), Seth et al., (2013) to:

Lines: 65-74 "Over eastern Africa, two rainy seasons occur: the so-called short rains from October to December and long rains from March to May. A significant increase in future rainfall during the long rainy season is usually simulated over East Africa, (Ongoma et al., 2018), although important biases exist in this region (Yang et al., 2015). For the West African monsoon, there are large rainfall differences simulated across GCMs (Biasutti et al., 2009; Monerie et al., 2020). However, simulated trends for CMIP3 and CMIP5 are similar with drying simulated during spring and an increase in precipitation simulated in summer (Biasutti and Sobel, 2009; Christensen et al., 2013; Biasutti, 2013; Seth et al., 2013). Dunning et al. (2018) show a later onset of the monsoon season with a northward shift of the rainbelt between August and December. The study of Biasutti and Sobel (2009), based on CMIP3 models, projects a shorter rainy season with a late start of the semi-arid African Sahel. A delayed start of the rainy season has also been demonstrated by Song et al. (2021)

using observed precipitation data. An extension of the dry season is simulated over the southern part of Africa (Mariotti et al., 2014).”

Table 2:

The equation of Pavj: "I" doesn't appear in the equation. Do you mean \Sigma_{I=1}^{I} by \Sigma_{n=1}^{I}?

The equation of SDIIj: Is "W" instead of "w" the last value in the sigma notation, i.e. (\Sigma_{w=1}^{W}PRwj)W^{-1} instead of (\Sigma_{w=1}^{w}PRwj)W^{-1}?

Answer: Yes, you are right, we have modified this table accordingly.

Figure 2:

Use consistent latitude format as in other figures (e.g. 20S and 20N instead of -20 and 20).

Answer: Corrected

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