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Interactive comment on "Enhanced Mediterranean water cycle explains increased humidity during MIS 3 in North Africa" *by* Mike Rogerson et al.

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We thank the two anonymous Reviewers of our draft manuscript for their detailed and constructive reviews, and are extremely pleased that they find our work both interesting and worthy of publication. We fully concur that the interpretation of the data we present is complicated by structure of the dataset, and we are happy both reviewers agree with us that the data itself is so unique as to make a pressing case for publication and, that our analysis of it is fair, balanced and reasonable.

Below, we respond to the comments in order. The location code given for each comment and response represents the page the comment occurs in, followed by paragraph and lines (C, , -). Anonymous Reviewer 1

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C2, 2, 3-4: “. . . ..however, the clarity of the manuscript could be improved by changing the structure, especially the Discussion section.” and C2, 2, 6-10: “. . . ..the current structure of the manuscript makes it hard for the reader to follow the arguments. . . .. and the factors influencing the stable isotopic composition of rainfall that need to be clarified / included.” Response: obviously, we set out to make the draft manuscript as clear as possible, but we are happy to clarify further through editing and re-structuring as recommended by this reviewer. This will include re-ordering the Discussion so that information arrives in the most useful order, and further improving the clarity of the figures. It is important to us to make our work as accessible as possible! The “few additional points” are discussed below.

C2, 3, 4-9 continuing to C3, 1, 1-5: “However, I disagree with some of the statements made in the paragraph starting in line 66. . . .. A northward shift of the tropical monsoon belt to 25oN would be sufficient for this.” Response: The Reviewer’s concern is essentially that we have exaggerated the lack of agreement between empirical evidence of wet conditions between 30-35oN and models, which generally do not get the monsoon so far north. They are also concerned we neglect the role of water recycling in the region 25-35oN. We are very happy to improve the discussion by including the water recycling argument, which we do overlook. On the other hand, we consider that the uncertainty in reconciling the empirical and physical lines of evidence is interesting and unresolved, and deserves to be highlighted in the way we do.

C2, 3, 5-7: “I would also like to see a bit more detail about what the lake and vegetation records from the Sahara suggest for the actual time period covered by the speleothems.” Response: Although beginning to be recognised as a humid period elsewhere in the Mediterranean basin (Langgut et al., 2018), MIS3 is not well expressed in the Sahara region. Consequently, there is limited pollen or lake constraints to develop our understanding from. Generally, the Libyan interior is considered arid or hyperarid throughout the last glaciation (Cancellieri E. et al., 2016). Recent re-evaluation of lake levels in southwest Egypt indicates a groundwater fed system was active around 41 ka (Nicoll, 2018), which is similar to dates for springline tufa systems at Kharga Oasis (Smith et al., 2007). We are not aware of continental MIS3 pollen records from the region, but marine pollen from Tunisia indicates more arid conditions through the last glacial than during the Holocene (Brun, 1991). There is a triple peak in runoff from the Nile recorded in the marine sediment record, with maxima at 60, 55 and 35ka, indicating higher rainfall within the upper Nile catchment (Revel et al., 2010). We will include a summary of this evidence in the introduction, to provide better context for our new data.

C2, 3, 10-12: “A short discussion of the effects of different boundary conditions and how it could affect northern African moisture should be included.” Response: We agree this would be useful, although keeping it short is a challenge for this complex system! Very briefly, the boundary conditions on northern African atmospheric moisture supply are 1) the sea surface temperature of the Atlantic and Mediterranean, 2) the surface water ïĄď18O of the same ocean regions, 3) land surface temperature of Africa and to a lesser extent southern Europe, 4) insolation (especially with respect to ITCZ position) and 5) the zonal pressure gradient across northern Africa.

C3, 1, 12-25: “I also think there should be a section in the introduction about the present day rainfall systems in the region. . . .. [error in citation of Celle-Jeanton et al 2001]. . . ..How were they [the rainfall end members] defined?........How were the averages in Figure 9 calculated?” Response: First – apologies for the error in the citation – the reference given in the References section is correct. We agree that including more detail about the modern rainfall system in the Introduction would be helpful. We also agree that we can improve description and definition of the end members. The Bet Dagan and Tunisian datasets we use are shown in Figure 5a, and do indeed have different meteoric water lines and D-excess characteristics. The sub-categories of rainfall within the Sfax dataset occupy different positions on the same meteoric water line (Celle-Jeanton et al., 2001). We have checked, and confirm that the same is true for the Bet Dagan data. The moisture sources used for the Bet Dagan site

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is taken from the regional meteorology (Black et al., 2010;Gat et al., 2003). Moisture sources for Tunisia are as defined by Celle-Jeanton et al (2001), and we refer readers to this primary reference. Averages are arithmetic means, as this better reflects behaviour over time within systems where water throughput in and out of the karst system is likely very rapid compared to speleothem growth – we do not expect to be able to resolve synoptic events in this record.

C3, 1, 25-27: “What synoptic processes were involved in the formation of rain clouds – convection, advection? What circumstances lead to convective rainfall in the region?” Response: Convective systems, cyclones, upper-level troughs and static instabilities can all drive rainfall patterns in the Mediterranean basin and these modes are reviewed in (Dayan et al., 2015). Convection essentially reflects the relatively high SST of the Mediterrnaean during the winter, but rising air masses generally also need significant advection of moisture to drive significant rainfall. Upper level troughs reflect large-scale circulation (e.g. Red Sea Trough) or reflect lee effects downstream of mountains in the western Mediterranean, and promote rainfall in their regions of formation. The dominant cyclogenic centre is in the Gulf of Genoa, and secondary centres are placed in south Italy, Crete and Cyprus. Cyclonic systems can also penetrate from the Atlantic, where the high SST of the winter Mediterranean tends to sustain and amplify them, in close analogy to convection forcing. The key static instability is the penetration of the tropical air mass into the subtropical Mediterranean, forming a ‘Saharan Cloud Band’ at middle and upper atmospheric levels. These originate from within the ITCZ. As Libya is very sparsely instrumented, there is no literature we can find to specifically identify the synoptic processes involved in cloud formation precisely over our site. However, the Levant region is very well instrumented. Here, most rainfall falls under winter, low pressure conditions, and is convective (Peleg and Morin, 2012). The responsible low pressure systems can relate to transient, shallow lows over northern Israel, or less frequently more long-lasting Cyprus Lows or Red Sea Trough systems (Peleg and Morin, 2012).

C3, 1, 27-29 continuing to C4, 1, 1-2: “Further adding to the point above, it seems that the discussion of factors influencing stable isotopic reconstruction of rainfall is focussed on only the effects of rainfall amounts, temperature and moisture source. These are important factors, but I think one important factor is missing and that is the effect of cloud formation processes on the stable isotopic composition of rainfall”. And C4, 1, 9-11: “The cloud formation processes of these winter storms and convection will affect the isotopic composition of the resulting rainfall. . .. . ..” Response: This is indeed an aspect we neglect, and deserves some further discussion. The high level of agreement between the absolute values of the fluid inclusion data and modern precipitation isotope data make it likely that similar condensation process are responsible for the MIS3 rainfall as are responsible today, making source effects the first order control on composition. Moreover, the modern precipitation and meteoric water lines derived from them already encompass the range of different condensation styles found in the modern Mediterranean. There are undoubtedly considerable further advances to be made from northern African speleothem fluid inclusion research, and we expect these nuances to be delineated by these future studies.

C4, 2, 3-7: “I think the arguments made for the mixing of the different end members would be much more clear if the discussion of the stable isotopic composition and the d-excess would be combined including clear definitions of the values for the three depositional phases of the speleothem and the modern rainfall end members”. Response: If the Reviewer feels this will make our work more accessible, we will be very happy to follow their guidance.

C4, 3, 1-5 continuing to C5, 1, 1-7: “There seems to be a discrepancy between some of the statements in the manuscript with regards to the Atlantic rainfall source. . .. . I think this needs to be clarified. . .. . First it is stated that increased convection during phases with a low precession parameter must be related to a northward shift of the ITCZ, then the convection is attributed to enhance internal convection.” Response: We do not see the core discrepancy that troubles the Reviewer on this point. We can provide little positive evidence for Atlantic-sourced water in our record, and it is likely that other sites on the Mediterranean margin may show the same. Equally, it is undeniably true that to alter the Mediterranean freshwater budget the water must be external – and both the winter westerlies and the monsoon source much of that water from the Atlantic. We conclude that the key water responsible for Mediterranean freshening is likely to be arriving as runoff, not direct rainfall (which is not controversial – (Grant et al., 2016)). Primarily, we are aiming to warn colleagues working in the Mediterranean terrestrial sphere that their evidence of wet / dry changes may not relate directly to fresh / salty conditions in the Mediterranean Sea. Hopefully, this will become clearer with the restructuring this Reviewer recommends. The suggestion that recycled water from the Sahara could be important is interesting. Water re-evaporated from rainfall in northern Africa should be isotopically light, reflecting this relatively depleted source. We do not see a population of depleted fluid inclusions that sit outside of the modern rainfall system that would suggest there is a substantial contribution from such a source. C5, 4, 1-3: “The last paragraph of the section starting in line 123 is not really about ‘the central North African speleothem record’. . .. . . and should maybe be in its own chapter”. Response: agreed.

C5, 6, 1-3 (repeated in C5, 9, 1-2): “The speleothems carbonate stable isotopic composition were published, so the sentence. . .. . can be removed” Response: Agreed.

C5, 7,1-3: “I think this section should include a clear definition of the three depositional phases, giving the range of fluid inclusion stable isotopes and d-excess. This would make the comparison much easier.” Response: Agreed.

C5, 11, 1-2 continued to C6, 1, 1-8: “Technical corrections”. Response: Agreed – these changes should be made.

C6 continued into C7: “Figures” (presentational and formatting considerations for figures1, 4, 5, 6, 7 and 8). Response: Agreed – these changes should be made.

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