Response to reviews for Manuscript No. egusphere-2024-1691

Speleothem evidence for late Miocene extreme Arctic amplification - an analogue for near future anthropogenic climate change?

by Umbo et al, submitted for publication in Climate of the Past.

Dear Prof. Murton

We kindly thank you, and the editor, for taking the time to review our manuscript and give such a considered response. You have made many excellent suggestions, the majority of which we agree with and will look to implement. I respond here to the main concern highlighted in your review which suggests a shift in the balance of the manuscript away from future carbon emissions from permafrost thaw to give a more focused palaeoclimate study of the late Miocene.

We appreciate that the permafrost modelling section of this paper is highly speculative, and we made considerable efforts to be upfront about this in the methods and discussion sections. However, we accept this is the weakest part of our study and will therefore adopt your recommendation to refocus the manuscript accordingly, removing sections 3.5 and 5.5 which deal with permafrost emissions estimates. This refocusing inevitably requires a restructuring of the introduction and discussion, reducing content on permafrost and expanding on paleoclimatic conditions during the Tortonian. The main conclusions of the paper remain valid: that we derive a much warmer, highly seasonal environment at our site during the Tortonian.

To address each of your suggestions in turn, I have given our response below in red.

Once again, thank you for such a thorough review. We will implement the vast majority of your suggestions and we feel that the resulting revised manuscript is a much improved, scientifically robust, study.

Yours sincerely

Umbo, et al.

List of specific feedback

The **introduction** focuses more on present-day environmental conditions in the Arctic and on 21st century global warming than on Miocene environments. I find this unbalanced and disappointing for a palaeostudy. Some of the arctic references are cited imprecisely (see below). I think the introduction does not do justice to the excellent palaeoenvironmental work carried out in this study. I find much of the introductory text a distraction and poor way of justifying a strong geological study. Instead it would be much more useful for readers to learn about late Miocene environments and the associated knowledge gaps and research questions in order to set out the context for this study. I suggest the authors rebalance the introduction, focussing on the late Miocene and simply noting that it may provide an analogue for an almost-permafrost-free world in the future.

Response: As discussed, we will refocus the paper away from future permafrost modelling and give the introduction a stronger palaeo-environmental focus. In doing so, many of the suggested introductory edits concerning permafrost (lines 54 – 80) may become redundant. However, we have still responded to them as it's unclear how much permafrost content will remain after the refocusing of the paper.

The **methods** used to address question 2 involve first extrapolating from one site to the whole late Miocene Arctic and second in estimating carbon emissions from the modern Arctic at 2100 (using permafrost vulnerability modelling), assuming warming of the modern Arctic atmosphere matches this study's late Miocene estimates. I question the validity of the question 2 methods on grounds of undue speculation (see comment on lines 491 – 512 below).

Response: Again, we take on board your concern of undue speculation and will remove quantitative future permafrost emissions modelling from the paper. Instead, we shall reference our Vaks et al manuscript, currently in review.

The **discussion** starts with quantitative temperature estimates for the Tortonian (section 5.1). This nicely sets the estimated palaeotemperature in the context of existing literature. However, it omits an essential discussion of the relationship between speleothem formation temperature and near-surface air temperature (see comment on line 292 below). Section 5.2 on stable oxygen isotope records attributes the d18O values of the Taba Bastaakh cave speleothems to temperature variations. A short discussion of how enhanced evaporation and moisture transport into northern Siberia may or may not have influenced stable isotope composition would be welcome (see comment about L458).

Response: With regards to the relationship between cave and surface temperature, we will include some exploration of this relationship. Please see my response below (line 292).

In addition, we will look to include some additional background on the relationship between moisture budget controls on $\delta^{18}O$ of speleothems. Please also see the response below (line 458).

To my mind 5.5 is unduly speculative (inferring pan-Arctic MAAT from a temperature at an unspecified depth in a single cave locality whose relationship with air temperature is not discussed). I think it would better to simply infer that higher values of MAAT during the late Miocene suggest permafrost was absent from this area. Instead of this tangential discussion about permafrost thaw and carbon emissions at 2100, I think more discussion is needed about the late Miocene conditions and ground-air temperature relationships at this cave site.

Response: As discussed, a refocus away from permafrost modelling will go a large way to overcoming these concerns.

Line 54: "a crucial climate tipping element (McKay et al., 2022).": suggest omit this or at least replace 'crucial' [which is unsubstantiated] with 'possible'. It is speculative, sensationalist science. Thermal inertia and complex relationships between ground thermal regime and the buffer layer of snow, vegetation etc. modulate permafrost dynamics.

Response: The word "crucial" has been replaced by "possible".

L54 – 55: "The Earth's largest terrestrial carbon pool (Strauss et al., 2024), thawing permafrost." The largest terrestrial carbon pool is 'permafrost' rather than 'thawing permafrost'.

Response: This sentence has been rewritten as "Permafrost is the Earth's largest terrestrial carbon pool (Strauss et al., 2024), and its future thaw will play a major role in climate trajectories.".

L55 – 56: "Permafrost degradation is occurring much faster, and earlier, than expected (Farquharson et al., 2019)". Please qualify this general statement. The Farquharson study concerns three sites in the Canadian High Arctic that are not relevant to e.g., areas of warm permafrost with boreal forest, or mountain permafrost or plateau permafrost or subsea permafrost.

Response: The statement has been qualified to state that the research applies to three sites in the Canadian high Arctic. We have also provided additional support for this statement by citing two Siberian studies that suggest faster thaw of permafrost in Siberia – closer to our study region - than previously projected. However given the previously discussed reorganisation of the manuscript to reduce permafrost related content, this content may be removed entirely for the final version.

L57: "a global network … show": the subject is singular, so the verb should be 'shows'.

Response: Corrected

L59: clarify what you mean by 'thaw slump rate': e.g., rate of growth or rate of initiation?

Response: We have added "initiation" to clarify.

L59: 'in Canada (Lewkowicz & Way, 2019)': this study concerns Banks Island (70,000 km2) rather than the whole of Canada. There are very large regions of the Canadian permafrost zone (e.g. The Barrens) where no or few thaw slumps occur. Please qualify. Ditto for 'east Siberia', which needs a reference.

Response: We have clarified that the Lewkowicz et al study applies solely to Banks Island, as well as provided a reference for the Siberia study.

L65 – 66: "with increased rainfall amount and reduced snowfall duration driving permafrost degradation…" The O'Neill and Burn (2017) study about snow cover is more nuanced. Reduced duration of snow in autumn and winter may favour ground cooling and permafrost aggradation; reduced duration of snow cover in spring may favour earlier warming of soil and active-layer deepening. Thicker snow in winter tends to limit heat loss from underlying soil.

Response: Thank you for clarifying this. We have split the sentence to consider rainfall and snowfall effects separately, clearly stating the competing effects of autumnal vs spring snow cover. This section now reads:

'Temperature has long been considered the main driver of permafrost stability, but recent studies have demonstrated the importance of precipitation characteristics. Increased rainfall amount has been shown to destabilise thaw slumps in northwestern Canada (Kokelj et al., 2015). Furthermore, changes in the timing of snow cover impact rates of heat transfer between soil and the atmosphere, with later autumnal snowfall increasing ground cooling and earlier spring melt speeding up ground heating (O'Neill & Burn, 2017).'

L68 – 69: "Best estimates project the extent of global thaw between 2 and 66 % by 2100". I think you mean 'near-surface permafrost thaw'? It is impossible to thaw 66% of hundreds of metres thickness of global permafrost by 2100 unless there is a catastrophic event such as another Mars-sized object impacting the Earth and vaporizing or melting much of the Earth's crust, as probably occurred about 4.5 Ga.

Response: Yes, we have clarified "near-surface". Once again however, this may be a moot point given the refocus away from permafrost modelling.

L80: "in regions of modern-day permafrost stability". Please clarify what this means.

Response: This wording is superfluous and has been removed.

L81: "Arctic warming has consistently exceeded the Northern Hemisphere mean by a factor of 3 - 4 during Quaternary interglacials": warming of what? Air, ground, sea?

Response: We have changed to "surface temperature anomalies" for clarification. The Miller et al. (2010) study looks at summer surface temperature anomalies, deriving combined atmospheric and ocean temperatures from climate models driven by known forcing and verified by proxy data.

L83 – 84: "Recently, Steinthorsdottir and colleagues (2021) proposed the Miocene (23.03 - 5.33 Ma) as a suitable palaeo-analogue for anthropogenic climate change." Anthropogenic climate change has been occurring for decades if not centuries. What time are you referring to? Today or sometime in the future?

Response: Added "future"

L85: "between 400 - 600 ppm": 'between' … 'and'

Response: Added "and"

L93: "palaeotemperatures": please be consistent with spelling: either 'ae', as here and L84, or 'eo' as L42. Are these ground or air temperatures?

Response: Thanks for spotting the inconsistency. We've added a British "a" to the couple of instance that we missed so that spellings are all consistent. I have clarified we have reconstructed multi-annual mean surface air temperatures.

L95: "future permafrost thaw": do you mean this or do you mean 'near-surface (upper metres) permafrost thaw?

Response: We have added the words "near-surface" to clarify.

L100 – 101: "Lower strata (up to ca. 50 m above current river level) comprises": comprise (plural subject)

Response: Corrected

L104: "active layer thaw depth": 'active-layer depth'.

Response: Corrected

Fig. 1A: add degrees and 'N' and 'E' to coordinates. Label Lena Delta on map. What do the green and yellow on the map indicate?

Response: Degrees N and E will be added to the figure and colouring explained in the figure caption and it will be clarified that green shading shows forested areas.

Fig. 1B: indicate scale on the photograph or in the caption.

Response: Corrected

L116 – 117: "Mean annual rainfall (2002 - 2017) is 169 mm and mean annual snow cover 0.3 m": should be 'was', as data are historical.

Response: Corrected

*L120 – 121: "Today, the caves are ice filled and inaccessible, but erosion of the cliff face has exposed relic caves with speleothems observed along the cliff walls. Observations of ongoing weathering of cave walls …": **How did you observe the cave walls if the caves are inaccessible?**

Response: The original text states "erosion of the cliff face has exposed relic caves" (i.e. caves have been eroded back such that speleothems sit on the cliff face). We have reworded slightly to emphasises that only the modern caves are infilled with ice and the interior of relic caves have been exposed by erosion. The text now reads:

*"The **modern** caves are ice filled and inaccessible, but erosion of the cliff face has **exposed the interior** of relic caves, with speleothems observed along the cliff walls."*

L146: "Final $\Delta 47$ values": please write out in full first, as per L161.

Response: Corrected

L189: "110±10 µg of sample was loaded": 'were' (microgrammes)

Response: We have reworded as "110±10 µg of **THE** sample was loaded" to avoid any ambiguity.

L191 – 192: "We use": 'used' to be consistent with past tense elsewhere in this paragraph.

Response: Corrected

L194 and caption to Table 1: "data is reported": 'are'

Response: Corrected

L211: "estimate potential soil organic carbon (SOC) emissions from the thawing region": how do you distinguish between CO2 and CH4 emissions, or do you convert data to CO2-equivalent?

Response: We do not, this is simply an estimate of total carbon vulnerable to thaw. However, this is now a moot point since emissions estimate content shall be significantly reduced as previously discussed.

Fig. 3: please indicate which graphs indicate STBB I – 1 and which STBB II.

Response: Will be corrected

*L256 – 260: **PCA analysis**. Please move to methods section.

Response: There was significant discussion whilst writing the paper as to where to include the statistical analysis of the data. This applies additionally to spectral analysis of trace elements, modern vs Miocene spectral analysis comparisons, and calculations of dripwater $\delta^{18}O$. We felt it helped to keep descriptions of novel statistical analysis next to the interpretation, rather than directing the reader back and forth to the methods section. We would argue that where we have utilised novel methods (i.e. modern vs Miocene seasonality comparisons, and calculations of dripwater $\delta^{18}O$) this structure is still preferable. However, in commonly utilised methods such as PCA and spectral analysis, we take on board the suggestion that this the methodology does sit more comfortably in the methods section. Hence, **we have moved lines 256 – 260 to the methods section, as suggested, alongside lines 270 – 271 "*We applied spectral analysis…*"**.

L263: "These PCs highlight two elemental groupings, the first…" This does not make sense. Please punctuate correctly or rewrite.

Response: Yes, this was somewhat clunky. We have reworded so it now reads:

~~*"These PCs highlight two elemental groupings,*~~ *The first PC is defined by correlations…"*

L264: "correlations with Ba, Sr, Mg, and U…": correlations of what? Or do you mean correlations between…? Ditto L267.

Response: We have reworded both L264 and L267 to read *"PC1 correlates with Ba, Sr, Mg etc…"* We think this makes it clearer.

L273: "dominant frequencies at ~ 0.3 mm and 0.5 mm": as frequency is usually measured in Hz, it is clearer here to use 'spatial frequencies'.

Response: We have replaced "frequencies" with "wavelengths"

L274: "We also observe cyclicity in P and Cu." Please indicate what it is.

Response: This information has been added.

L281: "The late Miocene is widely accepted to have been several degrees warmer than today." Please insert 'climate' after 'Miocene'.

Response: Will be corrected

*L286 – 287: "The regional modern annual ground temperature (MAGT) is -8.4°C, averaged along a 27 m borehole at the Samoylov Island Research Station". As a rule of thumb, ground temperature driven by heat conduction at depth z integrates surface conditions (variation in snow thickness, vegetation, organic layer, water content etc.) over a horizontal distance of about three times depth. So a borehole 27 m deep indicates surface conditions of a circle with a diameter of about 80 m. If you want to infer **regional MAGT**, you need multiple boreholes. A single borehole simply provides a point source of data, which may or may not be representative

of a region. Therefore delete 'regional'. If you want to use this to infer regional conditions, please indicate that you are drawing an inference.

Response: We have reworded, removing the word "regional" and stating that the temperature is an inference. The sentence now reads:

"Taba Bastaakh lies deep within the modern continuous permafrost zone with a MAAT of -12.3°C. We infer a mean annual ground temperature (MAGT) of -8.4°C, which we calculate by averaging temperature along a 27 m borehole at the Samoylov Island Research Station (Boike et al., 2013)."

*L292 and caption of Table 3: "We obtain quantitative estimates of Arctic temperatures at Taba Baastakh…": Please indicate the depth(s) of these speleothem formation temperatures. If the temperature concerns a specific depth in rock, then it will almost certainly differ from the MAAT, because ground temperatures tend to be a few to several degrees warmer than air temperatures in most modern Arctic regions. The difference between air temperature and ground surface temperatures (surface offset) and between ground surface temperatures and temperature at the top of permafrost (thermal offset) vary from site to site and through time. A recent attempt to estimate this for three permafrost cave locations during the Younger Dryas is given in https://cp.copernicus.org/preprints/cp-2023-72/ By contrast, your study suggest permafrost-free conditions, but nevertheless some form of buffer layer likely existed that modulated the impact of air temperatures on ground temperatures, so please discuss the possible nature of this buffer layer (e.g., vegetation, soil, organic matter; the associated Vaks et al. ms in review notes that "some tree growth extending to 80oN, i.e., 10o further north than today"; lines 73 - 74), perhaps using examples from modern warm regions. Also, please discuss the potential heat transfer mechanisms (conduction, convection) relevant to your caves, e.g., were they convectively cooled by cold-air drainage or simply by heat conduction? **In essence, readers need to understand (1) how you infer air temperatures from ground temperatures, (2) if there was a difference between them, and if so, (3) what this difference likely was.**

Response: Thank you for raising this clarification. We will add additional discussion exploring the relationship between cave and surface temperature and amend our estimates of MAAT accordingly. The relationship between cave and surface is unique to each location and is influenced by multiple factors including cave ventilation, depth, and surface cover. Deciphering the relationship requires in situ monitoring and given that the Taba Bastaakh caves have now near completely eroded, this is impossible.

As you highlight, prolongued snow cover can act to insulate the subsurface, resulting in higher cave temperatures compared to the surface mean. We assume that, given our rather warm clumped isotope temperature reconstructions, **s**now cover would have had a limited insulating effect at Taba Bastaakh. In such temperate locations, with high seasonal temperature contrasts, ice build-up within caves during the cold season has been shown to reduce temperatures in cave environments compared with the surface (https://doi.org/10.1029/2007JF000892) and we cannot rule out such an effect at our cave. Furthermore, as you state, there is evidence of tree growth at high latitudes during the Tortonian. In Eagle Cave, Spain, this has been demonstrated to reduce cave temperatures by around 2 degrees through insolation changes and modification of soil properties (https://doi.org/10.1016/j.epsl.2013.03.017). It is reasonable to assume that the impact of insolation reduction at Taba Bastaakh's higher latitude will be less dramatic than in Spain, but it's certainly possible that forest cover may have led to a slightly lower temperature within the

cave than the surface. Thus, we don't think surface/cave buffering is likely to have a huge impact on our surface temperature reconstructions and if anything, they would reinforce our conclusions of a considerably warmer Arctic Miocene. We will however add some background to show that these processes have been considered and to provide some context for the reader.

Fig. 4: the legend shows dark green circles 'Terrestrial…' whereas the plot shows light green circles. Please marry them.

Response: Thank you for spotting this. It has been rectified.

*L330 – 331: **site to Arctic extrapolation**: "Our temperature reconstructions provide new evidence of a ca. 18 to 23°C warmer terrestrial Arctic during the Tortonian…". I think your reconstructions tell us about conditions in one small area of the terrestrial Arctic. If you consider modern Arctic conditions along a latitude of about 72oN, they vary hugely from relatively warm conditions north of Iceland to very cold conditions e.g., in the western Canadian Arctic. To extrapolate from one site to the whole terrestrial Arctic is highly speculative. Please qualify.

Response: We have qualified. The sentence now reads:

"Our temperature reconstructions provide new evidence of terrestrial MAAT ca. 18 to 23°C warmer in the central Siberian Arctic during the Tortonian…"

***L459 – 460: Continentality**: "reduced continentality given global average sea levels ca. 10 m higher during the late Miocene compared with modern". Today, permafrost sites along the coast of the Arctic Ocean tend to be colder than sites at similar elevation inland (e.g., Tuktoyaktuk vs Inuvik: because of lingering sea ice in summer). A 10 m higher-than-present Miocene sea level suggests your site was coastal then, similar to today (but presumably without the Pleistocene Lena Delta separating it from winter sea ice). Please comment on how changing continentality may have affected the palaeotemperature estimates from your site. I doubt that palaeotemperature estimates from the coast will be exactly the same as those inland, even without summer sea ice in the Tortonian, because of sea-breeze cooling effects.

Response: We will explore this with an additional paragraph in the final manuscript. Although there's evidence to suggest a sea ice free Arctic during Tortonian summers, sea ice was likely present during the colder months. As you state, whilst this may not have had as prominent an influence as today's perennial sea ice on local cooling, no doubt it will have played a role in cooling coastal regions like Taba Bastaakh.

L343: "MIS 15a – 14": please write out in full at first usage.

Response: This will be corrected in the final manuscript

L344: "middle-Pleistocene": proper noun: Middle Pleistocene

Response: We have followed USGS guidelines which state "there is no defined mid or middle Pliocene and therefore middle should not be capitalized." We therefore reject this suggestion.

L346: "further south": 'farther'

Response: Corrected

L361: "Our reconstructed Lena Delta δ18Op values for the Tortonian…": please add them (e.g., in brackets), because I'm struggling to quickly find them (they are not in Table 3).

Response: In line 352 we state "Given the control of $\delta^{18}O_p$ on $\delta^{18}O_{dw}$, the latter provides an estimate for $\delta^{18}O_P$." We have reiterated here so that the sentence now reads: *" Assuming $\delta^{18}O_{dw}$ is the same as $\delta^{18}O_{p,}$ our reconstructed values"*

L384: "Mg/Ca and Sr/Ca as reliable 'wet vs. dry' proxies": please summarise the nature of the proxies for non-specialist readers.

Response: We have added the following sentences for clarity

'These alkali metals are transported via speleothem dripwaters and substituted into the carbonate lattice during speleothem deposition. In periods of low throughflow, Ca is preferentially removed from dripwaters through prior carbonate precipitation (PCP), increasing relative concentrations of Mg, Sr, and Ba.'

L385 – 386: "Sr/Ca is remarkably highly correlated with Ba/Ca and U/Ca": please give these correlations and their statistical significance (e.g., in brackets) or at least summarise them. Ditto L390, 392 and 405. I appreciate the full details are given in the supporting online material.

Response: This information will be added to the final manuscript.

L388: "Fewer studies": than what?

Response: "Fewer" has been replaced by "few".

L417: "dominant trace element cycles of 0.3 and 0.5 mm and 0.2 mm": clearer to say 'cycles corresponding to distances of …'. 5

Response: Changed as advised.

*L458: "**enhanced evaporation and moisture transport** into northern Siberia in the summer, compared with winter": how might this have impacted on d18O values reported in sections 5.2 and 5.3? Would the values be isotopically lighter than otherwise?

Response: As discussed above, we will address this with a paragraph giving some background about how moisture budget impacts $\delta^{18}O$. High latitude $\delta^{18}O$ is generally controlled by temperature and we reference several high latitude studies from Siberia within the manuscript which suggest this is the case in the modern day, and therefore likely applies to our site, and also during the Tortonian.

Reduced summer sea ice would be expected to result in enhanced seasonal contrast in $\delta^{18}O$ and a shift in the mean annual $\delta^{18}O$ of precipitation. Since our record is of insufficient resolution to resolve seasonal variability in $\delta^{18}O$, we cannot draw any conclusions about the former through our study.

For the latter, as you suggest, we'd expect moisture sourced from the Arctic to have very low $\delta^{18}O$ values compared with other other sources in the modern day. However, it's difficult to make any firm assertions about the Tortonian because of other competing influences. As discussed elsewhere, higher sea levels will have reduced continentality at our study site, which is generally associated with a shift to higher $\delta^{18}O$. Furthermore, the Tortonian ocean had a different isotopic composition (with lower $\delta^{18}O$) than the modern day (DOI: 10.1126/science.aba6853).

Given these competing influences we are weary of making any firm assertions as to how enhanced Arctic moisture transport would have impacted precipitation $\delta^{18}O$. But we will provide a more thorough background exploration to benefit the reader's understanding.

L477: "de Nooijer et al., 2020": please add to References.

Response: Thank you for spotting. Has been added.

L476: "Arctic warming of 7.2°C": please clarify what part of the climate system does this refer to: air, water, ground?

Response: We have clarified this is surface air temperature

*L491 – 512: "Using our new temperature reconstructions, we estimate total potential permafrost derived carbon emissions given future warming similar to that reconstructed for the Tortonian…". I think **this exercise is unduly speculative**. To extrapolate MAAT from one location across the whole late Miocene Arctic atmosphere above a terrestrial area many millions of km2 is highly speculative. Multiple sites are needed across the Arctic to determine MAAT variability, as exemplified in doi:10.1016/j.quascirev.2006.01.033 - Fig. 3 for last interglacial). Adding further speculation, the authors use the one-site approach to then estimate the mass of carbon within permafrost that is vulnerable to thaw in the underlying 3 m of soil by 2100. Modelling can produce figures of carbon emissions, but unless the input data are based on well constrained values and good mechanistic understanding of carbon input and output processes and rates, then I question the usefulness of the exercise. I do not think this section contributes usefully to the literature and instead obscures an otherwise excellent late Miocene study.

Response: As previously noted, all permafrost emissions modelling content will be removed from the manuscript.

L794: add initials to the list of authors.

Response: Thank you for spotting. Added.

Figure S1: please clarify the labelling of the x axis. Is this temperature? Units of measurement? What is the 10^6? What is T^2?

Response: We have clarified that T is the known temperature in kelvin.

Fig. S3: please enlarge the font size of the correlation coefficients. There is dead space on the correlation matrices to partly superimpose the PCA plots, which may help with enlargement.

Response: Plots have been remade with a larger font and split over two pages to make text easier to read.