

The Cryosphere Discuss., referee comment RC1  
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## Comment on tc-2022-238

Jigjidsurengiin Batbaatar (Referee)

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Referee comment on "Asynchronous glacial dynamics of Last Glacial Maximum mountain glaciers in the Ikh Bogd Massif, Gobi Altai mountain range, southwestern Mongolia: aspect control on glacier mass balance" by Purevmaa Khandsuren et al., The Cryosphere Discuss., <https://doi.org/10.5194/tc-2022-238-RC1>, 2023

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Khandsuren and her colleagues went to Ih Bogd, a beautiful massif in the middle of Gobi-Altai range to determine the timing of maximum glaciation there. They sampled in two valleys, one facing north and the facing south, and sampled from 28 glacial boulders for  $^{10}\text{Be}$  analysis. They followed the standard protocol to prepare their samples and their descriptions of the methods are clear. Their  $^{10}\text{Be}$  age results suggest that the glacier in the north-facing valley advanced later than the one in the south-facing valley. They attributed this seeming glacial asynchrony to differences in insolation affecting the energy balance for these paleoglaciers. The authors determined the insolation via numerical models and estimated the glacier length based on insolation and the temperature conditions at their study site. I would like this paper to be published for two reasons: 1) The new  $^{10}\text{Be}$  data reported in this article will provide important data points from the deep interior of central Asia and fills important data and knowledge gap in understanding the glacial history in cold continental environments; and 2) their modeling and the interpretation of the  $^{10}\text{Be}$  age data points to the importance of insolation on the glacier development, a factor often ignored for consideration in glacial studies from maritime environments.

I would like them to revise one important issue before publication: reporting of total uncertainty. In the current draft they calculated the standard deviation of the  $^{10}\text{Be}$  ages for a moraine, and reported it as the uncertainty of the group age. For example, the group age for moraine MIh1 is reported to be  $20.1 \pm 0.7$  ka, whereas individual external uncertainties of the ages range from 1.3 to 1.5 kyr. That is simply wrong. Please compound the external uncertainties of the ages with the standard deviation of the group age and report the compounded error as the total uncertainty of the group age. Make the revisions accordingly in the text and on the maps.

I also listed my line-by-line comments for the draft. My comments are long, but they're mostly suggestions to improve the paper and its presentation. I treated your draft as if it

was mine--sorry if I made comments and suggestions for minor items. I wish you the best for your future endeavors--J. Batbaatar (Bucknell University).

Ln 16–18: It's reads a bit awkward to say "facing south into" a valley.

Ln 19: The uncertainty for the exposure age is too low. The "timing" of the glaciations should be based on the "total uncertainty" of the group of ages--compounding total of the individual external errors and the st.dev of the spread. From my experience 10Be ages usually have ~20% total uncertainty.

Ln 25–26: It's redundant to mention the 10Be ages. Maybe say the timing "modeled extents are consistent within  $\pm 1$  sigma of the 10Be ages"? Is there uncertainty for the modeled ages?

Ln 48: delete "in" before "due to"

Ln 49: No need for "However,". Just start the sentence with "New ..."

Ln 53: No need for "~" before 100 ka. ">100 ka" would be OK and correct.

Ln 53: MIS is not introduced in the paper yet. It would be good to introduce MIS in Ln 44-46, saying "... (Clark et al., 2019), the timing of which roughly coincides with the extent of MIS 2 (Lisiecki and Raymo, 2005)" or something like that.

Ln 60: I understand that the name of the range is "Gichgine" (ᠭᠢᠴᠢᠭᠢᠨᠢ) in the non-possessive form. However, there's no other Gichgine exists (e.g., there's no Gichgine town/ᠭᠢᠴᠢᠭᠢᠨᠢ ᠨᠠᠵᠤ, and only Gichginii nuruu (range) exists. would it be appropriate to keep the name in possessive form if the name is used in conjunction with "range"? In short, I suggest "Gichginii Nuruu" or "Gichginii range".

Ln 62-63: You may want to specify that "a scale of a few hundred km" in "glacier length". A more relevant glacier metric to climate would be ELA, though. I suggest to report variation of ELA-depressions from one place to another. Glacier length can be very different even under the same ELA-depression due to bedrock slope, for example, without requiring a different perturbation in climate.

Ln 72: I suggest to replace "topographic changes" with "topographic variations" or "variations in topography". "topographic changes" may suggest that the topography is changing, but I understood that you meant glaciers in different topographic conditions.

Ln: 74-75: 1) You mentioned in the previous paragraph (e.g., Ln 65) that aspect can make a noticeable difference. Then why would you first assume to have "synchronous" glaciations on these valleys with different orientations? 2) One small phrase you may add to avoid such criticism is to specify that you expected different lengths on two valleys but timing of maximum advances would have been synchronous.

Ln 80: I strongly suggest to change Altay to Altai and Khangay to Khangai, and follow the modern Mongolian conventions to spell these names. Since the Russian occupation of central Asian countries, the transliterations of Mongol and Turkic names have been botched in Cyrillic letters and their romanized derivations. These countries have reclaimed their national identities since the collapse of the USSR and been trying to assert it worldwide since then. Please use the proper spelling according to the local conventions and spelling. Changing the spellings wouldn't require a lot of work -- just a "replace" function in Word.

Ln 83: What exactly mean to be "in the heart of Gobi"? Does it mean the precipitation there rainshadowed by Altai and Hangai, and is less influenced by them? or is temperature different? seasonality is different? I'm all for everything Mongolian, but I'm biased. Other readers may not understand or appreciate the significance of your study site.

Ln 87: Please be consistent in names. In Ln 80, you say "Gobi-Altai range" (which I prefer) but here you say "Gobi-Altay Mountain range". Saying "mountain range" is not only redundant, but is wrong. Please fix here and elsewhere in the paper.

Ln 90: Change to "gneiss" (singular) unless you want to specify the variety of the gneiss there.

Ln 91: Please change spelling to "Tumurtogoo". It is consistent with his name in Cyrillic, and the same romanized version was used in other publications (e.g., <https://www.gsj.jp/data/openfile/no0344/GeolBayankhongor.pdf>)

Ln 103-104: it could be redundant to say "less than 200 mm of precipitation per year" and "188 mm, an average of 2005–2019". Just say "annual precipitation is ~190 mm (2005–2019 average, NAMEM, 2020), while it reaches ~100 mm..."

Ln 109: add "it" before "starts to snow"

Ln 110-111: Maybe extrapolate the monthly average temperatures to the summit using the environmental lapse rate, just to demonstrate that it's cold up there, instead of saying "sometimes it snow". It's hard to grasp how frequently it happens without describing what "sometimes" entails. I would also note that environmental lapse rate is probably a minimum estimate for temperature extrapolation and dry lapse rate would suggest that the temperature at the summit is indeed cold in the desert. Your readers don't appreciate how cold it could get even in summer if you mention the temperatures at Bayangovi and Bogd.

Ln 121: change to "abundant"

Ln 122: remove "glacial" before "till". There's no other till than glacial, it's redundant.

Ln 123-123: stream (water) cannot flow out as fans (sediment). Maybe change to "sediments in the stream deposit later as alluvial fans"?

Ln 124: Please don't say "sediment transport by alluvial fan". Fan is a depositional landform made of sediments. It cannot move sediments. Streams, on the other hand, can move sediments and deposit them as alluvial fan.

Ln 128: replace "headwater" with "headwall"?

Ln 128: above ~3100 m than what? did you mean m asl? please fix also in Ln 129.

Ln 131-132: Bituut valley studied in Batbaatar et al. (2018) originates from the Otgontenger peak, in the Khangai. I don't understand the meaning of mentioning that here in Ih Bogd, unless you're suggesting that Bituut in Fig. 1 is the same Bituut reported in Batbaatar et al. (2018)? If that's the case, it's a big case of mistaken identity. The latitude and longitude of each sample were reported in Batbaatar et al. (2018) and you would have easily seen that their Bituut is not in Ih Bogd.

Ln 139-140: Did you talk to local herders to confirm the name of the valleys? That's usually the easiest and most trusted source.

Ln 145: Headwaters is a hydrological term describing the beginning of a stream, not the valley where the stream resides. Please change "headwaters" to "cirque" or "headwall"

here and other places in the article.

Ln 153: here and elsewhere, add dash in "clast-supported", like matrix-supported.

Ln 206–207: Please use a total uncertainty for the group age, accounting both the external uncertainty of the ages and the standard deviation of the group. See my comment for Ln 19 and below for the Results section.

Ln 223–225: First, judging from the ages mentioned for Ih Artsan, it seems like you've accepted LSDn scaling as factor. You need to say explicitly say so in the Methods (e.g., Ln 200). The mean of ages calculated using Stone scaling is 22.3 ka, which is  $\sim 2$  ka larger than 20.1 ka based on LSDn ages. This is a significant deviation, comparable to the total uncertainty of the individual ages. Second, I would not accept the standard deviation of the ages as the uncertainty for the total age for the moraine. This is just a metric for how tight your ages are. You can't ignore the external uncertainties of the ages. The total uncertainty should be a compounding error accounted for both the standard deviation of the spread and the individual external uncertainties. Here's how I calculate it: Total uncertainty =  $\text{SQRT}(\text{stdev}^2 + \text{average of external uncertainties}^2)$ . According to this calculation, the age for MIh1 moraine should be  $20.1 \pm 1.6$  ka (based on LSDn scaling) or  $22.3 \pm 2.1$  ka (based on St scaling). If we trust LSDn scaling, the age range is 18.5–21.6 ka, and the St scaling would suggest an age range of 20.2–24.4 ka. The true age is somewhere between these ranges, but we can't tell.

Ln 235: The age for Mj1 should be  $17.2 \pm 2.0$  ka (LSDn scaling  $\pm$ compounding errors). Please address this.

Ln 241: Please better define "undermined by growing ice". It's not clear what surface process is being implied here.

Ln 249: Please better define what you mean by "concordant". In the abstract you used "synchronous" which is a good term to suggest similar timing. However, "concordant" could mean moraines in two valleys could be similar in timing and extent. Which is it? Both? Say so. In other words, your hypothesis needs to be unambiguous.

Ln 250: I'm not too sure about 3 ka difference between these two moraines. As I said in my comments for Ln 223–225, the true age is somewhere within the range indicated by the total uncertainty, not the arithmetic mean. In other words, age for MIh1 is 18.5–21.6 ka and age for Mj1 is 15.1–19.2 ka. These two ranges overlap! I suggest to reframe your modeling experiment as not a test of asynchronous advances, but present it as a test of climate perturbations for these awesome glacier advances in the Gobi. Nobody's done that before, and that's totally normal and acceptable exercise to do. Or, you need to provide more evidence to support that indeed Jargalant glacier started advancing 3 kyr later than

Ih Artsan glacier. There's no evidence provided in the current draft to support that idea. Even if these "exposure" ages were indeed separated by 3 kyr, that doesn't mean the glaciers were advancing at different times.  $^{10}\text{Be}$  ages for these boulders merely tell you the time when the boulders were abandoned on the moraine crest. In other words, the boulder ages from terminal moraines (not recessional moraines) could indicate the timing of glacier standstill (Batbaatar et al. 2018, QSR), time of glacial advance (Heyman 2014, QSR), or completion of glacial advances (Heyman 2018, QSR). The point is, these boulder ages don't tell you exactly what the glacier was doing.

Ln 261: I'm afraid you need to spell out "JJA" in this first instance.

Ln 329: Please consider spelling out the modeling steps as First, Second, Third etc. or just use 1) 2) and 3) without st and th. The combination of "1st)" and "2nd)" looks awkward.

Ln 335: Yes, it snows sometimes in Gobi in summer. It snowed in late May at Sutai when I camped there in 2013, and my equipment was still frozen when I came back in June and I had to abandon it. But when you phrase it like that it sounds like anecdotal accounts. Please try to demonstrate the coldness of this continental climate by mentioning long-term average of the extreme minimum temperatures in June-July-August, scaled by lapse rate to high elevations of the moraines.

Ln 365: Please better describe what you mean by "A cross-section of the thickest ice was recognized as ELA" or provide justification for why ELA should be at the thickest part of the glacier.

Ln 373: Define "significant". Do you mean significant in statistical term or just to infer that the insolation was different enough between the valleys to cause different glacier advances?

Ln 375-376: Did the timing of max insolation at Ih Artsan coincide with min insolation at Jargalant? Please rephrase the sentence.

Ln 385: Please indicate that the melt was calculated using Eq. 12. It's worth repeating here referring back to the model.

Ln 388: please say that the glacier melt is in [m water equivalent]. Otherwise, melt of 4 m of snow or ice would be very different things.

Ln 388: Describe "higher" than what value, or just say it was a "substantially high value" for the area.

Ln 401–406: Why report timing from the models in two decimal points? The group ages are rounded to one decimal point, why not round the model timing to one decimal point as well (e.g., 20.3 ka and 17.1 ka).

Ln 412: Considering the age for the moraine (group age) should be reported with the total uncertainty, the statement "Ih Artsan glacier reached its maximum ... at  $20.1 \pm 0.7$  ka" is false. The age should be  $20.1 \pm 1.6$  ka, if you trust LSDn. Then there's the matter of St scaling.

Ln 414: No need to say "on the other hand", especially when you consider that the total uncertainty for the group ages from the two valleys overlap.

Ln 415: The group age should be  $17.2 \pm 2.0$  ka, accounting for external uncertainties of the individual ages and the age spread within the group.

Ln 487: First, you need to add a paragraph in the Methods or Results section, specifically and unambiguously describing how you interpret the  $^{10}\text{Be}$  exposure ages from boulders. According to this sentence in Ln 487, are you interpreting that these boulders were deposited and exposed to cosmic rays at the onset of deglaciation? It can be a good assumption, but you need to explicitly say so about your interpretation of  $^{10}\text{Be}$  ages. The context matters too. For example, Putnam et al. (2014) mapped terminal and recessional moraines separately based on geomorphic features and the  $^{10}\text{Be}$  ages meant different things depending on the moraine: timing of advance or standstills during retreat. Second, I'd re-emphasize the importance of total uncertainty in reporting group ages. Ih Artsan moraine deposition age is 18.5–21.6 ka, coinciding with the timing of local LGM based on Yu et al.'s (2017, 2019) Orog lake cores. I think this is awesome that the moraine records match with the lake records.  $^{10}\text{Be}$  ages are not precise enough for comparing ages within a few kyr.

Ln 556–560: First, this seems to belong in Results section, rather than in Discussion. No mention of these erosion rate was implied in the introduction section or the Methods section, so it caught me by surprise. Second, describe in more detail how you calculated the erosion rate based on the  $^{10}\text{Be}$  concentration in boulders. I don't understand it. Perhaps this confusion warrants a separate description in the Methods section about these erosion rates.

Ln 581–584: This reads like results, not discussion. For example, the erosion rates were not mentioned before this sentence, and the methods on calculation of erosion rates were not included in the Methods section. I'm sure about that. Please revise and make this

story of erosion rate into a coherent part of the paper.

Ln 804: Please spell out the acronyms for the organization names.

Ln 806: Please spell out the acronyms for the organization names.

Table 1:

- Is it global LGM in the title, like you mentioned in intro section? Please be consistent and use the same abbreviation you've used before.

- The values are all altitudes. Make a single note that they're all altitudes in m a.s.l and remove the redundant "altitude" from the table header?

- The glacier will always be above and upvalley from the terminal moraine. I understand it's probably negligible but isn't the minimum altitude \*inside\* of the moraine would be the glacier toe? This is just a technicality, though--I don't it'll make a difference for these small glaciers and moraines.

- I understand it's mentioned in the text, but please make note about the vertical uncertainty of the DEM you used, just to give the sense of uncertainty for these ELA estimates.

Table 2:

- there's a dash in "shield-ing" factor. remove it.

- please report the "summit" production rates you've used for these two samples.

- I think it's wrong to report the data from the same samples as "new" samples with completely different sample IDs. I strongly suggest to remove the last two rows for "summit plateau". The only difference between the real samples and the SP samples are that you've higher production rate calculated from shielding factor of 1 and higher altitude. Please describe it so explicitly in the text--not in the table-- and just say "we calculated new production rate based on altitude of 3625 m asl and shielding factor 1 and applied to  $^{10}\text{Be}$  concentrations for samples JAM003 and JAM006" and so on. If you report these as "new" samples with "real" sample IDs in the data table, the data will be scraped from the tables automatically someday and these repeats will be tabulated as separate samples, and the confusion will ensue. It's better be careful than sorry.

- Your interpretation of the data relied on the ages calculated using Lifton (2014) scaling. The implication or the reason for calculating the ages using Stone (2000) scaling was not mentioned in the discussion or results section. What was the purpose of reporting St-derived ages in the results table if you didn't use them in your interpretation at all?

Table 3:

- I suggest changing "Run" to "Model". Or simply say "Parameters used for..."

Figure 1:

- Very nice map!
- Why emphasize "Darkhad" in the (a) inlet? There's no mention of Darkhad in the text.
- place (a) inside the inlet map, just like in (b)
- include the label "Elevation, m asl" for the color-scale in (b)
- enlarge "N" of the north arrows in both (a) and (b). It's barely visible
- in caption: change "...described as a red box." to "...indicated with a red box".
- in caption: change "...areas show..." to "...areas indicate..."
- in caption: "See detailed maps of both valleys in Figs. 3-5."

Figure 2:

- I don't like how the black in (c) is not completely bounding the inlet. I suggest to enlarge the box in (a) accordingly, so that (c) will have bound by black lines perfectly. Why Bogd needs to be mapped outside the black box?
- why it says "not to scale" above the scale in (a) and (b)? Please remove those texts.
- I suggest to replace the north arrows in (a) and (b) with the north arrows you used in Fig. 1. That's much cleaner and appealing.
- Maybe change the color of the lakes to neutral gray or white, because the deep blues for MAP in (b) make the contrast low.
- I'm not sure about labeling the black box as "massif" because Orog nuur is not part of the massif, for example. Just label it "Study area in Ih Bogd" something like that.
- is the extent of the red box will be used somewhere later in other figures, or it's being referred to in the text? I would have gotten rid of it.
- I strongly suggest to align the x-axis of the blue bars for the precipitation with the -20C of the temperature. The x-axis for the bars don't need to align at 0C--it just looks awkward. Usually the minimum values of precip and temp of climographs align at the same x-axis (<https://en.wikipedia.org/wiki/Climograph>).

Figure 3:

- What's the black dashed line with an arrow in (c). Say so in the caption that it's a moraine ridge.

Figure 4:

- caption: why "valleys rise from cirque"? Perhaps valleys "extend" from the cirque? Please revise the phrasing.
- change "last" to "late"

Figure 5:

- Gorgeous images! Are these drone images you took during your trip? Say so in the caption. I would love to see the high-resolution version of these images.
- The hummocky terrain in Jargalant valley always puzzled me. What was the main criteria for delineating the white lines there? For example, the elongated features running ~parallel with the valley are believed to be the same flow features (like in rock glaciers)

the samples JAM006–010 and the outer three samples in MJ2 could be lumped in together. Then the inner two samples in MJ2 could be grouped together with the samples in MJ4. Just a thought...

Figure 6:

- The low standard deviation indicated by the dashed lines on these camel plots show the "tightness" of the age values around the mean. I would not have objected to the reporting of st-dev as just the metric for that. However, you've interpreted these st-deviations as the total uncertainty for the moraine age. Please compound the st-dev values with the external uncertainties of the ages and report the total uncertainty as the "true" age for the moraines.
- caption: "valleys" in Ln 44 (plural).

Figure 7:

- indicate in the caption that the values in color scales in (a–c) are in [WH/m<sup>2</sup>]. I know you mentioned the unit in the first sentence, but you still define what the color scales are in each map.
- how did you choose the values for yellow in these maps? This blue-red color-scale is clearly showing the distinction between the insolation on the summit and on the slopes, for example. In other words, the yellow colors are visualized to be the "inflection" points between the blue and red colors, very contrasting colors.
- The three maps look exactly the same to me, except the different values indicated in the color-scale on the bottom left corners. I don't think it's a very effective way to show the differences in insolation. One suggestion would be to show these insulations not as their absolute values, but "anomalies" from the modern values. Then it would be very apparent to the readers how much insolation has changed between LGM and modern conditions, which would be awesome and more useful!
- The minimum value for June 21 at 20 ka is 0. The minimum summer insolation at 21–20 ka is  $9.5 \times 10^7$  WH/m<sup>2</sup>. Any product of 0 should be zero, no? How does the 0 insolation could add up to  $9.5 \times 10^7$ ?
- place the white arrow for Ih Artsan on top of the black line.
- indicate the melt values in [m water equivalent], or just show the numbers on the maps and describe the units in the caption. Are these total glacier melt for the entirety of the times for each map? For example, does the 509 mm for Jargalant in (b) mean that ~510 m w.e. glacier ice melted in total within 1 kyr?
- Please revise this sentence "Melt when the present-day temperature in Jargalant is considered 0.5 °C (LGM anomaly is the same, -5.5 °C) colder than Ih Artsan is written in parenthesis." Maybe split it into two.
- Explain why lower insolation on north-facing slopes are correlated with more trees. You can't just show the difference of trees on south and north-facing slopes without a commentary. I can't find the reference, but the trees on north-facing slopes in Mongolia are associated with the active layer thickness (ALT). The north-facing slopes have thinner ALT and the permafrost is closer to the surface, allowing for trees to grow.

Figure 8:

- Please spell out Ih Bogd in (a). All other names are spelled out and it's awkward to have the main study area abbreviated like that.
- remove "not to scale" below the north arrow in (a)
- label Mongolia and China on the other sides of the border. The border line is not described in the legend or in the caption.

Figure 9:

- I don't understand the timing indicated by the colors and the labels on the profiles. They seem to contradict. For example, in (a) a yellow box labeled 18.57 ka is coinciding with light-blue glacier of 22.00 ka. If I understand it correctly, the two glaciers were confined to their cirques at 22 ka and advanced beyond their cirques until 20 ka in Artsan and until 17.1 ka in Jargalant? Then Artsan glacier has retreated to the yellow box area by 18.6 ka? Please provide a better explanation in the caption.

Figure 10:

- nice photos!

Figure 11:

- Very nice illustrations in c-d.

- what's LLGM in (d) and (e)? Describe in the caption.

- Why do you think the summit was ice-free during LGM? I thought of the glaciers on Ih Bogd and on Gichginii to be similar to modern Sutai: There was a large ice dome on covering the whole summit and the outlet glaciers flowed downhill into separate valleys. Take a look at this Sutai ice cap: <https://goo.gl/maps/WuuDyYDMkkuK23Ki9>. There's a clear ice divide, separating the ice cap into four different catchments. There you can clearly see the difference between the glacier-free south-facing slopes and the glaciated north-facing slopes. When the ice flow northward from the main ice dome, it develops into a well-defined valley glacier (sort of like outlet glaciers, if you will), but the south-facing part of the ice dome end abruptly near the summit margins without developing into a finger-like valley glaciers. This is also could be another demonstration of insolation differences between south- and north-facing slopes.

- Back to the assumption that the Ih Bogd summit was ice-free during gLGM. The transport of old summit material post-LGM makes sense. However, if the summit was ice-free during gLGM and the old material was moving with the glacier during gLGM, as indicated in (d), then the boulders on MJ1 should be also old. Please emphasize your point in the caption that the MJ1 till would have more plucked material than boulders with inheritance (orange pieces) but that changed completely the opposite post-LGM.