TECHNICAL COMMENT

ICE SHEETS

Comment on "Friction at the bed does not control fast glacier flow"

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Stearns and van der Veen (Reports, 20 July 2018, p. 273) conclude that fast glacier sliding is independent of basal drag (friction), even where drag balances most of the driving stress. This conclusion raises fundamental physical issues, the most striking of which is that sliding velocity would be independent of stresses imparted through the ice column, including gravitational driving stress.

Stearns and van der Veen (*1*) seek to address two important problems in glaciology: understanding the physics of glacier sliding and the parameterization of sliding in ice-flow models. Focusing on fast-flowing Greenland outlet glaciers, the authors combine observations of glacier geometry and surface velocity to infer the shear stress at the bed and the influence of subglacial water pressure on ice flow. On the basis of these inferences, the authors conclude that fast glacier sliding is independent of basal drag, even where basal drag balances a substantial fraction of the driving stress. This conclusion challenges the theoretical, experimental, and observational evidence for the important dependence of basal slip rate on basal drag (*2*) and raises fundamental physical issues. The most striking issue is that sliding velocity would be independent of stresses imparted through the ice column, including the gravitational driving stress. Here, we discuss the physical implications of the authors' conclusions and highlight weaknesses in their methodology, which indicate that the authors' results do not support their conclusions.

Stearns and van der Veen seek to test the Weertman-type sliding law, a basal boundary condition for the momentum equations describing fast-sliding glaciers, given as

$$U_\mathrm{b} = C\tau_\mathrm{b}^p \qquad (1)$$

where $U_\mathrm{b}(x, y)$ is the (spatially varying) basal slip rate, $C(x, y)$ is basal slipperiness, $\tau_\mathrm{b}(x, y)$ is basal drag (friction), and the authors assume that p is spatially constant. Basal slipperiness can be written as $C = A_\mathrm{s}N_\mathrm{e}^{-q}$, where $A_\mathrm{s}(x, y)$ is a sliding parameter, q is assumed spatially constant, and $N_\mathrm{e}(x, y)$ is a proxy for effective pressure, the difference between the ice overburden pressure and subglacial water pressure. To infer the unknown terms in Eq. 1, the authors use observations of surface velocity $U_\mathrm{s}(x, y)$ and ice geometry, adopting the common assumption that rapid glacier flow is dominated by slip at the bed ($U_\mathrm{b} \approx U_\mathrm{s}$). The exponent p in Eq. 1 is the object of the authors' main conclusion, and the prefactor C is taken as a spatially varying free parameter.

The Weertman-type sliding law (Eq. 1) is recognized as a simple, local parameterization of multiple physical processes, where C encapsulates spatially varying properties such as subglacial water pressure, bed roughness, and bed composition. The exponent p is often taken to denote the mode of sliding, with commonly accepted values ranging from $p = 1$ where regelation is important to $p = \infty$ for perfectly plastic (e.g., Mohr-Coulomb) beds. Many studies focus on understanding the terms in Eq. 1 from theory [e.g., (*3–5*)], experiments [e.g., (*7–8*)], and observationally constrained inverse methods [e.g., (*9*, *10*)], and some have inferred values of p by constraining models with time-dependent observations [e.g., (*11–14*)]. These studies conclude that $p > 1$, and in many cases researchers have inferred $p \gg 1$, indicating effectively plastic beds in some areas.

Stearns and van der Veen's conclusion that basal drag does not control glacier sliding comes from their inference that $p \approx 0$, a value that raises serious physical issues. Most important, $p \approx 0$ implies that basal slip is independent of the forces that drive flow within the ice column, as can be described by the depth-integrated momentum balance

$$\tau_\mathrm{d} = \tau_\mathrm{b} + 4\frac{\partial}{\partial x}\left(h\eta\frac{\partial U_\mathrm{s}}{\partial x}\right) + \frac{\partial}{\partial y}\left(h\eta\frac{\partial U_\mathrm{s}}{\partial y}\right) \qquad (2)$$

where x is along the velocity vector, h is ice thickness, η is the dynamic viscosity of ice, and τ_d is the gravitational driving stress. Setting $p = 0$ reduces the sliding law (Eq. 1) to an imposed flow velocity ($U_\mathrm{s} = C = A_\mathrm{s}N_\mathrm{e}^{-q}$) that is independent of the stresses within the ice column (Eq. 2). Thus, control of glacier slip rate would be independent of gravitational driving stress, and the basic tenet that glacier flow is driven by gravity would not apply. Slip at the ice-bed interface would require an extraneous driving mechanism to act on the base of the glacier, much like a conveyor belt. There is no reason to expect such a mechanism to exist. These concerns motivate an examination of the methods used to infer p.

To infer $p \approx 0$, the authors take the logarithm of Eq. 1 and fit a line through the data, where p is the slope in log-space (their figure 2A). However, a necessary condition for fitting a linear trend is that the intercept term, ln(C), is approximately constant for all U_s-τ_b pairs. This condition is not satisfied because the variance on the intercept—as gleaned from the authors' results and deduced from physical arguments and previous studies [e.g., (*9*)]—is approximately equal to the variance of the ordinate term ln(U_s). Thus, reliable values of p cannot be inferred from linear regression. Any apparent correlation, or lack thereof, in a plot of ln(U_s) versus ln(τ_b) could result from spatial variations in ln(C), casting substantial doubt on the results underpinning the authors' main conclusion.

Applying $p = 0$, Stearns and van der Veen then perform a second linear fit between ln(U_s) and ln(N_e) to argue for $q \approx 0.5$. The authors define N_e as proportional to the height above buoyancy, which they take as a proxy for effective pressure. Flow velocity U_s is expected to increase as effective pressure decreases because basal drag should scale with effective pressure, making $q > 0$ reasonable. However, water pressure measurements recorded in ice sheet boreholes indicate that effective pressures can be much lower than values implied by the height-above-buoyancy proxy [e.g., (*15*, *16*)]. Thus, although the authors' conclusion that basal slip rate negatively correlates with effective pressure is physically plausible, the height-above-buoyancy proxy for effective pressure is inconsistent with observations, making the authors' inferred value of q also questionable.

Stearns and van der Veen used new data in a novel study on the longstanding glacier-slip problem. Even though their main conclusion that slip is independent of friction at the bed is doubtful because it would require slip to be driven by the bed rather than by the gravitational driving stress, their approach highlights an encouraging trend in glaciology: New observations, driven largely by freely available remote sensing data, and improvements in models of basal processes continue to improve our understanding of the mechanics of glacier beds and sea level rise.

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