Point-by-point reply for Reyers et al.:
„On the importance of moisture conveyor belts from the tropical East Pacific for wetter conditions in the Atacama Desert during the Mid-Pliocene"

We thank all community members who provided comments on our manuscript for the appraisal of our manuscript. The comments helped us to further improve the presentation of the results in the manuscript. Our replies to the comments along with details on how we intend to revise the manuscript are printed in blue below the original comments in black. We also revise the color schemes in the figures for clarity.

Reply to RC2 by an anonymous referee

„I found this work very novel and interesting to read. The focus on moisture conveyer belts in the Atacama during the mid-Pliocene is an important contribution to understand the mechanisms of past and present rainfall events in the region. The experimental design is well accomplished, and I liked very much the use of SOM and clustering techniques for MCBs detection and pattern analysis."

Thank you for your appraisal of the manuscript.

„I have some general comments for different sections of the manuscript:
Introduction Authors mention that the increased rainfall in the Southern Atacama Desert is mostly duo to a northward displacement of mid-latitudinal westerlies and extra-tropical winter cyclones. In my opinion they cite literature that does not support this statement. For example, they cite Jordan et al., 2019 as evidence of southwestern moisture source but Jordan et al., 2019 identifies the tropical Pacific as the main moisture source of the March 2015 extreme rainfall event. Can please the authors clarify this inconsistency. Also, I noticed that Bartz et al., 2019 do not actually state a southwestern moisture source in their study, the same with Stuut and Lamy, 2017."

The thought of a southwestern moisture source was based on the following statements in the papers:

- **Bartz et al. 2019** mention: *„Thus, based on our observations and in comparison with marine palaeoclimate records "…", alluvial fan dynamics along the western flank of the Coastal Cordillera seems to be influenced by an interplay between northward-driven austral Westerlies, ENSO related positive SST anomalies, and variations in the strength and the position of the SE Pacific anticyclone.", which suggests a southwestern moisture source.*
- **Stuut and Lamy, 2017**: *"A tendency toward more El Niño-like conditions would be consistent with more humid conditions in northern Chile, as at present, within the northern winter rain belt of Chile, strong positive rainfall anomalies occur during El Niño events induced by a northward shift of the Southern Westerlies due to a weakening and northward displacement of the SE Pacificanticyclone (Ruttland and Fuenzalida, 1991).", which also suggests a southwestern moisture source.*
- **Jordan et al., 2019**: *"South of 22° S (northern part of the political division "II Region" of Antofagasta"), Pacific-sourced water vapor leads to precipitation in the Andes Mountains dominantly in winter (June-July-August) (zone III) (Houston and Hartley, 2003; Burgener et al., 2016). Through cutoffs and fronts from the mid-latitude westerlies (Vuille and Ammann, 1997) a decreasing amount of* precipitation reaches progressively northward." We remove the citation of Jordan et al. (2019) and add Vuille and Ammann, 1997.

The revised manuscript text is: "Intervals of increased rainfall in the Southern Atacama Desert are mostly attributed to a northward displacement of mid-latitudinal westerlies and accompanied extra-tropical winter cyclones (Vuille and Ammann, 1997, Stuut and Lamy, 2017; Bartz et al., 2019), which suggest a southwestern moisture source."

In line #80 authors state the hypothesis of the tropical Southeast Pacific as a moisture source for the Atacama but this was demonstrated in Bozkurt et al., 2016. It is possible to clarify how their hypothesis differs from the mechanism that triggered the events of March 2015? In its present writing form, it is not obvious the connection with Bozkurt et al., 2016's findings.

Indeed, the mechanisms identified by Bozkurt et al. (2016) for the March 2015 severe rainfall event in the Atacama could be an important mechanism in the past climate. However, the past and present constellations of the global atmospheric and oceanic circulations are substantially different and it remains to be tested whether the processes responsible for the March 2015 rainfall event are also statistically significant for a wetter Atacama in the Mid-Pliocene. Our high-resolution simulations for the Mid-Pliocene indicate that the essence of these mechanisms may also be importance in the paleoclimate context.

We modify the text to reflect this point: "The tropical Southeast Pacific northwest of the desert could be a potential moisture source for increased humidity in the mid-Pliocene, like assessments of the regional rainfall under present-day climate suggest (Bozkurt et al., 2016, Jordan et al., 2019; Böhm et al., 2021). However, the past and present constellations of the global atmospheric and oceanic circulations are substantially different."

We also add in the conclusion: "Our results support that higher SSTs lead to stronger rainfall in the Atacama, broadly consistent with the March 2015 case studied by Bozkurt et al. (2016)."

„Data and Methods
Can the authors please explain why using orbital parameters from the pre-industrial period and not the orbital parameters of the mid-Pliocene. Orbital forcing of later periods has proved to be useful in reproducing past climates. For example, Engelbrecht, F. A., and Coauthors, 2019: Downscaling Last Glacial Maximum climate over southern Africa. Quat. Sci. Rev., 226, https://doi.org/10.1016/j.quascirev.2019.105879. I understand that PlioMIP simulations use orbital parameters for 1850 but it would be very useful for the non-specialized community to understand why we are modelling the climate of mid-Pliocene using orbital parameters for present day. This forcing is not negligible as discussed by Willet et al., 2013 (Willeit, M., A. Ganopolski, and G. Feulner, 2013: On the effect of orbital forcing on mid-Pliocene climate, vegetation. Clim. Past, 9, 1749–1759, https://doi.org/10.5194/cp-9-1749-2013). This is important for ice sheets extension and therefore albedo and the global energy balance."

We chose the setup of the regional climate model to be as close as possible to the global PlioMIP2/PMIP4 experiment to ensure consistency across the model chain. In our regional experiment for the Atacama region, we have no large ice sheets that could be affected by this choice, although we agree that this aspect should be revisited when new global climate simulation for the Pliocene will be conducted in the future. We have added: „ (…) orbital parameters are as for the pre-industrial period (1850) to be consistent with the setup of PlioMIP2 experiments"

„What is the actual bias of WRF historical run? As precipitation is very reduced in the hyper-arid core of the Atacama, simulated vs observed precipitation can have many orders of magnitude of difference. This is not a problem and is common in modelling studies, but I missed a more robust measure of uncertainty of modelling experiments using WRFhist. "

We evaluated the rainfall from WRF_{hist} against a WRF simulation that downscales the ERA5 reanalysis for the same domain and spatial resolution (WRF_{era}). The results for the annual and seasonal mean precipitation patterns along with limitations are shown in Fig. 3 and are mentioned in Section 3.1. We now revise the paragraph to better highlight the evaluation results: "We evaluated the rainfall from WRF_{hist} against a WRF simulation that downscales the ERA5 reanalysis for the same domain and spatial resolution (WRF_{era}). There are quantitative differences in rainfall, but the aridity is overall satisfyingly reproduced by the WRF simulation that used data from the historical simulation of CESM2 at the lateral boundaries (WRF_{hist}). Specifically, the spatial patterns and the seasonal cycle of rainfall are qualitatively captured by WRF_{hist} (compare Fig. 3f-j with Fig. 3a-e). Both WRF_{era} and WRF_{hist}, show (…) Annual and seasonal rainfall amounts tend to be regionally overestimated by WRF_{hist} against WRF_{era}, but the hyper-aridity with only a few mm of rainfall per year is well simulated (Fig. 3f-j). We therefore conclude that the WRF simulations using CESM2 as boundary conditions are suitable for our research interest."

„Results

It is not clear to me which proxy data was used to validate model projections. Maybe these is all due to the lack of proxy records for such a long period of time. I think this is important since the authors assure that CESM2 agrees with reconstructions, but they don´t provide any evidence of to which extent the model agrees with proxy data. The only reconstructions available are those provided by Dowsett et al., 2013?"

There are more proxy data available. We add the new table below to summarize geological records from the wider study area that fall into the mid-Pliocene. The table contains details on the interpreted proxy data and statements on the wetter conditions relative to present-day, broadly consistent with CESM2 that we use as boundary data for our regional kilometer-scale simulation.

Name of site	Coordinates	Time period	Type of proxy data	Signal relative to modern climate	Reference
Cerro Soledad, Quillagua-Llamara basin	21.25° S; 69.5° W	3.2–2.7 Ma	CN dating of lake terraces	Wetter conditions in the Altiplano	Ritter et al. (2018)
Soledad Fm, Quillagua-Llamara basin	20-21° S; 69-70° W	4.2-2.6 Ma	ash layers in playa-lake sediments	Wetter conditions in the Altiplano	Vásquez et al. (2018)
Tiliviche Paleolake	19.5° S; 70° W	3.5-~3.0 Ma	salar deposits in the Tivliche paleolake	Wetter conditions in the Altiplano	Kirk-Lawlor et al. (2013)
Lauca basin	18.5° S 69.25° W	3.7–2.6 Ma	lacustrine and fluvial sediments	Local proxy for semi-arid conditions with increased precipitation	Gaupp et al. (1999)
Cordillera de la Sal, Salar de Atacama basin	23° S 68.25° W	3.5 – 2 Ma	lacustrine and mudflat deposits	Wetter conditions in the Cordillera	Evenstar et al. (2016)
Calama Basin	22.5° S 69° W	6 – 3 Ma	palustrine carbonates	Wetter conditions in the Altiplano	May et al. (2005)
Central Depression, Calama basin, and Preandean Depression	19.75 –23° S	8 – 3 Ma	fluviolacustrine and alluvial-fan deposits	Semi-arid conditions	Hartley & Chong (2002)
Coastal Cordillera draianges	23.45 - 29.9° S	> 2.1 Ma	CN dating and near surface ash ages	Wetter conditions	Amundson et al. (2012)

Table 1: Proxy data for wetter condition than present-day in the region of the Atacama Desert that fall into the mid-Pliocene.

The new table is referenced in the results: “These results for more rainfall are broadly consistent with proxy records for the wetter conditions in the mid-Pliocene compared to pre-industrial in the region, listed in Table 1. “

We further add citations for proxy data on the SST difference between the mid-Pliocence and present-day: “The model results are supported by proxy data indicating a global SST anomaly for the mid-Pliocene vs. pre-industrial of 2.3°C and 3.2–3.4°C based on foraminifera Mg/Ca and alkenones or alkenones only, respectively (McClymont et al., 2020). Specifically in the upwelling regions at the Peruvian margin, Deckens et al. (2007) reconstructed a Pliocene-modern SST change by 2.9°C”

„Still, if possible, authors can provide a measure of uncertainty in their modelling design. In modelling experiments for future projections, as an example, is very important to measure the level of uncertainty and therefore the model ensemble is used, and a range of possible climates is provided. I can guess authors did not use the ensemble because the mean precipitation tended to be lower than current climate (?). Still, the question is, if only one model is used, how can we be sure that CESM2 model results are not due to chance? At least authors should mention the limitations of using only 1 model.“

We decided to perform a regional downscaling experiment from global model output that showed the expected difference in the mean state between the mid-Pliocene and present-day. It would indeed be great to have more PlioMIP2 model simulations with the expected changes to assess to what extend our results are influenced by model-to-model differences. More paleo-simulations would be useful as testbed for model simulations for modern climate change, but running more models for paleo-climate seems difficult, especially for those models that have a high climate sensitivity like CESM2 (Burls and Sagoo, 2022). It would be valuable to have data from more global model simulation for the Pliocene or other warm climates available in the future. We talk about this aspect now in the conclusion: „ Our regional evaluation is interesting in the context of the relatively high climate sensitivity of CESM2 (Gettelman et al., 2019), which might be seen as an outlier in a larger ensemble of CMIP6 simulations for other time periods (Burls and Sagoo, 2022). It was proposed to use paleo-simulations as testbed for climate model performance to constrain climate sensitivity (Burls and Sagoo, 2022, Zhu et al., 2022). Our results suggest that paleo-simulations paired with regional downscaling to kilometre-scales might also be useful for better understanding and predicting regional climate changes with global warming, e.g., for the hydrological cycle that remains an outstanding challenge for global models with parameterised convection. If our mid-Pliocene simulation is a useful out-of-sample test, the fact that CESM2 outperforms other models with lower climate sensitivity for the mid-Pliocene climate in the region of the Atacama Desert would support a high climate sensitivity. It would be valuable to have data from more global model simulation for the Pliocene or other warm climates for similar downscaling experiments in future research, especially from CMIP6 models with a high climate sensitivity. This endeavour requires also further development of proxy data for paleo climates, of which there are still a limited number for the Pliocene.“