Final Response to Referee #1

We thank the reviewer Maria Fernanda Sanchez Goñi for the careful and thorough reading of our manuscript. The comments have been carefully considered and responded. Please find below our response to each comment.

General comments

1. ***The manuscript submitted by Velasquez et al. to the Climate of the Past presents a combination of global and regional model simulations to test the sensitivity of the glacial Alpine hydro-climate to northern hemisphere, Laurentidae and Fennoscandian, and local ice-sheet changes during the Last Glacial Maximum (LGM) and Marine Isotope Stage (MIS) 4. For the LGM, they find that thickening of the northern hemisphere ice-sheets, mainly the Laurentidae ice caps, and local ice-sheet topography generally lead to increase in winter precipitation and decrease in summer rainfall, both enhancing glacial conditions. In winter, dynamics processes related to the intensity and position of the Alpine winds explain the moistening in the southern part of the Alps while the simulated summer drying all over the Alps is related to thermodynamic processes, i.e. colder temperatures. In contrast, Fennoscandian ice-sheet changes have a negligible impact on the Alpine hydro-climate. For MIS 4, marked by lower global ice volume than the LGM, Velasquez et al. find wetter climate in the Alps attributed to thermodynamic processes, i.e. warmer temperatures. This manuscript is clearly written and convincing for the LGM. In contrast, I have several caveats related to the MIS 4 model results and comparison with the regional (western European) climate at that time when compared to that of the LGM (see below). Overall, this work deserves publication in CP after the authors address the comments that I have listed below. I am not a modelling expert, and I will only comment on the data discussed in this work.***

RESPONSE:

We thank you for your detailed comments. We will take care of the concerns related to analysis of the MIS4 climate and the comparison with the LGM in the following responses and in the revised manuscript.

Major comments

2. ***Lines 40-50: It would be relevant to cite the paper by Harrison and Digerfeldt (1993, Quaternary Science Reviews), one of the first paper showing that southern Europe was wet during the LGM (centered at 21 ka) based on the high water levels recorded in several lakes around the Mediterranean region. Iberian margin pollen records also provide evidence that the LGM in southern Europe was wetter than the Heinrich Stadial (HS) 2 and HS 1 bracketing it (Naughton et al., 2007, Marine Micropaleontology ; Turon et al., 2003, Quaternary Research).***

RESPONSE:

We agree that some pollen-based reconstructions show a wetter southern Europe compared to present day. Therefore, we will reformulate these lines (lines 40-50) and add this information in the revised version of the manuscript. Additionally, we will mention other studies that highlight the wetter conditions in southern Europe compared to other periods, e.g. Heinrich Stadials and Marine Isotope Stages. The changes will be done as follows:

"…The same data is also used to reconstruct the hydro-climatic response over Europe at LGM mainly showing drier conditions over Europe (reduction in precipitation of around 200 mm year^{-1}) compared to PD (Wu et al., 2007; Bartlein et al., 2011). Roucoux et al. (2005) indicated that the LGM was not necessarily a dry period everywhere in Europe. For instance, Turon et al. (2003); Roucoux et al. (2005); Naughton et al. (2007) and Ludwig et al. (2018) suggested that southern Europe was wetter compared to the rest of Europe and also to adjacent periods, i.e. the Marine Isotope Stage 3 (Voelker et al., 1997; Kreveld et al., 2000) and to the Heinrich event 1 and 2 (Sanchez Goñi and Harrison, 2010; Álvarez-Solas et al., 2011; Stanford et al., 2011). Compared to PD, many studies suggest that the wetter conditions in southern Europe can be explained by a southward shift in the North Atlantic storm track during the LGM (e.g. Hofer et al., 2012a; Luetscher et al., 2015; Merz et al., 2015; Ludwig et al., 2016; Wang et al., 2018; Raible et al., 2020; Lofverstrom, 2020). This southward shift is in line with other climate reconstructions that suggest circulation-induced changes in the moisture transport. For instance, Harrison and Digerfeldt (1993) found very different patterns of lake-level changes across Europe suggesting major changes in European atmospheric circulation patterns. Other climate reconstructions also suggest circulation-induced changes in the moisture transport (Florineth and Schlüchter, 2000). In this case, the atmospheric circulation is…"

3. ***Lines 50-54 and lines 407-415: To support the idea that MIS 4 was warmer and wetter than the LGM, Velasquez et al. only refer to global studies (Eggleston et al., 2016), Australasian records (De Deckker et al., 2019 ; Newham et al., 2017) and model simulations for the North Atlantic and Greenland climate (Hofer et al., 2012; Merz et al. papers) that cannot be used to account for the climate in Europe at that time and, particularly, at 65 ka, the date chosen for their simulations. This date is concomitant with the maximum of global ice volume during MIS 4 (Waelbroeck et al., 2002, Quaternary Science Reviews), coincides, within the chronological uncertainties, with Greenland Interstadial 18 and precedes the massive iceberg discharges in the North Atlantic leading to the HS 6, 64-60 ka (Sanchez Goñi et al., 2013, Nature Geoscience, Figure S3 of the supplementary information).***

To realistically compared the recorded and simulated climate in Europe at 65 ka, the authors should discussed their wind field and climate reconstructions in the context of the climate prevailing in the western European margin and the adjacent landmasses during this period, climate that is mainly controled by the westerlies during winter. The work by Sanchez Goñi et al. (2013, Nature Geoscience, Figure 2 and Figure S3 of the supplementary information) zooms in on MIS 4, and shows relatively wet and warm atmospheric conditions at 65 ka, based on the increase of heathlands and pine forest, contemporaneous with foraminifera-based warm summer sea surface temperatures in the western European margin, reaching 15°C in the Bay of Biscay and the SW Iberian margin and 10°C in the NW Iberian margin. However and in contrast with the authors' idea that the LGM was colder than MIS 4 in the European margin, higher sea surface temperatures in the Bay of Biscay (Sanchez Goñi, 2020, Evolutionary Human Sciences, Figure 2) and in NW and SW Iberia (Sanchez Goñi et al., 2008, Quaternary Science Reviews, Figures 3 and 4) are recorded during the LGM compared to MIS 4. Both periods are characterised by low and similar temperate forest abundance and similar heathlands development suggesting that MIS 4 was not warmer and wetter compared to the LGM.

RESPONSE:

We agree that the description of MIS4 is too short and the citations do not focus on the Europe climate. We thank the reviewer for highlighting these studies. In the revised manuscript, we will further introduce the MIS4 climate and briefly discuss its uncertainties. Therefore, we will include the studies of Sánchez Goñi et al. (2008) and Sánchez Goñi (2020) and we will also reformulate these lines and add more information as follows:

Lines 50-54:

"...MIS4 climate is less understood compared to LGM as proxy data availability is further reduced compared to the LGM. Globally, available paleoclimate reconstructions characterise MIS4 to be warmer than the LGM (e.g. Eggleston et al., 2016; Newnham et al., 2017; De Deckker et al., 2019) with a sea level drop of roughly 80 m compared to PD (e.g. Cutler et al., 2003; Siddall et al., 2008, 2010; De Deckker et al., 2019). Focusing on Europe, MIS4 shows relatively wet and warmer conditions at 65 ka compared to the period 85-50 ka (Sánchez Goñi et al., 2013). Still, Sánchez Goñi et al. (2008) and Sánchez Goñi (2020) found drier and colder conditions around the Iberian Peninsula during MIS4 compared to the LGM. This might suggest, similar to the LGM period, that the MIS4 climate was not necessarily homogeneously wetter and warmer across Europe."

Lines 407-415:

"...The MIS4 ($MIS4_{LGM}$) climate shows enhanced winter precipitation compared to the LGM. The reason is that the MIS4 climate state is in general warmer (Hofer et al., 2012a,b; Merz et al., 2013, 2014a,b, 2015, 2016) and thus more moisture is globally available. Wind changes do not contribute to these wetter conditions in the Alpine region as they become weaker and therefore reduce the orographically forced uplifts, which also suggests an overall reduction of the moisture transport to the Alps. Thus, we interpret the winter changes between MIS4 and LGM to be purely thermodynamically driven (Clausius–Clapeyron equation). In summer, $MIS4_{LGM}$ shows slightly wetter conditions at the northern face and drier conditions at the southern side of the Alps. The northern wetter conditions are induced by an increase in the tropospheric vertical wind shear enhancing convection processes. The drier conditions at the southern face of the Alps are explained by slightly clockwise rotated winds, which enhance the Foehn effect. Thus, dynamical processes are also relevant to explain the summer precipitation changes between MIS4 and LGM."

4. ***Line 395-406: The authors should add in the revised version of the manuscript the new evidence from a cryogenic carbonate record in the Alps (Spötl et al., 2021, Nature Comm.) showing heavy snowfall during autumn and early winter during the LGM. These results combined with thermal modelling, provide compelling evidence that the LGM glacier advance in the Alps was fuelled by intensive snowfall late in the year, likely sourced from the Mediterranean Sea.***

RESPONSE:

We appreciate the reviewer to bring to our attention this study. We will include this new evidence in the discussion and conclusions part of the revised version.

5. ***Lines 436-440: The authors should delete the references of Finlayson et al., 2004, 2006 and 2008 and that of Burke et al., 2014 and Baena Preysler et al., 2019. These works do not refer to the Alpine***

regions and, therefore, they are not relevant for this study.

<u>RESPONSE:</u>

We will delete these references in the revised version of the manuscript.

<u>Minor comments</u>

m1. ***Line 72: Please add Regional Climate Models to explain RCM.***

<u>RESPONSE:</u>

We will add it in the revised version of the manuscript.

m2. ***Line 158: Please replace « «eighth experiment » with « eighth experiments ».***

<u>RESPONSE:</u>

We cannot understand your suggestion as we refer to a single experiment in this sentence, i.e. the experiment number eight. To clarify any misunderstanding, we will reformulate this line in the revised manuscript as follows:

"...In the experiment number eight, we investigate..."

m3. ***Line 255: Please replace « associated to » with « associated with ».***

<u>RESPONSE:</u>

We will replace it in the revised version of the manuscript.

We would like to thank the reviewer Maria Fernanda Sanchez Goñi for the time invested in reviewing the manuscript so carefully. We are looking forward to meeting her/his expectations.

Best regards,

Patricio Velasquez (on behalf of the author team)

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