

Reviewer 3

General assessment

This manuscript presents an annually resolved, multiproxy study of the laminated Zerolín stalagmite from Ardales Cave, southern Iberia, aimed at reconstructing hydroclimatic variability across the MCA–LIA transition and assessing the possible role of cut-off lows. The authors combine petrographic and geochemical analyses with a well-constrained geochronological framework and modern cave observations. Particular attention is given to a well-laminated interval, where proxy behaviour and lamina-forming processes are investigated at high resolution. This process-based framework is subsequently used to interpret the longer stalagmite record.

*Annually laminated speleothems preserving this degree of temporal resolution are relatively uncommon and challenging to study. Considering the multiproxy approach applied here, I find the manuscript valuable and potentially suitable for publication in *Climate of the Past*. Nevertheless, I have several general concerns and questions that arose while reading the manuscript. I hope the authors will take these comments in a constructive manner, as they are not intended to undermine the overall value of the work. Some of them may also arise from my own misunderstanding of the manuscript. Therefore, if the authors can adequately clarify or justify these points, changes to the manuscript may not necessarily be required in every case.*

Response: We thank the reviewer for the positive assessment of the chronology, multiproxy approach, and process-based framework, and for the constructive comments and suggestions.

General comments

I found the manuscript generally well structured, and the sequence of reasoning leading from the interpretation of lamina-scale processes and geochemical proxies to the final hydroclimatic reconstruction is, overall, coherent.

My main concern relates to the degree of confidence attached to some of the final interpretations, particularly the attribution of specific intervals to an enhanced influence of cut-off lows. Several intermediate steps in the reasoning are appropriately expressed using terms such as “may”, “likely”, or “suggest”, reflecting the uncertainties involved. However, some of the subsequent interpretations appear more categorical than the underlying evidence may warrant. In particular, the identification of DANA-dominated intervals seems to rely on a chain of indirect inferences based on proxy behaviour, modern analogues, and regional comparisons. I therefore suggest that the final interpretations consistently retain the level of uncertainty present in the preceding reasoning and that the influence of DANAs be presented as a plausible atmospheric mechanism rather than as a firmly identified one, unless additional independent evidence can support this attribution.

Response: We thank the reviewer for this comment, with which we fully agree and which is shared by Reviewers 1 and 2. The level of confidence of the final interpretation now matches the chain of inference supporting it. The revised Section 5.5 distinguishes three levels. (i) Observations: high growth rates, Mg/Ca fluctuating around the record mean with recurrent positive excursions, and $\delta^{13}\text{C}$ values that do not discriminate these intervals from the rest of the record. (ii) The hydrological interpretation supported by these observations: a recharge regime that was not persistently reduced but was more irregular, with recurrent reactivation of Mg-enriched epikarst water. (iii) The atmospheric hypothesis: a greater relative contribution of late-summer–autumn Mediterranean-sourced precipitation, for which cut-off lows are a plausible synoptic mechanism by analogy with modern circulation studies (Nieto et al., 2007). Only the first two levels are constrained by the Zerolín data; the third is presented as consistent with, but not independently demonstrated by, the available evidence. The text also states that the proposed displacement of Mg-enriched epikarst water during recharge reactivation (Batiot et al., 2003; Aquilina et al., 2006)– was not captured by the two discrete site-specific monitoring campaigns, and that the lack of coherence with other regional records during these intervals is consistent with, but not diagnostic of, a locally expressed precipitation regime.

The wording has been harmonized accordingly. Categorical formulations such as “it is here that the influence... becomes a key explanatory factor” and “a proliferation of autumn precipitation events associated with cut-off lows” have been replaced by expressions such as “compatible with an increased relative contribution of...” in Section 5.5 and in the Figure 8 caption. The same harmonization has been applied to the Introduction and the Conclusions. Finally, we identify the independent evidence needed to test this hypothesis: additional high-resolution records from southern Iberia, documentary series of autumn heavy rainfall, and moisture-source tracers.

Specific comments

Modern cave monitoring or observations

I found the contribution of the modern cave observations somewhat underrepresented considering their importance for the interpretation of the speleothem record. They are not mentioned in the Abstract, and the main Methods section only briefly states that field campaigns were conducted in 2016 and 2018 and that dripwater samples were collected under contrasting hydrological conditions. More detailed analytical information appears only in Appendix A, while some of the cave-air CO₂ and ventilation data used in Figure 7 are derived from previously published work.

I think this component should be described more explicitly in the Methods. In particular, the authors should clarify how many dripwater samples and/or drip sites were analysed, whether the 2016 and 2018 campaigns represent individual sampling events or longer monitoring periods, how drip intervals were measured, which analyses were performed on the samples, and how the meteorological, cave-air CO₂, and ventilation datasets were obtained and integrated into the interpretation. It would also be useful to clearly distinguish observations generated specifically for this study from data obtained from previous publications.

Response: We thank the reviewer for this observation. We agree that the modern cave observations were under-described. The revised Abstract now briefly identifies both types of modern cave evidence: dripwater hydrochemistry and cave-air pCO₂ monitoring. The revised Methods and Appendix A clarify that the site-specific dripwater dataset derives from two discrete sampling campaigns, conducted in April 2016 under dry conditions and in March 2018 under very wet conditions. In both campaigns, dripwater was collected from the same drip point above Zerolín's original growth position, where calcite precipitation has continued since the stalagmite was collected in 2007. The drip interval was measured during sampling by timing the interval between successive drops. The revised text also distinguishes observations generated for this study from external information: regional meteorological data were obtained from AEMET, whereas the cave-air pCO₂ and ventilation patterns used in the seasonal interpretation were taken from previously published Ardales Cave monitoring (Cantalejo, 2013; Fernández-Cortés et al., 2022). Detailed analytical procedures and the complete dripwater hydrochemistry remain in Appendix A to avoid unnecessary duplication in the main Methods.

Location in the prepared revision: Abstract, Section 3.1 and Appendix A (including Table A1 and Figure A1).

Line 219: lamina thickness

The reported thicknesses of the alternating opaque white and translucent dark laminae (~3 µm and ~1 µm, respectively) seem inconsistent with other information provided in the manuscript. If I understand correctly, one light–dark couplet represents approximately one year of growth. However, the lamina-counting results indicate an average growth rate of approximately 800 µm yr⁻¹. Thus, a light–dark couplet with a combined thickness of only ~4 µm would not be compatible with the reported annual growth rate. Moreover, the scale shown in Figure 3 suggests substantially thicker laminae. Please check these values and units and clarify whether the reported 1–3 µm thicknesses refer to some finer-scale microstructural feature rather than to the annual laminae themselves.

Response: We thank the reviewer for identifying this inconsistency. The originally reported thickness values were incorrectly transcribed in the original text and have been corrected. As already apparent from the scale shown in Figure 3 of the original manuscript, the laminae are several tenths of a millimetre thick. Light laminae typically range from ~0.3 to 1 mm and dark laminae from ~0.1 to 0.3 mm, with ~0.6 mm and ~0.2 mm, respectively, representing approximate typical thicknesses across the laminated interval. These values are also broadly consistent with the average growth rate of ~800 $\mu\text{m}/\text{yr}$ estimated for the laminated interval.

Location in the prepared revision: Section 4.1 and Figure 3.

Lines 406–407: S/Ca, P/Ca and Y/Ca

After discussing S/Ca and its relationships with P/Ca and Y/Ca, the authors suggest that maxima in these elements should correspond to periods of abundant rainfall associated with cave ventilation and decreasing cave-air CO₂. I am not sure that these processes can be directly coupled in this way at Ardales Cave. According to the modern cave dynamics described in the manuscript, precipitation is highest during winter, whereas winter is characterized by restricted ventilation and higher cave-air CO₂. Conversely, stronger ventilation and lower CO₂ occur mainly during the warmer and generally drier part of the year. Therefore, as currently written, the statement seems somewhat inconsistent with the seasonal cave dynamics described elsewhere in the manuscript. If the authors are specifically referring to intense late-summer or autumn rainfall events occurring while the cave is still well ventilated, this should be stated explicitly. Otherwise, I suggest disentangling the effects of rainfall/infiltration, cave ventilation, pCO₂, and growth rate rather than implying that they necessarily covary.

Response: We agree with the reviewer. The original wording incorrectly implied that abundant rainfall, enhanced cave ventilation, and decreasing cave-air pCO₂ necessarily covary at Ardales Cave. The revised discussion now separates infiltration/solute or colloidal transport from cave ventilation and depositional controls. It states that winter recharge occurs mainly under restricted ventilation and relatively high cave-air pCO₂, whereas stronger ventilation and lower cave-air pCO₂ characterize the warmer and generally drier season. Co-enrichment in S/Ca, P/Ca, and Y/Ca is therefore interpreted as potentially reflecting a combination of enhanced infiltration/transport and depositional conditions favouring supersaturation or growth, rather than as direct evidence that rainfall maxima coincide with enhanced ventilation or low cave-air pCO₂. This also matches the proxy hierarchy in the new table of proxy controls prepared for the revised manuscript, where S/Ca, P/Y-related transport, and ventilation are kept as distinct controls rather than collapsed into one seasonal driver.

Location in the prepared revision: Section 5.1 and the proposed new table of proxy controls.

Technical and editorial comments

Line 76

I suggest replacing “geomorphological context” with “orographic setting” or “geographical setting”. The preceding description refers mainly to the position of the site between mountain ranges and their influence on precipitation gradients rather than to geomorphological processes.

Response: We agree. “Geomorphological context” has been replaced by “orographic setting”, which better describes the role of the surrounding mountain ranges in shaping precipitation gradients.

Line 169

Please check the stated detectability threshold. Line 167 indicates a threshold of ~80 μm (~4 pixels), whereas line 169 states that laminae thinner than 8 μm were considered below detectability. I assume that 8 μm is a typographical error and should read 80 μm .

Response: We agree. This was a typographical error. The detectability threshold has been harmonised at ~80 μm , consistent with the ~20 μm pixel resolution and the four-pixel criterion used in the lamina-counting analysis.

Line 329

I would reconsider the section title “Speleothem as a paleoclimate proxy”, as it is very broad and does not accurately describe the content of the section. Something more specific, such as “Geochemical variability between light and dark laminae” or “Geochemical characteristics of annual laminae”, might be more informative.

Response: We agree. The section title has been changed to “Geochemical characteristics of light and dark laminae”, which more directly reflects the content of the section.

Line 363 / Figure 7

The term “conceptual model” may be appropriate, but the figure appears to combine observational data with schematic or interpretative proxy behaviour. I suggest clearly indicating in the caption which curves represent measured or published data and which components are conceptual or inferred.

Response: We agree. The Figure 7 caption now distinguishes the provenance of each component explicitly. Monthly precipitation represents instrumental observations from the Campillos AEMET station, while cave-air pCO_2 and ventilation patterns derive from published monitoring (Fernández-Cortés et al., 2022). In contrast, the Mg/Ca seasonal trajectory and lamina-forming sequence are conceptual/inferred rather than measured monthly series. Sr/Ca is no longer plotted as a monthly curve because its interpretation is primarily growth- and partitioning-sensitive; its relative seasonal behaviour, together with Mg/Ca and $\delta^{13}\text{C}$, is described qualitatively in a supplementary table prepared for the revised manuscript.

Location in the prepared revision: Figure 7 caption and the proposed supplementary table of seasonal proxy behaviour.

Lines 181 and 261

The high-resolution interval is described as extending from 317 to 340 mm, which corresponds to 23 mm, whereas line 261 refers to a 20 mm segment. Please check and harmonize these values.

Response: We agree. The high-resolution interval extends from 317 to 340 mm and is therefore 23 mm long. The Methods and Results now consistently refer to a 23 mm interval (Sections 3.3 and 4.3).

Location in the prepared revision: Sections 3.3 and 4.3 and the high-resolution figure captions.

Line 450

“JOHNSON et al., 2006” should follow the same capitalization style as the other references.

Response: We agree. The citation has been standardized as “Johnson et al. (2006)” in the revised manuscript.

Line 453

A full stop is missing at the end of the sentence.

Response: Thank you. The corresponding sentence has been checked and the punctuation corrected in the revised manuscript.

Line 651

A space is missing between “time,” and “dolomitic”.

Response: Thank you. The spacing has been corrected in the revised manuscript.