

RC1: 'Comment on egusphere-2025-1893', Jason Box, 29 Jul 2025

Summary

The submitted article is very well written, is comprehensive in its treatment and has clear graphics. The synoptic compositing is effective in advancing process understanding. What would help advance process understanding would be the study present what role variable meltwater retention played in the extreme days and seasons, provided that the retention model has a realistic response to melt intensity and snowfall from the previous year, the latter factor (snowpack) to represent snow retention capacity.

Thank you very much for carefully reading our manuscript and providing helpful comments. Below, we address the reviewer comments and explain how we revised the manuscript. Reviewer comments are in black and our replies are in red. The line numbers in our replies are as in the revised manuscript.

During the period of the review process, inadequate code was found on the albedo calculations, which was fixed in the revised manuscript. The modification resulted in slight changes of the numbers in the manuscript. We note that the changes do not impact on any important results and interpretations of the study. The revisions due to the code update are listed below.

- Model performance was improved. RMSE between the observations and calculations were changed from 0.28 to 0.23 m w.e. a^{-1} for the SMB (Fig. 2), and from 0.65 to 0.50 $\text{m}^3 \text{s}^{-1}$ for the daily runoff (Fig. 3).
- Glacier ablation during 1950–1960 was slightly suppressed. As a result, the year of the most negative mass balance was changed from 1960 to 2019 (L316–317, L451). Also, occurrence of the high runoff exceeding 99th percentile during 1950–1965 decreased (Fig. 5b).

****high level critique** in no particular order of importance...**

Consider to analyze the rainfall for the 2015 and 2016 events from CARRA data?

We thank the reviewer for this suggestion, which helped us to resolve detailed precipitation pattern along the coast of Greenland. Composite analysis on the rain-induced peak runoff days revealed intensive precipitation in the northwestern part of the ice sheet with a fine spatial resolution of 2.5 km. It is clear that the CARRA data improves understanding of the precipitation events, thus we included the numbers and composite map in the revised manuscript (Figs 7 and S8, L368–370, 404, 406).

ERA5-Land reanalysis dataset, what about coarse resolution, how its downscaled is important and how representative of local gradients is a big question

The ERA5-Land variables were calibrated in this study to best reproduce the observed variations at SIGMA-B (Fig. S2). Therefore, it represents the most suitable dataset for extending the analysis back to 1950. Since precipitation is not measured by the SIGMA-B AWS, direct comparison between the reanalysis and observed variations have not been made. To investigate the performance of the precipitation from ERA5-Land dataset, we compared it with that from the CARRA reanalysis data, which has a finer spatial resolution of 2.5 km than ERA5-Land (2.5 × 13.5 km) (Fig. R2). Although extreme precipitation events (>60 mm d⁻¹) are not reproduced in ERA5-Land, overall performance exhibited fairly good agreement, showing that the linear regression lies along the slope of 1 (dashed line in Fig. R2). The comparison indicates that the precipitation variability is very well captured in ERA5-Land, when compared with the higher resolution dataset. Even if the CARRA reanalysis were used as model input, the multiplier correction would likely yield comparable results with those from ERA5-Land. To describe the good performance of the calibrated precipitation timeseries from ERA5-Land, we added the results of the comparison with the CARRA reanalysis dataset in L227–231 and Figure S5.

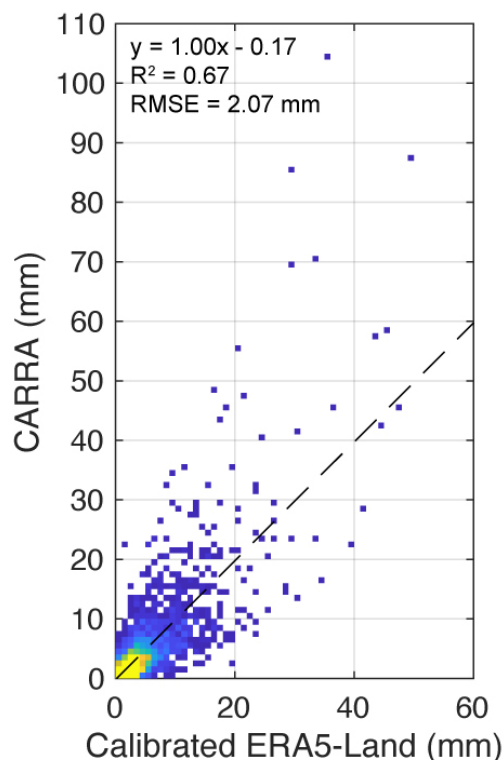


Figure R2: Daily precipitation in 1991–2023 from ERA5-Land calibrated by precipitation multiplier versus the CARRA reanalysis. The dashed line indicates a linear regression through the data. The linear regression equation is shown along with the coefficient of determination (R^2) and RMSE.

147, temperature lapse rate obtained from the daily ERA5 pressure level data, how do the numbers compare with Fausto et al 2009 'A new present-day temperature parameterization for Greenland'?

We compared monthly temperature lapse rate calculated in this study with that reported by Fausto et al. (2009) as well as the value used in Kondo et al. (2021) which was calculated by air temperature observations at Qaanaaq. Summer mean (June, July, August) lapse rate showed good agreement among the three dataset, with $-5.1^{\circ}\text{C km}^{-1}$ (this study), $-5.0^{\circ}\text{C km}^{-1}$ (Fausto et al., 2009), and $-5.7^{\circ}\text{C km}^{-1}$ (Kondo et al., 2021). However, seasonal variations of the lapse rate showed different characteristics between the values computed in Qaanaaq (this study and Kondo et al.) and that reported by Fausto et al. (Fig. R3). The reason of the discrepancy is unclear and beyond the scope of this manuscript. Possible explanation for the difference is that Fausto et al. (2009) derived the lapse rate using the data between ablation and accumulation zones in the Greenland ice sheet, where geometrical characteristics substantially differs from the coastal ice cap located at relatively low elevations up to 1150 m a.s.l. In the revised manuscript, we briefly described the comparison with Kondo et al. (2021) as the most relevant observational dataset on site (L159–160).

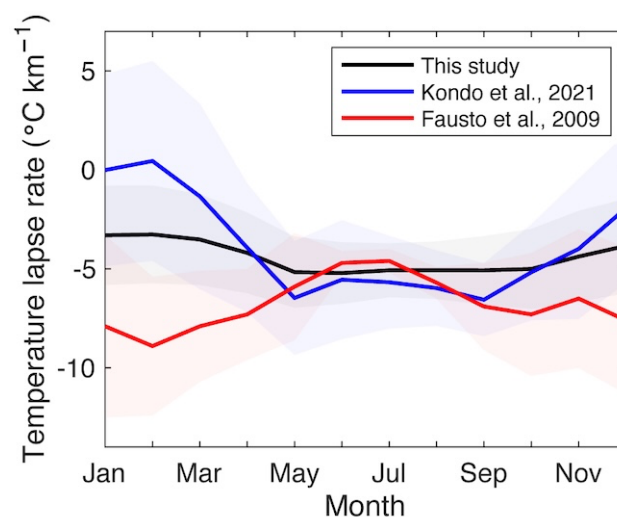


Figure R3: Monthly mean air temperature lapse rate presented by this study (black), Kondo et al. (2021), and Fausto et al. (2009).

Fausto, R. S., Ahlstrøm A. P., Van As D., Bøggild C. E., Johnsen S. J.: A new present-day temperature parameterization for Greenland. *J. Glaciol.*, 55, 95–105, doi:10.3189/002214309788608985.

Kondo, K., Sugiyama, S., Sakakibara, D., and Fukumoto, S.: Flood events caused by discharge from Qaanaaq Glacier, northwestern Greenland, *J. Glaciol.*, 67, 500–510, doi:10.1017/jog.2021.3, 2021.

263 "78% of the runoff on both days" very interesting, perhaps unique finding, if I understand that rainfall was the majority of runoff. If so, try to highlight the result in abstract and conclusions

We thank that the reviewer for finding a value in the number. We included it in abstract (L13) and conclusions (L501).

314 "rainfall exhibited a 2.2-fold increase from 1951–1960 to 2010–2020" try to highlight the result in abstract and conclusions

We added the number in abstract (L15–16) and conclusions (L507).

fig 6 suggest instead of °C/decade, try "change" or "trend" as the trend slope from regression multiplied by the number of years. Then possibly in abstract and conclusions can state temperature increased by _°C over the period...same with precipitation parameter trends

The number (“/decade”) in the manuscript is calculated by the trend slope from regression analysis. To clarify this point, we added the text in Figure 6 as “The dashed lines in (c) and (d) are linear regressions of the data with $p < 0.01$. The trend slope of the regression is also shown.”. The numbers of the trend were added in the abstract (L14–15) and conclusions (L505–506).

329 "top three daily runoff events being caused primarily by rainfall", discuss retention on those dates, how depleted? saturated snow?

According to the model results, the snowpack in the elevation range of 1050–1150 m a.s.l. had mean water retention capacity of 13 mm w.e. on 21 August 2023, a day before the largest peak runoff on 22 August 2023. Almost all of the retention capacity (>99%) has depleted as a result of the rain event on 22 August, which lead to runoff from the region above 1050 m a.s.l. However, contribution of the snow-covered area to the total runoff remained minor (11%), which is below the average on the annual maximum runoff days (18%). Similar conditions were found on the second and third largest runoffs in 2001 and 2012, when the snowpack was saturated on the annual maximum runoff days. It is clear that the snowpack was saturated by the rain events, however, such conditions commonly occurred during the rain and melt events and is not unique to the top-ranked runoff days. Therefore, we believe further discussion on the retention processes is not very informative, and would like to leave the text as it is.

334 "unclear relationship", what about retention findings from model?

No big melt or rain events have been computed in 1997, which is the reason why the annual maximum runoff was suppressed ($3.4 \text{ m}^3 \text{ s}^{-1}$). Even if there was no capacity of water retention within the snowpack, the runoff will be $4.1 \text{ m}^3 \text{ s}^{-1}$ and still holds the unclear relationship, given even greater runoff was computed as $4.8 \text{ m}^3 \text{ s}^{-1}$ in 1995. Therefore, we consider water retention of snowpack had minor effects on this point. However, the model may not adequately reproduce thick firm layer as well as formation of ice layers within the firm which can impede downward water infiltration and facilitate runoff from the accumulation area (Machguth et al., 2016; Mikkelsen et al., 2016). These points were added in the text (L355–358) as overall limitation of the model results.

Machguth, H., MacFerrin, M. van As D., Box, J. E., Charalampidis, Colgan, W., Fausto, R. S., Meijer, H. A. J., Mosley-Thompson, E., van de Wal, R. S. W.: Greenland meltwater storage in firn limited by near-surface ice formation, *Nature Clim. Change*, 6, 390–393, doi:10.1038/nclimate2899, 2016.

Mikkelsen, A. B., Hubbard, A., MacFerrin, M., Box, J. E., Doyle, S. H., Fitzpatrick, A., Hasholt, B., Bailey, H. L., Lindbäck, K., and Pettersson, R.: Extraordinary runoff from the Greenland ice sheet in 2012 amplified by hypsometry and depleted firn retention, *Cryosphere*, 10, 1147–1159, doi:10.5194/tc-10-1147-2016, 2016.

****low level comments****

"io" means "instead of"

Main Text

"local glaciers" io "peripheral glaciers", peripheral is a recent language mistake we can fix by using a more accurate term

We corrected the term throughout the text as suggested (L28, 34, 40, 373).

"relatively small area of Greenland (4%)" depends on level of connectivity, see doi:10.5194/tc-6-1483-2012 and use a range of % and cite the article

We added the range of area percentage and citation (L30).

37 "from local glaciers" io "from glaciers"

We correct the text as suggested (L40).

40-50 is also possible to find reports of infrastructure bridge damage near Nuuk, for example in Kobbefjord after rainfall in 2022 <https://x.com/NuukNERO/status/1573959848991014913>

We added the text in L49–50.

66 cite also Ahlstrøm 2017 Sci Reports

We included Ahlstrøm et al., 2017 Sci. Adv. in the citation (L70).

83 add day/month the aws installed

We added the installation date of 19 July 2012 (L88–89).

90 perhaps add Williamson PNAS or other supporting work outside of Japanese publications

This paragraph describes darkening processes revealed specifically on Qaanaaq Glacier by the studies conducted on site. We are hesitant to include studies reported on the other sites since the biological processes may differ from the studied glacier.

188 "agreement" to "good agreement"

We corrected the text as suggested (L203).

190 what is RMSE after bias correction, would be smaller than 0.07?

We added the RMSE after the bias correction (L206–207).

197 "runoff was measured in the summer periods during 2017–2019 at 1.4–2.0 km from the glacier terminus (Mankoff et al., 2020;" how is the Mankoff data used? I think that is not a measurement but a model?

The data of the discharge measurements were included and published in Mankoff et al. (2020) as validation for the RCMs. Detailed analysis on the discharge data was conducted in Kondo et al. (2021) to elucidate mechanisms of the flood events happened in Qaanaaq. Therefore, we include both of the citations here.

214 "slightly" add % difference

We deleted the sentence since the underestimation was improved as a result of the modification of the albedo calculations.

218 "good agreement" add % difference

We added the percentage difference as suggested (L237).

265 see also Fausto GRL and Frontiers from 2016 for possible citation in addition to (Nghiem et al., 2012).

We added Fausto et al. (2016) GRL in the citation to describe the melt event covering the Greenland ice sheet on the day (L284). We refrain to include Fausto et al. (2016) Frontiers since the study focuses on regional

characteristics of ice melt on southern Greenland.

Fig 5 red stars do not seem needed as the maximum is illustrated already

We deleted the red asterisks from Figure 5.

Fig 5 runoff "fraction" seems better than depth

We corrected the text as suggested (Fig. 5).

301 "glacier mass budget surplus" io "positive glacier mass balance"

We corrected the text as suggested (L321).

303 "climatic mass balance" is more conventional than "glacier mass balance", see Glossary of Glaciology, IAHS Cogley

We appreciate the suggestion. The text was corrected throughout the text (L77, 109, 145, 232, 323, 442, 445).

355 "rain event at Summit station on the Greenland ice sheet in the summer of 2021" was more like "light rain" or "mist" which occurred after snowfall, see Summit Figure S5a in Box study Supplement and relevant discussion

We corrected the text from "rain event" to "light rain (3.4 mm)" according to the study by Box et al. (2022) (L381).

450 good point "atmospheric circulation patterns are not captured by the Earth system models used in CMIP5 and CMIP6"

Thank you very much for finding the value here.

Summary

The article is very well written and understandable. Its scientific conclusions are sound and the work is well motivated by the lack of discharge data going back into the past. Some more details in the methodology could help the understanding of the reader (details below). The discussion from the point of view of synoptic and climatic controls is enlightening, but some of the suggested causal linkages are more implied than clearly demonstrated (details below).

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Scientific comments:

450 - The authors claim that the pressure patters in fig. 9 ‘trigger’ the high runoff events, which may well be true, but as far as the work that is shown goes, the linkage is only demonstrated in one direction, namely that the pressure pattern is present when a runoff event occurs. It is not demonstrated that every time the pressure pattern occurs, a runoff event follows. It’s not imperative in the context of the study to do that, but the choice of the word ‘trigger’ is maybe overstating the depth of the analysis somewhat.

We agree that the term may carry too much emphasis. The text was changed as “corresponded with” (L478).

With respect to the association between GBI and higher surface temperatures, the manuscript talks exclusively about the role of warm air advection, mostly in connection with cited previous work. I wonder whether decreased cloudiness and higher shortwave radiation also may play a role occasionally, or what the relative

importance of the two mechanisms is (e.g. 445, 475).

We compared annual runoff from Qaanaaq Glacier with summer mean downward shortwave and longwave radiations (Fig. R1). The downward shortwave radiation in summer has been decreasing over the studied period, and does not correlated with the increase in the glacier runoff as well as top-ranked annual runoffs. Although high annual runoff occasionally corresponded with the increased shortwave radiation (e.g. 2007 and 2015), it is not representative for the runoff characteristics and not very informative to describe in the manuscript. Conversely, summer mean downward longwave radiation had been increasing during the period, which is consistent with the previous study reporting increased cloudiness in northwestern Greenland (Noël et al., 2019) (L472–473). Therefore, decreased cloudiness and higher shortwave radiation are not the case for driving high runoffs on this region, and we would like to leave the text as it is.

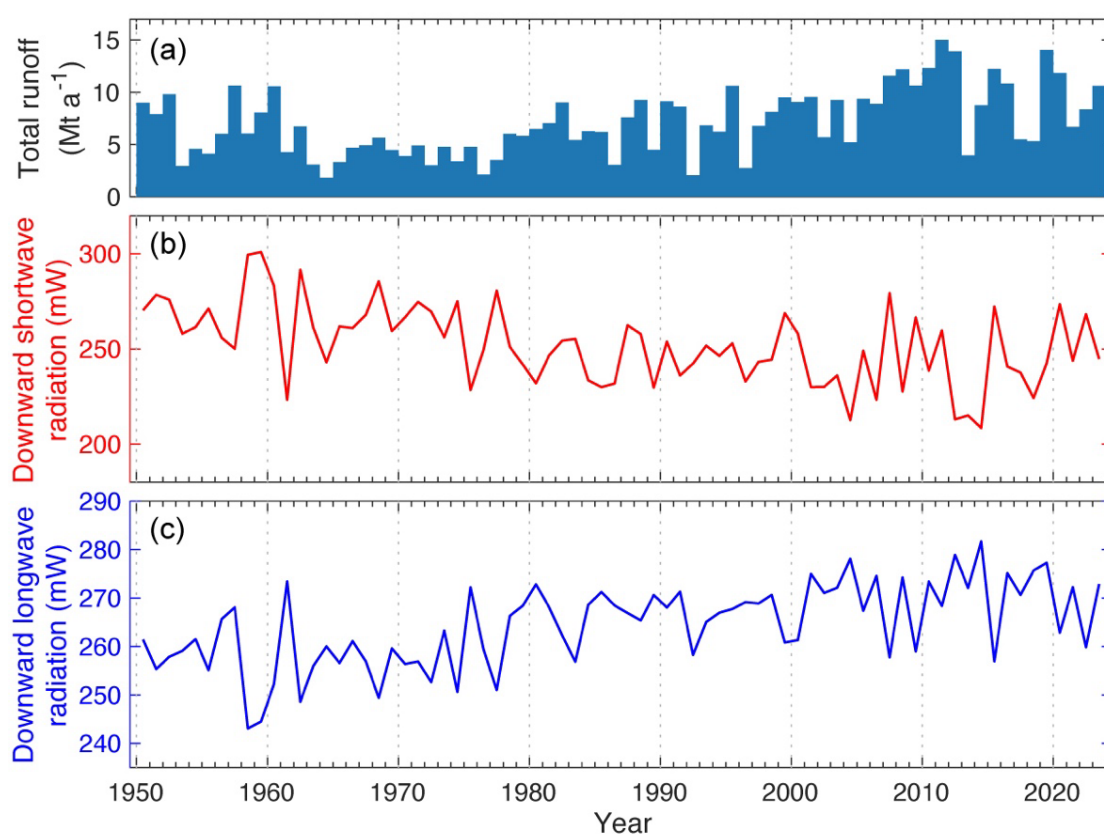


Figure R1: (a) Modelled annual runoff. (b) Summer mean downward shortwave radiation. (c) Summer mean downward longwave radiation.

Noël, B., van de Berg, W. J., Lhermitte, S., and van den Broeke, M. R.: Rapid ablation zone expansion amplifies north Greenland mass loss, *Sci. Adv.*, 5, eaaw0123, doi:10.1126/sciadv.aaw0123, 2019.

Since the composites in fig. 7 contain only very few events, it would be quite nice if the text commented very

briefly also on how representative they are for the individual events. In particular, the claim about the atmospheric rivers driving the runoff events, is it true for every single one of the 3 events?

Yes, the composite figures show the representative states of the atmospheric variables. For the rain-induced runoff peaks, although the atmospheric river during the event on 22 August 2023 was particularly intense as described in the manuscript, the other two days also exhibited moisture transport exceeding $150 \text{ kg m}^{-1} \text{ s}^{-1}$ over Baffin Bay, which is consistent with the definition of atmospheric river. We added these points in L378–379.

Technical comments:

A list of variables measured by the AWS would be nice.

We added the observed variables in the description of the AWS (L89–90).

In the methodology, I would appreciate a bit more clarity on whether the non-glaciated part of the catchment is included in the modelling, in particular since rainfall is found to be important in the high-runoff scenarios. If the area is too small to make an appreciable difference, this can just be stated.

We thank the reviewer for pointing out the lack of the description. Ice-free terrain is included in the model to calculate snowmelt and rainfall over the area. The description was added in Section 3.1 (L122–123, 131–134).

A little more detail on the tuning of the rainfall estimates from ERA to the glacier surface elevation changes could also help the understanding - e.g. is the whole year taken into consideration (suggested by fig. S4a)? Then how is the snow density calculated / taken into account?

The tuning of the precipitation parameter was based on the results within the period 2013–2019. The new snow density and snow densification parameters were optimized by a Monte Carlo simulation conducted in a previous study to best reproduce the observed snow surface height and albedo in the accumulation zone of the northwestern part of the Greenland ice sheet (Fujita et al., 2021). These procedures were added in the revised manuscript (L175–178).

Fujita, K., Matoba, S., Iizuka, Y., Takeuchi, N., Tsushima, A., Kurosaki, Y., and Aoki, T.: Physically Based Summer Temperature Reconstruction From Melt Layers in Ice Cores, *Earth Space Sci.*, 8, e2020EA001590, doi:10.1029/2020EA001590, 2021.

In the model description (3.1), I would find it clearer to say ‘daily averages’ instead of just ‘daily values’ (if indeed it is daily averages that are being used).

We have checked the “daily” term throughout the text as listed below.

- daily surface melt rate (m w.e. d⁻¹), daily runoff depth (m d⁻¹), daily runoff (m³ s⁻¹), daily mass balance (m w.e. d⁻¹)

“Daily runoff (m³ s⁻¹)” refers to “daily mean runoff”, and the other terms refer to “daily total”. However, we would like to keep these terms as they are to follow general usages commonly seen in glaciology and hydrological literatures. Please let us know if you still think “daily mean” and “daily total” are better choices.

A short comment on whether the strong nonlinearity in the Stefan-Boltzmann Law is problematic or not at that level of temporal discretisation might be helpful.

We compared longwave emission from the surface calculated at hourly and daily time intervals. The results showed 0.015% of difference, thus influence of temporal discretization is considered to be negligible. We added this point at L143–144.

The sequence of equations 7-9: Why not directly just use T_z ?

This is because to calibrate L_{calib} with the observed L at the SIGMA-B AWS, which is only possible by the procedure described in the manuscript. After the downward longwave radiation from ERA5-Land (L_{ERA}) was adjusted to the SIGMA-B elevation (L_{calib}) with calibrated air temperature (T_{calib}), L_{calib} was compared with the observation and corrected using the linear regression equation as shown in Figure S2e and L168–169. After the correction, L_{calib} is distributed over the elevation range using T_z .

Also, does the calibration of ERA5 temperature happen after the lapse rate adjustment to the elevation of SIGMA-B?

ERA5 temperature (T_{ERA}) was directly corrected with the air temperature observations at SIGMA-B using the linear regression equation (Fig. S2a). Therefore, the lapse rate adjustment is implicitly included in the linear regression equation.

110 - “The conductive heat flux, G , (W m⁻²) was calculated from the temperature profile of the subsurface snow/ice#: evokes the impression that the subsurface temperature profile is an input (and where would that information come from?), when in reality it is just part of the model.

Subsurface snow/ice temperature was calculated within the model using heat transfer equations. This point was added in the text (L116–117).

55, 300, 420 - When discussing the role of snowfall, it becomes clear only later in the text that in the context of

its importance for ablation it is its effect on albedo in the summer that is referred to (the reader may first think of winter accumulation). This could be made a bit clearer (e.g. in 300).

We agree this point. To clarify the role of winter snowfall on summer glacier ablation, we added the text “suggesting snowfall was important for summer glacier ablation and runoff by modulating glacier surface conditions during the ablation seasons” at L318–319.

445 - “increase in annual runoff since 2000 coincided with the years with the top-ranked summer GBI”: is a little unclear, if I interpret fig 9 correctly, the time after 2000 is both when the top-ranked GBI years occur and when the years with highest runoff occur, but it is not necessarily a year-by-year coincidence, i.e. not every year with top-ranked GBI has top-ranked runoff.

The annual runoff variations are not necessarily expected to exhibit complete year-by-year relationship with the GBI amplitude, since the computed glacier runoff is a result of complex interaction among meteorology and glacier surface conditions. In this sentence, we intended to describe the major role of the top-ranked summer GBI to drive pronounced increase in the runoff since the year 2000, and not necessarily pointing year-by-year coincidence. Therefore, we prefer to leave the text as it is.

Fig 9: The nature of the fields displayed is not completely clear to me. The anomalies are with respect to averages over what time spans? And the ‘regression anomalies’ - I presume this is the regression coefficient of Z500 with respect to GBI?

Regression anomaly means the deviation of the meteorological variables from the trend line calculated during the period within 1940–2023, to eliminate the temporal trend (e.g. atmospheric warming) and investigate the control of GBI. To make it clear in the manuscript, the caption in Figure 9 was corrected as “anomaly from the temporal trend”.