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 RC1 by Teresa Jordan

„Overall, this is an excellent contribution to paleoclimate studies of the Atacama desert of the west coast of South America, as well as a being a thought-provoking treatment of what future extreme events may arise in the Atacama Desert during a warmer climate future.
The largest excursion from hyperaridity in the Atacama Desert more recently than about 10 Ma was during the Pliocene, and this is the focus of Reyers et al. atmospheric modeling study. The proxy record has not firmly established most of the key parameters of the Pliocene wetter climate – was it only slightly wetter but over a very long period of time (e.g., 500,000 years) allow accumulated impacts on the landscape, or was it intensely wetter for some shorter period of time (e.g., 1000 years) which caused rapid changes of landscape features? Nor is it firmly established the timing of the wettest interval. Some data point to the wettest interval in the 20°S Atacama at the very beginning of the Pliocene (e.g., Jordan et al., 2014; Evenstar et al. 2017), thus not coinciding with the mid-Pliocene boundary conditions used by Reyers et al. (their conditions are appropriate to 3.2 Ma. Nevertheless, given the dearth of rigorous atmospheric studies that attempt to evaluate the warmer conditions of the Pliocene, I find Reyers et al's analyses to be both novel and important. In light of the lack of detailed proxy understanding of the Pliocene wetter climate extracted thus far from the geological record, perhaps the authors should state in their conclusions that the applicability to interpreting paleoclimate history also requires improved chronological resolution and more advanced proxy data.“

Dear Teresa Jordan,

thank you very much for your evaluation of our study. We included the following in the revised conclusion: „This endeavour requires also further development of proxy data for paleo climates, of which there are still a limited number for the Pliocene.“.

„Read as a person who is not an atmospheric scientist, I find the premises and methods to be clearly stated, and the nature of the experiments to be very good choices for both Pliocene conditions and with reference to the March 2015 extreme rain event case study. With only minor exceptions, the results presented support well the interpretations and conclusions.
The authors 'choices of features to illustrate in figures and the simple clarity of the illustrations are very good. The connection between topics in the text and corresponding figure was easy to match.
The choices of materials to reference is suitable. In a few cases in which I know well the paper that is cited I recommend that the authors re-examine the paper cited and more clearly (or accurately) represent its conclusions.“

Thank you, we carefully revise the manuscript text for clarity, e.g., by adding more details for citations and interpretations. Please refer to our replies below for more details.

„Abstract: Easy to understand
Data and Methods, section 2:

The authors describe very clearly their analysis and machine learning methods. These topics are entirely outside of my expertise, yet I could follow the description easily.
Introduction: This frames the problem well, from a geological perspective.“

Thank you for your feedback.

„A sentence spanning lines 54- 57 describes a prior interpretation that atmospheric circulation over South America east of the Andes controlled increased precipitation in the Atacama in the past, ie, paleoclimate. The citation of references is ambiguous. On first reading, it appeared that Jordan et al. (2019) and Amidon et al. (2017) both advocated this interpretation. However, Jordan et al described the previous literature on this topic but concluded that it is incorrect for the situations in the Atacama Desert of interest in their paper. (Amidon et al's paper focus on the eastern flank of the Andes, where perhaps the interpretation is correct.) While the authors of that paper are pleased that their description could be understood and contributed to thought, the citation should be changed to make clear that they conclude it to be incorrect.“

The discussion of the topic in the cited papers were useful. We revise the text for clarity: “Past rainfall variations in the Northern Atacama and the Andes have been linked to latitudinal shifts of the extra-tropical westerlies in the Southern Hemisphere (Amidon et al., 2017). Also, cut-off lows as seen in March 2015 have been proposed as possible mechanism for wetter conditions in the past (Jordan et al., 2019).”

„A sentence spanning lines 66 to 68 treats the March 2015 extreme rain event and cites Jordan et al (2019) for relating that tropical Pacific-sourced event to a paleoclimate hypothesis. Because Jordan et al (2019) did not present isotopic data for paleoclimate proxies, the citation is somewhat distorted. Were a citation to be added to either Herrera and Custodio (2014) or Herrera et al. (2018), then the paleoclimate proxy isotope data would be encompassed and Reyers et al. intent for the sentence could be better fulfilled.
Herrera, C., and Custodio, E., 2014, Origin of waters from small springs located at the northern coast of Chile, in the vicinity of Antofagasta: Andean Geol, v. 41, p. 314–341.
Herrera, C., Gamboa, C., Custodio, E., Jordan, T., Godfrey, L., Jódar, J., Luque, J.A., Vargas, J., and Sáez, A., 2018, Groundwater origin and recharge in the hyperarid Cordillera de la Costa, Atacama Desert, northern Chile: Science of The Total Environment, v. 624, p. 114–132.“

We change the sentence for clarity: „Based on the characteristic isotopic composition of rain water (e.g., Herrera and Custodio, 2014) from the March 2015 event, Jordan et al. (2019) proposed that the processes involved in this event might also play an important role in increased paleoclimate rainfall in the Atacama Desert“

„Line 79: Please remove the citation of Jordan et al. (2019). That paper advocates that the tropical Pacific is a key contributor to moisture in the Atacama Desert, and only describes the sources promoted by the other authors for completeness. Jordan et al's analysis aligns better with Böhm et al 2021 than with the other papers listed, and could be cited at the end of the sentence which terminates in the middle of Line 80.“

We revise it as suggested: „ If MCBs played an important role in that period, this would imply that in addition to the previously suggested regions southwest or east of the Atacama Desert (Stuut and Lamy, 2017; Bartz et al., 2019; Amidon et al., 2017) also 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). “

„Line 95: One of the two words with the same root, “description” and “described” should be removed, and the sentence slightly rewritten.“

Agreed, now: „Dowsett et al. (2016) describes PRISM4 in detail. “

„Line 121. I believe this is the first call for Fig. 1. The caption for Fig. 1 should specific what “surface temperature” refers to. Sure, among atmospheric scientists perhaps it is understood that this means “air temperature 1 m above the surface, irrespective of whether the surface is water or soil”. But the paleoclimate-geologist does not know (and may have guessed incorrectly.)“

Figure 1 shows the topography and is first referred to in the introduction, which is now more explicit: „(…) shown in Fig. 1.“
We added the details for the temperature in the caption of Figure 2: „ (…) (a) near-surface air temperature (at 2m above ground in °C), (b) sea-surface temperature (in °C) (…)“

„Results
Section 3.1: Mid-Pliocene against present-day climate
Line 177. It seems appropriate to also refer to empirical data for the magnitude of temperature anomaly during the mid-Pliocene.“

Yes, we add: “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“

„At the end of this section (Lines 209-210) the Atacama is split into two sectors, N and S, for further analysis. The choice of boundary between the two sections and the E-W dimensions of the sectors corresponds well to both modern and paleo-climate subdivisions.“

The choice of the subdivision is motivated by the different seasonal cycles of rainfall between the northern and southern part of the hyperarid Atacama region. We add this information in the manuscript: “The seasonal cycle of rainfall shifts from winter-dominated in the south to summer-dominated in the north of the Atacama Desert (Houston, 2006; Reyers et al., 2020). In order to account for these differences, we split the hyper-arid core into a northern and southern region (see black boxes in Fig. 3n), which has also been done similarly in previous studies (e.g. Böhm et al., 2020). To quantify the cause of the winter rainfall increase (see Fig. 3n), we compute the spatial means of daily rainfall over these two regions.”

"Line 210-211. A phrase should be added to remind the reader what are the “things” of which there are 15 in both the mid Pliocene and historical simulations (this is the number of symbols). It is clearly stated that each “thing” is a spatial mean. However, it is not stated whether those 15 “things” are computational repetitions of the same model (like a Monte Carlo simulation) or something else (is 15 the maximum number of days it rained?). Perhaps this was explained in the Data and Methods sections, but the reader needs clarification at this point in the text.“

Agreed, we change it to: „Then we rank the spatially averaged daily rainfall amounts according to their magnitude and display the results in percentile-percentile plots for the mid-Pliocene against the present-day simulation (Fig. 4)“. There is one dot for each value in the data set. There are many overlying dots close to zero, but these appear as just one dot in the chosen figure type and therefore it seems as if there are around 15 dots.

„Section 3.2; Potential drivers for stronger rainfall events in the mid-Pliocene
Figure 4: It would be slightly easier for the reader if, within the boxes that contain (a) and (b), the words “north” and “south” occur. Yes, that information is in the caption. But for the person glancing repeatedly at the figure while reading the text, this added label would be advantageous.“

We add the words in the figure.

Line 242: The text should refer specifically to the inset within Fig. 7. The feature emphasized in this and the next sentences cannot be seen in the large-area plot.

Agreed, it is now: „The extremely strong southward mass fluxes are more frequent in WRF_{mP} than in WRF_{hist} (inset in Fig. 7).“

Line 250 and caption for Figure 8: The first appearance of the word “cluster” in the sentence (line 250) and caption should be plural (i.e., “clusters”).

Thanks, we correct it.

Figure 8. It seems peculiar that the most common cluster, with 79 occurrences per winter (cluster 8), has 0 kg/m-s of water vapor. I deduce this from the lack of any color on the yellow-green scale. Has color been accidently omitted? Perhaps the color bar needs a different stretch so that a non-zero value is visible? If 0 is the correct interpretation of Fig. 8 cluster 8, then the caption and text ought to mention this. At present, Line 252 discusses this cluster with reference to easterly IWVF, which I do not see.

There is no sufficiently strong moisture advection from the West in cluster 8 to fulfil the criterion of a MCB. The IWVF is not zero, but below the chosen threshold of 350 kg m^{-1} s^{-1} for MCBs. The moisture for the rainfall in the North of the Atacama Desert rather stems from Easterly directions, described in lines 250-253 with reference to Reyers et al. (2021) for further details. We add in the caption: „ Note that we show IWVF exceeding 350 kg·m^{-1}·s^{-1} in accordance with the definition of MCBs for the mid-Pliocene (see Methods). “

Line 254. Clusters 1, 2, 5, 7, 9 for the mid-Pliocene are described as similar. To my eye, 7 does not belong in this group. Its IWVF looks more like 3 or 4. This leaves the impression that the designation of “zonal” is quite arbitrary. It would be appropriate to describe the differences in the systems responsible for clusters 3, 4, and 7 (e.g, was it SST that differences? Or wind strength?).

We give more details for clarifying why we think these clusters are similar to each other in the revised text:
„ Cluster 1, 2, 5, 7, and 9 include more zonally oriented IWVF with landfall in central or southern Chile with origins further towards the South of the Pacific, e.g., when compared to cluster 4. Also cluster 3 is associated with moisture advection from regions South of 20°S but includes also some transport from further North with a more tilted axis towards meridional directions compared to cluster 1, 2, 5, 7, and 9. These clusters with dominant moisture advection from regions South of 20°S play a minor role for winter rainfall in the Atacama Desert (see red-blue shading in Fig. 8). In contrast, the IWVF clusters 4 and 6, which occur approximately every second winter in WRF_{mP}, produce the largest rain amount during winter in the hyper-arid core of the Atacama Desert. “ We focus on the clusters 4 and 6 that lead to rainfall events in the Atacama Desert, since we aim to explain why the Pliocene Atacama was less arid, but the moisture uptake paired with the circulation patterns prevent rainfall in the desert in cluster 3 and 7. We also add in the conclusion: „ (…) e.g., for understanding physical processes leading to different MCBs. “

„Line 258-260. Clusters 1, 4, 6, 7, 8 for Historical are described as similar. The text speaks of “landfall south of 25°S”. Was that also the criteria used when comparing the Mid-Pliocene clusters, but was not stated?“

We used the dominant origin of moisture paired with rainfall activity in the core of the Atacama as criteria. Please see reply to previous comment.

„Line 263. The text should note that the “magnitude” considered is integrated water vapor.“

Revised to: „(…) have much smaller IWV (…)“

„Line 263. The text states that the Historical MCBs that provide most of the rain (Fig. 9, clusters 3 and 9) are shifted south relative to those of the mid-Pliocene (Fig. 8, clusters 4 and 6). I do not see a significant latitudinal difference. The long axes of the mid-Pliocene clusters cross the 80°W meridian at about 18 and 19°S; the long axes of Historical clusters cross 80°W at 21°S and 17°S. If this is significantly different, the authors need to demonstrate the significance statistically.“

The change in latitude is less apparent than for the magnitude of IWV. We revised the text to make the differences clearer: „However, compared to the MCBs of WRF_{mP} (Fig. 8), the MCBs in WRF_{hist} (in Fig. 9) have much smaller IWV and can have different transport characteristics, e.g., indicated by wind maxima that are shifted towards the South and East. Take for instance, the smaller IWV and different wind pattern in cluster 4 (6) for WRF_{mP} in Fig. 8 against cluster 9 (3) for WRF_{hist} in Fig. 9.“

„Lines 264-265. It is stated that the MCBs of the mid-Pliocene are of clearly different origins than present-day. Clarification is needed of this statement. It seems to me that a few degrees of latitude would not constitute a “different origin” unless those few degrees place the air mass transport path over significantly different parts of the ocean, for instance, markedly different SST. If there is an important difference of this type, the authors should state this as justification of the statement that the origins are “clearly different.”“

We have removed the word „clearly“. Please also see our reply to the previous comment.

„Line 268. The phrasing is unclear. I believe it would be correct if written “Examples of the wind fields at 4000 m asl. are shown in Fig. 8 and 9.”“

We revise the text for clarity: „The strengthening of the north-westerly MCBs in WRF_{mP} might suggest that the wind speeds associated with these MCBs are higher in the mid-Pliocene leading to rainfall on land, but this is not visible in the output. We computed the composite of mean wind speeds for each of the MCB clusters associated with rain in the desert. The resulting composite of wind speeds in the clusters are marked for a typical moisture transport height of 4000m asl. in Fig. 8 and 9. Interestingly, the mean wind speeds in the two clusters in WRF_{mP} have a similar magnitude like in WRF_{hist}. However, the region with peak winds is shifted to the north-west in WRF_{mP}. We therefore conclude that the MCBs during the mid-Pliocene that lead to rain in the Atacama are not only stronger, but in some cases also have origins and characteristics that are different from those that occur under present-day conditions.“

Lines 286-288. This sentence is correct in detail (Bozkurt et al. did evaluate the impact on rainfall had the SST been lower in late March 2015), but contorts the logic relative to the purpose to Reyers et al. The reader must know independently that the SST was anomalously high during late March 2015 in order to understand that Bozkurt et al. study a real versus hypothetical system opposite to the current study. I think this can be rewritten for greater clarity.

Yes, we add details: „(…) Bozkurt et al. (2016) show that a hypothetical reduction of the SST in the eastern tropical Pacific during the March 2015 rainfall event, which occurred during anomalously high SST, significantly decreases the precipitable water (…)“

Line 286. Bozkurt et al. specified that there was uncertainty about how SST impacted the March 2015 event, whether through activity in the marine boundary layer or through convection. This new paper specifies that the MCB is not expressed in the marine boundary layer. Is there a value to the authors reflecting back on this aspect of the Bozkurt et al. paper?

We add: „ 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). “

Line 295. A verb and adverb are missing. Insert “are” in the phrase “occur in the mid-Pliocene but ARE not PRESENT during present-day conditions”.

Thanks, we add verb and adverb.

Lines 300-304. It should be noted, however, that the isotopic composition of the March 2015 rain at coastal sites clearly indicates that the rain in that event had a tropical Pacific water source. This has not been made compatible with the B2021 atmospheric models. (Data presented in Jordan et al., 2019).

We add: „ Interestingly, the isotopic analysis of the collected rain water in coastal regions from the March 2015 event indicates a tropical Pacific origin for the water (Jordan et al., 2019). While B2021 did not specifically address this particular event, they show tropical and subtropical Pacific origins for cases that are weaker in terms of humidity along the identified trajectories. The uncertainty to identify the most representative target location and time for the trajectory calculation may cause stronger events to appear weaker. “
Further research, e.g., using more coinciding isotopic and trajectory analyses, would be helpful to clarify ultimately.

„Conclusions and Outlook
Line 308. As a generality, in the Conclusions the authors should speak of the full names of features rather than using acronyms. Some readers will only look at the Conclusions, not all the preliminary material, and they will not gather anything useful by learning that MCBs did something. They will learn more if the statement is that Moisture Converyor Belts did something.“

Agreed, we introduce MCB, SST, and ENSO in the revised conclusion. We also add more information on the implication of the work in the context of newly available literature: „ Our regional evaluation is interesting in the context of the relatively high climate sensitivity of CESM2, 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., concerning 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.“

„Lines 391-395. The Bozkurt et al. references is duplicated.“

Thanks, we remove the duplication.