Climate of the Past Discussions

Clim. Past Discuss., author comment AC2
https://doi.org/10.5194/cp-2021-149-AC2, 2022

Reply on RC2

David T. Liefert and Bryan N. Shuman

Author comment on "Expression of the "4.2□ka event" in the southern Rocky Mountains, USA" by David T. Liefert and Bryan N. Shuman, Clim. Past Discuss., https://doi.org/10.5194/cp-2021-149-AC2, 2022

We thank the reviewer for a thoughtful assessment of our manuscript and have substantially modified the text and figures based on this input. In response to the major discussion points, we added text expanding on our reasoning for the controls on the study lake's carbonate $d^{18}O$ and how regional hydroclimate changes ca. 4.2 ka could have driven the observed isotopic changes. We include a general response to the reviewer's major comments here and specific comment responses below. The manuscript has been revised accordingly.

General response to reviewer:

We agree that site-specific factors (like those listed by the reviewer and addressed in the manuscript) that lead to differences in the absolute values and variability of carbonate $d^{18}O$ among lakes can make inter-lake comparisons challenging. While the differences in hydrologic setting at each lake are not assumed to override hydroclimate-driven changes in lake-water $d^{18}O$, such as drought, they can affect the seasonal and overall sensitivity of the system.

For example, Anderson (2012) uses the varying degrees of evaporative enrichment to explain the range in values of both modern lake-water and Holocene carbonate $d^{18}O$ in Bison and Yellow Lakes of central Colorado, USA, as well as why their shared hydroclimate history is expressed differently in their sediment records. For this reason, seasonal patterns in modern lake-water $d^{18}O$ and/or water-balance measurements are generally used to determine how hydroclimate changes should influence lake-water and carbonate $d^{18}O$ in lakes (e.g., to distinguish endorheic and flowthrough basins, which record hydroclimate changes much differently).

Using this framework, we added text discussing how evidence in both our study lake's modern setting and sediment record indicate that the timing of carbonate formation may record a winter or springtime isotopic signal rather than summer (as is assumed for most lakes), and how a shift toward less snowfall relative to rain at ca. 4.2 ka could have manifested the anomalously positive carbonate $d^{18}O$ because the isotope composition of mean annual precipitation potentially became heavier (higher evaporation would have amplified these changes but may not have affected the lake's carbonate $d^{18}O$ if carbonates form in winter or spring). We also further discuss why common site-specific factors influencing lake-isotope systems are unlikely to explain the offset in $d^{18}O$ among the regional isotope records compared to our study lake.

Although we were initially skeptical of the 4.2 ka event's significance in North America, our study lake potentially indicates regional snow drought at ca. 4.2 ka when a growing number of fossil-pollen, lake-level, and dune-field chronology records also indicate drought in the Southern Rocky Mountains from southern Wyoming to northern Colorado. It remains unclear why the other $d^{18}O$ records within the region do not record a prominent change at 4.2 ka, but by comparing the variability and absolute values of $d^{18}O$ in the isotope records we show that there may be fundamental differences in the ways that the lakes have recorded hydroclimate changes that are not yet fully understood. Despite this uncertainty, evidence of drying from the other types of proxy evidence within the region match the expectation of snow drought based on the positive shift in the study lake's carbonate $d^{18}O$, which was probably driven by a positive shift in the isotope composition of mean annual precipitation as snow declined relative to rain.

Response to individual comments:

Regarding the Abstract/Introduction and general framing: I found the description of the '4.2 ka event' a little confusing. The authors switch between describing an event at 4 vs 4.2 ka (are these the same thing?), and also provide quite vague background about the global nature of the event compared to the greater detail provided for North America (including potential forcings). I'd suggest just a sentence or two about the event in a global context before jumping more immediately into discussing the event in the context of North American climate (which, after all, is the focus of this paper)

A sentence has been added at line 67 to expand the discussion of possible drivers of the event globally.

It would be nice to see some discussion of possible anthropogenic influences on this (and other) lakes, even if it's just a referenced statement like 'there was probably not any anthropogenic influence'

Text was added to line 482 explaining that we have no reason to expect anthropogenic influence.

Line 26: define 'ka' at the first instance

The suggested change has been made.

Line 28: abrupt **global** drying?

The sentence was revised to indicate that evidence of drying exists primarily in the Northern Hemisphere.

Line 35: "…records from Colorado do not record it." – what exactly is 'it'? we've lost the subject that this 'it' should be attached to

"it" has been changed to "drought."

Line 40: 'the strong enrichment…..summer months today' I suspect that this sentence may be referencing an erroneous comparison of lake water $\delta^{18}O$ and lake carbonate $\delta^{18}O$ values that I point out later on. If so, this should be removed.

Text was added to line 232 at the end of the Methods describing how we calculated temperature-dependent fractionation of calcite formation and conversion of VSMOW to VPDB. See responses to comments below for more

changes.

Line 45: 4 ka and not 4.2 ka? Is this meant to be the same 'event'?

Correct. Records from around the world interpreted to support the "4.2 ka event" span multiple hundreds of years around 4 ka and many do not begin or are not centered directly on 4.2 ka. On Line 30 we now reference this point.

Line 50: list dates (in parentheses) of the YD chronozone as a reminder for us

The suggested change has been made.

Line 59-61: This sentence is a bit grammatically ambiguous; I suggest rearranging it along the lines of 'However, some regions show increased precipitation, which is consistent with…"

Done

Line 62: 'Recent' -> 'Recent **model**'

The suggested change has been made.

Line 67: Unless I'm mis-remembering, Ault et al 2018 specifically describes drought in western North America (i.e. this isn't globally applicable). In any case, I suggest that by here you have already focused in on the nature of the '4.2 event' in North America (not globally)

Ault et al. indeed describes dynamics in western NA, but their finding that abrupt climate changes can occur from intrinsic climate variability (as opposed to some external forcing) is relevant to 4.2 ka studies globally and provides context for distinguishing the event from other Holocene variability, much of which was driven by external processes. By not changing or removing this paragraph to focus on North America, it provides the background on the event in a global context requested in the first bullet point of this review. No change was made.

Line 75-76: put the 'in the North American midcontinent' modifier earlier in the sentence; this is grammatically ambiguous as written

The sentence has been separated into two for clarity.

Line 80: I suggest putting the 'However' at the start of this sentence for clarity

Done

Line 84: what exactly is a 'dune record'? Is this a 'dune-field chronology' as per below? If yes, you should write that out here too

Done

Line 83: 'Rocky Mountains **of North America**'

Done

Line 85: It would be good if here you also listed the proxy record types that don't show evidence for a 4.2 ka event

Some record types have been listed as examples.

Line 94-97: Two 'prominent's in one sentence (just in case you want to change one)

The first instance was removed.

Line 97 (last word): again, what is 'It'?

The sentence was clarified to indicate a drying event.

Line 100: 'By contrast, the 4.2 ka…' -> 'By contrast, **a** 4.2 ka…'

The existing text is accurate because the 4.2 ka event is thought to represent a single climatic anomaly identifiable from multiple sources rather than one of many 4.2 ka events. No change was made.

Line 117: measurements of what? Something like 'Measurements of modern lake water physical and geochemical characteristics can help…' might be clearer

The sentence was clarified to indicate isotopic measurements.

Line 177: controls on what? Lake carbonate $\delta^{18}O$? Lake water $\delta^{18}O$? Other?

This is likely referencing line 117. Carbonate d18O was added for clarification.

Line 121: You could reference Figure 1 here

The suggested change was made.

Line 127: spell out 'water isotopes' at the first instance i.e. 'water stable isotopic compositions ('water isotopes' hereafter)'

Done.

Line 132: 'interpretations of **the stable isotopic composition of lacustrine carbonate interpreted in terms of past hydroclimate variability**' or similar

The sentence has been revised similarly.

Line 142: 'but high elevations' -> 'but high**-elevation sites**'

The sentence was reduced for clarity.

Line 145: could you just say 'average annual temperature range'?

The existing sentence describes the annual temperature extremes rather than average range. No change was made.

Line 146: add reference

Done.

Line 163: were these precipitation/groundwater samples collected at the same time/over the same time interval as the lake water samples? Either way, you should state the collection dates.

Done.

Figure 1: Add a spatial scale of some sort to inset a (eg lat/lon). It would also be good to highlight Bison & Yellow lakes in some way, given you do a lot of explicit comparison of your new observations with similar observations from these lakes. Additionally, could you not slightly extend box b so that it includes Little Molas Lake? It would be good to be able to see it, given you show data from this lake in Figure 7 and it's a bit odd that it's the only lake cut out.

The suggested changes were made.

Line 164: 'Isotopic ratios **of all water samples** were measured…'

Done.

Line 166: Here (or at least somewhere) you should state that water stable isotopic ratios are reported relative to VSMOW (this is an important distinction from your carbonate values, for which you do state the standard)

Text has been added to this paragraph to indicate the water standard.

Line 182: 'At the same time' at the same time as what, exactly? Better just to state the time again (I am guessing January 2017, in which case something like 'In January 2017, we also collected…')

Done.

Line 186-line 189: Your methodology here is a bit unclear. Do you mean to say that you roasted the samples at 550 degrees, then performed stable isotopic analysis on the carbonate from that roasted sediment? What are the oxidizing agents mentioned in line 188? Did you oxidise the roasted/raw sediment, or just the roasted sediment? It would also be good to show the results of this comparison (mentioned in line 188) as a supplementary figure

This sentence has been revised for clarity.

Line 189-190: grammatically ambiguous; I think you mean to say that you sieved out the fine fraction, and then measured the stable isotopic composition of that fine fraction using the mass spec?

Correct. The sentence has been revised for clarity.

Line 192: if the calcite isn't ostracod tests, then what is it? Amorphous fine-grained? Unidentified but probably autochthonous? Do you have any SEM (or other microscope) images of this carbonate? It would help the reader a LOT throughout the rest of the paper to have at least some idea of the nature of this lake carbonate

In this sentence and the next we elaborated on the type of calcite present and our reasoning.

Line 195-198: I don't really understand what you are trying to say in this sentence; consider re-writing into several shorter sentences each describing one thing. Also you state here that you isolated conifer needles, but I don't see them on Table 1(?)

The sentence was clarified and split into two. Conifer needles were referenced in error and have been removed.

Line 204 and all later instances where you report stable isotopic compositions of lake **water**: I assume that these values are relative to VSMOW, which is an important distinction from your lake carbonate $\delta^{18}O$ values which are reported relative to VPDB. These two things are **not directly comparable in terms of their absolute values**

This point is addressed in other comments, but here the text only refers to the composition of lake water, so no change was made.

Line 205: unless I am mistaken, the 'thick black line' on Figure 2 is the LEL defined by your samples, but also shows the range in values (comparable to the arrows for the other lakes)? I found this a bit confusing so probably other readers will as well. Maybe re-think how you show the various data on this figure.

Correct, this line shows both the range in samples and slope of the local evaporation line. The sentence was revised to explain more clearly that the slope of the line tracing HL's range in lake water isotope values (which define HL's local evaporation line) follow the local evap line of lakes in the CO Front Range.

Line 207: 'Several consecutive years'?? Where are these data from? In the methods, you mention only that you collected lake water samples in 2017.

The methods (line 192) were corrected to indicate the range of sampling dates (2015–2017). A sentence was added to Fig. 2's caption to indicate the data shown are only from 2017.

Line 208: '**water** isotope values at HL'

Done.

Line 214-215: Are the water isotope values from these lakes truly comparable in terms of absolute range of variability? Do the measurements represent approximately the same seasonal range/duration of collection?

The preceding sentence (now line 276) was revised to indicate the months and approximate year when Anderson collected these samples, which was earlier than 2017 (Anderson doesn't provide the exact year of when they were collected) but represents the same seasonal range as sample from HL.

Line 218: Actually, just eyeballing the inset plot in Figure 2, it looks like the snow/rain ratios at the two lakes were quite different in 2017 when your data were collected

This sentence was revised to clarify that it's the long-term average conditions that are similar rather than specific years. The average conditions are more important than individual years because carbonate oxygen isotope values in these lakes are integrated over multiple years or decades.

Line 222: Provide a reference for the lake-water temperature range at HL

Text was added to lines 188 and 204 in the methods to indicate that water temperatures were measured with lake water samples and concurrently with depth using the pressure transducer.

Line 231: Add a citation at the end of this sentence

Done.

Figure 2: from what data were the dotted LELs calculated? You should put the references explicitly in the figure caption. Also for ease of reading, at the filled black dots and thick black line to the figure legend

The references are in the second sentence of the caption but were moved up in the sentence for ease of reading. The legend was revised.

Line 239: Remove both instances of 'in' after the percentages

Done.

Line 244: Here is another instance where I'd really like to know already how the carbonate is being produced in this particular lake!

"Authigenic" was added for clarification.

Figure 4 (and also Figure 5): It would be better if you combined these two figures, by simply plotting all the timeseries from Figure 4 on a **time axis**, and then showing the age-depth model as a supplementary figure (along with the core image, which doesn't add a huge amount given how narrowly it is shown). That would make later comparisons of these timeseries much easier. You could also then highlight time windows of interest.

It would also be much better (and would aid in some later interpretation) to follow modern best practice & incorporate the chronological uncertainty into your plotted timeseries (which are currently shown on only one realisation of the age-depth model) – there are many examples of this in recent palaeoclimate literature, as well as guides as how to do such things (e.g. the recently-published geoChronR package from McKay et al).

Uncertainty bands have been added to Figure 5. Figure 4 was not changed so that it is clear to the reader how the raw data and age-depth model were used to generate the $\delta^{18}O$ time series in the following figure, particularly as it relates to the changes around 4.2 ka during a high rate of sediment accumulation (which isn't apparent if we plotted all the data on a time axis).

Line 259-260: might as well just say 'there is no significant trend'

Done.

Line 262: are these 'isotope excursions' statistically significant? That is, did you define them quantitatively in some way? Or are you just eyeballing peaks? If the former, you should describe the method that you use to identify anomalous intervals. If the latter, then you should either attempt some quantitative analysis, or say explicitly that the 'excursions' are qualitative.

The excursions are now defined as deviations from the mean (e.g., the excursion at 4.2 ka represents a departure from the mean of three standard deviations).

Line 282: You need to define how exactly a change in the ratio of snowfall to rain manifests as a change in lake carbonate $\delta^{18}O$.

Two sentences were added here to expand this discussion.

Figure 6: Consider plotting these three records on their own y-axes. This would make the plot a lot clearer, and also the absolute values are not really of value here, but rather the variability

Plotting the records this way is consistent with the original author's (Anderson, 2012) approach and helps put into context their interpretations, which we build from to make sense of our record. We also expanded our discussion (both in the introduction and second half of the discussion) of why comparing the absolute values among the records is helpful for understanding the drivers and limitations isotope records. No change was made.

Line 292-293: are 'the records' mentioned here all in the Medicine Bow Mountains? Throughout the discussion I lose track of which records do versus do not have evidence for a climatic anomaly at 4.2 ka, and also where they are (Medicine Bow Mountains, other parts of the Rockies etc). This could be quite easily clarified via a **table** (probably near Figure 1), listing the names of each site that you mention in the text, the proxy type, the region name, and whether or not there is evidence for some sort of event around 4.2 ka (and what that event was – drying, warmth other etc).

Done, see Table 1.

Line 304: 'high-elevation lakes' – there are only a few that you are referring to, so it would be clearer for the reader if you listed them by name

The suggested change has been made.

Line 307: 'the sediment stratigraphies **in these three lakes**'

Done.

Line 320: is there reason to suspect that this age is out of sequence? If so, this should be mentioned in the results. This potential bias from the age-depth model could also be addressed by showing age uncertainty on you plots as I suggest above

Text was added here to explain the reasoning for why the age could be out of sequence.

Line 330: From what you have plotted here, in most cases the sedimentological changes at 4.2 ka do indeed look unique, but I wouldn't say that that is the case for the isotopic values

The sentence has been reworded accordingly.

Line 333: 'associated with the widespread climatic anomaly'- this is the hypothesis you're testing here, so you can't really cite it as being associated with the widespread North American drought (which is also something that you are assessing!)

This text has been removed as suggested.

Line 347: 'when **precipitation at** high-elevation sites…'

The sentence was clarified, "sites" in this context referred to high-elevation lakes and their water-level declines.

Line 348: How, exactly would these changes result in high lake carbonate $\delta^{18}O$? Some known influence on precipitation $\delta^{18}O$, which is then passed on to the lake carbonate $\delta^{18}O$?

The sentence was expanded to help clarify this point.

Line 361: 'Given the potential prominence of the 4.2 ka drought at HL': I'm still not exactly convinced of a mechanism linking the high lake carbonate $\delta^{18}O$ values and local drought conditions

See response to comment regarding line 390 below.

Line 376: This section might be better off at the start of the discussion – that way the reader has been introduced to the possible drivers of carbonate $\delta^{18}O$ values in the various lakes, the climatic implications of which can then be placed into the wider context

This section of the discussion has been revised to frontload some of these concepts. We did not move it to the front of the discussion so that the hydroclimatic implications remain the emphasis rather than the possible controls on isotope records.

Line 390: I am not convinced that there is much worth in comparing the absolute magnitude of carbonate $\delta^{18}O$ values from different lakes, especially given how far they are apart. There are WAY too many processes (climatic and otherwise) that can affect absolute values, even if there are common drivers of variability

This discussion was revised to clarify our reasoning, see the two paragraphs starting on line 485.

Line 398: So increased lake carbonate $\delta^{18}O$ at HL indicates less snowpack? Why, exactly? I think that you allude to various possible reasons but you should clearly outline the connection in terms of water isotope systematics.

This paragraph and the one following it were combined and substantially revised to clarify our reasoning.

Lines 403-406 and 411-416: Unless I am mistaken, here you seem to be directly comparing the absolute values of lake water $\delta^{18}O$ (relative to VSMOW) and lake carbonate $\delta^{18}O$ (relative to VPBD). This is not valid. Even when autochthonous lake carbonate precipitates using lake water as its source water, the fractionation depends on various things including the temperature at the point of carbonate precipitation (this is an unknown, in your case). Any conclusions that you have drawn based on comparison of absolute lake water and lake carbonate $\delta^{18}O$ values should either be removed, or re-thought in the context of anomalies.

Lines 403-406 were revised to include the range in core-top carbonate $\delta^{18}O$ calculated from lake water $\delta^{18}O$ and the measured lake water temperatures, then moved to the results beginning on line 349. The reference to Bison Lake's values on line 411 was removed.

Line 417-421: this information would have been nice to know much earlier on – you could possibly sneak it into the results when you outline the specific conductance (or at least when you first discuss result from HL).

This information is already in the Results beginning on line 293.

Line 463: 'approximately 1% lower at HL' what exactly is lower than what?

The sentence was revised.

Paragraph starting line 460: The premise of this paragraph seems a little flawed to me. Again, discussing difference in absolute magnitudes of lake carbonate $\delta^{18}O$ between these

three lakes is not particularly valuable, given the huge range of things (carbonate phase, seasonality, precipitation regime, seasonal cycle of precipitation $\delta^{18}O$, groundwater input, groundwater $\delta^{18}O$, local geology……) which could affect these absolute values, and which you don't have enough information to tease out. It's a comparison of variability(trends and other features of the timeseries) which is interesting (and relevant)

This paragraph has been revised to directly address the points raised here and to expand on our reasoning for discussing both the magnitude and range of $\delta^{18}O$.

Line 476: what are they 'surprisingly' negative?

The sentence was expanded for clarity.