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Supplement of

Proglacial lakes substantially modulate the surface mass balance of deglacial ice sheets

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S1 Supplementary materials

S1.1 Ice sheet configuration

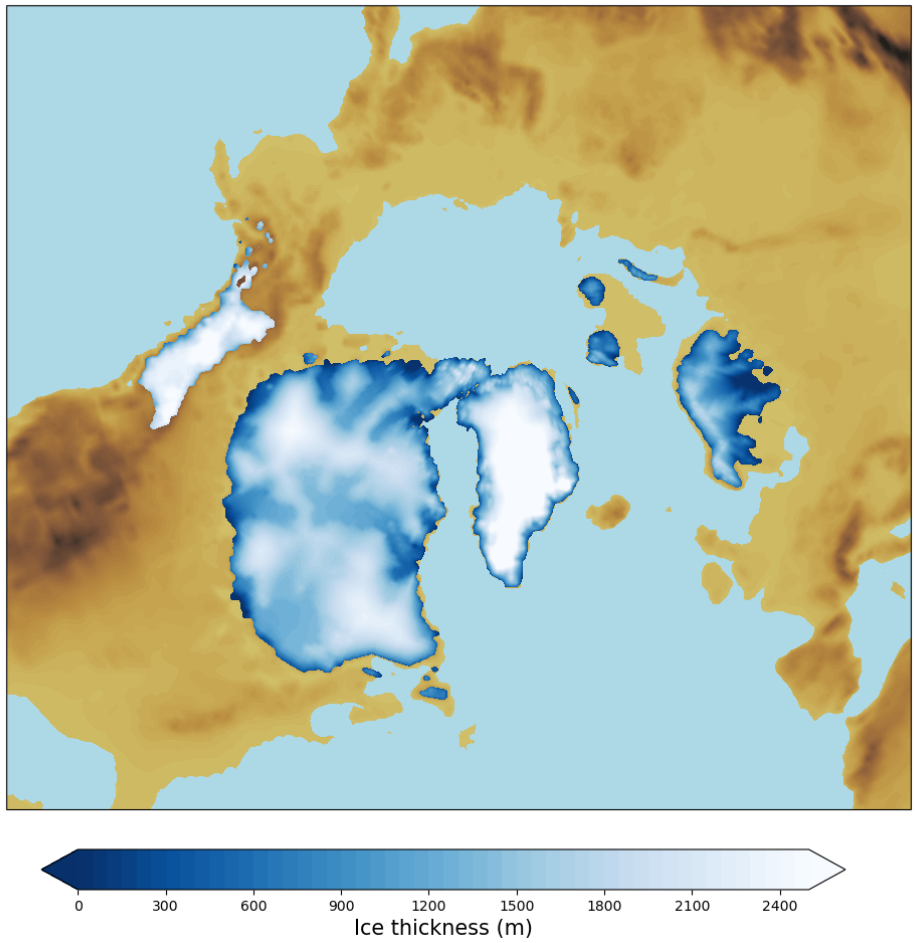


Figure S1. Northern hemisphere ice cover at 13 ka according to Tarasov et al. (2012).

S1.2 Seasonality of Climate and Surface Mass Balance

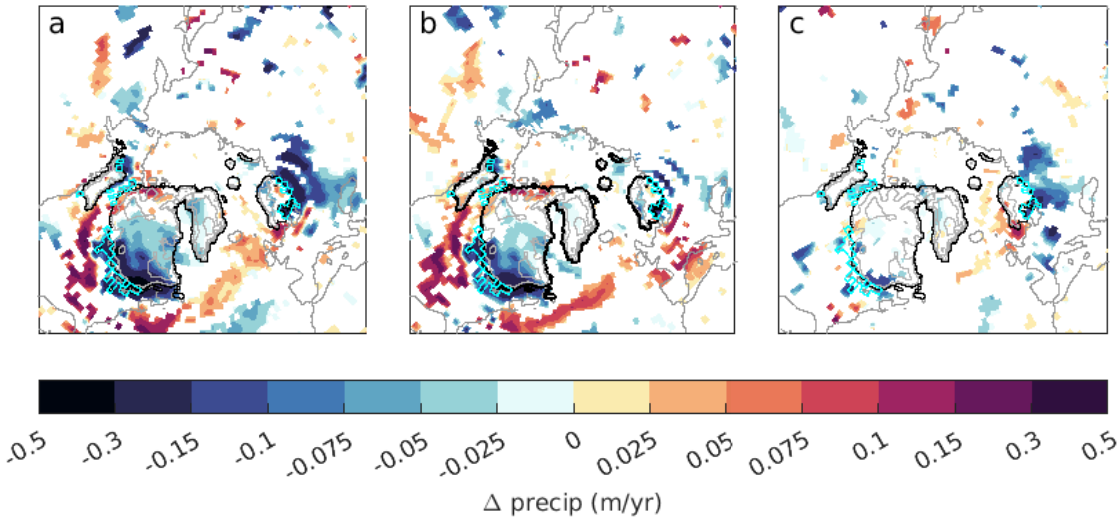


Figure S2. Mean summer precipitation (JJA) anomaly with respect to $REF13ka$ for experiment $PL13ka$ (a) and $PL13ka_{warm}$ (b), and difference between experiment $PL13ka$ and $PL13ka_{warm}$ (c). Anomalies which are not significant according to a t-test with 95% confidence level are masked out. Black contours indicate ice sheet margins and cyan lines indicate proglacial lakes. The topography of the ice sheets at 5km resolution which was used for the SMB calculation is depicted as grey contours for 1000, 2000 and 3000m elevation.

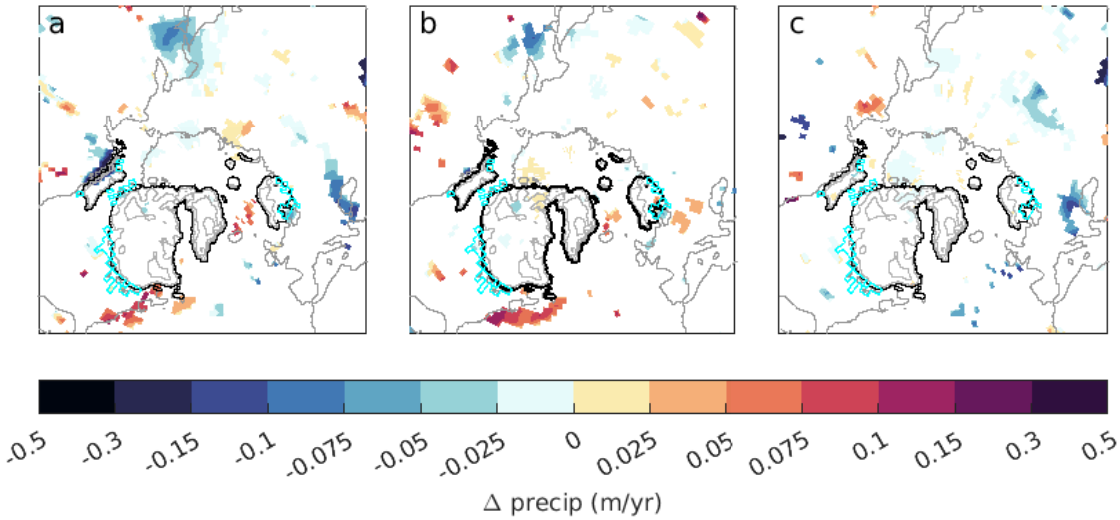


Figure S3. Same as Fig. S2 but for mean winter precipitation anomaly (DJF)

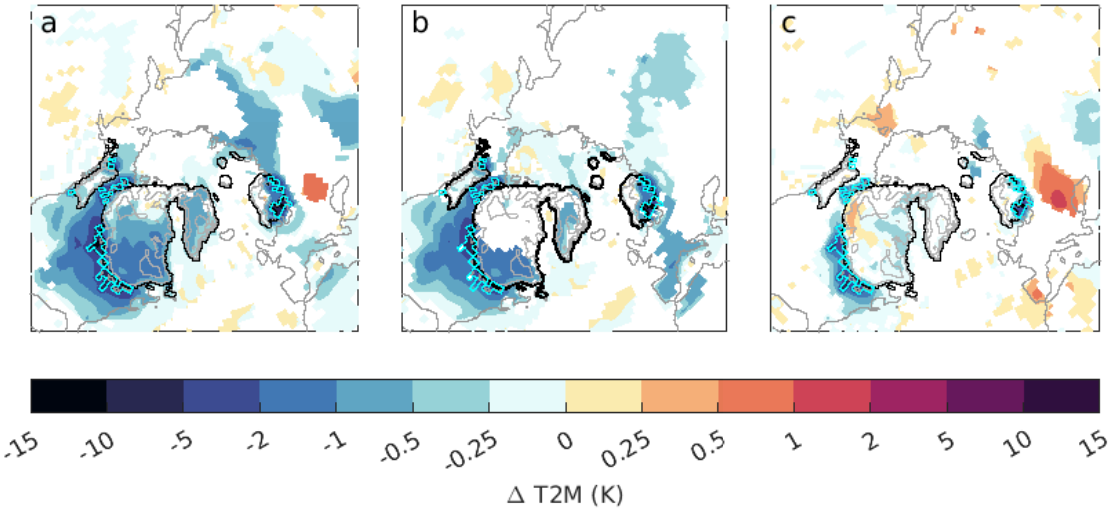


Figure S4. Same as Fig. S2 but for summer near surface temperatures

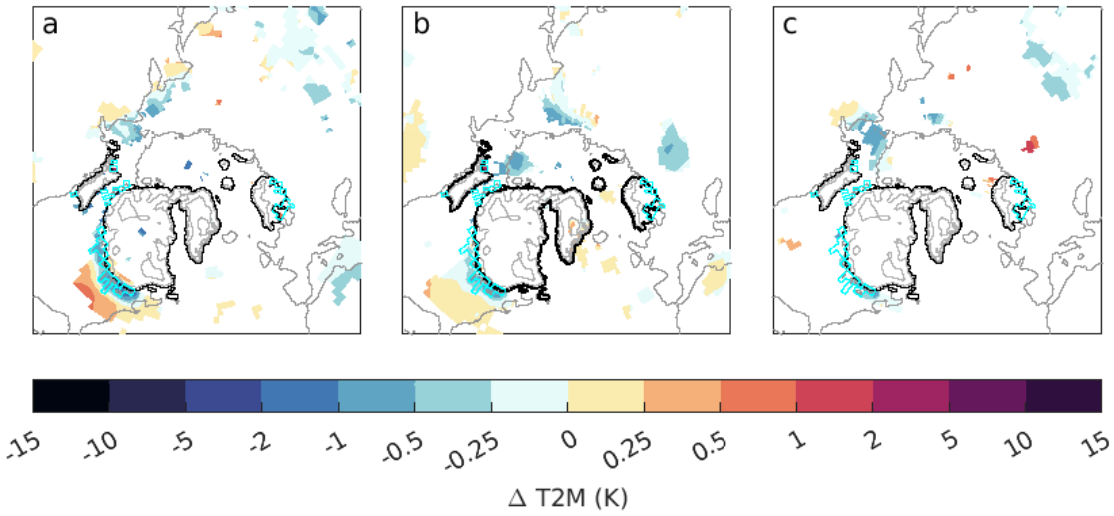


Figure S5. Same as Fig. S2 but for winter near surface temperatures.

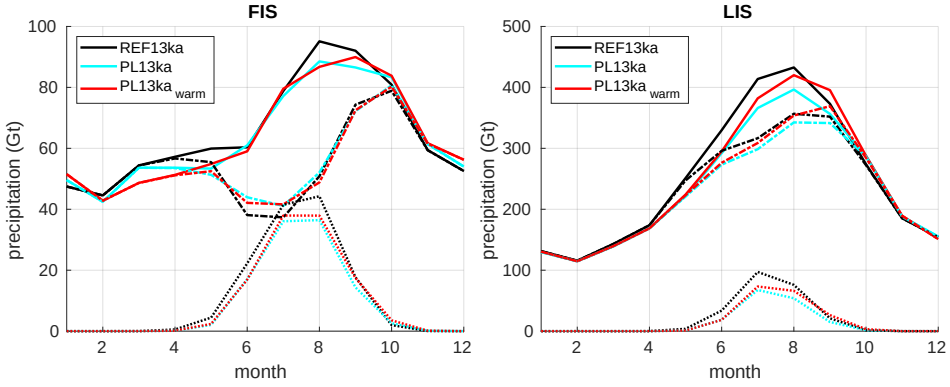


Figure S6. Monthly mean total precipitation (solid lines), snow (dash-dotted) and rain (dotted) over the Fennoscandian and Laurentide Ice sheets for the experiments $REF13ka$ (black), $PL13ka_{warm}$ (red) and $PL13ka$ (cyan)

Table S1. FIS seasonal contributions to SMB in [GT/season].

	Variable	$REF13ka$	$PL13ka_{warm}$	$PL13ka$
DJF	SMB	145	151	146
	snow	145	151	146
	refreeze	0	0	0
	melt	0	0	0
	rain	0	0	0
MAM	SMB	136	145	153
	snow	167	151	157
	refreeze	28	14	13
	melt	58	21	17
	rain	5	3	2
JJA	SMB	-1230	-822	-715
	snow	126	133	137
	refreeze	146	145	141
	melt	1502	1099	992
	rain	108	93	90
SON	SMB	195	191	210
	snow	213	214	214
	refreeze	14	14	13
	melt	31	38	17
	rain	19	21	17

Table S2. LIS seasonal contributions to SMB in [GT/season].

	Variable	$REF13ka$	$PL13ka_{warm}$	$PL13ka$
DJF	SMB	401	396	400
	snow	401	396	400
	refreeze	0	0	0
	melt	0	0	0
	rain	0	0	0
MAM	SMB	517	507	507
	snow	564	531	529
	refreeze	32	20	20
	melt	80	44	42
	rain	4	1	1
JJA	SMB	-1366	-880	-807
	snow	969	939	914
	refreeze	524	519	517
	melt	2860	2339	2238
	rain	207	158	140
SON	SMB	733	755	787
	snow	810	843	816
	refreeze	22	25	20
	melt	98	113	49
	rain	23	30	17

S1.3 Estimating the mass of ice that needs to melt at the ice-lake interface to maintain cold summer surface temperatures in experiment $PL13ka$

Recent surface temperature observations from present-day proglacial lakes show maximum summer values of 4 to 6 °C (Sugiyama et al., 2021; Dye et al., 2025). However, these lakes are not a perfect analogue for the much larger proglacial lakes at the margins of the rapidly retreating ice sheets of the Allerød and their surface temperature is not known. By capping surface temperatures at 4 °C in experiment $PL13ka$, we have chosen a scenario at the lower end of the likely temperature spectrum. Overriding simulated lake surface temperatures creates a heat sink within the model, which should be interpreted as heat loss from melting ice in the proglacial lakes. Our experiment design does not allow us to quantify the effective heat loss. As a makeshift solution we here apply a simple one-dimensional thermodynamic lake model to estimate the amount of ice that would need to melt in the lake to generate the same surface temperature as in experiment $PL13ka$.

The lake model is a finite difference model resolving the 1D vertical temperature profile of a lake by discretizing the water column and solving the diffusion equation at equidistant layers. Input for the lake model is taken from atmospheric output of experiments $PL13ka_{warm}$ and $PL13ka$: as forcing we use 2m-temperature, downward longwave radiation, downward shortwave radiation and seaice cover from multi-year monthly means averaged over the proglacial lakes at the southern margins of the North American (south of 55 °N, *LIS-PL* forcing), and Fennoscandian Ice Sheets (*FIS-PL forcing*) and we use corresponding surface temperatures to evaluate and constrain the lake model. At first we use forcings from experiment $PL13ka_{warm}$ and choose model parameters so that surface temperatures simulated by the lake model agree reasonably well with the surface temperatures from the atmospheric output over the respective lakes (Fig. S7, solid lines). We then use the same model parameters in combination with forcing from experiment $PL13ka$, but here every time step we additionally cool the lake surface to the lake surface temperature from $PL13ka$ and calculate the corresponding heat flux required for this cooling (Fig. S7, dashed lines). All experiments are initialized with a uniform temperature of 4 °C and are equilibrated with yearly repeating forcing over 250 years. The model assumes no horizontal heat transport and neglects advective processes.

Result: Our model experiments exhibt seasonal temperature variations in the upper 20 m of the water column and constant temperature of 4 °C at depth (Fig. S8). When we apply forcing and additional cooling from experimrent $PL13ka$ the respective accumulated heat loss per year is $0.7 \times 10^9\ Wm^{-2}$ for the FIS-PL forcing and $1.2 \times 10^9\ Wm^{-2}$ for the LIS-PL forcing which corresponds to approximately 215 Gt and 360 Gt of melting ice that is required to cool a lake area of $100000\ km^2$ accordingly.

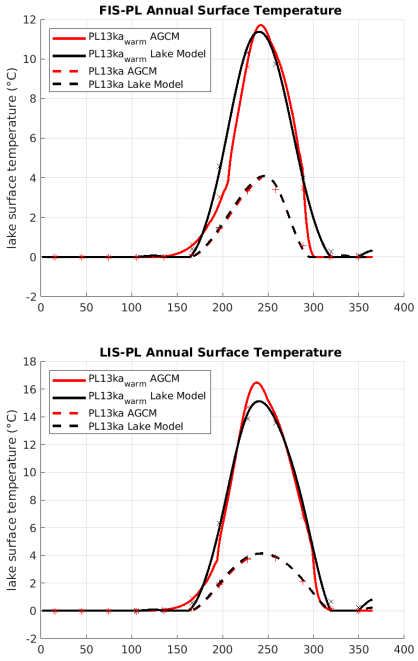


Figure S7. Annual lake surface temperature for FIS-PL forcing (lupper panel) and LIS-PL forcing (below) from atmosphere model (black) and one-dimensional lake model (red). Solid lines are for forcing from experiment $PL13ka_{warm}$ and dashed line are for experiment $PL13ka$.

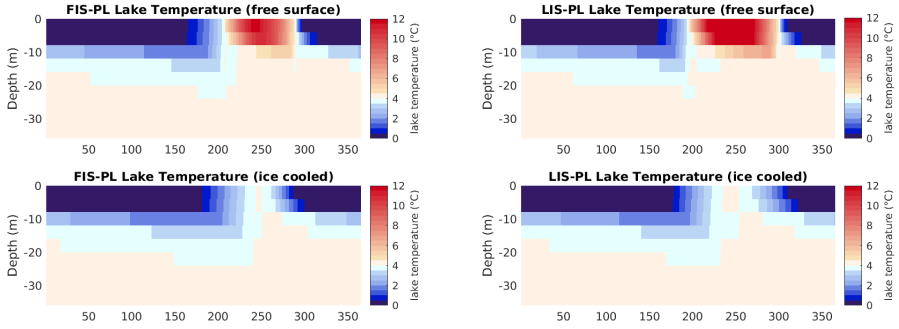


Figure S8. Temperature stratification in the upper 40m of the lake model for FIS-PL (left panel) and LIS-PL (right) forcing from experiment $PL13ka_{warm}$ (upper panel) and for experiment $PL13ka$ (below).

Model Configuration

Spatial and Temporal Discretization

- Vertical Grid: The water column is divided into i=0..49 equidistant layers with a water temperature T_i and thickness `dz` = 4 m.
- Mixed Layer Depth: A mixed layer depth (`mld` = 12 m) is used to parameterize vertical diffusivity.

- Time Stepping: The model uses a daily time step (`dt` = 86,400 s) and simulates 250 years to reach equilibrium.

Physical parameters

Thermal diffusivity:

$$\alpha_i = \begin{cases} 2 \times 10^{-5}\ \mathrm{m}^2/\mathrm{s}, & i\,dz \le \mathrm{mld}, \\ 5 \times 10^{-7}\ \mathrm{m}^2/\mathrm{s}, & i\,dz > \mathrm{mld}. \end{cases}$$

Water properties:

- Density (ρ_w) = 1,000 kg/m^3
- Specific heat capacity (c_{pw}) = 4,186 J/kg·K
- Latent heat of fusion (L_i) = 334,000 J/kg
- Freezing point (Tf) = 273.15 K

Parameters of the surface energy balance:

- Emissivity of water (ϵ_w) = 0.97
- Stefan–Boltzmann constant ($\sigma = 5.67 \times 10^{-8}\ W/m^2/K^4$)
- Heat transfer coefficient ($h = 30\ W/m^2/°C$ for LIS-PL and $h = 20\ W/m^2/°C$ for FIS-PL forcing)

Calculation of the surface temperature T_0

The model is forced by the surface heat flux (Q_{surface}) which is calculated as:

$$Q_{\text{surface}} = \text{SWD} + \text{LWD} - \text{LWU} + \text{SHF}$$

where:

- LWU = upward longwave radiation ($\epsilon_w \sigma T_0^4$)
- SHF = sensible heat flux ($h(T_{\text{air}} - T_0)$)
- temperature of lake surface (prognostic) T_0

The climate forcing is derived from monthly mean climate output (interpolated to daily resolution) averaged over proglacial lakes of the LIS and FIS from experiment $PL13ka_{warm}$ or $PL13ka_{warm}$.

- 2-m air temperature, T_{air}
- Incoming shortwave radiation, `SWD`
- Downward longwave radiation, `LWD`
- Sea ice cover, `seaice`
- Surface temperature from atmospheric output, T_{surf}

Each timestep the temperature of ice-free parts of the surface are computed:

$$T_{\text{ice free}} = \max(T_f, T_{\text{surf}} + \frac{Q_{\text{surface}}}{\rho_w c_{pw} \Delta z} \Delta t)$$

and ice covered parts are assumed to be at freezing point. The temperature of the surface layerT_0 is set to

$$T_0 = (1 - \text{seaice}) T_{\text{ice free}} + \text{seaice} T_f$$

Proglacial Cooling Constraint:
For proglacial lakes, the surface temperature of ice free parts of the lake is further constrained to not exceed the surface temperature of experiment PL13ka. The additional energy required to enforce this cooling (dQ) is calculated as:

$$dQ = (T_0 - T_{\text{surf}})(\rho_w c_{pw} \Delta z)$$

Calculation of the temperature profile:

Temperatures in the water column are updated using a finite difference scheme of heat diffusion:

$$\frac{\partial T_i}{\partial t} = \frac{1}{\Delta z} \left[\alpha_{\text{if}} \frac{T_{i+1} - T_i}{\Delta z} - \alpha_{\text{if}} \frac{T_i - T_{i-1}}{\Delta z} \right]$$

where α_{if} is the harmonic mean of diffusivities at layer interfaces.

Density and Stratification:
Density is calculated as a function of temperature:

$$\rho(T) = 5.5289 \times 10^{-8} T^3 - 8.5016 \times 10^{-6} T^2 + 6.5622 \times 10^{-5} T + 0.99987$$

If the water column becomes unstable (ρ decreases with depth), layers are adiabatically reordered to enforce stable stratification.

Ice Melt Estimation

The total mass of ice melt (dM) required to maintain the cool lake surface temperatures of experiment PL13ka is calculated by integrating the additional energy consumption over a lake area ($100,000$ km$^2 = 1 \times 10^{11}$ m^2):

$$dM = \sum (dQ) \times (1 \times 10^{11} \text{ m}^2) / L_i / (1 \times 10^{12} \text{ kg/Gt})$$

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