Comment on: “Friction at the bed does not control fast glacier flow” by L. A. Stearns and C. J. van der Veen

Brent M. Minchew[1], Colin R. Meyer[2], Samuel S. Pegler[3], Bradley P. Lipovsky[4], Alan W. Rempel[2], G. Hilmar Gudmundsson[5], and Neal R. Iverson[6]

1. Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA
2. Department of Earth Science, University of Oregon, Eugene, OR
3. School of Mathematics, University of Leeds, Leeds, UK
4. Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA
5. Geography and Environmental Sciences, Northumbria University, Newcastle, UK
6. Department of Geological and Atmospheric Sciences, Iowa State University, Ames, IA

Abstract

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

Main text

Stearns and van der Veen 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 the ice flow. Based on these inferences, the authors conclude that fast glacier sliding is independent of basal drag, even where basal drag balances a significant 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 (Cuffey and Paterson, 2010), 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. In this comment, we discuss the physical implications of the authors’ conclusions and highlight weaknesses in the 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

$$U_b = C\tau_b^p \tag{1}$$

where $U_b(x, y)$ is the (spatially varying) basal slip rate, $C(x, y)$ is basal slipperiness, $\tau_b(x, y)$ is basal drag (friction), and the authors assume p is spatially constant. Basal slipperiness can be written as $C = A_s N_e^{-q}$, where $A_s(x, y)$ is a sliding parameter, q is assumed spatially constant, and $N_e(x, y)$ 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 $U_s(x, y)$ and ice geometry, adopting the common assumption that rapid glacier flow is dominated by slip at the bed ($U_b \approx U_s$). Importantly, 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 like 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., Weertman, 1957; Lliboutry, 1968; Schoof, 2010), experiments (e.g., Kamb, 1991; Tulaczyk et al., 2000; Iverson, 2010), and observationally constrained inverse methods (e.g., Morlighem et al., 2013; Shapero et al., 2016), and some have inferred values of p by constraining models with time-dependent observations (e.g. Gudmundsson, 2007; Joughin et al., 2010; Minchew et al., 2016; Gillet-Chaulet et al., 2016). 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 importantly, $p \approx 0$ 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

$$\tau_d = \tau_b + 4\frac{\partial}{\partial x}\left(h\eta\frac{\partial U_s}{\partial x}\right) + \frac{\partial}{\partial y}\left(h\eta\frac{\partial U_s}{\partial y}\right) \tag{2}$$

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 ($U_s = C = A_s N_e^{-q}$) 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 fast 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 Fig. 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., Morlighem et al., 2013) — 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 $\ln[\tau_b]$ could result from spatial variations in $\ln[C]$, casting significant 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. Lüthi et al., 2002; Andrews et al., 2014). Thus, while 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. While 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 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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