Referee’s main comments

1. The abstract on its own is unclear. You should better clarify what type of model experiment(s) you perform (time period?, boundary conditions?) that lead to the changes in atmospheric circulation and sustained wet conditions (or not). Reading the abstract on its own, I was rather confused about what exactly was done in this study. For example, the result that persistent La Nina conditions inhibit moisture transport to the Altiplano is counterintuitive based on everything we know about ENSO impacts in this part of the world, and requires more context in the abstract.

Response:

We acknowledge that the abstract should be more explicit about the specific type of model experiment we carried out. Although we focused on multi-decadal to centennial-scales trends, and therefore our experiment targeted a specific time period, our modeling study explores the effect of two contrasting oceanic-atmospheric boundary conditions on long-term hydroclimate responses. Thus, we consider our simulations to be closer to the boundary conditions type of experiment.

Although a short statement about the characteristics of our modeling experiment is included in the Abstract of the original manuscript (Lines 20-22), we acknowledge more details can be introduced to it. For this reason, we have added some additional information to the abstract, in particular:

- The regional model used
- The specific oceanic boundary conditions utilized
- The cyclical nature of the model forcing and the lack of interannual variability

Regarding the results of our modeling experiment and La Niña impacts over the hydroclimate of the Altiplano, we have added in the Abstract of the revised manuscript a direct mention about how our results contradict the present-day relationship between ENSO and the Altiplano, and how this contradiction can be relevant for interpreting paleoclimate records in the region.

2. Discussion lines 65-70: The issue of climate models failing to reproduce observed hydroclimate changes in the region was already documented by Rojas et al. in Climate of the Past (2016). Maybe add this study as an additional example to this discussion.

Response:

We appreciate this suggestion and, after reviewing the mentioned article, we have included a reference to the results obtained by Rojas et al. (2016) in the Introduction of the revised manuscript.

3. Fig. 1b. I think this Figure requires a better explanation. I can’t really see a clear pluvial event in these records. The actual proxies plotted should be discussed in the text or the Figure caption so it is clear what they show and how they should be interpreted.

Response:

This is also a constructive suggestion that supports the analysis and interpretation of our results. We have added the interpretations of each of the records included in Fig. 1b in the Introduction of our revised manuscript, as suggested by the referee.

4. The horizontal resolution of the simulation is quite course (55 km). In fact the WRF model run is coarser than the driving ERA5 dataset. Hence in effect you are upscaling and not downscaling. Why not use a 2nd embedded domain with higher horizontal resolution over the Altiplano region?

Response:

This is a very relevant comment indeed. As the referee mentioned, our WRF model grid is indeed larger than the ERA5 forcing dataset, and therefore our experiment represents an upscaling of the lateral grid. We highlight here that we have not used the term “downscaling” in the original manuscript, although we do acknowledge that an explicit mention of the upscaling nature of our simulations ought to be added. We have included a comment regarding the decrease in the resolution of our experiment in the Methods section of the revised manuscript.

Why not use a 2nd embedded domain with higher horizontal resolution over the Altiplano region?

We would like to comment that the relatively low resolution of our experiments results from the following reasons:

Firstly, as we aimed to explore the large-scale mechanisms of long-term precipitation change, it was necessary to employ a continental-scale domain, one sufficiently large to capture the modes of variability that control the moisture transport to the Altiplano from the margins of the Pacific and Atlantic ocean basins. Secondly, the requirement to simulate extraordinarily long, 100-yr periods, with boundary conditions provided at 3-hr intervals and hourly model outputs, increases significantly the computational resources (CPU time and storage) needed to conduct our simulations, preventing our ability to utilize an additional embedded domain or a lower grid size. Furthermore the current computational/processing capabilities in our national institutions impeded us from performing a high-resolution WRF simulation (<10 km) and/or a secondary domain in a reasonable time. In fact, the execution time of these simulations cannot be reduced because there is a scalability limit in relation to the number of cores used, so the waiting time for the results depends exclusively on the computing speed of the available computing nodes at the Chilean National Laboratory of High-Performance Computing (NLHPC) .

5. You force the WRF model with ERA5 boundary conditions and then validate your WRF results with the same ERA5 dataset. That seems like circular reasoning. While the validation with CHIRPS is independent, I would not include the ERA5 comparisons unless you aim to investigate the added value from downscaling.

Response:

We agree with the referee regarding this comment, and we have excluded the comparison with ERA5 reanalysis when discussing the validation of the WRF model in the revised manuscript. We also agree that such comparison does indeed provide important information regarding the spatial coherence of the upscaling processing. Hence, we have discussed the similarities and differences with the ERA5 dataset in the light of exploring the results the upscaling performed for our experiment.

6. I am a bit concerned about the long-term drift in your model simulations. But it may reflect the fact that the model was forced with boundary conditions that constitute an extreme wet-year outlier. Sustaining such extreme conditions for 100 years would likely require changes in the boundary conditions that favor maintaining massive moisture transport to the Altiplano year after year. In the current environment, recharging the atmosphere with sufficient moisture is unlikely without imposing some kind of interannual climate variability that was suppressed in these simulations.

Response:We agree with the reviewer's comments regarding the long-term drift and its possible link to the cyclic boundary conditions of the experiments. Indeed, the experimental forcing protocol suppresses interannual variability and imposes a cyclic annual forcing on both the boundary conditions and the surface data, particularly in the sea surface temperature field. However, the trend towards declining precipitation in the highlands and its increase in other regions is observed in both the experiments that replicate the conditions of extremely wet years (1983/1984 and 2011/2012) as well as in normal years (2003/2004). Based on our analyses we guess that the precipitation drift responds to progressive changes in the circulation regime that modify moisture transport and local evapotranspiration processes in particular in the Atlantic basin where the subtropical anticyclone experiment a continuous reduction that change the SACZ activity and location.

7. Figure 4: The differences in circulation between the initial and final decade are rather hard to identify. I suggest you incorporate Fig. S9 which shows the difference between the two time periods directly into Fig. 4. It will help to highlight the actual changes. For the right column with the transect, it would make more sense to invert the color scale for humidity so more humid conditions are shown in blue and drier conditions are depicted in red, as this would be more consistent with the changes in vertical velocity depicted in the left column.

Response:

We appreciate all these constructive suggestions made by the referee. Indeed, it becomes somehow difficult to visualize the differences between the initial and final decades of the simulation, especially for the 800 hPa circulation + specific humidity (q) diagram depicted in the center column of Fig. 4. Following the referee's suggestion, we have modified this figure, which now includes plots for the direct differences between the first and final decades of the 1983/1984 and 2011/2012 simulation periods for both:

- The 200 hPa circulation (u,v) + vertical velocity (w)
- The 800 hPa circulation (u,v) + specific humidity (q)

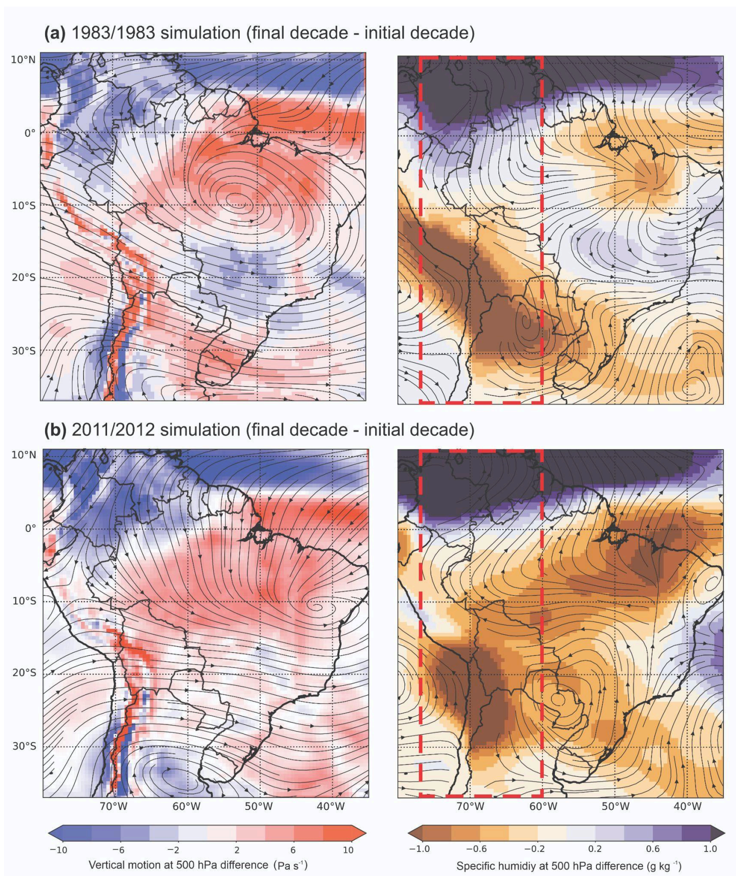

Figure 4. Comparative panel depicting differences between the averaged atmospheric and moisture circulation during the initial and final decades of the 1983/1984 and 2011/2012 WRF simulations. (a) Difference between the final and initial decade of the 1983/1984 simulation. Left panel: vertical motion at 500 hPa (colored) along with composite upper-level (200 hPa) zonal and meridional wind differences (streamlines). Negative (positive) differences indicate increased upward (downward) motion in the final decade relative to the initial decade. Right: specific humidity at 500 hPa (colored) along with composite lower-level (800 hPa) zonal and meridional wind differences (streamlines). The red rectangle denotes the region where the longitudinal mean anomalies are calculated for Fig. 5. (b) Same for the 2011/2012 simulation.

For the "transect" plots on the right column of Fig. 4, we have now inverted the color scale for humidity, as suggested by the referee. Unlike the 200 and 800 hPa diagrams, these "transect" plots express much more clearly the differences in circulation and moisture transport generated over the simulation's periods. Since these plots depict anomaly values relative to the entire 100-yr simulation mean, calculating the differences between the initial and final anomalies will introduce an additional (an unnecessary) layer of complexity for their interpretation. For these reasons, we have decided to keep such plots unchanged. However, since these are not direct differences like the 200 and 800 hPa diagrams of Fig. 4, we decided to include these "transect" plots in a new different figure (Fig. 5), so as not to cause any confusion between these two types of plots.

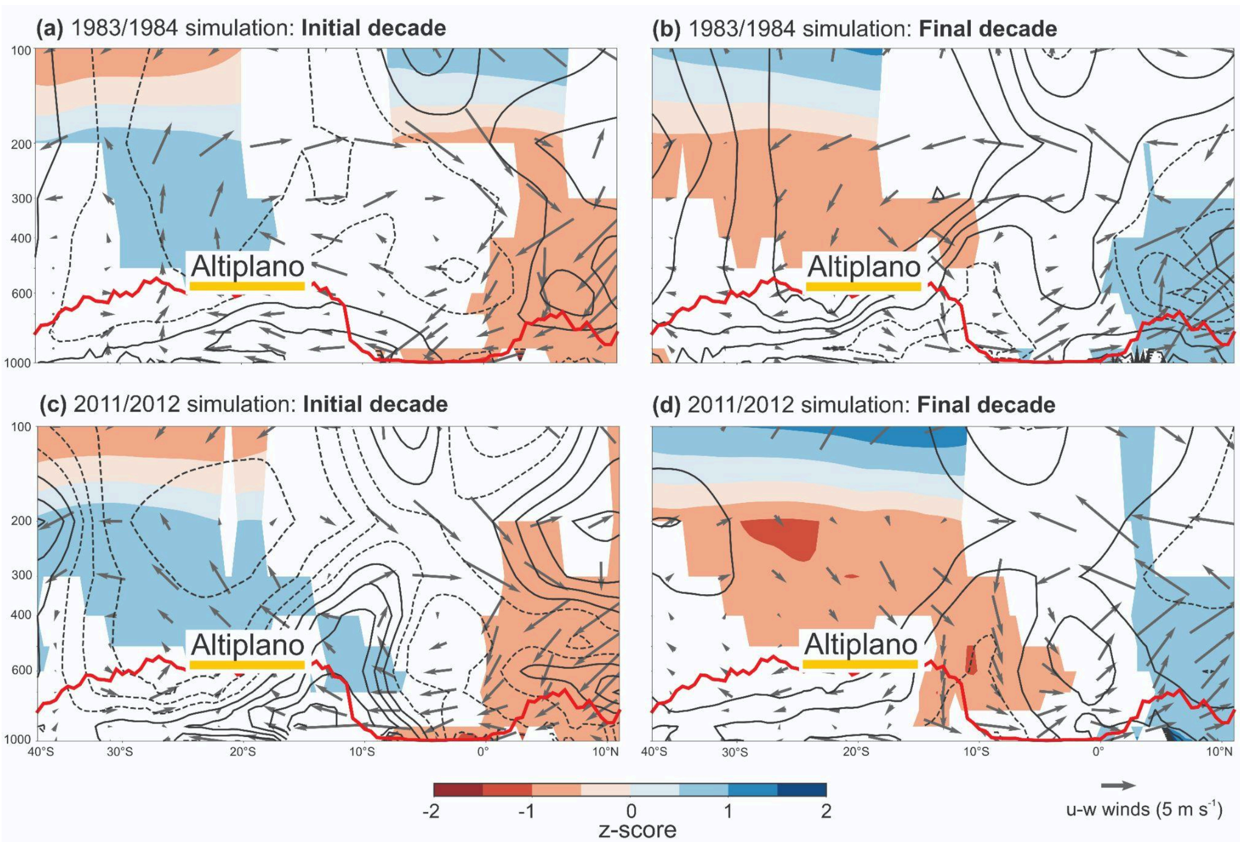

Figure 5. Pressure (hPa)-latitude cross section with anomalies (z-scores) for specific humidity (colored), integrated vertical and meridional circulation (vectors), and zonal winds (contours) for the initial and final decades for the 1983/1984 and 2011/2012 simulation. The longitudinal means for all variables are calculated over the region delimited by the red rectangles in Fig. 4. Anomalies in the pressure-latitude sections were calculated as standard deviations from the 100-yr means. Continuous (dashed) contours indicate westerly (easterly) zonal wind anomalies. The red line represents the profile of maximum elevation of the Andes cordillera and the position of the Altiplano is marked. (a) and (b) First and final decade of the 1983/1984 simulation. (c) and (d) Same for first and last decades of the 2011/2012 simulation.

8. Figure 5: Same comment: it intuitively makes more sense to reserve blue colors for wetter and red colors for drier conditions. Hence I would suggest inverting the color scale.

Response: We have inverted the color scales as suggested by the referee.

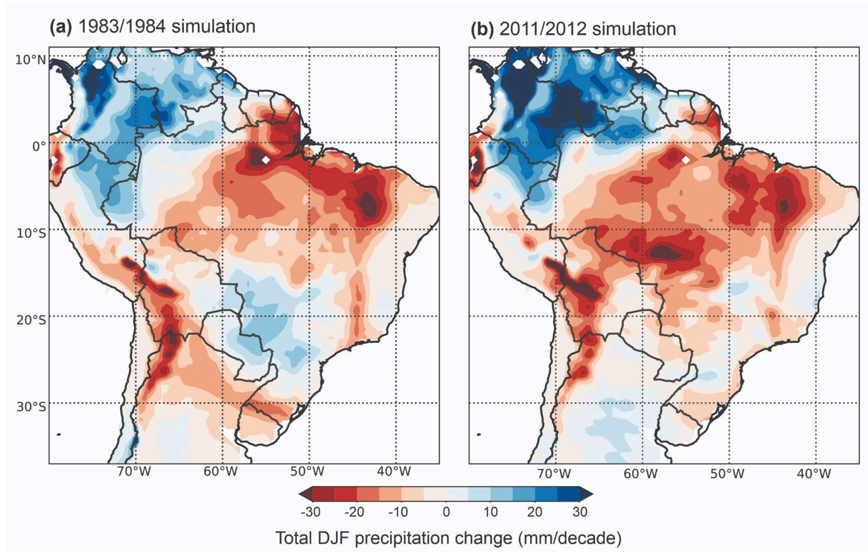

Figure 6. Total DJF precipitation trends (mm per decade) in South America for the 1983/1984 and 2011/2012 simulations. Trends are calculated using a linear regression for the entire 100-yr simulation period.

9. The modeling setup is certainly interesting and the results are worth exploring. Nonetheless, it needs to be clearly stated that these are not realistic representations of boundary conditions that led to wetter conditions in the past, given that neither greenhouse gasses, volcanic, solar or orbital conditions were changed. Hence the focus here is exclusively on sustained modern wet-year boundary conditions (with a perpetual climatology and zero interannual variability), while many of the sustained changes in the past were likely externally forced. On pages 12-13 there is a long discussion about the implications of this study for paleoclimatic interpretations, e.g. during Heinrich 1, the late Holocene and the Little Ice Age. Please add a statement at the start of this discussion regarding the lack of realistic past boundary conditions and external forcings, thus limiting the ability of these simulations to serve as analogues for paleoclimatic interpretations.

Response:

We appreciate this comment from the referee. We are aware that our experiment offers just an idealized representation and not a realistic scenario of boundary conditions leading to past hydroclimate anomalies. In agreement with the referee, we have now added a few sentences at the beginning of the "Discussion and Conclusion" section of our revised manuscript, contending that the results and interpretation should be taken with caution as our simulations do not use any realistic past boundary conditions like the ones employed in transient simulations.

Despite these real limitations, we contend that the impact of tropical Pacific or Atlantic ocean SSTs in the Holocene hydroclimate variability of the Altiplano is a matter of current debate (e.g. Jara et al., 2022; Luecke et al., 2022; Wong et al., 2021), and therefore our experiment is testing forcing mechanisms relevant to regional paleoclimatology. Although we did not alter forcing variables such as greenhouse gasses, volcanic, solar, or orbital conditions; our experiment generates useful information about the causes, mechanisms, and large-scale spatial pattern of long-term climate variability in the Altiplano and South America, which can be used to complement proxy-based reconstructions, especially records covering the mid or late-Holocene period were orbital and greenhouse parameters approached pre-industrial levels.

10. Lines 305-311: When discussing the 2nd mode of Campos et al. (2019), please note that this study has since been updated by Orrison et al. (2022) with newer proxy data and the inclusion of an isotope-enabled model. They were able to show that the 2nd mode effectively represent SACZ variability.

Response: We appreciate this update about the published literature. Accordingly, we have included in the revised manuscript a reference to Orrison et al. (2022) to support our argument about changes in SACZ variability.

Minor edits:

Line 30: hypothesis => hypotheses

Response: Done

Line 45: pacific => Pacific

Response: Done

Line 53: year = years

Response: Done

Line 79: et al => et al.

Response: Done

Legend Figure 1b: polle => pollen

Response: Done

Legend Figure 1b: cell => cellulose

Response: Done

Line 101: degenerate => weaken

Response Done

Figure S2: above panel a) you imply that q 800 hPa is plotted, yet in the legend you write q 500 hpa => please clarify. The same applies to panel b) but here it is unclear whether omega is plotted at 200 hPa (title) or 500 hPa (caption). Finally, for vertical velocity in c) you write the unit is also m/s. Should it not be Pa/s (since you are plotting the data as a function of pressure level)? Also, please add a unit vector for vertical motion in the same way as you did for u and v. Note that some of these comments also apply to Fig S5.

Response:

The captions of Figure S2. state "S*pecific humidity (q) at 500 hPa (shaded; g kg−1) along with integrated zonal and meridional winds at 800 hPa (streamlines)*". Hence, we disagree that we are implying the q is plotted at 800 hPa. The same applies for panel (b), as its captions clearly mentions "*Vertical motion (w) at 500 hPa (shaded; Pa s−1) and integrated zonal and meridional winds (u,v) at 200 hPa (streamlines)*". The corresponding pressure level for all variables are explicitly mentioned. For (c), we have added the integrated vertical and meridional winds unit in m s^{-1}, and also its approximate value in Pa s^{-1}.

We also note that the unit label for the specific humidity was not added. We have corrected this.

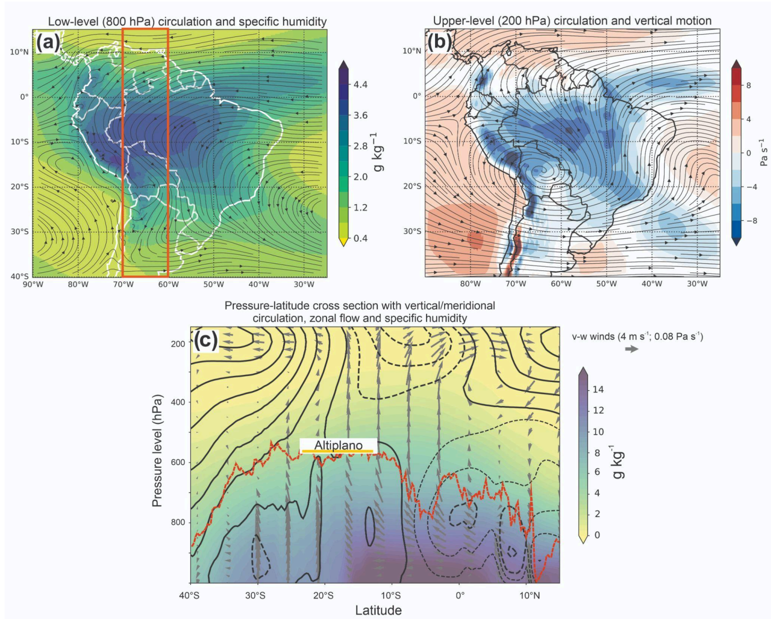

Figure S2. 1951–2022 South America DJF climatology. (a) Specific humidity (q) at 500 hPa (shaded; g kg−1) along with integrated zonal and meridional winds at 800 hPa (streamlines; m). (b) Vertical motion (w) at 500 hPa (shaded; Pa s−1) and integrated zonal and meridional winds (u,v) at 200 hPa (streamlines). Upward (downward) motion is depicted as negative blue (positive red) values. (c) Pressure-latitude cross section showing the integrated vertical and meridional circulation (v,w; vectors; m s−1; Pa s−1), zonal winds (u; contours), and specific humidity (q; shaded). The longitudinal means are calculated using v, w, u and q within the region delimited by the red rectangle in (a). Westerly (easterly) circulation is depicted as continuous (dashed) lines, with labels at 4 m s-1 intervals. The dashed red line of the image represents the profile of maximum elevation of the Andes cordillera along the red rectangles in (b), calculated as the maximum topographic elevation. The position of the Altiplano is labelled in the figure (c). All atmospheric data correspond to ERA5 reanalysis.

Caption Figure S4: Climate Hazards Center InfraRed Precipitation with Station data => Climate Hazards Group InfraRed Precipitation with Station data

Response: Done

Caption Figure S4: CHIRPS data is plotted in orange, not green color

Response: Caption changed accordingly

Caption Figure S4: what do you mean with 'grilled' precipitation dataset? Maybe 'gridded'?

Response: Yes, we meant "gridded" and we have changed accordingly.

Table 1 and throughout the paper:The index you use is called the 'Nino3.4' index, not the 'El Nino 3.4' index. After all, this index is also used to characterize La Nina and neutral conditions in the central equatorial Pacific.

Response: This is correct, we have amended accordingly in Table 1 and throughout the text.

Caption Figure S5: s-1 => superscript '-1'

Response: corrected

Table 1: Southeastern => Southeastern

Response: corrected

Line 175: Climate Center for Atmospheric Research => National Center for Atmospheric Research

Response: Done

Line 209: parameterization => parameterization

Response: We employed British English style in our manuscript, and therefore we prefer “parametrization”. We are willing to change to the other spelling alternative in the revised manuscript if the Editor suggests so.

Line 212: intimal => initial

Response: Done

Figure S7: October => October

Response: Changed

Line 286: accumulative => cumulative

Response: Done

Line 302: dryer => drier

Response: Done

Line 334: indicate in which journal this article was published.

Response: We have indicated the journal as suggested

Line 376: delete: ‘J. o. G. R. A.:’

Response: Done

Line 377: reference is incomplete: where was this paper published?

Response: We have added the corresponding journal.

Line 388: you forgot to list a co-author of this paper; J. Michaelsen

Response: We have added the author as suggested

Line 389: reference is incomplete: where was this paper published?

Response: We have added the corresponding journal

Line 406: add volume or issue number or doi, so article can be traced.

Response: Added

Line 474: delete ‘J. E. R. L.:’

Response: Added

Line 475: reference is incomplete: where was this paper published?

Response: We have added the corresponding journal

Supplement references: the Journal name where Hersbach et al (2020) was published is missing

Response: We have added the corresponding journal

References

- Jara, I.A., Maldonado, A. and de Porras, M.E., 2022. Did modern precipitation drivers influence Centennial Trends in the highlands of the Atacama desert during the most recent Millennium?. Geophysical Research Letters, 49(1), p.e2021GL095927.
- Luecke, A., Kock, S., Wissel, H., Kulemeyer, J.J., Lupo, L.C., Schaebitz, F. and Schittek, K., 2022. Hydroclimatic record from an Altiplano cushion peatland (24° S) indicates large-scale reorganization of atmospheric circulation for the late Holocene. PLoS One, 17(11), p.e0277027.
- Wong, M.L., Wang, X., Latrubesse, E.M., He, S. and Bayer, M., 2021. Variations in the South Atlantic Convergence Zone over the mid-to-late Holocene inferred from speleothem δ18O in central Brazil. Quaternary Science Reviews, 270, p.107178.