Simulation of the Greenland Ice sheet over two glacial cycles: Investigating a sub-ice shelf melt parameterisation and relative sea level forcing in an ice sheet-ice shelf model.

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Supplementary information

Section S1 Preliminary SSM parametersiation – Methods 1-3: Results from simulations with shelves and RSL forcing

Below is a detailed description of the results from the preliminary set of simulations investigating the sub-ice shelf melt (SSM) parametersiation Methods 1-3 (Table2, Fig.S2). The aim of these first sensitivity simulations was to examine sensitivity of the Greenland Ice sheet (GrIS) evolution using an SSM parametersiation as adopted in previous studies.

S1.1 Results for Method1: Constant SSM (Fig.S2, Table2)

In all simulations with a high SSM1 > 2 m/yr the ice sheet did not expand beyond the present day (PD) coastline, as the SSM was too high close to the edge of grounded ice sheet, to permit the floating ice shelves to thicken and ground. This is a very similar result as was found with the simulations using sheet-only. Only by reducing SSM1 < 0.75 m/yr was an expanse beyond the PD margin initiated. Simulations with a very low SSM1 (SSM1 < 0.25 m/yr) resulted in an ice sheet which expanded to the edge of the model domain, as the SSM was too low and additionally there was no imposed increase at the continental shelf break. This limited the possible range of SSM1 to between 0.25 – 0.75 mm/yr. Within this range, the ice sheet expands beyond the PD coastline, but there is no corresponding retreat during the Last Interglacial (LIG) minimum or by PD.

From these results, it was concluded that to capture the growth-retreat pattern inferred from the observational data requires a relatively low SSM1 close to the edge of the grounded ice margin to promote the initial expanse of the ice sheet. Secondly, an increase in the SSM at deeper water depths, especially by the continental shelf break, is required to prevent the ice grounded to the edge of the model domain.

S1.2 Results for Method 2: Stepped SSM (Fig.S2, Table2. TableS2)

As stated in the Sect.1, Colleoni et al., 2014 adopted a stepped SSM parametersiation when investigating the growth of the North Hemisphere Ice sheets over MIS7 and MIS5. This SSM parametersiation, and associated SSM1 and SSM2 values were adopted as the basis for Method 2, (highlighted in italics Table S2), but for an extended range of WD1 values (from 450 to 600 and 800m). Additionally, the results were investigated for a choice of low and high A_s, 0.1×10^{-10} $m^8N^{-3}yr^{-1}$ and 1.0×10^{-10} $m^8N^{-3}yr^{-1}$ respectively.

Adopting the same set of SSM parameters as Colleoni et al., 2014 did not simulate a glacial-interglacial growth pattern consistent with observational data; the ice sheet expanded beyond the PD coastline, but there was again, no corresponding retreat back to the PD margin. Increasing WD1 (up to 800m) which decreases the SSM between a water depth of 450 and 800 m, increased the spatial extent of the grounded ice sheet at both glacial maximums (Penultimate Glacial maximum (PGM) and Last Glacial Maximum (LGM)) improving the fit to the observational data. Conversely the PD misfit (relative to the observed GrIS (Bamber et al.,2013) is increased, with grounded ice remaining along the NW margin and an increased thinning (relative to a WD1 of 450m (up to 1000m)) along the inland retreated SW margin.

As was described for the sheet-only simulations (Sect.4), the spatial extent at the glacial maximum is highly sensitive to the choice of sliding coefficient, A_s. Comparing the results for the two A_s values, adopting a higher A_s (reducing the bed roughness, A_s 1.0×10^{-10} $m^8N^{-3}yr^{-1}$) resulted in: (1) an earlier (~ 20 kyr) advance and increased spatial extent at the glacial maximums, grounding across the Melville Bugt, and along the NW margin to the edge of Smith Sound; (2) An improved PD reconstruction along the SW margin (relative to sheet-only simulation) with an impeded inland retreat, resulting in a thicker (> 1000m) ice sheet; (3) An increase in the spatial extent and thickness of grounded ice remaining beyond the PD coastline along the NW, at PD; (4) An reduction in LIG ice-volume equivalent sea level (ESL) contribution, ~ -1.0 m (relative to sheet-only simulations, TableS1), due to this remaining grounded ice at PD.

From these simulations, it was concluded that adding the stepped SSM increase at deeper water depths prevented the run-away expanse of the ice sheet. The use of a constant SSM value up to WD1 and the edge of expanded grounded ice margin does not promote the thinning and retreat of the ice sheet back to the PD margin. This implies that a variable or increasing SSM may be required to drive the retreat of the expanded ice margin back to the PD coastline. This was investigated with Method 3.

S1.3 Results for Method 3: Exponential and constant (Fig.S2, Table2, TableS3)

Over the range of SSM1, SSM2 and WD1 values investigated for Method 3, again there was no choice of parameters that resulted in an advance and retreat of the ice sheet over the two glacial cycles, as inferred in the observational data described in Sect. 2.

Regardless of the choice of SSM2 (2.45-10 m/yr) or WD1 (475-700m), adopting a SSM1 > 0.75 m/yr (as was found for Method1, Sect.S1.1) resulted in very limited (if any) expanse of the grounded ice sheet beyond the PD coastline. Therefore, simulations using higher values of SSM1 were disregarded. There was however one simulation where for a higher SSM1 (SSM1=1.0 m/yr) combined with a WD1=800m, the ice sheet expanded (highlighted in italics Table S3). Due to the exponential increase in SSM with water depth adopting a deeper WD1, 800m, reduced the SSM between water depths of 0-700m to less than 0.1 m/yr, promoting the offshore expanse of the ice sheet. Conversely, the SSM was then too low at deeper water depths (> 800m) (controlled by SSM2) to initiate retreat during interglacial periods. These results highlighted that adopting an exponential relationship of SSM with water depth (as opposed to stepped SSM as in Method2, Sect.S1.2) can promote the offshore expanse and spatial extent of the ground ice sheet.

Increasing SSM2 (from 2.45 to 10 m/yr, for the same SSM1 and WD1), results in a higher SSM at water depths greater than WD1, thereby restricting the spatial extent of the grounded ice sheet at glacial maximums. To counteract this, WD1 must be increased (> 600m) to shift the sharp rise in SSM associated with the transition between SSM1 and SSM2 (see illustration Fig.S2) to deeper water depths. This reduces the SSM close to the outer margin of the expanding ice sheet and promotes offshore expanse. These results highlighted the sensitivity of the reconstructed ice sheet to the SSM over the water depth range 400-700m, close to the transition point between SSM1 and SSM2. Additional the results of Method 3 emphasized that the use of a sharp transition between SSM1 and SSM2 was not (1) realistic for the likely nature of SSM below a floating ice shelf, and (2) not able to promote a retreat back to the PD margin. Therefore, an exponential increase in SSM between WD1 and WD2 was introduced, with the development of Method 4.

Section S2 Results for the Optimum SSM parameterization Method 4: Exponential (Fig.S2)

In the following sections the results from the suite of simulations conducted to investigate the sensitivity to A_s, SSM1, SSM2, and WD1 in Method 4 are discussed (see Tables S4-S7 and Table3).

S2.1. Results for simulations investigating the sensitivity to variations in A_s and SSM1 (Table S4)

The first suite of simulations using Method 4, investigated the sensitivity of the GrIS evolution to variation in A_s (0.04 – 1.2 $\times 10^{-10}$ $m^8N^{-3}yr^{-1}$) and SSM1 (0.25-5 m/yr), combined with a constant WD1 and SSM2. In all simulations with a high SSM1 > 5 m/yr there was no expanse of the ice sheet beyond the PD coastline, regardless of the choice of A_s, as found with Methods 1-3 (Sect.S1).

Combining a lower SSM1 (< 5 m/yr) with a progressive increase in sliding (A_s from 0.04 $\times 10^{-10}$ $m^8N^{-3}yr^{-1}$ to 1.2 $\times 10^{-10}$ $m^8N^{-3}yr^{-1}$) resulted in a warmer basal ice temperature, an increase in ice velocity and a more expansive ice sheet at glacial maximums (PGM and LGM). However, the observational data (see Fig.1) were still not captured, with misfits remaining along the eastern and SW margin. To the south, although the spatial extent is increased, the ice sheet is thinner by up to ~ 800m, due to a warmer basal temperature and increase in ice velocity. Along the northern margin (relative to the south) with the increase in A_s, the ice temperature was lower and the velocity slower. This promoted an increase in the residence time leading to an earlier expanse of the ice beyond the PD coastline and a thickening (up to 1000m).

During interglacial periods (over the LIG and up to PD), with the progressive increase in A_s combined with the increase in the SAT, there was a variable spatial and temporal response between the southern and northern margin. Across the SW, due to the warmer ice temperatures, the inland retreat of the ice margin is increased, increasing the PD misfit (for example, see Fig.S4). Along the NW margin, retreat was initiated first at the western margin (across the Smith Sound, Kane Basin, Fig.1) as the velocity increased within the narrow outlet fjords (i.e Humboldt glacier) that feed the grounded ice sheet in this region. When the grounded ice margin reached the edge of the Nares Strait, retreat was initiated to the east, from the Hall Basin. This unzipping pattern of retreat is as proposed by Jennings et al., 2011

Increasing A_s increased the LGM ESL contribution, ~ 1m (Table S4). However, this is not due to a significant increase in the ice volume at LGM, rather due to a reduction in the PD ice volume (~ 0.3 $\times 10^{15}$ m^3) resulting from the thinner and more extensive inland retreat of the SW margin. Combining a high A_s (> 1.0×10^{-10} $m^8N^{-3}yr^{-1}$) and a SSM1 < 5 m/yr (see simulations highlighted by * Table S4) for the first time, promoted not only an expanse of the ice sheet beyond the PD margin, but a retreat back to the PD margin at interglacial periods. However, as mentioned above, the misfit of the simulated PD GrIS was increased, with significant inland lateral retreat of the SW margin. This highlights the role of the choice of adopted A_s, in controlling the glacial-interglacial evolution of the GrIS.

In conclusion, from this suite of simulations (with a WD1 = 475 m) to generate the glacial-interglacial growth pattern requires a relatively high amount of sliding (A_s > 1.0×10^{-10} $m^8N^{-3}yr^{-1}$), combined with a SSM1 < 5 m/yr. Next the sensitivity to the changes in WD1 will be investigated to try and fully capture the spread of observational data.

S2.2. Results for simulations investigating sensitivity to variations in WD1 (Table S5)

From the relationship between SSM and water depth (see eq.1) with a shallower WD1 (< 475m), the SSM closer to the ice margin is increased. This may restrict the expanse of the ice sheet beyond the PD coastline (as described in Sect. S1.3, see Table S5) but also may drive a retreat during interglacial periods. The initiation of an interglacial retreat has been a key feature yet to be resolved in earlier simulations. Conversely, a deeper WD1 (> 475m) reduces the SSM near to and surrounding expanded ice margin, and may promote an increase in the spatial extent of the ice sheet at glacial periods, but will affect the retreat back to the PD coastline. This relationship was investigated in this second suite of simulations by varying the adopted WD1 value, (between 300 and 700m) in combination with either a relatively low (A_s 0.1×10^{-10} $m^8N^{-3}yr^{-1}$) or high (A_s = 1.0×10^{-10} $m^8N^{-3}yr^{-1}$) amount of basal sliding. Three SSM1 values were chosen: 0.25, 0.5 and 1 m/yr.

There was a critical WD1 value, (for each SSM1, A_s), at which the SSM was sufficiently reduced over shallow water depths to promote an expanse of the grounded ice sheet but sufficiently high at deeper water depths surrounding the grounded ice margin to promote retreat back to the PD coastline (highlighted by * on Table S5). For example, in the suite of simulations with SSM1=0.25 m/yr (A_s=0.1×10^{-10} $m^8N^{-3}yr^{-}$) this critical water depth was constrained to a narrow window between 550-600m. With a WD1 within this range, the difference in the resultant SSM at shallow water depth is small (< 0.01m/yr up to 500m). At deeper water depths (> 600m), the differences are substantial, up to 10 m/yr. It is this difference that is important for the regions along the NW margin (Hall Basin, Smith Sound), where the paleo water depth ranges between 500-700m at the edge of the expanded ice margin and a retreat by PD had previously not been simulated. It is this resultant increased SSM over these water depths that drives the retreat back to the PD coastline (highlighted by the simulation with *). With an increase in the A_s (higher basal sliding), the critical water depth is reduced to WD1 < 350m (compare the shaded simulations on Table S5).

Increasing the WD1 did not produce the expected increase in glacial maximum extent such to capture the observed data (Fig.1). The spatial extent along the NE and SW margin were relatively insensitive to the WD1 value. However, this was not the case for the SE and NW. In simulations with a WD1 > 600m the ice volume increased by 0.4 $\times10^{15}$ m^3, with the ice margin expanding significantly near the Sermilik, and out across the Melville Bugt and Upernavik Archipelago. However, the use of this higher WD1 values prevented the corresponding retreat back to the PD coastline during interglacial periods. With an increase in WD1, the total LGM ESL contribution increased (on average 0.3 m), but again this was primarily due to the remaining grounded ice along the NW margin at PD, rather than significantly larger contribution from the glacial periods.

This suite of simulations illustrated that the onset of the ice sheet retreat during the interglacial is sensitive to a narrow range of WD1 values (depending on the choice of A_s and SSM1). Secondly, it is over this range of water depths, surrounding the grounded ice margin that the choice of SSM2 may become influential, as will be investigate below. It is again noted, the increasing the WD1 did not generate the significant improvement that was expected.

S2.3. Results for simulations investigating sensitivity to variations in SSM2 and WD1 (Table S6 and Table S7)

The final suite of simulations investigated the impact of variations in SSM2 at (or near) the critical water depth with the aim of (1) promoting an increase in the spatial extent of the ground ice sheet at the glacial maximums to capture the observed data (Fig.1); (2) driving a retreat of the expanded grounded ice margin during interglacial periods. Variation in SSM2 (150-10 m/yr) were first examined over a fixed WD1 (475m) (TableS6) and then secondly, based on this analysis, the impact of changes in WD1 (400-600m, TableS7) were considered.

Firstly, the reduction in SSM2 did not generate the expected increase in the spatial extent of the grounded ice sheet and resolve the remaining misfits to the observed data (total ice volume increase ~ 0.3×10^{15} m^3). The NE and SW margin were again relatively insensitive to the resultant changes in SSM2. The NW margin was highly sensitive, with a lower SSM2 (< 0.25 m/yr) increasing the expansion to the west, across through the Smith Sound and thickening by over 1500 m. However, reducing the SSM2 to generate this larger NW extent significantly increased the volume of grounded ice remaining at PD across this region, increasing the misfit to the observed.

Second, in all simulations (Table S6) adopting a reduction in SSM2 (from 150 m/yr) combined with the average WD1=475m, there was no retreat of the grounded ice margin during interglacial periods. This was as to be expected, as reducing SSM2 would thereby reduce the SSM at deeper water depths near the expanded ice margin. However, the simulations with only a small reduction in SSM2 (between 150-75 m/yr) by PD the margin remained grounded across the Nares Strait at only a few grid points. It was this narrow range of SSM2 values that were then adopted for the second stage, of varying WD1 (400-600m, Table S7).

Combining a moderate reduction in SSM2 with an increase in WD1 (> 475m) reduced the SSM at the deeper water depths surrounding the expanded grounded ice margin. However, this was still not sufficient to impact on the glacial maximum extent, mainly promoting a thicker ice sheet and increase in grounded ice at PD. For example, at a water depth of 600m, the SSM reduced by only 3.2 m/yr when WD1 was increased from 475 to 600m (for a SSM2=100 m/yr, SSM1=1m/yr, $A_s=1.0\times10^{-10}$ $m^8N^{-3}yr^{-1}$). However, combining a reduction in both WD1 and SSM2 (475 to 400m, 100m/yr or 75 m/yr) promoted the required retreat of the grounded ice margin by PD (as highlighted by the * simulations in Table S7). For example, reducing SSM2 and WD1 to 100m/yr and 400m increased the SSM by > 1m/yr at water depths close to and beyond the grounded ice margin. This increase in SSM was sufficient to drive the retreat during interglacial periods. At shallower water depths (< 300m) the increase SSM was less than 0.1 m/yr, therefore there was minimal impact on the ability of the floating ice shelf to thicken, grounded and expand during glacial periods.

Section S3 Relationship between temporal variability in SAT forcing and total grounded Ice Volume

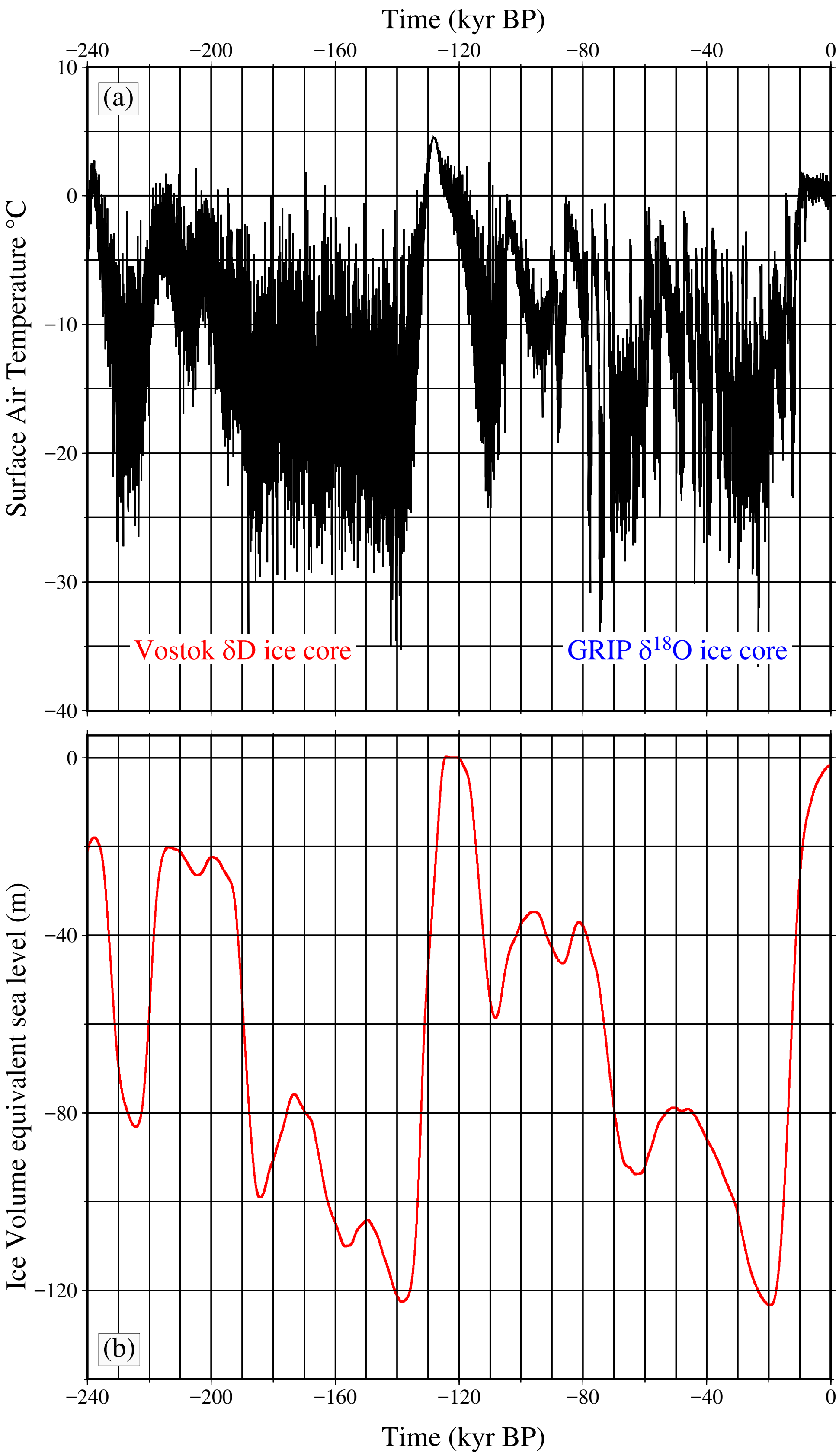
There is an evident correlation between the temporal variability of SAT forcing and the total ice volume in all simulations (Fig. S5); the periods of maximum ice volume (PGM, LGM) corresponding with the minimum in SAT and vice versa (Fig.S1). This implies that the timings of the glacial-interglacial variations are strongly dependent on the adopted SAT forcing. However, there is a highly variable spatially and temporal response between different regions of the ice sheet. This is discussed in greater detail in Sect. 5.2.2 and outlined below.

Between ~ 200 kyr BP and PGM (~ 136 kyr BP) as the ice sheet expands offshore and centrally thickens, the total ice volume increases, reaching a maximum of between 4.43×10^{15} m^3 to 4.50×10^{15} m^3. Once the offshore expanse of the NW margin is initiated (between 200-180 kyr BP), it continues to advance, grounding across the Nares Strait, the Hall Basin and Smith sound, reaching a maximum between ~170-145 kyr BP. The timing of this expanse is dependent on the choice of A_s; with an earlier expanse in the high A_s simulations. In contrast (Fig.7), the SW margin undergoes numerous short lived advances and retreats, approximately correlated with the higher order fluctuations in the SAT forcing, reaching a stable extent later than across the NW (~ 140 kyr BP).

During the sharp rise in SAT, from the PGM minimum (~-25ºC) to the LIG peak of 4.5°C at ~ 128 kyr BP, the ice sheet retreats to a smaller than PD extent, with the inland retreat of the SW margin (Fig.5b). At the LIG minimum, 123 kyr BP, the range in the ice volume of 2.68×10^{15} m^3 and $2.76\times10^{15} m^3$ (Fig.S5), is primarily driven by the adopted A_s parameter; a higher A_s resulting in the lowest ice volume due to the thinner, more retreated SW margin.

As the SAT cools towards the LGM minimum (~ -23ºC), the ice sheet expanded offshore, reaching a maximum ice volume at ~ 19 kyr BP of between 4.38×10^{15} m^3 and 4.47×10^{15} m^3 (Fig.S5b). Comparing the two glacial maximums (PGM to LGM), the expanse of the ice sheet across the NW was consistently larger during the PGM, (see Fig.5a and 5c). The maximum surface elevation (~ 3200m) and spatial extent along the NE, SE and SW margin remained largely unchanged. It is believed this difference is primarily driven by the slightly cooler SAT, ~ -25°C compared to ~ -23°C (Fig.S1).

All simulations result in a total PD ice volume larger than the observed, ranging between 3.28×10^{15} m^3 and 3.39×10^{15} m^3 (Fig.S5c). There was minimal difference in the spatial extent of the grounded ice sheet between the final nine simulations; with a underprediction across the retreated SW margin and a central overprediction and along most of the coastlines (Fig.S4). The high A_s simulations resulted in the lowest PD ice volume (Fig.S5, 3.28×10^{15} m^3), but the underprediction along the SW margin is significantly increased by > 1000m (relative to Mid/Low A_s simulations).



235 **Figure S1: (a) Surface Air Temperature forcing (SAT, °C) taken from Helsen et al., 2013. (b) Ice volume equivalent Sea level (ESL) (black line) taken from Bintanja et al., 2008 adopted in all simulations with ESL forcing (no RSL forcing).**

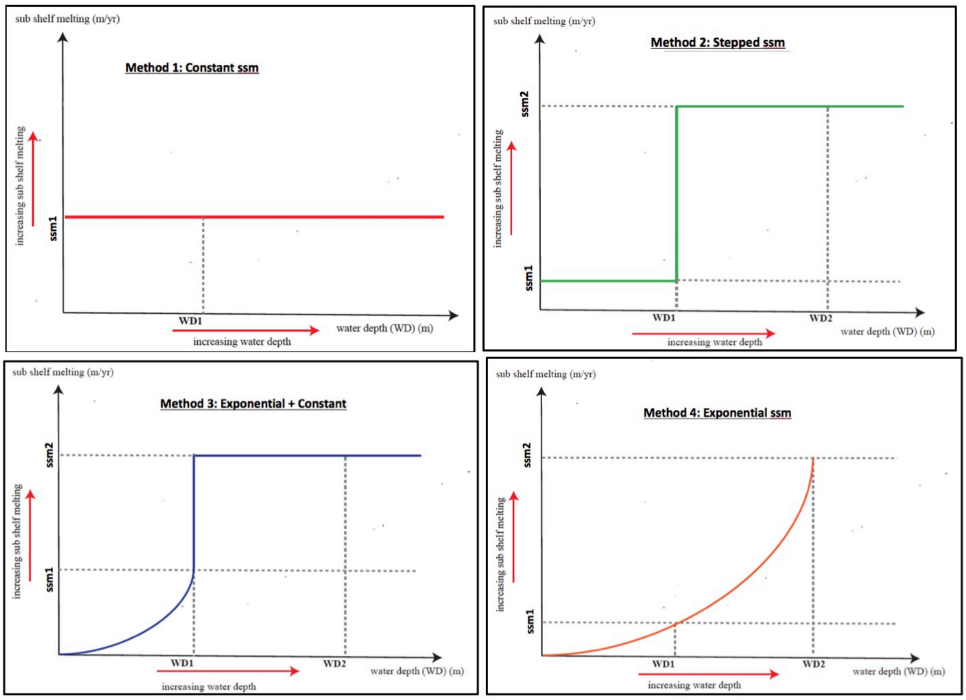


Figure S2: Schematic illustration of the four sub-ice shelf melting (SSM) parameterisation adopted in the with shelves simulations: (a) Method 1: Constant SSM (Red line): constant value at all depths (SSM1); (b) Method2: Stepped SSM (green): Two defined SSM values above/below water depth1, SSM1 < waterdepth1 > SSM2; (c) Method 3: Exponential + Constant (blue): Exponential increase up to a defined water depth1, sharp increase to constant value (SSM2); (d) Method 4:Exponential (red) an exponential increase defined by a set of two SSM and water depth values, (SSM1,SSM2, waterdepth1,waterdepth2).

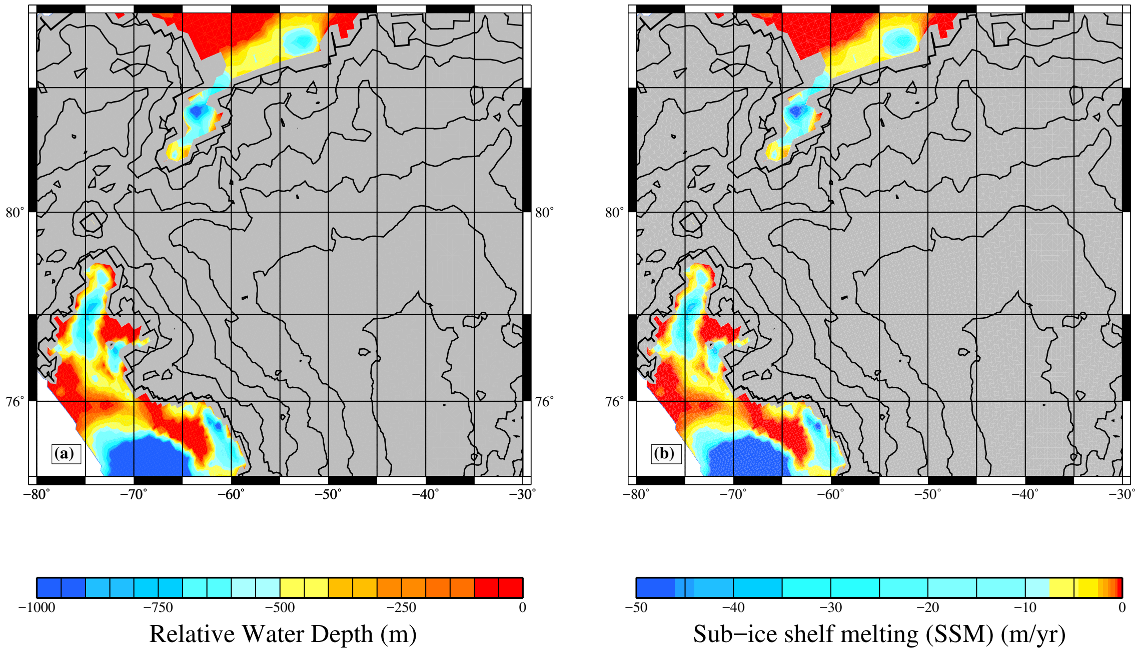


Figure S3: Example of the relationship between relative water depth (a) and sub-ice shelf melting (SSM) adopted in Method 4: Exponential SSM. As the relative water depth increases, the sub shelf melting (SSM) increases. The grey shaded region marks the grounded ice extent at LGM using the parameters highlighted in Table3, with a contour interval of 500m.

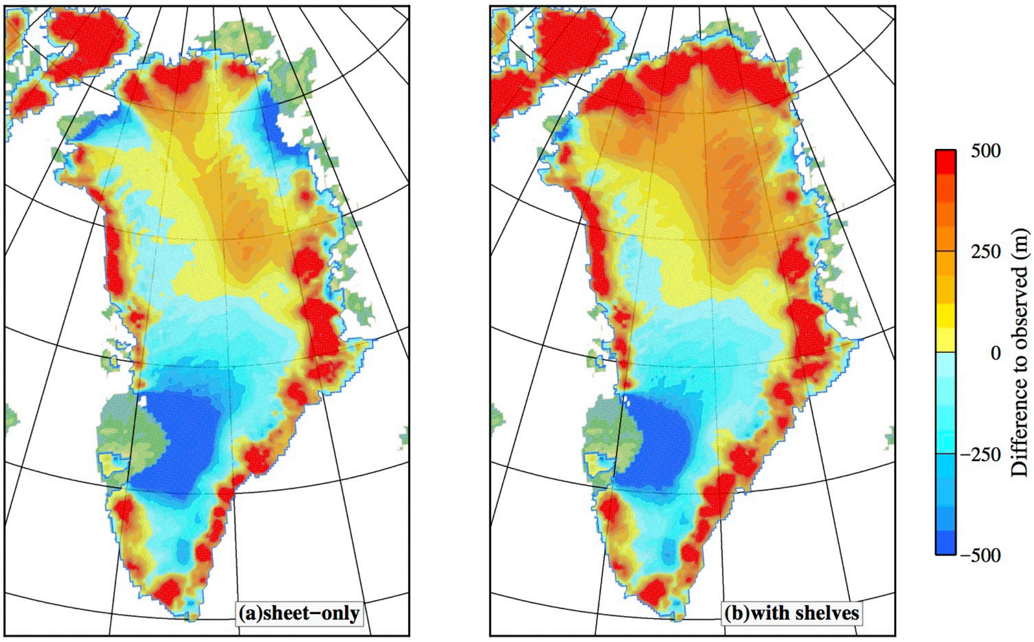


Figure S4: Difference in the simulated present day surface elevation (relative to observed surface elevation (Bamber et al., 2013) for the sheet-only (shown in Fig.4) and the with shelves simulation (shown in Fig.5), where positive value indicates an overprediction.

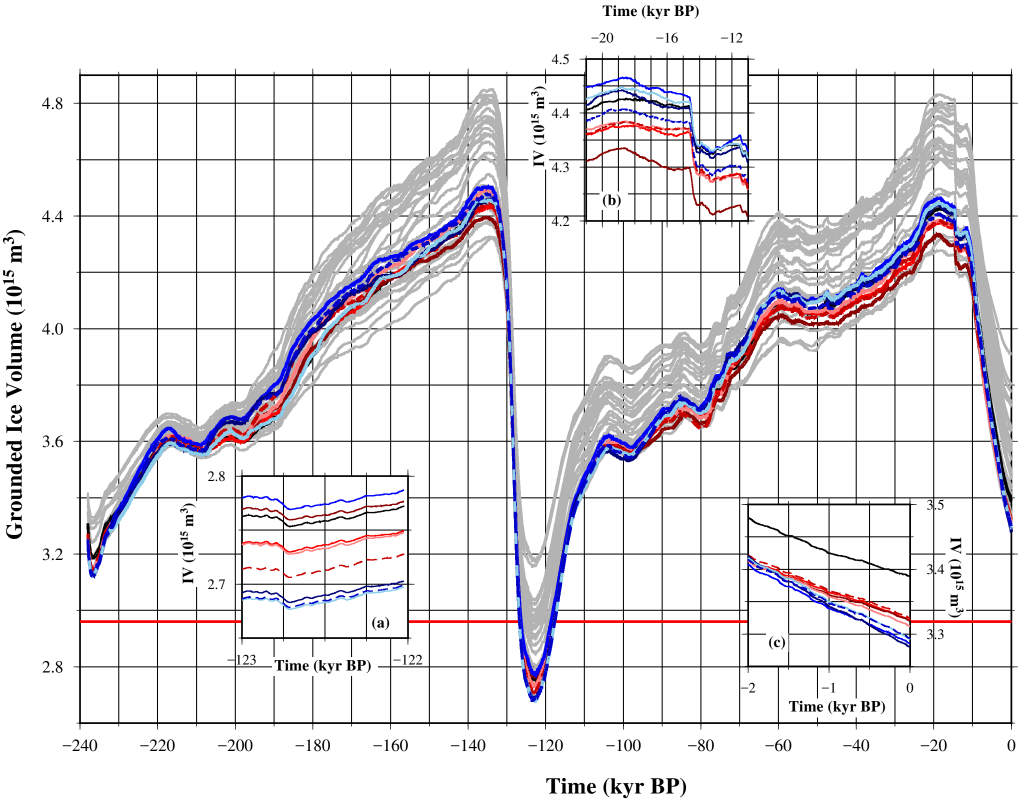


Figure S5: Grounded Ice volume (IV, 10^{15}m3) from the suite simulations with shelves combined with RSL forcing and SSM Method 4 simulations (grey lines) and optimum nine simulations on Table 3 (see table for colours and parameters). The solid red line marks the present-day ice volume, 2.96 $\times 10^{15}$m3 (Bamber et al., 2013) The three inlay panels illustrate the variation between the nine optimum simulations for: (a) the LIG minimum (123-122 kyr BP); (b) at the onset of the final deglaciation (21 – 11 kyr BP) and (c) in the present-day volume (2 – 0 kyr BP).

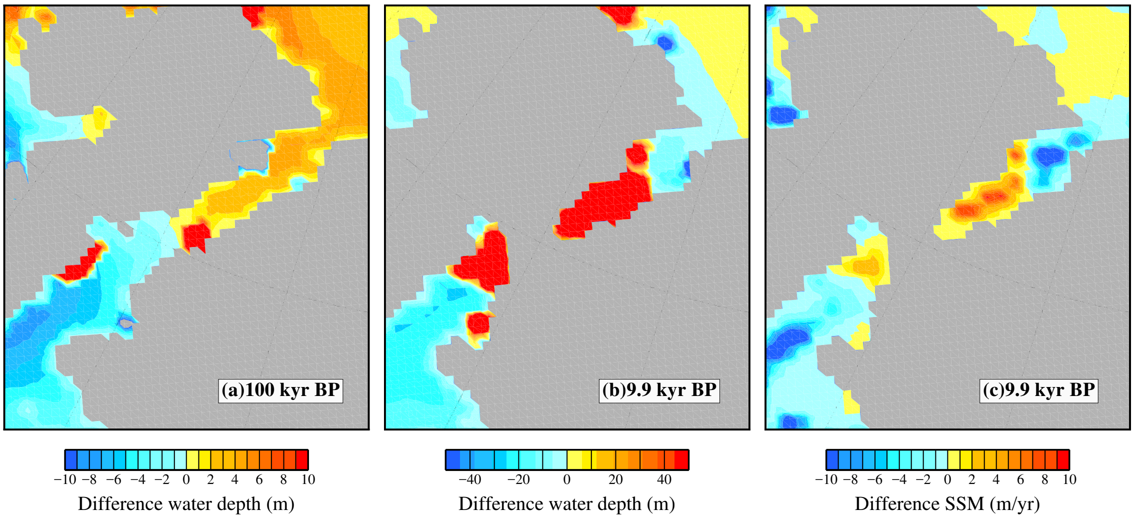


Figure S6: Difference in simulated water depth (a, b) and sub-ice shelf melting (SSM) (c) between simulations AvA_s+AvSSM1 and AvA_s+AvSSM1_redSSM2 (Table3) using with shelves combined with RSL forcing and Method 4. The main differences between these two simulations is the choice of SSM2: 100 m/yr (AvA_s+AvSSM1) compared to 75 m/yr (AvA_s+AvSSM1_redSSM2). Grey shaded region marks area of grounded ice sheet at each time step. Note that the colour scale extends beyond that illustrated in each panel.

Table S1-S7: A series of excel spreadsheet summarising the results of the various sensitivity studies conducted.