List of revisions 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. Reyes

Thank you for your efforts thus far in processing our manuscript, and to the reviewers whose efforts have gone towards significantly improving our manuscript. I provide detail of the changes below which we have made in response to the reviewer's comments. All changes can be seen in the revised manuscript.

Major revisions

In response to RC2 (Julian Murton) feedback, which suggested the permafrost modelling content of the paper was overly speculative, we agree this is a fair criticism and have significantly restructured the manuscript, removing the permafrost modelling content and refocusing it as a predominantly palaeoclimatological study of the late Miocene. We have removed sections 3.5 and 5.5 and significantly restructured the introduction and interpretation to reflect this. The introduction now expands upon existing knowledge of the Miocene climate with a significant amount of new content.

To address the concerns of reviewer CC1 (Author Aldeman) that more emphasis needs to be given on the difficulty in applying deep time analogues to near future climate change, particularly the issue of differing boundary conditions in the Miocene compared with the near future, again we feel this is a fair criticism and so we have added the following caveats to our introduction and conclusion respectively:

Lines 85 – 86: *'Whilst past warm intervals represent imperfect analogues for near future climate because of differences in climate forcing, these periods can provide important examples of planetary response to atmospheric warming.'*

Lines 489 – 497: *"Our estimates provide useful constraints on near-future Arctic warming, but we emphasise that different planetary scale boundary conditions in the Miocene compared with today mean our deep-time reconstructions provide imperfect analogues for anthropogenic warming. Whilst the Miocene marked a large-scale expansion of global ice sheets, both northern and southern hemisphere ice sheets were highly dynamic, particularly in Greenland which was likely only partially glaciated (Steinthorsdottir et al., 2021b). Evidence from ice-wedge pseudomorphs suggests the onset of high-latitude Northern Hemisphere permafrost formation occurred in the late Pliocene (~3 Ma) (Opel et al., 2025) and it is very likely that the Northern Hemisphere was permafrost-free during the Tortonian (Vaks et al., 2024 in review). These, and other, slow planetary-scale feedbacks will have played a major role in the Miocene global energy budget that are unlikely to be of similar significance in driving near future temperatures."*

Both CC1 and RC2 expressed caution in applying our site-specific temperatures to the wider Arctic. In response we have toned down the language in the paper, for instance replacing the general term "Arctic" with the more specific "central Siberian Arctic"

In response to reviewer RC1's suggestion to adopt the D47 Crunch data processing method to calculate comparison Δ_{47} values for input into the Calibration of Anderson et al, we have done so. Section 3.1 (methodology) and 4.1 (clumped isotope results) have been significantly updated to reflect this. Recalculation was a useful exercise, and it was reassuring that the two different means of deriving temperatures gave very similar values. Table one has been updated as a result to contain all clumped isotope calculations and combined with the original Table 3 as proposed in the review.

Detailed response to PC2 revisions

In considering RC2's comments, several of the minor corrections suggested in the introduction (between lines 55 and 80) are now redundant with the new structure and therefore we have not covered in the detailed list of changes below. Otherwise, I have listed the reviewer comments in bold with our edits in red.

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.

Edit: The word "crucial" has been replaced by "possible" (line 57)

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?

Edit: Added "future" (line 66)

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

Edit: Added "and" (line 69)

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

Edit: Changed to "palaeotemperature" throughout the manuscript.

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

Edit: This content has been removed

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

Edit: Corrected (line 101)

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

Edit: This content has been removed

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?

Edit: Coordinates added to the map and colours explained in figure caption

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

Edit: Cliff height added to figure caption

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.

Edit: We have now updated this record to the nearby Tiksi site. This was considered a better record since the Boike et al. (2019) record considered only rainfall, omitting smowfall from the record. The Text now reads "*The closest available mean annual rainfall estimate is 309 mm (1980 - 2018), measured at the Tiksi meteorological station 90 km southeast of Taba Bastaakh.*" (line 119 - 120)

*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**

Edit: 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 after a few meters, but erosion of the cliff face has **exposed the interior** of relic caves, with speleothems observed along the cliff walls." (line 123 - 124)*

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

Edit: "Final clumped isotope (Δ_{47}) values" (line 150)

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

Edit: We have reworded as "110±10 µg of **THE** sample was loaded" to avoid any ambiguity. (line 203)

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

Edit: Corrected (line 205)

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

Edit: Changed to "Δ_{47} values are reported"

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?

Edit: This content has now been removed

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

Edit: Labels have been added to the final figure

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

Edit: Moved to section 3.4 (methods)

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

Edit: Reworded. Now reads “*We identify two dominant principal components (PCs) in each sample, accounting for 55.5 and 70.2 % of the variance in STBB I – 1 and STBB II – 7 respectively (Table 2, Fig. S3).The first PC correlates with Ba, Sr, Mg, and U*” (line 285 - 286)

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

Edit: We have reworded both L264 and L267 to read *“The first PC correlates with Ba, Sr, Mg etc…”* We think this makes it clearer. (now line 286)

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’.

Edit: We have replaced “frequencies” with “wavelengths” (line 295)

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

Edit: This information has been added. It now reads “*We also observe cyclicity in P (~ 0.3 mm and 0.5 mm in STBB I – 1, ~ 0.2 – 0.25 mm in STBB II – 7) and Cu (~0.2 mm, in STBB I – 1 only).”* (line 295 - 296).

L281: “The late Miocene is widely accepted to have been several degrees warmer than today.” Please insert ‘climate’ after ‘Miocene’.

Edit: Added (line 304)

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.

Edit: 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).” (line 310 – 3312)

*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.**

Edit: We have added additional discussion exploring the relationship between cave and surface temperature. Since the caves have completely eroded in the modern day, we choose not to make any attempt to quantify how the overburden might have impacted cave temperatures. However the discussion provides some wider context for the reader and highlights potential discrepancies between our reconstructed temperatures and mean surface temperatures. We have added:

"Since erosion has mostly removed the Miocene overburden and brought our samples to the surface, it's impossible to know the full impact that ventilation and conduction may have had on the Taba Bastaakh cave temperatures. We suggest the insulating effects of winter snow and shading from summer vegetation likely counteracted each other with minimal overall effect. For instance, in cold regions, snow acts to insulate the ground, reducing heat loss to the atmosphere (Molnar, 2022). This insulating effect has been shown to lead to cave temperatures 5-7°C higher than surface air temperatures in cold regions with persistent (ca. 233 days per year) snow cover (Töchterle et al., 2024). Our $T_{\Delta 47}$ reconstructions between 6.6 and 11.1°C suggest a mean annual surface temperature between modern day Stockholm (Moberg, 2021) and London (Met Office, 2024), which experience significantly less than 233 days of snow cover per year. We therefore envisage limited effect of snow insulation at Taba Bastaakh. In addition, there is palynological evidence that the Miocene treeline stretched as far north as 80°N (Steinthorsdottir et al., 2021b) and thus it is reasonable to assume a degree of forest cover at Taba Bastaakh during that time. Monitoring studies in Eagle Cave, Spain showed that transition from shrubland to forest resulted in a reduction in cave temperature up to 2°C due to changes in insolation and modification of soil properties (Domínguez-Villar et al., 2013). Given the higher latitude of Taba Bastaakh it would be reasonable to assume a reduced impact from insolation shielding compared with Eagle Cave however a small offset (< 2°C) is possible between our cave reconstructions and surface temperatures." (lines 336 – 357)

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

Edit: The figure has been updated

*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 Siberian Arctic during the Tortonian..." (line 379 – 380)

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.

Edit: We have added the following paragraph (lines 348 - 357)

"Given global average sea levels ca. 10 m higher during the late Miocene compared with modern (Miller et al., 2005), Taba Bastaakh might have occupied a more coastal position than the present day In the modern Arctic, lingering summer sea ice can act to reduce coastal air temperatures compared with inland locations at the same elevation (e.g. Tuktoyaktuk and Inuvik in the Canadian Arctic (Hamma, 2022)) through increased albedo and latent heat effects (Vihma, 2014). Miocene Arctic Sea ice was much reduced compared to the modern day (Stein et al., 2016) suggesting this effect may be limited. Nearby cold month temperature reconstructions from the coastal site Temmirdekh-khaj (Fig. 1) of between -2.8°C and + 1.1°C (Popova et al., 2012), considerably warmer than modern, support this notion, although we cannot rule out the possibility of lingering cold season sea ice reducing temperatures more than equivalent latitude inland locations."

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

Edit: Added (line 419)

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

Edit: We have followed USGS guidelines which state "there is no defined mid or middle Pliocene and therefore middle should not be capitalized." Therefore, we have kept the original text.

L346: "further south": 'farther'

Edit: Corrected (line 518)

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).

Edit: We have added the this context at the beginning of the sentence so it now reads "*Assuming $\delta^{18}O_{dw}$ reflects $\delta^{18}O_{p}$, our reconstructed values for the Tortonian suggest*" (line 441)

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

Edit: We have added the following sentences for clarity:

"These alkali metals are transported via 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. " (lines 451 – 453)

L385 – 386: "Sr/Ca is remarkably highly correlated with Ba/Ca and U/Ca": please give these correlations and their statistical signifiance (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.

Edit: This information has been added. It now reads:

"Sr/Ca is remarkably highly correlated with Ba/Ca ($r = 0.98$, p-value < 0.01 in STBB I – 1 and $r = 0.55$, p-value < 0.01 in STBB II – 7) and U/Ca ($r = 0.59$, p-value < 0.01 in STBB II – 7 and $r = 0.83$, p-value < 0.01 in STBB II – 7) along the entire growth length of both Taba Bastaakh samples" (Lines 469 – 473)

L388: "Fewer studies": than what?

Edit: "Fewer" has been replaced by "few". (line 473)

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

Edit: Changed as advised (line 502)

*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?

Edit: We have added the following discussion (line 424 – 428)

"We note that the more negative $\delta^{18}O$ of the Miocene Ocean may have compounded a shift to more negative $\delta^{18}O$ values (Westerhold et al., 2020), but this would have been somewhat offset by reduced continentality at Taba Bastaakh (generally associated with positive shifts in $\delta^{18}O$) given the ca. 10 m higher global sea level (Miller et al., 2005). Given these competing influences we do not propose any firm assertions on the impact source values of $\delta^{18}O$ compared with the modern day on the $\delta^{18}O$ signal."

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

Edit: 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?

Edit: We have clarified this is surface air temperature (line 392)

*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.

Edit: This content has now been removed

L794: add initials to the list of authors.

Edit: Thank you for spotting. Added (line 707)

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?

Edit: We have clarified that T is the known temperature in kelvin in the figure caption

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.

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