Response to Referee 2

We appreciate the suggestions and open comments raised by Referee 2. We agree that our modeling experiment was not constructed with realistic paleoclimate forcing conditions, and that our paleoclimate suggestions should be taken carefully. Here we provide compelling evidence to sustain that our model simulations generate realistic long-term climate dynamics in response to the Pacific and Atlantic SSTs conditions used as external forcing. Despite the idealized nature of our WRF simulations, they provide novel and interesting insights into the causes and mechanism of long-term precipitation change in the Altiplano, a region where proxy and modeling data is still scarce. As stated in the discussion and conclusion of our submitted manuscript, such insights allowed us to assess the research questions raised in the introduction and they have the potential to contribute to the analysis and interpretation of regional paleoclimate reconstructions. Therefore, we consider our study to be worth publishing in Climate of the Past.

Below we have addressed the comments raised by the referee.

Referee #2 suggestions and open questions:

The general setup is very artificial, since only three years (i.e. 1983, 2003 and 2011) are simulated in a perpetual mode (under present-day conditions). This setup complicates a translation back into real world conditions. Therefore statements like „To our understanding, this study presents the first regional climate modelling experiment of long-term hydroclimate responses in the southern Altiplano, yielding novel information regarding the mechanisms that govern precipitation variability at centennial timescales." is misleading, because the simulation itself is not representing a realstic 100 year period. It is just a repetition of particular years showing above normal (neutral) precipitation over the Altiplano. At least the authors should simulate a full ENSO cycle with 7-10 years and also include more information from the Atlantic Multidecadal Variability (AMV), for a more realistic simulation of the impacts of basic modes of natural climatic variability. The authors even indicate the importance of the eastern equatorial Pacific and southwestern Atlantic in their correlation map between the SSTs and the of DJF precipitation variability in the southern Altiplano (cf. Fig S3b).

Response:

As mentioned before, we acknowledge the artificial nature of our simulations, and we agree with the referee that this should have been mentioned more clearly in the manuscript. We have now stated the idealized characteristics of our experiment in the abstract, introduction, and discussion sections of a modified version of our manuscript. Yet, the selection of the 1983/1984, 2003/2004 and 2011/2012 annual cycles to force our simulations is nor arbitrary. In section 3.1 we show that the 1983/1984 and 2011/2012 DJF seasons were both extraordinarily humid austral summers in the Altiplano (see also Fig. S4), linked to distinct, and well-defined SSTs anomalies (Fig. 2). We note that these summer seasons represent the two leading atmospheric mechanisms determining present-day interannual DJF precipitation variability in the central Andes region (Segura et al., 2020). Hence, their selection is adequate to address whether these mechanisms are able to sustain longer-term anomalies under or experimental conditions. The 2003/2004 period, on the other hand, was a neutral hydroclimate year, necessary to use as a control period to test to what extent the observed trends are developed in response to the model internal variability.

Additionally, we acknowledge that the artificial setup of our simulations implies that the paleoclimate inferences discussed in our manuscript require careful consideration. In a revised version of our manuscript, we have been explicit about these limitations at the start of the discussion section, as it was also suggested by Referee 1. Nevertheless, we contend that -despite the unrealistic nature of our experiment- our modeling results are useful to explore potential long-term precipitation trends and evaluate if the drivers of present-day humid seasons have the potential to sustain the extended pluvial events documented in published reconstructions. This information is certainly relevant for the Altiplano and for South America, where long-term climate datasets are very limited. We further maintain that we carried out an original experimental setup, identifying extraordinary hydroclimatic DJF seasons to force a detailed regional climate model. This methodology has not -to our knowledge- been employed before in this area. Hence, the sentence:

"*To our understanding, this study presents the first regional climate modelling experiment of long-term hydroclimate responses in the southern Altiplano, yielding novel information regarding the mechanisms that govern precipitation variability at centennial timescales*."

is actually not completely misleading as commented by the referee. Yet, we agree that it would be preferable to toned down the second part of the sentence to account for the uncertainties emerging for the idealize nature of our experiment:

"*To our understanding, this study presents the first regional climate modelling experiment of long-term hydroclimate responses in the southern Altiplano*. *Despite the idealized nature of our simulations, we have generated novel information regarding the potential mechanisms associated with precipitation variability at centennial timescale*s".

Regarding the simulation of a full ENSO cycle with 7-10 years and the inclusion of Atlantic Multidecadal Variability (AMV) for a more realistic simulation, we have acknowledged that our experiment does not introduce any source of interannual or decadal variability, and we have explicitly added this limitation to a modified version of our original manuscript. We did not want to focus exclusively on ENSO or the AMV for this manuscript, as the aim of the study was testing if specific oceanic/atmospheric conditions could generate extended periods of anomalous precipitation in our study region.

In Fig. 3 the authors present the summertime precipitation evolution in their 100 year perpetual model simulations. All experiments, including the control experiment show a very strong decline from approx. 700 mm to 200 mm for the high precipitation events and from 500 mm to again 200 mm for the control experiment. Here I wonder why all experiments converge to the same value of 200 mm. The control experiment exactly demonstrates that the results are based on some internal model dynamics. I would expect that when the external forcing is meteorological the same at the boundaries each year, also precipitation levels should stay at least at similar (initial) levels. Therefore the question is where does all the moisture end up ? How would an experiment with considerably lower initial summertime precipitation over the Altiplano look like ? Would this also happen in reality that the Altiplano summertime precipitation would end at 200 mm ? In this context also the question remains whether the geographical domain of the regional climate model around South America is too small to account for oceanic impact (ENSO/AMV) and how/if this information is still inherited via the borders from the driving ERA5 reanalysis over the entire 100 years cycles.

Response:

This is certainly an interesting comment that raises several issues. We will address it point by point:

"Here I wonder why all experiments converge to the same value of 200 mm"

Effectively, all simulations (including our control run) show negative precipitation trends, although not all of them converge to 200 mm as stated by the referee. The common drifts are acknowledged and discussed in the result sections of the original manuscript (lines 193-203). More importantly, the common hydroclimate trajectories in the Altiplano results from different mechanisms of atmospheric circulation and moisture transport. These differences indicate the existence of realistic, externally-driven long-term dynamics in each simulation, which are discussed in the manuscript and can clearly be observed in the Fig. A below, which tracks the differences in specific humidity between the start and final periods of our three simulations:

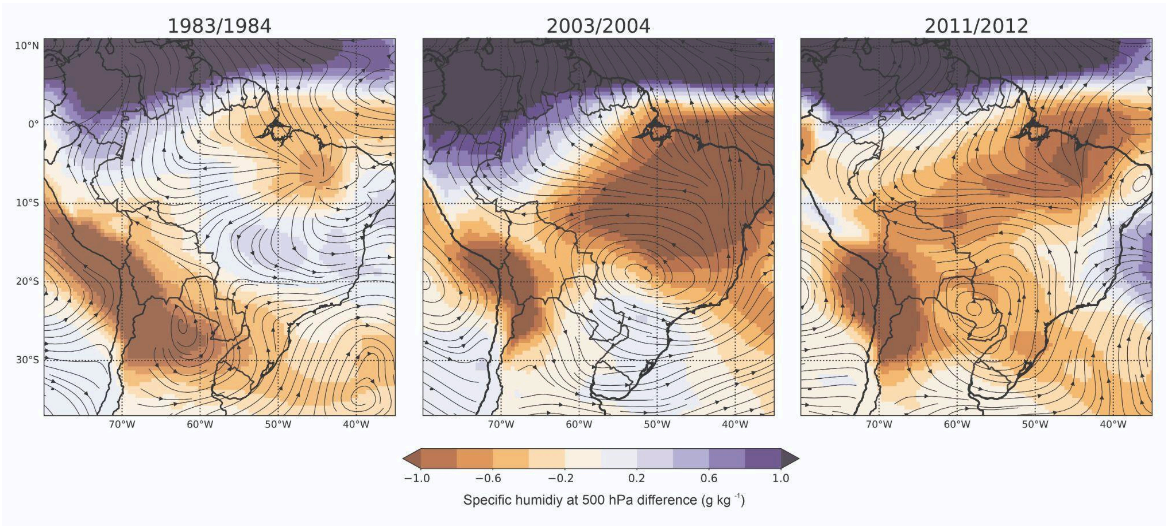

Figure A: Comparative panel depicting differences between the averaged specific humidity at 500 hPa (colored), along with composite lower-level (800 hPa; streamlines) zonal/meridional circulation during the initial and final decades of the WRF simulations.

Although all three simulations show significant reductions in specific humidity over the Altiplano, the 1983/1984 simulation exhibits small increments in specific humidity over the western/central Amazon and the SACZ region, whereas the other two simulations show the opposite trend for these regions. Significant differences in moisture content can also be seen in Uruguay, northern Perú and southern Brazil. As shown in Fig. 4 of our original manuscript, the drying of the Altiplano in the 2011/2012 simulation is associated with reduced humidity and upward motion in these two regions (largely imposed by cool SSTs anomalies in the subtropics and warmer anomalies in the southern Atlantic, see Fig. 2 below). By contrast, the drying in the 1983/1984 simulation is not linked to decreased humidity levels eastward from the Altiplano, but largely resulting from a prominent upper-troposphere easterly wind anomaly, as discussed in our manuscript. In sum, based on these differences, we assert that our model simulations (and the resulting precipitation trajectories) are sensitive to the distinct Pacific and Atlantic SSTs conditions used as external forcing. Hence, we disagree with the referee that our results are based on some internal model dynamics. We will provide additional evidence to refute this referee's assertion in the following responses. We further note that fig. A has been added to a modified version of the original manuscript, as suggested by Referee 1.

"Where does all the moisture end up?"

As shown in Fig. S8 of the original manuscript (see below), austral summer precipitation in our entire continental domain shows positive variations relative to the initial conditions over the 100-yr period in two of the three simulations (2003/2004 and 2011/2012), while the other (1984/1984) ended up with values similar to the initial state.

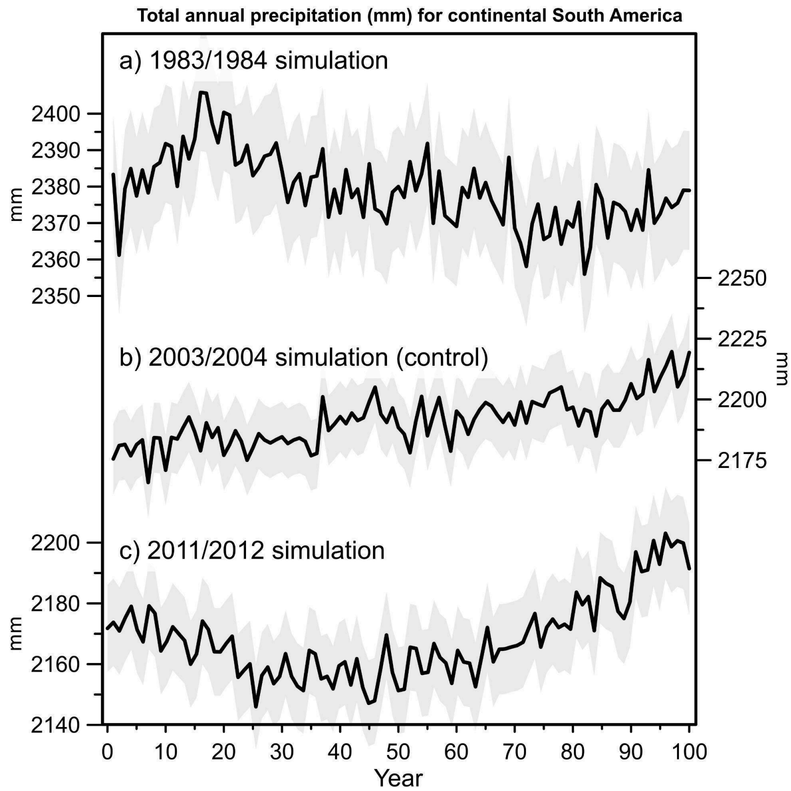

Figure S8 (original manuscript). Total annual precipitation (mm) trends for continental South America (> 10 masl) in our three modeling simulations. The shading areas correspond to the 95% confidence interval for each precipitation.

The results presented in Figure S8 imply that moisture content is not decreasing over the entire simulation domain, despite the negative trends reported for the Altiplano. Fig. 5 of the original manuscript (see below) shows that precipitation levels in both the 1983/1984 and 2011/2012 simulations increased significantly over northern Perú, Colombia, Venezuela and the northern tropical Atlantic (blue areas).

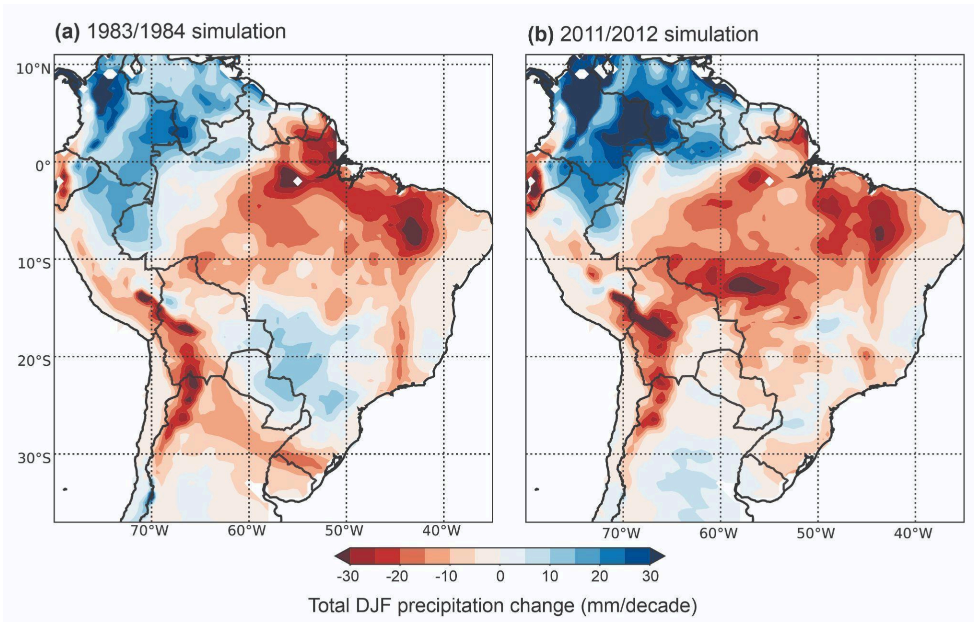

Figure 5 (original manuscript). Total DJF precipitation trends (mm per decade) in South America for the 1983/1984 and 2011/2012 simulations. Trends are calculated using a linear regression for the entire 100-yr simulation period.

Overall, our results show a northward moisture shift, from central Brazil and the central Andes, at the onset of the simulations, to northern South America and the northern tropical Atlantic by the last years of the experiments.

"How would an experiment with considerably lower initial summertime precipitation over the Altiplano look like?"

This is a very interesting point raised by the referee. We focused exclusively on positive hydroclimatic DJF seasons because our study aims to test whether the oceanic and atmospheric drivers accounting for those seasons are able to sustain extended pluvial events documented in paleoclimate sequences. However, we have actually conducted an additional 100-yr WRF simulation using the 1997/1998 DJF season as a boundary condition for a perpetual experiment. The 1997/1998 interval was a strong El Niño year and one of the driest historical austral summer seasons in the Altiplano (see Fig. S4c of the original manuscript). Figure B below shows DJF precipitation trends for the southern Altiplano in our 1997/1998 WRF simulation along with the other three experiments presented in our manuscript:

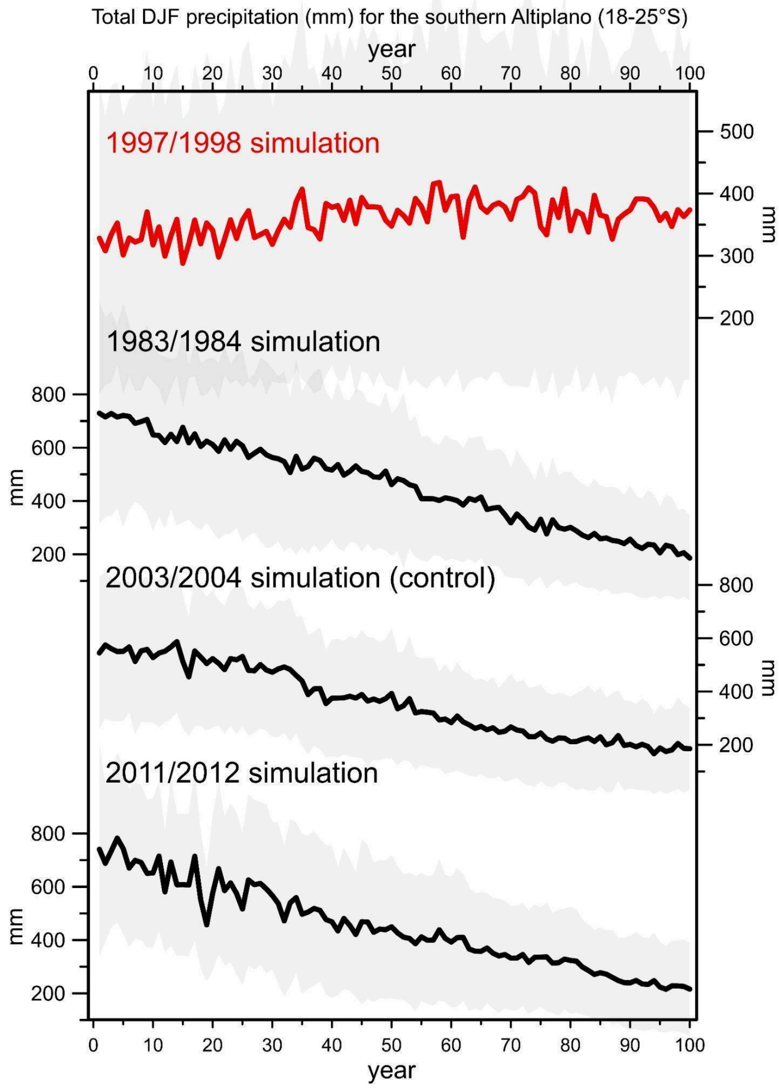

Figure B: Total summertime precipitation averages (mm) for the southern Altiplano region simulated in four 100-yr WRF runs. The grey shading encompasses one standard deviation from the regional averages.

Unlike the previous 3 experiments, the 1997/1998 simulations show a higher amount of precipitation at the end of the simulated period, without any downward trend as the other three simulations presented in our manuscript. This new simulation suggests that the drivers of the dry 1997/1998 DJF are able to promote an distinct internal response, with positive precipitation anomalies over the Altiplano. More importantly for this discussion, these results support our assertion that the model dynamics is influenced by external boundary conditions, and therefore the resulting long-term precipitation responses and atmospheric mechanisms are relevant for the interpretation of the paleoclimatic records. Because the results and discussion of this new 1997/1998 simulation lie beyond the scope of our study and because they are the focus of a different manuscript currently in preparation, we are inclined not to include this 1997/1998 simulation in our main manuscript or in the Supplements. However, we are open to adding this new information if the Editor requires it.

The question remains whether the geographical domain of the regional climate model around South America is too small to account for oceanic impact (ENSO/AMV) and how/if this information is still inherited via the borders from the driving ERA5 reanalysis over the entire 100 years cycles.

As mentioned earlier, the spatial configuration of our model effectively induces hydroclimate changes in the study area, with the magnitude and tendency of the precipitation response dependent on the SST configuration imposed in the forcing. We also note that our modeling domain was designed to maximize the oceanic component of its borders. This oceanic boundary context can be seen in Fig. 1 of our original manuscript. However, to better characterize if the domain size able to capture the Pacific and Altlantic SSTs anomalies used a boundary controls, we have added the simulation domain to Fig. 2 in a modified version of our manuscript, as seen in the right panels below:

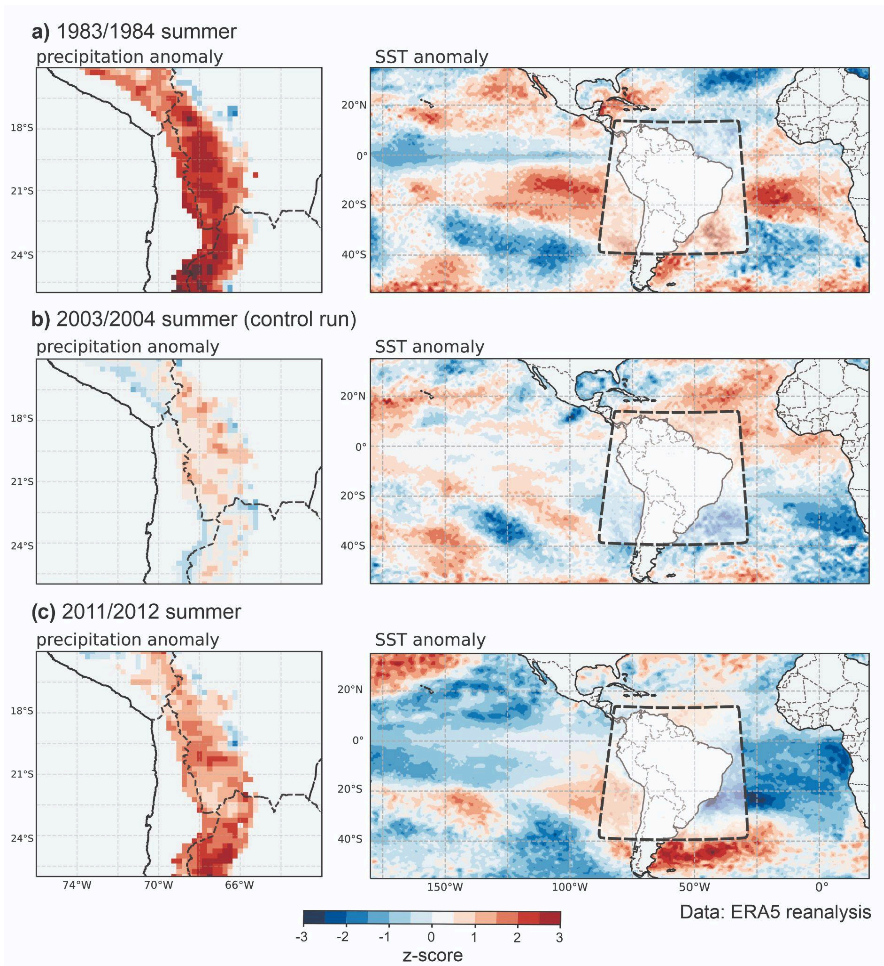

Figure 2. Hydroclimate and oceanic anomalies (z-scores) during the DJF periods selected for the climate simulation experiment. (a) precipitation and SST anomalies for the 1983/1984 summer. (b) same as (a) for the 2003/2004 summer (the selected control run). (c) same as (a) for the 2011/2012 summer. All anomalies are calculated as standard deviations from the 1951-2021 mean (z-scores). The dashed gray lines on the right panels delineate the WRF simulation domain.

As seen in the figure above, the size of the simulation domain is adequate to capture the different Atlantic and Pacific SST anomalies imposed as boundary conditions.

All experiments are carried out without any consideration of changes in orbital forcings (cf. Berger 1978), but only external forcings representing conditions of the late 20th and early 21st century. Conditions 2,000 years very different, with lower northern winter insolation and higher late northern summer/early autumn insolation, accentuating the annual insolation cycle. This might also have had an effect on the precipitation

dynamics but cannot be explored with the present setup. Therefore authors should use paleoclimatic Earth System model simulations representing the background conditions of their period of interest and then force their model either with a quasi-equilibrium simulation of the time period or a transient time slot. This would implicitly include i) a more realistic representation of the general external background conditions and ii) also warrant a more realistic simulation of natural climate variability that is important for comparisons with all kinds of empirical archives.

Response:

These are again very interesting comments, which raise several issues worth discussing here. We will address them one by one:

"Conditions 2,000 years very different, with lower northern winter insolation and higher late northern summer/early autumn insolation, accentuating the annual insolation cycle"

As the referee commented, we did not compute any change in orbital configurations for our simulations. We consider that a more explicit mention to the unchanged nature of our external forcing (including orbital variations) would be necessary; and consequently we have added an explicit reference to this limitation at the beginning of the discussion of a new revised version of our manuscript. To visualize how much different were orbital conditions 2000 years ago, we have computed the northern (20°N) June and December insolation over the last 21,000 years, based on the Berger and Loutre (1991) orbital data table (see fig. C below).

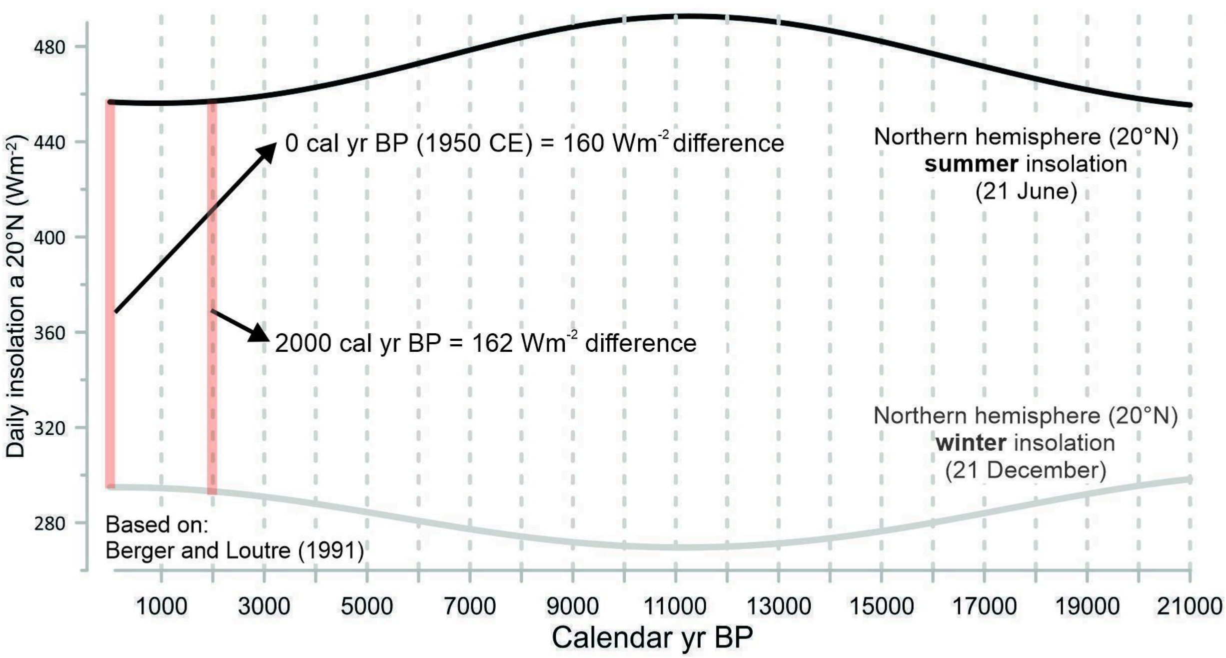

Figure C. Northern hemisphere (20°N) summer and winter insolation curves according to Berger and Loutre (1991).

As pointed out by the referee, the annual insolation cycle at northern latitudes is accentuated by 2000 cal yr BP, although only by a marginal amount (difference between modern and 2000 cal yr BP seasonal variations = 2 Wm^{-2}) compare full range Holocene seasonal differences (e.g., difference between modern and 11,000 cal yr BP = 25.3 Wm^{-2}).

We can also take into consideration the Southern Hemisphere (18°S) summer insolation, which have arguably impacted the intensity of the South American monsoon over the Andes region at centennial-to millennial timescales (e.g., Hou et al., 2020; Ward et al., 2019). As shown Fig. D below, austral summer isolation 2000 years ago is almost identical to modern values, specially when considering the entire amplitude of Holocene variability.

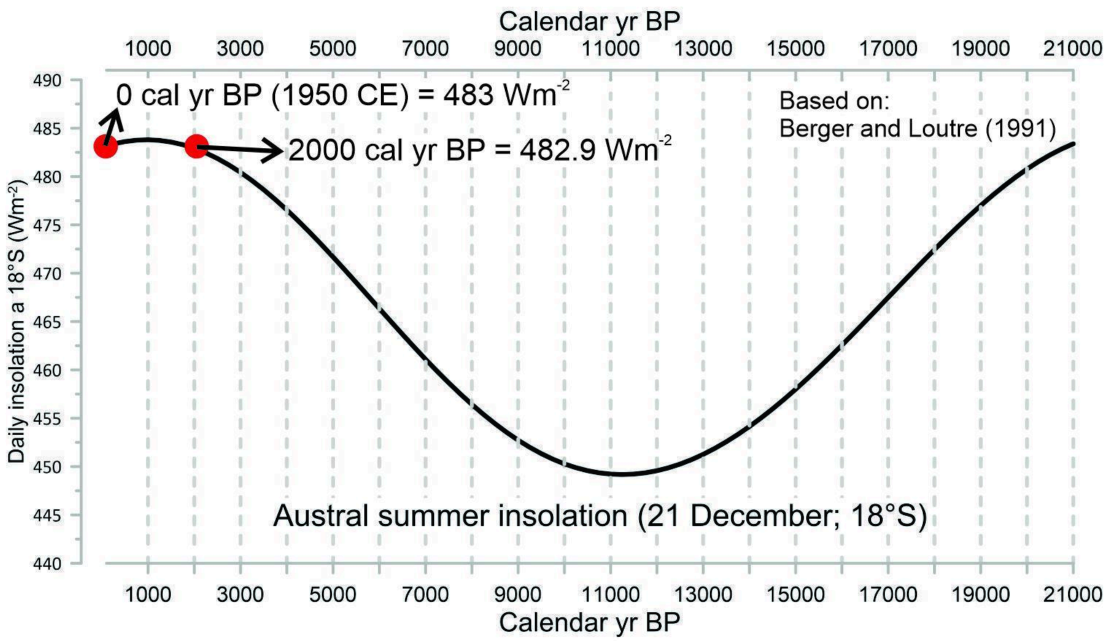

Figure D: Southern Hemisphere (18°S) summer (21 December) insolation variability over the last 21,000 years based on the calculation of Berger and Loutre (1991).

Based on all this evidence, we disagree with the referee that orbital conditions 2000 years ago were radically different than today. These results also imply that insolation was not necessarily linked to the late Holocene pluvial events documented in the Altiplano. Hence, we contend that despite the fact that our modeling experiment did not employ past orbital parameters, our results are relevant for regional paleoclimatology.

"Therefore authors should use paleoclimatic Earth System model simulations representing the background conditions of their period of interest and then force their model either with a quasi-equilibrium simulation of the time period or a transient time slot"

We agree that the suggested methodology would include more realistic past boundary conditions. However, our simulation experiment aimed to explore whether some of the SSTs anomalies in the Pacific and/or Atlantic basin observed today are able to generate centennial-scale precipitation anomalies in the Altiplano, and thus performing a transient climate downscaling or a near-equilibrium simulation was beyond the scope of our study. We contend that this experimental design and the results presented in our manuscript represent a significant contribution to the paleoclimatology of South America. The following phase of our research project is to perform a dynamical downscaling of a globally-force transient climate simulation, using the WRF model with a significantly higher resolution. The results and experience of carrying out the experiment presented in our manuscript will be of great help for this and other future experiments.

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