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Toward a universal glacier slip law

Brent Minchew and Ian Joughin

Glaciers and ice sheets are important components of the climate system and shape the character of Earth's surface. Among the notable effects of glacier flow are erosion and sedimentation, and variations in global sea levels. These effects depend on drag and slip rates at ice-bed interfaces, and thus the mechanisms that facilitate slip. Parameterizations of drag with slip-rate are typically called sliding or slip laws and are a longstanding topic of research in glaciology. Recent observations of accelerating glacier flow and rates of mass loss from Greenland and Antarctica, along with recognition that decadal- to centennial-scale projections of sea-level rise are highly sensitive to the representation of slip in ice-sheet models, highlight the need to better understand and parameterize glacier sliding [1, 2, 3, 4]. On page ***, Zoet and Iverson [5] derive a simple physical model and conduct experiments that provide important insights into the mechanisms that facilitate slip in glaciers underlain by deformable sediment. The slip law they present has a similar form to laws derived for sliding over rigid beds, thereby supporting a simple, universal form of the slip law that could improve projections of ice-sheet contributions to sea level.

It is not immediately obvious that a universal slip law should exist because myriad processes act at the ice-bed interface. Glaciers slide over beds that vary from rigid bedrock to deformable sediment, with slip defined as the combination of sliding along the ice-bed interface and deformation of the bed itself [6]. Irrespective of composition, glacier beds have roughness features that influence drag but are difficult to characterize from observations [7,8]. Water at the bed acts as a lubricant. When this water is pressurized to near the overburden pressure of the glacier, cavities can form downstream of bumps, decoupling the ice from the bed [8,9]. Thus, basal water pressure influences slip while introducing complexities as it varies spatially and temporally in response to changes in basal and surface melt rates and evolution of hydrological systems above, below, and within the glacier [6,10].

The potential for a universal form of the slip law is underpinned by the fact that total drag is the sum of skin friction and form drag. Skin friction describes the resistance to sliding along an interface, while form drag is due to the pressure gradient associated with flow around an object. In the context of a slip law, the important distinctions between the two are their dependencies on water pressure and the rate of slip at the bed. Form drag strongly depends on flow speed but does not directly depend on water pressure. Conversely, skin friction strongly depends on water pressure but is essentially independent of the slip rate. Thus, a slip law that represents only skin friction may be considered perfectly plastic (rate-independent), similar to Coulomb friction, a staple of introductory physics where drag equals the product of a friction coefficient and effective normal stress (pressure), the difference between overburden and water pressure [11,12]. On the other hand, a slip law representing only form drag with no cavity formation is rate-strengthening (drag increases with slip-rate) and can take the form of a power-law relation between drag and slip-rate [7]; allowing for cavity formation admits rate-strengthening, rate-weakening, and perfectly plastic behavior, depending on the bed properties and slip rate [9].

Zoet and Iverson derive a simple slip law for sediment-covered glacier beds wherein the total drag is governed by form drag at slow slip rates and skin friction at faster rates. Form drag dominates when the bed is rigid and ice flows around clasts at the ice-bed interface. Skin friction dominates when the bed is deforming and friction acts on sediment grain boundaries. Thus, the transition between the two drag mechanisms is controlled by the shear strength (or yield stress) of the sediment, defined as the product of the effective pressure and the tangent of the internal friction angle [11,12]. Zoet and Iverson benchmark their model with several laboratory experiments carried out with a ring-shear device. These experiments were conducted under drained conditions (constant pore water pressure), with and without centimeter-scale clasts imbedded in the sediment, and at slip rates ranging from zero to moderately fast by glacier standards (~500 m/yr). Overall, they find good agreement between their model and experiments.

Zoet and Iverson focus on glaciers with deformable beds but their slip law has the same form as the so-called regularized-Coulomb sliding law originally derived for glaciers sliding over rough, rigid beds [9]. At slow slip-rates, the two laws represent form drag due to flow of ice around roughness features. The transition to plasticity at faster slip rates in the rigid-bed model arises from cavity formation that reduces the ice-bed contact area, and thereby form drag. The limit on drag at rapid sliding rates is governed by the product of effective pressure and the tangent of the maximum bed slope, known as Iken's bound [13], which is a different physical mechanism with the same functional form as skin friction in the Zoet and Iverson model. Despite the differences in physical mechanisms, the deformable-bed and rigid-bed models yield the same parameterization, suggesting that the form of the regularized-Coulomb sliding law is universally applicable to glaciers irrespective of bed type [1]. A major benefit of this similarity is that observationally constrained models can be used to infer the slip law parameters without prior knowledge of whether the bed is rigid or deforming.

The potential for a universal form of the slip law is encouraging but remains to be thoroughly tested with observations. The increasing availability of remote sensing datasets have enabled a few relevant studies by providing measurements of spatio-temporal variations in glacier flow velocity and surface elevation. The majority of these studies support the use of the regularized-Coulomb sliding law [1,14,15], though more work is needed to test the robustness of this slip law and constrain the parameters. Zoet and Iverson have provided strong evidence from laboratory experiments suggesting that the regularized-Coulomb sliding law works similarly well for deformable beds as theory and observation suggest for rigid beds [1,9,15]. This is an encouraging development that we expect will help reduce uncertainties in sea-level projections.

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