

Response to Reviewer 2

General comments: The authors perform an Independent Component Analysis (ICA) to global GIC mass estimates from the GRACE and GRACE-FO satellite gravimetry missions over 2002–2024 in order to explain variability in ice mass associated with NAO and PDO. They present spatio-temporal variability across varying scales and further strengthen their arguments with regression analyses of atmospheric variables. Multiple regression highlights how accounting for NAO- and PDO-related variability impacts the estimated trend of gravimetric-derived mass estimates up to quarter/third of their magnitude.

This study contributes to the understanding of the impact of large-scale and regional climate variability on gravimetric estimates of GICs, focusing on the Arctic. They present their methods and results in a concise way. The manuscript is a good read and shows a mature stage. I have three significant concerns that should be addressed in the revision.

Response: We thank the reviewer for the positive assessment of our study and for the constructive comments. We have addressed the three main concerns point by point and revised the manuscript accordingly, with particular attention to the interpretation of the NAO- and PDO-related variability, its influence on trend estimates, and the implications for future Arctic glacier mass change. The specific revisions are described in our responses below and highlighted in the revised manuscript.

Q1: Most regression analysis in this study rely solely on direction and strength. The statistical metrics need to include significance testing.

R1: We thank the reviewer for highlighting this important issue. We have added statistical significance testing to the regression analyses throughout the revised analysis. For the regional $NAO_{\Sigma} - PDO_{\Sigma}$ regression, coefficient uncertainties and significance are now evaluated using the AR(1)-GLS covariance, with two-sided tests for the individual climate-index coefficients and a joint test of the null hypothesis that both coefficients are zero (Sect. 2.8; Table S6). We additionally test the significance of the combined climate-associated trend contribution (Table S7). For the time-differenced sensitivity analysis, significance is evaluated using a heteroskedasticity- and autocorrelation-consistent covariance matrix (Sect. 2.9; Fig. S17; Table S9). The corresponding p values are now reported alongside the regression and partial-variance results in Sects. 3.4 and 3.5.

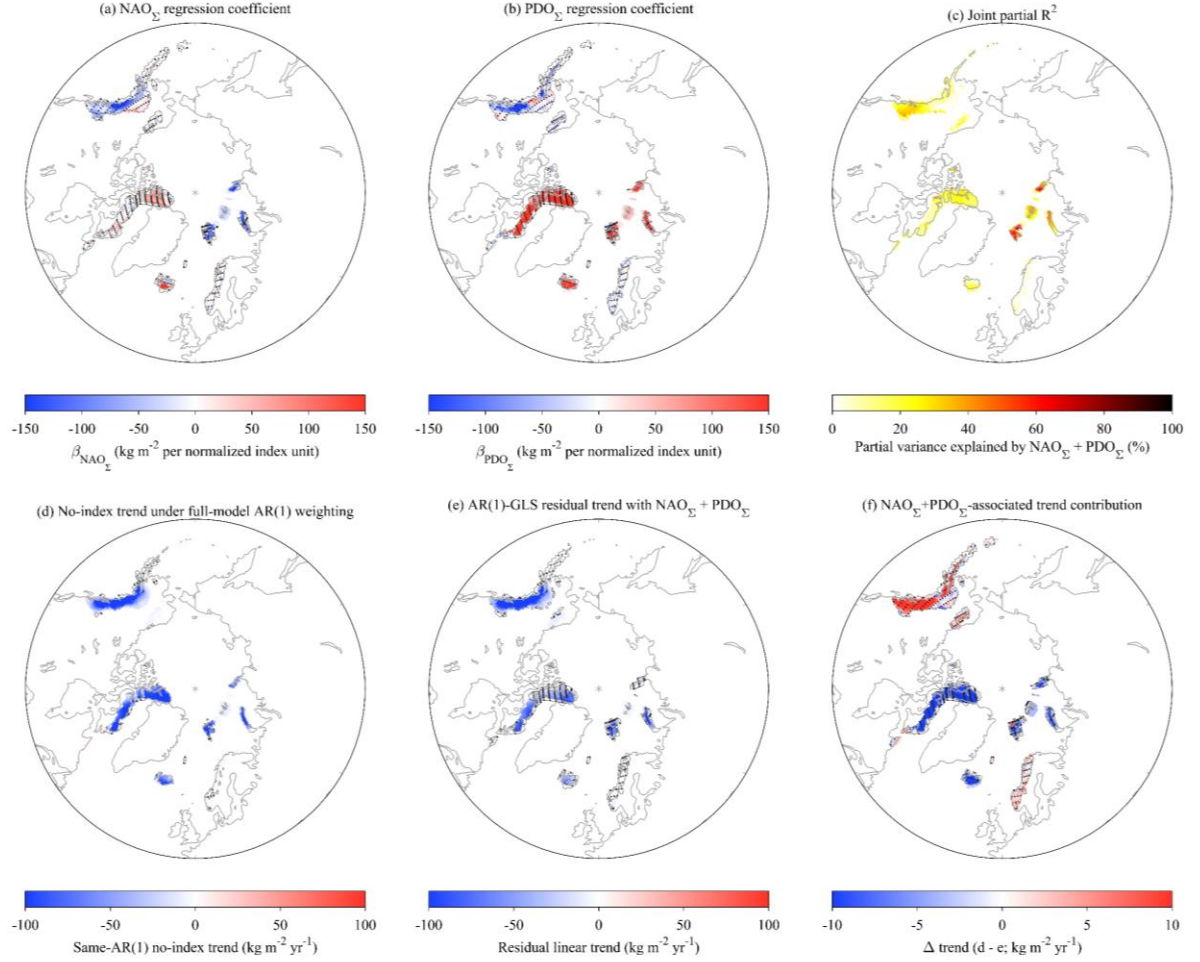


Figure 4: Results of multivariate regression. a,b, Climate-index regression coefficients for NAO_{Σ} (a) and PDO_{Σ} (b). c, Percentage of the joint partial variance explained by the NAO_{Σ} and PDO_{Σ} terms. d–f, Linear trends from regressions without (d) and with (e) the climate indices, and their 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.

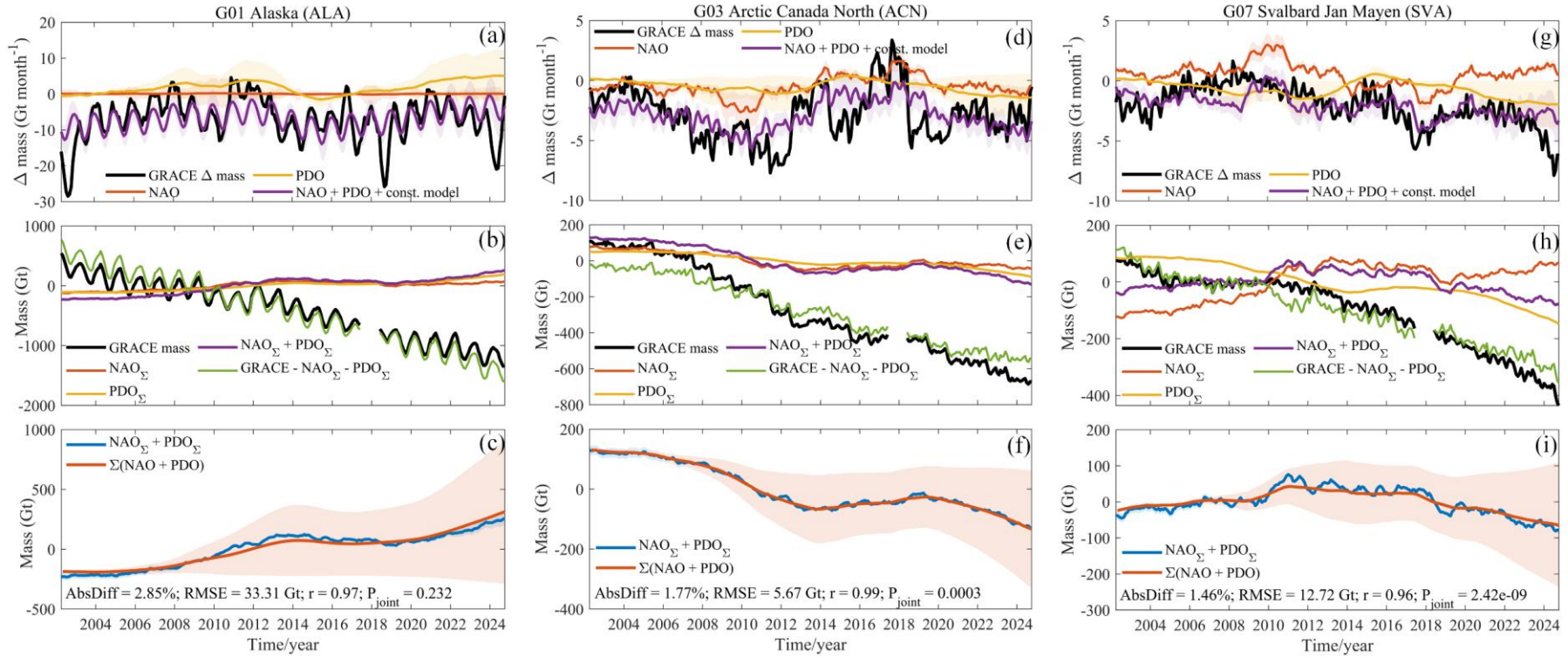


Figure S17: Results of multivariate regression using time-differenced GRACE/GRACE-FO mass anomalies for Alaska (a–c), Arctic Canada North (d–f) and Svalbard (g–i). Panels a, d and g show the time-differenced GRACE/GRACE-FO data together with the fitted NAO and PDO components and the full model. Panels b, e and h show the undifferenced GRACE/GRACE-FO mass anomalies and the corresponding NAO_Σ and PDO_Σ components. Panels c, f and i compare the time-integrated NAO+PDO component from the differenced regression with the $\text{NAO}_\Sigma + \text{PDO}_\Sigma$ component estimated from the undifferenced regression. A 25-month running mean is used in all three regions. AbsDiff, RMSE and r quantify the agreement between the two formulations, and P_{joint} gives the joint significance of the NAO and PDO terms in the differenced regression.

45 **Table S6. Regional associations between cumulative climate indices and glacier mass change.**

RGI regions	ϕ_{AR1}	$\beta_{NAO_{\Sigma}}$	$P_{NAO_{\Sigma}}$	$\beta_{PDO_{\Sigma}}$	$P_{PDO_{\Sigma}}$	$P_{NAO_{\Sigma}+PDO_{\Sigma}}$	R^2_{partial} (%)
Alaska (ALA)	0.922	-4.37 ± 33.53	0.795	-154.44 ± 99.12	0.002	0.006	57.0
Arctic Canada North (ACN)	0.917	17.84 ± 17.57	0.043	44.83 ± 50.98	0.080	0.012	61.4
Arctic Canada South (ACS)	0.893	5.10 ± 14.25	0.475	11.92 ± 38.33	0.535	0.548	42.7
Iceland (ICE)	0.635	11.95 ± 4.24	<0.001	-2.45 ± 9.78	0.617	<0.001	43.1
Svalbard (SVA)	0.893	-37.75 ± 15.37	<0.001	42.80 ± 41.31	0.039	<0.001	76.8
Scandinavia (SCA)	0.503	-0.50 ± 2.98	0.736	-1.79 ± 6.85	0.602	0.695	1.2
Russian Arctic (RA)	0.553	-37.01 ± 6.61	<0.001	40.33 ± 15.22	<0.001	<0.001	64.8

46 Notes: Regression coefficients are estimated from the full multivariate model including a linear trend, annual and semiannual terms, and the cumulative NAO and PDO indices.
47 Uncertainties are 2σ from the AR(1)-GLS covariance matrix. $P_{NAO_{\Sigma}}$ and $P_{PDO_{\Sigma}}$ are two-sided tests of the individual regression coefficients. $P_{NAO_{\Sigma}+PDO_{\Sigma}}$ tests the null
48 hypothesis that both climate-index coefficients are zero. R^2_{partial} quantifies the additional variance explained jointly by NAO_{Σ} and PDO_{Σ} relative to the model without climate
49 indices.

50 **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)	<i>P</i> _{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

51 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,
52 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-
53 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.
54 The 95% confidence interval and *P* value refer to the combined climate-associated trend contribution.

55 **Table S9. Sensitivity of the time-differenced regression to smoothing-window choice across Arctic glacier regions**

RGI regions	Selected window (months)	AbsDiff_pct (%)	RMSE (Gt)	r	P_{NAO}	P_{PDO}	P_{joint}
Alaska (ALA)	25	2.85	33.31	0.97	0.913	0.162	0.232
Arctic Canada North (ACN)	25	1.77	5.67	0.99	<0.001	0.157	<0.001
Arctic Canada South (ACS)	43	1.85	7.47	0.95	0.269	0.929	0.354
Iceland (ICE)	13	3.70	8.86	0.44	0.799	0.410	0.712
Svalbard (SVA)	25	1.46	12.72	0.96	<0.001	0.050	<0.001
Scandinavia (SCA)	13	142.06	3.26	0.98	0.645	0.922	0.899
Russian Arctic (RA)	31	33.28	7.85	0.94	<0.001	<0.001	<0.001

56 Note: For each region, the preferred running-mean window was selected from 13, 25, 31, 37, 43 and 55 months as that minimizing the absolute difference in cumulative climate-
57 related mass change relative to the corresponding undifferenced regression solution. AbsDiff is the absolute percentage difference in cumulative climate-related mass change
58 between the two formulations; RMSE and r are the root-mean-square difference and Pearson correlation, respectively, between their reconstructed climate-related components.
59 P_{NAO} and P_{PDO} test the individual coefficients of the raw monthly NAO and PDO indices, and P_{joint} tests the null hypothesis that both coefficients are zero. P values were
60 calculated using a heteroskedasticity- and autocorrelation-consistent (HAC) covariance matrix to account for temporal dependence introduced by smoothing. Significance was
61 not used to select the preferred smoothing window.

Q2: I'd like to see how eventually the estimated ice mass variability and associated trends that are attributed to NAO- and PDO-related variability compares to other regional ice mass estimates across the Arctic (i.e. stemming from geodetic methods, such as shown in Fig. S2).

R2: We thank the reviewer for this suggestion. We have added comparisons with two independent regional glacier mass-change datasets: CryoSat-2 swath altimetry and DEM-based geodetic estimates. The new Supplementary Figs. S22 and S23 compare the temporal evolution of the unadjusted GRACE mass-change series and the residual series after accounting for NAO_Σ- and PDO_Σ-related variability with the independent estimates over their respective common observation periods. We also quantify the corresponding regional trends and their differences in Supplementary Tables S11 and S12.

The comparisons show generally close agreement between the unadjusted GRACE trends and the independent regional estimates, while separating the fitted NAO/PDO-related variability changes the inferred trends in a region-dependent manner and does not systematically improve contemporaneous agreement. These results and their interpretation have been added to Sects. 3.5 and 4.3.

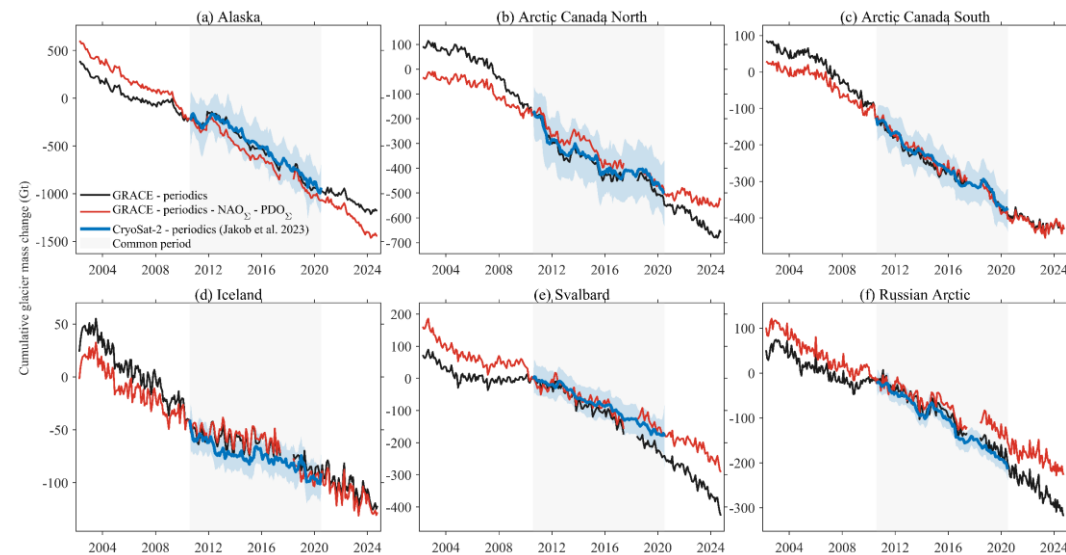


Figure S22: Comparison of original GRACE/GRACE-FO glacier mass change, GRACE/GRACE-FO after removal of the fitted NAO_Σ- and PDO_Σ-related components, and CryoSat-2 altimetry estimates (Jakob and Gourmelen, 2023) for six Arctic regions. Black and red lines show the original GRACE/GRACE-FO series and 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.

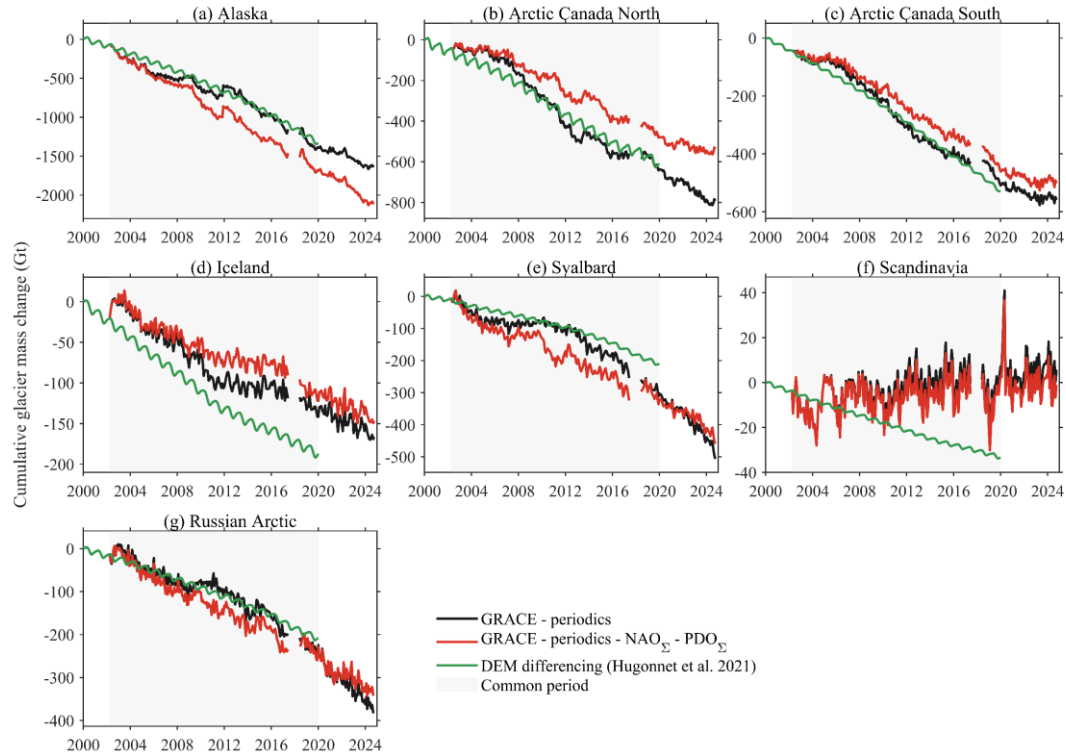


Figure S23: Comparison of original GRACE/GRACE-FO glacier mass change, GRACE/GRACE-FO after removal of the fitted NAO_{Σ} - and PDO_{Σ} -related components, and DEM-differencing estimates (Hugonnet et al., 2021) across seven Arctic regions. Black and red lines show the original GRACE/GRACE-FO series 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.

97 **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

98 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
99 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
100 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
101 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.

102 **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

103 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
104 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
105 semiannual signals are removed from the GRACE time series before trend estimation, whereas the DEM-differencing (Hugonnet et al., 2021) series are used directly.
106 Uncertainties are reported as ±2σ. Trend differences are absolute differences relative to the DEM-differencing estimate and are given in Gt yr⁻¹.

Q3: You discussed long-term trends and variability of NAO and PDO over the last decades. Given that you found how NAO and PDO explain variability in mass estimates and impact mass loss trends, please add a section in the discussion section that addresses future projections and trajectories of NAO and PDO variability and anomalies and mass trends in the Arctic.

R3: We thank the reviewer for this suggestion. We have added a new Discussion subsection (Sect. 4.4) on the future evolution of the NAO and PDO and the implications for Arctic glacier mass change. We discuss the uncertainty in future NAO and PDO variability and place these changes within the context of continued warming-driven glacier loss. We also clarify that the relationships identified over 2002–2024 should not be extrapolated deterministically; if they persist, future climate-mode variability may modulate regional mass-loss rates and decadal departures from the long-term warming-driven trajectory.

Specific comments:

Q4: L99-100: “We compared the GRACE-derived mass trends for the seven Arctic glacier regions with previously published regional estimates from earlier studies.” Needs a reference to Fig. S1.

R4: Corrected. We have added the relevant figure references to this sentence. Following the revised Supplementary figure numbering, the sentence now reads:

“We compared the GRACE-derived mass trends for the seven Arctic glacier regions with previously published regional estimates from earlier studies (Figs. S1 and S2). The results show that our regional Arctic glacier mass-change estimates are consistent with the existing literature.”

Q5: L174-184: List in this paragraph which atmospheric variables you did assess and justify your choice. Did you also include or tested separately for March-May (MAM) and September-November (SON)? If not, justify.

R5: Agreed. We have added the atmospheric variables assessed and their physical rationale in Sect. 2.6, and clarified the use of JJA and DJF as representative core atmospheric windows. We did not analyse MAM and SON separately. Our aim was not to perform an exhaustive four-season attribution, but to diagnose the characteristic atmospheric conditions of the core ablation and accumulation seasons within the broader March–September and September–March mass-balance partitions. Transitional months are therefore already included in these broader seasonal intervals.

Q6: L294-296: The abbreviations for the regions must appear way earlier in the script as those are used throughout all Figures of the Supplementary and are referred to already in the Methods section.

R6: Agreed. We have moved the definitions of all seven Arctic region abbreviations to Sect. 2.1, where they are now introduced when the study regions are first described. The abbreviations are then used consistently throughout the Methods, Results and Supplementary figures.

Q7: L303-310: Here and throughout to study, I am missing an assessment of statistical significance. The statistical metrics shown solely rely on strength and direction.

R7: Agreed. We have added significance estimates to the ICA–climate-index correlations. The

correlation between Arctic IC1 and NAO_{Σ} is $r = -0.84$ with Monte Carlo $p = 0.004$, and that between Arctic IC2 and PDO_{Σ} is $r = 0.85$ with $p < 0.001$ (Sect. 3.1; Table S2). Significance testing has also been added to the subsequent regression analyses as described in Sects. 2.8–2.10.

Q8: L310: Color scale misses label. Also, uses cmw.e. while other part of the manuscript uses cm EWH. I'd recommend sticking to one of the SI units.

R8: Agreed. We have added labels to the colour bars in Fig. 1a,b and revised the terminology to identify these quantities as Scaled spatial response. Because the ICA loadings are scaled by their maximum absolute value, they are dimensionless. The mass-change quantities elsewhere retain their appropriate physical units.

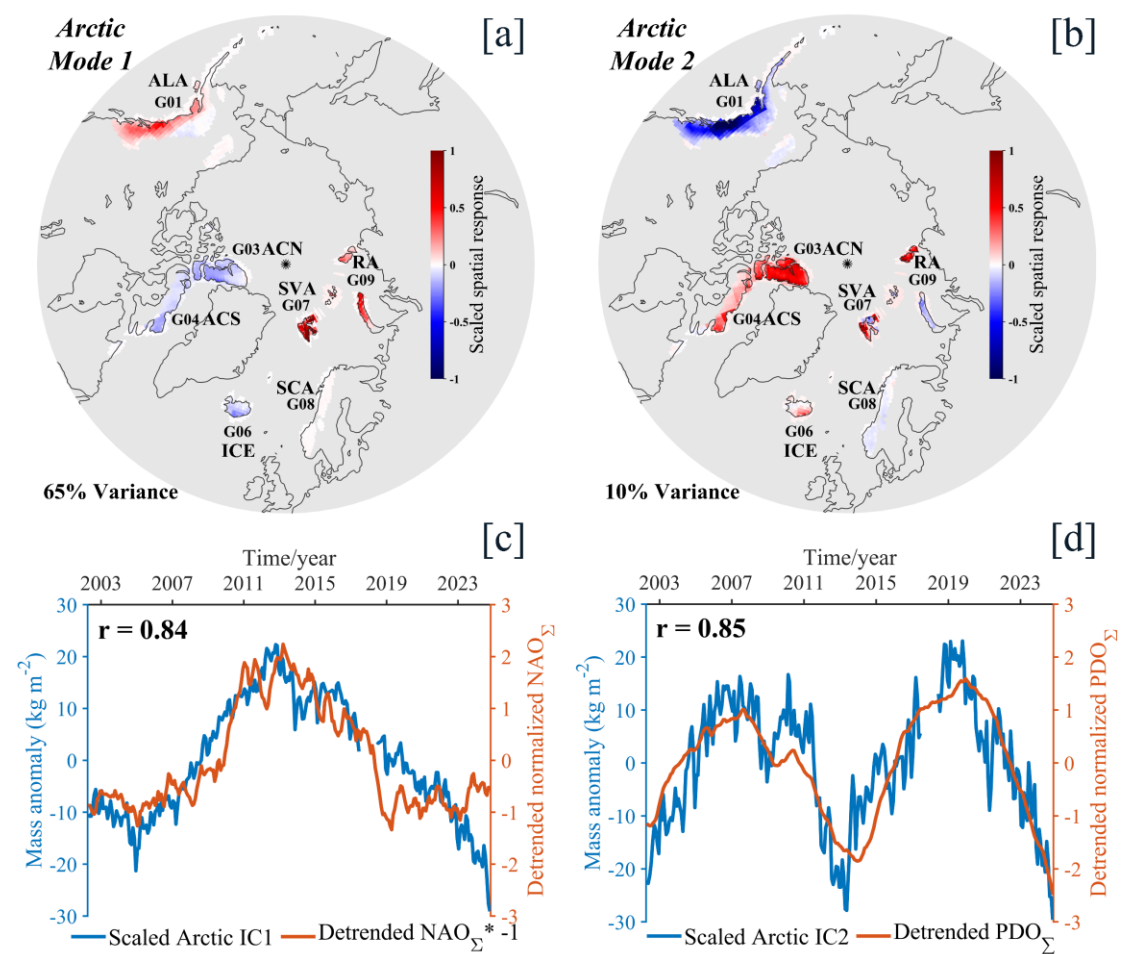


Figure 1: Leading independent modes of Arctic glacier mass variability. a, b, Time-invariant spatial loading patterns of the first two ICA modes (Arctic Mode 1 and Arctic Mode 2), derived from the full 2002-2024 detrended GRACE/GRACE-FO mass anomaly time series for Arctic GICs across seven regions, explaining 65% (a, c) and 10% (b, d) of the interannual variance, respectively. c, d, Corresponding independent components IC1 and IC2 (blue) shown together with the detrended NAO_{Σ} (c) and PDO_{Σ} (d) indices (orange). All time series are normalised over 2002–2024. The secondary modes are presented in Fig. S15.

Q9: L315-316: This paragraph needs to be moved to Section 3.2 and needs to refer to Fig. 2,3. The regional co-variation is only discussed later, and the argument is not sufficiently supported here when referring to Fig. 1a,b.

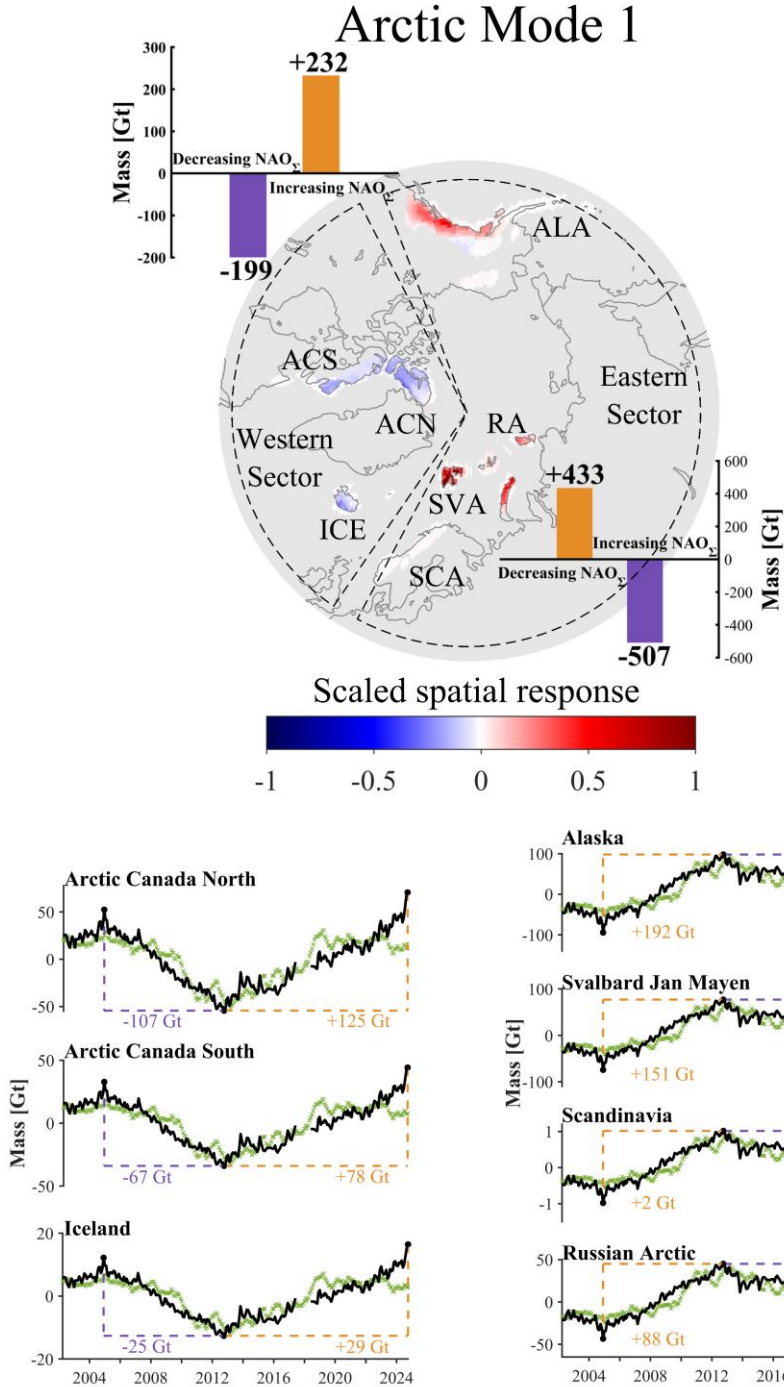
R9: Agreed. We removed the regional co-variation paragraph from Sect. 3.1 and incorporated the Mode 1 and Mode 2 descriptions into Sects. 3.2 and 3.3, respectively, where they are now directly supported by Figs. 2 and 3. Sect. 3.2 now describes the Mode 1 co-variation of ACN, ACS and ICE versus ALA, SVA, SCA and RA, while Sect. 3.3 describes the different Mode 2 grouping of ACN, ACS, ICE, SVA and RA versus ALA and SCA.

Q10: L325-345: Color scales miss labels and bars need a different color signature as they do not relate to the continuous color scale of the map plot. In that sense, consider also using a positive and negative y-axis for Mass to avoid ambiguity. Also, the smoothing of the interannual mass anomaly variation appears here for the first time – this should already be included in the Methods section. Lowest and highest values indicating to maximum mass differences before and after 2012 should refer to the actual mass values and not the smoothed curve. Vertically dashed lines for the blue color must have same color as the font. Here too, consider moving away from the red/blue color coding to avoid ambiguity with the map plot color scale.

R10: We thank the reviewer for these suggestions. We revised Figs. 2 and 3 to improve the distinction between the spatial loading maps and the regional mass-anomaly diagnostics. We added labels to the colour scales of the spatial loading patterns and changed the bar colours from red/blue to purple/yellow, with positive and negative cumulative mass anomalies plotted on positive and negative y-axes, respectively. We also revised the colours of the corresponding dashed markers so that they are distinct from the red/blue map colour scale and consistent with the associated labels.

We removed the Hodrick–Prescott smoothing from the regional mass-anomaly time series, so no additional smoothing method is now required in the Methods section. The maximum mass differences are now defined directly from the unsmoothed reconstructed mass values rather than from a smoothed curve. The captions of Figs. 2 and 3 have been revised accordingly.

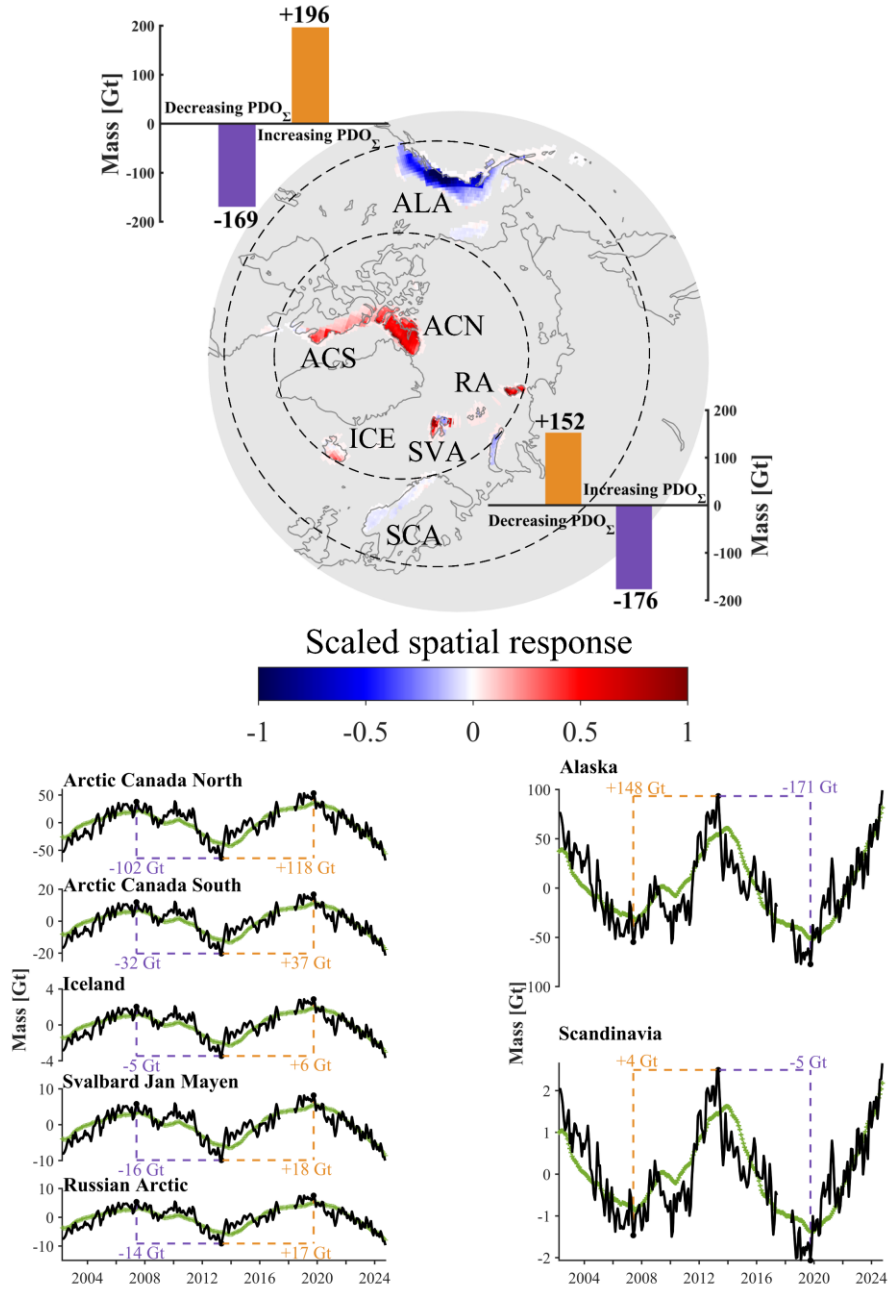
The revised figures are shown below:



188

189 Figure 2: Spatial loading pattern of Arctic Mode 1. The spatial loadings are derived from the ICA
 190 decomposition of the full 2002–2024 detrended GRACE/GRACE-FO record and are fixed in time. The
 191 Arctic glacier regions are grouped into a Western Sector (G03, G04, G06) and an Eastern Sector (G01,
 192 G07, G08, G09) according to the NAO-related mode. Bar plots show the summed positive and negative
 193 interannual mass anomalies in each sector during intervals of increasing and decreasing NAO_{Σ} . The
 194 lower panels illustrate interannual mass anomaly variations for selected regions, with the left subpanels
 195 representing the Western Sector and the right subpanels representing the Eastern Sector. The black curves
 196 denote the reconstructed regional mass variations associated with Arctic Mode1, calculated from Eq. (4).
 197 The purple and yellow dashed lines indicate the maximum mass differences before and after 2013,
 198 referenced to the lowest (left) or highest (right) values within the study period. The green crosses denote
 199 the fitted NAO_{Σ} contribution from the regional regression model.

Arctic Mode 2



200

201 Figure 3: Spatial loading pattern of Arctic Mode 2. The spatial loadings are derived from the ICA
 202 decomposition of the full 2002–2024 detrended GRACE/GRACE-FO record and are fixed in time. Based
 203 on the regionally averaged Mode 2 response, ACN (G03), ACS (G04), ICE (G06), SVA (G07) and RA
 204 (G09) form a central Arctic group, whereas ALA (G01) and SCA (G08) form a peripheral group. Bar
 205 plots show the summed positive and negative interannual mass anomalies in the two groups during
 206 intervals of increasing and decreasing PDO_Σ anomalies. The lower panels show reconstructed regional
 207 mass variations associated with Arctic Mode 2, with the peripheral-group regions displayed on the left
 208 and the central-Arctic-group regions on the right. The black curves represent the reconstructed regional
 209 mass variations associated with Arctic Mode 2, calculated from Eq. (4). The purple and yellow dashed
 210 lines mark the maximum mass differences before and after 2013, referenced to the highest (right) or
 211 lowest (left) values over the study period. The green crosses denote the fitted PDO_Σ contribution from
 212 the regional regression model.

Q11: L346-347: in the map plot in Fig. 3 it looks like some regions (i.e. ICE) are divided between the two zones. Please elaborate or justify.

R11: We agree that this required clarification. The apparent division of Iceland in the original Fig. 3 resulted from the schematic guides used to illustrate the Mode 2 spatial organization; these were not used to define the regional grouping. The classification is based on the sign of the regionally averaged Mode 2 contribution. ACN, ACS, ICE, SVA and RA therefore form the central Arctic group, whereas ALA and SCA form the peripheral group. Local spatial loadings can vary within an individual glacier region, which explains the apparent within-region heterogeneity. We have revised Fig. 3 and clarified this regional-mean classification in Sect. 3.3.

Q12: L362-363: To support the statistical measure of partial variance, the significance must also be assessed.

R12: Agreed. We now assess the statistical support for the partial-variance estimates using the corresponding multivariate-regression significance tests. Individual NAO_{Σ} and PDO_{Σ} coefficients are tested separately, and a joint test evaluates the null hypothesis that both climate-index coefficients are zero (Sect. 2.10; Table S6). The revised Sect. 3.4 now reports these significance levels alongside the partial R^2 values.

Q13: L369: Has the significance been tested for the conclusion about Scandinavia? If so, please state the significance/confidence level. What would be the argument then that the shape of the mass variability of SCA shown in Fig. 3 is so similar to ALA if insignificant? Please elaborate and justify.

R13: We thank the reviewer for raising this point. We have now explicitly tested the regional significance of the NAO_{Σ} and PDO_{Σ} terms. For Scandinavia, the PDO_{Σ} coefficient is not significant ($\beta_{PDO_{\Sigma}} = -1.79 \pm 6.85$), $p = 0.602$; the joint $NAO_{\Sigma} + PDO_{\Sigma}$ test is also not significant ($p = 0.695$), and the two climate terms explain only 1.2% of the additional variance (Table S6, see Comment Major 1).

We have also clarified why the temporal form of the Scandinavia and Alaska Mode 2 reconstructions can appear similar despite the lack of a significant regional PDO_{Σ} association in Scandinavia. Both regional reconstructions are projections of the same Arctic IC2 through same-sign Mode 2 loadings, so they inherit a similar temporal shape. However, the Mode 2 loading over Scandinavia is much weaker, giving a much smaller reconstructed amplitude and therefore not implying a significant regional PDO_{Σ} response. This clarification has been added to Sect. 3.3.

The revised text states: “*The Mode 2 loading over SCA is weak, and its independent association with PDO_{Σ} is not significant ($p = 0.602$; Table S6). The similar temporal form of the SCA and ALA reconstructions reflects their projection of the same Arctic IC2 through same-sign loadings, but the much smaller SCA amplitude does not indicate a significant regional PDO_{Σ} response.*”

Q14: L370-393: Can you explain why for Svalbard and the Russian Arctic the GRACE-periodics overestimate mass change throughout mid/late-2000ish to late-2010ish and then underestimate mass change since the early-2020s when compared to the GRACE-periodics-NAO-PDO (Fig. 4)? Different

reference periods show the same trend even stronger (Fig. S22 g,i). Please elaborate and discuss.

R14: We thank the reviewer for raising this point. We have clarified this behaviour in Sect. 3.5. In both Svalbard and the Russian Arctic, the fitted NAO_{Σ} coefficients are negative whereas the PDO_{Σ} coefficients are positive. Because the two cumulative indices evolve differently through time, their opposing contributions combine to produce a non-linear, multi-year climate-related component. This causes the fit without the climate-index terms to lie above the full regression through much of the mid/late-2000s to late-2010s, but below it from the early 2020s (Fig. 5e, g). The two climate terms are jointly significant in both regions and explain 76.8% and 64.8% of the additional variance in Svalbard and the Russian Arctic, respectively. We also tested alternative reference periods (Fig. S24g, i); the same broad multi-year structure persists because changing the reference period alters mainly the linear component of the cumulative indices, whereas the multi-year departures responsible for the curvature remain.

Q15: L451-453: Please use the same key number for your argument related to Alaska (i.e. compare to L22-23.

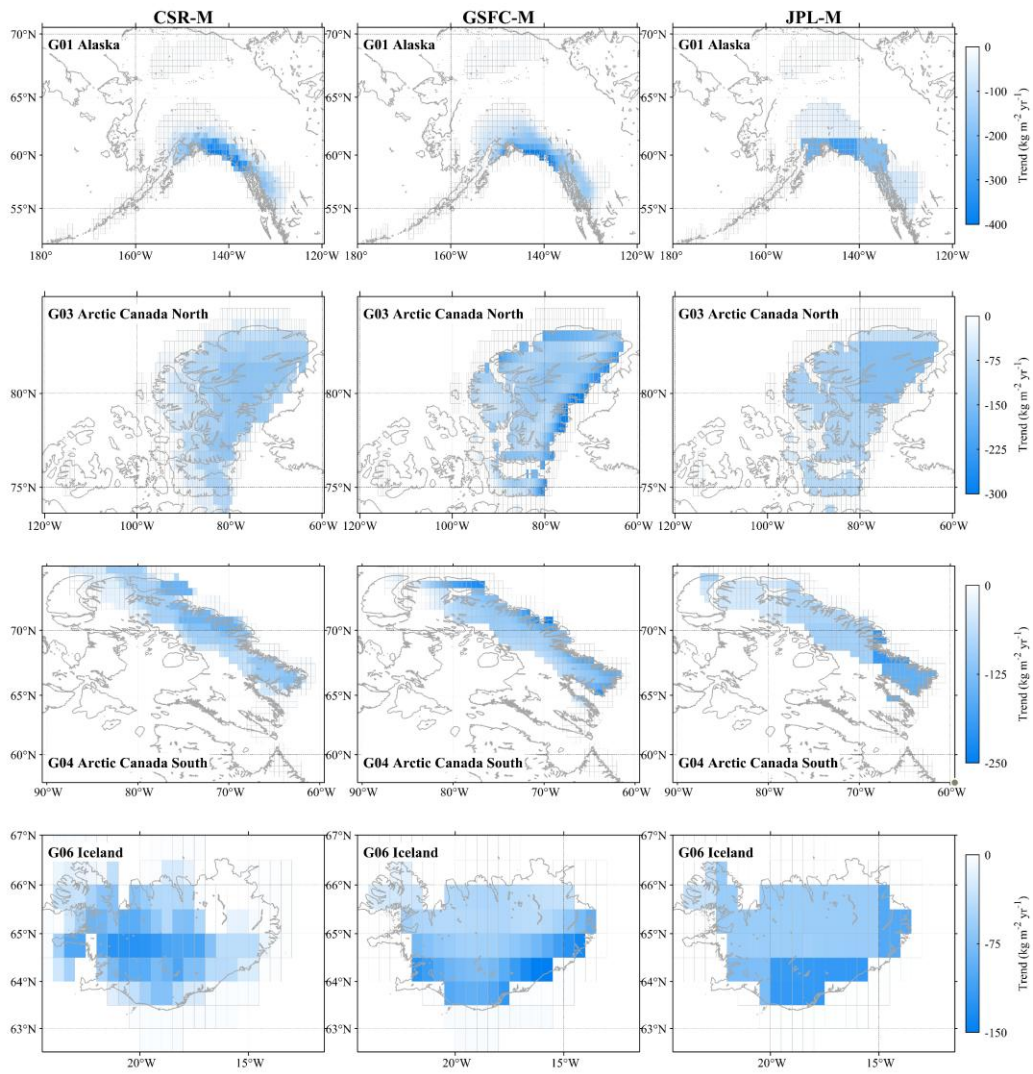
R15: Corrected. The original 25% and 33% values reflected different reference values for the same Alaska trend difference. We have standardised the comparison throughout the manuscript, and both the Abstract and Conclusion now report that the unadjusted trend is about 25% less negative than the residual trend after accounting for NAO- and PDO-related variability.

Q16: Supplementary.: Consider providing the supplementary data as Comma Separated Values (csv) files rather than txt files. The conversion should be quite straight forward.

R16: Agreed. Supplementary data files previously provided as .txt files have now been converted to .csv format.

Q17: Figure S1: Uses cmw.e. while other sections in the manuscript use cm EWH. I'd recommend sticking to one of the SI units. Map plots need a scale or coordinate grid.

R17: Agreed. We have revised Fig. S1 by converting the mass-anomaly units to $kg\ m^{-2}\ yr^{-1}$, and by adding labelled latitude-longitude grid lines to provide spatial reference. The revised Figure S1 is shown below.



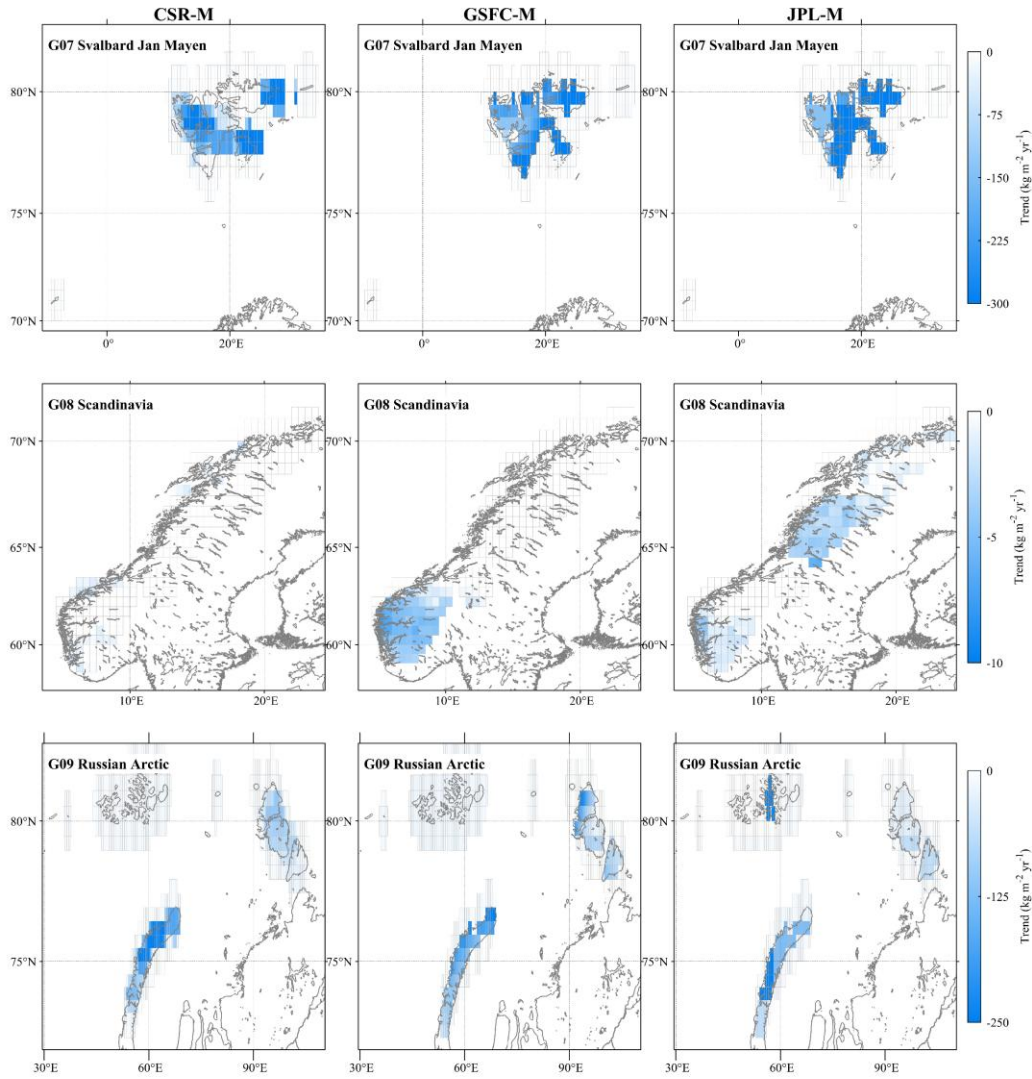


Figure S1: Spatial trends of GRACE Mascon solutions across selected glacier and ice-cap regions. Shown are the spatial masks used to delineate the major global glacier and ice-cap complexes, including the Arctic regions (G01, G03, G04, G06–G09). Based on the Randolph Glacier Inventory version 7.0, a 1° buffer was applied to define the final glacier-specific regional masks. Blue shading indicates glacier-covered grid cells, with color intensity representing the trend in glacier mass change observed during the GRACE observation period.

Q18: Figure S5: [h] and [i] miss information in the figure caption what exactly is shown.

R18: Corrected. We have expanded the caption of Fig. S5 to specify explicitly what is shown in panels h and i. Panel h now identifies the correlations of annual balance with the warm- and cold-season contributions, $r(B, S)$ and $r(B, W)$, and panel i defines the seasonal dominance index $D_2 = r(B, S)^2 - r(B, W)^2$, with positive and negative values indicating warm- and cold-season dominance, respectively.

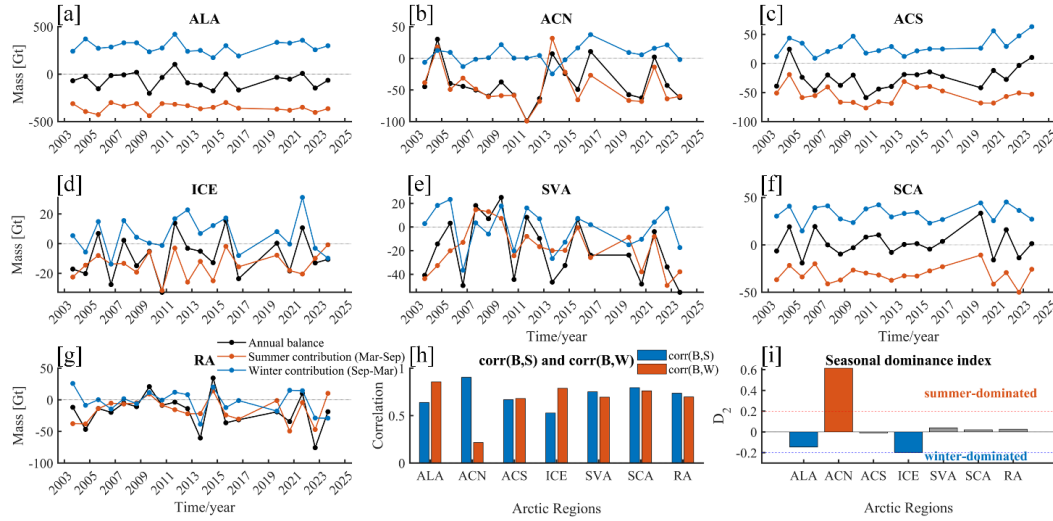


Figure S5: Annual balance and seasonal contributions across Arctic glacier regions. Annual balance was defined from March to March of the following year, so that the full melt season is included within a single balance year. For each region, the seasonal analysis was based on 19 valid annual-balance years, excluding years affected by the GRACE/GRACE-FO mission gap. The annual balance was partitioned into a warm-season contribution (March–September) and a cold-season contribution (September–March of the following year). Panels a–g show the annual balance together with its warm- and cold-season contributions for ALA, ACN, ACS, ICE, SVA, SCA and RA, respectively. Panel h shows the correlations of annual balance B with the warm-season contribution S , $r(B, S)$, and the cold-season contribution W , $r(B, W)$, for each region. Panel i shows the seasonal dominance index $D_2 = r(B, S)^2 - r(B, W)^2$, which measures the difference in the fractions of annual-balance variance associated with the two seasonal contributions. Positive values indicate warm-season dominance and negative values indicate cold-season dominance.

Q19: Figure S19: Color scale misses label.

R19: We thank the reviewer for noting this omission. We have revised Fig. S19 to include a label on the color bar (“Scaled spatial response”), so that the quantity represented by the map colors is now clearly identified.

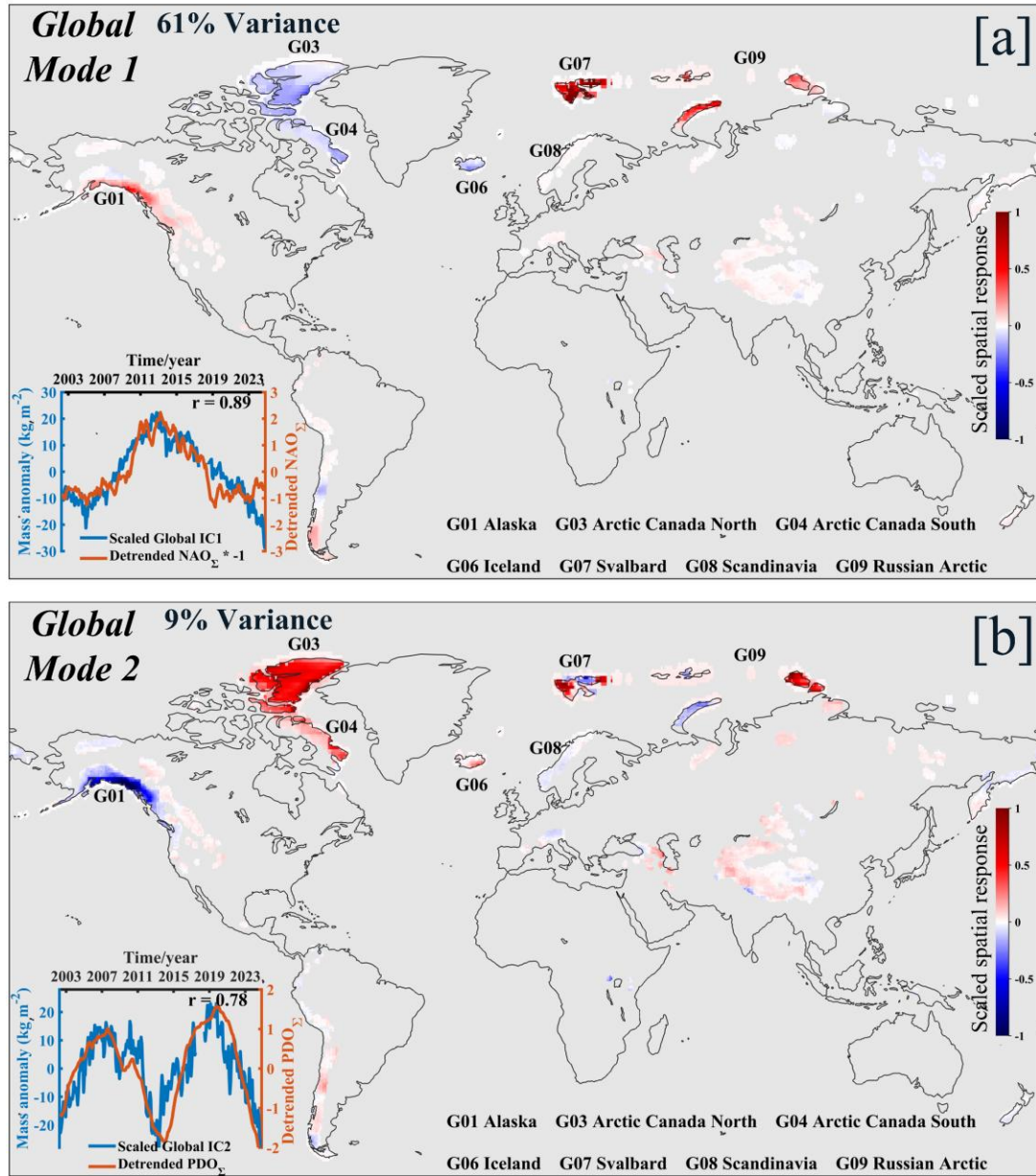


Figure S19: Leading ICA modes in the global GRACE/GRACE-FO GIC regional record. Panels a–b show the first two ICA modes derived from detrended regional mass change time series from the global GIC record, explaining 61% and 9% of the interannual variance, respectively. Time series of the ICs are shown together with the detrended NAO_{Σ} and PDO_{Σ} indices. The Arctic subset comprises Alaska, Arctic Canada North, Arctic Canada South, Iceland, Svalbard, Scandinavia, and the Russian Arctic, corresponding to RGI regions G01, G03, G04, and G06–G09 (Fig. S18).