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A data-consistent, high-resolution model of the last glaciation in the Alps achieved with physics-driven AI

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Reconstructing the last glaciation of the European Alpine Ice Field via numerical modelling has been challenged by persistent model-data disagreements, including large overestimations of its former thickness. Here, we tackle this issue by applying the Instructed Glacier Model, a three-dimensional, high-order, and thermo-mechanically coupled model enhanced with physics-informed machine learning. This new approach allows us to produce an ensemble of 100, Alps-wide and 17 thousand-year-long (35-18 ka) simulations at 300 m spatial resolution. Unfeasible with traditional models due to computational costs, our experiment substantially increases model-data agreement in both ice extent and thickness. The model-data offset in ice thickness, for instance, is here reduced by between 200% and 450% relative to previous studies. The results yield implications for more accurately reconstructing former ice velocities, ice temperatures, basal conditions, glacial erosion processes, glacial isostatic adjustment, and climate evolution in the Alps during the Last Glacial Maximum. Furthermore, the switch to GPU-based computations enables us, for the first time, to also couple our Alpine Ice Field model with three-dimensional and time-transgressive ice advection of particles (tens of millions). Here, particles are seeded to mimic both the subglacial (e.g. abrasion, plucking) and supraglacial (e.g. rockfall) origins of glacially-transported sediments. Using our ensemble best-fit simulation, we present the results of tracking the sink-to-source transport trajectories of distinct LGM ice-contact deposits (e.g. terminal moraines), and the LGM source-to-sink transport trajectories of specific surface lithologies, throughout the Alps. We find that modelling the Alps-wide glacial transport of particles also helps us better understand the complex internal ice dynamics of the former Alpine Ice Field, including transfluences and the zipping/unzipping behaviours of different tributary glaciers. More generally, this work demonstrates that physics-informed AI-driven glacier models can overcome the bottleneck of high-resolution continental-scale modelling required to accurately describe complex topographies and ice dynamics.