Spatial and temporal mass loss from the Greenland Ice Sheet since 1900

Kristian K. Kjeldsen[1], Niels J. Korsgaard[1], Anders A. Bjørk[1], Shfaqat A. Khan[2], Svend Funder[1], Nicolaj K. Larsen[3], Jonathan L. Bamber[4], Jason E. Box[5], William Colgan[5], Michiel van den Broeke[6], Marie-Louise Siggaard-Andersen[1], Chris Nuth[7], Anders Schomacker[1], Antony J. Long[8], Sarah A. Woodroffe[8], Bo Vinther[9], Camilla S. Andresen[5], Eric Steen Hansen[1], Bent V. Odgaard[3], Jesper Olsen[10], Ruud Hurkmans[4], Eske Willerslev[1] and Kurt H. Kjær[1]*

[1]Centre for GeoGenetics, Natural History Museum, University of Copenhagen, Copenhagen, Denmark.

[2]DTU Space - National Space Institute, Technical University of Denmark, Department of Geodesy, Kgs. Lyngby, Denmark.

[3]Department of Geoscience, Aarhus University, Aarhus, Denmark.

[4]Bristol Glaciology Centre, University of Bristol, Bristol, United Kingdom.

[5]Geological Survey of Denmark and Greenland, Department of Marine Geology and Glaciology, Copenhagen, Denmark.

[6]Institute for Marine and Atmospheric Research, Utrecht University, Utrecht, The Netherlands.

[7]Department of Geosciences, University of Oslo, Oslo, Norway

[8]Department of Geography, University of Durham, Durham, United Kingdom.

[9]Niels Bohr Institute, Centre for Ice and Climate, University of Copenhagen, Copenhagen, Denmark.

[10]Department of Physics and Astronomy, Aarhus University, Aarhus, Denmark.

*Corresponding author, e-mail: kurtk@snm.ku.dk

The response of the Greenland Ice Sheet (GrIS) to changes in global temperature during the 20th century remains contentious[1]. This is largely due to difficulties in estimating spatial- and temporal distribution of ice mass changes prior to 1992, where no Greenland-wide observations are available[2]. Previously, the only estimates of 20th century change are derived through surface mass balance (SMB) reconstruction and an empirical relationship with ice discharge[3–5], while other centennial long estimates are based on energy balance modeling[6] and glacier mass balance - and climate modeling[7]. Consequently, no estimates of the contribution from the GrIS to global mean sea level (GMSL) prior to 1990 are included in the Fifth Assessment Report (AR5; Ref[8]) of the Intergovernmental Panel on Climate Change (IPCC). Here, we calculate spatial mass loss across the entire GrIS from 1900 to the present using aerial imagery from the 1980s to create a digital elevation model, thus allowing for high resolution and accurate mapping of geomorphic features related to the maximum extent of the GrIS during the Little Ice Age ($\mathrm{LIA_{max}}$)[9]. We estimate the total mass loss and its spatial distribution for three periods: 1900-1983 (-75.1±27.8 Gt/yr), 1983-2003 (-73.8±37.1 Gt/yr) and 2003-2010 (-186.4±18.9 Gt/yr). Intriguingly, many areas undergoing current changes are identical to those that experienced considerable thinning throughout the 20th century, and thus we predict that the spatial mass loss pattern will continue into the future, at least until glaciers become grounded. Using two SMB-models[10,11] we partition the SMB contribution which shows significant decrease in surface accumulation since 2003, while the dynamic residual is persistent over the past 110 years. Overall, our observational-based findings reveal that during the 20th century the GrIS has contributed some 25.0 ± 8.8 mm of GMSL rise thus adding to the closure of the 20th century sea level budget.

Estimates of mass change of ice sheets during the past decades are derived using a number of observational based methods, e.g. Input-Output Method (IOM), satellite gravimetry, or through surface elevation change rates (dH/dt), using satellite and airborne observations extending back to 1992[2]. However, prior to 1992 estimates are based on modeling exercises that rely on historical climate- and ice discharge observations extrapolated to yield integrated Greenland-wide estimates of past changes[3–7]. However, these approaches lack vital information on long-term spatial patterns of mass loss, which provide a context necessary in order to understand present and future mass loss processes[9].

We use aerial stereo photogrammetric imagery recorded during 1978-1987 to map $\mathrm{LIA}_{\mathrm{max}}$ trimlines and lateral- and end-moraines, thereby quantify the vertical ice surface difference between the $\mathrm{LIA}_{\mathrm{max}}$ and 1978/87 (Fig. 1, Methods), with a relative vertical uncertainty of the mapped geomorphic features of 1m(Ref.[9]). Considering that the GrIS was near balance in the 1970s - 1980s[3], we use 1983 to obtain a rate of mass loss. Elevation differences after 1983 are derived from airborne- and satellite altimetry, combined with a digital elevation model developed from the aerial imagery (Methods). We use this geodetic approach to calculate spatially distributed thinning patterns and ice mass loss of the GrIS for three periods (Fig. 2a-c); $\mathrm{LIA}_{\mathrm{max}}$ (1900) to 1983, 1983 to 2003, and 2003 to 2010. We note that some areas of the GrIS are omitted due to the lack of LIA data points (Methods).

Figure 2a-c shows annual mass loss rates for the three periods. We calculate a net mass loss of -6233±2307 Gt (-75.1±27.8 Gt/yr) since the onset of glacier retreat from their $\mathrm{LIA}_{\mathrm{max}}$ positions to 1983 (Fig. 2a). In northwest Greenland, where the majority of the ice sheet discharges through marine outlet glaciers, we find significant and widely distributed thinning, leading to a mass loss of -27.6±6.2 Gt/yr corresponding to 37% of the total mass loss (Table 1). In west and southwest Greenland, we find peripheral thinning mainly near the two large marine outlet glaciers Jakobshavn Isbræ (JI) and Kangiata Nunata Sermia (KNS), while significant changes also occurred at the land-based Frederikshåb Isblink (FIB) and Qassimiut Lobe (QL), the latter being intersected by relatively smaller fjords draining its eastern part. Along the southeast coast, a region dominated by large marine outlet glaciers, thinning was extensive and in some areas it has propagated almost to the ice divide, causing a mass loss of -30.6±4.4 Gt/yr (41%). Here two of the largest outlet glaciers in Greenland[3], Kangerdlussuaq (KG) and Helheim (HG), show distinct different patterns, with KG being the single largest contributor (-10.6±1.2 Gt/yr) to the total mass loss, accounting for 14% of the total mass loss (Extended dataset XX), while HG appears to be near balance, despite glacier front positions reveal considerable inter-period variability[9,12]. In east, northeast, and north Greenland thinning is less extensive and in some areas the ice margin remains at or very close its $\mathrm{LIA}_{\mathrm{max}}$ position.

We calculate a net mass loss of -1475±741 Gt (-73.8±37.1 Gt/yr) for the period spanning 1983 to 2003 (Fig. 2b). Generally, peripheral thinning was less widespread and many of the largest outlet glaciers showed a decreasing mass loss (Table 1). During this period 83% of the total mass loss occurs in the northwest and southeast while JI alone accounts for 6%, indicating that loss in the remainder of the ice sheet is limited. Interestingly, we find a relatively high mass loss for an epoch that encompasses the 1980s, a periods when the ice sheet was considered near balance[3], while an increasing mass loss in the late 1990s and early 2000s[13] would counterbalance, and thus suggest that our mass loss rate spanning two decades is in agreement with other studies[3,13].

Between 2003 and 2010 we estimate a mass loss of -1305±132 Gt, -186.4±18.9 Gt/yr based on the employed ice mask (Fig. 2c), whilst using the same ice mask as (Ref.[14]) we arrive at a mass loss of -250 ± 21 Gt/yr, in agreement with others[2,13]. We find that net mass loss more than doubled relative to the former period, but also relative to the net mass loss rate throughout the 20th century. The latter observation is comparable to other studies that also identify accelerated mass loss in the early 21st century relative to late 20th century[3,5,15]. Many areas undergoing current changes are identical to those which experienced considerable thinning throughout the 20th century, with the exception of HG (Fig. 2a-c). Consequently, comparing the 20th century thinning pattern to that of the last decade, and assuming a similar warming pattern, we argue that the present mass loss pattern will hold also for future ice sheet mass loss, at least until marine outlet glaciers become grounded.

To assess the components of 20th century mass loss we use updated SMB estimates from (ref.[10])(Fig. 2D-F), hereinafter referred to as $\mathrm{SMB}_{\mathrm{Box}}$, which has been refined on a number of points, e.g. by implementing a more physical based retention scheme, and been revised to increase agreement with RACMO2/GR[11] (Methods). A dynamic residual is calculated by subtracting surface lowering due to SMB processes from the total mass loss (Fig. 2G-I). Not surprisingly we find a large dynamic contribution to mass loss in the SE and NW, dominated by marine-terminating glaciers, whilst in other regions the ice margin experience a positive dynamic mass contribution to compensate as the lowering of the ice surface due to SMB exceeds the net surface lowering. Our results suggest that the variability of the dynamic contribution to mass loss of the GrIS since the

LIA_{max} is less than the uncertainties during the three intervals 1900-1983, 1983-2003 and 2003-2010. Previous results have attributed the mass loss during 2000-2008 to being equally split between persistent decreasing SMB and increasing discharge[16],while more recent estimates suggest changes in SMB is becoming the dominant driver for the increasing mass loss[14,17]. Here, we find that, albeit short-term dynamic variability may affect the mass loss, on centennial timescale the dominant driver for mass loss of the ice sheet, is the variability of SMB processes (Fig. 3a).

The temporal variability of the mass balance during the 20th century (TMB) is examined using SMB_{Box} and modeled ice discharge derived as function of runoff using a 6-years trailing average, in a similar approach as other studies[3,5,18], using ice discharge data from (Ref.[17]) (Methods). During 1900-2010 we find a total mass loss of -10071 ± 1346 Gt (28.0 ± 3.7 mm GSLR), which, despite that we use a smaller ice mask, is slightly higher than that of (Ref.[5]). Although we note that the TMB-method is particularly sensitive to the ice discharge used as input, we find good agreement with the mass loss found using the geodetic method presented above; thus adding confidence to the results presented in this study.

Our TMB-method suggests considerable variability in the mass loss from the GrIS during the 20th century (Fig. 3b). The highest rates occur during the late 1920s and early 1930s, a period during which the rate of temperature increase was higher than during the recent decade[19], and which also coincides with large glacial retreat in southeast Greenland[12]. Following substantially lower mass loss rate during the 1940s, even close to balance, our model suggest mass loss rates during the 1950s and 1960s similar to those observed during the late 1990s and early 21st century[13], while from 1960s to 1980s our results are comparable to other modeling results which suggest mass loss during the 1960s and an ice sheet near balance during the 1970s-1980s[3], although, due to a smaller ice mask, our numbers may be higher.

In the AR 5(ref.[8]) the 20th century GMSL budget was assessed by comparing GMSL derived from tide-gauges against observations of the different contributors, leading to a residual during 1901-1990. However, prior to 1993 no observational records of the contribution from GrIS or the Antarctic Ice Sheet (AIS) are included. The failure to close the GMSL budget for the period 1901-1990 has been attributed to underestimation of the individual contributors, including the polar ice sheets[1,8]. A recent study revisited the 20th century GMSL using a probabilistic technique only to find a considerable lower rate of 20th century GMSL rise prior to 1993, thus closing the budget without including contributions from the polar ice sheets[20]. However, our results show that during the 20th century the GrIS has contributed significantly to GMSL rise (Fig. 3c). In particular the geodetic approach that is based on observations from aerial imagery, which shows considerable thinning along the margin of the ice sheet, is regarded as a conservative minimum estimate of mass loss (Extended discussion). Summarized we find a total mass loss of 9013 ± 3181 Gt from the LIAmax (1900) to 2010, equivalent to 25.0 ± 8.8 mm of global sea level rise (GSLR), and -10071 ± 1346 Gt (28.0 ± 3.7 mm GSLR) using our TMB-method. Comparing our results to GMSL recontructions[20–22] shows that during the 1900-1983 the contribution from GrIS to GMSL at least ranged between 10.7%-17.4%, whilst during 1983-2003 and 2003-2010 the contribution from GrIS ranges between 10.3%-15.8% and 11.1%-17.8%, respectively (Fig. 3d). For comparison using the same ice mask as (Ref. [14]) we find that during 2003-2010 the contribution to GMSL rise ranged between 14.9%-23.9%.

Our results, based on observations from aerial imagery, provide a spatial pattern of a centennial-long, conservative estimate of mass loss from the GrIS, which enables a long-term record of the dynamic contribution to mass loss applicable in modeling exercises, while importantly also adding to the closure of the 20th century GMSL budget[1,8].

Method/SI

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Author contributions

Additional information

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Captions

Figure 1: 3D-models of Kangerdlussuaq Glacier. a, The reconstructed Little Ice Age (LIA) -ice surface and **b,** The 2013 ice surface. The LIA marks a cold period and lead to the expansion of the GrIS, often framed within the time interval from 1450-1850 [23]. A spectacular indication that the GrIS has been shrinking over the last century is the fresh trimlines, i.e. pronounced boundaries between abraded and less abraded bedrock on valley sides and fresh non-vegetated moraines close to the present glacier fronts in many parts of Greenland (Fig. 1), both, considered to mark the culmination of LIA-advances and mainly formed during the 1700s or at the end of the 1800s [24]. We assign "1900" AD as a Greenland-wide time stamp of when the glaciers started retreat from their LIA maximum position (LIA_{max}), albeit we note that this varies regionally and locally[9,25,26]. So far any attempt to reconstruct long-term surface elevations beyond the scope of individual outlet glaciers has been prevented by the lack of a proper Greenland-wide elevation model, which allows accurate observations of moraine- and trimline heights representing the former ice sheet extent during the LIA.

Figure 2: Surface elevation change rates in Greenland since the LIA maximum. a-c, Observed surface elevation change rates in m yr^{-1} during LIA_{max} (1900) -1983 (a), 1983-2003 (b), and 2003-2010 (c). **d-f,** Total elevation change rates in m yr^{-1}owing to SMB fluctuations using SMB_{BOX} during LIA_{max} (1900) -1983 (d), 1983-2003 (e), and 2003-2010 (f). **g-i,** Dynamically driven residual in elevation rates in m yr^{-1} during LIA_{max} (1900) -1983 (g), 1983-2003 (h), and 2003-2010 (i). Some areas have been omitted due to lack of available LIA data (Extended Methods).

Figure 3: Mass loss and implication of GMSL. a, Black bars represent the mass loss derived from the geodetic approach covering the three periods LIA_{max} (1900) -1983, 1983-2003, and 2003-2010, while dotted gray lines, solid gray lines, and gray bars shows annual and 5-year running mean, and averaged results from the TMB reconstruction, respectively. **b,** Blue bars show SMB_{BOX} in m yr^{-1} and red bars represent the dynamic residual (in m yr^{-1}), whilst the green line shows the ice discharge as function of runoff using a 6-years trailing average. The results suggest that for long-term mass loss SMB variability is the governing factor, while on centennial time-scale the dynamic residual is more constant with more

short-termed variability. **c,** Cumulative mass loss since $\mathrm{LIA}_{\mathrm{max}}$ from the geodetic approach (black line) and from the TMB reconstruction (gray line). **d,** Considering different solutions of the 20th century GMSL rise [20–22], our results shows the minimum relative input of the GrIS to GMSL rise, which ranges between 10.3%-17.8%, during $\mathrm{LIA}_{\mathrm{max}}$ (1900) - 2010; thus underlining a significant contribution from Greenland during the 20th century.

Table 1. **Mass Balance and components during LIAmax(1900) - 2010.** Mass loss, $\mathrm{SMB}_{\mathrm{Box}}$, and the dynamic residual of the Greenland Ice Sheet and the individual regions derived using the geodetic approach.