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A rate-and-state friction law for glaciers

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Glacier surges are dynamic instabilities where the ice velocity can increase by orders of magnitude for a period of time. A large portion of the increased motion during a surge is attributed to basal sliding, and the surging region can propagate both downstream and upstream at velocities reaching kilometers per year, and gradually affect the entire glacier. Even though several surge mechanisms have been proposed, many features of fast glacier flow remain elusive.

Basal sliding is the crucial factor for understanding glacier surges, and has been subject to numerous theoretical, numerical and experimental studies. Basal shear stress of hard bed glaciers is known to exhibit a velocity strengthening – velocity weakening transition, and it is commonly assumed that the basal shear stress is a function of velocity and effective normal stress. However, ice-rock friction experiments have revealed that the frictional response to step changes in velocity is not instantaneous, and that ice-rock friction increases as a function of time when the system is at rest. This suggests that the evolution of the basal shear stress is governed by both length and time-scales. We introduce an empirical rate and state friction formulation that applies for hard bed glaciers and demonstrate, using Elmer/Ice, that dynamical instabilities can be explained as a velocity strengthening-weakening transition. An instability is triggered by locally increasing the water pressure so that the basal shear stress transitions from velocity strengthening to velocity weakening, which leads to a transfer of shear stress from the glacier base to the glacier margins. The basal shear stress evolves over a characteristic length-scale for the opening of cavities, which controls the upstream and downstream propagation of the surge. We also observe basal perturbations with little to no propagation when the system is far from the strengthening-weakening transition. Our results call for a better understanding of the processes that control the transition from velocity strengthening to velocity weakening of the basal shear stress and an extension for soft-bedded glaciers that rest on deformable, unconsolidated sediments.