Reviewer 1 comments, and our response

Review of "Greenland's annual and interannual mass variations from GRACE/GRACE-FO linked with climatic indices"

Summary: This paper seeks to understand how annual to decadal-scale variability in the mass change of the Greenland Ice Sheet is related to a set of climate indices and parameters. After decomposing the mass change time series into the top five principal components (Pcs), numerous cross correlations are performed between the PCs and climate variables using a cross wavelet transform. The most significant relationships with the highest correlations are then discussed. The correlations for annual variability are summarized and some causal relationships investigated in previous studies are noted. I have some major concerns as to the design of the study, the lack of a clear and comprehensive connection to the peer-reviewed literature, and the quality of the writing. Until these major comments are addressed, it is difficult to evaluate many of the specifics of the study.

We would like to thank reviewer 1 for his constructive comments, pointing out the lack of publications supporting the effects and causes mentioned in our manuscript and derived directly from the observed co-relationships. Some parts have been rewritten to make the text more concise and understandable.

Major Comments:

1. The methods in this study have the potential to be part of an investigation into causal relationships between Greenland Ice Sheet mass loss and other climate processes (King et al., 2023).

Thank you for your detailed and pertinent comment. You raise some important points about the methodology and contribution of this study. Here are a few points to address your concerns:

1) **Lack of literature review and physical basis:**

You are right to stress the importance of a thorough literature review and physics-based discussion to contextualize the relationships studied. This would help to better justify methodological choices, such as the timeframes and frequencies analyzed, and avoid misinterpretations. We recognize that this shortcoming may make the results less convincing, and pledge to incorporate more climatic literature into the state of the art, as well as in the discussion **of** this new version of the manuscript.

You will find, following this, part of the added references and their contribution. If we have missed relevant references, please do not hesitate to enlighten us.

(King and Christoffersen, 2024): Use the same approach of cumulative indices, but for Antarctica, it is the study that follows the one from King et al., 2023 (reference on which our study's methodology was built upon).

(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 are 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.

(Hanna et al., 2013): Correlate the GBI, NAO, and AMO indices to Greenland's runoff and temperature. Showing that GBI has a higher correlation coefficient than NAO.

(Preece et al., 2022): Show there exist three blocking patterns that produce increasing melt in different locations depending on the type of blocking.

(Hanna et al., 2015): Indicate that NAO tends to decrease in summer and has more variability in winter. They show it is happening while the GBI tends to increase in summer and be more variable in winter.

(Hanna et al., 2018): In this communication, they show that the recent increase in blocking events in summer may be influenced by the positive AMO, which is related to negative NAO. (Davini et al., 2012)

(Lewis et al., 2021): Observe that strong blocking increases precipitation grain sizes, which in turn reduces the albedo. This also causes an increase in surface temperature, fewer storms, more shortwave radiation, and maximizes the albedo feedback. (Box et al., 2012; Dozier et al., 1981; Tedesco et al., 2011)

(Silva et al., 2022): Use GBI and NAO altogether. They show that a variable surface warming is happening in winter, and that there is an increase in shortwave radiation when higher pressure stands over Greenland.

(Tedesco et al., 2013): Indicate that persistent anticyclonic conditions, NAO's anomalies, and surface albedo and temperatures were drivers of the massive ice loss event of 2012.

(Fettweis et al., 2008): show that Greenland's atmospheric variability and ice sheet melting are correlated to NAO and that it explains extreme temperature in 2003 and melting in 2007.

(Shang et al., 2022): Found that summer mass variations are correlated to the NAO, with temperature-associated precipitation and runoff.

(Li et al., 2022): use the EOF method to find a correlation between ice mass variation and indices such as NAO and AMO. They suggest a relation between the Pacific Decadal Oscillation and the Icelandic Low. The NAO seems to be linked to the West-East dipole of precipitation (correlation in the west and anti-correlation in the east), and AMO to the runoff and temperature.

(Bjørk et al., 2018): have the same results for NAO.

(Sun et al., 2019): observe the close annual and interannual relationship between NAO, the sea surface temperature (SST), which is reflected by the AMO, and the Atlantic Meridional Overturning Circulation.

(Chen et al., 2015): also add the importance of El Niño–Southern Oscillation index to the relation between NAO and SST.

(Kim et al., 2021): show that the AMO is interconnected to the AMOC with a periodicity of 10 to 30 years. It was observed that a positive AMOC induces, with a delay of 7 years, a positive AMO thanks

to meridional heat transport. When the AMO is at his highest, it leads to a reduced water density in the Atlantic sinking area and is the origin of the negative phase of the AMOC.

(Jo et al., 2024): indicate that SST are projected to intensify in summer due to increased heat input and less mixing, whereas in winter they will diminish with the strengthening of vertical mixing.

(Noël et al., 2014): The effect of SST on Greenland remains coastal. They do not appear to influence the central part of the GIS.

(Wood et al., 2021): The SST, salinity, and the geometry of glaciers' ocean-terminating outlets are the main parameters behind their calving behavior.

(Carnahan et al., 2022): observe that ocean forcing is primordial, but not necessary for future mass loss.

(Carrivick et al., 2023): mention the evolution of glaciers. After their retreat, ocean-terminating glaciers transform into land-terminating glaciers, which diminish the discharge term in the mass balance and, in turn, slow the ice loss. However, a land-terminated glacier can change to become lake-terminated, which creates strong calving and accelerates the mass loss.

References:

Bjørk, A. A., Aagaard, S., Lütt, A., Khan, S. A., Box, J. E., Kjeldsen, K. K., Larsen, N. K., Korsgaard, N. J., Cappelen, J., Colgan, W. T., Machguth, H., Andresen, C. S., Peings, Y., and Kjær, K. H.: Changes in Greenland's peripheral glaciers linked to the North Atlantic Oscillation, Nature Clim Change, 8, 48–52, https://doi.org/10.1038/s41558-017-0029-1, 2018.

Box, J. E., Fettweis, X., Stroeve, J. C., Tedesco, M., Hall, D. K., and Steffen, K.: Greenland ice sheet albedo feedback: thermodynamics and atmospheric drivers, The Cryosphere, 6, 821–839, https://doi.org/10.5194/tc-6-821-2012, 2012.

Carnahan, E., Catania, G., and Bartholomaus, T. C.: Observed mechanism for sustained glacier retreat and acceleration in response to ocean warming around Greenland, The Cryosphere, 16, 4305–4317, https://doi.org/10.5194/tc-16-4305-2022, 2022.

Carrivick, J. L., Boston, C. M., Sutherland, J. L., Pearce, D., Armstrong, H., Bjørk, A., Kjeldsen, K. K., Abermann, J., Oien, R. P., Grimes, M., James, W. H. M., and Smith, M. W.: Mass Loss of Glaciers and Ice Caps Across Greenland Since the Little Ice Age, Geophysical Research Letters, 50, https://doi.org/10.1029/2023gl103950, 2023.

Chen, S., Wu, R., and Chen, W.: The Changing Relationship between Interannual Variations of the North Atlantic Oscillation and Northern Tropical Atlantic SST, Journal of Climate, 28, 485–504, https://doi.org/10.1175/jcli-d-14-00422.1, 2015.

Davini, P., Cagnazzo, C., Neale, R., and Tribbia, J.: Coupling between Greenland blocking and the North Atlantic Oscillation pattern, Geophysical Research Letters, 39, https://doi.org/10.1029/2012gl052315, 2012.

Dozier, J., Schneider, S. R., and McGinnis, D. F.: Effect of grain size and snowpack water equivalence on visible and near-infrared satellite observations of snow, Water Resources Research, 17, 1213–1221, https://doi.org/10.1029/wr017i004p01213, 1981.

Fettweis, X., Mabille, G., and Erpicum, M.: Circulations atmosphériques et anomalies de fonte à la surface de la calotte glaciaire du Groenland, Bulletin de la Société Géographique de Liège, 51, 2008.

Hanna, E., Jones, J. M., Cappelen, J., Mernild, S. H., Wood, L., Steffen, K., and Huybrechts, P.: The influence of North Atlantic atmospheric and oceanic forcing effects on 1900–2010 Greenland summer climate and ice melt/runoff, Intl Journal of Climatology, 33, 862–880, https://doi.org/10.1002/joc.3475, 2013.

Hanna, E., Cropper, T. E., Jones, P. D., Scaife, A. A., and Allan, R.: Recent seasonal asymmetric changes in the NAO (a marked summer decline and increased winter variability) and associated changes in the AO and Greenland Blocking Index, Int. J. Climatol, 35, 2540–2554, https://doi.org/10.1002/joc.4157, 2015.

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.

Jo, A. R., Lee, J., Sharma, S., and Lee, S.: Season-Dependent Atmosphere-Ocean Coupled Processes Driving SST Seasonality Changes in a Warmer Climate, Geophysical Research Letters, 51, https://doi.org/10.1029/2023gl106953, 2024.

Kim, H., An, S., and Kim, D.: Timescale-dependent AMOC–AMO relationship in an earth system model of intermediate complexity, Intl Journal of Climatology, 41, https://doi.org/10.1002/joc.6926, 2021.

King, M. A. and Christoffersen, P.: Major Modes of Climate Variability Dominate Nonlinear Antarctic Ice-Sheet Elevation Changes 2002–2020, Geophysical Research Letters, 51, https://doi.org/10.1029/2024gl108844, 2024.

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

Lewis, G., Osterberg, E., Hawley, R., Marshall, H. P., Meehan, T., Graeter, K., McCarthy, F., Overly, T., Thundercloud, Z., Ferris, D., Koffman, B. G., and Dibb, J.: Atmospheric Blocking Drives Recent Albedo Change Across the Western Greenland Ice Sheet Percolation Zone, Geophysical Research Letters, 48, https://doi.org/10.1029/2021gl092814, 2021.

Li, Z., Chao, B. F., Zhang, Z., Jiang, L., and Wang, H.: Greenland Interannual Ice Mass Variations Detected by GRACE Time-Variable Gravity, Geophysical Research Letters, 49, https://doi.org/10.1029/2022GL100551, 2022.

Noël, B., Fettweis, X., Van De Berg, W. J., Van Den Broeke, M. R., and Erpicum, M.: Sensitivity of Greenland Ice Sheet surface mass balance to perturbations in sea surface temperature and sea ice cover: a study with the regional climate model MAR, The Cryosphere, 8, 1871–1883, https://doi.org/10.5194/tc-8-1871-2014, 2014.

Preece, J. R., Wachowicz, L. J., Mote, T. L., Tedesco, M., and Fettweis, X.: Summer Greenland Blocking Diversity and Its Impact on the Surface Mass Balance of the Greenland Ice Sheet, JGR Atmospheres, 127, https://doi.org/10.1029/2021jd035489, 2022.

Shang, P., Su, X., and Luo, Z.: Characteristics of the Greenland Ice Sheet Mass Variations Revealed by GRACE/GRACE Follow-On Gravimetry, Remote Sensing, 14, 4442, https://doi.org/10.3390/rs14184442, 2022.

Silva, T., Abermann, J., Noël, B., Shahi, S., Van De Berg, W. J., and Schöner, W.: The impact of climate oscillations on the surface energy budget over the Greenland Ice Sheet in a changing climate, The Cryosphere, 16, 3375–3391, https://doi.org/10.5194/tc-16-3375-2022, 2022.

Sun, C., Li, J., Kucharski, F., Xue, J., and Li, X.: Contrasting spatial structures of Atlantic Multidecadal Oscillation between observations and slab ocean model simulations, Clim Dyn, 52, 1395–1411, https://doi.org/10.1007/s00382-018-4201-8, 2019.

Tedesco, M., Fettweis, X., Van Den Broeke, M. R., Van De Wal, R. S. W., Smeets, C. J. P. P., Van De Berg, W. J., Serreze, M. C., and Box, J. E.: The role of albedo and accumulation in the 2010 melting record in Greenland, Environ. Res. Lett., 6, 014005, https://doi.org/10.1088/1748-9326/6/1/014005, 2011.

Tedesco, M., Fettweis, X., Mote, T., Wahr, J., Alexander, P., Box, J. E., and Wouters, B.: Evidence and analysis of 2012 Greenland records from spaceborne observations, a regional climate model and reanalysis data, The Cryosphere, 7, 615–630, https://doi.org/10.5194/tc-7-615-2013, 2013.

Wood, M., Rignot, E., Fenty, I., An, L., Bjørk, A., Van Den Broeke, M., Cai, C., Kane, E., Menemenlis, D., Millan, R., Morlighem, M., Mouginot, J., Noël, B., Scheuchl, B., Velicogna, I., Willis, J. K., and Zhang, H.: Ocean forcing drives glacier retreat in Greenland, Sci. Adv., 7, https://doi.org/10.1126/sciadv.aba7282, 2021.

2) Risk of "p-hacking":

We understand your concerns about the exploratory approach and the risk of suggesting false or misleading relationships. While it was not our intention to practice "p-hacking", we recognize that the current methodology could give this impression. We plan to reformulate our approach so that it is guided more by clear hypotheses and existing knowledge, while limiting the number of correlations tested to avoid abusive interpretations.

A typical example is the observations made for the 'Periodicity superior to 15 years' which, from our point of view, is simply a period to watch over the next few decades and cannot be confirmed in the context of this time series, which is far too short to go any further. Aware of the confusion that these remarks may cause, we have removed this paragraph '5.3.2 Periodicity superior to 15 years' from the final text.

3) Contribution to existing literature:

We appreciate your suggestion to structure the study around a gap in the literature, as in King et al. (2023). This would clarify the added value of our work. We will revise our introduction and discussion to better highlight the new perspectives or hypotheses this study proposes, in relation to recent research on mass loss from the Greenland ice sheet, the climatic indices and meteorological parameters.

4) Writing clarity and precision:

We recognize that we lacked conciseness, clarity and that our word choice could have been misleading. We will rewrite the manuscript to take into account your edits and more.

In summary, we take your comments very seriously and are committed to improving the manuscript by strengthening its anchorage in the existing literature, clarifying its objectives and refining the methodology to avoid any ambiguity. We thank you again for your constructive suggestions, which will help to reinforce the quality and rigor of our work.