Reviewer 2 comments, and our response

This manuscript presents a detailed analysis of Greenland Ice Sheet (GIS) mass variations using GRACE/GRACE-FO data (2002–2023) and investigates their connections with climatic indices (NAO, GBI, AMO) and meteorological parameters (temperature, precipitation, albedo). The study employs Empirical Orthogonal Function (EOF) decomposition and wavelet analysis to identify dominant modes of variability and their relationships with external forcings. The topic is timely and relevant to understanding GIS mass balance under climate change. While the methodology is generally sound, some aspects require clarification, validation, and refinement to strengthen the conclusions.

The use of GRACE/GRACE-FO data (COST-G solutions) is appropriate, and the handling of gaps (interpolation and FFT-based gap-filling) is reasonable. Inclusion of multiple climatic indices (NAO, GBI, AMO) and meteorological parameters (temperature, precipitation, albedo) provides a holistic view of GIS mass balance drivers. The 3.5-year lag between AMO and GIS mass loss is an interesting result, plausibly explained by freshwater transport timescales. The proposed annual cycle (Fig. 5) synthesizes interactions between atmospheric, oceanic, and cryospheric processes coherently.

There are still some major issues that should be properly addressed before consideration of publication.

We would like to thank reviewer 2 for his constructive remarks on the lack of clarity and precision of the different parts of our study. Parts of the manuscript have been rewritten to take into account those comments.

- **The higher EOF modes (M2–M5) are less interpretable, and their physical significance is unclear. M5's peaks in 2017–2018 could reflect interpolation artifacts rather than real signals.**
  - **M2-M5:**

    It is true that our explanation was insufficient in regard to why we chose to use EOF modes (M2-M5). We will rewrite the manuscript to add a more thorough explanation.

    Here we explain the points that affected our reasoning and allowed us to confirm which mode mainly shows a real signal.

    We simulate the null hypothesis of temporally uncorrelated structure through randomization of the temporal dimension. We observed that the eigenvalue from the first 12 modes exceeds that of the one generated through shuffling. We also verified if the modes were different from autocorrelated random processes by comparing the frequency content to that of red noise. Modes M1 to M5 had stronger frequencies than the red noise. We confirm that the modes are distinct from one another through North's test. In that test, Figure A, only the first four modes are shown to be distinct from one another, and their error bars do not overlap with the following mode. We use this last conservative test as a basis to use M1 to M4, and added M5, which is at the limit, passing the first two tests and showing a different behavior from other modes with its two peaks.

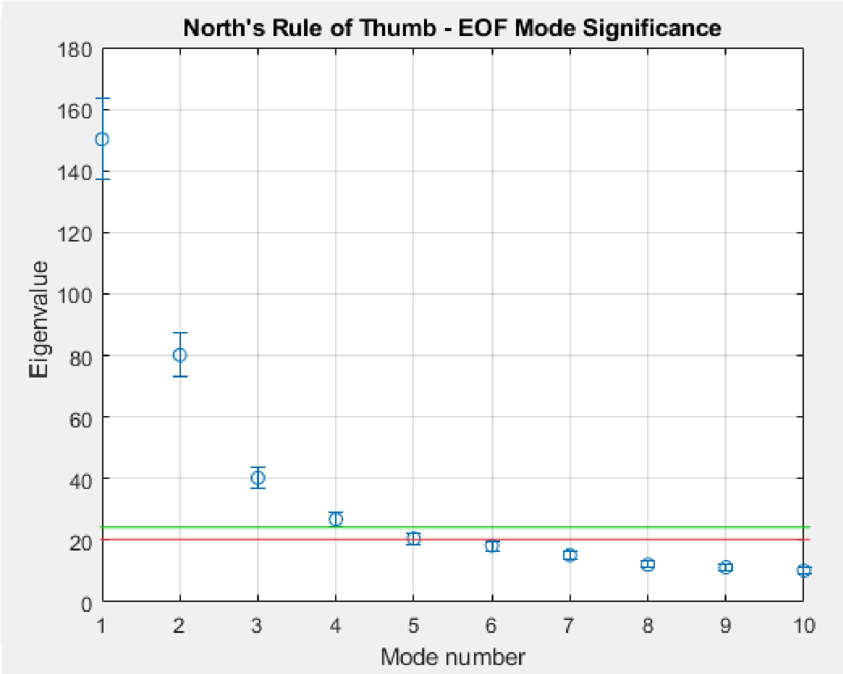

Figure A: Eigenvalues of the first ten EOF modes with their error bars using North's test. All modes above the green line are distinct from one another (M1 to M4), the red line shows the overlap between M5 and M6, and all subsequent modes are also overlapping with e ach other.

It also seems possible to link the EOF modes of mass variations to the EOF modes of Temperature and Precipitation variations. M2 from the EOF of Greenland mass changes is somewhat correlated to mode 2 of the EOF of Greenland's precipitation, and M3 and M4 of mass changes to mode 1 of Greenland's temperature (TDT). This confirms what was shown in Table 1 and Figure 3. (Figure B)

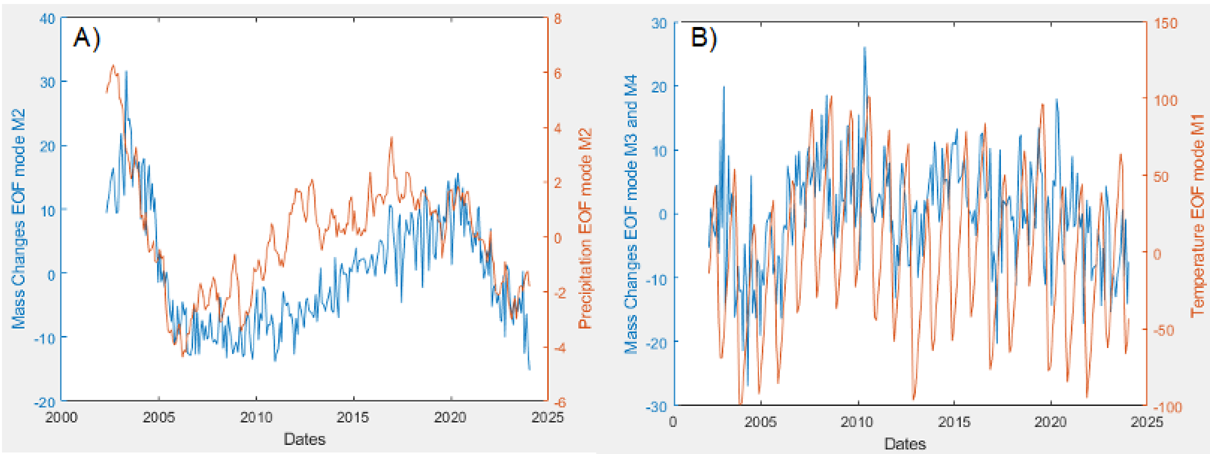

Figure B: The EOF mode of the ice sheet mass changes is shown in blue, and the EOF mode of the meteorological parameters (Precipitation and Temperature) is shown in red. In A), mass change mode M2 is compared to the mode 2 of Precipitation, and in B) is the comparison of the M3 and M4 of mass changes with the mode 1 of Temperature.

- **M5's peaks:**

We lacked precision on the dates of the two peaks; we will address this issue. The first one is in November 2016, and the second one is in November 2017, during the 11-month gap (July 2017 - May 2018) between the two satellite missions.

The two peaks with 50 and 20 Gt each are stronger than the high-frequency noise-like signal of an amplitude of ~10 Gt.

We agree that the second peak is an interpolation artifact. The peak disappears when we alter the chosen preceding year for the interpolation (e.g., using 2015-2016 instead of 2016-2017).

Nonetheless, the first peak is not in this gap or any other lacking month (e.g., September-October 2016). This peak also shows high correlation with precipitation (between 2016 and 2017) in the Cross-Correlation Wavelet analysis (Figure 7). Moreover, we know that in October 2016, a large amount of precipitation was recorded over Greenland (Stendel, 2018). It was in that period that the remnants of Hurricane Nicole reached Greenland's south-eastern coast (Stendel, 2018). Even with the October month lacking, the effect of those events seems to linger till November on the gravimetric data.

Stendel, M.: Polar Portal Season Report 2017, DMI, GEUS, DTU-Space and DTU-Byg, 2018.

- **The 11-year solar cycle link seems plausible but speculative given the short (22-year) dataset**

Albeit short, 22 years of data, our results are in line with what several studies (line 370-373 "Drews et al., 2022; Georgieva et al., 2007; Kuroda et al., 2022", or Mares et al., (2022) have already showcased for the correlations between solar cycles and indices such as NAO and AMO. Judith Lean (2017) provides an explanation of the principles behind the dynamical response of the atmosphere with an increase in solar irradiance. The proposed explanation shows that an increase of 0.1% of solar irradiance can increase Earth's global surface temperature by around 0.1°C. It is also indicated that the atmospheric responses is stronger 0.3°C at 20 km, and that equator–to–pole, as well as the vertical thermal gradient, are altered, modifying the dynamical processes of the different climatic systems. We will add these last two references to the article.

Drews, A., Huo, W., Matthes, K., Kodera, K., and Kruschke, T.: The Sun's role in decadal climate predictability in the North Atlantic, Atmos. Chem. Phys., 22, 7893–7904, https://doi.org/10.5194/acp-22-7893-2022, 2022.

Georgieva, K., Kirov, B., Tonev, P., Guineva, V., and Atanasov, D.: Long-term variations in the correlation between NAO and solar activity: The importance of north–south solar activity asymmetry for atmospheric circulation, Advances in Space Research, 40, 1152–1166, https://doi.org/10.1016/j.asr.2007.02.091, 2007.

Lean, J.: Sun-Climate Connections, Oxford Research Encyclopedia of Climate Science., https://doi.org/10.1093/acrefore/9780190228620.013.9, 2017.

Kuroda, Y., Kodera, K., Yoshida, K., Yukimoto, S., and Gray, L.: Influence of the Solar Cycle on the North Atlantic Oscillation, JGR Atmospheres, 127, e2021JD035519, https://doi.org/10.1029/2021JD035519, 2022.

Mares, C., Dobrica, V., Mares, I., Demetrescu, C.: Solar Signature in Climate Indices, *Atmosphere*, *13*, 1898, https://doi.org/10.3390/atmos13111898, 2022.

- **The >15-year signal is intriguing but statistically uncertain**

  We will remove mentions of this intriguing >15-year signal.

- **The cumulative approach for indices (NAO, GBI, AMO) is innovative but lacks a clear physical basis. How do cumulative indices better represent mass balance than raw anomalies?**

  This approach allows the observation of a time-integrated variable, which is the cumulated effect of an index, and not each instantaneous event separated from one another, as in the raw index. When they are linked to one another, a raw index event is related to the instantaneous speed of mass variations. Thus, the time-integrated indices are related to the observed time-integrated mass variations from gravimetric satellites, rather than the mass flux as the raw indices do.

  This approach has already been used by Mazzarella A., 2013, between the NAO and sea surface temperature, or also by King M. and Christoffersen P., 2024, for ENSO index, GRACE data, as well as altimetry data. In Line 90-93 we explain this approach was also used in the case of Antarctica (Kim et al., 2020; King et al., 2023; Paolo et al., 2018).

  Mazzarella, A.: Time-integrated North Atlantic Oscillation as a proxy for climatic change, *Natural Science*, 5, 149-155, https://doi.org/10.4236/ns.2013.51A023, 2013.

  Kim, B.-H., Seo, K.-W., Eom, J., Chen, J., and Wilson, C. R.: Antarctic ice mass variations from 1979 to 2017 driven by anomalous precipitation accumulation, Sci Rep, 10, 20366, https://doi.org/10.1038/s41598-020-77403-5, 2020.

  King, M. A., Lyu, K., and Zhang, X.: Climate variability a key driver of recent Antarctic ice-mass change, Nat. Geosci., 16, 1128–1135, https://doi.org/10.1038/s41561-023-01317-w, 2023.

  King, M. A., & Christoffersen, P.: Major modes of climate variability dominate nonlinear Antarctic ice-sheet elevation changes 2002–2020, *Geophysical Research Letters*, 51, e2024GL108844, https://doi.org/10.1029/2024GL108844, 2024.

  Paolo, F. S., Padman, L., Fricker, H. A., Adusumilli, S., Howard, S., and Siegfried, M. R.: Response of Pacific-sector Antarctic ice shelves to the El Niño/Southern Oscillation, Nature Geosci, 11, 121–126, https://doi.org/10.1038/s41561-017-0033-0, 2018.

- **No independent validation (e.g., altimetry, regional climate models) is provided to cross-check GRACE-derived mass changes.**

  We will add a paragraph to show that our results are in accordance with what has been found in previous studies, such as that of altimetry data from Khan et al. (2024) and the results from the IMBIE team of 2023.

  You can find in Figure C, our GRACE-derived mass variations, in red, the altimetry one from Khan et al., 2024, in green, and the one from the mix of methods (Altimetry, Gravimetry, Input-Output method) of the IMBIE team, 2023, in blue. We also show the linearly detrended version of our data against that of Khan et al. (2024) in Figure D.

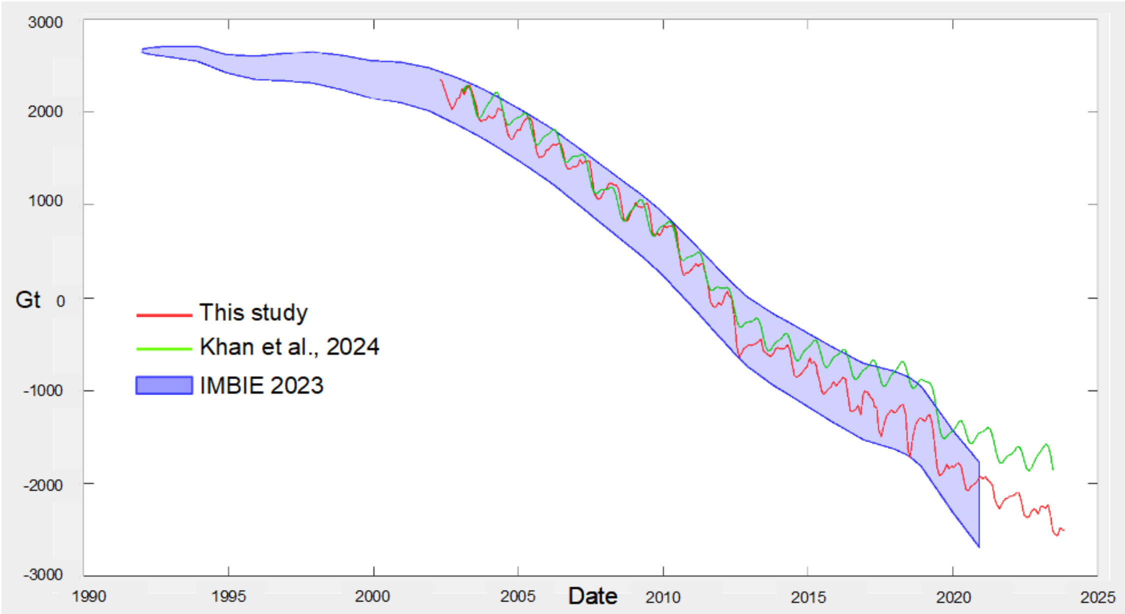

Figure C: Greenland mass variations in Gt since 1992 to 2024. This study's GRACE-derived mass variations are in red; Khan et al. (2024) altimetry data are in green, and the IMBIE team results from 2023 are in blue.

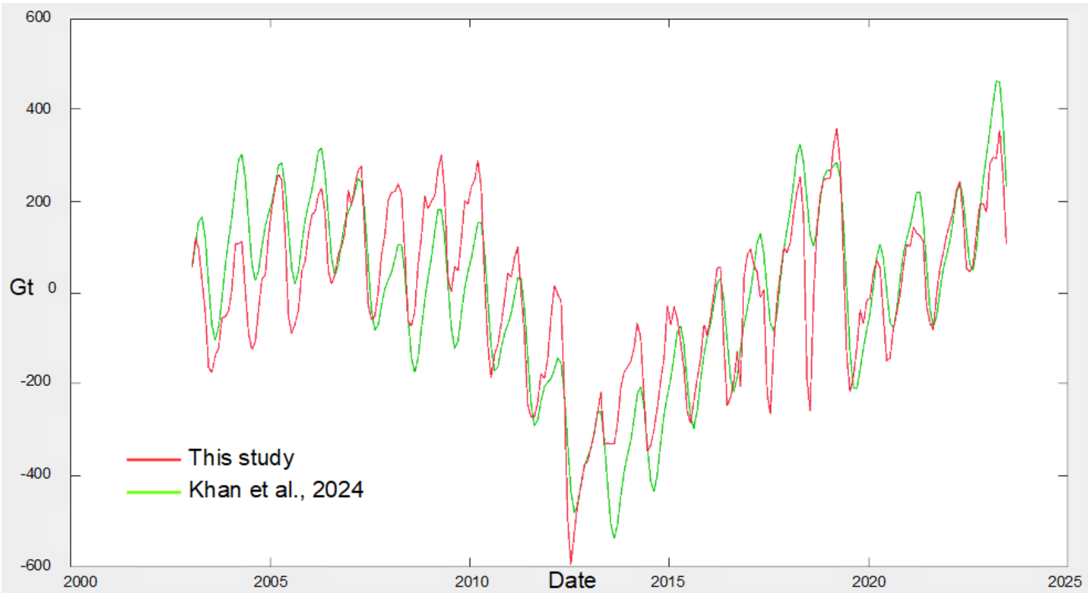

Figure D: Greenland linearly detrended mass variations, in red are the results of this study, and in green the ones from the altimetry study of Khan et al., 2024.

Khan, S. A., Seroussi, H., Morlighem, M., Colgan, W., Helm, V., Cheng, G., Berg, D., Barletta, V. R., Larsen, N. K., Kochtitzky, W., van den Broeke, M., Kjær, K. H., Aschwanden, A., Noël, B., Box, J. E., MacGregor, J. A., Fausto, R. S., Mankoff, K. D., Howat, I. M., Oniszk, K., Fahrner, D., Løkkegaard, A., Lippert, E. Y. H., and Hassan, J.: Smoothed monthly Greenland ice sheet elevation changes during 2003–2023, Earth Syst. Sci. Data Discuss. [preprint], https://doi.org/10.5194/essd-2024-348, in review, 2024.

Otosaka, I. N., Shepherd, A., Ivins, E. R., Schlegel, N.-J., Amory, C., van den Broeke, M., Horwath, M., Joughin, I., King, M., Krinner, G., Nowicki, S., Payne, T., Rignot, E., Scambos, T., Simon, K.

M., Smith, B., Sandberg Sørensen, L., Velicogna, I., Whitehouse, P., A, G., Agosta, C., Ahlstrøm, A. P., Blazquez, A., Colgan, W., Engdahl, M., Fettweis, X., Forsberg, R., Gallée, H., Gardner, A., Gilbert, L., Gourmelen, N., Groh, A., Gunter, B. C., Harig, C., Helm, V., Khan, S. A., Konrad, H., Langen, P., Lecavalier, B., Liang, C.-C., Loomis, B., McMillan, M., Melini, D., Mernild, S. H., Mottram, R., Mouginot, J., Nilsson, J., Noël, B., Pattle, M. E., Peltier, W. R., Pie, N., Sasgen, I., Save, H., Seo, K.-W., Scheuchl, B., Schrama, E., Schröder, L., Simonsen, S. B., Slater, T., Spada, G., Sutterley, T., Vishwakarma, B. D., van Wessem, J. M., Wiese, D., van der Wal, W., and Wouters, B.: Mass Balance of the Greenland and Antarctic Ice Sheets from 1992 to 2020, ESSD – Ice/Glaciology, https://doi.org/10.5194/essd-2022-261, 2023.

- **Some methodological details are unclear (e.g., "time-weighted thermal availability," wavelet significance thresholds)."**

  We will make things clearer in the manuscript, but here is an explanation.

  The "time-weighted thermal availability" is our transformed Temperature parameter, TDT, a time-integrated temperature parameter. It corresponds to the mean of all positive temperatures ($T > 0°c$) of a month (i), multiplied by the time duration where $T > 0°c$ is reached during this same month (i) (Line 133-138 explains this as Eq. 1).

  On the Cross-Wavelet analysis, the black contours are estimated, using Monte Carlo simulation, against red noise, with a 2-sigma threshold. That translates to a 5% significance level, meaning there is an only a 5% chance that the circled areas happened by chance, and a 95% confidence that all other zones beyond the black contours are noise. (Grinsted et al., 2004)

Overall, this study makes a valuable contribution to understanding GIS mass variability and its climatic drivers. The methodology looks sound, and the results seems plausible, but some claims (e.g., solar cycle link, >15-year periodicity) require caution due to dataset limitations.