# Missing sea-level rise in southeast Greenland during and since the Little Ice Age

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# 18 Abstract

19 The Greenland Ice Sheet has been losing mass at an accelerating rate over the past two decades. 20 Understanding ice mass and glacier changes during the preceding several hundred years, prior to 21 geodetic measurements, is more difficult because evidence of past ice extent in many places was later 22 overridden. Saltmarshes provide the only continuous records of Relative Sea Level (RSL) from close 23 to the Greenland Ice Sheet that span the period of time during and since the Little Ice Age (LIA) and 24 can be used to reconstruct ice mass gain and loss over recent centuries. Saltmarsh sediments collected 25 at the mouth of Dronning Marie Dal, close to the Greenland Ice Sheet margin in southeast Greenland, 26 record RSL changes over the past c. 300 years through changing sediment and diatom stratigraphy. 27 These RSL changes record a combination of processes that are dominated by local/regional changes in 28 Greenland Ice Sheet mass balance during this critical period that spans the maximum of the LIA and 29 20th Century warming. In the early part of the record (1725-1762 CE) the rate of RSL rise is higher 30 than reconstructed from the closest isolation basin at Timmiarmiut, but between 1762-1880 CE the RSL 31 rate is within the error range of rate of RSL change recorded in the isolation basin. RSL begins to 32 slowly fall around 1880 CE, with a total amount of RSL fall of 0.09  $\pm 0.1$  m in the last 140 years. 33 Modelled RSL, which takes into account contributions from post-LIA Greenland Ice Sheet Glacio-34 isostatic Adjustment (GIA), ongoing deglacial GIA, the global non-ice sheet glacial melt fingerprint, 35 contributions from thermosteric effects, the Antarctic mass loss sea-level fingerprint and terrestrial 36 water storage, over-predicts the amount of RSL fall since the end of the LIA by at least 0.5 m. The GIA 37 signal caused by post-LIA Greenland Ice Sheet mass loss is by far the largest contributor to this 38 modelled RSL, and error in its calculation has a large impact on RSL predictions at Dronning Marie 39 Dal. We cannot reconcile the modelled RSL and the saltmarsh observations, even when moving the 40 termination of the LIA to 1700 CE and reducing the post-LIA Greenland mass loss signal by 30 %, and 41 a 'budget residual' of  $+\sim3$  mm/yr since the end of the LIA remains unexplained. This new RSL record 42 backs up other studies which suggest that there are significant regional differences in the timing and 43 magnitude of the response of the Greenland Ice Sheet to the climate shift from the LIA into the 20<sup>th</sup> 44 Century.

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Keywords: Greenland, relative sea level, saltmarsh, glacio-isostatic adjustment, Little Ice Age, sea-level
budget

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#### 49 **1. Introduction**

Studies using a range of different geodetic methods all agree that the Greenland Ice Sheet (GrIS) has been losing mass at an accelerating rate over the past two decades (Bevis et al., 2019, 2012; Chen et al., 2021; Khan et al., 2015; Moon et al., 2012; Pritchard et al., 2009; The IMBIE Team, 2020; van den Broeke et al., 2009). There is however less known about when and at what rate ice mass loss occurred in Greenland during the last millennium until the start of the satellite and GPS eras, when Greenland underwent periods of climate warming and cooling (Briner et al., 2020; Khan et al., 2020; Kjær et al., 2022). Using Little Ice Age (LIA) trimlines and stereo-photogrammetric imagery recorded between 1978-1987, Kjeldsen et al. (2015) estimated an average Greenland-wide total ice mass loss of c. 75
Gt/yr during the 20th Century. However, understanding how the rate of mass loss varied during the
20<sup>th</sup> Century is more complex because it requires us to put a date on the end of the LIA, and to find a
way of reconstructing mass loss fluctuations without the help of continuous geodetic data.
Understanding ice mass and glacier changes during the preceding several hundred years is even more
difficult because evidence of past ice sheet extent in many places has been overridden by later advances
(Briner et al., 2011; Kjær et al., 2022).

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65 Salt marshes in nearfield settings record the timing and magnitude of fluctuations in ice mass during 66 the last few centuries through changes in relative sea-level (RSL) (e.g. Long et al., 2012). RSL reflects 67 the interplay of different cryosphere and oceanic processes but the dominant process close to an ice 68 sheet is the visco-elastic signature of local and regional mass changes through time (Farrell and Clark, 69 1976). Salt marshes form in the upper part of the intertidal zone and can continuously accumulate 70 organic sediment (Allen, 2000). Salt marshes in Greenland are generally small features with a very 71 short growing season, low sedimentation rates and may be affected by interactions with winter shore-72 fast ice (Lepping and Daniëls, 2007). However, they can survive in these conditions and provide the 73 only continuous records of RSL from close to the GrIS that span the period during and since the LIA 74 and can be used to reconstruct ice mass gain and loss over recent centuries (Long et al., 2012, 2010; 75 Woodroffe and Long, 2009).

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77 This study reports for the first time a continuous RSL record over the past ~300 years from a salt marsh 78 within 5 km of the ice sheet margin in southeast Greenland. The sediments and plant remains in the 79 marsh record RSL fluctuations over the last few hundred years and therefore provide a unique record 80 of changes in regional RSL during and since the LIA in Greenland. We predict local RSL changes by 81 creating a sea-level budget which includes predictions from a Glacio-Isostatic Adjustment (GIA) model 82 with c. 430 Gt ice mass loss in southeast Greenland between the end of the LIA and 2010 (as defined 83 by Kjeldsen et al., 2015), and estimates of other contributions since the end of the LIA including mass 84 loss from Greenland peripheral glaciers, non-Greenland ice, the thermosteric contribution and the effect of terrestrial water storage in the 20<sup>th</sup> and 21<sup>st</sup> Centuries. Comparing the modelled sea-level budget and 85

the saltmarsh data provides an opportunity to consider potential errors in both methods and suggest how we might bring model and data estimates closer together, as well as develop better understanding of the nature of historical RSL in southeast Greenland and implications for coastline response to future, enhanced GrIS and peripheral glacier melt.

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### 91 2. Study site and methods

# 92 2.1 Field site and glacial history of the region

93 The saltmarsh record is from 63.470°N, -41.925°W at the head of Dronning Marie Dal in southeast 94 Greenland (Figure 1A, B, Fig 2). The saltmarsh is fed by freshwater and sediment from Dronning Marie 95 Dal, a formerly glaciated valley that drains part of the nearby Skinfaxe outlet glacier. Dronning Marie 96 Dal is at the head of the 50 km long marine fjord Søndre Skjoldungesund which together with Nørre 97 Skjoldungesund encompass the glaciated island of Skjoldungen (Figure 1C). The northern fjord has a 98 bedrock sill mid-fjord at c. 215 m below sea level, while the southern fjord has a narrow central section 99 with a sill located at 77 m below sea level (Kjeldsen et al., 2017). The narrow stretch connecting the 100 two fjords at their inland extent is generally shallow, sheltering the salt marsh at Dronning Marie Dal. The region is dominated by long, steep-sided marine fjords with the GrIS ending at the coast in marine-101 102 terminating outlet glaciers.



104 Figure 1. A) Map of Greenland © Google Earth, B) Southeast Greenland region showing the location

105 of the field site (Dronning Marie Dal) alongside other studied fjords, C) Dronning Marie Dal saltmarsh

106 *at the head of Sondre Skjoldungesund, between the Skinfaxe and Thrum glacier margins.* 

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108 Relatively little is known about the deglacial history of the southeast compared to the southwest of 109 Greenland. Most work has been undertaken in the large fjords (e.g. Kangerdlugssuag, Sermilik, Køge 110 Bugt, Gyldenløve, Bernstorffs Fjord, Figure 1) to the north of the field area using <sup>10</sup>Be measurements 111 to reconstruct fjord deglaciation. During the LGM the ice sheet reached the shelf edge (50-80 km from 112 the outer coast) in this region and in the offshore Kangerdlugssuag Trough to the north of the study area 113 the ice sheet started to retreat by c. 17 ka BP (Funder et al., 2011). Onshore deglaciation at the outer 114 coast occurred earlier to the north (Kangerdlugssuag - 11.8 +/- 1ka BP) compared to the south 115 (Bernstorffs Fjord - 10.4 +/- 450 ka BP), driven by incursion of warm Atlantic water into the fjords 116 from the Irminger Current, moderated by local coastal bathymetry and atmospheric warming during the 117 early Holocene (Dyke et al., 2018, 2014; Hughes et al., 2012). <sup>10</sup>Be dates on boulders from outer and 118 inner Skjoldungesund suggest deglaciation here occurred in the early Holocene (inner fjord by 10.4 119  $\pm 0.4$  ka BP) (Levy et al., 2020). Following retreat from the shelf edge, the deglaciation model HUY3 120 simulates retreat onshore by 10 ka BP, which largely agrees with the field evidence from 121 Skjoldungesund, with the ice sheet slightly inland of its LIA maximum position at 4 ka BP (Lecavalier et al., 2014). The deglacial marine limit is low in this region (c. 20-40 m) suggesting less deglacial 122 123 mass loss compared to elsewhere in Greenland (Funder and Hansen, 1996). Observations of strandlines 124 up to 75 m above sea level in this region, reported by Vogt (1933) are cut into bedrock and are highly 125 unlikely to be of marine origin.

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The HUY3 geophysical model predicts slight crustal subsidence at the coast today caused primarily by a local late Holocene neoglacial readvance (resulting in RSL rise of 1-1.5 mm/yr over the last 1000 years) (Lecavalier et al., 2014). However, a recent GPS-derived GIA model (GNET-GIA) offers an alternative solution with GIA uplift calculated at +2.8mm/yr and +3.1 mm/yr at nearby HJOR and TREO GPS sites (Figure 1), which would result in pre-20<sup>th</sup> Century RSL fall at Dronning Marie Dal (Khan et al., 2016). By comparing GPS data and absolute gravity observations over a 20-year period, van Dam et al (2017) also suggest ongoing GIA uplift of +4.5 +/- 1.4 mm/yr at Kulusuk (300 km to the north). These GIA estimates, based on modern observations, are corrected for elastic deformation in response to modern mass balance changes to predict ongoing deglacial GIA. The most recent examination of Greenland GIA model outputs and GPS data by Adhikari et al. (2021) suggests that residual uplift caused by mass loss since the Medieval Warm Period, and in particular since the LIA, accompanied by a reduced mantle viscosity on sub-centennial timescales, can explain the observed discrepancy between uplift rates from HUY3 and elastic-corrected GPS uplift rates around Greenland.

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141 LIA moraines are situated ahead of the current frontal margins of the GrIS and local glaciers in this 142 region and demonstrate clearly that glacial retreat has occurred during the 20th Century (Bjork et al., 143 2012). The instrumental temperature record from Tasiilag indicates 2°C per decade of warming 144 between 1919 and 1932 CE (the early twentieth-century warming (ECW)), followed by cooling during 145 the 1950's to 1970's and steady temperature rise of 1.3°C per decade since 1993 (Bjork et al., 2012; 146 Chylek et al., 2006; Wood and Overland, 2010). Despite these decadal temperature fluctuations, and 147 the overall pattern of post-LIA retreat of southeast Greenland glaciers, the nearest glaciers to the field 148 site (Skinfaxe and Thrym, Figure 1C) have been relatively stable at their present positions since at least 149 the 1930s (Bjork et al., 2012). It is important to note however that Skinfaxe sits on a ledge in its fjord 150 system so would require significant thinning to dislodge it from its current position and Thrym Glacier 151 appears to be resting on a shallow bedrock rise (Bjork et al., 2012; Morlighem et al., 2017). The total 152 ice mass loss from the two drainage basins closest to the field site (Central East and South-East in 153 Kieldsen et al., 2015) is 249 Gt between the end of the LIA and 1983, 134 Gt between 1983 and 2003 154 and 45 Gt between 2003 and 2010, based on the volume of loss from LIA trimlines and more recent air 155 photos. There is a significant increase  $(\sim 70\%)$  in the amount of regional mass loss during the post-1983 period compared to earlier in the 20<sup>th</sup> Century. We hypothesise that regional ice mass loss since the end 156 157 of the LIA should produce a visco-elastic GIA response recorded as variable 20th century RSL change 158 by local salt marsh sediments, such as those at Dronning Marie Dal (Figure 2).



Figure 2. A) photograph looking East down the Dronning Marie Dal valley towards the head of Sondre
Skoldungesund and the salt marsh where the valley meets the fjord. B) photograph of the Dronning
Marie Dal salt marsh showing the low-angled relief of the marsh and zonation of salt marsh vegetation
(high marsh in the foreground).

# 181 2.2 Reconstructing RSL using saltmarsh sediments

We collected salt marsh sediments by digging a small pit using a spade from the present-day high salt marsh at the mouth of Dronning Marie Dal (Figure 1C, 2). The analysed sediment section is 13 cm thick, with organic silt containing saltwater-tolerant diatoms situated over compacted sand-rich silt where no diatoms are present (Figure 3). We sampled the fossil sediment section at 0.25 cm intervals in the top 1 cm, and at 0.5 cm intervals further downcore to provide high-resolution RSL estimates, bearing in mind the slow rate of sedimentation in most Greenlandic salt marshes (Long et al., 2012; Woodroffe and Long, 2009). To reconstruct local RSL we investigated diatom assemblages across the 189 present-day salt marsh in the same location to understand changes in assemblages with elevation across 190 the upper part of the intertidal zone (Figure 3A). We then compared these assemblages to those found 191 through the sediment core using a visual assessment technique, that places weight on certain taxa that 192 change abundance at clearly defined elevations (Long et al., 2012, 2010; Woodroffe and Long, 2009). 193 The main species used to reconstruct RSL are the high marsh/freshwater species *Pinnularia intermedia*, 194 and the high to low marsh species Navicula cincta and Navicula salinarum. Using elevation zones 195 inhabited by key species alone to reconstruct RSL introduces artificial jumps into a RSL record when 196 moving from a sample reconstructed from within one zone to the next sample which may be 197 reconstructed in a different zone. To create an RSL reconstruction with no artificial jumps within it we 198 use a smoothing function which allows the PMSE (palaeo-marsh surface elevation) to change within 199 each zone, noting the progressive way that the key diatom taxa change up core. For instance the 200 progressive rise in *Pinnularia intermedia* in the top 4 cm suggests smoothly falling RSL during this 201 period. We therefore modify the PMSE results for the zoned reconstruction to allow for the progressive 202 change seen in the diatoms (Table S2). This is backed up by the LOI data which suggests a progressive 203 rise in organic content in the top 4 cm indicative of rising PMSE. We prefer this method over a transfer 204 function approach (e.g. Barlow et al., 2013) because it relies on certain indicator species that occur at 205 narrowly defined levels, but also utilises other evidence such as vertical diatom succession and the 206 stratigraphy to interpret changes in RSL. In addition we do not tune the RSL reconstructions to present 207 day RSL, rather the most recent index point reflects its diatom-based reconstruction and therefore 208 present day RSL lies within the vertical error term of this reconstruction. This is done to prevent a 209 spurious jump in recent RSL caused by a vertical offset between the mid-point in the earlier diatom-210 based reconstructions and the present-day marsh-surface elevation, which would happen if this was 211 used to tune the core-top sample reconstruction.

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We initially calculated the elevations of modern and fossil saltmarsh samples to mean sea level (MSL) using a high-precision dGPS. However due to technical issues with post-processing we instead rely on tidal data from Timmiarmiut (100 km to the S) and tidal predictions from Tasiilaq (300 km to the NE) collected during our fieldwork, along with knowledge about saltmarsh vegetation zonation in Greenland and their general relationship to tidal levels, to relate fossil and modern saltmarsh elevations to mean 218 sea level (MSL). The tidal data from Timmiarmiut show that although the timing of daily tidal 219 fluctuations differs to predictions for Tasiilag, the amplitude of tidal fluctuations is remarkably similar 220 (within 0.1 m). The tidal range (lowest to highest astronomical tide) at the outer coast is approximately 221 3.7 m. We have some confidence therefore that tidal predictions for Tasiilag are applicable (with a time 222 correction) along the outer coast anywhere between Tasiilag and Timmiarmiut, although the distances 223 involved are large. This leaves the issue of tidal range amplification or dampening in fjord-head settings 224 to consider, as the Dronning Marie Dal site is c. 50 km up-fjord from the open ocean (Figure 1C). This 225 is considered elsewhere in Greenland by Richter et al., (2011) who show that this effect is variable due 226 to fjord bathymetry and cross-section geometry, and ranges from -9 cm to +14 cm up fjord compared 227 to the fjord mouths on the west coast in fjords of similar length to Søndre Skoldungesund. Modern 228 saltmarsh vegetation at Dronning Marie Dal grows between 0.1 m above Highest Astronomical Tide 229 (HAT) and 0.08 m below Mean High Water of Spring Tide (MHWST) levels, which is very similar to 230 saltmarsh vegetation ranges we have observed elsewhere in southeast and southwest Greenland 231 (unpublished data and Woodroffe and Long, 2010, 2009). We are therefore confident that any effect of 232 the fjord-head setting on tidal range is small. We have not included an uncertainty estimate in our 233 overall RSL reconstruction to reflect this, because the uncertainty in the proxy elevations is already of 234 a similar magnitude (±0.10-0.15 m, see Table S2 in Supplementary Information).

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# 236 2.3 Chronology

237 To provide a chronology to constrain the timing of reconstructed RSL changes we use a range of 238 complementary methods to maximise the precision of the resultant age-depth model. Very low 239 concentrations of <sup>210</sup>Pb in the sediments required us to use other methods to provide recent 240 sedimentation rates. We investigated the presence of Total Mercury (Hg) (mg/kg, which includes both 241 mineral and atmospheric deposition) within the sediments using acid dissolution and quadrapole ICP-242 MS as an indicator of anthropogenic emissions. Other studies in western and northern Greenland note 243 that between 1850-1900 CE there is more than a 2-fold increase in abundance of total Hg in lake 244 sediments compared to late Holocene levels (Bindler et al., 2001; Lindeberg et al., 2006; Shotyk et al., 245 2003; Zheng, 2015), whereas Perez-Rodriguez et al. (2018) see a rapid increase in Hg abundance from 246 1880 onwards in southern Greenland. We therefore assume that the onset of detectable Hg above

247 background level in the Dronning Marie Dal saltmarsh sediments at 4-4.5 cm indicates an age of 1850-248 1900 CE and use  $1875 \pm 25$  CE in the age-depth modelling described below. For the earlier part of the 249 sediment record we submitted seeds and leaves from saltmarsh and nearby freshwater plants picked from multiple horizons within the sediment for AMS <sup>14</sup>C dating at the <sup>14</sup>Chrono centre at Queen's 250 251 University, Belfast (Table 1). We generated an age-depth model for the whole sequence using the 252 *P* Sequence approach with variable k in Oxcal v. 4.3 using the IntCal20 calibration curve (Bronk 253 Ramsey, 2009; Ramsey and Lee, 2013; Reimer et al., 2020). The resultant age-depth model uses the Hg chronohorizon (1850-1900 CE) and three <sup>14</sup>C dates from lower in the sequence to estimate the age 254 255 of every 0.25 cm of sediment in the sediment section with associated uncertainty (Table 1 and Table S2 256 in supplementary information). The chronological uncertainty reported throughout this study is the 257 95% probability distribution (Bronk Ramsey, 2009).

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We exclude the <sup>14</sup>C ages at 6-6.5 cm (UBA28477) and 9-9.5 cm (UBA28478) from the age-depth model because they were on extremely small samples (<0.3 mg carbon) and are from samples that mix seeds and leaves from high salt marsh with freshwater plants that would not have been growing close together at the time (based on the palaeoenvironment recorded by the fossil diatom assemblage, and the distribution of diatoms and vegetation types on the present-day saltmarsh) (Table 1). The dated macrofossils from lower in the sequence are more likely to be autochthonous as the diatoms record a high marsh to freshwater environment, close to HAT, at the time of deposition.

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Table 1. Radiocarbon dated samples from the Dronning Marie Dal saltmarsh core. Samples at 6-6.5
and 9-9.5 cm are not included in the chronology because they were on extremely small samples (<0.3</li>
mg when graphitized) and mix seeds and leaves from different sources.

Core depth (cm)	Lab number	<sup>14</sup> C age (yr BP)	<sup>14</sup> C age error (yr/1 sigma)	F <sup>14</sup> C	F <sup>14</sup> C error	Calibrated age yr CE (unmodelled)	Cal curve	Dated material	Used in age model ?
6-6.5	UBA284 77	Modern	n/a	1.02 65	0.142 1	n/a	n/a	Carex subspathacea seeds and Empetrum nigrum leaves	N
9-9.5	UBA284 78	Modern	n/a	1.01 07	0.005 2	n/a	n/a	Carex subspathacea seeds and Empetrum nigrum leaves	N
10-10.5	UBA284 81	208 BP	67	n/a	n/a	1520-1950	INTC AL20	Carex subspathacea seeds	Y
11.5-12	UBA284 76	134 BP	93	n/a	n/a	1528-1950	INTC AL20	Carex subspathacea seeds	Y
12-13	UBA284 79	44 BP	45	0.99 453	0.005 55	1683-1930	INTC AL20 + NHZ 1	Carex subspathacea seeds	Y

272 2.4 Modelling RSL

273 2.4.1 Deglacial RSL change

274 There is a high degree of uncertainty on the rate of GIA in south-east Greenland, owing largely to the 275 lack of Holocene RSL data points to constrain deglacial history. Marine ingression into an isolation 276 basin at Timmiarmiut (100 km SW of Dronning Marie Dal) at c. 1140 CE (Table 2, also see Figures 277 S1, S2 and Table S1 in the supplementary information) gives an empirical estimate of regional GIA and 278 suggests that the linear rate of background RSL change over the past millennium is in the range of +0.2279 to +0.8mm/yr (Table 2). We therefore use a mid-point value of +0.5 mm/yr as the rate of RSL change 280 due to ongoing deglacial GIA in this study, rather than model predictions outlined in Section 2.1 which 281 are not validated using RSL data from this region.

Table 2. Isolation basin sea-level index point from Timmiarmiut used to calculate the rate of RSL due
to ongoing GIA in this study.

Location	Sill	Reference	RSL	Max	Min	Cal	<sup>14</sup> C	Lab code
(lat,lon)	height	Water Level	( <b>m</b> )	cal	cal	age	age	
	(m			age	age	error		
	MTL)			CE	CE	+/-		

Timmiarmiut	1.33 +/-	Ingression	-0.24	1044	1243	99.5	873	AAR
XC1403A	0.5	(MHWST to	+/- 0.5				+/- 30	25631
(62.4987, -		HAT)						
42.2577)								

#### 286 2.4.2 Post Little Ice Age Greenland contribution

287 The post-LIA contribution to RSL at Dronning Marie Dal is computed using the sea level algorithm of 288 Kendall et al. (2005) computerised by Milne and Mitrovica (2003). This code computes the geoidal and 289 crustal response to ice and ocean loads on a spherically-symmetric Earth discretized into 25 km-thick 290 elastic layers as defined by Dziewonski and Anderson (1981), and three viscous layers comprising a 291 lithosphere, upper and lower mantle. Lithospheric thicknesses (L) in the range 71-120 km are considered, with upper mantle ( $v_{UM}$ ) and lower mantle ( $v_{LM}$ ) viscosities of 0.1-1 x 10<sup>21</sup> and 1-50 x 10<sup>21</sup> 292 293 Pa s explored to quantify the effect on predicted RSL change of different assumptions about Earth 294 viscosity structure. The post-LIA ice history for the GrIS is derived from Kjeldsen et al. (2015) who 295 used a collection of aerial imagery from 1978-1987 CE to compare to historical trimlines assumed to 296 be indicative of a maximum LIA position of the ice sheet and use 1900 CE as a Greenland-wide year 297 of retreat from the maximum position, while acknowledging considerable local and regional 298 differences. The extrapolation method of point-scale changes in ice thickness over this time period to 299 the rest of the Greenland Ice Sheet is detailed in the methods section of Kjeldsen et al. (2015).

300

301 2.4.3 Contribution from Greenland glaciers

302 Changes in ice thickness in peripheral Greenland glaciers is determined in exactly the same way as the 303 post-LIA Greenland contribution. The peripheral Greenland glacier mass balance history is extracted 304 from Marzeion et al. (2015) and considered separately from the global glacier dataset (Section 2.4.4) 305 due to their proximity to the field site; the RSL response is computed as described in Section 2.4.2.

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307 2.4.4 Contribution from global glaciers

We calculate the sea level contribution from global glaciers by first computing the global fingerprint for a +1mm/yr barystatic contribution from glacier complexes defined in Marzeion et al. (2015, 2012) since 1902. For the purposes of this calculation, we distribute the mass change across the glacierised regions equally since the use of a 512 harmonic truncation masks sub 100 km-scale variability in ice 312 thickness change across regions outside of Greenland. Ice thickness change will vary internally to each 313 glacierised area, but the great distance between southeast Greenland and many of the sources of melt 314 means that the solution is insensitive to spatially inhomogeneous changes in ice thickness within the 315 source regions. Ice thickness changes for each of the global glacier complexes are discretized into 316 decadal loading intervals and the global sea level response is computed using the density configuration 317 in the Preliminary Reference Earth Model (PREM) (Dziewonski and Anderson, 1981). We use a 318 lithospheric thickness of 96 km to represent a global average applied to all glacial sites and omit the 319 viscous component from this calculation. Dronning Marie Dal is proximal to glacier sources in Iceland 320 and Baffin Bay so should display some level of sensitivity to ice loss distribution over these glacierised 321 areas. However, it is in the 'near field' with respect to both of these sites, and therefore the use of a 322 more realistic ice loss distribution in these areas (e.g. peripheral thinning) will reduce the relative sea-323 level rise recorded in southeast Greenland. The influence of low-latitude glaciers is excluded from the 324 sea level fingerprint calculations, as the areas of mass loss are below the spatial resolution of the 325 fingerprinting code. This simplified method produces similar results that of Frederikse et al. (2020).

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327 2.4.5 Contribution from the Antarctic Ice Sheet

Loss of ice mass from either East or West Antarctic Ice Sheets will produce a relatively uniform sea-328 329 level change fingerprint over the northern Hemisphere (Bamber and Riva, 2010; Mitrovica et al., 2001). Recent Antarctic Ice Sheet change (1992-present) is relatively well-documented and quantified 330 331 (Meredith et al., 2019) compared to the period represented by the RSL data in this study. However, a 332 recent study by Frederikse et al. (2020) that applied a Monte Carlo approach to balance the budget of 333 global sea-level rise since 1900 used estimates of 20th century Antarctic Ice Sheet mass balance obtained 334 from Adhikari et al. (2018) where the focus of mass loss throughout the 20th century is thought to be in 335 the West Antarctic Ice Sheet, amounting to a global sea-level change of  $0.05 \pm 0.04$  mm/yr. We use the 336 resulting ensemble from Frederikse et al's (2020) analysis to compute Antarctic Ice Sheet contribution 337 at Dronning Marie Dal.

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**339** 2.4.6 Contribution from steric changes

To compute the contribution from salinity and temperature changes in the nearby ocean, the 340 341 Thermodynamic Equation of Sea Water (McDougall and Barker, 2011) (algorithm available here: 342 https://www.teos-10.org/) was applied to compute the steric height of the ocean. This uses a suite of 343 proximal monthly temperature-depth and salinity-depth profiles extracted from the CMIP6 database for the 'historical' experiments covering the period 1850-2014. The 'historical' experiment was chosen to 344 345 produce timeseries of depth-dependant potential temperature and salinity because the experiment forms 346 part of the principal set of CMIP6 simulations, and the forcing datasets provided to the AOGCMs are 347 consistent with a set of atmospheric and ocean observations (Eyring et al., 2016). We use only one configuration of the variant ID, which relates to initialisation time and procedure, specific model 348 349 physics and forcing (r1i1p1f1) across all AOGCMs considered (NASA-GISS-E2, CESM2, AWI, 350 CanESM5 and FGOALS). The model output from the CMIP6 database has a spatial resolution in the 351 range of 50-200 km, so we use profiles located within 300 km of Dronning Marie Dal to calculate an 352 average trend in steric height for the nearby ocean. The steric heights are computed to reference depth 353 levels of 500 m, 1000 m, 2000 m and 3000 m. Computing steric heights to different reference levels 354 allow us to determine which depth(s) in the ocean are contributing to steric height variability. Ivchenko 355 et al. (2008) determined that for the North Atlantic for the period 1996-2006, applying a reference level 356 of 1000-1500 m was sufficient to capture steric height variability, although this study provides trends 357 in steric height across the maximum depth level available by each model in the region proximal to 358 Dronning Marie Dal.

359

# 360 2.4.7 Terrestrial Water Storage

To estimate the contribution of changes in terrestrial water storage we utilise the ensemble of timeseries of Frederikse et al. (2020) covering the time-period 1900-2018 CE. This dataset was compiled by including the effects of natural variability in water reservoirs attributed to hemispheric-scale atmospheric and ocean circulation changes (Humphrey and Gudmundsson, 2019), changes in storage from dam building (Chao et al., 2008) and groundwater depletion activities (Döll et al., 2014; Wada et al., 2016).

In the next section the results from the field work, RSL reconstruction and sea-level modelling are then
compared to better understand changes in mass balance and RSL over recent centuries in southeast
Greenland.

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372 **3. Results** 

# 373 3.1 Modern diatom assemblages

374 Diatoms are zoned by elevation across the upper part of the intertidal zone at Dronning Marie Dal, with 375 individual species providing useful information for reconstructing RSL. Above 2.2 m MTL (>0.34 m 376 above HAT) no diatoms were found in surface sediments, probably because the environment is too arid. 377 There is a distinctive assemblage containing *Pinnularia intermedia* (>10 % at HAT, increasing to ~55 378 % in the highest samples) which ends at ~2.2 m MTL. We use this as a proxy sea level indicator to 379 reconstruct palaeo-marsh surface elevation changes when we find *Pinnularia intermedia* either < 10 %, 380 between 10-20 % and above 20 % in fossil counts (Figures 3A and B and Table S2 in supplementary 381 information). These zones are supplemented at lower elevations by a relatively narrow assemblage 382 zone in the high to low marsh where *Pinnularia intermedia* values are negligible, *Navicula cinta* is >5 383 % and *Navicula salinarum* is not present (Figure 3A and Table S2 in supplementary information). We 384 find these diatom assemblage zones in every marsh we have studied in southeast and southwest 385 Greenland and use them to reconstruct RSL rather than using a transfer function approach as their precision is as good as or better (Pinnularia intermedia is present in >15 marshes between 59° and 69° 386 387 N in southwest and southeast Greenland with a vertical range of 0.2-0.4 m; unpublished data and Long 388 et al., 2012, 2010; Woodroffe and Long, 2010, 2009). This approach also allows us to consider changes 389 in other parameters (e.g. changes in these species abundance between samples and sediment Loss on 390 Ignition) when producing palaeo-marsh surface elevation estimates.

391

# 392 *3.2 Core stratigraphy and biostratigraphy*

The core stratigraphy consists of a compacted basal freshwater organic silt-clay, grading upwards into organic high saltmarsh sediments, and then into a slightly silt-rich organic low salt marsh towards the surface, with an increase in LOI values towards the surface (Figure 3B). Diatoms are well preserved in the core and show a trend of falling palaeo-marsh surface elevation upwards from the base of the sequence as *Pinnularia intermedia* declines and *Navicula cincta* increases in abundance (alongside the
absence of low marsh species *Navicula salinarum* which provides additional information about palaeomarsh surface elevations in this part of the core). In the top 3 cm *Pinnularia intermedia* increases in
abundance recording RSL beginning to fall and palaeo-marsh surface elevation increasing (Figure 3B).





402

Figure 3. A) Modern diatom data from the marsh at Dronning Marie Dal. Data are expressed as %
total diatom valves (%TDV). Only data >10% TDV are shown. B) Fossil diatom counts, palaeo-marsh
surface elevation reconstruction and total Mercury measurements from the Dronning Marie Dal
saltmarsh core. Diatoms are expressed as a %TDV and only taxa with >10% TDV are shown.

407 *Stratigraphy is shown in lefthand box where grey = saltmarsh sediment, black = freshwater peat. Total* 

408 Mercury (mg/kg) was measured on salt marsh sediment using quadrapole ICP-MS.

409

### 410 *3.3 RSL reconstructions*

411 The saltmarsh sediments and diatoms indicate long term RSL rise. The rate of RSL rise at the start of 412 the record (+~7 mm/yr between 1725-1762 CE; Figures 4B and C) is significantly higher than the rate 413 reconstructed from the closest isolation basin at Timmiarmiut ( $+0.5 \pm 0.3 \text{ mm/vr}$ ; Table 2). This may 414 be due to LIA ice growth, including the nearby Skinfaxe glacier delivering sediment-laden meltwater 415 to Dronning Marie Dal, causing local ice loading and rapid infilling of accommodation space and salt 416 marsh development. The rate of RSL rise declines rapidly over the period 1762-1880 CE to +0.4 mm/yr 417 and is within the error range of the isolation basin rate during most of this period ( $+0.5 \pm 0.3 \text{ mm/yr}$ ). 418 This trend of rapid and then slowly rising RSL between 1725-1880 CE is likely due to changes in the 419 local LIA ice load over this time period combined with ongoing millennial-scale GIA. The HUY3 420 model predicts +1.44 mm/yr of RSL rise over the past 1000 years in this region (Lecavalier et al. 2014) 421 which is larger than but the same sign as the salt marsh and isolation basin RSL data during this period. 422 Other recent estimates of centennial-scale GIA (Khan et al., 2016; van Dam et al., 2017) suggest that 423 RSL should have been falling over the past few hundred years at Dronning Marie Dal. The isolation 424 basin and salt marsh data instead suggest that RSL was rising or close to stable from c. 1100 CE until 425 c. 1880 CE.

426

Since 1880 CE RSL began to fall, which is indicated clearly in the diatom record by the decline in *Navicula cincta* up core and the reintroduction and increasing abundance of *Pinnularia intermedia*, a high marsh diatom species after 1900 CE (Figure 3B). There is ~ $0.09 \pm 0.1$  m of RSL fall since 1880 CE, which if calculated as a constant rate of change is  $-0.72 \pm 1.7$  mm/yr RSL fall (Figures 4B and C, Table 3, Table S2 in supplementary information). Because of the lack of direct dating control in upper part of the core and the slow rate of sedimentation it is not possible to infer decadal changes in RSL rate during the 20<sup>th</sup> Century.



436 Figure 4A) age-depth model using three <sup>14</sup>C ages and the Hg chrono-horizon, B) Dronning Marie Dal
437 RSL curve, C) rates of RSL change through time inferred from the RSL and age data.

435

# 439 3.4 Modelled RSL changes

440 Published calculations of post LIA Greenland mass loss and other RSL contributors start at 1900 CE 441 (e.g. Kjeldsen et al., 2015; Marzeion et al., 2015), so we focus on this part of the salt marsh RSL record 442 to compare the reconstructed RSL with a modelled sea-level budget. The different contributions to the 443 sea-level budget are summarised in Table 3 and Figure 5. For an average Earth model configuration of L = 96km,  $v_{UM}$  = 0.5 x 10<sup>21</sup> Pa s and  $v_{LM}$  = 10 x 10<sup>21</sup> Pa s, post-LIA ice mass loss (from the GrIS only) 444 445 resulted in sea level change of -5.9 mm/yr at Dronning Marie Dal between 1900-2010 CE. Between 446 1983-2010 CE the modelled RSL rate was -10.1 mm/yr. Any chosen Earth configuration within the 447 parameter range explored does not significantly affect the predicted sea-level change; for 1900-2010 CE, the range of RSL fall was between -6.7 to -5.8mm/yr and 1983-2010 CE between -11.7 to -9.9 448 449 mm/yr. Using a fixed lithospheric thickness of 96km, the modelled total sea level fall arising from post-450 LIA mass loss across a suite of earth models with upper mantle viscosities ranging from 5 x  $10^{19} - 1$  x  $10^{22}$  Pa s and lower mantle viscosities in the range of 1 x  $10^{21} - 5$  x  $10^{22}$  Pa s was 0.65 to 0.86m, a 451 452 difference of 0.21m which is within the uncertainty range of the RSL reconstruction (Figure 4B). The 453 upper mantle viscosity is the largest contribution to this uncertainty accounting for both upper and lower 454 bounds of this range. The effect of reducing the lithospheric thickness from 120km to 46km reduces the

amount of modelled relative sea level fall by only a few cm. The contribution of peripheral Greenland 455 456 glaciers to RSL was on average  $-1.7 \pm 0.2$  mm/yr between 1903 CE and present day; with decadal-scale contributions of -3 to -5 mm/yr between 1923 and 1943 CE. Global glacier mass loss contributes +0.24 457  $\pm$  0.06 mm/yr RSL rise between 1903-2009 CE. Antarctica has contributed more significantly to sea-458 459 level change in recent years; for the period 1992 to 2016 CE, the Antarctic Peninsula and the West 460 Antarctic Ice Sheet are thought to have resulted in  $+0.06 \pm 0.73$  mm/yr of barystatic sea-level change 461 (Meredith et al., 2019). However, for the period 1850-2014 CE Frederikse et al. (2020) compute +0.08  $\pm$  0.02 mm/yr, rising to +0.2mm/yr  $\pm$  0.05 mm/yr between 1970-2018 CE. 462

463

464 The range of values for the modelled steric contribution are in Table 4. They represent an upper estimate 465 of the magnitude and range of the steric component as only profiles showing significant RSL trends are 466 used when calculating the mean. From 1850-2014 CE, trends in steric height are in the range -0.23 to 467 +0.18 mm/yr for a reference depth level of 1000 m and -0.36 to +0.28 mm/yr over a depth range of 468 2000 m. An observation-based analysis of trends in steric height by Frederikse et al. (2020) shows the 469 steric contribution from the upper 2000m of the ocean close to Dronning Marie Dal between 1957-2018 470 CE is +0.13 mm/yr (we include steric trends derived for the period 1950-2014 in Table 4 for comparison). All models considered in Table 4 have larger values than Frederikse et al. (2020)'s 471 472 estimates. Finally, the impact of terrestrial water storage amounts to a sea level fall of  $-0.13 \pm 0.06$ mm/yr at Dronning Marie Dal over the 20<sup>th</sup> century. 473

474

The different contributions to RSL are summed and plotted alongside the saltmarsh RSL data in Figure 5. The sum of components predicts RSL fall of between 0.58-0.93 m since 1900 CE. This prediction is dominated by the contribution of GIA caused by post LIA Greenland and peripheral glacier mass loss, which is only counteracted a little by the other components which mostly predict small amounts of RSL rise. The saltmarsh data only reconstruct ~0.08 ±0.1 m of RSL fall since 1880 CE producing a large mismatch between the sea-level budget and the saltmarsh RSL data.

481

- 483 Table 3. Calculated amounts and rates of RSL change from the various contributors to the RSL budget
- 484 *at Dronning Marie Dal. Rates of RSL change are supplied with* ± 2*-sigma uncertainty unless specified:*
- 485 \* uncertainty reflects assumed  $\pm 10\%$  error on rates which is larger than  $\pm 2$ -sigma. \*\* steric sea level
- 486 contribution calculated from the average of significant trends for the 0-2000m depth interval from three
- 487 models in Table 4. \*\*\* GIA from nearby isolation basin ingression with uncertainty calculated from
- 488 upper and lower elevation reconstruction uncertainties.

Contribution to sea-level budget	Local or global	Time period (CE)	Contribution to RSL change (mm), upper and lower estimates calculated for common period of 1900-2012 CE	Rate of RSL change (mm/yr) assumed for common period of 1900-2012 CE
GIA caused by post LIA ice mass loss*	Local	1900-2010	-724, -593	$-5.9\pm0.6$
GIA caused by Greenland peripheral glacier mass change*	Local	1903-2012	-202, -166	$-1.7 \pm 0.2$
Millennial-scale deglacial GIA***	Local	1900-2018	33, 88	$+0.5 \pm 0.3$
Local total				$-7.1 \pm 0.6 \text{ mm/yr}$
Global glaciers	Global	1903-2012	20, 33	$+0.24\pm0.06$
Antarctica	Global	1900-2018	0, 18	$+0.08\pm0.08$
Steric**	Global	1850-2014	-39, 39	$+0.00 \pm 0.35$
Terrestrial water storage	Global	1900-2018	-21, -8	$-0.13 \pm 0.06$
Global total				+0.19 ± 0.35 mm/yr
Total modelled RSL change at Dronning Marie Dal 1900-2012 (see Figure 5)			-933, -589	$-6.9 \pm 1.5 \text{ mm/yr}$
Rate of RSL change from saltmarsh data (1880-2014)				-0.72 ± 1.7 mm/yr

490

<sup>491</sup> Table 4: Mean trends in steric height anomalies for three reference levels (500, 1000 and 2000m) 492 calculated from profiles within 300km of Dronning Marie Dal using five models participating in the 493 CMIP6 analysis. In all cases, experiment variant ID was r1i1p1f1. Numbers in brackets denote number 494 of profiles displaying significant trends in steric height from which the mean and 2-sigma trends were 495 calculated. The AWI model produced no significant trends for either time-period whilst GISS-E2 did 496 not produce significant trends for 1850-2014 CE.

Model ID	Resolution	Resolution	0-500m	0-1000m	0-2000m				
	(space)	(time)							
1850-2014 CE									
GISS-E2	200km	Monthly	-	-	-				
CESM2	100km	Monthly	$0.08 \pm 0.01$ (34)	0.17 ± 0.01 (26)	$0.09 \pm 0.01$ (7)				
FGOALS	100km	Monthly	$0.14 \pm 0.12$ (7)	$0.18 \pm 0.16 (11)$	$0.28 \pm 0.04$ (6)				
AWI	25km	Decadal	-	-	-				
CanESM5	100km	Monthly	$-0.12 \pm 0.1$ (13)	$-0.23 \pm 0.08$ (13)	$-0.36 \pm 0.06$ (13)				
1950-2014 CE									
GISS_E2	200km	Monthly	$0.17 \pm 0.02$ (10)	$0.36 \pm 0.03$ (6)	$0.75 \pm 0.05$ (3)				
CESM2	100km	Monthly	$0.63 \pm 0.15$ (37)	1.3 ± 0.11 (26)	$1.24 \pm 0.07$ (7)				
FGOALS	100km	Monthly	$0.43 \pm 0.17$ (11)	0.57 ± 0.18 (12)	0.81 ± 0.15 (6)				
AWI	25km	Decadal	-	-	-				
CanESM5	100km	Monthly	0.97 ± 0.34 (15)	$1.1 \pm 0.32$ (13)	$0.96 \pm 0.2$ (8)				

499



500

Figure 5: Observed and modelled relative sea level change from 1900-2010 CE as a function of recent and late Holocene Greenland ice thickness changes (GIA caused by the GrIS, Greenland peripheral glaciers and millennial-scale GIA; the 'local' signal) and from sources outside of Greenland (steric signal, AIS, terrestrial water storage and global glaciers). The sum of the modelled components is shown as the grey shaded area and the GrIS and peripheral glacier contributions are shown with an estimated  $\pm 10\%$  uncertainty. The black crosses are the salt marsh-based RSL reconstruction.

### 508 4. Discussion

509 The dominant contributors to post-LIA RSL change at Dronning Marie Dal are the adjustment of the 510 solid Earth and changes in geoid height in response to both post-LIA and millennial-scale Greenland 511 ice sheet changes. These contributors (ongoing GIA from the last deglaciation, post LIA Greenland 512 mass balance and mass loss from peripheral Greenland glaciers) amount to a modelled sea-level fall of 513 -7.1 mm/vr between 1900-2010 CE. By contrast, the RSL contributors unrelated to cryospheric change 514 in Greenland only amount to modelled sea-level rise of +0.19 mm/yr, giving a total RSL fall of -6.9 515 mm/yr between the end of the LIA and present (Table 3). This clearly does not fit with the observations 516 from the salt marsh data (Figures 4B, 5), which suggests that the rate of RSL fall between 1900-2013 517 CE is  $-0.72 \pm 1.7$  mm/yr.

518

# 519 *4.1 Timing of the end of the LIA and Greenland ice sheet and peripheral glacier contribution*

To try to bring the post-LIA sea-level budget closer to the salt marsh observations, we explore two possible sources of uncertainty in the dominant post LIA Greenland signal: 1) timing of the start of post-LIA mass loss in Greenland and 2) greater uncertainty in modelled sea level associated with post-LIA GrIS and peripheral glacier mass loss.

524

525 To explore the possibility that the total post-LIA Greenland mass loss occurred over a longer time period 526 we create five scenarios where the LIA maximum ice termination in Greenland is adjusted to begin at 527 1700, 1750, 1800, 1850 and 1900 CE, and the rate of mass loss is scaled accordingly with the end point 528 remaining at 2010 (as in Kjeldsen et al., 2015). We know that the LIA ice sheet response was different 529 around Greenland with multiple advance phases forced by different driving mechanisms, and it is 530 simplistic to suggest that the whole of the ice sheet began to lose mass simultaneously at 1900 CE (Kjær 531 et al., 2022), albeit it may serve as a Greenland-wide year. By adjusting the LIA termination date (and 532 therefore the start of Greenland and peripheral glacier mass loss) we can investigate the impact of earlier 533 ice retreat on RSL at Dronning Marie Dal. In this sensitivity analysis we recognise that moving the 534 LIA termination date in our modelling means that we are assuming the LIA ended simultaneously earlier 535 around the whole of Greenland, which is no more nuanced than assuming LIA termination at 1900 CE. 536 We also note that the glaciers closest to Dronning Marie Dal appear to have been at their LIA maximum

position in the early 20<sup>th</sup> Century, which does not agree with an earlier LIA end in this location (Bjork
et al., 2012), and a recent alkenone-based sea-surface temperature reconstruction from Nørre
Skjoldungesund suggests considerable warming here occurred late, between c. 1915-1945 CE
(Wangner et al., 2020). The analysis does however allow a first-order investigation into the sensitivity
of modelled post-LIA sea level to the length of time over which the post-LIA mass loss occurred.

542

543 The second parameter that we vary as part of this sensitivity study is the total amount of post-LIA RSL 544 change from the GrIS and peripheral glaciers, by assuming an error of up to -30% on these calculations. 545 Kjeldsen et al. 2015 report uncertainties in their mass loss estimates for the Southeast sector of the ice 546 sheet between 7-15 %, and so this sensitivity analysis allows us to test the effect on RSL at Dronning 547 Marie Dal of a smaller amount of mass loss since the end of the LIA in this region.

548

Varying both LIA termination date and total post LIA mass loss from the GrIS and peripheral glaciers affects how much sea-level change from other components is required to close the post-LIA budget (Figure 6). The 'budget residual' in Figure 6 refers to the misfit in mm/yr between the RSL change reconstructed by the saltmarsh data and RSL change predicted by the sea-level budget calculations. In essence this is the amount of sea-level change that we still need to 'find' to close the budget even after we modify the timing and total amount of mass loss from the dominant contributors to RSL change of GrIS and peripheral glacier retreat since the end of the LIA.

556

557 The time-period over which post LIA mass loss occurs is important for understanding the degree of 558 volume mismatch between the RSL observations and modelled contributions from the maximum extent 559 to present. Figure 6a indicates that moving the LIA termination date from 1900 CE to 1700 CE reduces the 'budget residual' required to fit the RSL data from  $\sim+5$  to  $\sim+4$  mm/yr. This residual is reduced 560 further (to ~+3 mm/yr) when considered alongside a 30% reduction in the amount of RSL fall 561 562 originating from the GrIS and peripheral glaciers compared to values computed using RSL from ice 563 histories generated by Kjeldsen et al. 2015 (GrIS) and Marzeion et al. 2015 (peripheral glaciers) (Figure 564 6b). Figures 6c and d further illustrate these results. Figure 6c, where there is no reduction in the 565 amount of post-LIA mass loss shows a poor fit to the RSL data when the LIA termination is moved to

between 1700-1800 CE, and there remains a +3.5 -5 mm/yr 'budget residual' which must be accounted for from other parts of the sea-level budget. In Figure 6d, a better fit to the RSL data is possible with a 30 % reduction in Greenland and peripheral glacier mass-loss and LIA termination at 1800 CE. The remaining 'budget residual' is +3 mm/yr which again must be accounted for from other parts of the sealevel budget.

571

572 The smallest calculated 'budget residual' (~+3 mm/yr) has to be found from processes causing sea-level 573 rise in southeast Greenland, such as millennial-scale Greenland GIA, Antarctic Ice Sheet melt, the steric 574 effect, and global glacier melt. The modelled sea-level budget suggests that these processes are only 575 small contributors to total sea-level change, with the sum of sources from outside Greenland only +0.19576 mm/yr since 1900 CE. The steric effect has the largest uncertainty, which we consider in Section 4.8 577 alongside other potential sources of error in our calculations. It is difficult however to see how the 578 contributors to RSL rise in southeast Greenland could be significantly larger before 1900 CE given the 579 cooler regional temperatures of the LIA.



581

582 Figure 6. a, b) Misfit plots showing model data-fit where combinations of 'budget residuals' and LIA 583 termination dates are considered with (a) no assumed error in the RSL contribution from the GrIS and 584 (b) a 30% reduction in magnitude of sea-level change associated with local changes in the GrIS. Areas 585 within the white lines have a statistically equivalent fit to the RSL data, c) Modelled RSL from all 586 combinations of LIA termination date and budget residual, assuming no error in the RSL contribution 587 from the GrIS. Area within the black line denotes all possible combinations of RSL trends from LIA 588 terminations from 1750-1900 CE and budget residual rates between 0-6mm/yr. Grey shaded area 589 corresponds to RSL trends from within white lines on Figure 6a, demonstrating a statistically equivalent 590 fit to the data. For illustrative purposes, the red line denotes a modelled RSL scenario with a LIA 591 termination date of 1900 CE (assumed LIA termination date in Kjeldsen et al. 2015) and a budget 592 residual rate of +4mm/yr the blue line a modelled RSL scenario with a budget residual rate of +5mm/yr593 and LIA termination date of 1900 CE. d) As part c except grey shaded area corresponds to RSL trends 594 from Figure 6b, demonstrating a statistically equivalent fit to the data. For illustrative purposes, the 595 red line denotes a modelled RSL scenario with a budget residual rate of +3mm/yr and LIA termination

date of 1700 CE; the blue line a modelled RSL scenario with a budget residual rate of +4mm/yr and 597 LIA termination date of 1900 CE.

598

#### 599 4.2 Reliability of saltmarsh RSL data

600 Saltmarshes and their microfossil communities are widely used in temperate locations and previously 601 in west and south Greenland to reconstruct recent RSL changes with high precision (e.g. Kemp et al., 602 2009, 2017; Long et al., 2012, 2010; Woodroffe and Long, 2009). At Dronning Marie Dal, the first 603 half of the RSL record (1725-1880 CE) is harder to interpret because early, rapid RSL rise may indicate 604 either a local LIA loading signal or a non RSL factor (e.g. sediment supply changes) as the marsh 605 became established. What we can say with certainty is that RSL began to fall at or soon after 1880 CE, 606 suggesting additional contributors to RSL or changes in the dominance of existing contributors caused 607 this change in the sign and rate of RSL. We are also confident of the total amount of RSL fall between 608 1880 CE and present, which is less than predicted by any permutation of the sea-level budget modelling 609 (Figure 5). We acknowledge however that these reconstructions come from a single sediment core and 610 although the stratigraphy appeared consistent across the marsh during fieldwork it would be ideal to 611 replicate these results within another core from the same marsh and also from other marshes close to 612 the ice sheet margin in this region in the future.

613

614 There is no indication of hiatuses within the marsh sediment and based on surveys of modern marshes 615 here and elsewhere in Greenland the elevation range of the key diatom species *Pinnularia intermedia* 616 used in the palaeo-marsh surface elevation calculations is robust. A RSL fall of ~0.6-0.9 m since 1900 617 CE as predicted by the sea-level budget modelling, would have lifted what was a high marsh 618 environment at the start of the period (indicated by the taxa at ~5 cm depth, Figure 3B) out of the 619 intertidal and into the adjacent freshwater zone where diatoms are not preserved due to extreme aridity. 620 The continuous preservation of intertidal diatoms through the sediment sequence to the surface where 621 modern saltmarsh plants were growing during sampling (Figure 2) rules out this possibility. Even the 622 smaller amount of RSL fall (~0.2 m) since 1900 CE predicted by an earlier LIA termination date (1800 623 CE) and 30% smaller GrIS contribution (Figure 6) is unlikely because the diatoms suggest a mid-high 624 marsh environment at 1900 CE and the core top elevation is within the high marsh zone, a vertical distance based on analysis of modern diatoms at Dronning Marie Dal of ~0.1 m, which is half of the predicted RSL fall (~0.2 m). Greenland saltmarshes accrete very slowly and only record sustained RSL changes over decades, and therefore short-timescale variability in contributors (e.g. due to decadal temperature fluctuations in the 20<sup>th</sup> Century) is not distinguishable in the saltmarsh data. However, the total amount of RSL fall and the timing of the change from RSL rise/stability to RSL fall is robustly reconstructed and we are confident that this provides an important test of Greenland RSL modelling.

631

# 632 *4.3 Limitations of RSL modelling*

633 Regional sea level budgets deviate significantly from the global budget, are challenging to compute and 634 have been deemed part of the 'Regional Sea-Level Change and Coastal Impacts' Grand Challenge by 635 the World Climate Research Programme (WCRP, 2022). Of the different items in the sea-level budget 636 for Dronning Marie Dal, the large uncertainty in the steric contribution could potentially be the source 637 of additional sea-level rise which would help decrease the 'budget residual' identified in Figure 6. The 638 data in Table 4 do not fully capture the range of uncertainty in the steric component of sea level. These 639 uncertainties arise from poor to non-existent capture of the dynamics of coastal regions, namely the 640 propagation of the change in steric height of the open ocean to the fjord location and the lack of observations to constrain model output in the early 20<sup>th</sup> Century. 641

642

643 The field site is located at the head of the 50 km long marine fjord Søndre Skoldungesund and therefore 644 the steric contribution may be different to that calculated from the open ocean estimates within 300 km 645 of Dronning Marie Dal averaged in this study. A multibeam study of the fjord by Kjeldsen et al. (2017) 646 shows the fjord is between 1.1-3.1 km wide, up to 800 m deep in the outer part, with a shallow (77m 647 deep) sill at mid-fjord and shallow depths inside the sill. The fjord water is cold to the base along its 648 length, with no apparent intrusion of warmer Atlantic water from the shelf edge. The mixed predictions 649 of steric height changes from the different models suggest that this region is poorly constrained within 650 global steric datasets (Table 4). Given the lack of intrusion of warm Atlantic water into the fjord today 651 it is unlikely that there has been a more positive contribution of steric height from 20th Century warming. 652 However, with significant mass loss from the Greenland Ice Sheet since the LIA and an influx of cold

yet low-salinity meltwater into the fjord it is possible that the local halosteric component is

underestimated.

655

A second issue with the steric height calculation is the potential for the CMIP6 models to misrepresent 656 657 changes in the dynamic height of the ocean caused by shifts in the location of ocean currents, such as 658 the East Greenland Current (EGC) over time. A recent study of North Atlantic dynamic sea level and 659 its response to GrIS meltwater and temperature increase indicates general Atlantic Meridional 660 Overturning Circulation decline and increase in sea-surface height with increased GrIS melting, but the 661 response of the cold EGC is complex and in southeast Greenland the effect of warming and increased 662 meltwater on sea-surface height is minimal (Saenko et al., 2017). Given that Kjeldsen et al. (2017) 663 suggest the EGC does not currently penetrate into the Søndre Skoldungesund fjord the impact of any 664 dynamical changes in the EGC since the LIA are likely to be minor.

665

666 A third possible source of uncertainty in the sea-level budget is the application of the sea level code 667 used to calculate GIA, specifically the spectral resolution with which the algorithm predicts the sea 668 level response to loading increments. The mass balance history from Kjeldsen et al. (2015) is presented on a 1x1 km spatial grid, but the sea level code utilises a spectral harmonic truncation of 256. The 669 670 effects on predicted RSL of the reduction in resolution has been demonstrated previously with near-671 field relative sea level being more affected by harmonic truncation than far field sites (Spada and Melini, 672 2019). A move towards a higher degree spherical harmonic truncation (>1024) would be necessary to 673 faithfully reproduce sea level fingerprint histories associated with small outlet glaciers and should be 674 considered in the future (Adhikari et al., 2015).

675

Despite the limitations outlined above, this study presents a first test of a post-LIA sea-level budget in the nearfield location of southeast Greenland. There is clear and unexplained difference between the RSL history recorded by salt marsh sediments (a small RSL fall since the end of the LIA) and the RSL budget which suggests significant RSL fall during this period. The sensitivity tests show that the budget can fit the salt marsh RSL data if the amount of mass loss from the GrIS and peripheral glaciers is less, and it took place over a longer period (Figure 6d), but even so a +2.5 mm/yr unexplained 'budget residual' remains. RSL reconstructions from salt marshes in southwest Greenland (Long et al., 2012,
2010; Woodroffe and Long, 2010, 2009) also suggest that the dominant signal in southern Greenland is
RSL rise into the 20<sup>th</sup> Century, which correlates with the long term (pre ~1880 CE) trend of RSL rise at
Dronning Marie Dal.

686

# 687 5. Conclusions

Saltmarsh sediments collected at the mouth of Dronning Marie Dal, close to the GrIS margin in southeast Greenland, record RSL changes over the past c. 300 years in changing sediment and diatom stratigraphy. These RSL changes record a combination of processes that are dominated by local/regional changes in GrIS mass balance during this critical period that spans the maximum of the LIA and 20th Century warming.

693

694 In the early part of the record (1725-1762 CE) the rate of RSL rise is higher than reconstructed from 695 the closest isolation basin at Timmiarmiut, but between 1762-1880 CE the rate decreases to within the 696 error range of the isolation basin RSL rate. This trend is likely due to changes in the local LIA ice load 697 over this time-period combined with ongoing millennial-scale GIA, or other local processes as the salt 698 marsh is established. Other recent estimates of centennial-scale GIA (Khan et al., 2016; van Dam et 699 al., 2017) suggest that RSL should have been falling over the past few hundred years at Dronning Marie 700 Dal. The isolation basin and salt marsh data instead suggest that RSL was rising or close to stable from 701 c. 1100 CE until c. 1880 CE. RSL begins to slowly fall around 1880 CE, with a total amount of RSL 702 fall of  $0.09 \pm 0.1$  m since 1880 CE.

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Modelled RSL, which takes into account contributions from post-LIA GrIS GIA, ongoing deglacial GIA, the global non-ice sheet glacial fingerprint, the contribution from thermosteric effects, an estimate of the Antarctic fingerprint and the contribution from terrestrial water storage, over-predicts the amount of RSL fall since the end of the LIA by at least 0.5 m. The GIA signal caused by post-LIA GrIS mass loss is by far the largest contributor, and error in its calculation has the largest potential to impact RSL predictions at Dronning Marie Dal. We cannot reconcile the modelled contributions and the saltmarsh observations, even when moving the termination of the LIA to 1700 CE, and reducing the post-LIA 711 Greenland mass loss signal by 30%. A 'budget residual' of ~+3 mm/yr since the end of the LIA remains 712 unexplained. Explaining the difference between salt marsh RSL data and the modelled RSL budget 713 since the end of the LIA and determining the timing of the LIA termination should be a key future 714 research objectives which can be addressed through reducing uncertainty on each component to the sea-715 level budget, collecting more empirical data on the recent history of the GrIS and by replicating the salt

716 marsh RSL record presented here elsewhere in this and other regions of Greenland.

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718 *Author Contribution* 

SAW, LMW, AJL and KKK designed the study, SAW, KKK and KHK undertook fieldwork, NLMB
undertook the laboratory analysis, and SAW and LMW prepared the manuscript with contributions
from all co-authors.

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723 The authors declare that they have no conflict of interest.

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