

Response to Reviewer 1

Summary: This manuscript uses three GRACE/GRACE-FO Mascon products from JPL, CSR, and GSFC spanning 2002–2024 to investigate interannual-to-decadal variability in glacier and ice-cap mass changes globally and across the Arctic. The authors apply ICA to extract the dominant spatiotemporal modes and relate them to the cumulative NAO index and cumulative PDO index. They then employ a multiple regression model incorporating a linear trend, annual and semiannual cycles, and the climate-mode indices to assess the influence of these climate modes on regional glacier mass variability and long-term trend estimates. However, several issues should be addressed before the manuscript can be considered for publication.

Response: We thank the reviewer for the careful assessment of our manuscript and for identifying the issues that required further clarification and revision. We have addressed all comments point by point and revised the manuscript accordingly, including the treatment and interpretation of the climate-related variability and its influence on the estimated glacier mass-change trends. The specific changes are detailed in our responses below and are highlighted in the revised manuscript.

Major comments:

Q1: Equation (2) defines B as the mixing matrix. In the standard ICA formulation, if X denotes the observed signals, Y the independent source signals, and B the mixing matrix, the mixing model should be $X = BY$. However, Equation (2) in the manuscript is written as $X = B^{-1}Y$. Please clarify the definition of B and explain the reason for this formulation. If B actually denotes the unmixing/separation matrix (or its inverse), the notation and terminology should be revised consistently.

R1: We thank the reviewer for identifying this notation error. B is the mixing matrix, and the original form of Eq. (2) was incorrect. We have revised Sect. 2.7 so that the ICA formulation is now written as

$$X = BY,$$

where X is the data matrix, Y contains the independent temporal components, and B is the mixing matrix. The corresponding unmixing matrix is defined as

$$Y = WX, W = B^{-1}.$$

The reconstruction of component k is now written as

$$X_k = b_k y_k,$$

where b_k is the k th column of B and y_k is the corresponding temporal independent component. The notation and terminology have been revised consistently throughout Sect. 2.7.

Q2: The relationship between NAO/PDO variability and Arctic glacier mass change has been widely recognized. In Sections 3.1 and 3.2, the ICA analysis demonstrates significant correlations between the dominant components of detrended glacier mass variability and the NAO/PDO indices. These results appear to establish the influence of NAO and PDO on interannual or low-frequency variability after removal of the linear trend, but they do not by themselves explain how these climate modes are related

to the long-term mass-change trend. This distinction should be clarified, and additional evidence is needed to support any interpretation linking the ICA results to long-term trends.

R2: We thank the reviewer for highlighting this important distinction. We agree that the ICA analysis of detrended GRACE/GRACE-FO data identifies interannual-to-decadal variability but does not by itself quantify contributions to the linear mass-change trend. We have therefore clarified this distinction explicitly in Sect. 3.3. The influence on the fitted trends is evaluated separately using the undetrended multivariate regression in Eq. (8), in which the linear trend and the NAO_{Σ} - and PDO_{Σ} -related terms are estimated simultaneously.

We have also added spatial regression results showing the NAO_{Σ} and PDO_{Σ} coefficients, their joint partial variance, the trends estimated with and without the climate-index terms, and their difference, which represents the fitted climate-associated contribution to the 2002–2024 trend (Fig. 4). The corresponding regional trend contributions and their statistical significance are reported in Table S7; these contributions are significant in Alaska ($p = 0.001$) and Arctic Canada North ($p = 0.019$). We additionally repeated the regression after detrending the cumulative climate indices and found that the fitted NAO_{Σ} and PDO_{Σ} coefficients were effectively unchanged (Table S10), showing that the estimated climate-index coefficients are largely insensitive to the linear components of the cumulative indices.

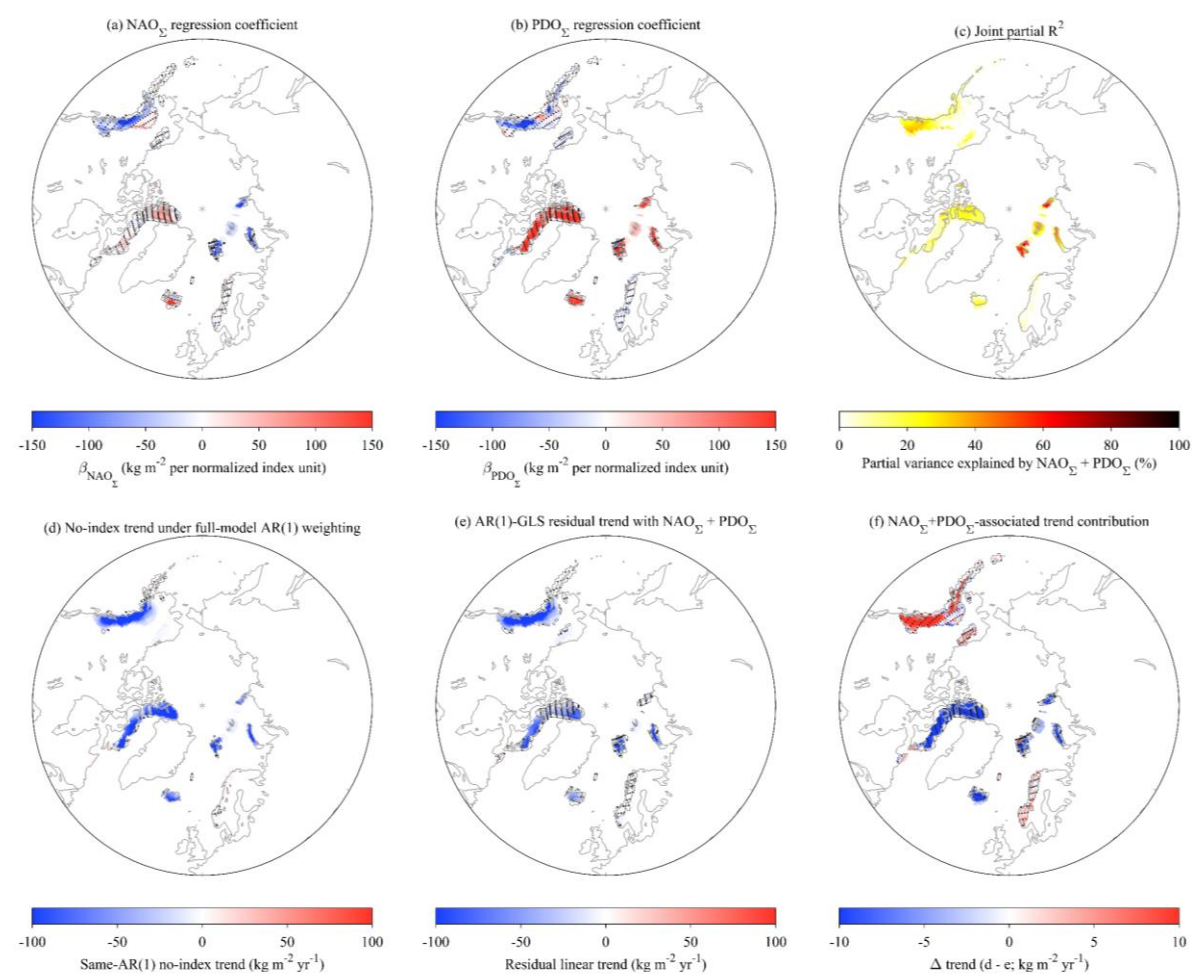


Figure 4: Results of multivariate regression. a,b, Climate-index regression coefficients for NAO_{Σ} (a)

and PDO_{Σ} (b). c, Percentage of the joint partial variance explained by the NAO_{Σ} and PDO_{Σ} terms. d–f, Linear trends from regressions without (d) and with (e) the climate indices, and their difference (f), which represents the fitted $NAO_{\Sigma}+PDO_{\Sigma}$ -associated contribution to the 2002–2024 trend. The regression in d uses the same AR(1) weighting as the full AR(1)-GLS model in e, ensuring an internally consistent trend partition. In a, b, d, e and f, stippled areas bounded by thin outlines are not significantly different from zero at the 95% confidence level.

63 **Table S7. Partitioning of regional glacier mass-change trends into residual and climate-associated components.**

RGI regions	Without index trend under the same AR(1) weighting (Gt yr ⁻¹)	Residual trend after accounting for climate indices (Gt yr ⁻¹)	Trend_NAO _Σ (Gt yr ⁻¹)	Trend_PDO _Σ (Gt yr ⁻¹)	Trend_NAO _Σ + PDO _Σ (Gt yr ⁻¹)	95% CI (Gt yr ⁻¹)	P _{climate trend}
Alaska (ALA)	-68.42 ± 4.95	-92.26 ± 15.53	+0.53 ± 4.07	+23.31 ± 14.96	+23.84 ± 14.75	[9.32, 38.36]	0.001
Arctic Canada North (ACN)	-36.58 ± 2.49	-27.65 ± 7.94	-2.16 ± 2.13	-6.76 ± 7.69	-8.92 ± 7.55	[-16.36, -1.48]	0.019
Arctic Canada South (ACS)	-25.37 ± 1.72	-22.96 ± 5.83	-0.62 ± 1.72	-1.79 ± 5.75	-2.41 ± 5.57	[-7.89, 3.08]	0.388
Iceland (ICE)	-6.92 ± 0.39	-5.85 ± 1.35	-1.43 ± 0.51	+0.36 ± 1.45	-1.07 ± 1.30	[-2.35, 0.21]	0.102
Svalbard (SVA)	-19.25 ± 1.94	-17.39 ± 6.28	+4.56 ± 1.86	-6.42 ± 6.20	-1.86 ± 6.00	[-7.77, 4.05]	0.536
Scandinavia (SCA)	+0.73 ± 0.25	+0.40 ± 0.94	+0.06 ± 0.36	+0.27 ± 1.02	+0.33 ± 0.90	[-0.56, 1.22]	0.470
Russian Arctic (RA)	-15.56 ± 0.68	-13.99 ± 2.09	+4.44 ± 0.79	-6.00 ± 2.26	-1.56 ± 2.01	[-3.54, 0.42]	0.122

64 Notes: All trends are in Gt yr⁻¹, and uncertainties are 2σ. The without index trend is estimated using the same AR(1) covariance weighting as the full climate-index model,
65 allowing an internally consistent decomposition. The residual trend is the linear trend estimated after including NAO_Σ and PDO_Σ in the regression. The combined climate-
66 associated trend is the sum of the NAO_Σ- and PDO_Σ-associated contributions and is equal, to numerical precision, to the difference between the no-index and residual trends.
67 The 95% confidence interval and P value refer to the combined climate-associated trend contribution.

68 **Table S10. Effect of detrending the cumulative climate indices on fitted regression coefficients.**

RGI regions	$\beta_{\text{NAO}\Sigma}$	$\beta_{\text{NAO}\Sigma, \text{detrended}}$	$\Delta\beta_{\text{NAO}\Sigma}$	$\beta_{\text{PDO}\Sigma}$	$\beta_{\text{PDO}\Sigma, \text{detrended}}$	$\Delta\beta_{\text{PDO}\Sigma}$
Alaska (ALA)	-4.37 ± 33.53	-4.37 ± 33.53	5.3×10^{-13}	-154.44 ± 99.12	-154.44 ± 99.12	-2.8×10^{-13}
Arctic Canada North (ACN)	17.84 ± 17.57	17.84 ± 17.57	2.2×10^{-13}	44.83 ± 50.98	44.83 ± 50.98	-1.8×10^{-12}
Arctic Canada South (ACS)	5.10 ± 14.25	5.10 ± 14.25	1.9×10^{-13}	11.92 ± 38.33	11.92 ± 38.33	2.2×10^{-13}
Iceland (ICE)	11.95 ± 4.24	11.95 ± 4.24	-2.1×10^{-14}	-2.45 ± 9.78	-2.45 ± 9.78	-5.1×10^{-14}
Svalbard (SVA)	-37.75 ± 15.37	-37.75 ± 15.37	-9.2×10^{-14}	42.80 ± 41.31	42.80 ± 41.31	3.6×10^{-13}
Scandinavia (SCA)	-0.50 ± 2.98	-0.50 ± 2.98	3.3×10^{-15}	-1.79 ± 6.85	-1.79 ± 6.85	5.8×10^{-15}
Russian Arctic (RA)	-37.01 ± 6.61	-37.01 ± 6.61	1.4×10^{-14}	40.33 ± 15.22	40.33 ± 15.22	7.0×10^{-13}

69 Note: Values are regression coefficients $\pm 2\sigma$. $\Delta\beta$ denotes the difference between the coefficients obtained using the detrended and original cumulative indices.

Q3: The manuscript does not yet provide a sufficiently clear explanation of why NAO and PDO would affect the estimated long-term glacier mass-change trends. Is there an identifiable physical mechanism through which persistent phases or low-frequency variability of these climate modes project onto the finite GRACE/GRACE-FO observation period and thereby lead to an underestimation or overestimation of the long-term trend? A more explicit physical interpretation is needed to distinguish genuine climate-driven long-term changes from trend biases caused by decadal variability over a relatively short observational record.

R3: We thank the reviewer for raising this point. We agree that the physical link between persistent climate variability and finite-period trend estimates required a clearer explanation. We have revised Sects. 4.2 and 4.3 to make the physical and statistical interpretation clearer. The revised discussion links NAO/PDO-related circulation variability to glacier mass change through seasonal surface-mass-balance pathways affecting winter accumulation and summer melt. Persistent phases of these modes can therefore produce multi-year mass anomalies which, because GRACE/GRACE-FO observes cumulative mass change over only about two decades, can influence the fitted linear trend. In the regression, this effect is represented by trends in NAO_{Σ} and PDO_{Σ} , whose contributions to regional mass-change trends depend on the fitted regional response. We also clarify that the remaining linear trend is not interpreted as a uniquely externally forced trend, since other multi-year to decadal variability may remain.

Q4: I recommend comparing the corrected long-term trends with independent external observations, such as satellite altimetry or other available glacier mass-balance products. Such a comparison would provide an important validation of the proposed correction and help demonstrate whether accounting for the climate modes actually improves the trend estimates.

R4: We thank the reviewer for this suggestion. We have added an independent comparison using regional glacier mass-change estimates from CryoSat-2 swath altimetry and DEM-based geodetic observations. For each dataset, we compared the external estimate with both the unadjusted GRACE trend and the residual GRACE trend after accounting for the NAO_{Σ} - and PDO_{Σ} -related components over identical common observation periods. These comparisons are now presented in Sect. 3.5, and shown in the new Supplementary Figs. S22 and S23 and Tables S11 and S12.

The comparison shows that the unadjusted GRACE trends are generally close to the independent estimates, whereas accounting for the climate-related components changes the agreement in a region-dependent manner. Agreement with CryoSat-2 improves in Arctic Canada North and Svalbard, but not in the other available regions, and there is no systematic improvement relative to the DEM-based estimates. We therefore do not interpret removal of the fitted climate-related components as a correction that should necessarily improve agreement with contemporaneous observations. Rather, the resulting residual trend represents the linear component remaining after the fitted NAO/PDO-related variability has been separated. We have clarified this distinction in Sect. 4.3.

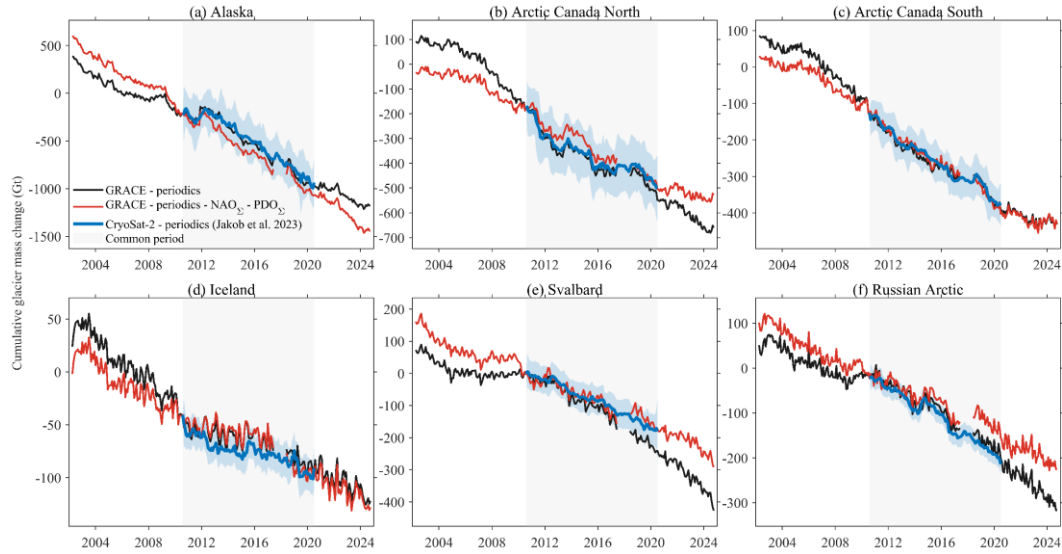


Figure S22: Comparison of original GRACE/GRACE-FO glacier mass change, GRACE/GRACE-FO after removal of the fitted NAO_{Σ} - and PDO_{Σ} -related components, and CryoSat-2 altimetry estimates (Jakob and Gourmelen, 2023) for six Arctic regions. Black and red lines show the original GRACE/GRACE-FO series and the series after removal of the fitted NAO_{Σ} - and PDO_{Σ} -related components, respectively; blue lines show CryoSat-2 estimates. Annual and semiannual signals were removed from all series, with trends and interannual variability retained. CryoSat-2 shading denotes the 95% confidence interval. The CryoSat-2 series and the GRACE/GRACE-FO series after removal of the fitted NAO_{Σ} - and PDO_{Σ} -related components were aligned to the original GRACE/GRACE-FO series at the first valid CryoSat-2 month. Grey shading indicates the common observation period.

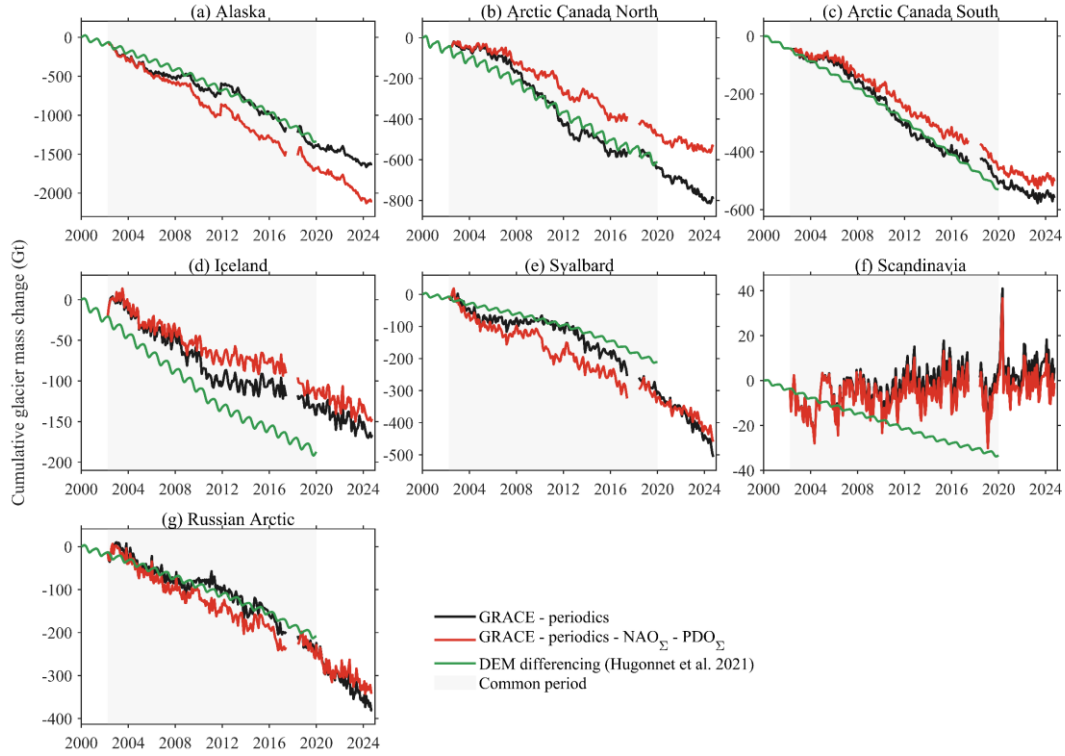


Figure S23: Comparison of original GRACE/GRACE-FO glacier mass change, GRACE/GRACE-FO after removal of the fitted NAO_{Σ} - and PDO_{Σ} -related components, and DEM-differencing estimates (Hugonnet et al., 2021) across seven Arctic regions. Black and red lines show the original GRACE/GRACE-FO series and the series after removal of the fitted NAO_{Σ} - and PDO_{Σ} -related components, respectively; green lines show DEM-differencing estimates for Alaska, Arctic Canada North, Arctic Canada South, Iceland, Svalbard, Scandinavia and the Russian Arctic. Annual and semiannual harmonic terms were removed from both GRACE/GRACE-FO series, while the DEM-differencing series were used directly. For comparison of relative mass changes, both GRACE/GRACE-FO series were vertically aligned to the DEM-differencing estimate at April 2002, whereas the DEM series retained its original reference level. Green shading denotes the supplied 95% confidence interval, and grey shading indicates the common GRACE/GRACE-FO–DEM observation period.

127 **Table S11. Comparison of regional glacier mass-change trends from GRACE and CryoSat-2 over their common observation period.**

RGI regions	Trend_GRACE (Gt yr ⁻¹)	GRACE trend after accounting for NAO _Σ and PDO _Σ (Gt yr ⁻¹)	Trend_CryoSat-2 (Gt yr ⁻¹)	Trend difference: GRACE vs. CryoSat-2 (Gt yr ⁻¹)	Trend difference: GRACE after accounting for NAO _Σ and PDO _Σ vs. CryoSat-2 (Gt yr ⁻¹)
Alaska (ALA)	-82.89 ± 15.71	-87.43 ± 11.38	-82.71 ± 12.39	0.18	4.72
Arctic Canada North (ACN)	-32.12 ± 8.25	-29.79 ± 5.27	-29.03 ± 8.18	3.09	0.75
Arctic Canada South (ACS)	-22.99 ± 2.79	-24.79 ± 1.83	-23.33 ± 3.10	0.34	1.46
Iceland (ICE)	-3.86 ± 1.01	-5.12 ± 1.33	-3.92 ± 0.88	0.06	1.20
Svalbard (SVA)	-24.36 ± 1.79	-16.16 ± 2.98	-18.43 ± 1.48	5.93	2.27
Russian Arctic (RA)	-17.78 ± 1.43	-12.37 ± 2.03	-18.87 ± 2.49	1.09	6.50

128 Note: Trends are estimated over August 2010–July 2020 using an AR(1)-GLS model that accounts for temporal correlation in the residuals. The GRACE trends after accounting
129 for NAO_Σ and PDO_Σ are estimated after removing the fitted NAO_Σ- and PDO_Σ-related components from the GRACE/GRACE-FO time series. Annual and semiannual
130 signals are removed from the GRACE and CryoSat-2 (Jakob and Gourmelen, 2023) time series before trend estimation. Uncertainties are reported as ±2σ. Trend differences
131 are absolute differences relative to the CryoSat-2 estimate and are given in Gt yr⁻¹. Scandinavia is not included because no CryoSat-2 regional estimate is available.

132 **Table S12. Comparison of regional glacier mass-change trends from GRACE and DEM-differencing estimates over their common observation period.**

RGI regions	Trend_GRACE (Gt yr ⁻¹)	GRACE trend after accounting for NAO _Σ and PDO _Σ (Gt yr ⁻¹)	Trend_DEM- differencing (Gt yr ⁻¹)	Trend difference: GRACE vs. DEM (Gt yr ⁻¹)	Trend difference: GRACE after accounting for NAO _Σ and PDO _Σ vs. DEM (Gt yr ⁻¹)
Alaska (ALA)	-68.85 ± 10.89	-87.65 ± 4.73	-69.94 ± 5.47	1.09	17.71
Arctic Canada North (ACN)	-36.61 ± 6.39	-26.62 ± 2.49	-32.68 ± 1.77	3.93	6.06
Arctic Canada South (ACS)	-27.18 ± 2.33	-23.48 ± 1.40	-27.42 ± 1.15	0.23	3.93
Iceland (ICE)	-7.47 ± 0.96	-5.93 ± 0.58	-9.29 ± 0.93	1.82	3.37
Svalbard (SVA)	-14.86 ± 3.35	-16.59 ± 1.58	-11.23 ± 1.63	3.64	5.36
Scandinavia (SCA)	+0.66 ± 0.37	+0.33 ± 0.36	-1.65 ± 0.07	2.31	1.98
Russian Arctic (RA)	-12.27 ± 1.17	-13.19 ± 0.82	-10.77 ± 0.69	1.50	2.42

133 Note: Trends are estimated over April 2002–January 2020 using an AR(1)-GLS model that accounts for temporal correlation in the residuals. The GRACE trends after
134 accounting for NAO_Σ and PDO_Σ are estimated after removing the fitted NAO_Σ- and PDO_Σ-related components from the GRACE/GRACE-FO time series. Annual and
135 semiannual signals are removed from the GRACE time series before trend estimation, whereas the DEM-differencing (Hugonnet et al., 2021) series are used directly.
136 Uncertainties are reported as ±2σ. Trend differences are absolute differences relative to the DEM-differencing estimate and are given in Gt yr⁻¹.

Minor comments:

Q5: For the “Spatial patterns” shown in Figures 1 and 2, please specify clearly whether they represent a particular time/epoch or a spatial pattern derived from or averaged over the entire study period.

R5: Clarified. The spatial patterns in Figs. 1 and 2 do not represent a particular epoch or a temporal average. They are time-invariant spatial loading patterns derived from the ICA decomposition of the full 2002–2024 detrended GRACE/GRACE-FO record, while their temporal evolution is represented by the corresponding ICs. We have clarified this in Sect. 3.1 and in the figure captions and now refer to them as “spatial loading patterns”.

Q6: The manuscript should be carefully checked for subject–verb agreement, wording, and terminology consistency. For example, in Section 4.1, “sustained meridional circulation are” should be changed to “sustained meridional circulation is,” or the subject should be rewritten in the plural. In addition, terms such as “Arctic ice mass variability” and “Arctic glacier mass variability” should be used consistently throughout the manuscript.

R6: Agreed. We carefully checked the manuscript for subject–verb agreement, wording and terminology consistency. The grammatical error in Sect. 4.1 has been corrected from “sustained meridional circulation are” to “sustained meridional circulation is”. We also standardised terminology throughout the manuscript, including the use of “Arctic glacier mass variability”, the warm- and cold-season mass-balance contributions, and the ICA spatial-loading terminology.

Q7: The upper and/or lower limits of the summation in Equation (1) appear to be written incorrectly. Please check and correct them.

R7: Corrected. The upper limit of the summation in Eq. (1) was written incorrectly. We have corrected it from k to 2, corresponding to the annual ($k = 1$) and semiannual ($k = 2$) harmonic terms.