Impact of spatial resolution on large-scale ice cover modelling of mountainous regions - Supplement

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Experiments with smoothed DEMs

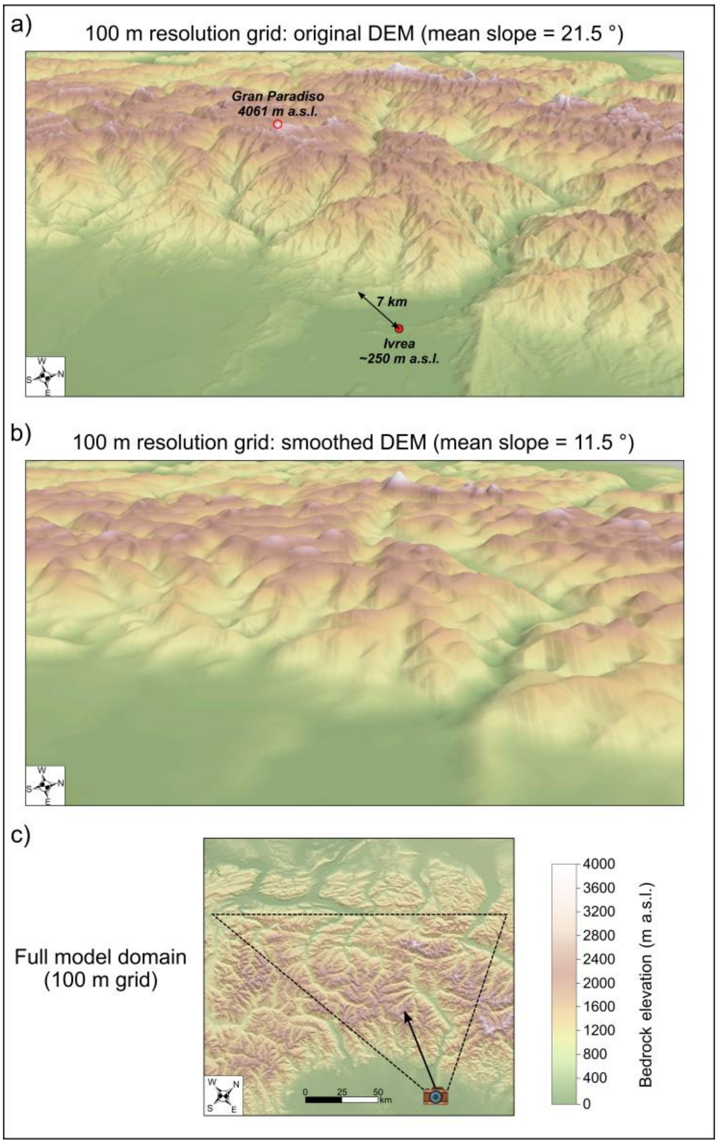

Figure S1 Comparison of (a) original and (b) smoothed DEM, both at 100 m resolution. The smoothed DEM is based on the 2000-m DEM using cubic resampling at 100 m. The perspective of (a) and (b) inside the model domain (original 100-m DEM) is shown in (c). All panels were produced using ArcGIS Pro 3.2.2 (Esri).

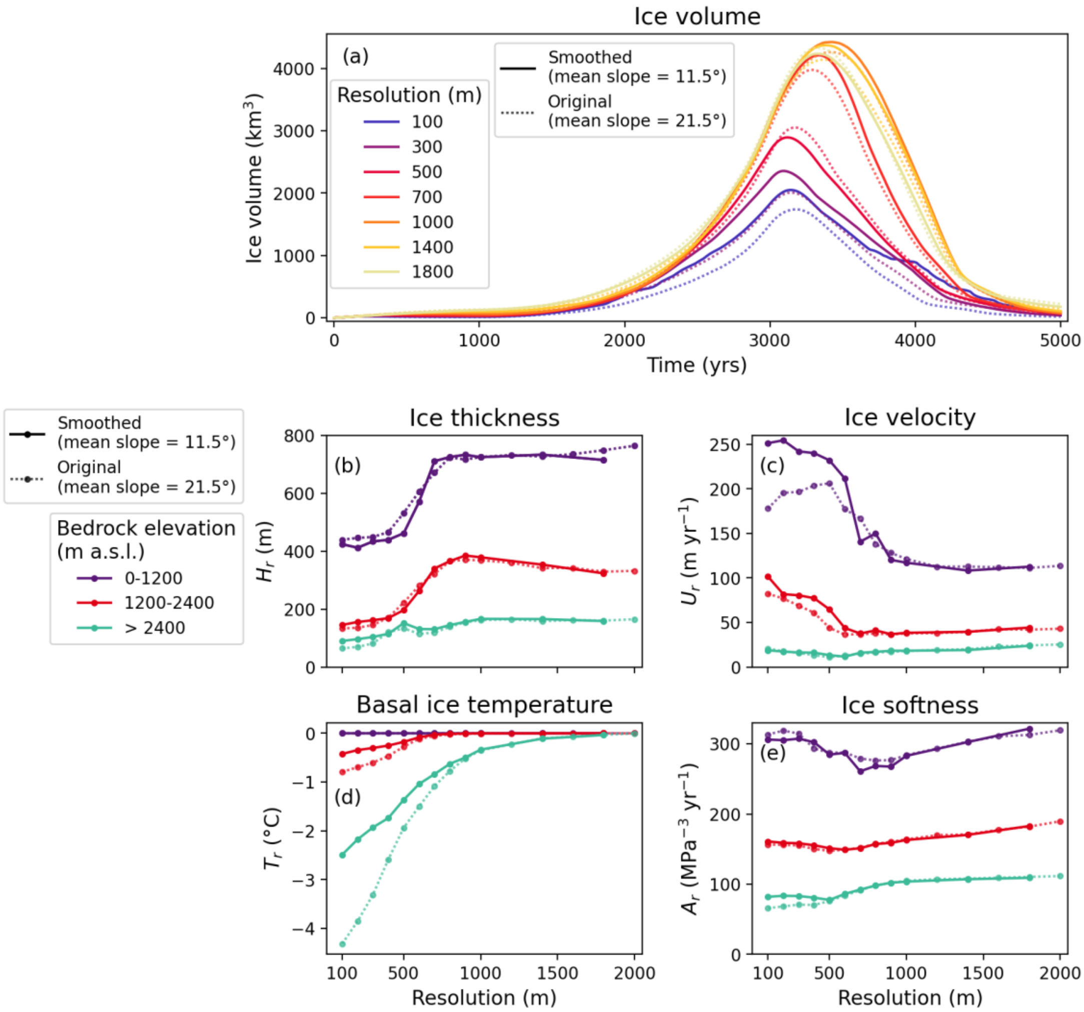

Figure S2 Comparison of simulations with smoothed DEMs (based on the 2000-m DEM which is cubic resampled to finer resolutions, with a mean slope of 11.5°) to simulations with the original DEMs (with a mean slope of 21.5°). (a) Temporal evolution of ice volume, at 100, 300, 500, 700, 1000, 1400, 1800 m resolutions. (b)–(e) Model output variables at full glaciation averaged over glaciated area at different resolutions, distinguished between low (0–1200 m a.s.l.), mid (1200–2400 m a.s.l.), and high (>2400 m a.s.l.) bedrock altitudes: (b) Ice thickness H_r, (c) depth-averaged ice velocity U_r, (d) basal ice temperature T_r, (f) depth-averaged Arrhenius factor A_r. In all subplots, solid lines correspond to results based on the smoothed DEMs, and dashed lines correspond to results based on original DEMs.

Additional model outputs

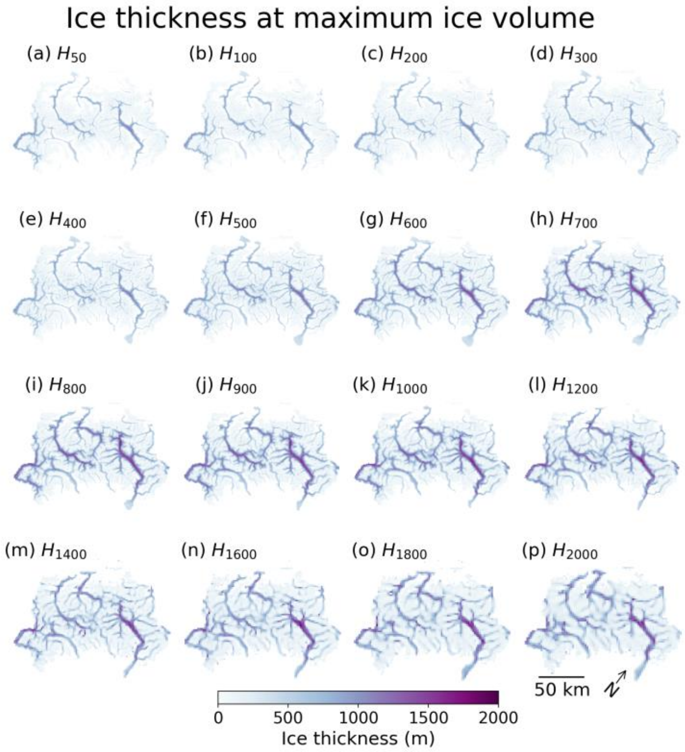

Figure S3 Ice thickness H_r at maximum ice volume for models at resolution r = 100, 200, 300, 400, 500, 600, 700, 800, 900, 1000, 1200, 1400, 1600, 1800, and 2000 m.

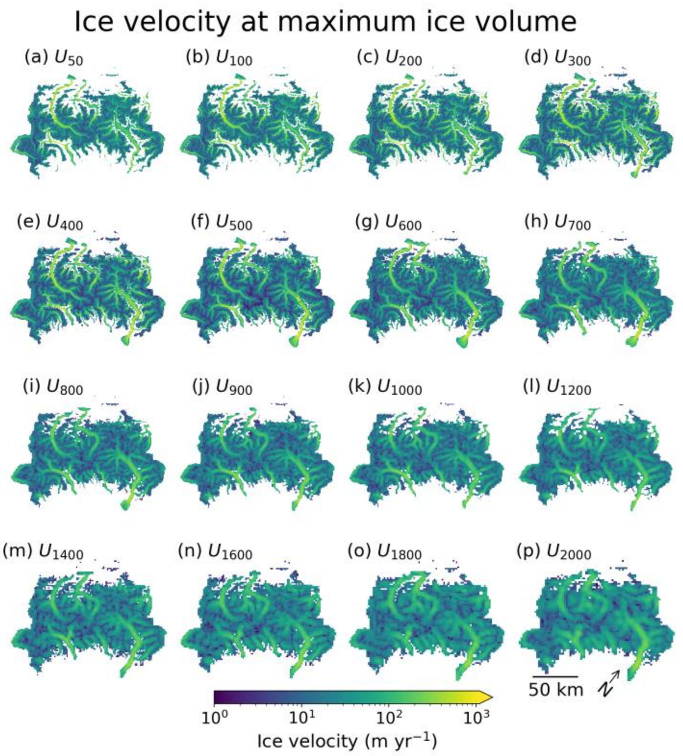

Figure S4 Depth-averaged ice velocity U_r at maximum ice volume for models at resolution r = 100, 200, 300, 400, 500, 600, 700, 800, 900, 1000, 1200, 1400, 1600, 1800, and 2000 m.

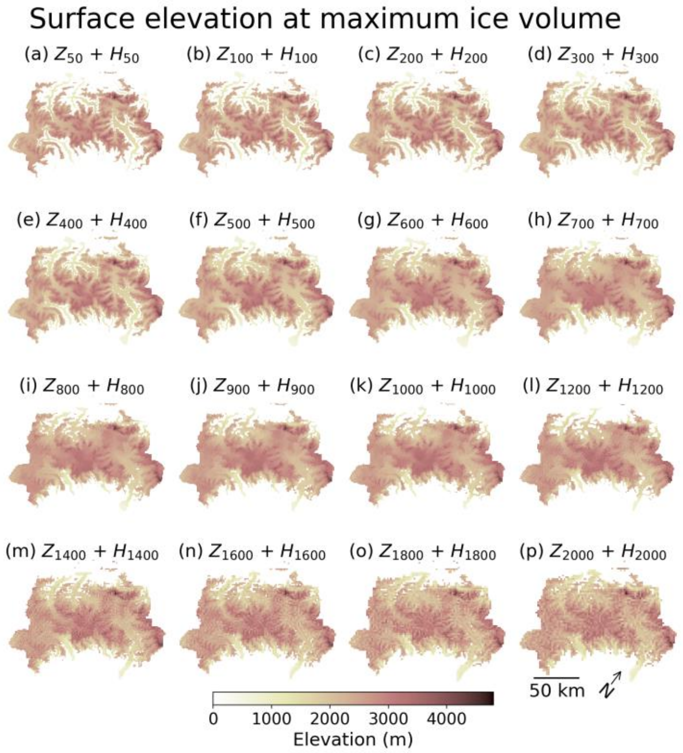

Figure S5 Surface elevation (bedrock elevation Z_r and ice thickness H_r) at maximum ice volume for models at resolution r = 100, 200, 300, 400, 500, 600, 700, 800, 900, 1000, 1200, 1400, 1600, 1800, and 2000 m.

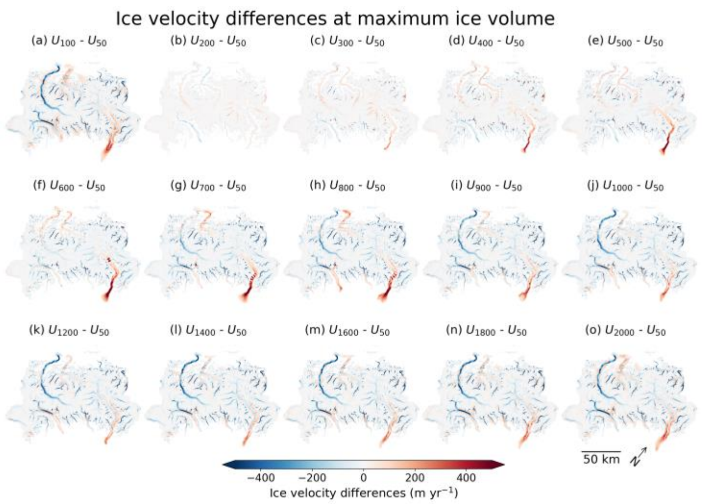

Figure S6 Depth-averaged ice velocity differences U_r-U_{50} at maximum ice volume between models at resolution r = 100, 200, 300, 400, 500, 600, 700, 800, 900, 1000, 1200, 1400, 1600, 1800, 2000 m resolution and the 50 m run.

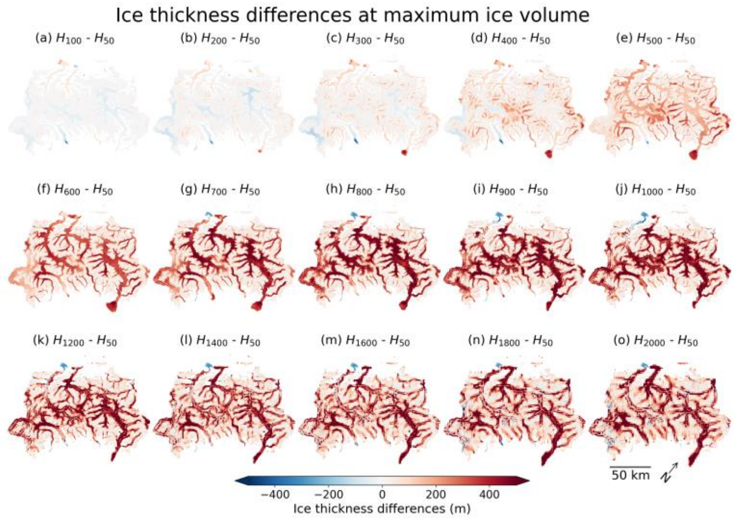

Figure S7 Ice thickness differences H_r-H_{50} at maximum ice volume between models at resolution r = 100, 200, 300, 400, 500, 600, 700, 800, 900, 1000, 1200, 1400, 1600, 1800, 2000 m resolution and the 50 m run.

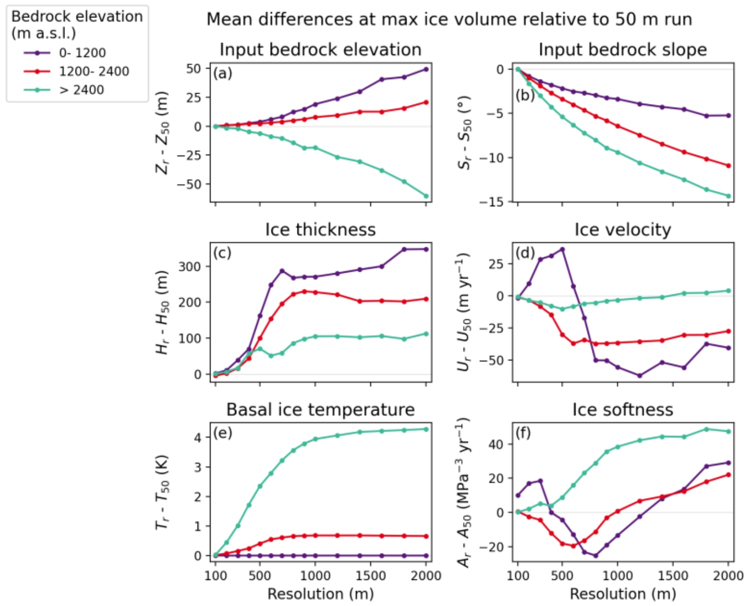

Figure S8 Mean differences relative to the 50 m simulation. (a) Bedrock elevation in the DEMs Z_r-Z_{50}, (b) bedrock slope in the DEMs S_r-S_{50}, (c) ice thickness H_r-H_{50}, (d) depth-averaged ice velocity U_r-U_{50}, (d) basal ice temperature T_r-T_{50}, and (f) depth-averaged Arrhenius factor A_r-A_{50}. Differences in (c)–(f) are taken at maximum ice volume. All differences are averaged across the glaciated area at low (0–1200 m a.s.l.), mid (1200–2400 m a.s.l.), and high (>2400 m a.s.l.) altitudes.

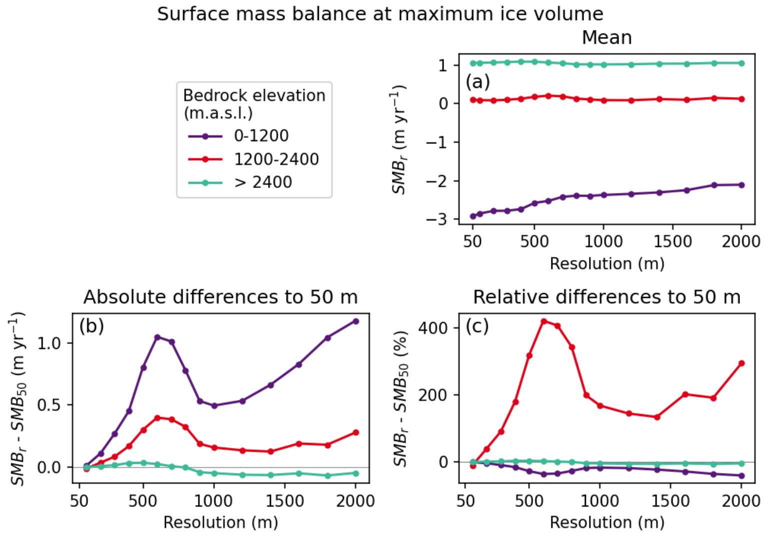

Figure S9 Surface mass balance (SMB) at full glaciation. (a) SMB, (b) Absolute differences SMB_r-SMB_{50} between SMB in simulations at resolution r and SMB in 50 m simulation, (c) Relative differences SMB_r-SMB_{50} between SMB in simulations at resolution r and SMB in the 50 m simulation to the 50 m run. All values are averaged across the glaciated area at low (0–1200 m a.s.l.), mid (1200–2400 m a.s.l.), and high (>2400 m a.s.l.) altitudes.

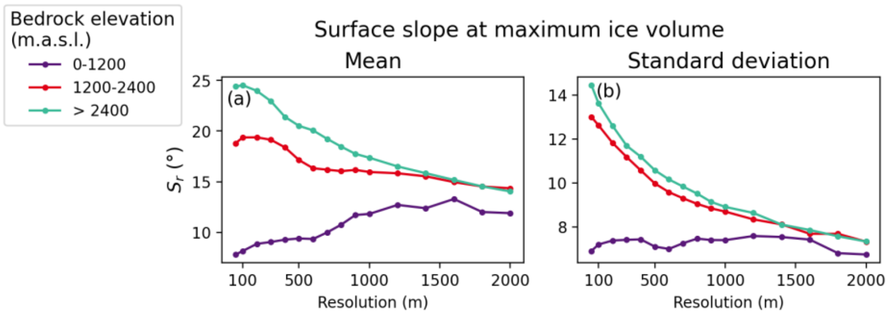

Figure S10 (a) Mean and (b) standard deviation of slope angle of surface elevation (bedrock elevation and ice thickness) at full glaciation across the glaciated area at low (0–1200 m a.s.l.), mid (1200–2400 m a.s.l.), and high (>2400 m a.s.l.) altitudes.

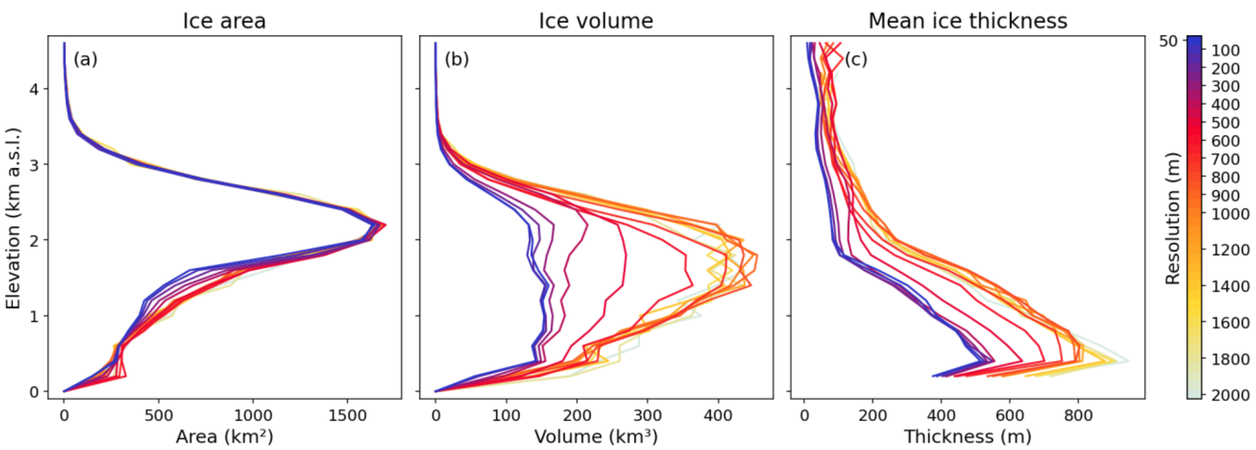

Figure S11 (a) Ice area, (b) ice volume, and (c) mean ice thickness across bedrock elevation at full glaciation averaged over 200-m elevation bins.

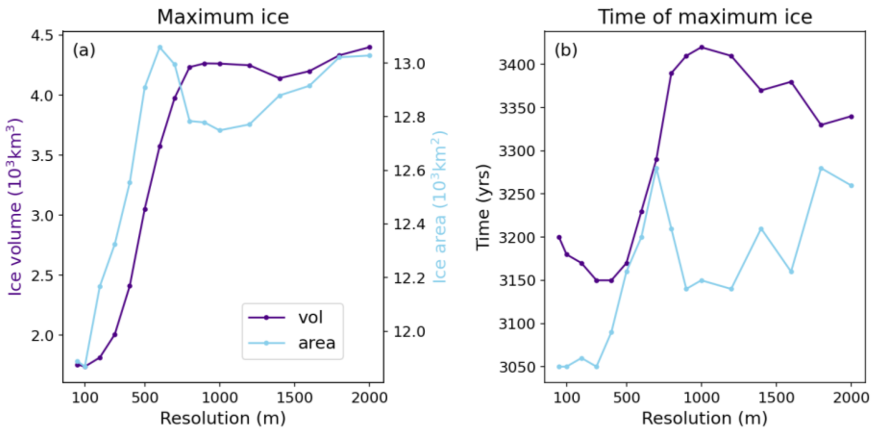

Figure S12 (a) Maximum ice volume (purple) and area (blue), (b) time of maximum ice volume (purple) and area (blue) at all resolutions.

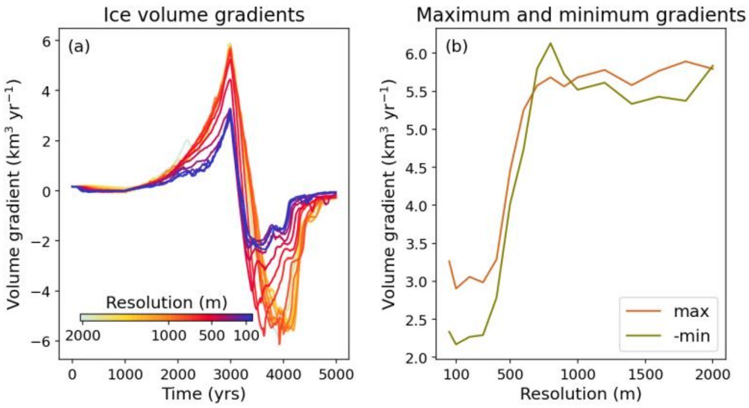

Figure S13 (a) Temporal evolution of ice volume gradients of all resolution runs. (b) Maximum (brown) and inverse minimum (green) ice volume gradient of resolution runs.

Simulations using slower temperature forcing

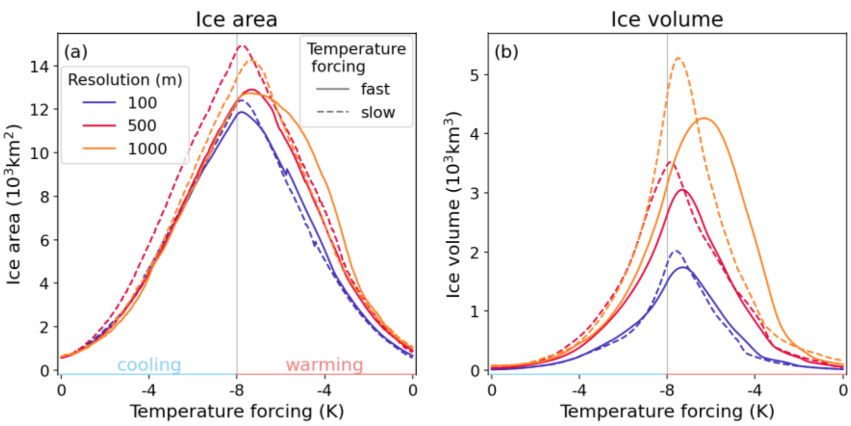

Figure S14 Ice area (a) and volume (b) of fast (solid line) and slow (dashed line) temperature forcing runs at 100 (blue), 500 (red), and 1000 m (orange) resolution.

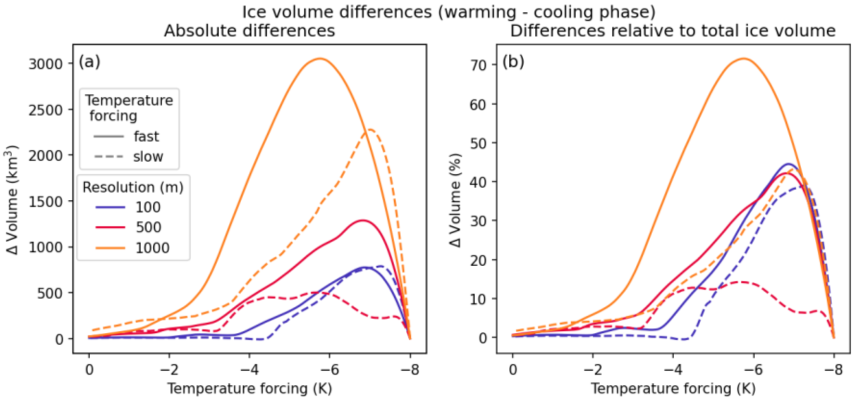

Figure S15 Differences of ice volume at times with the same temperature forcing value during the warming and cooling phases (warming minus cooling phase). (a) Absolute differences, (b) differences relative to the total ice volume. Solid lines are simulations using the fast (4 K/kyrs) and dashed lines are simulations using the slow (2 K/kyrs) temperature forcing at 100 (blue), 500 (red), and 1000 m (orange) resolution.

Model parameters and climate input

Table S1 Model parameters from Leger et al. 2025's ensemble best-scoring simulation, simulation 37.

IGM module / parameter name	Description	System component	Value	Unit
Surface mass balance				
smb_accpdd_update_freq	Frequency at which the Surface Mass Balance (SMB) is updated	Surface mass balance	1.0	yr
accpdd_refreeze_factor	Positive Degree Day refreezing factor	Surface mass balance	0.6156090086419556	n/a
smb_accpdd_thr_temp_snow	Threshold temperature for solid precipitation	Surface mass balance	0.0	°C
smb_accpdd_thr_temp_rain	Threshold temperature for liquid precipitation	Surface mass balance	2.0	°C
smb_accpdd_melt_factor_snow	Positive Degree Day melt rate for snow	Surface mass balance	1.20409532638	m *we* °C^{-1} yr^{-1}
smb_accpdd_melt_factor_ice	Positive Degree Day melt rate for ice	Surface mass balance	2.8262694332550296	m *we* °C^{-1} yr^{-1}
smb_accpdd_shift_hydro_year	This serves to start Oct 1 the acc/melt computation	Surface mass balance	0.75	yr
smb_accpdd_ice_density	Density of ice for conversion of SMB into ice equivalent	Surface mass balance	910.0	kg m^{-3}
smb_accpdd_wat_density	Density of water	Surface mass balance	1000.0	kg m^{-3}
Ice flow				
filo_enhancement_factor	Flow law enhancement factor	Ice flow	1.3885266806845515	n/a
iflo_regu_glen	Regularisation parameter for Glen's flow law	Ice flow	0.0	n/a
iflo_regu_weertmann	Regularisation parameter for Weertman's sliding law	Basal sliding	10^{-10}	n/a
iflo_exp_glen	Glen's flow law exponent	Ice flow	3.0	n/a
iflo_exp_weertman	Weertman's law exponent	Basal sliding	4.0	n/a
iflo_gravity_cst	Acceleration due to gravity of a free falling object	Ice flow	9.81	m s^{-2}
iflo_ice_density	Density of ice	Ice flow	910.0	kg m^{-3}
iflo_Nz	Number of grid points for the vertical discretisation	Ice flow	10.0	n/a
iflo_vert_spacing	Discretisation density to get more points towards glacier bed than surface	Ice flow	4.0	n/a
iflo_thr_ice_thk	Threshold ice thickness for computing strain rate	Ice flow	0.1	m

IGM module / parameter name	Description	System component	Value	Unit
iflo_dim_arrhenius	Dimension of the Arrhenius factor (horizontal 2D or 3D)	Ice flow	3.0	n/a
iflo_retrain_emulator_freq	Frequency at which the emulator is retrained, 0 means never, 1 means every time step	Neural network	2.0 (50, 100 m res.)*, 7.0 (else)	time step
iflo_retrain_emulator_lr	Learning rate for the retraining of the emulator	Neural network	10^{-5}	n/a
iflo_retrain_emulator_nbit	Number of iterations at each time step for retraining the emulator	Neural network	1.0	iterations
iflo_force_max_velbar	Artificially upper-bound of ice velocities	Ice flow	3000.0	m yr^{-1}
iflo_network	Type of network, it can be cnn or unet	Neural network	"cnn"	n/a
iflo_nb_layers	Number of layers in the Convolutional Neural Network (CNN)	Neural network	16.0	n/a
iflo_nb_blocks	Number of block layer in the U-net	Neural network	4	n/a
iflo_nb_out_filter	Number of output filters in the CNN	Neural network	32.0	n/a
iflo_conv_ker_size	Size of the convolution kernel	Neural network	3.0	n/a
iflo_dropout_rate	Dropout rate in the CNN	Neural network	0	n/a
iflo_min_sr	Minimum strain rate	Ice flow	10^{-5}	yr^{-1}
iflo_max_sr	Maximum strain rate	Ice flow	1.0	yr^{-1}
thk_slope_type	Slope limiter for the ice thickness equation (godunov or superbee)	Ice flow	"superbee"	n/a
vflo_method	Method to retrieve vertical velocities (kinematic, incompressibility)	Ice flow	"incompressibility"	n/a
Time				
time_start	Simulation start	Time	0.0	yr
time_end	Simulation end	Time	5000.0 (9000.0 with slow temperature forcing)	yr
time_save	Save output frequency	Time	10.0	yr
time_cfl	CFL number for the stability of the mass conservation scheme	Time	0.3	
time_stp_max	Maximum time step allowed, used only with slow ice	Time	10.0	yr
Enthalpy				
enth_water_density	Density of water	Enthalpy	1000.0	kg m^{-3}
enth_spy	Number of seconds in a year	Enthalpy	31556926.0	seconds
enth_ki	Conductivity of cold ice	Enthalpy	2.1	W m^{-1} K^{-1}
ent_ci	Specific heat capacity of ice	Enthalpy	2009.0	W s kg^{-1} K^{-1}
enth_Lh	Latent heat of fusion	Enthalpy	334000.0	W s kg^{-1}
ent_KtdivKc	Ratio of temperate versus cold ice diffusivity	Enthalpy	0.1	n/a
enth_claus_clape	Clausius-Clapeyron constant	Enthalpy	7.9×10^{-8}	K Pa^{-1}
enth_melt_temp	Melting point at standard pressure	Enthalpy	273.15	K
enth_ref_temp	Reference temperature	Enthalpy	223.15	K
enth_till_friction_angle_bed_min	Lower bed elevation threshold for yield stress	Yield stress	-444.8608285471192	m a.s.l.
enth_till_friction_angle_bed_max	Upper bed elevation threshold for yield stress	Yield stress	2982.864772500515	m a.s.l.
ent_till_friction_angle_phi_min	Minimum till friction angle in bed-elevation dependent scheme	Yield stress	15.0	°
enth_till_friction_angle_phi_max	Maximum till friction angle in bed-elevation dependent scheme	Yield stress	50.0	°
enth_uthreshold	Pseudo-plastic sliding law U threshold	Sliding	1244.8467164648443	m yr^{-1}
enth_drain_rate	Water draining rate	Yield stress	0.001	mm yr^{-1}

IGM module / parameter name	Description	System component	Value	Unit
enth_till_wat_max	Maximum water till thickness	Yield stress	2.0	m
enth_default_bheatflx	Geothermal heat flux	Basal melt	0.065	W m^{-2}
temperature_offset_air_to_ice	Surface air-to-ice temperature offset	Enthalpy	2.9022389684294243	°C
enth_tauc_min	Lower caping bound for yield stress	Yield stress	10000.0	Pa
enth_tauc_max	Upper caping bound for yield stress	Yield stress	1 0000000000.0	Pa
Avalanche				
avalanche_update_freq	Update frequency of the avalanche module	Avalanche	5.0	yr
avalanche_angleOfRepose	Angle of repose. For bed slopes above this, ice "avalanches"	Avalanche	45.0	°
Gflex				
gflex_update_freq	Update frequency of the gFlex GIA module	Glacial isostatic adjustment	50.0	yr
gflex_default_Te	Lithospheric effective elastic thickness	Glacial isostatic adjustment	45556.89245060796	m
gflex_dx	Spatial grid resolution of the gFlex GIA module	Glacial isostatic adjustment	2000.0	m

Table S2 Initial monthly temperature and precipitation (similar to present-day). The data is derived from climate data averaged over 1981–2010 from a weather station in Modane, France, located at 1228 m a.s.l. within the model domain (Meteo France, 2022), precipitation values were uniformly multiplied by 1.6. Throughout the model runs, temperature values were modified by the temperature forcing.

Month	**Temperature** (°C)	**Precipitation** (kg m^{-2} yr^{-1} *we*)
January	-1.4	1040.610
February	-0.4	1150.180
March	3.3	876.608
April	6.4	974.000
May	11.4	1065.120
June	14.4	1129.840
July	16.9	788.000
August	16.6	1046.270
September	12.8	1040.240
October	8.7	1246.100
November	2.2	1217.500
December	-0.8	1074.540