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Mass balance reconstruction for the Rhine glacier, Swiss Alps, at the Last Glacial Maximum from three-dimensional thermo-mechanical modeling

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Climate proxies based on pollen records, macrofossil assemblages, or speleotherms indicate cold and dry conditions during the Last Glacial Maximum in Northern-Central Europe. A high-resolution full-Stokes three-dimensional thermo-mechanical model of the Rhine glacier, Swiss Alps, at the Last Glacial Maximum indeed indicates extremely dry conditions with mass balance ablation gradients as low as 0.01 m/a/100m. This balance gradient is necessary to match modeled LGM extent with observations of LGM moraines in the Swiss plateau. Extremely low balance gradients could be due to (1) extreme temperature inversion, (2) increasing shadow towards the ice margin due to termination of glacier in deep valleys or gorges, (3) debris cover of increasing thickness towards the margin, or (4) accumulation of wind-blown snow at the glacier margin. There is no evidence for (2) or (3) for the margin of the Rhine glacier which terminated in a wide piedmont lobe. The other two hypotheses have not been tested for LGM conditions at the margin of the Rhine glacier. Higher ice temperature (which reduces ice viscosity) and more sliding (higher ratio of sliding to surface velocity) would favor an extended glacier margin at a higher ablation gradient but these effects are already included in the numerical model. These results suggest a discrepancy between observations and present knowledge of climate and ice sheet flow which cannot be easily explained and need further investigation.