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

By Umbo et al.

The **fundamental research question** addressed by this manuscript *is what were the environmental conditions (palaeotemperature, hydrology and seasonality) at a site near the mouth the present-day Lena River during the late Miocene Tortonian Stage?* This question is important, because late Miocene data from high northern latitudes are very sparse, and addressing it will be of interest to geoscientists studying the Neogene Period, geochemists with interests in speleothems and dating, permafrost scientists interested in deep geological time, and geologists studying northern Siberia. A secondary research question is *can we estimate the extent of thaw of [near-surface] permafrost by 2100 assuming that the Arctic atmosphere warms to a similar degree as it did in the late Miocene?* This question is important to the climate change community and to permafrost science and engineering.

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. If you really want to contribute to the permafrost-carbon debate, I think your methodology for question 2 needs to be much more rigorous (discussed below). The introduction must also state clearly how this ms differs from the Vaks et al. ms in review.

The **methods** used to address question 1 concern analysis of stable isotopes and trace elements to reconstruct palaeo-hydrology and seasonality, and clumped isotope and fluid inclusion palaeothermometry to estimate speleothem formation temperatures. I have limited knowledge of such methods, but believe that these methods have been applied carefully and systematically, with attention to details such as standard error inspiring confidence in the results. 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).

The **results** of the geochemistry and dating, as far as I can judge, are presented carefully and fully. Uncertainties are systematically discussed in the supplementary online materials.

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). Sections 5.3 (d18O signal of palaeo-dripwater) and 5.4 (seasonal hydrological regime) are outside of my expertise. Section 5.5 (Near-future Arctic climate and implications for permafrost thaw) overlaps substantially with the Vaks et al ms (in review), which I have read. 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.

Overall, I think that the ms makes a valuable contribution to palaeoenvironmental knowledge of a single site in northern Siberia during the late Miocene. The permafrost thaw and carbon emissions section reads to me like a

trendy red herring tacked onto an otherwise substantive piece of geological research. I suggest this part is omitted or at least shortened to a brief qualitative statement (the quantitative carbon emissions estimates to my mind are too poorly constrained to be useful scientifically). Therefore I recommend major revisions and a refocussing of the ms onto the late Miocene.

Below are some points to consider, mostly minor. The main ones are indicated by '*'.

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.

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'.

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.

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

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

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.

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.

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.

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

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?

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?

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

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

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

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

L104: “active layer thaw depth”: ‘active-layer depth’.

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?

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

*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?**

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

L189: “110±10 µg of sample was loaded”: ‘were’ (microgrammes)

L191 – 192: “We use”: ‘used’ to be consistent with past tense elsewhere in this paragraph.

L194 and caption to Table 1: “data is reported”: ‘are’

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?

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

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

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

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

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’.

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

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

*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.

*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.**

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

*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.

***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.

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

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

L346: "further south": 'farther'

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).

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

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.

L388: "Fewer studies": than what?

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

*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?

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

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

*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.

L794: add initials to the list of authors.

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?

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.

Julian Murton
18th July 2024