TECHNICAL RESPONSE

ICE SHEETS

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

Leigh A. Stearns[1]* and Cornelis van der Veen[2]

Minchew *et al*. take issue with our main conclusion that friction at the glacier bed does not control fast glacier flow. In this response, we further justify our methodology. We also point out that numerical studies referred to by Minchew *et al*. rely on inversions that are based on a sliding relation in which sliding speed is proportional to basal drag. Furthermore, observational studies referred to by Minchew *et al*. apply to glaciological settings that do not correspond to the terminal regions of Greenland outlet glaciers that we studied.

The objective of our study (*1*) was to test the commonly used sliding relation against available data for 140 Greenland outlet glaciers, and not to better understand the physics of sliding, as erroneously claimed by Minchew *et al*. (*2*). Indeed, we acknowledge that "the full implications for model behavior of replacing the commonly used sliding relation … are not evident" (*1*).

To test the sliding relation, we used publicly available data on ice velocity and glacier geometry. To ensure that only regions dominated by sliding were considered, we imposed a minimum value for the observed annual variations in surface speed. This means that for the majority of glaciers, only the 15 km upstream of the terminus were considered. We estimated basal drag using the force-budget technique (*3*), which requires no assumption regarding the form of the sliding relation.

Minchew *et al.* refer to several modeling studies to support their claim that a Weertman-type sliding relation is generally accepted as a simple parameterization of many physical processes. However, all these studies (*4*–*9*) are based on inversion methods and rely on Weertman-type sliding to estimate a basal friction coefficient. Thus, none of these studies can be used to actually test how well the Weertman-type sliding relation applies. The fact that these studies find some agreement between model and observations does not prove the validity of the model, only that there are sufficient tuning parameters. We do point out that on Hofsjökull, Iceland, "Basal shear tractions … are independent of basal slip rate in areas of faster slip" (*7*), consistent with our findings.

Minchew *et al.* disagree with our methodology on the basis that the intercept term must have small variance for a regression to be valid. As written by Minchew *et al.*, the intercept term, $\ln(C)$, contains not only the sliding parameter but also the effective pressure. The condition that this term has small variance would automatically eliminate the possibility that the basal drag term is unimportant. If the slope of the regression line of basal drag is approximately zero, the variance in $\ln(C)$ must be the same as the variance in $\ln(U_s)$, which violates the requirement for regression, according to Minchew *et al.* We consider the role of effective pressure in a separate term, and a more appropriate intercept term is $\ln(A_s)$, where A_s is the sliding parameter. Variations in $\ln(A_s)$ are an order of magnitude smaller than the variation in both $\ln(U_s)$ and the basal drag and effective pressure terms. Thus, their argument for rejecting our methodology is misleading.

We conducted two separate regressions rather than one multiple regression. This procedure is appropriate when considering different physical processes and is justified a posteriori by the lack of any relation between the three predictor variables (A_s, τ_b, and H_{ab}) used in our regression model (*10*). The large error in basal drag is random and still allows the regression line to be estimated.

Although our conclusion is that $p \sim 0$, the average slope value for all 140 glaciers is slightly offset from zero, namely $p = 0.13$, pointing to a rather small role for basal drag in controlling the sliding velocity. This implies that the theory for ice flow over a perfectly plastic bed does not apply here, because that model requires very large values for the exponent.

The Weertman sliding relation is based on theoretical considerations valid for an idealized hard bed characterized by protruding obstacles that provide the sole resistance at the bed. It is doubtful that this model applies anywhere, but it certainly does not apply on Greenland outlet glaciers likely underlain by glacial sediments. Although further theoretical work has been done, there seems little consensus on the form of the sliding relation; this depends on the specifics of the bed and the presence of subglacial sediments (*11*).

Experiments on till samples are rather restrictive and apply to specific glaciological settings only. For example, Kamb (*12*) and Tulaczyk *et al.* (*13*) studied samples from Whillans Ice Stream, Antarctica, known to flow under very small basal drag over a layer of deforming till. The extent to which this model for ice flow can be applied to other (paleo-) ice sheets remains a matter of discussion (*14*, *15*).

We acknowledge the shortcomings of height above buoyancy as a proxy for effective basal pressure and state that "the height above buoyancy does not accurately describe seasonal water pressure variations in the subglacial drainage system." Nonetheless, at the grounding line, this remains a valued approximation (accounting for a minimal pressure effect to allow fresh water to escape from under the glacier). Many borehole studies have inferred much lower effective pressures, but these observations are typically much farther inland than the 20 km from the grounding line that we considered and thus are not relevant to our study. Meyer *et al.* (*16*) suggest that the correlation between sliding speed and the inverse of height above buoyancy can be explained by mass-balance considerations and scaling arguments.

Minchew *et al.* are incorrect when stating that the slip rate would be independent of lateral drag or gradients in extensional stresses. These terms are directly linked to velocity gradients as expressed in their equation 2; thus, if the slip rate changes, so will both force balance terms.

Minchew *et al.* conclude that if the conclusion of (*1*) is correct, the basic tenet that glacier sliding is driven by gravity does not apply. It is tempting to speculate on the mode of glacier flow suggested by our analysis. Perhaps the flow of laterally constrained outlet glaciers in Greenland is akin to the shelfy-stream model, with the downglacier ice essentially being pushed forward by the downward-moving mass of interior ice. On a floating ice shelf, the velocity is determined by the discharge across the grounding line, not by local processes. We suggest that perhaps the "effective" grounding line is farther upstream and outlet glaciers may be more like ice shelves, albeit with sufficient basal drag to compensate for the driving stress. Formulating a physical model to explain our observations is the next step. Rejecting our conclusion simply because no physical mechanism has been proposed is not justified.

[1]Department of Geological Sciences, University of Kansas, Lawrence, KS, USA. [2]Department of Geography and Atmospheric Science, University of Kansas, Lawrence, KS, USA.
*Corresponding author. Email: stearns@ku.edu

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