Response to Reviewers: The Anomalously Warm Summer of 2023 Over Greenland as Compared to Previous Record Melt Summers of 2012 and 2019

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General Remarks

We thank the Editor and both Reviewers for their constructive feedback and helpful suggestions on our manuscript. We have addressed all comments as detailed below. Line numbers in our responses refer to the **tracked changes document** provided with the responses.

Response to Reviewer 1

Response to General Comments

Reviewer Comment 1.1:
This paper analyzes spectrometer data from GOME-2, ERA5 reanalysis fields, and 10 km MAR meltwater output to evaluate the role of clouds atop the Greenland Ice Sheet (GrIS) in shaping the three most anomalous melt summers since 1979, which were 2012, 2019, and 2023 with the latter receiving the least attention to date. The authors find comparisons between these cases in terms of elevated two-metre air temperatures, melt area, and meltwater production over the ice sheet. They also find similarities between 2012 and 2023 in terms of July cloudiness linked to anomalous accumulation zone melt, though 2023 cloudiness was relatively more widespread across the ice sheet. The authors note that a colder-than-average June 2023 precluded that summer melt season from competing with 2012 for the largest melt summer on record.

Overall, the paper provides a timely comparison of monthly atmospheric circulation, clouds, and GrIS surface conditions through the progression of summers that experience notable melt. Pending some additional details about data products and considerations regarding methods (e.g., base period calculation), the paper could be a good fit for the journal and contribution to the literature on cloud-radiative effects on extreme monthly and seasonal GrIS melt. Comments are provided below by line number (L) of the submitted manuscript.

Author Response:

We appreciate the reviewer's positive evaluation and recommendation to publish our work.

Response to Specific Comments

Reviewer Comment 1.1:
L5 and L8: Negative anomalies in what?

Author Response:
Here the text is referring to negative R^{TOA} anomalies. Both mentions of negative anomalies in the abstract are now clarified. See the tracked changes document **lines 6-9**.

Reviewer Comment 1.2:
L35: Is this role of clouds dependent on their type and occurrence within the summer season?

Author Response:
Yes, that is correct, with a high occurrence in low-level liquid clouds over the accumulation zone being the most persistent contributor to cloud-induced surface melt (Bennartz et al., 2013; Mattingly et al., 2020).

Reviewer Comment 1.3:
L50: "higher-level" data products and model results such as?

Author Response:
All of the data used is described in the Data and Methods section. Here, higher-level data products refer to the Energy Balanced and Filled (EBAF) top-of-atmosphere (TOA) data provided by the Clouds and the Earth's Radiant Energy System (CERES) project (NASA/LARC/SD/ASDC, 2023), as well as the Greenland Ice Sheet Today (GIST). data collection (Mote, 2007, 2025). Model data refers to data from the Modèle Atmosphérique Régionale (MAR) regional climate model v3.14 (Haacker et al., 2024). An additional sentence was added directing the reader to the next section to read about the full list of the data products used. See the tracked changes document **line 57**.

Reviewer Comment 1.4:
L78-80: What is the accuracy of GOME-2 retrievals? Have these measurements been validated by surface observations, especially over the GrIS?

Author Response:
GOME-2 radiance and irradiance data are measurements rather than retrievals and the accuracy of these measurements is detailed in Munro et al. (2016). Spectral calibration is carried out daily and the instrument is spectrally stable. Degradation is monitored throughout the lifetime of the instruments and corrected during data reprocessing. There has been no dedicated validation over the GrIS, though the radiometric accuracy is expected to hold over the GrIS as it does elsewhere.

Reviewer Comment 1.5:
L103-107: Why use ERA5 versus another global reanalysis? Specifically, how does ERA5 two-

meter temperature compare versus other global atmospheric reanalyses over the ice sheet?

Author Response:

We made use of the ERA5 dataset for the following reasons:

- ERA5 is the highest resolution global reanalysis covering a long time span that is well-suited for this study.
- In terms of global atmospheric reanalysis, ERA5 has been shown to be the most robust over the GrIS (Chen et al., 2026).
- While the regional Arctic System Reanalysis (ASR) has been shown to simulate near-surface better than ERA5 (Delhasse et al., 2020), it covers a much shorter time span than ERA5 and does not include the Extreme melt summers of 2019 and 2023.

We have added a sentence in section 2.3 that refers to Chen et al. (2026) for readers to see how ERA5 compares against other global atmospheric reanalyses over the ice sheet. See the tracked changes document **lines 115-116**.

Reviewer Comment 1.6:
L137: Are 2012, 2019, and 2023 included in the 2007-2024 mean? If so, how do anomalies compare in Fig 2 if those years are removed? Are results impacted?

Author Response:

Yes the anomalous years are included in the climatology that is subtracted from the data in order to compute anomalies. By removing these data points from the time-frame over which the climatology is calculated, the anomalies become more extreme.

Reviewer Comment 1.7:
L143: The Geological Survey of Denmark and Greenland (GEUS), which manages the PROMICE weather station network, took over operations of GC-Net weather stations 2020 (see https://promice.org/about/). It would be a good idea to confirm that more recent ERA5 datasets (2021-2024) do or do not assimilate data from one or both of these networks.

Author Response:

Fausto et al. (2021) report that PROMICE AWS are not included in any reanalysis product such as ERA5, whereas Covi et al. (2025) explicitly state that GC-Net is assimilated. We have found no proof of this having changed in recent years.

Reviewer Comment 1.8:
L237: ”coming in second” since when and second to which year?

Author Response:

A clarification has been added to the sentence in question. See the tracked changes document **line 252**.

Reviewer Comment 1.9:
L284: What type(s) of clouds enhance meltwater run-off?

Author Response:

Low-level liquid clouds are the strongest contributors to cloud-induced surface melt due to longwave warming effects, and therefore are the most likely to enhance meltwater runoff (Bennartz et al., 2013; Mattingly et al., 2020). Stratiform clouds in particular, because of their spatial extent, maximize this warming over large areas of the GrIS, leading to more runoff.

Reviewer Comment 1.10:
L295: A note here is warranted whereabouts on the GrIS this fixed elevation threshold may not accurately estimate the ELA.

Author Response:

The fixed threshold is no longer referred to as the equilibrium line altitude to avoid confusion. See the tracked changes document **lines 309-311, 317** and **318**.

Reviewer Comment 1.11:
L132: ...and daily data forced by ERA5 reanalysis. Also, is this daily-averaged or sub-daily? Please clarify.

Author Response:

The data product we used is the aggregated daily data. The forcing at the lateral boundaries of MAR happens every 6 hours. This has now been made clear. See the tracked changes document **lines 142-143**.

Reviewer Comment 1.12:
L272: ”and go in opposite directions” – this portion of the sentence could be re-written to improve clarity.

Author Response:

”Go in opposite directions” has been reworded to ”vary inversely” for clarity. See the tracked changes document **line 287**.

Reviewer Comment 1.13:
L155: Should ”all three months” be ”all three weeks”?

Author Response:

The sentence is referring to the Julys of 2012, 2019 and 2023. The word ”months” has been switched to ”Julys” for clarity. See the tracked changes document **line 165**.

Reviewer Comment 1.14:
Figure 9: The top portions of panels (a) and (b) are illegible due to the placement of the legends overlaid on the data.

Author Response:

We removed the data point from the legend as it is rather self-explanatory that the data points are blue circles and hope that this way, the data point in the legend will not be confused with the actual data points. Having made this change, the smaller legend no longer covers any data points. We made a similar change to Fig. 6 for consistency. We hope that this change addresses the concerns brought to our attention by the reviewer. The updated Figs. 6 and 9 can be seen in the tracked changes document.

Reviewer Comment 1.15:
L312: Would suggest adding "regional" before "model" for clarity.

Author Response:

We added "regional" in front of "model" as suggested. See the tracked changes document **line 329**.

Response to Reviewer 2

Response to General Comments

Reviewer Comment 2.0:
The analysis would be more effectively communicated if the authors devoted some text earlier in the manuscript to briefly explain the significance of VIS-NIR reflectance to GrIS mass balance. In other words, what relevant physical processes does it inform on and how?

Related to my previous comment, the framing of the analysis in the introduction seems a bit inconsistent with the discussion. Understanding the contrasting mechanisms that promote melt of the ice sheet – namely, clear-sky vs cloud longwave forcing – is cited in the introduction as a primary motivation for the study, but the authors cite prior work in section 4.1 (L201) establishing that the primary measurement they utilize to conduct their analysis, , is not an effective indicator of cloud cover over the ice sheet. If, as suggested in section 4, was not intended to be used to monitor cloud cover, that could be clarified when addressing my first comment above.

While the maps in Figs 2-4 show anomalies with respect to the long-term mean, many of the statistical relationships between and other meteorological and SMB/SEB variables (Figs 5 and 6) appear to be derived using mean values of these fields. This means that the provided correlation coefficients may be strongly reflective of any shared seasonal cycles in these variables rather than a true physical link. To avoid this, the seasonal cycle should be removed from each variable before computing the correlation.

Author Response:

We thank the reviewer for their thorough analysis of our work and the important points they brought to our attention.

The framing of the analysis is the result of how the findings were obtained. Namely, we looked at R^{TOA} in conjunction with other datasets and identified the causes behind the anomalous reductions in reflectance in 2012, 2019 and 2023. As such, the goal of this study was not to create a novel method to detect melt using VIS-NIR but rather attribute the changes we are seeing in GOME-2 R^{TOA}. However, given our findings, the reviewer is right to point out that the use of VIS-NIR measurements in the study of the GrIS is not addressed in the introduction section. Such a discussion has now been included. See the tracked changes document **lines 50-54**.

The fact that GOME-2 R^{TOA} is not an effective indicator of cloud cover over the GrIS is a finding that derives from the spatiotemporal analysis of R^{TOA} alongside other data products. The intention was to investigate what is the dominant driver of reflectance changes during extreme melt summers, which we found to be surface melt. This finding is one of the results of our analyses that we reported on in the discussion section, while describing how we got there in the previous sections. However, as we show in the manuscript, clouds contribute to surface melt, corroborating past studies (Bennartz et al., 2013; Van Tricht et al., 2016; Mattingly et al., 2020). Thus, while what we see in the monthly R^{TOA} data is caused by surface changes rather than cloud cover changes, clouds directly contributed to the surface changes we observe in the extreme melt summers that were predominantly cloudy (2012 and 2023). As a result, understanding the impact of cloud longwave warming effects and a lack thereof is still one of the primary motives behind our study, and it is a topic we discuss extensively in the discussion section.

Figs. 5 and 6 show the correlation coefficients computed between the JJA averages of the parameters shown, not the full monthly datasets. As such, seasonality does no affect the correlation coefficients since it is not a part of the JJA-averaged data that is used to compute them. This has now been made clear in the captions of the time series figures.

Response to Specific Comments

Reviewer Comment 2.1:
Abstract: Including a sentence briefly explaining the physical significance/relevance of to the ice sheet would make the abstract more accessible to a wider audience.

Author Response:

A brief sentence has been added to underline the physical significance and relevance of the GrIS at the start of the abstract. See the tracked changes document **line 1**.

Reviewer Comment 2.2:
L9-10: Consider whether the use of parenthetical formatting is necessary here. I personally feel that the terms in parenthesis are clearer and would read well on their own; i.e., "... both clear-sky conditions, observed in 2019, and cloudy conditions, observed..."

Author Response:

The sentence in questions has been modified as suggested. See the tracked changes document **lines 10-11**.

Reviewer Comment 2.3:
L20: replace ”the melting” with ”melt”

Author Response:

The suggested substitution has been implemented. See the tracked changes document **line 22**.

Reviewer Comment 2.4:
L27: delete ”as a whole”

Author Response:

The suggested change has been applied, also in the next sentence. See the tracked changes document **lines 29** and **31**.

Reviewer Comment 2.5:
L41: Consider different, more descriptive phrasing to open this sentence; e.g., ”Although it produced less melt than that of 2012, the summer of 2023...”

Author Response:

The sentence has been adjusted. It now reads: ”The summer of 2023, although it produced less melt than 2012 and 2019, had several noteworthy melt events spanning late-June to mid-July as well as a prominent multi-day episode in the second half of August (see Fig. 1).” See the tracked changes document **lines 43-45**.

Reviewer Comment 2.6:
L48: The second half of this sentence, ”...for the period of interest as well 2012 and 2019 for reference,” is not needed here.

Author Response:

The second part has been deleted as suggested. See the tracked changes document **line 51**.

Reviewer Comment 2.7:
L63: The parentheses are not needed here

Author Response:

The parentheses have been removed as suggested. See the tracked changes document **line 70**.

Reviewer Comment 2.8:
L78: The phrasing here makes it sound like your results include band 3 imagery. But the next sentence suggests that band 3 was not utilized. If the latter is true, consider rephrasing to something like, ”While band 3 (437-610 nm) includes part of the visible spectrum, band 4 better captures...”

Author Response:

The text has been adjusted and the sentence now reads: "While band 3 (437–610 nm) includes a large part of the visible spectrum, band 4 better captures reflectance changes associated with extreme melt summers due to the higher absorption coefficient of ice and snow in the the red and near-infrared portion of the spectrum (Cooper et al., 2021)." See the tracked changes document **lines 86-89**.

Reviewer Comment 2.9:
Fig. 2 and 3: The authors describe this in the main text, but I would suggest making the difference between these two figures clearer up front in the captions. Perhaps with a short, descriptive title at the start of each caption that notes that Fig. 2 shows JJA values while Fig. 3. shows July alone.

Author Response:

Figures now have the time-frame which they represent inserted at the start of the caption as requested. See modified figure captions in the tracked changes document for Figs. 2, 3, 4, 10, A1, C1, C2, C3 and C4.

Reviewer Comment 2.10:
L161: Please verify that the in-text references to the figures throughout this paragraph are correct. The opening line discusses anomalies, but references Fig 4a-c, which depicts cloud cover anomalies. I believe the next sentence should refer to Fig. 4, not Fig. 3. And the last sentence (L167) should refer to Fig. 4D-F, correct?

Author Response:

We thank the reviewer for catching our mistake in figure referencing. The first reference has been moved to the end of the sentence as intended, and the references referring to Fig. 3 now correctly refer to Fig. 4. See the tracked changes document **lines 171-173** and **177**.

Reviewer Comment 2.11:
L169: I suggest using the more specific "JJA" instead of "summer-wide." Also, the authors suggest that the fact that the anomalies in Fig. 4 are not as pronounced as those in Figs 2 and 3 implies that July conditions dominate the JJA average. But Fig. 3 shows select atmospheric fields for July alone. Considering this, and given the logic presented by the authors, shouldn't the anomalies in Fig. 4 be consistent with Fig 2 but not Fig. 3?

Author Response:

The use of the word "summer-wide" has been substituted with "JJA" as suggested. What we are suggesting is that since the difference between July and JJA anomalies is small when it comes to cloud properties, it is not necessary to also feature a July cloud anomaly figure in the main text since both figures tell a similar story. If the patterns between Fig. 4 and Fig. A1 are similar, it follows that July conditions influenced the JJA-averaged cloud property distribution. For readers who want to compare and contrast the two figures, there is a sentence directing them to the appendix.

Reviewer Comment 2.12:
L185: What is the basis for the statement that, "Like in 2012, a lot of melt produced in 2023 was either refrozen or deposited." If Fig. 6c, please reference this at the conclusion of the sentence. Also, "a lot" is quite vague. Would it be possible to compute the fraction of meltwater production that was retained?

Author Response:

The text has been modified such that avoids vague statements like "a lot". Fig 6C is now referenced at the end of the sentence as suggested. The variable meltwater refreezing and deposition represents the amount of meltwater retained as a solid. MAR's one-dimensional Soil Ice Snow Vegetation Atmosphere Transfer scheme (SISVAT) (Ridder and Gallée, 1998) cannot simulate lateral meltwater flow or ponding, meaning supraglacial lakes and surface water retention are not explicitly resolved. As a result, the amount of meltwater retained as solid (what is currently shown in Fig. 6C) is the best proxy for the total amount retained.

Reviewer Comment 2.13:
L200: Given the Lelli et al. (2023) results, was the original intent of this analysis to use the GOME2 data as a melt indicator or a cloud cover indicator?

Author Response:

The original intent of this study was to investigate the changes in reflectance over the GrIS. While findings from Lelli et al. (2023) made us investigate whether the changes we were seeing were caused by clouds, through the spatiotemporal analysis of GOME-2 R_λ^{TOA} and all the other datasets used in this study, it became apparent that the primary cause behind the anomalous reductions in R_λ^{TOA} over the GrIS are caused by the surface. While radiative transfer modeling results from Lelli et al. (2023) suggest that the presence of clouds over the GrIS is expected to increase reflectance, the secondary effect of cloud-induced melt captured by the monthly averages and the associated reduction in R_λ^{TOA} likely outweighs the expected small increase.

Reviewer Comment 2.14:
L219: If GOME-2 data is used as a melt indicator, is there any advantage to using this product over passive microwave brightness temperatures?

Author Response:

The text has been modified to include the advantages GOME-2 R_λ^{TOA} has over passive microwave as follows: "In this way GOME-2 R_λ^{TOA} provides additional information that complements passive microwave data products like GIST. Namely, passive microwave observations are typically interpreted as a binary melt/no-melt classification based on thresholding brightness temperatures (e.g. Mote, 2007; Colosio et al., 2021), whereas GOME-2 R_λ^{TOA} provides continuous information on surface reflectance and albedo, as well as cloud radiative properties, both of which influence the surface energy balance and are linked to melt variability and preconditioning." See the tracked changes document **lines 230-235**.

Importantly, GOME-2 R_λ^{TOA} is not meant to be used instead of passive microwave, but rather alongside it. Passive microwave is still more robust in detecting melt and works year-round.

Reviewer Comment 2.15:
L224: delete the ”is” after ”Greenland-wide”

Author Response:

Thank you for catching the mistake; it has now been corrected. See the tracked changes document **lines 239**.

Reviewer Comment 2.16:
L324: This seems like an important finding that may warrant being featured in the abstract.

Author Response:

The finding has now been included in the abstract as the final sentence: ”Furthermore, were it not for the colder-than-average June in 2023, our findings show that the total summer melt would likely have rivaled the extreme levels observed in 2012.” See the tracked changes document **lines 14-15**.

Reviewer Comment 2.17:
L351 and L375: It may be a bit strong to say that blocking over Greenland is ”expected” to become more frequent. Preece et al. (2023) present one line of evidence that Arctic amplification may promote anticyclonic conditions over Greenland. Modeling and observational analysis also point to a link between declining sea ice in Baffin Bay and increased Greenland blocking and should be acknowledged here:

Liu, J., Chen, Z., Francis, J., Song, M., Mote, T., and Hu, Y.: Has Arctic Sea Ice Loss Contributed to Increased Surface Melting of the Greenland Ice Sheet?, J. Climate, 29, 3373–3386, https://doi.org/10.1175/JCLI-D-15-0391.1, 2016.

Sellevold, R., Lenaerts, J. T. M., and Vizcaino, M.: Influence of Arctic sea-ice loss on the Greenland ice sheet climate, Clim Dyn, 58, 179–193, https://doi.org/10.1007/s00382-021-05897-4, 2022.

However, GCM simulations consistently suggest a decline in Greenland blocking frequency, so this is very-much still an open question:

Delhasse, A., Hanna, E., Kittel, C., and Fettweis, X.: Brief communication: CMIP6 does not suggest any atmospheric blocking increase in summer over Greenland by 2100, International Journal of Climatology, 41, 2589–2596, https://doi.org/10.1002/joc.6977, 2021.

Hanna, E., Fettweis, X., and Hall, R. J.: Brief communication: Recent changes in summer Greenland blocking captured by none of the CMIP5 models, The Cryosphere, 12, 3287–3292, https://doi.org/10.5194/tc-12-3287-2018, 2018.

Author Response:

The recommended literature has been included in the discussion and the wording revised in line with their findings. See the tracked changes document **lines 366-373** and **394-401**.

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