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Supplement of

A new sub-grid surface mass balance and flux model for continental-scale ice sheet modelling: validation and last glacial cycle

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1 Results for the stepwise regression fit

A model is constructed to minimizing ice volumes results misfits between the sub-grid model and ISSM. To determine which topographic characteristics significantly reduces the misfits, a stepwise multilinear regression method is used. Simulation are run to steady state (2 kyr) using a constant precipitation rate of 1 mm/yr and a sea level temperature forcing of $0\,^{\circ}\mathrm{C}$. These simulations are performed over 3 sets of 7 topographic regions.

Using the flow direction, the number of local maxima (tested with radius sizes of 2, 6 and 10 grid cells) and the sum of the squared slopes in the regression model did not reduce the misfits. The other characteristic tested are the terrain ruggedness, the variance in the slopes, $slopevarNorm$, and the standard deviation of the surface elevation topography S_{std}.

Table S1 summarizes the results of the stepwise regression fit when these parameters are used in different combinations (cases 1 to 8). 'In' indicates that this variable does minimize the differences between the ice volume generated by ISSM and the model generated with the stepwise regression fit. 'Out' indicates no minimization and the variable is not kept in the regression model. The stepwise regression fit is tested on experiments using the first and third topographic data set ("ids1"), the first and the second ("ids2") and the second and the third ("ids3"). A fourth experiment ("all ds") uses all the data. In that last case, no data are left to test the model obtained. 'rmse*e+10 (3ds)' represents the root mean square error, in 10^3 m^3 of ice, between the ice volume generated by ISSM and the model generated by the stepwise regression fit results, using the three data sets. The regression model, V_{regmod}, that generates the lowest misfits accounts only for the standard deviation of the topography (case 7) and is define as:

$$V_{regmod} = 0.79 V_{SG} + 2.2017e8\ S_{std} \tag{1}$$

Table S1. Stepwise regression fit results

	ids1	ids2	ids3	all ds	rmse sum
case 1					
Ice volume SG	'In'	'In'	'In'	'In'	
terrain ruggedness	'In'	'Out'	'In'	'In'	
slopevarNorm	'In'	'Out'	'In'	'In'	
S_{std}	'In'	'In'	'In'	'In'	
rmse*e+10 (3ds)	7.3981	2.3025	8.9690	7.3981	26.068 (6)
case 2					
Ice volume SG	'In'	'In'	'In'	'In'	
terrain ruggedness	'Out'	'Out'	'In'	'In'	
S_{std}	'In'	'In'	'Out'	'In'	
rmse*e+10 (3ds)	2.9883	2.3025	5.6907	2.9883	13.970 (2)
case 3					
Ice volume SG	'In'	'In'	'In'	'In'	
terrain ruggedness	'Out'	'Out'	'In'	'In'	
slopevarNorm	'Out'	'In'	'Out'	'Out'	
rmse*e+10 (3ds)	8.2247	2.6692	5.6907	8.2247	24.809 (4)
case 4					
Ice volume SG	'In'	'In'	'In'	'In'	
slopevarNorm	'Out'	'Out'	'Out'	'Out'	
S_{std}	'In'	'In'	'In'	'In'	
rmse*e+10 (3ds)	2.9883	2.3025	2.1609	2.9883	10.440 (1)
case 5					
Ice volume SG	'In'	'In'	'In'	'In'	
terrain ruggedness	'Out'	'Out'	'In'	'In'	
rmse*e+10 (3ds)	8.2247	4.1280	5.6907	8.2247	26.268 (7)
case 6					
Ice volume SG	'In'	'In'	'In'	'In'	
slopevarNorm	'Out'	'In'	'In'	'In'	
rmse*e+10 (3ds)	8.2247	2.6692	3.1347	8.2247	22.253 (3)
case 7					
Ice volume SG	'In'	'In'	'In'	'In'	
S_{std}	'In'	'In'	'In'	'In'	
rmse*e+10 (3ds)	2.9883	2.3025	2.1609	2.9883	10.440 (1)
case 8					
Ice volume SG	'In'	'In'	'In'	'In'	
rmse*e+10 (3ds)	8.2247	4.1280	5.3374	8.2247	25.915 (5)

2 Surface elevation and velocities on an inclined plane when different numbers of hypsometric levels are used (Fig.S1)

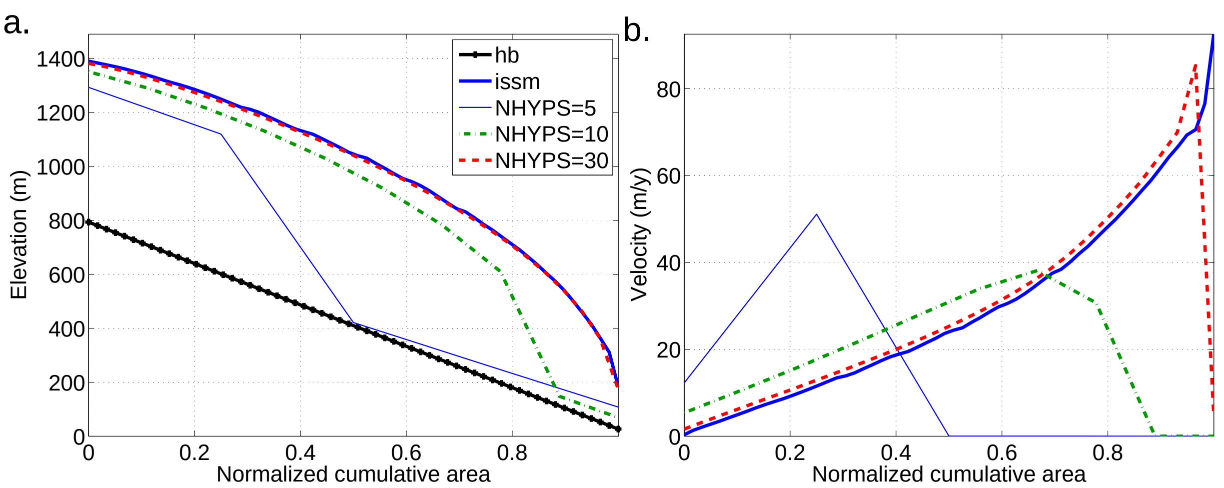

Figure S1. Sensitivity to the number of hypsometric levels for an experiment using a sea level temperature set to 0 °C and the desertification factor to 0.5. **a.** Represents the surface elevation and **b.** the velocities' profiles after 2 kyr.

3 Percentage of hypsometric levels jumps (Fig.S2)

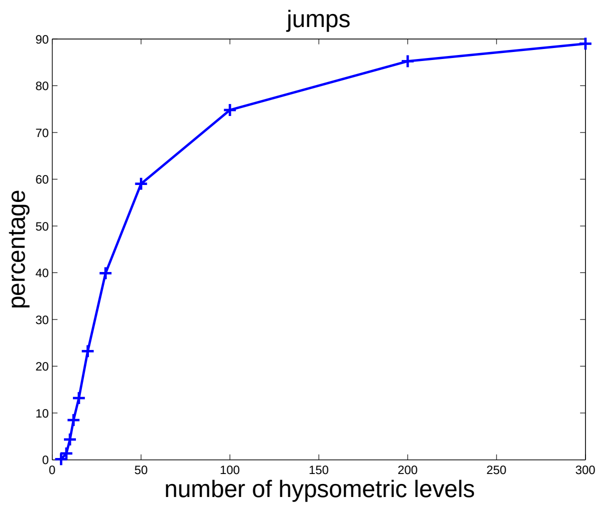

Figure S2. Average percentage of hypsometric level jumps in the 21 regions analyzed when different number of hypsometric levels are used.

4 Ice characteristics at steady state for six different regions in the Canadian Rockies (Fig.S3)

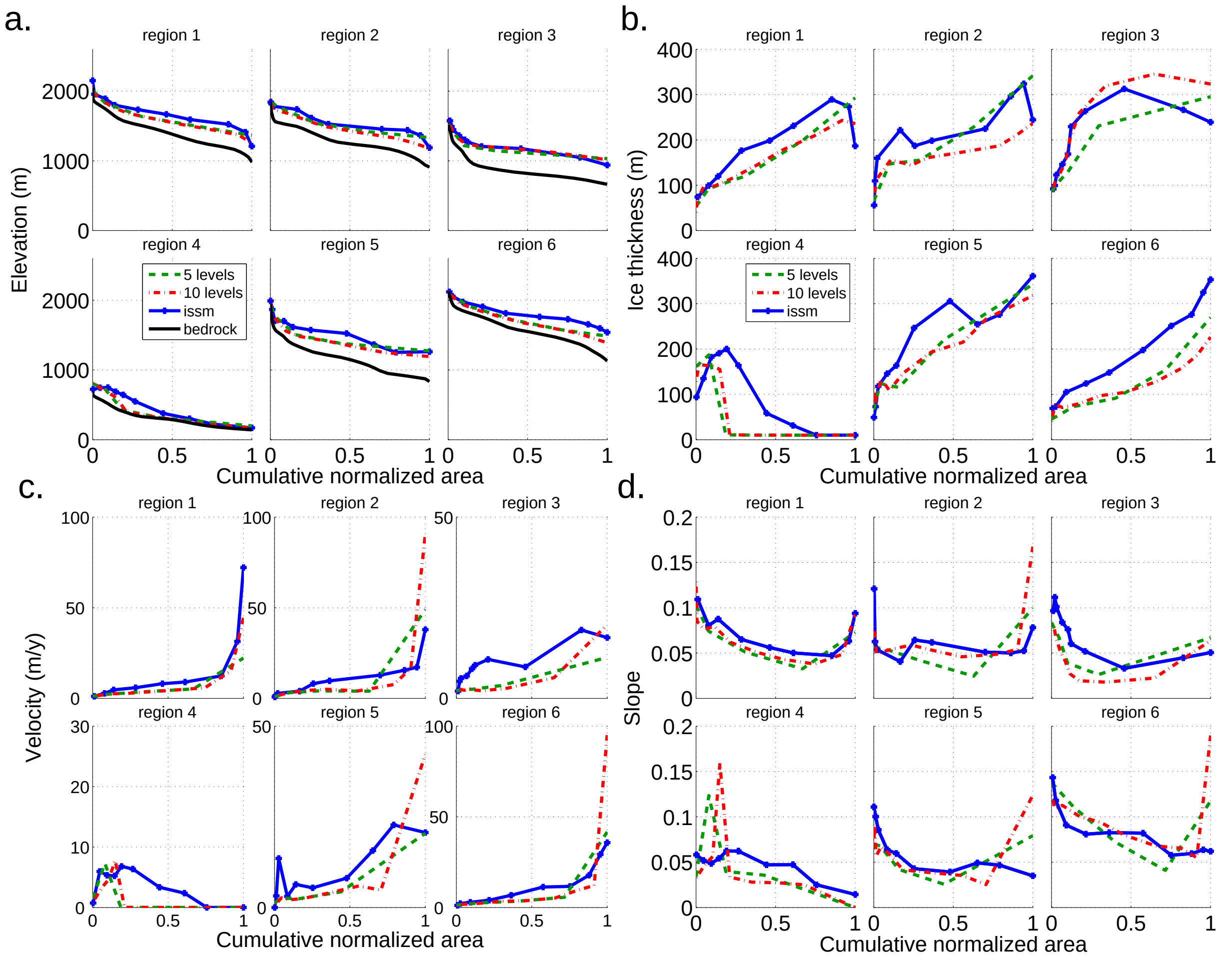

Figure S3. Comparison of the ice characteristics when different hypsometric levels are used in the SG model. Result shown at steady state after 2 kyr simulation for six different regions. **a.** represents the surface elevation, **b.** the ice thickness, **c.** the velocities and **d.** the slopes. Solid black line represents the bed topography using 30 hypsometric levels. Solid blue lines are related to ISSM. The other lines correspond to the SG model results using 5 (dashed green lines) and 10 (dashed-doted red lines) hypsometric levels.

5 Ice evolution on an inclined plane for different forcings (Fig.S4)

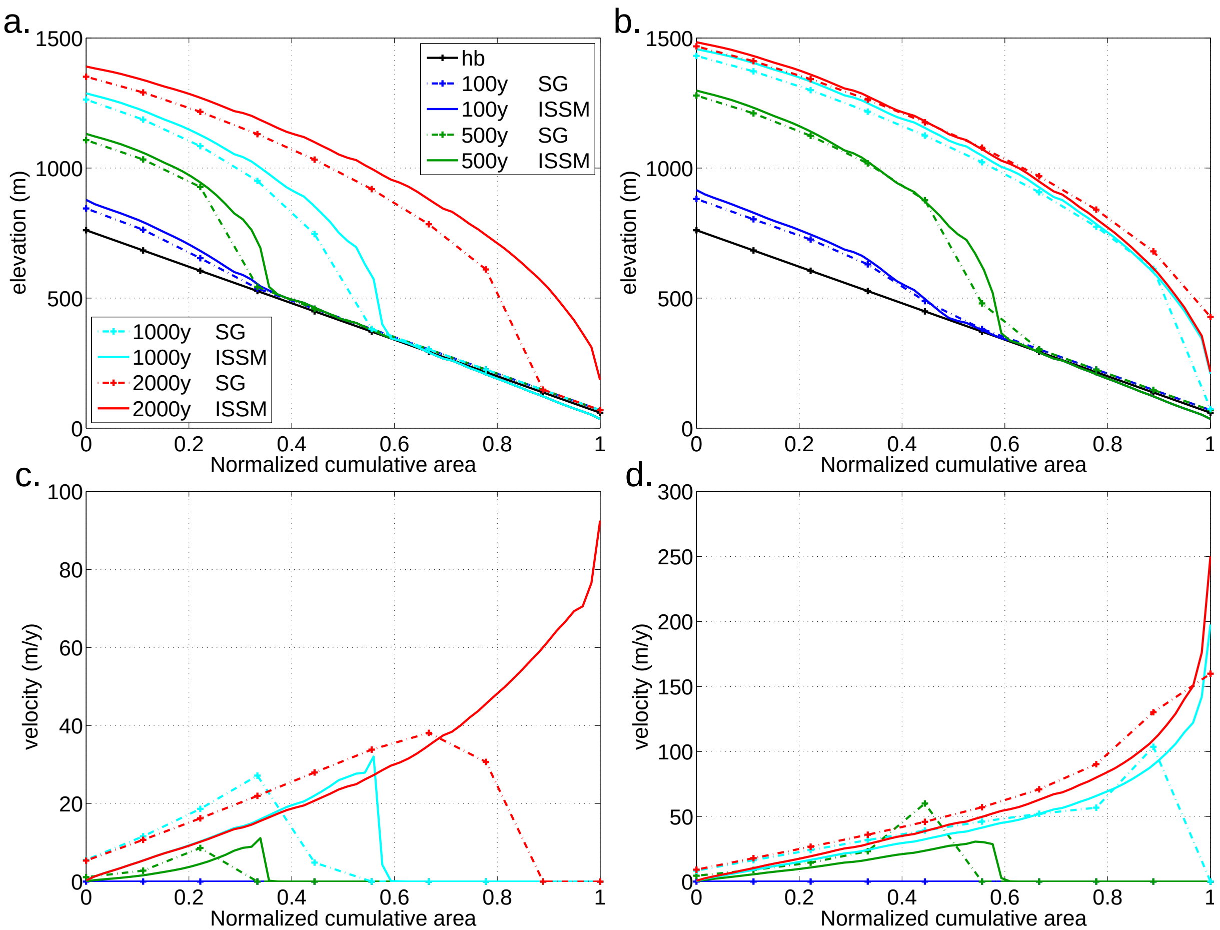

Figure S4. Surface elevation and velocities evolution over an inclined plane using ISSM and the SG model. Simulations use a sea level temperature forcing of 0 °C and an elevation desertification factor of 0.5 in **a** and **c**, and 0 in **b** and **d**.

6 Ice characteristics evolution when different parameterization method are used (Fig.S5)

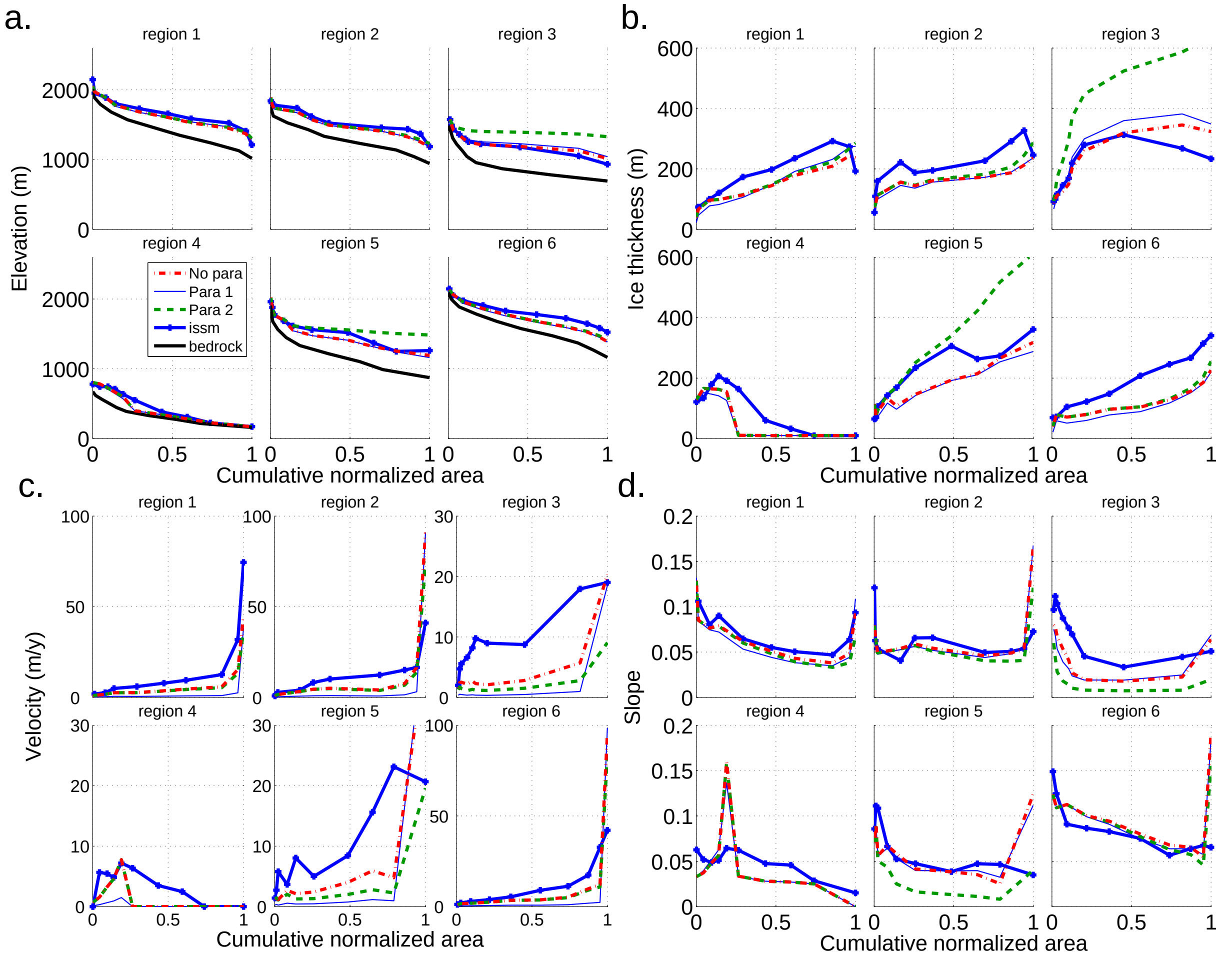

Figure S5. Comparison of the ice characteristics when different parameterization are used in the SG model. Result shown at steady state after 2 kyr simulation for six different regions. **a.** Represents the surface elevation, **b.** the ice thickness, **c.** the velocities and **d.** the slopes. Solid black line represents the bed topography using 30 hypsometric levels. Solid blue lines are related to ISSM. The other lines correspond to the SG model results with no additional parameterization (dashed red lines), the parameterization of the velocities at every levels (para 1, solid cyan lines) and the parameterization of the slope at the lowest level (Para 2, dashed-doted green lines). 10 hypsometric levels.

7 Simulation for a case where more ice is generated when the SG model is activated (Fig.S6)

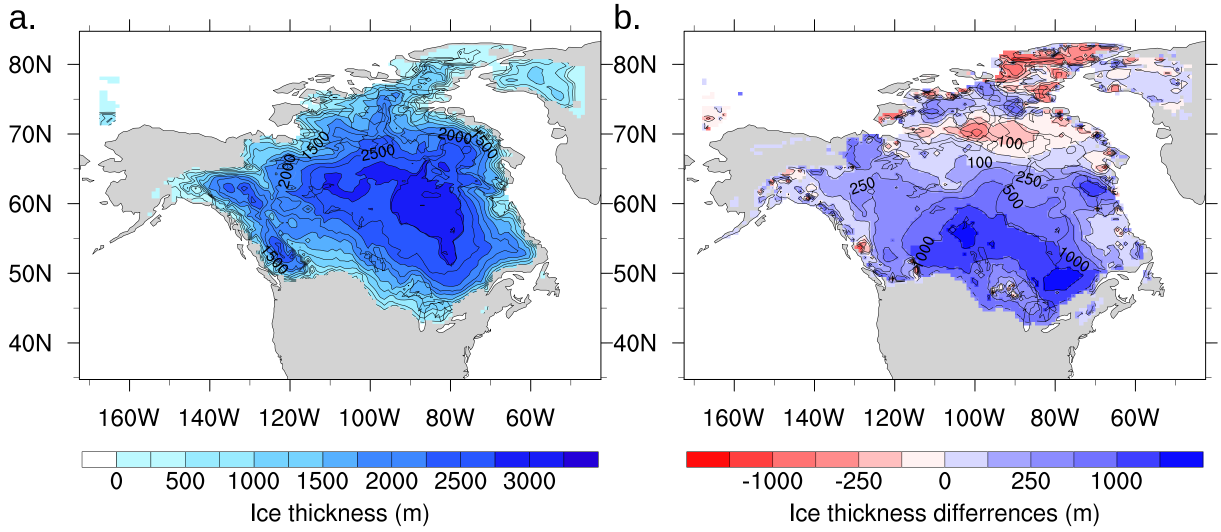

Figure S6. Ice thickness comparison at 50 ka, using a parameter vector representing a increase of ice thickness when the SG model is used. **a.** Ice thickness when SG is activated. **b.** Ice thickness differences between simulations where the SG model is on and off.

8 Maximum positive and negative differences (Fig.S7)

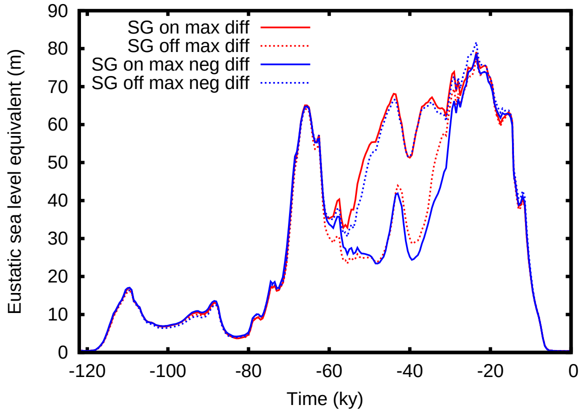

Figure S7. Ice volume evolution using the ensemble parameter vectors representing the maximum positive (red) and negative (blue) differences between simulations with the SG model activated or not.

9 Flux method comparison (Fig.S8)

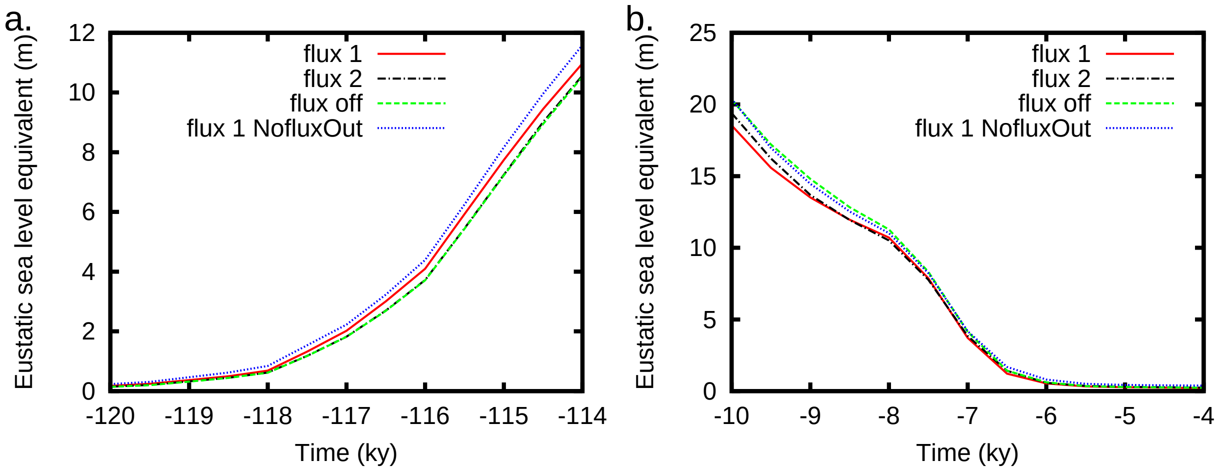

Figure S8. Ice volume evolution for a simulation over North America with the SG model turned on (**a.** during inception and **b.** deglaciation). "flux 1" represents the flux code used in our SG model and "flux 2", the flux code used in Marshall et al. (2011) experiment. "flux off" represents the simulation where no flux is allowed between SG levels.

10 Ice volume redistribution on coarse grid (Fig.S9)

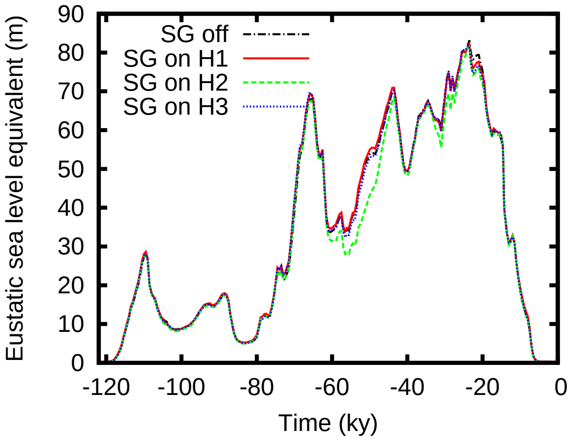

Figure S9. Total ice volume evolution for a simulation using one of the parameter vector that generates the better fit to calibration constraints. Different curves represent simulation where different methods are used to redistribute ice a the CG level when the SG model is activated.

References

Marshall, S. J., White, E. C., Demuth, M. N., Bolch, T., Wheate, R., Menounos, B., Beedle, M. J., and Shea, J. M.: Glacier water resources on the eastern slopes of the Canadian Rocky Mountains, Canadian Water Resources Journal, 36, 109–134, 2011.