



An ensemble reconstruction of Greenland ice sheet surface elevation for 1850 and 1980

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Abstract. The Greenland Ice Sheet (GrIS) has experienced sustained mass loss over recent decades in response to Arctic warming, raising concerns about its sensitivity to climate change and its future contribution to sea-level rise. Understanding when and how rapidly the GrIS began to decline provides important constraints on its response to ongoing and future warming. Previous studies have shown that glacier retreat across Greenland began at different times, with some glaciers retreating as early as the mid-19th century and others not until the late 20th century. Although historical evidence (e.g., historical maps, expedition logs) as well as dating of geomorphological features have enabled the reconstruction of ice-front positions for many Greenland glaciers during the 19th and 20th centuries, the timing, magnitude, and spatial distribution of Greenland-wide thinning since the Little Ice Age (LIA, ~1300–1850 CE) remain poorly constrained. Here, we reconstruct Greenland-wide ice surface elevation for 1850 and 1980 using ice-sheet boundaries representative of each period. We generate an ensemble of 127 reconstructions that samples the main sources of uncertainty in past ice-sheet geometry and estimate the spatial distribution of elevation change since 1850. Our reconstruction uses the mass distribution (MD) approach, which combines satellite-era observations of elevation change rates, estimates of total ice-sheet mass change since 1850, and a contemporary digital elevation model to infer past ice-sheet geometry. Using our reconstructed ice-sheet geometries and evolving ice boundaries, we reinterpret existing Greenland-wide mass-change estimates, including those of Mankoff et al. (2021), and obtain a total mass loss equivalent to 26.8 mm SLE between 1850 and 2015 (0.16 mm SLE yr⁻¹). Of this total, 15.6 mm SLE occurred during 1850–1980 (0.12 mm SLE yr⁻¹), 5.6 mm during 1980–2007 (0.21 mm SLE yr⁻¹), and 5.5 mm during 2007–2015 (0.69 mm SLE yr⁻¹). These results indicate that the average mass-loss rate during 2007–2015 was approximately six times greater than during 1850–1980. Uncertainty of ice surface elevation within the ensemble is primarily controlled by the total ice-sheet mass change since 1850 used to constrain the reconstructions and secondarily by the spatial pattern of observed elevation change rates. Our reconstructions, which explicitly account for historical ice-sheet boundaries, differ substantially from reconstructions based on a contemporary ice mask, highlighting the importance of representing temporal changes in ice extent when reconstructing past Greenland geometry.



23 1 Introduction

24 The Greenland Ice Sheet (GrIS) is experiencing accelerated mass loss in response to anthropogenic warming, having lost nearly
25 5,000 Gt of ice over the past three decades (Otosaka et al., 2022). Its contribution to global mean sea-level rise increased from
26 about 5% in 1993 to 25% in 2014, making Greenland one of the dominant contemporary contributors to sea-level rise (Chen
27 et al., 2017). The rate of mass loss has increased by a factor of six since the 1980s (Mouginot et al., 2019) and by a factor of
28 five over the past 30 years (Otosaka et al., 2022). Modelling studies suggest that, under sustained high-end warming, the GrIS
29 could disappear as soon as within the next 1,000 years (Aschwenden et al., 2019), which would add approximately 7 m of
30 global mean sea-level rise (Morlighem et al., 2017). Both the timing and magnitude of this potential contribution are critical
31 for coastal adaptation planning.

32 Historical estimates of ice-sheet change are important for several reasons. A key motivation is climate-change attribution:
33 understanding how ice sheets varied in the past provides essential context for recent changes and helps to distinguish mass
34 loss driven by natural variability from that driven by anthropogenic forcing (Roe et al., 2021). In addition, reconstructions of
35 past ice-sheet states are fundamental for improving ice-sheet models that are used to project future mass loss and sea-level
36 contribution. In practice, such reconstructions can be used for model initialization, calibration, and evaluation. For example,
37 all simulations contributing to the ISMIP6 projections for the 21st century were initialized prior to 2015—the beginning of
38 the projection period. Around 1/4 of the simulations were initialized around 2007 due to the availability of a Greenland-wide
39 DEM for this year (Morlighem et al., 2017), while all others were initialized between 1979 and 2000 (Goelzer et al., 2020).
40 However, because ice-sheet-wide observations or reconstructions prior to the 2000s have been lacking, simulations initialized
41 before the 2000s were typically started either from modern observed geometries (i.e., ice elevation, thickness and extent) or
42 from geometries produced through long model spin-ups (Goelzer et al., 2020). The latter approach often produces substantial
43 mismatches between modelled and observed geometries, with the cost of poorly representing the ice sheet geometry in the
44 simulations, which can undermine the reliability of subsequent projections (Goelzer et al., 2017). Consequently, improved
45 knowledge of past ice-sheet geometry and mass changes is essential for refining projections of future sea-level rise.

46 Knowledge of ice-sheet mass balance is derived from a range of observational approaches. Traditional methods include
47 satellite altimetry, which measures changes in ice sheet elevation which can be converted into volume changes; gravimetry,
48 which detects variations in the Earth's gravity field; and the input–output (IO) method, which estimates mass balance by
49 comparing mass gains (input) and losses (output). While altimetry and gravimetry-based estimates are limited to the eras
50 spanned by their corresponding satellites, beginning in 1991 and 2002, respectively (Thomas et al., 2006), the IO method
51 combines ice velocity observations with surface mass balance products produced from atmospheric reanalysis data and has
52 been produced for periods as far back as 1840 (Mankoff et al., 2021). Although one study has estimated total Greenland
53 mass change since the 19th century (Mankoff et al., 2021), only a limited number of ice-sheet-wide products that combine
54 observations with empirical approaches resolve the spatial distribution of mass changes prior to the satellite era (Khan et al.,
55 2020; Kjeldsen et al., 2015).



The further away from the observational era, the greater the levels of uncertainty in ice sheet state (Mankoff et al., 2021). The Little Ice Age (LIA) represented the culmination of the Neoglacial cooling that took place between ~ 8 ka before present and 1850 (McKay et al., 2018), and is thought to have been reversed by the onset of anthropogenic warming (Kaufman et al., 2009). Despite increasing research on the GrIS variability in the past centuries, the timing and magnitude of the GrIS response to anthropogenic warming during and after the LIA remain an open and actively debated question. Some studies suggest that the GrIS continued to gain mass until the late twentieth century, reflecting a delayed dynamic response to climatic forcing (Box and Colgan, 2013; Mouginito et al., 2019; Yang et al., 2022). Other studies indicate that the ice sheet was in balance around 1850, with the onset of sustained mass loss occurring in the late nineteenth century—approximately a century earlier than suggested by other estimates (Kjeldsen et al., 2015; Mankoff et al., 2021). Resolving this long-standing uncertainty is central to improving our understanding of the response time of the GrIS to a changing climate.

To fully understand the timing and magnitude of the GrIS response to climate change, it is important to characterize the state of the ice sheet before major retreat began. To add more insight into this problem, we here reconstructed Greenland-wide DEMs for 1850—often referred to as the termination of the LIA (Kjær et al., 2022)—and 1980, using corresponding ice extent boundaries for both periods (Salmani et al., 2026), accompanied by a thorough quantification of their uncertainties. This allowed us to extend the reconstruction beyond the contemporary ice extent across the entire ice sheet. We generated an ensemble of 1850 ice-sheet states and evaluated the methodology by applying the same framework to three reference years (1980, 2007, and 2015), for which independent observations of ice elevation are available. That provides an important step toward resolving the spatiotemporal response of the ice sheet to climate change and enabling ice-sheet models to more realistically simulate its evolution during the nineteenth and twentieth centuries.

2 Methods

2.1 Mass Distribution approach

In this study, we conceptualize and present the Mass Distribution (MD) approach, a method to reconstruct the GrIS configuration in the past. This method uses a combination of datasets available in the literature to generate a Greenland-wide elevation map in 1980 and 1850. The input datasets are: (1) a satellite-based observed map of elevation changes (Gao et al., 2026; Khan et al., 2024; Nilsson and Gardner, 2024; Zhang et al., 2021), (2) a reference Digital Elevation Model (DEM) (Howat et al., 2015, 2022), (3) an estimate of total volume/mass change between 1850 (or desired predicted year) and the nominal date of the reference DEM (Mankoff et al., 2021), and (4) a boundary corresponding to the ice sheet extent in the predicted period (e.g., Salmani et al. (2026) for realistic 1850 and 1980 boundaries and the European Space Agency (ESA) Climate Change Initiative (CCI) ice mask Rastner et al. (2012) for 2007 and 2015 reconstructions representing a contemporary boundary). The satellite-based observed map of elevation changes (dh/dt) is a Greenland-wide elevation change map averaged over the observational period (e.g., the last three decades), and provides a spatial weight for our mass distribution. The reference DEM ($h_{DEM,t}$) is a contemporary Greenland-wide DEM at nominal year t , from which the total elevation change between the LIA and t is subtracted. The estimate of total volume change between the LIA and t (ΔV_{LIA-t}) is a literature-based estimate of total volume



change between the predicted year and the nominal date t of the reference DEM. As literature provides mass change estimates instead of volume, those were converted to volume by assuming a constant ice density. The boundary corresponding to the ice sheet extent in the predicted period, is an observed or reconstructed continuous boundary of the GrIS that is assigned to the same period as the predicted elevation. The reconstructed LIA surface elevation (h_{LIA}) is calculated using Eq. (1):

$$h_{LIA} = h_{DEM,t} - \Delta V_{LIA-t} \times W_{dh/dt}, \quad (1)$$

where the LIA, here referred as to 1850, could be replaced by any year desired for reconstruction, and the spatial weight for the mass distribution, $W_{dh/dt}$, is given by

$$W_{dh/dt} = \frac{\overline{dh/dt}_{(x,y)}}{\sum_{i=1}^N \overline{dh/dt}_i}, \quad (2)$$

where $\overline{dh/dt}_{(x,y)}$ is the temporal average dh/dt over the observation period at every x and y location, and $\sum_{i=1}^N \overline{dh/dt}_i$ is the spatial sum of dh/dt at all locations. In regions between the present-day and the LIA boundary, we linearly interpolated the dh/dt maps. Then, we subtracted that elevation change map from a reference DEM, ending up with a Greenland-wide elevation map in 1850. To be consistent with DEM (Howat et al., 2015), the elevations are reported in meters above the WGS84 Ellipsoid.

Our approach was inspired by previous studies that reconstructed glaciers around the world in the LIA. The MD approach follows Adhikari et al. (2021), who uniformly distributed the mass change since 1850 over a contemporary DEM in peripheral glaciers and ice caps around Greenland to reconstruct the LIA elevation for Glacioal Isostatic Adjustment (GIA) modelling purposes. We improve on this strategy by applying a spatial variability to weight mass changes based on observed spatial patterns. The method assumes that the spatial variability did not change between 1850 and the averaged last three decades, 1995-2025. Figure 1 shows the application of the MD approach to the Sermeq Kujalleq (Jakobshavn Isbrae) region. Although the illustrations picture 1850 (the LIA) as our reconstruction date, the MD method can be applied to any desired year, as long as the mass change since the reference DEM date and the ice sheet boundary are referenced for that specific year.

We test the sensitivity of the MD method to different input datasets by producing an ensemble of possible 1980 and 1850 states. For example, we take dh/dt from four different sources: Gao et al. (2026) spanning 1994-2020, Khan et al. (2024) spanning 2003-2023, Nilsson and Gardner (2024) spanning 1992-2023, and Zhang et al. (2021) spanning 1991-2020. Within the Gao et al. (2026) dataset, we assess the sensitivity to firn models by using dh/dt fields derived from three different firn models. Combined with the other datasets, this results in a total of six distinct dh/dt inputs. For each input, we compute (1) the average over the full period available, and (2) the average over the 2003–2009 interval only, as this period is supported by a denser satellite observational record. In addition, we included two different reference DEMs and produced ensemble members using either the GIMP1 in 2007 (Howat et al., 2015) or the GIMP2 in 2015 (Howat et al., 2022). Some ensemble members used Eq. (1) over the entire period between LIA and t , while others used the observed dh/dt from the 6 different sources during the observation period, while using the Eq. (1) only during the time period lacking direct observations. Finally, we tested the sensitivity of the MD approach to the mass change input by having a Minimum, a Median and a Maximum mass, based on the



average and the standard deviation range calculated of Mankoff et al. (2021) mass balance estimates since 1840. Table 1 shows the mass change estimates for all studied intervals that were used to produce our ice elevation ensembles, calculated from Mankoff et al. (2021) yearly product. The mass change is also shown in volume units (i.e., mm SLE) after conversion. The Minimum and Maximum mass change values were produced by adding and subtracting, respectively, the cumulative error of $\pm 86 \text{ Gt yr}^{-1}$ from Mankoff et al. (2021) product, estimated in their study. Since the standard deviation is a cumulative sum over of Mankoff et al. (2021) average error of $\pm 86 \text{ Gt yr}^{-1}$, longer time intervals present wider ranges of uncertainty. A consequence of such increasing uncertainty over large periods, is that for two periods (1850-2007 and 1850-2015), the Minimum mass shows a gain of mass, as the cumulative error being higher than the Median loss of mass. In addition, Table 2 shows uncertainties in those estimates. We estimated the uncertainty in elevation change between each time interval separately for the Median, Minimum, and Maximum scenarios. For each scenario, we calculated the total volume change for every ensemble member and took the standard deviation across members.

Time interval	Minimum mass	Median mass(Med)	Maximum mass (Max)
1850–1980	$1.9 \times 10^3 \text{ Gt} / 5.2 \text{ mm SLE}$	$-9.3 \times 10^3 \text{ Gt} / -25.7 \text{ mm SLE}$	$-20.5 \times 10^3 \text{ Gt} / -56.7 \text{ mm SLE}$
1980–2007	$-75 \text{ Gt} / -0.2 \text{ mm SLE}$	$-2.5 \times 10^3 \text{ Gt} / -6.9 \text{ mm SLE}$	$-4.9 \times 10^3 \text{ Gt} / -13.5 \text{ mm SLE}$
2007–2015	$-1.6 \times 10^3 \text{ Gt} / -4.4 \text{ mm SLE}$	$-2.3 \times 10^3 \text{ Gt} / -6.4 \text{ mm SLE}$	$-3.1 \times 10^3 \text{ Gt} / -8.6 \text{ mm SLE}$
1850–2015	$365.6 \text{ Gt} / 1.0 \text{ mm SLE}$	$-13.9 \times 10^3 \text{ Gt} / -38.4 \text{ mm SLE}$	$-28.2 \times 10^3 \text{ Gt} / -77.9 \text{ mm SLE}$

Table 1. Mass change values used for the ensemble production. Median values represent the accumulated mass change over the respective intervals calculated from the mass change estimates of Mankoff et al. (2021). Minimum and maximum values account for the cumulative uncertainty based on a standard deviation of $\pm 86 \text{ Gt yr}^{-1}$. Sea-level-equivalent values were calculated using $361.8 \text{ Gt} = 1 \text{ mm SLE}$.

Time interval	Minimum mass uncertainty	Median mass uncertainty	Maximum mass uncertainty
1850–1980	$62 \text{ Gt} / 0.2 \text{ mm SLE}$	$191 \text{ Gt} / 0.5 \text{ mm SLE}$	$398 \text{ Gt} / 1.1 \text{ mm SLE}$
1980–2007	$629 \text{ Gt} / 1.7 \text{ mm SLE}$	$749 \text{ Gt} / 2.1 \text{ mm SLE}$	$1,318 \text{ Gt} / 3.6 \text{ mm SLE}$
2007–2015	$491 \text{ Gt} / 1.4 \text{ mm SLE}$	$2,329 \text{ Gt} / 6.4 \text{ mm SLE}$	$3,345 \text{ Gt} / 9.2 \text{ mm SLE}$
1850–2015	$1,963 \text{ Gt} / 5.4 \text{ mm SLE}$	$800 \text{ Gt} / 2.2 \text{ mm SLE}$	$1,447 \text{ Gt} / 4.0 \text{ mm SLE}$

Table 2. Uncertainties in the estimated mass changes calculated using the Minimum, Median, and Maximum ice mass scenarios from Mankoff et al. (2021) for the studied time intervals.

A combination of all input choices for the MD approach, mentioned in the previous paragraph, allowed for an ensemble of 127 members that captures a wide range of uncertainties in the methodology. For instance, the uncertainty in product source and post-processing techniques of contemporary dh/dt spatial pattern is taken into account by including dh/dt inputs from four different studies (Gao et al., 2026; Khan et al., 2024; Nilsson and Gardner, 2024; Zhang et al., 2021) and varying the period used to derive the climatology. Uncertainty in total mass change since 1850 or 1980 is taken into account by considering the uncertainty range in the mass change estimates (Mankoff et al., 2021). The uncertainty in the contemporary DEM product is taken into account by using two different products for both 2007 and 2015 (Howat et al., 2015, 2022).



Figure A6 shows the errors associated with these DEM products, illustrating the need to sample this source of uncertainty. For the modern ice sheet topography, we utilized the MEaSUREs GrIMP Digital Elevation Model (NSIDC-0715, Version 2). While the dataset comprises imagery spanning 2008–2020 (with a median acquisition year of 2015) and is vertically registered to 2019–2020 ICESat-2 altimetry, we treat the modern snapshot as a nominal 2015 baseline. Given our 170-year study timescale (1850–present), the multi-year variance within the modern mosaic introduces a minor structural uncertainty to the century-scale trends. In addition, uncertainties associated with the treatment of firn are partially accounted for by including four dh/dt products derived using different firn densification models (e.g., GEMB, GSFC, and IMAU) or assuming a constant ice density of 917 kg m^{-3} . However, our conversion of the mass-change estimates from (Mankoff et al., 2021) to volume change assumes a constant ice density as the mass change is not resolved spatially. Importantly, both the dh/dt products and the associated firn corrections rely on the assumption that contemporary spatial patterns are representative of those in 1850 and 1980. Uncertainties associated with this assumption are not sampled in the present study because Greenland-wide observations prior to the satellite era are insufficient to constrain historical dh/dt patterns and the spatial and temporal evolution of firn properties and the climatic forcing controlling firn densification.

We performed a Principal Component Analysis (PCA) to characterize the variability within the 127-member ensemble comprising our 1850 reconstruction. The ensemble was arranged into a two-dimensional matrix in which each column represented one member (e.g., each distinct reconstruction) and each row represented a spatial grid cell. At each grid cell, the ensemble-mean elevation was subtracted, such that the PCA was applied to elevation anomalies relative to the ensemble mean. The resulting principal-component scores describes the contribution of each principal component to individual ensemble members and the corresponding loading vectors describe their spatial patterns. The fraction of total ensemble variance explained by each component was used to assess the relative importance of the dominant modes of variability.

One important contribution of our study is the use of realistic ice boundaries in the ice-surface elevation reconstructions for 1850 (Salmani et al., 2026) and 1980 (Kjeldsen et al., 2020). Previous studies resolving spatially varying mass changes across Greenland have assumed a static ice boundary over time (Kjeldsen et al., 2015), thereby excluding mass changes occurring beyond the contemporary ice extent. This omission may be particularly important because the highest rates of elevation and mass change occur near the ice-sheet margins. To quantify the effect of changing ice extent on the estimated mass change, we compared estimates derived using period-specific ice masks for 1850, 1980, and the contemporary period (Rastner et al., 2012) with estimates restricted to the contemporary ice boundary (Rastner et al., 2012).

2.2 Validation of reconstructions

We validated and evaluated the MD reconstruction method by applying it to estimate ice elevation in three years when there is an observed DEM for comparison: 1980s (Korsgaard et al., 2016), 2007 (Howat et al., 2015) and 2015 (Howat et al., 2022). We chose the 1980s as our main validation period because it is the oldest date within the recent past where there is an available DEM that was constructed from aerial photogrammetry in the periphery of the ice sheet (Korsgaard et al., 2016), similar to Kjeldsen et al. (2015). For the validations of the MD approach against the AERODEM, we masked out low reliability data in the AERODEM by including only pixels with Figure-Of-Merit (FOM) greater than or equal to 40 (Korsgaard et al., 2016). We

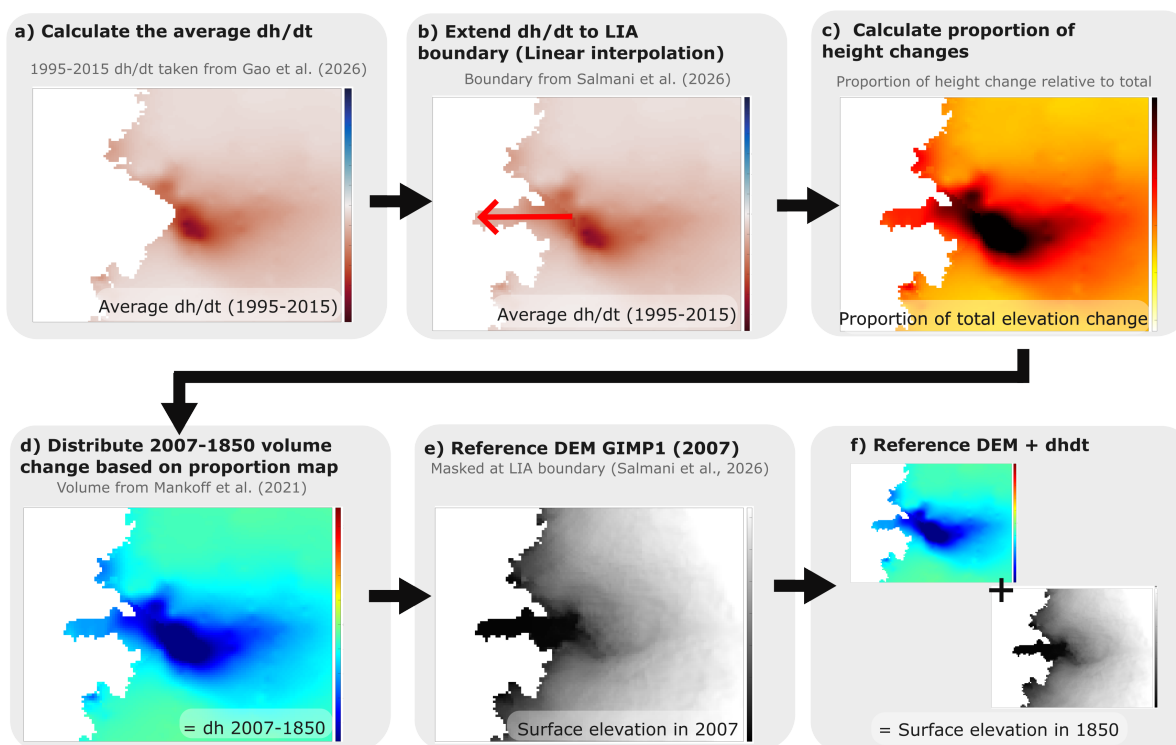


Figure 1. Schematic workflow of the Mass Distribution (MD) approach applied to Jakobshavn Isbrea, showing: a) the average elevation change dh/dt from (Gao et al., 2026) in a present day mask; b) same as a, but extended to the LIA boundary (Salmani et al., 2026) using linear interpolation; c) calculated map of proportion of total mass change based on the spatial pattern in b; d) ice elevation change between 2007 and 1850 calculated from distributing the mass change from Mankoff et al. (2021) using the spatial pattern in c; e) the ice elevation from GIMP1 DEM (Howat et al., 2015); f) the estimated ice elevation in 1850 by subtracting elevation change in d from the GIMP1 DEM in 1850.

also used the PROMICE ice mask (Kjeldsen et al., 2020) for that reconstruction, with corrections from Salmani et al. (2026). Since the AERODEM is only available for the ice sheet periphery and does not allow a comparison over the entire ice sheet, we also performed an evaluation of our method in the years 2007 and 2015, using the GIMP1 and GIMP2 DEMs for comparison. Such model-observations comparison also aids in selecting ensemble members that best match observations. For example, the Taylor Diagram in Figure A2 shows that the ensemble mean has a better agreement with observations compared with any individual ensemble member.

In addition, Figure 2 aids in comparing observations against modelled elevations in 1980, 2007 and 2015 through histograms and scatter plots. In the 1980s, the highest elevation frequency was between 5 and 1,200 meters (Fig. 2a), while in 2007



180 and 2015, the highest frequency was between 2,000 and 3,000 meters (Fig. 2c and e). That is because the 1980s DEM only
181 encompasses the ice sheet periphery, while the 2007 and 2015 DEMs encompass the entire ice sheet. In the 1980s, the greatest
182 differences appear to be in elevations lower or equal to 100 meters, where the ensemble mean overestimates the frequency of
183 low elevations. In the 1980s, the ensemble mean underestimates the elevation distribution between 300-700 meters, though
184 the differences are lower over 600 meters (Fig. 2a). That is confirmed on the scatter plot (Fig. 2b), where the main spread
185 seems to occur in lower elevations. The 2007 and 2015 show similar patterns, where the greatest differences between modelled
186 and observed elevations are in median elevations between 700-2,700 meters (Fig. 2d and f), though the greater distribution of
187 elevations is around 2,000-3,000 meters (Fig. 2c).

188 Ensemble mean elevations show excellent agreement with reference DEMs at all validation time slices ($r^2 \geq 0.998$; RMSE
189 = 14–20 m), with near-identical elevation distributions (Fig. 2), indicating that the Mass Distribution approach preserves large-
190 scale topographic structure while introducing only minor residual differences. The near-perfect coefficient of determination r^2
191 in all cases can be explained by the magnitude of elevation differences (15-20 m) being only 0.8% of the typical elevation
192 values (2,500 m).

193 3 Results

194 3.1 Ensemble variability

195 We assess ensemble variability and its dominant sources of spread using a Principal Component Analysis (PCA) applied to the
196 1850 elevation reconstructions. The first two principal components (PC1 and PC2) explain 46% and 26% of the total variance,
197 respectively, accounting for 72% of the ensemble variability, while the remaining 28% is more evenly distributed across higher-
198 order principal components (Fig. A3). Figure 3 shows the distribution of ensemble members in the space defined by PC1 and
199 PC2. Each point represents one realization of the 1850 reconstruction. Colors denote the imposed 1850–2007 mass constraint
200 (Minimum, Median, and Maximum estimates from Mankoff et al. (2021)), while marker shapes indicate the dh/dt source used
201 in the MD approach.

202 The distribution in PC1–PC2 space highlights systematic patterns in the ensemble (Fig. 3). Ensemble members clearly
203 separate along PC1 according to the imposed total mass change. Realizations using the Minimum, Median, and Maximum
204 mass constraints form distinct clusters along this axis, indicating that PC1 primarily reflects differences in the magnitude of
205 integrated mass change. This demonstrates that uncertainty in total mass change is the leading source of variability within
206 the ensemble. In contrast, PC2 captures variability associated with differences in the spatial pattern of elevation change. Most
207 realizations cluster near zero in PC2, but two distinct groups of four realizations each exhibit large negative PC2 values. All of
208 these outliers correspond to reconstructions using the Zhang et al. (2021) dataset, indicating that this dh/dt product introduces
209 spatial patterns that differ substantially from those derived from the other datasets. Overall, the PCA reveals a hierarchical
210 structure in ensemble variability: the imposed total mass change controls the dominant mode of variability (PC1), while the
211 choice of dh/dt dataset primarily governs the secondary mode (PC2). These two factors together explain most of the spatial
212 spread in the 1850 reconstructions.

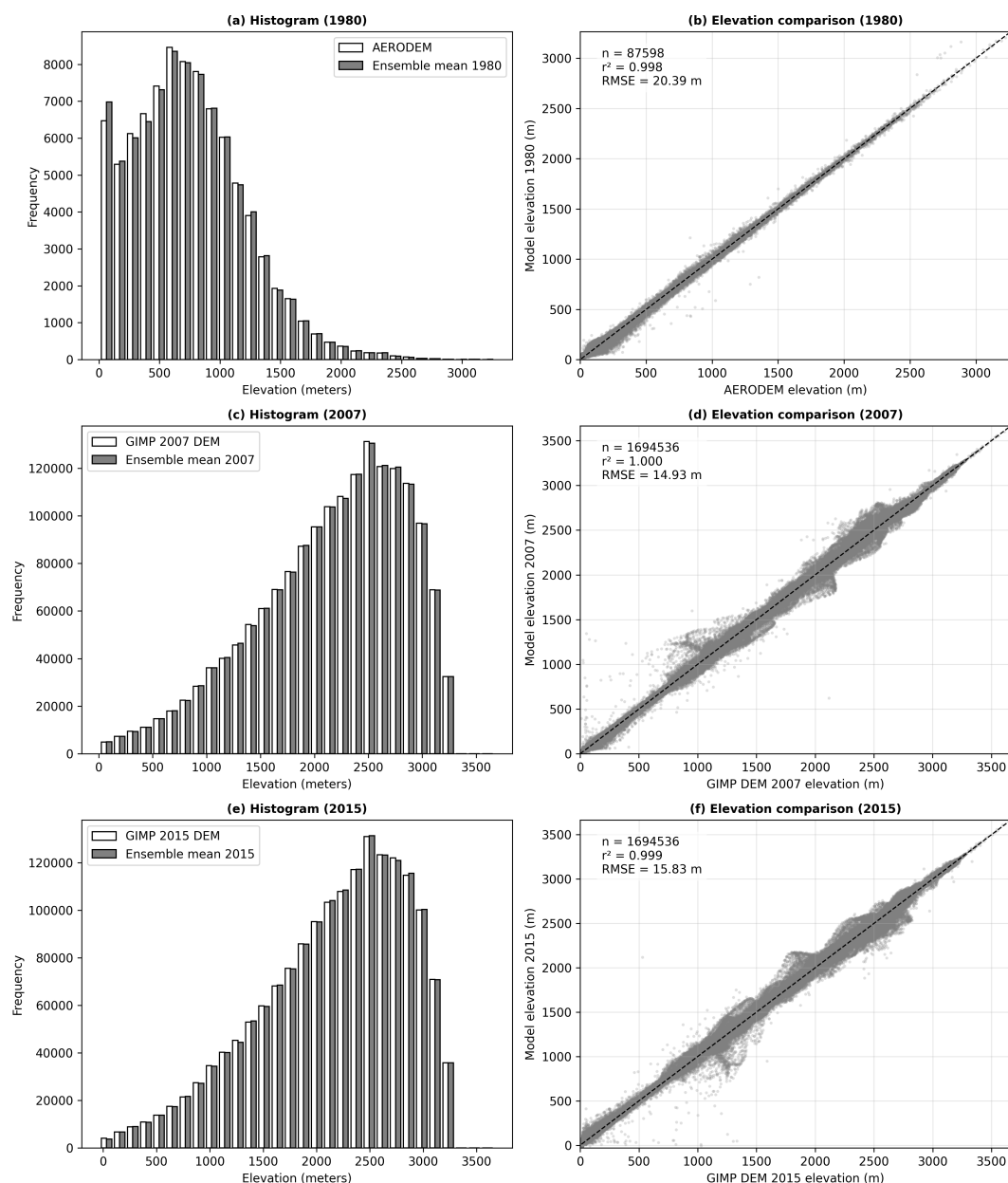


Figure 2. Statistical comparison between the reconstruction ensemble mean and observational Digital Elevation Models (DEMs). (a) Frequency distribution (histogram) and (b) regression analysis (scatter plot) of elevation values for the 1980s (AERODEM). Panels (c) and (d) show the corresponding histogram and scatter plot for 2015 (GIMP2).

213 Understanding the spatial patterns of the ensemble variability can help us pinpoint areas of greater uncertainty. To com-
214 plement the evaluation of variability within the ensemble, Fig. 4 shows the total elevation change between 2007 and 1850

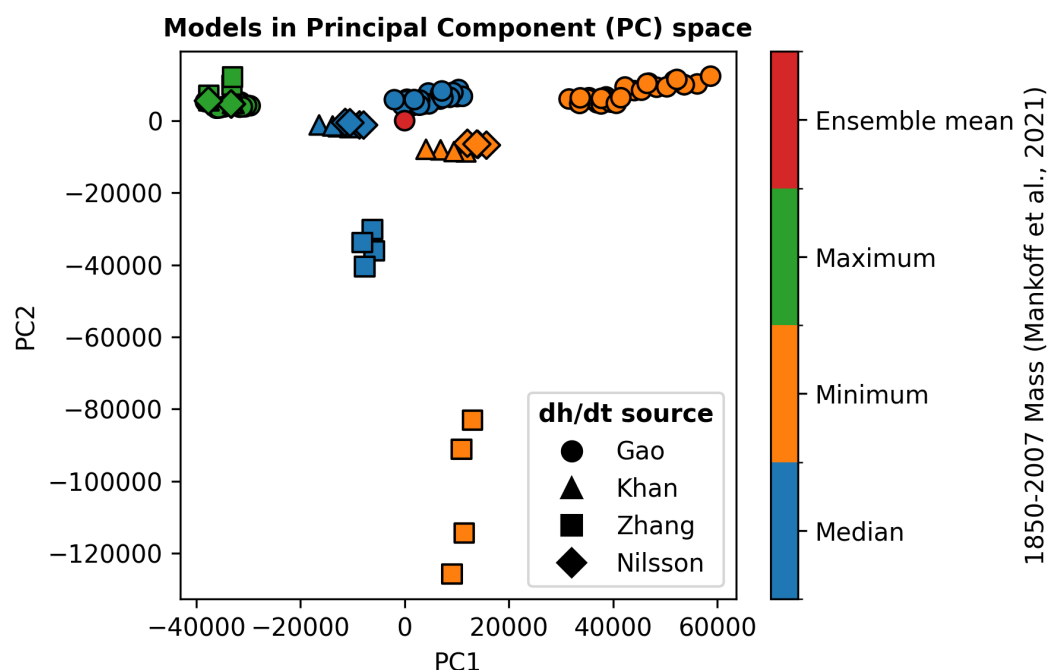


Figure 3. Principal Component Analysis (PCA) of the ensemble of 1850 reconstructed elevations plotted according to the input mass change between 1850 and 2007 (Maximum, Median or Minimum), and source of dh/dt dataset ((Gao et al., 2026), Khan et al. (2024), Zhang et al. (2021) or Nilsson and Gardner (2024)).

reconstructed using different inputs to the MD method. The figure highlights the influence of two key inputs: the dh/dt dataset (varying across columns) and the imposed total mass change (varying across rows). The imposed mass change strongly influences the magnitude of the reconstructed elevation differences. Reconstructions using the Minimum mass scenario (Fig. 4i–l) show relatively small elevation changes across most of the ice sheet, with near-zero changes over large areas and localized regions of slight thickening along some outlet glaciers. In contrast, the Maximum-mass scenario produces substantially larger thinning along the ice-sheet margins, particularly along major outlet glaciers, while the ice-sheet interior remains largely unchanged. Differences between mass scenarios exceed 200 m locally along the margins, whereas the interior of the ice sheet shows comparatively little sensitivity to the imposed mass constraint.

In addition to the influence of the total mass change, the choice of dh/dt dataset introduces distinct spatial patterns in the reconstructed elevation changes. Reconstructions based on Khan et al. (2024) exhibit relatively smooth spatial gradients with limited spatial variability across the ice sheet (Fig. 4b, f, and j). In contrast, reconstructions derived from Zhang et al. (2021) display stronger spatial heterogeneity, characterized by sharp transitions between areas of large thinning and near-zero change, particularly along the eastern and southeastern margins of Greenland (Fig. 4c, g, and k). Similarly, the reconstructions based on Nilsson and Gardner (2024) show pronounced elevation changes concentrated along glacier flowlines, with smoother transitions in the surrounding areas (Fig. 4d, h, and l). In comparison, other dh/dt datasets (e.g., (Gao et al., 2026) and (Khan



et al., 2024)) tend to distribute elevation changes more broadly across glacier catchments rather than concentrating them along narrow outlet-glacier pathways. These spatial contrasts are consistent with the PCA results, confirming that total mass change and the choice of dh/dt dataset represent the two dominant sources of ensemble variability.

To further evaluate the spatial variability within the ensemble, we computed the standard deviation of elevation across all ensemble members for each reconstruction year (Fig. 5). This metric quantifies the spatial distribution of ensemble spread in reconstructed ice-sheet elevation. Across all time slices, the largest variability occurs along the ice-sheet margins (>10 meters in many regions), whereas the interior shows comparatively low spread (~1-3 meters of spread in most of the accumulation zone). This pattern reflects the fact that most elevation changes occur along outlet glaciers and coastal sectors, while the interior of the ice sheet remains relatively stable. Regions with the largest ensemble spread include eastern Greenland, which is characterized by complex topography and numerous marine-terminating glaciers, including major outlet glaciers such as Helheim and many others that are shorter and narrower.

The magnitude of ensemble spread also increases for reconstructions further in time from the two reference DEMs (2007 and 2015). In particular, the standard deviation along the ice-sheet margins increases from values generally below 1–2 m in the 2015 reconstruction to locally more than 10 m in the 1850 reconstruction. This reflects the longer temporal extrapolation required to reconstruct earlier states of the ice sheet, which is a consequence of the accumulated errors in the mass change input taken from Mankoff et al. (2021). The range between the Minimum and Maximum mass is larger for periods that are further away from the reference DEM because the standard deviation of 86 Gt yr^{-1} is cumulative over the predicted period and the reference DEM year. The 2015 reconstruction is approximately 7 years away from its reference DEM (2007), whereas the 1850 reconstruction extends 157 or 165 years from the reference elevation dataset, depending on the reference DEM used (2007 or 2015). In contrast, the ensemble spread in the interior of the ice sheet remains small and relatively consistent across all reconstruction years, indicating that uncertainties in the MD approach primarily affect regions where elevation changes are largest.

3.2 Elevation change through time

To understand how the GrIS has evolved since the LIA, we analyzed the spatial elevation changes across the entire ice sheet and how they translated into total mass change and mass change rates. Figure 6 illustrates the ensemble mean of these changes across four periods: 1850–1980, 1980–2007, 2007–2015, and the full 1850–2015 interval. The top row (Fig. 6a–d) displays the total elevation change (m), with the cumulative mass loss indicated in millimeters of sea level equivalent (SLE) in the upper right of each panel. The bottom row (Fig. 6e–h) shows the elevation change rate (m yr^{-1}) with the the total mass change rate (mm SLE yr^{-1}) indicated in the bottom right for the same respective intervals, highlighting the acceleration of ice loss over time.

Figure 6 reveals a significant and accelerating loss of ice mass across the GrIS since the end of the LIA. Panels (a–d) show a total cumulative mass loss of 26.8 mm SLE between 1850 and 2015, which occurred in distinct stages: 15.6 mm SLE (1850–1980), 5.6 mm SLE (1980–2007), and 5.5 mm SLE (2007–2015). While the majority of the total mass loss (58%) occurred during the long historical period before 1980, the rate of loss has intensified dramatically in recent decades, as the

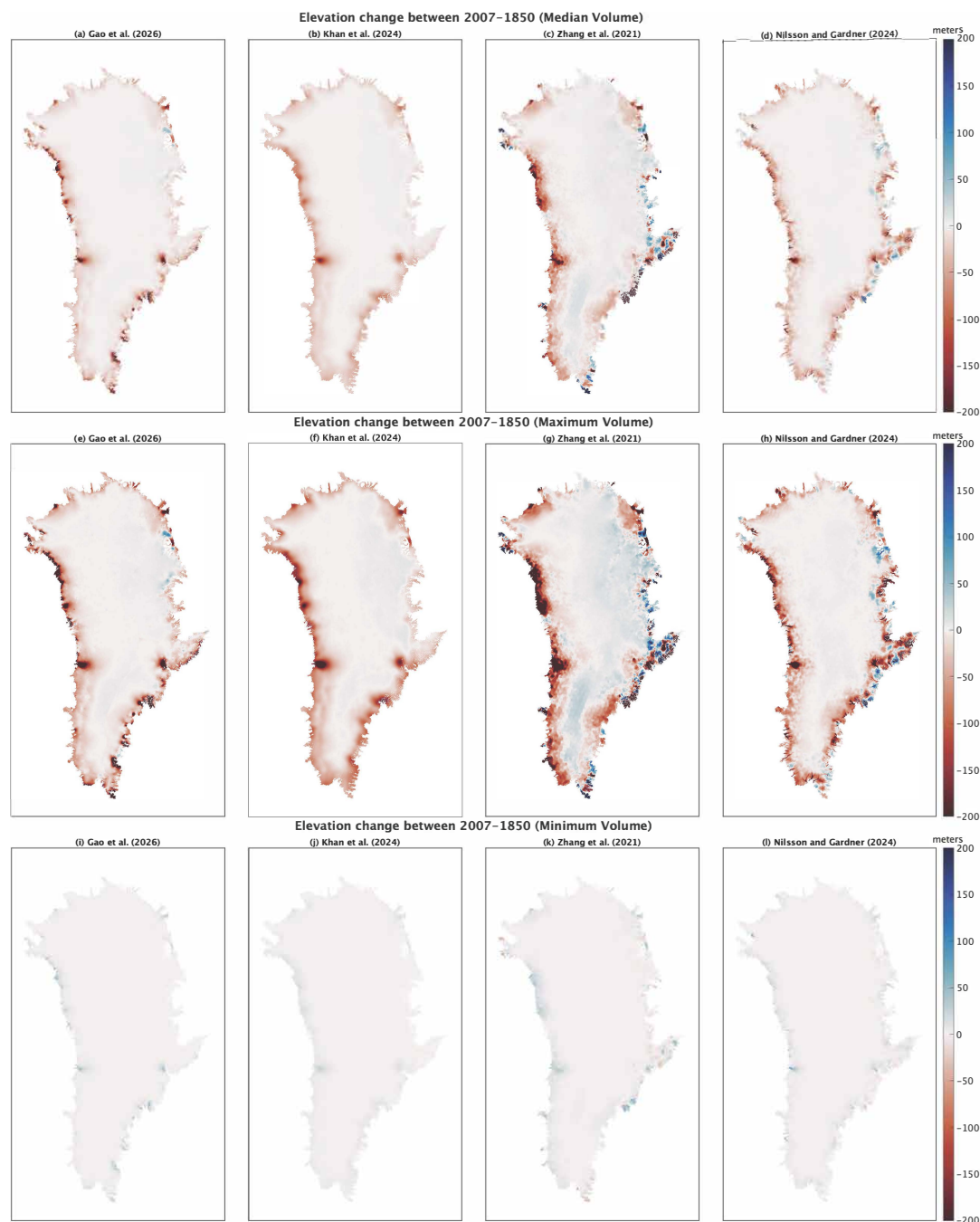


Figure 4. Elevation change between 1850 and 2007 plotted according to the input mass change between 1850 and 2007 (Maximum, Median or Minimum), and source of dh/dt dataset ((Gao et al., 2026), Khan et al. (2024), Zhang et al. (2021) or Nilsson and Gardner (2024)).

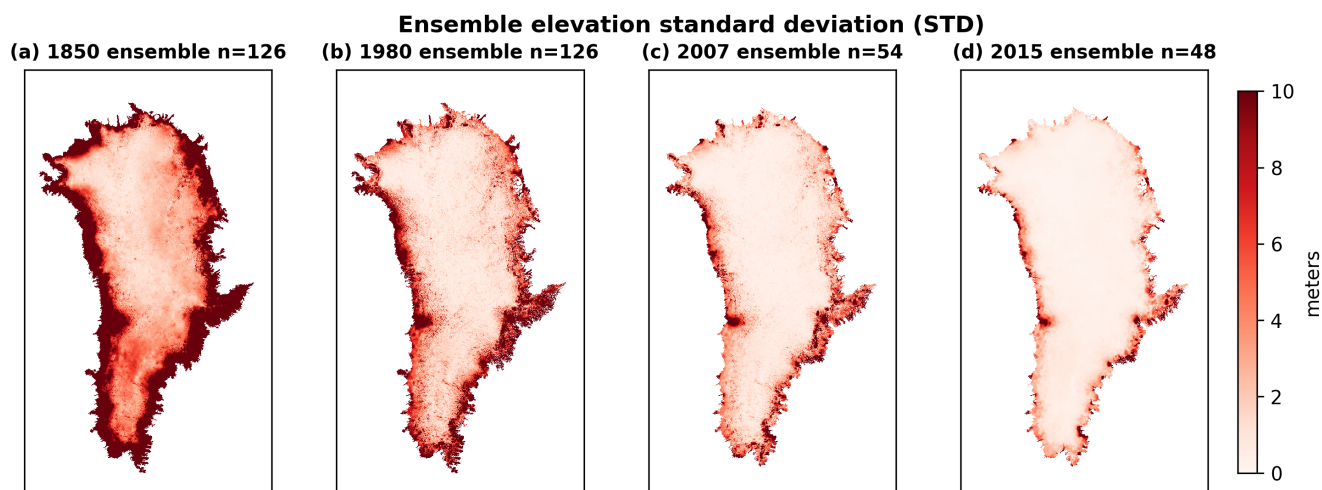


Figure 5. Standard Deviation (STD) of reconstruction ensemble for a) 1850; b) 1980; c) 2007; and d) 2015.

mass loss was distributed over a shorter time span. As shown in panels (e–h), the average mass change rate for the entire period was $0.16 \text{ mm SLE yr}^{-1}$, but this rate nearly doubled from $0.12 \text{ mm SLE yr}^{-1}$ (1850–1980) to $0.21 \text{ mm SLE yr}^{-1}$ (1980–2007), eventually reaching $0.68 \text{ mm SLE yr}^{-1}$ after 2007. The rate of mass loss in the most recent interval ($0.69 \text{ mm SLE yr}^{-1}$) is almost 6 times higher than the pre-1980 rate ($0.12 \text{ mm SLE yr}^{-1}$), highlighting a rapid late-century acceleration in Greenland’s contribution to global sea level rise.

The regional distribution of mass loss since the LIA across the seven IMBIE basins is shown in Fig. A5. The proportional contribution of each basin remained consistent across time intervals, a result of the assumption that the spatial pattern of mass change remains static within the MD approach. Throughout all studied intervals, the Northwest (NW) region was the primary contributor to mass loss, accounting for -4.20 mm SLE (1850–1980), -1.32 mm SLE (1980–2007), and -1.43 mm SLE (2007–2015). Cumulatively, the NW contributed -7.05 mm SLE , representing 26.3% of the total GrIS mass loss (26.8 mm SLE). This was followed by the Southeast (SE) and Central East (CE) regions, which contributed -5.52 mm SLE (20.6%) and -3.69 mm SLE (13.8%), respectively. In contrast, the Northeast (NE) region remained relatively stable, representing only 4.1% (-1.09 mm SLE) of the total mass loss. Notably, even though there were regions of mass gain, specially in the ice sheet interior (Fig. 4), all IMBIE regions experienced a net mass loss over all studied periods.

3.3 Impact of ice mask on mass change estimations

A key contribution of this study is the application of time-evolving ice masks for both 1980 and 1850 reconstructions as well as the spatially-resolved mass change estimates since the mid-19th century. Because the most significant mass changes occur at the ice sheet margins — which have retreated substantially since the LIA — failing to account for these shifting boundaries can introduce considerable uncertainty into long-term mass balance estimations. To quantify this effect, we show in Table 3 a

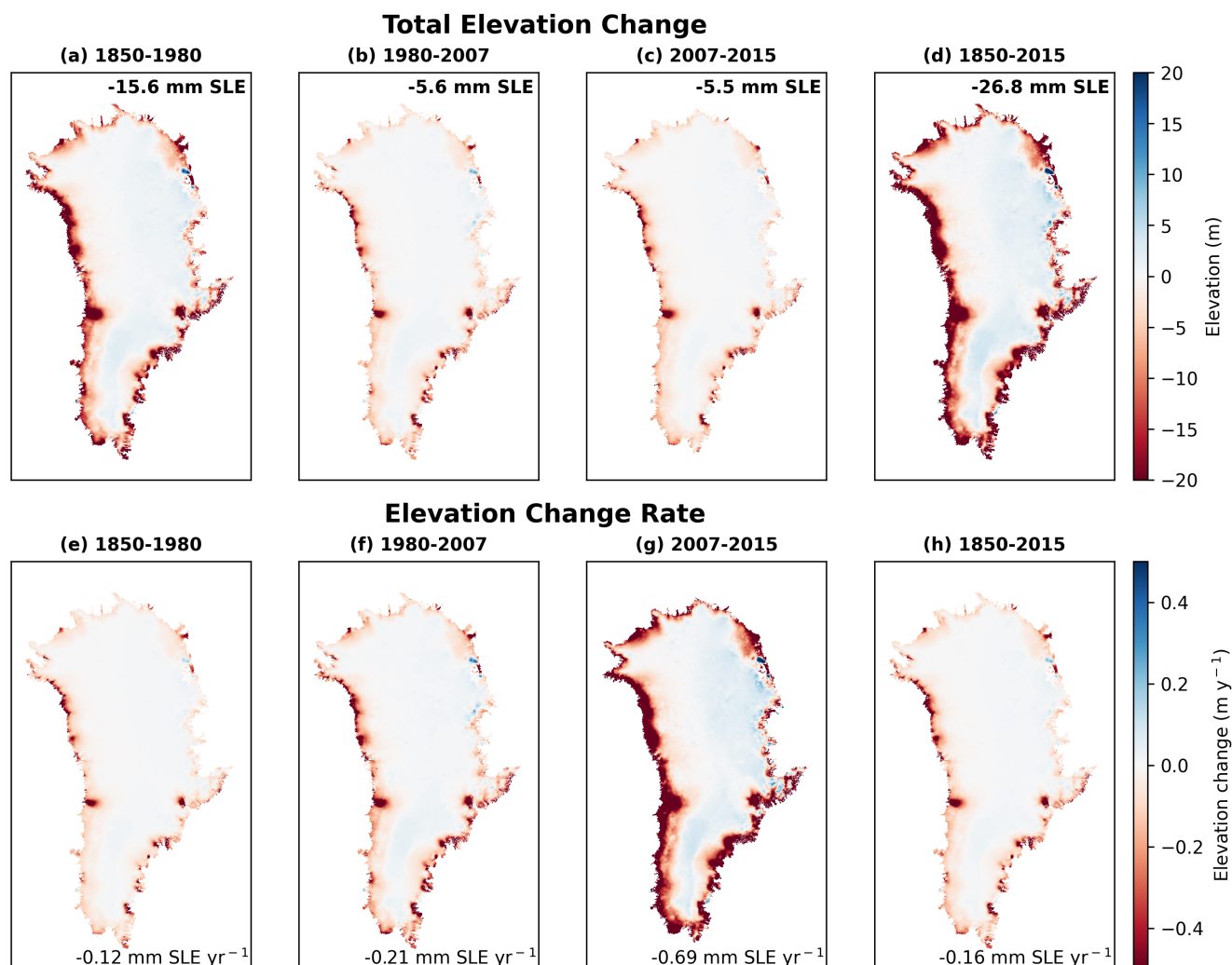


Figure 6. Total elevation change in meters between (a) 1850-1980, (b) 1980-2007, (c) 2007-2015 and (d) 1850-2007 is shown in the first row. Elevation change rate in m yr^{-1} between (a) 1850-1980, (b) 1980-2007, (c) 2007-2015 and (d) 1850-2007 is shown in the second row.

283 comparison of mass change estimates that accounted for time-evolving masks against those that had the ice boundary cropped
 284 to the present-day extent from Rastner et al. (2012), to exemplify the impact of mass change estimates using a static mask from
 285 the contemporary period. Such comparison highlights the potential bias introduced when using a modern ice sheet geometry
 286 to represent historical states.

287 Table 3 reveals the sensitivity of GrIS mass balance estimates to the choice of ice mask. The discrepancy between the
 288 two methods is most pronounced during the post-LIA period. Using the time-evolving representative mask, we estimate a
 289 total mass loss of 5,644.1 Gt (15.6 mm SLE) between 1980-1850. In contrast, the static ESA CCI ice mask (Rastner et al.,



Regional contribution to Greenland SLE by IMBIE basin

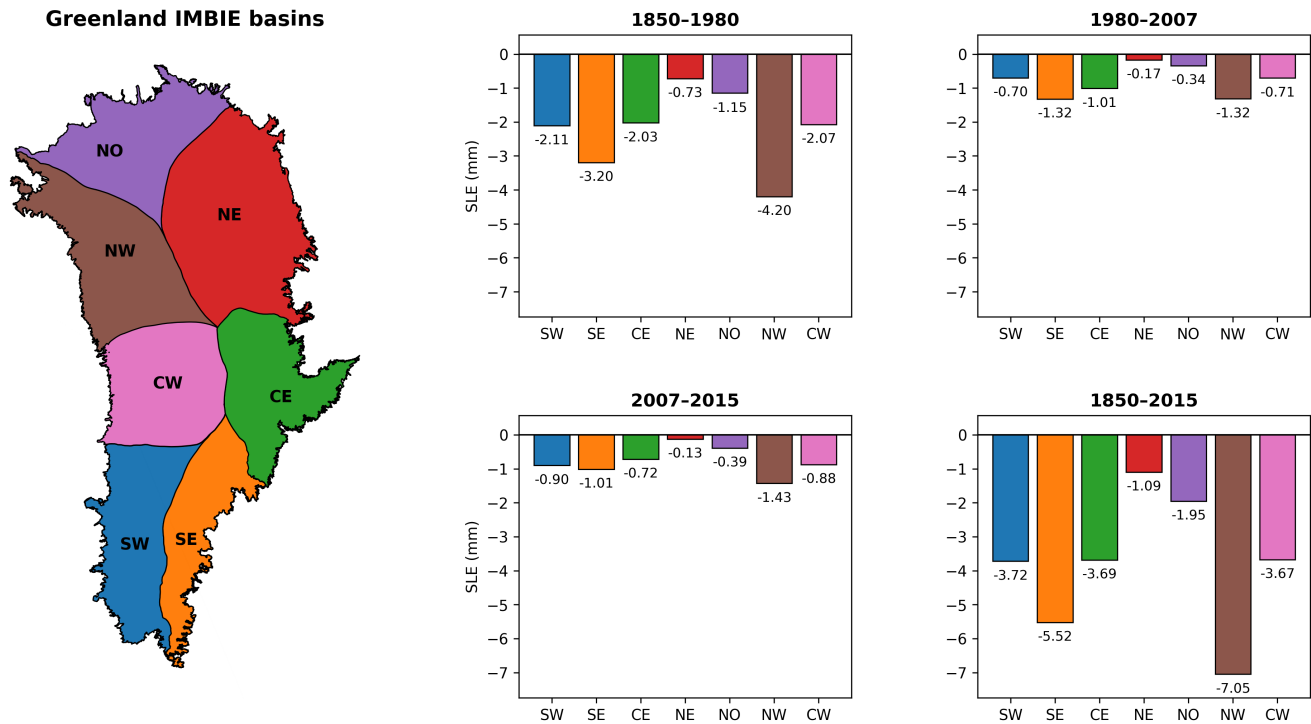


Figure 7. Mass change over four time intervals (1850-1980, 1980-2007, 2007-2015 and the full studied period 1850-2015), shown in terms of mm of sea level equivalent (SLE) over IMBIE basins: Southeast (SE), Central East (CE), Northeast (NE), North (NO), Northwest (NW), Central West (CW), and Southwest (SW)

Time interval	Mass change: Representative ice mask	Mass change: CCI ice mask (Rastner et al., 2012)	Difference
1850-1980	5,644 Gt / 15.6 mm SLE	4,559 Gt / 12.6 mm SLE	1,085 Gt / 3 mm SLE
1980-2007	2,026 Gt / 5.6 mm SLE	1,881 Gt / 5.2 mm SLE	145 Gt / 0.4 mm SLE
2007-2015	1,990 Gt / 5.5 mm SLE	1,990 Gt / 5.5 mm SLE	0 Gt / 0 mm SLE
1850-2015	9,696 Gt / 26.8 mm SLE	8,285.2 Gt / 22.9 mm SLE	1,411 Gt / 3.9 mm SLE

Table 3. Impact of the ice mask on the estimated mass change. Total mass change between studied time intervals: 1850-1980, 1980-2007, 2007-2015 and 1850-2015 using the respective mask for each year, compared to using the European Space Agency (ESA) Climate Change Initiative (CCI) ice mask (Rastner et al., 2012).

2012) yields 4,558.7 Gt (12.6 mm SLE). This difference of 1,085.4 Gt (3 mm SLE) indicates that a static contemporary mask
underestimates early-period mass loss by approximately 19%, likely due to its failure to account for thinning and retreat in
areas that are currently ice-free but were glaciated in the mid-19th century.



The "mask effect" diminishes as the ice sheet geometry approaches the modern state. For the 1980–2007 interval, the difference in mass loss estimates reduces to 144.7 Gt (0.4 mm SLE), which corresponds to 7.1% of the estimates using a representative mask. By the final period (2007–2015), the estimates from both masks converge completely (0 Gt difference), as both 2007 and 2015 reconstructions were based on the same ice mas (i.e., ESA CCI ice mask from (Rastner et al., 2012)). That the decrease in the influence of the ice mask could signify that the mass changes after 1980 were more distributed over the ice sheet interior, while the mass changes in the 1980-1850 period were more concentrated in the margins. That could be a reflection of a dynamic thinning as a response to the 1850-1980 retreat.

Over the full study period (1850–2015), the integrated mass loss using the time-evolving mask is 9,696.2 Gt (26.8 mm SLE), compared to 8,285.2 Gt (22.9 mm SLE) when using the static mask, representing a 14.6% lower estimate. The total difference of 1,411.0 Gt (3.9 mm SLE) highlights that accounting for the evolving ice sheet boundary is critical for accurately quantifying the long-term contribution of the GrIS to global sea level rise.

3.4 Case studies: the three primary outlet glaciers in Greenland

We evaluated the historical thinning and retreat of the three largest outlet glaciers of Greenland: Jakobshavn Isbræ, Helheim, and Kangerlussuaq. Together they hold 1.3 m SLE and drain around 12% of the GrIS surface area (Khan et al., 2020). Analyzing these three glaciers allows us to investigate different patterns of retreat. Both Helheim and Kangerlussuaq are located along the eastern margin of GrIS, while Jakobshavn Isbræ lies on the western margin. Another aspect we can examine is how different bedrock geometries influence glacier retreat. Jakobshavn Isbræ and Kangerlussuaq both lie on a retrograde bed slope, which can increase their susceptibility to non-linear retreat (Schoof, 2007), whereas Helheim rests on a complex but predominantly non-retrograde bed geometry (Khan et al., 2020).

The historical thinning and retreat of Jakobshavn Isbræ glacier since the LIA is shown in Figure 8, together with elevations extracted from a DEM at the LIA trimline (Salmani et al., 2026). The 2007 and 1980 reconstructed profiles demonstrate good agreement with available observations (Fig. 8b). The 1980 reconstruction shows the most discrepancy compared to observations, specifically an abrupt elevation drop towards the ice front near the boundary of the contemporary mask (Rastner et al., 2012) and the region that extends the contemporary mask to the LIA boundary. That transition corresponds to the boundary where the dh/dt was extrapolated in the MD approach, as observational data for dh/dt are unavailable over the contemporary mask. This sharp transition is a methodological artifact of the interpolation method and the dh/dt source, and is less pronounced in the 1850 profile. Jakobshavn Isbræ retreated approximately 25 km between 1850 and 1980, and a further 12 km between 1980 and 2007 (Fig. 8b). In higher elevation sections along the flowline, the model ensemble mean indicates that the glacier thinned ~350 meters between 1850 and 1980, and further ~200 meters between 1980 and 2007, amounting a cumulative thinning of 550 meters (Fig. 8b). The thinning that occurred before 2015 took place while the ice front was positioned over a neutral bed slope, suggesting that these changes were primarily climate-driven rather than dynamically driven, in agreement with previous literature that found that warming of subsurface waters was responsible for the retreat of Jakobshavn Isbræ in the 1990s (Holland et al., 2008). By 2015, however, the glacier front lay on a retrograde slope that becomes



increasingly negative with further retreat, potentially making the glacier more susceptible to accelerated retreat through the combined effects of atmospheric/oceanic warming and dynamic instability.

The reconstructed 1850 elevation at Jakobshavn varies substantially across the ensemble (Fig. 8c). In higher elevations, at 40 km distance along profile, the spread reaches up to 2,500 meters. The lower bound suggests an ice front positioned 40 km inland relative to the reconstructed LIA ice front (Salmani et al., 2026), whereas the upper bound shows elevations reaching 2,500 m that drop abruptly to 800 m along the flowline near the 1980 front position. While both the upper and lower bounds of the ensemble spread include extreme scenarios, they act as boundary constraints that collectively produce an ensemble mean profile closely aligned with observational data (Fig. 1c). This suggests that the range captures the structural uncertainty inherent in the interpolation across the mask boundaries. These results indicate that the main errors in the reconstructions are concentrated around the limits of the contemporary ice sheet boundary due to interpolation errors, or around high elevations due to the wider scale of elevation change.

The historical thinning and retreat of Helheim Glacier since the LIA is shown in Figure 9. Similar to the Jakobshavn Isbræ reconstructions, both the 2007 and 1980 profiles show good agreement with observational data (Fig. 9b), successfully capturing the characteristic undulations in the elevation profile. The glacier thinned by approximately 200 m between 1850 and 1980, followed by an additional 150 m between 1980 and 2007, resulting in a total thinning of 350 m over the study period. The ensemble spread, as shown in Figure 9c, exhibits significant variability. In lower elevations, the spread reaches around 1,000 m (e.g., 400–500 m).

The historical thinning and retreat of Kangerlussuaq Glacier since the LIA is shown in Figure 10. Consistent with our findings for Jakobshavn Isbræ and Helheim, the 1980 and 2015 reconstructed profiles align well with observations over the entire profile (Fig. 10).

Unlike the thinning at Helheim, which is concentrated near the terminus, Kangerlussuaq displays a more sustained, progressive thinning across the entire profile length as it retreats (Fig. 10b). Between 1850 and 1980, the glacier thinned by approximately 200 m, with an additional 50 m of thinning occurring after 1980, resulting in a cumulative vertical thinning of 250 m. The ensemble spread (Fig. 10c) indicates a higher degree of confidence in the mean profile compared to Helheim, with the ensemble members clustering more tightly (higher spread of ~2,500), reflecting a more stable model response for this particular flowline geometry. That associated with the lower magnitude of thinning in Helheim.

4 Discussions

Our mass-change estimates, derived from the ensemble-mean elevation-change maps, show that the GrIS lost 26.8 mm SLE (9,696.2 Gt) between 1850 and 2015, corresponding to a mean loss rate of 0.16 mm SLE yr⁻¹ (57.8 Gt yr⁻¹). The rate increased nearly sixfold, from 0.12 mm SLE yr⁻¹ during 1850–1980 to 0.69 mm SLE yr⁻¹ during 2007–2015. Our estimated mass loss since the LIA falls within the uncertainty range reported by Kjeldsen et al. (2015) (9,013 ± 2,436 Gt). However, their estimate covers 1900–2003, whereas ours covers 1850–2015, reflecting different assumptions regarding the timing and extent of the LIA maximum. When evaluated over a comparable period, our estimate would therefore likely fall toward the lower end

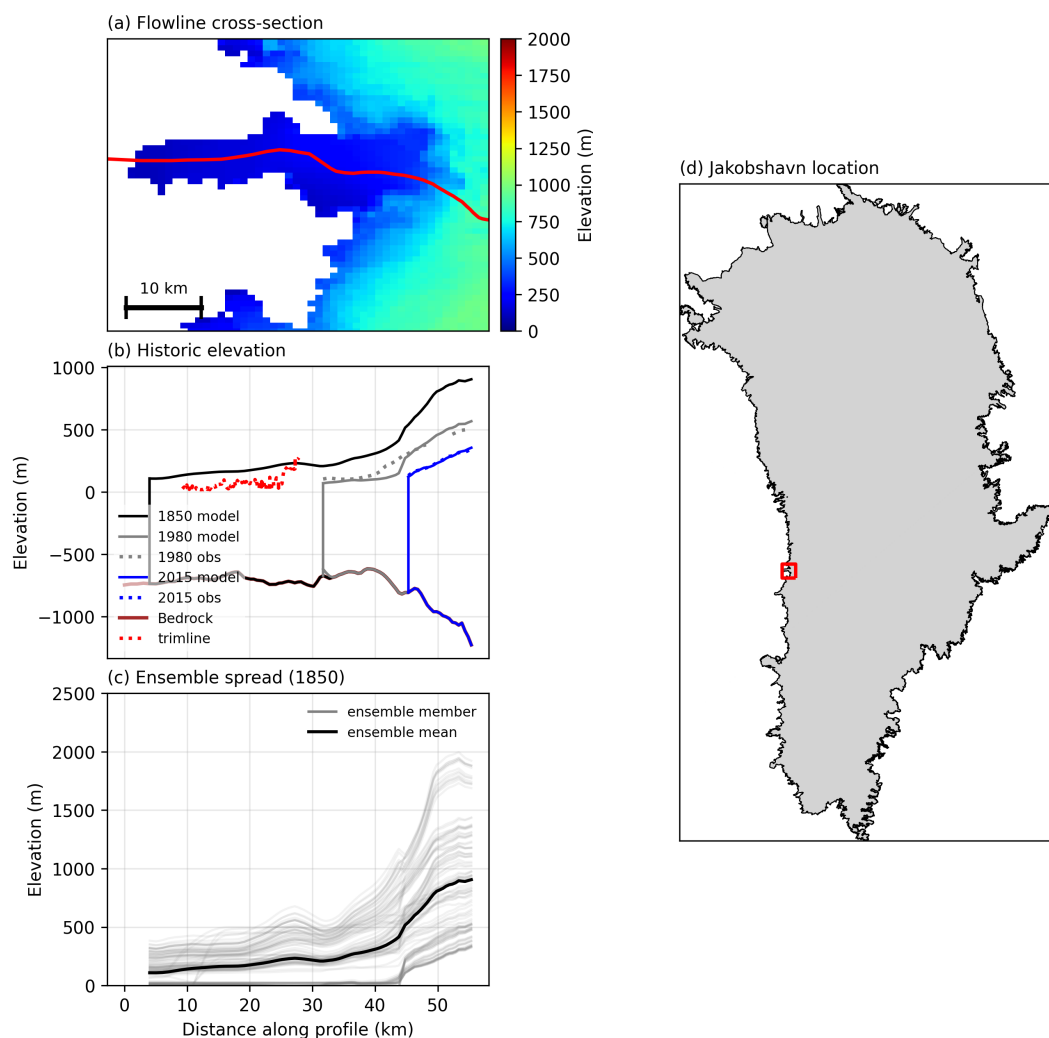


Figure 8. Cross-section of reconstructed and observed ice elevation for Jakobshavn Isbræ since 1850. (a) Plan view of the glacier surface elevation; the red line denotes the location of the approximate flowline cross-section used in panels (b) and (c). (b) Reconstructed surface elevations for 1850 (black solid line), 1980 (grey solid line), and 2015 (blue solid line). Observed elevations for 1980 and 2015 are indicated by grey and blue dotted lines, respectively. (c) Reconstructed 1850 ice-surface elevations for individual ensemble members (gray) and the resulting ensemble mean (black), illustrating the ensemble spread along the transect. (d) Red box indicated the location of Jakobshavn Isbræ relative to the Greenland ice sheet outline. All elevation data are referenced to the WGS84 ellipsoid.

359 of their uncertainty range. Our estimates also differ slightly from those of Mankoff et al. (2021). Although the mass-change
 360 estimates of Mankoff et al. (2021) were used to constrain the individual ensemble members, our final values were recalculated
 361 from the ensemble-mean elevation at each grid cell and therefore do not necessarily reproduce the original constraints exactly.

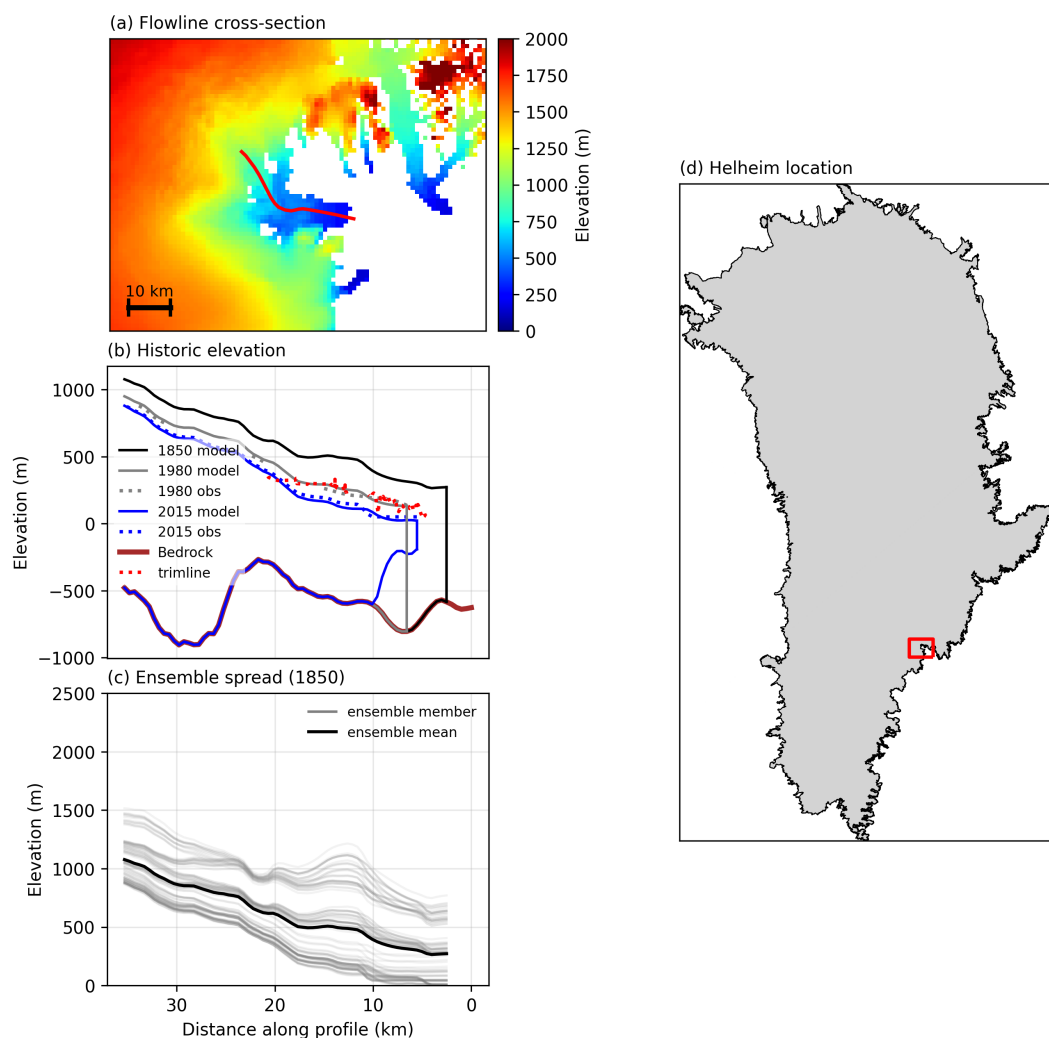


Figure 9. Cross-section of reconstructed and observed ice elevation for Helheim since 1850. (a) Plan view of the glacier surface elevation; the red line denotes the location of the approximate flowline cross-section used in panels (b) and (c). (b) Reconstructed surface elevations for 1850 (black solid line), 1980 (grey solid line), and 2015 (blue solid line). Observed elevations for 1980 and 2015 are indicated by grey and blue dotted lines, respectively. (c) Reconstructed 1850 ice-surface elevations for individual ensemble members (gray) and the resulting ensemble mean (black), illustrating the ensemble spread along the transect. (d) Red box indicated the location of Helheim relative to the Greenland ice sheet outline. All elevation data are referenced to the WGS84 ellipsoid.

362 Accordingly, our results represent a reanalysis of these mass-change estimates rather than an independent estimate and remain
363 subject to uncertainties inherited from Mankoff et al. (2021).

364 Mass changes are not spatially homogeneous across the ice sheet but instead exhibit pronounced mass loss near the margins
365 and modest mass gain in parts of the interior accumulation zone. Interior mass gain may be partly explained by increased

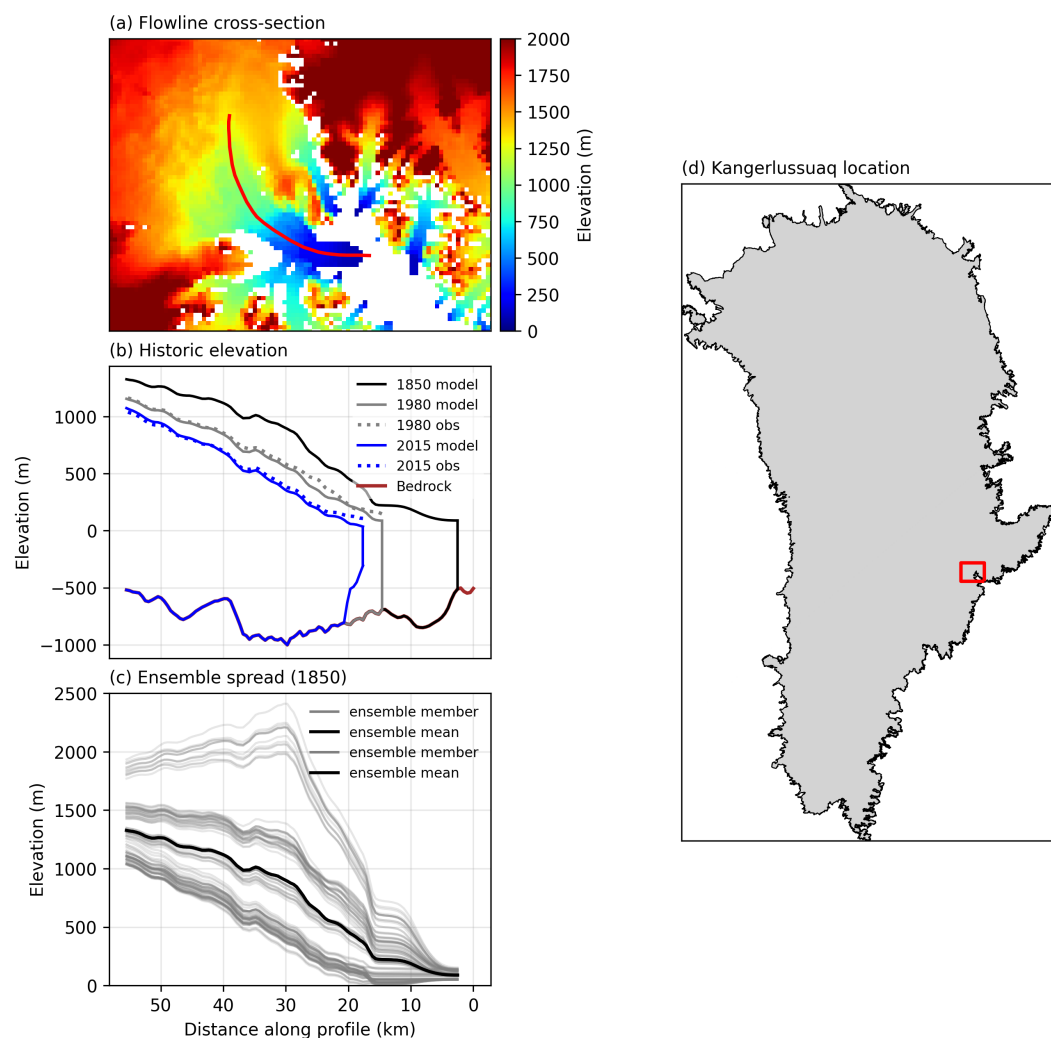


Figure 10. Cross-section of reconstructed and observed ice elevation for Kangerlussuaq since 1850. (a) Plan view of the glacier surface elevation; the red line denotes the location of the approximate flowline cross-section used in panels (b) and (c). (b) Reconstructed surface elevations for 1850 (black solid line), 1980 (grey solid line), and 2015 (blue solid line). Observed elevations for the 1980s and 2015 are indicated by grey and blue dotted lines, respectively, and are used for validation and evaluation of our reconstruction approach. (c) Reconstructed 1850 ice-surface elevations for individual ensemble members (gray) and the resulting ensemble mean (black), illustrating the ensemble spread along the transect. (d) Red box indicated the location of Kangerlussuaq relative to the Greenland ice sheet outline. All elevation data are referenced to the WGS84 ellipsoid.

366 snowfall associated with oceanic and atmospheric warming (Ettema et al., 2009). Khan et al. (2020) also identified cumulative
 367 surface-elevation gain in the ice-sheet interior during 2003–2023, although the area experiencing gain was more spatially
 368 restricted than in our reconstruction for 1850–2015, suggesting that the region of interior thickening has contracted over time.



369 Warming has contrasting effects across the ice sheet: in the ablation zone, a greater fraction of precipitation falls as rain and
370 may enhance surface melt, whereas in the accumulation zone, increased snowfall can produce modest mass gain. The resulting
371 peripheral thinning and interior thickening may steepen the ice-sheet surface and increase the gravitational driving stress acting
372 on outlet glaciers. This increase in surface slope, together with the reduced buttressing provided by floating ice tongues, could
373 contribute to outlet-glacier acceleration. However, the loss of buttressing is expected to exert a stronger influence on glacier
374 acceleration and the associated increase in ice discharge (King et al., 2020). Changes in ice rheology may partly counteract
375 these dynamic effects and can, under some conditions, produce slower velocities in a warmer climate (MacGregor et al.,
376 2016). Because the ice-sheet thermal structure adjusts over timescales longer than a few centuries, however, this rheological
377 response is unlikely to dominate the changes considered here. These considerations suggest that the LIA ice sheet was generally
378 slower-flowing than the present-day ice sheet and that further acceleration may occur in the future, particularly because total
379 precipitation, including both snowfall and rainfall, is projected to increase during the twenty-first century (Boberg et al., 2025).

380 The magnitude of mass change also varied substantially across regions, reflecting differences in both climatic forcing and
381 glacier dynamics across the Greenland Ice Sheet. Most of the mass loss occurred in the NW and SE regions, whereas the NE
382 remained relatively stable throughout the study period. These regional patterns can be compared with the retreat estimates of
383 Salmani et al. (2026) over similar time intervals. Both our reconstruction and the results of Salmani et al. (2026) indicate that
384 the NW experienced the greatest overall ice loss and retreat between 1850 and the 2000s. In their study, the NW exhibited the
385 highest retreat rates during all periods except 2000s–2022, when retreat rates in the CE, SE, and NO regions exceeded those in
386 the NW by approximately $10 \text{ km}^2 \text{ yr}^{-1}$. In contrast, the NE experienced the smallest cumulative mass loss in our reconstruction,
387 yet Salmani et al. (2026) found relatively high retreat rates there during 2000s–2022. This apparent discrepancy likely reflects
388 differences in the time periods represented by the two studies. Our spatial pattern of mass change is constrained by satellite-era
389 observations spanning approximately 1990–2015, which include the period of increased snowfall and temporary mass gain in
390 northeastern Greenland during the 1990s. Consequently, our reconstruction attributes relatively little net mass loss to the NE,
391 whereas the retreat analysis captures the subsequent period of accelerated glacier retreat.

392 Our results and those of Salmani et al. (2026) highlight the strong spatial and temporal variability of the GrIS mass changes
393 makes direct intercomparisons challenging unless the analyses span the same time period. A limitation of our methodology
394 is the assumption of a nearly constant spatial pattern of mass change through time. Specifically, the reconstruction relies on
395 satellite altimetry-derived dh/dt fields, from which spatial weighting factors are calculated and assumed to remain constant
396 throughout the reconstruction period. Consequently, temporal variations in the distribution of mass change that occurred prior
397 to the satellite era are not fully represented. We note that, because our reconstruction focuses on centennial-scale changes, it
398 is expected to be less sensitive to short-term fluctuations in the spatial distribution of mass change decadal fluctuations these
399 spatial patterns.

400 In recent decades, the northern regions increased their contribution to total mass change due to a shift in atmospheric
401 circulation after 1990, which culminated in the advection of warm, humid air from Baffin Bay toward the ice sheet (Noël
402 et al., 2019). The NO and NW regions were particularly affected by this circulation pattern. Concurrently, these large-scale
403 atmospheric changes transported cold, dry air toward southern Greenland. This spatial contrast may explain why our results,



which rely on post-1990 spatial weights to distribute mass change, underestimate the contribution of southern Greenland to the total mass loss over earlier periods. In addition, our results do not resolve the mild mass-gain period around 1960–1990 because it is obscured by the net mass loss calculated over the longer periods analyzed here. Evidence of this period is also reflected in the reduced retreat rates reported by Salmani et al. (2026) between the 1980s and 2000 in the NE and SE regions, while the other regions either remained close to balance or continued to retreat. More generally, the MD approach cannot capture such temporal variations in the spatial pattern of mass change.

Our results improve our understanding of the GrIS response to warming and provide a longer-term context for interpreting contemporary changes. Ice sheets were once regarded as relatively static components of the climate system, responding slowly to climatic forcing. However, observations of rapid, nonlinear changes have challenged this view, demonstrating that an initial climatic perturbation can be amplified by internal feedback mechanisms (Rott et al., 1996; Steiger et al., 2017). Nevertheless, considerable uncertainty remains regarding when the GrIS began to decline in response to anthropogenic warming and how much mass loss is already committed under the climate conditions experienced to date. The termination of the Little Ice Age (LIA) broadly marks the transition from Neoglacial cooling to widespread glacier retreat, but its timing is not precisely defined. Some studies place the end of the LIA around 1900 (Kjær et al., 2022), while others suggest that the GrIS did not begin experiencing net mass loss until after 1980 (Yang et al., 2022). However, observational evidence indicates that some Greenland glaciers began retreating before 1900 (Csatho et al., 2008; Lea et al., 2014), and recent ice-core analysis suggests that warming in Greenland began around 1800 CE, although its timing and magnitude varied regionally and seasonally (Hörhold et al., 2023).

Whether the GrIS began to respond to this warming earlier in the 1800s or later in the late 1990s would reveal how fast the ice sheet can respond to the climate. Our estimation that the GrIS lost 15.6 mm SLE (5,644.1 Gt) between 1850–1980, suggests that the ice sheet was already losing mass and undergoing significant melt before 1980. The 1850–1980 mass loss could have been steady over the entire period, or it could have happened closer to 1980. Since there is evidence of mild cooling and re-advance after 1960, it is more likely that such retreat took place between 1850–1960. These events emphasize that the ice sheet can respond faster to a climate forcing than previously thought. This sensitivity has contrasting implications under different future climate scenarios: sustained warming could promote rapid and potentially irreversible retreat (Gregory et al., 2020), whereas a sustained reduction in greenhouse-gas concentrations could slow or reverse the externally forced response, allowing natural climate variability to exert a greater influence on ice-sheet change.

Our reconstructions can be used by the scientific community in different ways. One example is to initialize or validate ice sheet models. As there is a large uncertainty on how the ice sheet geometry looked like in the past, many ice sheet models that simulate the 19th and 20th centuries are often initialized with the modern geometry or a spun up geometry (Muntjewerf et al., 2020), resulting in a non-representative initial ice volume and geometry that can propagate biases throughout the simulation (Goelzer et al., 2018). Having an available reconstruction of the GrIS in 1850 will allow for models to accurately represent its geometry through time. Another usage of such dataset is to estimate the Glacial Isostatic Adjustment (GIA), as local timing and magnitude of the ice load history have a large effect on GIA models, therefore an accurate representation of ice sheet evolution in the recent past can help close the sea level budget in the last centuries. For example, Woodroffe et al. (2023) used salt marsh sediments combined with GIA modelling to reconstruct the relative sea level of Dronning Marie Dal, a location in southwest



of Greenland. After varying the LIA termination from 1900 to 1700, and applying a 30% reduction in the total amount of mass lost, the RSL mismatch reduced from 30% (5 mm yr^{-1} to 3 mm yr^{-1}).

Our work adds to the previous literature by reconstructing the elevation over the entire ice sheet based on a consistent boundary attributed to the end of the LIA (Salmani et al., 2026), while accounting for the mass changes since the LIA that occurred beyond the extent of contemporary ice. Previous studies that reconstructed the LIA-present day mass changes in Greenland were either limited to the contemporary mask (Kjeldsen et al., 2015), or derived mass changes that accounted for a time evolving boundary, but were limited to only a few outlet glaciers (Khan et al., 2020). The consideration of mass changes over the present-day mask can have a significant impact on the GIA modelling accuracy, as most of the mass changes are concentrated near the margins. That is also important for the ice physics modelling aspect, as the location of the grounding line has a major impact on the sensitivity of outlet glaciers to climate. As accurately modelling the grounding line for historical simulations depend on a realistic representation of the historical ice sheet ice surface elevation, our product can potentially aid in improving the accuracy of ice sheet models.

5 Conclusions

We reconstructed the Greenland-wide ice surface elevation in 1850 and 1980 based on reconstructed and observation-based ice masks for both periods (Salmani et al., 2026). We conceptualized and applied the MD approach, which combines available estimations of the total mass change since 1850 with spatial mass change patterns from satellite observations to build an ensemble of ice elevation distribution in the studied periods. We then validated and evaluated our reconstructions by comparing estimations with available DEMs, and applied our methodology to assess the mass changes between 1850-2015, as well as further investigate the retreat of the three major Greenlandic glaciers: Jakobshavn Isbræ, Kangerlussuaq and Helheim.

We found that using the actual 1850 ice sheet extent, as opposed to using the contemporary extent for 1850, increased the 1850-2015 mass change estimate by 20%. This highlights the importance of ice sheet extent choice when estimating ice mass change. The results were evaluated and validated against observations, showing a good representation of spatial patterns for the elevation distribution. The MD approach enabled the construction of an ensemble of 127 members, capturing a wide range of uncertainties in our estimates.

We assessed mass changes in Greenland since 1850, and found that ice thinning rates during 2007-2015 were nearly 6 times greater than during the 1850-1980 period, reflecting an accelerating response to warming. These results further indicate that the long-term decline of the GrIS likely initiated prior to 1960, suggesting that the ice sheet varies largely in phase with climatic fluctuations and can respond to climate forcing more rapidly than previously thought. These findings have important implications for the future evolution of the ice sheet and its contribution to sea level rise. Under sustained warming, the ice sheet could approach an irreversible retreat more rapidly than anticipated. Conversely, under reduced greenhouse gas concentrations, the ice sheet may remain responsive to natural climate variability, potentially avoiding major increases in sea level contribution.

Our product, freely and openly available to the scientific community, provides a valuable resource for the GIA and ice sheet modelling communities to improve estimates of sea level change and ice sheet evolution.



472 *Code availability.* The code developed for and used in this study will be made publicly available in a suitable repository upon publication of
473 the manuscript.

474 *Data availability.* The datasets generated in this study will be made publicly available in a suitable repository upon publication of the
475 manuscript.

476 Appendix A

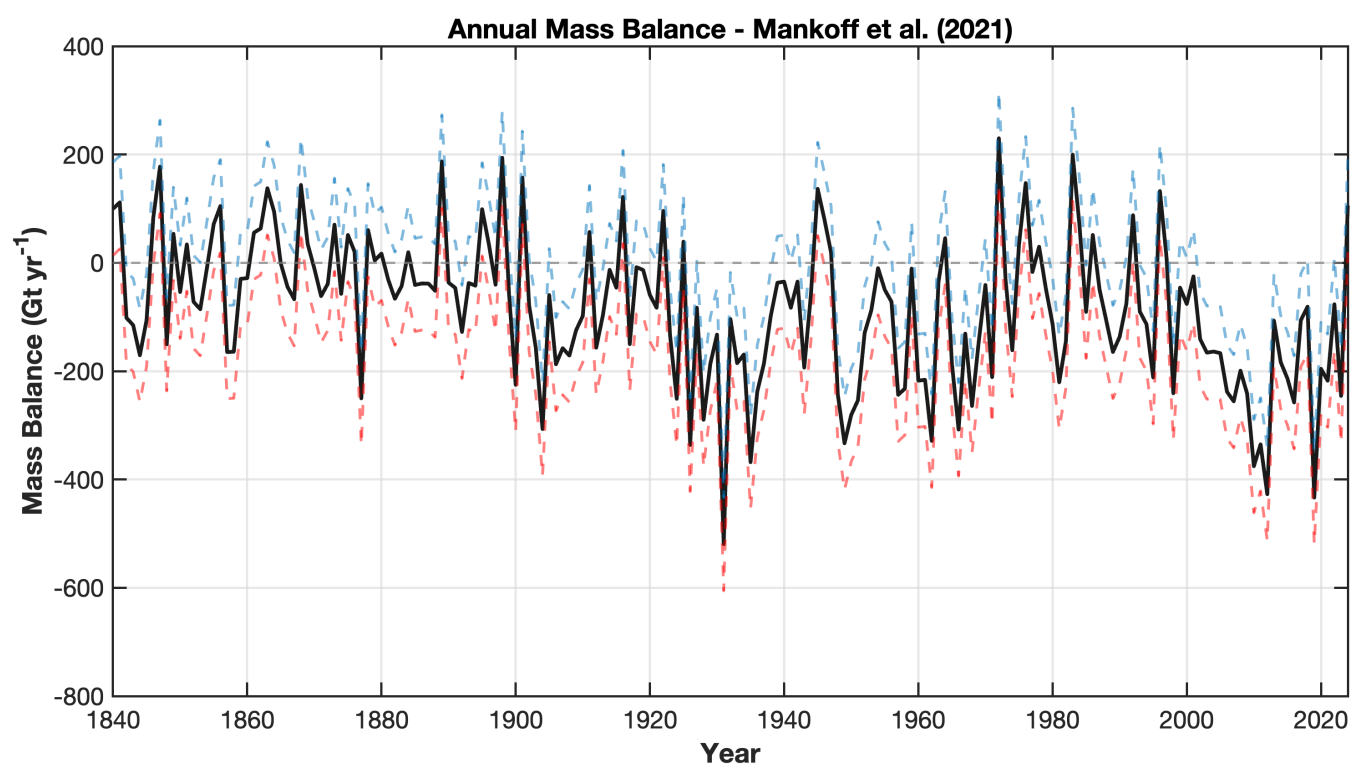


Figure A1. Estimated Greenland ice sheet mass balance from 1840-2025 (black solid lines), with its respective upper and lower uncertainty boundaries (blue and red dashed lines, respectively).

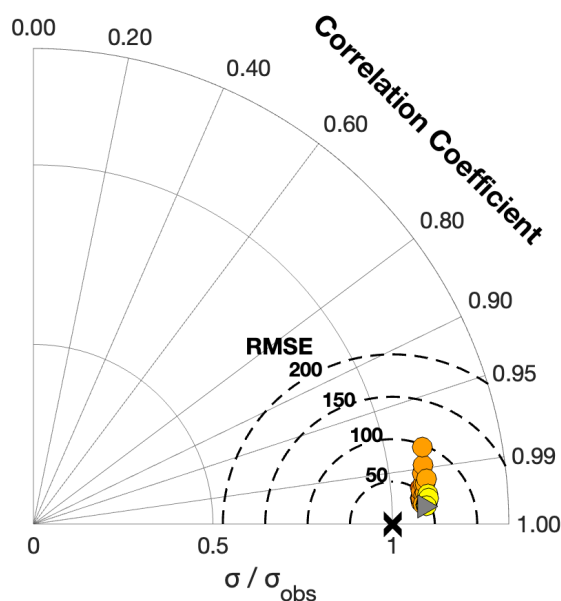


Figure A2. Taylor Diagram showing the performance of the 1980 ensemble of ice surface elevation reconstruction against the 1980 AEROD-DEM (Korsgaard et al., 2016), marked by the black X. The diagram marked the Correlation Coefficient, the ratio between modelled and observed standard deviation (σ/σ_{obs}), and root mean square error (RMSE). Colored circles are the ensemble members, and the gray triangle is the ensemble mean.

477 **A1**

478 *Author contributions.* ACML led the study and contributed to conceptualization, formal analysis, visualization, and writing. SN, BC, JB, and
479 KP contributed to conceptualization and manuscript review. MS and HG provided data and contributed to manuscript review. DF contributed
480 to discussions and manuscript review. JC contributed to discussions.

481 *Competing interests.* At least one of the (co-)authors is a member of the editorial board of The Cryosphere.

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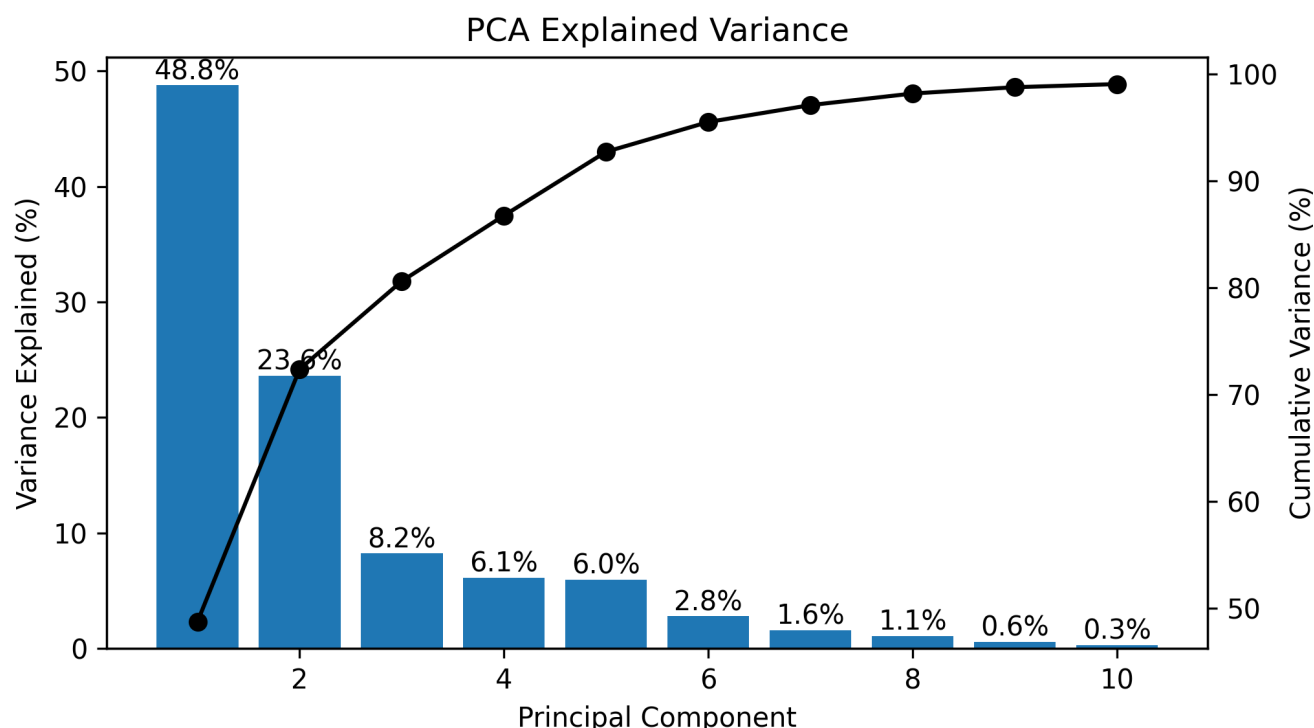


Figure A3. Percentage of variance explained by the first 10 principal components (blue bars) and the corresponding cumulative explained variance (black line) from the principal component analysis (PCA) of the ensemble of reconstructed Greenland ice sheet surface elevations in 1850.

References

- Adhikari, S., Milne, G., Caron, L., Khan, S., Kjeldsen, K., Nilsson, J., Larour, E., and Ivins, E.: Decadal to centennial timescale mantle viscosity inferred from modern crustal uplift rates in Greenland, *Geophysical Research Letters*, 48, e2021GL094040, 2021.
- Aschwanden, A., Fahnestock, M. A., Truffer, M., Brinkerhoff, D. J., Hock, R., Khroulev, C., Mottram, R., and Khan, S. A.: Contribution of the Greenland Ice Sheet to sea level over the next millennium, *Science advances*, 5, eaav9396, 2019.
- Boberg, F., Hansen, N., Mottram, R., Fettweis, X., and van den Broeke, M. R.: 21 st century change in precipitation on the Greenland Ice Sheet using high resolution regional climate models, *EGUsphere*, 2025, 1–20, 2025.
- Box, J. E. and Colgan, W.: Greenland ice sheet mass balance reconstruction. Part III: Marine ice loss and total mass balance (1840–2010), *Journal of Climate*, 26, 6990–7002, 2013.
- Chen, X., Zhang, X., Church, J. A., Watson, C. S., King, M. A., Monselesan, D., Legresy, B., and Harig, C.: The increasing rate of global mean sea-level rise during 1993–2014, *Nature Climate Change*, 7, 492–495, 2017.
- Csatho, B., Schenk, T., Van Der Veen, C. J., and Krabill, W. B.: Intermittent thinning of Jakobshavn Isbrae, West Greenland, since the little ice age, *Journal of Glaciology*, 54, 131–144, 2008.

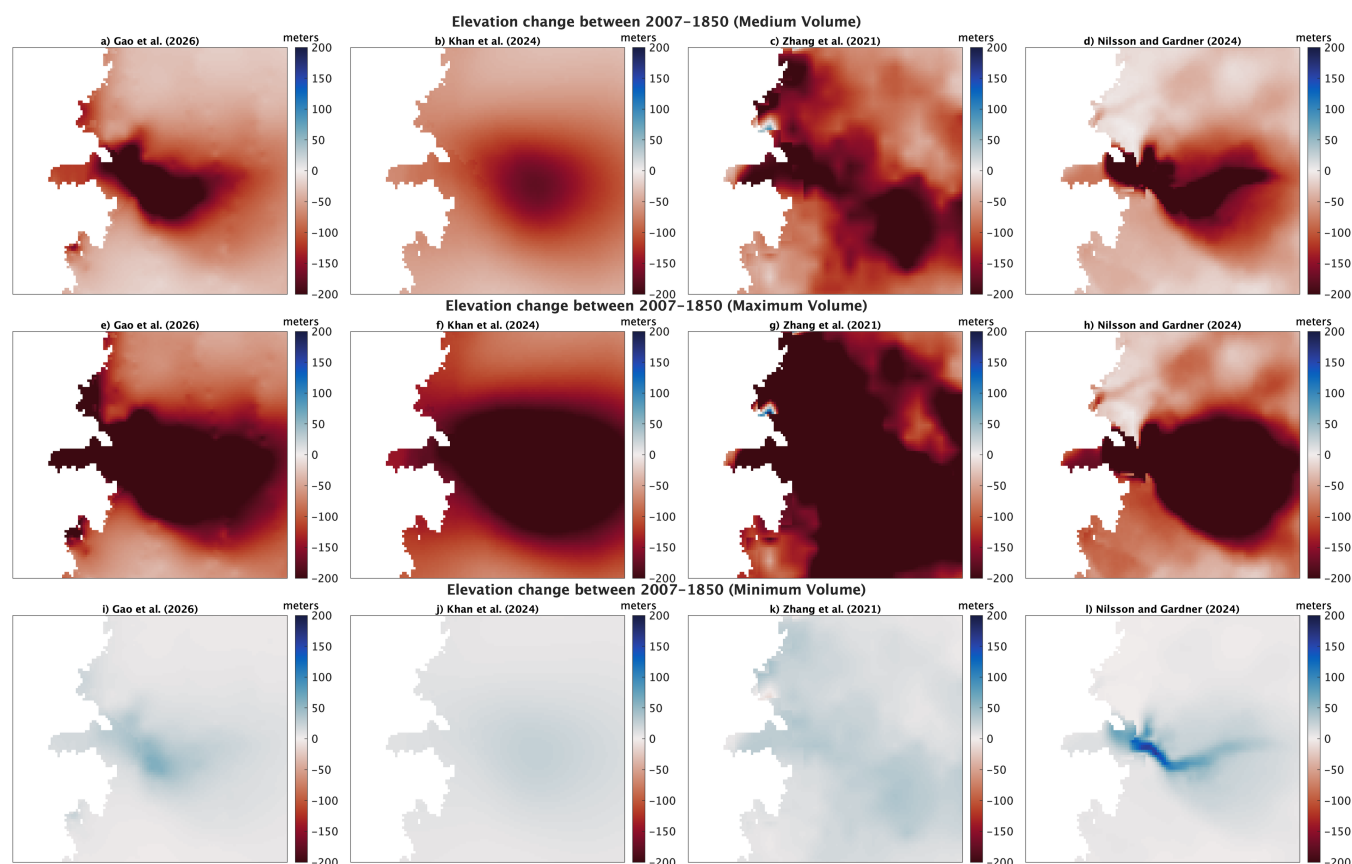


Figure A4. Elevation change between 1850 and 2007 at Jakobshavn Isbræ plotted according to the input mass change between 1850 and 2007 (Median, Maximum and Minimum, respectively) over different rows, and according to the source of dh/dt dataset (Gao et al. (2026), Khan et al. (2024), Zhang et al. (2021) or Nilsson and Gardner (2024), respectively), in the different columns.

- 498 Ettema, J., van den Broeke, M. R., van Meijgaard, E., van de Berg, W. J., Bamber, J. L., Box, J. E., and Bales, R. C.: Higher surface mass
499 balance of the Greenland ice sheet revealed by high-resolution climate modeling, *Geophysical Research Letters*, 36, 2009.
- 500 Gao, H., Csatho, B., Schenk, A. F., Croteau, M. J., Adhikari, S., Parmuzin, I., Schlegel, N.-J., Brils, M., van den Broeke, M. R., Felikson, D.,
501 et al.: Nearly three decades of laser altimetry reveal strong regional contrasts and glacier-driven ice losses in Greenland, 2026.
- 502 Goelzer, H., Robinson, A., Seroussi, H., and van de Wal, R. S.: Recent Progress in Greenland Ice Sheet Modelling, *Current Climate Change*
503 *Reports*, 3, 291–302, <https://doi.org/10.1007/s40641-017-0073-y>, 2017.
- 504 Goelzer, H., Nowicki, S., Edwards, T., Beckley, M., Abe-Ouchi, A., Aschwanden, A., Calov, R., Gagliardini, O., Gillet-Chaulet, F., Gollidge,
505 N. R., et al.: Design and results of the ice sheet model initialisation experiments initMIP-Greenland: an ISMIP6 intercomparison, *The*
506 *Cryosphere*, 12, 1433–1460, 2018.
- 507 Goelzer, H., Nowicki, S., Payne, A., Larour, E., Seroussi, H., Lipscomb, W. H., Gregory, J., Abe-Ouchi, A., Shepherd, A., Simon, E., Agosta,
508 C., Alexander, P., Aschwanden, A., Barthel, A., Calov, R., Chambers, C., Choi, Y., Cuzzzone, J., Dumas, C., Edwards, T., Felikson, D.,
509 Fettweis, X., Gollidge, N. R., Greve, R., Humbert, A., Huybrechts, P., Le clec’h, S., Lee, V., Leguy, G., Little, C., Lowry, D. P., Morlighem,



Regional contribution to Greenland SLE by IMBIE basin

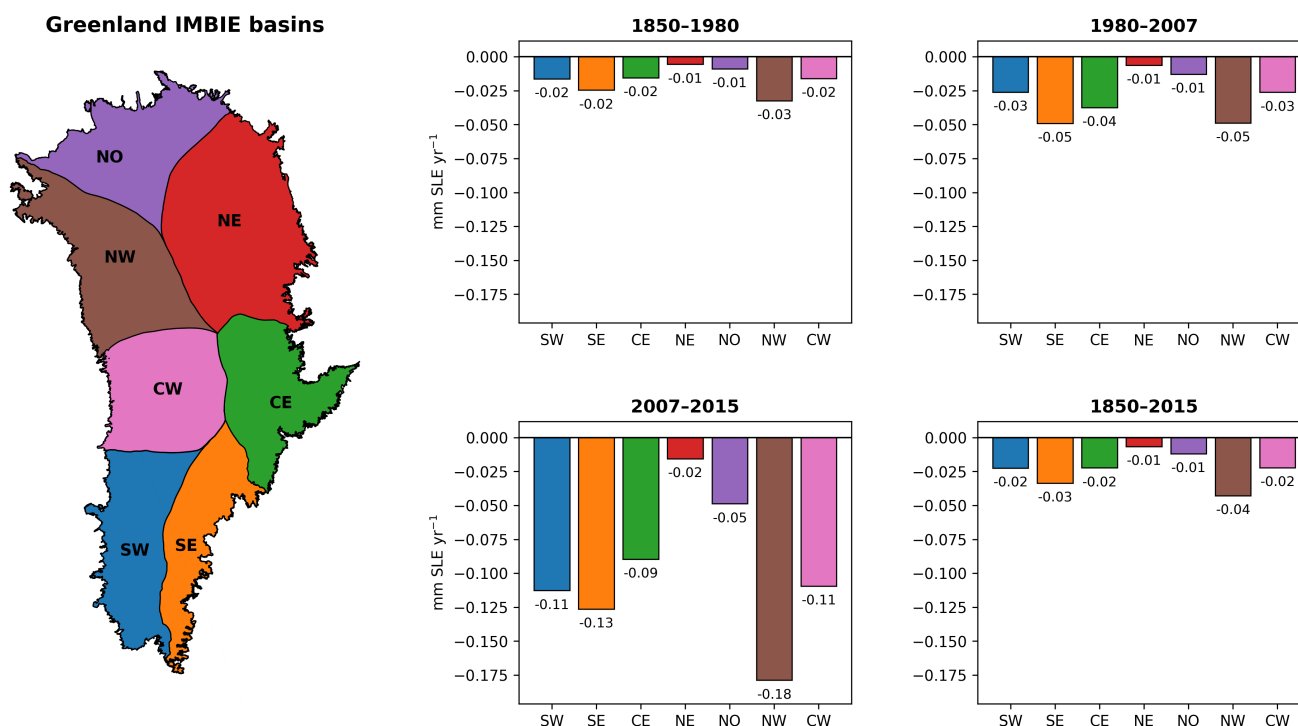


Figure A5. Mass change rate over four time intervals (1850-1980, 1980-2007, 2007-2015 and the full studied period 1850-2015), shown in terms of mm of sea level equivalent (SLE) per year over IMBIE basins: Southeast (SE), Central East (CE), Northeast (NE), North (NO), Northwest (NW), Central West (CW), and Southwest (SW)

- 510 M., Nias, I., Quiquet, A., Rückamp, M., Schlegel, N.-J., Slater, D. A., Smith, R. S., Straneo, F., Tarasov, L., van de Wal, R., and van den
511 Broeke, M.: The future sea-level contribution of the Greenland ice sheet: a multi-model ensemble study of ISMIP6, *The Cryosphere*, 14,
512 3071–3096, <https://doi.org/10.5194/tc-14-3071-2020>, 2020.
- 513 Gregory, J. M., George, S. E., and Smith, R. S.: Large and irreversible future decline of the Greenland ice sheet, *The Cryosphere*, 14,
514 4299–4322, 2020.
- 515 Holland, D. M., Thomas, R. H., De Young, B., Ribergaard, M. H., and Lyberth, B.: Acceleration of Jakobshavn Isbræ triggered by warm
516 subsurface ocean waters, *Nature geoscience*, 1, 659–664, 2008.
- 517 Hörhold, M., Münch, T., Weißbach, S., Kipfstuhl, S., Freitag, J., Sasgen, I., Lohmann, G., Vinther, B., and Laepple, T.: Modern temperatures
518 in central–north Greenland warmest in past millennium, *Nature*, 613, 503–507, 2023.
- 519 Howat, I., Negrete, A., and Smith, B.: MEaSURES Greenland Ice Mapping Project (GIMP) Digital Elevation Model, Version 1,
520 <https://doi.org/10.5067/NV34YUIXLP9W>, 2015.
- 521 Howat, I., Negrete, A., and Smith, B.: MEaSURES Greenland Ice Mapping Project (GrIMP) Digital Elevation Model from GeoEye and
522 WorldView Imagery, Version 2, <https://doi.org/10.5067/BHS4S5GAMFVY>, 2022.

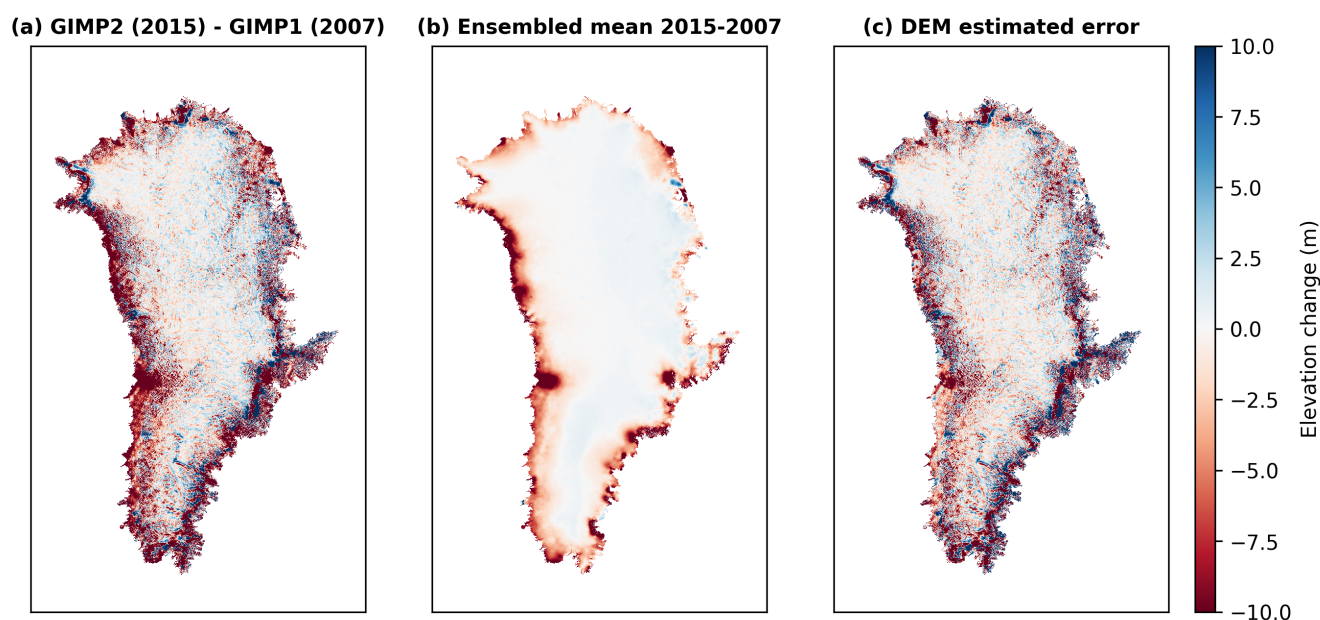


Figure A6. Estimated Digital Elevation Model (DEM) error. (a) Elevation difference between GIMP1 and GIMP2 DEMs; (b) Ensemble mean elevation change pattern for the 2015-2007 period; (c) DEM estimated error (i.e., difference between (a) and (b)).

- 523 Kaufman, D. S., Schneider, D. P., McKay, N. P., Ammann, C. M., Bradley, R. S., Briffa, K. R., Miller, G. H., Otto-Bliesner, B. L., Overpeck,
524 J. T., Vinther, B. M., et al.: Recent warming reverses long-term Arctic cooling, *Science*, 325, 1236–1239, 2009.
- 525 Khan, S. A., Bjørk, A. A., Bamber, J. L., Morlighem, M., Bevis, M., Kjær, K. H., Mouginit, J., Løkkegaard, A., Holland, D. M., Aschwanden,
526 A., et al.: Centennial response of Greenland's three largest outlet glaciers, *Nature Communications*, 11, 5718, 2020.
- 527 Khan, S. A., Seroussi, H., Morlighem, M., Colgan, W., Helm, V., Cheng, G., Berg, D., Barletta, V. R., Larsen, N. K., Kochtitzky, W., et al.:
528 Smoothed monthly Greenland ice sheet elevation changes during 2003–2023, *Earth System Science Data Discussions*, 2024, 1–34, 2024.
- 529 King, M. D., Howat, I. M., Candela, S. G., Noh, M. J., Jeong, S., Noël, B. P., van den Broeke, M. R., Wouters, B., and Negrete, A.: Dynamic
530 ice loss from the Greenland Ice Sheet driven by sustained glacier retreat, *Communications Earth & Environment*, 1, 1, 2020.
- 531 Kjær, K. H., Bjørk, A. A., Kjeldsen, K. K., Hansen, E. S., Andresen, C. S., Siggaard-Andersen, M.-L., Khan, S. A., Søndergaard, A. S.,
532 Colgan, W., Schomacker, A., et al.: Glacier response to the Little Ice Age during the Neoglacial cooling in Greenland, *Earth-Science
533 Reviews*, 227, 103984, 2022.
- 534 Kjeldsen, K. K., Korsgaard, N. J., Bjørk, A. A., Khan, S. A., Box, J. E., Funder, S., Larsen, N. K., Bamber, J. L., Colgan, W., Van Den Broeke,
535 M., et al.: Spatial and temporal distribution of mass loss from the Greenland Ice Sheet since AD 1900, *Nature*, 528, 396–400, 2015.
- 536 Kjeldsen, K. K., Khan, S. A., Colgan, W. T., MacGregor, J. A., and Fausto, R. S.: Time-Varying Ice Sheet Mask: Implications on Ice-Sheet
537 Mass Balance and Crustal Uplift, *Journal of Geophysical Research: Earth Surface*, 125, e2020JF005775, 2020.
- 538 Korsgaard, N. J., Nuth, C., Khan, S. A., Kjeldsen, K. K., Bjørk, A. A., Schomacker, A., and Kjær, K. H.: Digital Elevation Model and
539 orthophotographs of Greenland based on aerial photographs from 1978-1987 (G150 AERODEM) (NCEI Accession 0145405), 2016.



- 540 Lea, J. M., Mair, D. W., Nick, F. M., Rea, B. R., Weidick, A., Kjaer, K. H., Morlighem, M., Van As, D., and Schofield, J. E.: Terminus-driven
541 retreat of a major southwest Greenland tidewater glacier during the early 19th century: insights from glacier reconstructions and numerical
542 modelling, *Journal of Glaciology*, 60, 333–344, 2014.
- 543 MacGregor, J. A., Colgan, W. T., Fahnestock, M. A., Morlighem, M., Catania, G. A., Paden, J. D., and Gogineni, S. P.: Holocene deceleration
544 of the Greenland ice sheet, *Science*, 351, 590–593, 2016.
- 545 Mankoff, K. D., Fettweis, X., Langen, P. L., Stendel, M., Kjeldsen, K. K., Karlsson, N. B., Noël, B., Van Den Broeke, M. R., Solgaard, A.,
546 Colgan, W., et al.: Greenland ice sheet mass balance from 1840 through next week, *Earth System Science Data*, 13, 5001–5025, 2021.
- 547 McKay, N. P., Kaufman, D. S., Routson, C. C., Erb, M. P., and Zander, P. D.: The onset and rate of Holocene Neoglacial cooling in the Arctic,
548 *Geophysical Research Letters*, 45, 12–487, 2018.
- 549 Morlighem, M., Williams, C., Rignot, E., An, L., Bamber, J., Chauche, N., Dowdeswell, J., Dorschel, B., Holland, D., Holland, D., et al.:
550 BedMachine v3: Complete bed topography and ocean bathymetry mapping of Greenland from multi-beam radar sounding combined with
551 mass conservation, 2017.
- 552 Mouginot, J., Rignot, E., Bjørk, A. A., Van den Broeke, M., Millan, R., Morlighem, M., Noël, B., Scheuchl, B., and Wood, M.: Forty-six
553 years of Greenland Ice Sheet mass balance from 1972 to 2018, *Proceedings of the national academy of sciences*, 116, 9239–9244, 2019.
- 554 Muntjewerf, L., Petrini, M., Vizcaino, M., Ernani da Silva, C., Sellevold, R., Scherrenberg, M. D., Thayer-Calder, K., Bradley, S. L., Lenaerts,
555 J. T., Lipscomb, W. H., et al.: Greenland Ice Sheet contribution to 21st century sea level rise as simulated by the coupled CESM2. 1-CISM2.
556 1, *Geophysical Research Letters*, 47, e2019GL086 836, 2020.
- 557 Nilsson, J. and Gardner, A. S.: Elevation change of the Greenland Ice Sheet and its peripheral glaciers: 1992–2023, *Earth System Science*
558 *Data Discussions*, 2024, 1–28, 2024.
- 559 Noël, B., van de Berg, W. J., Lhermitte, S., and van den Broeke, M. R.: Rapid ablation zone expansion amplifies north Greenland mass loss,
560 *Science advances*, 5, eaaw0123, 2019.
- 561 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.,
562 et al.: Mass balance of the Greenland and Antarctic ice sheets from 1992 to 2020, *Earth System Science Data Discussions*, 2022, 1–33,
563 2022.
- 564 Rastner, P., Bolch, T., Mölg, N., Machguth, H., Le Bris, R., and Paul, F.: The first complete inventory of the local glaciers and ice caps on
565 Greenland, *The Cryosphere*, 6, 1483–1495, 2012.
- 566 Roe, G. H., Christian, J. E., and Marzeion, B.: On the attribution of industrial-era glacier mass loss to anthropogenic climate change, *The*
567 *Cryosphere*, 15, 1889–1905, 2021.
- 568 Rott, H., Skvarca, P., and Nagler, T.: Rapid collapse of northern Larsen ice shelf, Antarctica, *Science*, 271, 788–792, 1996.
- 569 Salmani, M., Csatho, B., Briner, J., Nowicki, S., Parmuzin, I., Eberhardt, H., Gao, H., Luzardi, A. C., and Talebigheshlaghi, G.: Nearly half
570 of Greenland’s post-Little Ice Age area loss occurred since 2000, 2026.
- 571 Schoof, C.: Ice sheet grounding line dynamics: Steady states, stability, and hysteresis, *Journal of Geophysical Research: Earth Surface*, 112,
572 <https://doi.org/https://doi.org/10.1029/2006JF000664>, 2007.
- 573 Steiger, N., Nisancioglu, K. H., Åkesson, H., de Fleurian, B., and Nick, F. M.: Non-linear retreat of Jakobshavn Isbræ since the Little Ice
574 Age controlled by geometry, *Cryosphere Discuss*, 2017, 1–27, 2017.
- 575 Thomas, R., Frederick, E., Krabill, W., Manizade, S., and Martin, C.: Progressive increase in ice loss from Greenland, *Geophysical Research*
576 *Letters*, 33, 2006.



- 577 Woodroffe, S. A., Wake, L. M., Kjeldsen, K. K., Barlow, N. L. M., Long, A. J., and Kjær, K. H.: Missing sea level rise in southeastern
578 Greenland during and since the Little Ice Age, *Climate of the Past*, 19, 1585–1606, <https://doi.org/10.5194/cp-19-1585-2023>, 2023.
- 579 Yang, H., Krebs-Kanzow, U., Kleiner, T., Sidorenko, D., Rodehacke, C. B., Shi, X., Gierz, P., Niu, L., Gowan, E. J., Hinck, S., et al.: Impact
580 of paleoclimate on present and future evolution of the Greenland Ice Sheet, *Plos one*, 17, e0259 816, 2022.
- 581 Zhang, B., Wang, Z., An, J., Liu, T., and Geng, H.: A 30 year monthly 5 km gridded surface elevation time series for the Greenland Ice Sheet
582 from multiple satellite radar altimeters, *Earth System Science Data Discussions*, 2021, 1–24, 2021.